

REPORT OF THE PERFORMANCE IN ICE-COVERED WATERS COMMITTEE

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I. GENERAL

1. MEMBERSHIP AND MEETINGS

The Committee appointed by the 16th ITTC consisted of the following members:

E Mäkinen (Chairman)
J Alekseyev
G Frankenstein
H Kitagawa
D Maksutov
M Michailidis
R Milano
J Schwarz

During the term the Committee experienced significant changes. Following the tragic death of Michailidis, M Williams was appointed his successor as the representative of NRC Canada.

Due to reorganization of the arctic activities in Wärtsilä, E Mäkinen had to resign and E Enkvist was elected his successor both as a member of the Committee and as the Chairman.

R Milano had to resign due to rearrangement of his work.

The Committee met on three occasions: Hanover, CRREL, August 1982; Hamburg, HSVA, September 1983 and the final meeting in Helsinki, WARC, February 1984.

2. RECOMMENDATIONS OF THE 16th ITTC

2.1 General Recommendations

2.1.1 The Symbols listed in Appendix A of the 16th ITTC be used until they are approved by the Information Committee.

2.1.2 Continue the development of analytical prediction methods for the forces on and for the performance of vessels and structures in ice.

2.1.3 Continue and encourage the development of model ice.

2.1.4 Continue model and full scale testing in ice (including ice properties and conditions) and every opportunity be taken to make careful correlation analysis between model and full scale results.

2.2 Immediate Tasks for the Committee

2.2.1 Continue the testing of the ITTC Ice Committee's standard model and that the comparison of test results and full scale predictions be reviewed and reported.

2.2.2 Investigate the fundamental effects of friction in ice-breaking. This is to be achieved by re-testing the standard model at other friction values which are to be determined by the new Committee.

2.2.3 Review the present techniques used in propulsion testing.

2.2.4 Model and full scale experiments, including ice impact force measurements, be initiated on ships and structures in all ice conditions.

II. REVIEW OF RESEARCH ON MODELING IN ICE
OF IMPORTANCE TO THE ITTC

INTRODUCTION

During the term the work of the Committee has mainly concentrated on reviewing work related to the recommendations of the 16th ITTC. The first part of the Report addresses the Immediate Tasks for the Committee, and in the second part the General Recommendations are reviewed and commented.

In addition, ARCTEC CANADA have delivered tables of results from model tests to the Ice Committee, but as the tests were performed during an implementation period with changes of the model ice dopant and as no full report has been received, the results are not included in this summary.

1. STANDARD MODEL TESTS

Proposed Test Program:

The test program is presented in the proceedings of the 16th ITTC and this Report will mainly concentrate on presenting results from the tests.]]

Run	Ice Thickness meters	Ice Strength kPa	Velocity m/sec.
1 to 3	0.45	400	0.5, 2.5, 5.5
4 to 6	0.70	400	0.5, 1.5, 5.5
7 to 9	0.45	800	0.5, 2.5, 5.5
10 to 12	0.70	800	0.5, 1.5, 5.5

1.1 Model Tests with R-Class Icebreakers

As part of the project of the Ice Committee the following facilities have conducted model tests with the R-class models:

The models, one 1:20 and one 1:40, were circulated between the facilities and according to a decision of the Ice Committee the surface treatment was not changed in any way. Each participating laboratory made their own friction tests, using a plank which accompanied the model, with results as follows:

Participating Ice Test Facilities:

Name	Scale Factor
U.S. Army Cold Regions Research and Engineering Laboratory (CRREL)	20
Hamburgische Schiffbau-Versuchsanstalt (HSVA)	20
Norwegian Hydrodynamic Laboratories (NHL)	40
The Arctic and Antarctic Institute (AARI)	40
Wartsila Helsinki Shipyard (WADAM)	20
Japan Ship Research Institute (JSRI)	20

Friction Coefficient Results:

Tank	Test Results
HSVA	Not tested - $f_D = 0.04$ assumed
CRREL	0.038 - 0.044
NHL	0.09 - 0.13
AARI	0.078 - 0.08
WADAM	0.032 - 0.062
JSRI	0.04 - 0.07

The main particulars of the R-class icebreakers are:

Length - between perpendiculars	87.93 m
Length - load waterline	93.00 m
Beam - maximum	19.36 m
Draft - amidships	6.93 m
Displacement	7632.3 m ³
C _B	0.611
C _P	0.665
C _W	0.799
Number of propellers	2
Type of propellers	Unducted
Installed power	11000 kW

The type of model ice was as follows:

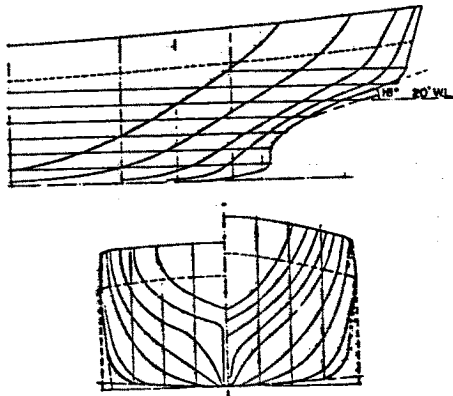
HSVA	Carbamide
CRREL	Carbamide
NHL	Artificial
AARI	Saline
WADAM	Saline
JSRI	Saline

The original towing test data are presented in the following tables.

Figure 1 shows the bow lines and body plan.

FIGURE 1

ABBREVIATED LINES PLAN "R" CLASS ICEBREAKER



"R" CLASS ICEBREAKER

The Committee agreed to present only the original data from each facility in this summary, as any analysis and processing seems to distort comparison. In the original reports, see reference list, various techniques for analysing and expansion to full scale are presented. Ref. [1] to [7]

TABLE 1
HSVA TOWED RESISTANCE TESTS

DATE OF TEST	TEST NO.	h_I (MM)	δ_F (RPA)	V (M/S)	R_{IT} (N)
08.10.81	1.1	36.0	25.0	.110	40.6
	2.1	36.0	25.0	.310	51.2
	3.1	36.0	25.0	.710	81.4
	4.1	36.0	25.0	.120	43.2
13.10.81	5.1	51.0	27.0	.320	96.7
	6.1	51.0	27.0	.700	128.0
	7.1	50.0	27.0	.110	78.5
07.01.82	10.1	36.0	41.0	.110	53.0
	11.1	36.0	41.0	.710	90.4
	12.1	36.0	41.0	.310	55.6
21.07.82	13.2	49.0	43.0	.310	114.0
	14.2	49.0	43.0	.700	132.0
	15.2	49.0	43.0	.120	106.0
27.10.82	16.1	23.5	41.0	.109	22.2
	17.1	23.0	41.0	.690	49.5
	18.1	23.0	41.0	.310	30.4
29.10.82	19.1	22.5	21.0	.098	17.0
	20.1	22.5	21.0	.679	42.6
	21.1	22.0	21.0	.297	20.4
03.11.82	22.1	35.0	40.0	.108	27.8
	23.1	34.5	40.0	.691	63.8
	24.1	34.0	40.0	.299	46.8
05.11.82	26.1	35.5	17.5	.107	21.8
	27.1	35.0	17.5	.692	49.6
	28.1	35.0	17.5	.308	37.4

TABLE 2
CRREL TOWED RESISTANCE TESTS

V (m/s)	h_I (cm)	δ_F (kPa)	E (MPa)	R_{IT} (N)	R_{OW} (N)	R_I (N)
0.13	2.84	47.00	94.00	57.00	0.00	57.00
0.38	3.00	47.00	94.00	67.75	3.50	64.25
0.35	3.12	55.00	40.00	89.00	3.00	85.00
0.62	3.55	50.00	40.00	96.10	7.20	88.90
0.13	3.72	45.00	40.00	75.20	0.00	75.20
0.13	3.61	25.00	32.00	32.10	0.00	32.10
0.62	3.66	25.00	32.00	64.50	7.20	57.30
0.37	4.00	25.00	32.00	49.80	3.30	46.50
0.11	2.06	39.00	33.00	23.30	0.00	23.30
1.31	2.15	55.00	35.00	113.90	32.00	81.90
0.59	2.25	47.00	33.00	51.60	6.60	45.00
0.12	2.15	30.00	33.00	21.40	0.00	21.40
1.19	2.27	45.00	33.00	99.20	26.00	73.20
0.60	2.41	38.00	33.00	45.40	6.80	38.60
0.11	2.15	26.00	25.00	25.80	0.00	25.80
0.57	2.33	30.00	25.00	48.00	6.40	41.60
1.28	2.46	35.00	25.00	98.30	30.00	68.30
0.11	3.54	25.00	30.00	32.80	0.00	32.80
0.33	3.78	30.00	30.00	60.20	2.90	57.30
0.56	3.96	34.00	30.00	73.70	6.00	67.70

Notes:

R_{IT} = total measured resistance

R_{OW} = resistance in clear-water, from CRREL tests

$$R_I = R_{IT} - R_{OW}$$

TABLE 3
NHL TOWED RESISTANCE TESTS

TEST	BENDING STRENGTH δ_F (N/m ²)	COMPRESSION STRENGTH δ_C (N/m ²)	SHEAR STRENGTH τ_S (N/m ²)	MODULUS OF ELASTICITY E (N/m ²)	ICE THICKNESS h_I (cm)	VELOCITY v (m/s)	TOTAL RESISTANCE R_{IT} (N)
1	$32.0 \cdot 10^4$			$2813 \cdot 10^4$	0.625	0.064	8.52
2	$22.1 \cdot 10^4$			$1714 \cdot 10^4$	0.58	0.385	25.50
3	$24.95 \cdot 10^4$			$2640 \cdot 10^4$	0.62	0.904	60.96
4	$13.98 \cdot 10^4$	$6.13 \cdot 10^4$	$0.56 \cdot 10^4$	$1528 \cdot 10^4$	1.02	0.070	25.08
5	$14.25 \cdot 10^4$			$1229 \cdot 10^4$	1.10	0.48	74.64
6	$31.63 \cdot 10^4$	$7.97 \cdot 10^4$	$3.39 \cdot 10^4$	$2790 \cdot 10^4$	1.05	0.88	107.13
10	$8.73 \cdot 10^4$		$1.54 \cdot 10^4$	$825 \cdot 10^4$	0.60	0.075	12.47
11	$10.46 \cdot 10^4$		$1.41 \cdot 10^4$	$743 \cdot 10^4$	0.6	0.42	36.62
12	$18.32 \cdot 10^4$		$1.70 \cdot 10^4$	$1016 \cdot 10^4$	0.55	0.845	56.05
13	$9.8 \cdot 10^4$		$1.73 \cdot 10^4$	$908 \cdot 10^4$	1.1	0.072	18.50
14	$13.42 \cdot 10^4$	$4.29 \cdot 10^4$	$1.81 \cdot 10^4$	$1432 \cdot 10^4$	1.1	0.42	79.44
14 REP.	$9.74 \cdot 10^4$	$3.99 \cdot 10^4$	$1.53 \cdot 10^4$	$1095 \cdot 10^4$	1.125	0.395	74.30
15	$12.61 \cdot 10^4$		$1.57 \cdot 10^4$	$2218 \cdot 10^4$	1.1	0.877	106.94
16	$6.66 \cdot 10^4$	$3.68 \cdot 10^4$	$1.2 \cdot 10^4$	$1048 \cdot 10^4$	1.75	0.080	37.91
17	$13.37 \cdot 10^4$	$4.29 \cdot 10^4$	$1.87 \cdot 10^4$	$1898 \cdot 10^4$	1.70	0.395	99.24
18	$11.35 \cdot 10^4$		$1.73 \cdot 10^4$	$1568 \cdot 10^4$	1.70	0.875	196.03

TABLE 4
AARI TOWED RESISTANCE TESTS

Date	δ_F (kPa)	h_T (mm)	R_{IT} (N)	V (m/s)
Water salinity $S_W = 12 \text{ ‰}$				
28.11.80	42.0	17.6	7.95	0.14
02.12.80	42.0	17.3	8.80	0.27
03.12.80	43.0	17.6	9.60	0.35
04.12.80	41.0	17.4	10.55	0.45
05.12.80	41.0	17.3	7.80	0.13
15.12.80	42.0	11.2	5.80	0.20
16.12.80	42.0	11.5	6.46	0.28
17.12.80	42.0	11.4	7.15	0.37
18.12.80	42.0	11.2	7.60	0.46
19.12.80	41.0	11.6	5.60	0.12
Water salinity $S_W = 4.1 \text{ ‰}$				
05.01.81	88.0	17.5	11.0	0.2
06.01.81	84.0	17.4	13.65	0.42
06.01.81	83.0	11.3	8.90	0.35
07.01.81	83.0	17.5	12.05	0.31
07.01.81	84.0	11.0	7.30	0.23
08.01.81	83.0	17.4	10.20	0.16
08.01.81	85.0	11.2	6.05	0.03
09.01.81	82.0	17.5	9.80	0.06
14.01.81	84.0	11.2	10.35	0.50

TABLE 5
WADAM TOWED RESISTANCE TESTS
($\delta_F = 0$ FROM PRESAWN TESTS)

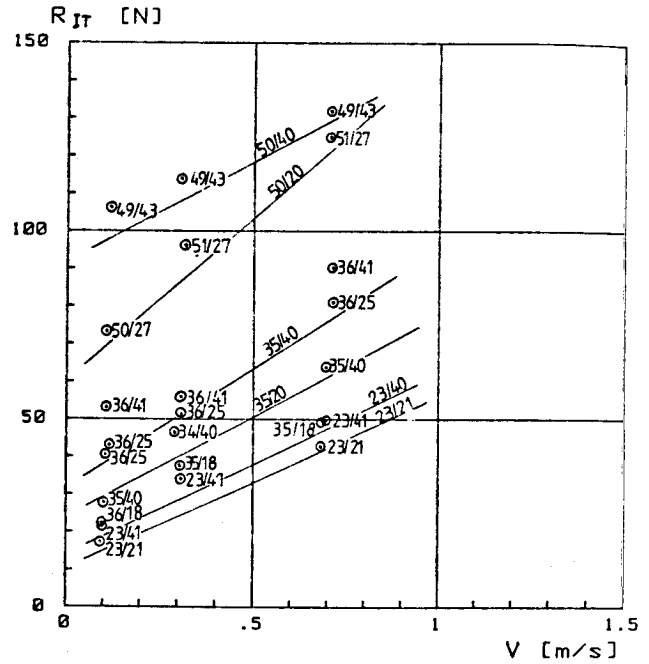
Date	V (m/s)	h_T (mm)	δ_F (kPa)	E (kPa)	R_{IT} (N)
810310	0.58	36	26	5534	70.04
	0.58	37	0	0	41.50
	0.13	34	0	0	13.54
810311	0.14	35	0	0	14.22
	0.58	38	0	0	54.15
	0.59	32	31	5643	52.58
810312	1.24	23	0	0	86.62
810313	0.58	37	0	0	35.90
	0.58	36	28	5773	69.5
	0.12	33	0	0	13.24
810316	1.25	39	0	0	133.22
810317	0.59	22	19	2491	32.27
	0.12	23	0	0	8.14
	0.58	20	0	0	22.17
810318	1.25	23	0	0	87.11
810319	0.12	22	0	0	6.87
	0.58	23	0	0	25.02
	0.58	19	20	2534	27.66
810320	1.25	37	0	0	114.58
810224	0.58	24	0	0	24.82
	0.58	25	22	2976	49.83
	0.14	20	0	0	8.44
810325	1.25	23	0	0	85.25
810326	0.59	36	32	6774	68.18
	0.12	38	0	0	14.62
	0.59	33	0	0	42.48
810327	1.25	37	0	0	115.56

TABLE 6
JSRI TOWED RESISTANCE TESTS

* = doubtful

RUN NO.	h_T mm	σ_F kPa	E MPa	V m/s	R_{IT} N
1	22.4	52.9	14.04	0.112	24.16
2	22.4	52.9	14.04	1.230	97.90
3	22.7	43.7	10.52	0.335	30.88
4	22.7	43.7	10.52	1.006	67.70
5	23.9	36.7	8.37	0.559	45.98
6	23.9	36.7	8.37	0.783	56.26
7	37.0	13.6*	3.81*	0.559	109.98
8	37.0	13.6*	3.81*	0.783	121.76
9	34.9	21.2*	3.55*	0.335	92.78
10	34.9	21.2*	3.55*	1.006	147.30
11	35.3	65.0	10.29	0.112	71.92
12	35.3	65.0	10.29	1.230	167.52
13	12.0	53.9	24.72	0.112	5.82
14	12.0	53.9	24.72	1.230	58.94
15	12.2	59.6	30.03	0.559	20.22
16	12.2	59.6	30.03	1.006	43.24
17	21.3	43.1	9.76	0.559	37.60
18	21.3	43.1	9.76	1.006	64.20
19	21.3	45.4	14.76	0.112	18.00
20	21.3	45.4	14.76	1.230	93.26
21	20.7	36.6	13.36	0.559	33.04
22	20.7	36.6	13.36	1.230	86.84
23	9.9	55.6	33.52	0.112	4.44
24	9.9	55.6	33.52	1.230	51.54
25	22.7	36.5	10.87	0.112	17.24
26	22.7	36.5	10.87	1.230	91.64
27	37.2	43.5	7.52	0.112	61.50
28	37.2	43.5	7.52	1.230	143.14
29	35.6	36.3	6.02	0.557	66.82
30	35.6	36.3	6.02	0.783	84.86
31	21.8	26.6	7.54	0.112	15.50
32	21.8	26.6	7.54	1.230	84.36
33	21.1	26.7	9.85	0.559	33.24
34	21.1	26.7	9.85	0.783	48.44
35	35.8	35.2	5.43	0.112	33.64
36	35.8	35.2	5.43	0.559	72.42
37	35.8	35.2	5.43	1.230	118.30

HSVA



Figs. 2-5: Results from towing tests.

The points are directly plotted uncorrected points, the numbers indicating thickness (mm)/bending strength (kPa).

The lines are tentative manual plots drawn without any attempt to apply regression analysis.

CRREL

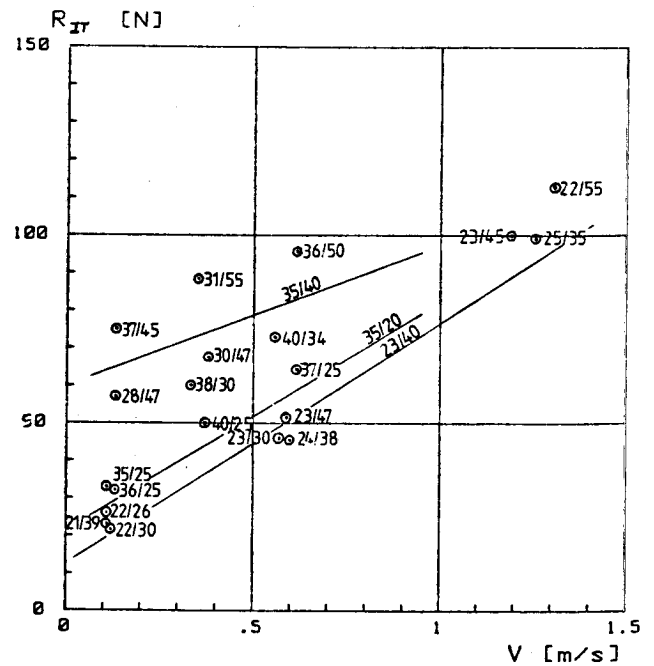


Fig. 3

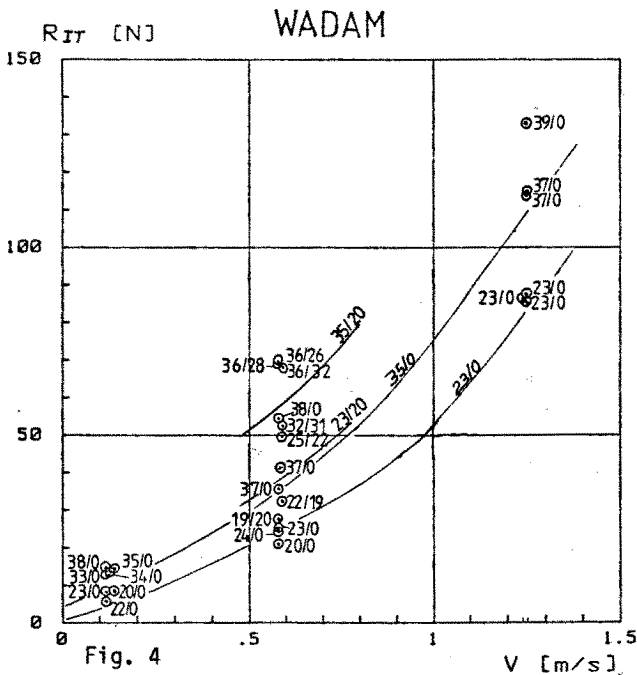


Fig. 4

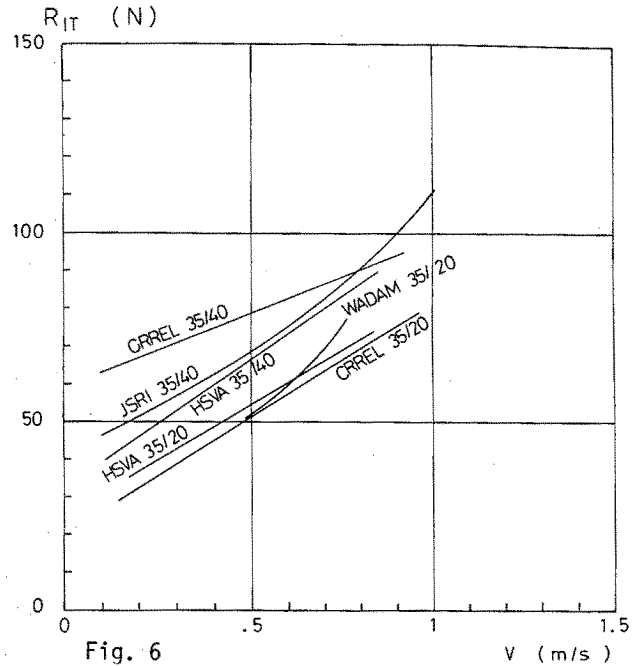


Fig. 6

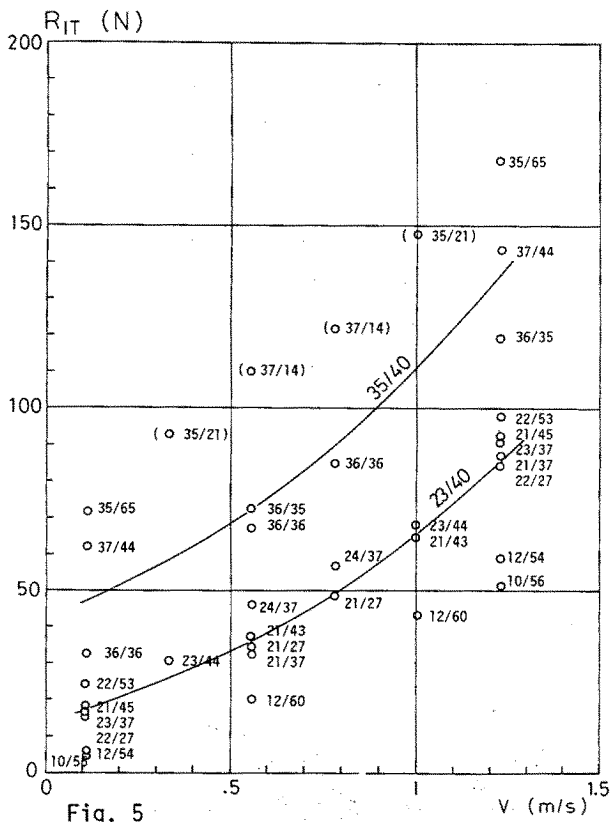


Fig. 5

Fig. 6 shows a comparison of some of the manually plotted results with the 1:20 model. Although the customary empirical corrections of each laboratory are not included, the picture still gives rise to serious consideration by those engaged in ice resistance research.

1.2 Propulsion Tests

The propulsion tests to be made as a part of the ITTC Ice Committee sponsored analysis of the CCGS R-class icebreaker were run with the 1:20 model equipped with propellers designed to NRC specification but built and provided by HSVA.

The propulsion tests were run by the four largest participating ice tanks, CRREL, HSVA, JSRI and WADAM

1.2.1 CRREL Results. In the CRREL propulsion tests, the model remained connected to the towing post of the test basin carriage. For each selected towing velocity and ice condition, the ship propellers were set at two rpm's and the thrust and torque on the propellers were measured together with the pull exerted on the towing post. From the experimental data measured for each pair of tests at nominally identical velocity and ice condition, the propeller's rpm at which the pull would be zero was interpolated as well as the corresponding propeller thrust and torque, and the total ice resistance was calculated from the resistance tests performed earlier.

TABLE 7
MODEL SELF-PROPULSION POINTS CALCULATED BY CRREL

V (m/s)	h_T (cm)	δ_F (kPa)	R_{IT} (N)	n_{IA} (rpm)	T_{IA} (N)	Q_{IA} (Nm)	J_{IA}	K_{TIA}	$10 K_{QIA}$
0.11	2.73	33.5	36	305	36	0.70	0.105	0.384	0.363
0.11	2.73	24.0	27	293	25	0.65	0.109	0.291	0.367
0.11	3.70	22.0	37	348	37	0.93	0.092	0.305	0.373
0.11	3.25	36.5	47	394	46	1.20	0.081	0.296	0.375
0.31	3.67	25.0	49	488	71	1.70	0.185	0.298	0.346
0.34	3.43	42.0	65	498	77	2.07	0.199	0.310	0.405
0.56	2.63	41.5	60	491	79	1.70	0.332	0.328	0.342
0.54	2.85	26.5	47	466	62	1.62	0.338	0.285	0.362
0.55	3.87	30.0	71	545	84	2.25	0.294	0.283	0.368
0.55	3.61	44.0	83	609	112	3.20	0.263	0.302	0.419
1.23	2.73	47.5	114	728	130	3.35	0.492	0.245	0.307
1.26	2.82	28.0	94	740	140	3.45	0.496	0.256	0.306

1.2.2 HSVA Results. The tests run at HSVA were actual self-propulsion, where the ship model was propelled under its own power with only umbilical wires for electrical power and data transmission. The results of the HSVA tests are listed in Table 8.

TABLE 8
SELF-PROPULSION TESTS AT HSVA

Date of test	Test NO	h_T (mm)	δ_F (kPa)	V (m/s)	n_{IA} (1/S)	T_{PIA} (N)	T_{stdIA} (N)	Q_{PIA} (Nm)	Q_{STDIA} (Nm)	P_{DI} (W)
29.03.83	1102.1	35.0	19.5	.156	6.11	22.4	19.9	.71	.60	50
	1101.1	35.0	19.5	.819	12.00	55.6	56.3	2.30	2.17	337
30.03.83	1302.1	22.0	19.0	.384	6.16	21.0	17.4	.60	.60	46
	1301.1	22.0	19.0	1.190	12.60	55.2	54.9	2.11	1.96	322
6.04.83	1202.1	35.0	20.0	.487	8.37	28.0	24.6	1.18	1.14	122
	1201.1	35.0	20.0	.800	10.90	45.6	41.8	1.81	1.74	243
7.04.83	1402.1	23.0	19.0	.663	8.56	25.7	25.3	1.02	1.00	102
	1401.1	23.0	19.0	1.130	11.40	42.8	38.1	1.49	1.41	200
27.04.83	1601.1	23.0	22.0	.725	8.90	25.7	23.9	1.39	1.15	142
29.04.83	1702.1	34.0	19.0	1.010	12.10	48.9	43.5	2.02	1.99	305

It can be noted that these tests were run for the two required ice thicknesses but at only one ice strength ($\delta_F = 20$ kPa).

1.2.3 JSRI Results. The propulsion tests were run with the model towed at constant speed, free in pitch, roll, heave and surge, and the propeller revolutions are adjusted to the model self-propulsion point. The thrust and torque on both propellers were measured independently. The test results are presented in Table 9.

TABLE 9
JSRI SELF-PROPULSION TESTS IN LEVEL ICE
R-CLASS ICEBREAKER MODEL

Run No	h_I mm	δ_F kPa	E MPa	V m/s	N_I rps	$T_{p_{IA}}$ N	$T_{s_{IA}}$ N	$Q_{p_{IA}}$ mN	$Q_{s_{IA}}$ mN
1	21.5	21.3	6.08	0.122	4.37	10.04	9.98	0.265	0.314
2	21.5	21.3	6.08	0.553	7.36	22.46	22.09	0.755	0.853
3	23.0	19.3	5.95	0.783	8.60	27.55	25.53	1.000	1.127
4	21.7	23.4	8.97	1.230	12.17	51.66	50.27	1.803	1.989
5	37.4	37.2	5.13	0.112	6.40	23.46	22.25	0.559	0.657
6	37.4	37.2	5.13	0.561	10.60	40.31	41.82	1.950	1.921
7	23.1	30.4	8.21	0.108	4.43	10.66	9.88	0.245	0.284
8	23.1	30.4	3.21	0.550	7.99	24.94	24.32	0.941	1.176
9	35.5	34.9	5.74	1.230	14.69	73.83	76.12	3.391	-----
10	23.3	42.7	10.09	1.230	13.11	60.26	59.57	2.332	2.773
11	22.1	42.6	11.66	0.783	9.50	34.80	34.82	1.186	1.323
12	22.2	40.8	9.22	0.112	4.97	13.72	12.87	0.323	0.343
13	22.2	40.8	9.23	0.335	6.39	19.86	19.65	0.519	0.598
14	36.0	40.7	5.97	0.783	11.63	52.19	49.34	2.244	2.597
15	34.6	50.6	8.40	1.006	14.91	84.09	83.75	3.891	4.253
16	23.6	37.8	8.54	1.007	11.89	51.24	50.45	1.989	2.283
17	37.9	38.3	4.94	1.008	15.53	92.25	93.15	4.390	4.626
18	21.7	22.8	5.82	0.335	5.01	11.25	10.30	0.304	0.333
19	21.7	22.8	5.32	1.010	12.02	55.67	55.23	1.764	1.862

1.2.4 WADAM Results. The propulsion tests run at WIMB were not run in level, solid ice but rather in presawn ice. These tests were run with the model towed by the carriage at predicted speed and propeller rpm.

The total propeller thrust and torque were measured together with the pull (F_{TOW}) exerted by the towing mechanism. The results of these propulsion tests are given in Table 10.

TABLE 10
RESULTS FROM PROPULSION TESTS
(all tests performed in presawn ice)

Date	V (m/s)	h_I (mm)	n_{IA} (rpm)	T_{TOTIA} (N)	Q_{TOTIA} (NM)	σ_F (kPa)	E (kPa)	F_{TOW} (N)
810414	0.13	24	305	29	1.1	18	2196	105.24
	0.58	22	474	55	1.6	18	2196	102.2
810415	1.24	25	775	105	2.5	21	3512	129.76
810416	0.58	25	467	52	1.4	31	4573	104.55
	0.13	25	392	46	1.3	31	4573	86.11
810422	1.25	25	844	129	3.0	21	2011	95.03
810423	0.13	20	340	31	1.0	17	1658	95.82
	0.59	19	543	72	1.7	17	1658	78.26
810424	1.25	25	705	69	2.3	26	2682	155.66

Figure 7 presents those data points, delivered power P_D vs velocity, from CRREL, HSVA and JSRI tests most nearly corresponding to the nominal ice conditions ($\sigma_F = 20$ kPa, $h_T = 2.25$ cm) and ($\sigma_F = 20$ kPa, $h_T = 3.5$ cm). Data from WADAM tests were omitted since these tests were run in presawn ice rather than in level ice.

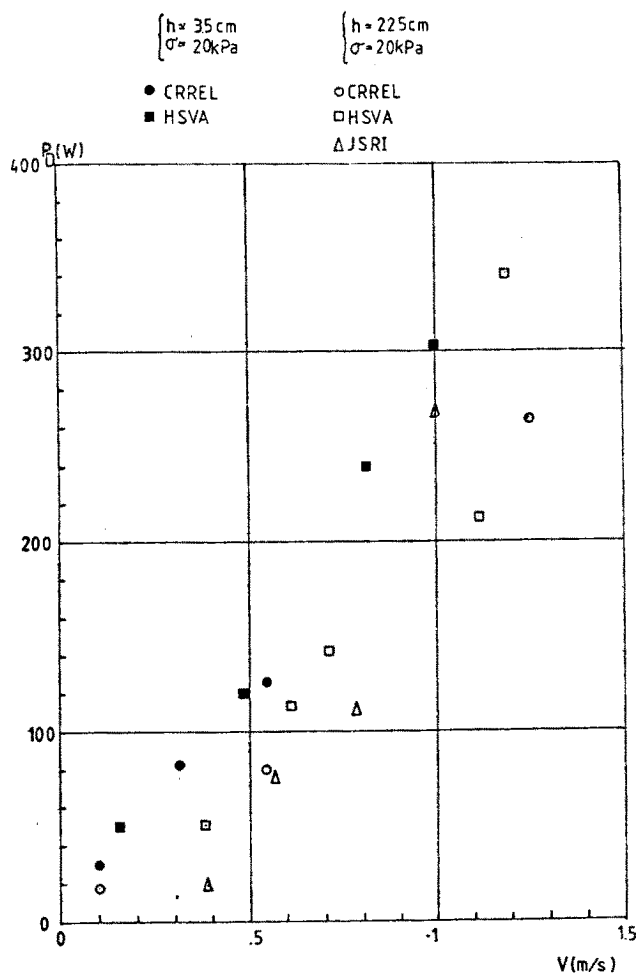


Fig. 7: Comparison of some of the results from propulsion tests.

1.3 Full Scale Prediction

Following the recommendations of the 16th ITTC, the Committee carefully considered the possibility of comparing the model test data with full scale test data published so far for the R-class icebreakers.

It was found that this task requires model testing either at a realistic coefficient of friction or at two different coefficients of friction. At present, the model has been tested only with the original smooth surface treatment. Thus it was decided not to present any full scale predictions at this stage, as this would mean neglecting the crucial influence of mechanical friction on the ice-breaking process.

Two different sets of full scale data have been obtained with the R-class icebreakers, that reported by Arctec with CCGS Pierre Radisson [8] and that by Michailidis et al CCGS Franklin [9]. Both sets represent relatively elaborate trials. Some difficulties still appear in the published reports, in particular:

- the thrust calibration by a bollard test, using a dynamometer is missing;
- the result is presented as thrust, not resistance, and different methods of obtaining resistance produce different resistance curves;
- a very high coefficient of friction is given in one report, drawing attention to the need for a standard method of friction measurement, complemented by hull roughness data;
- the two test series are made at different drafts;
- data on snow density and uniaxial compressive strength of the Ice are missing.

The importance of reliable full scale data for the R-class is amplified by the number of different model tests which have been carried out for this ship. Furthermore, the Committee agreed that because of the impossibility of controlling environmental conditions, any full scale data in ice should be checked by multiple trials.

For these reasons, completeness, reliability and repeatability, the Committee strongly recommends that a third test series with this class of ships is undertaken. Several members stated that their organisations would be ready to send scientists to take part in the work on such a test series. The Committee notes that NRC is willing to undertake such tests, and will make a proposal to Canadian Coast Guard.

In this connection it was found that the list of various data to be collected during testing, which is included in the ITTC 1978 report, is outdated and it is recommended that work will be commenced on its updating.

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2. FRICTION IN ICEBREAKING

Among the parameters which significantly affect ice forces on structures, the friction coefficient between ice and the structure's surface is possibly the most elusive to quantify. A review of past work in the area of ice friction reveals much disagreement between results from various investigations as is apparent from Table 1, which summarizes the main findings of studies performed from 1939 to 1983, [ref. 1 to 12].

The IAHR-Working Group on Standardizing Testing Methods in Ice made recommendations for ice friction measurement procedures [13], and the ITTC Committee on Ships in Ice Covered Waters specified the conditions of ice friction measurements in conjunction with the International Model Test Program of an icebreaker [14].

The IAHR recommendations and ITTC requirements may ensure consistency in model test measurements of the friction factor and therefore enable comparison between results from different test facilities. They do not assure that the measured friction factor correctly represents that between the structure and the ice during either model or field tests.

Attempts to measure the friction coefficient by moving a hand-held instrumented rig with an ice piece against a ship hull above the bow waterline are not promising, because they showed the result to be sensitive to surface pressure which will be much higher in case of contact between the ice edge and hull during breaking, ref. [5], [6] Vuorio and Teinonen.

From full scale tests with ships in pre-sawn ice combined with an analytical procedure Enkvist [17] concluded that the dynamic friction factor of a conventionally painted ship hull is in the order of 0.16 and for a newly epoxy treated 0.08. The procedure used is logical but contains many steps and the full scale data suffer from scatter.

Mäkinen et al [18] presented data from the Valpas-class of Finnish Coast Guard Cutters, showing that the condition of the hull surface has a pronounced influence on the ice resistance. Later tests carried out by Wärtsilä with large ships confirm this finding, but as the difference between a new uncoated hull and a new epoxy coated hull depends entirely on the condition of the uncoated hull during tests, it is difficult to specify generally applicable figures on the difference.

A recent study [15] was undertaken as an attempt to clarify some, if not all, of the discrepancies between results of previous investigations, to identify more completely those parameters which most affect ice friction and to make recommendations for future more detailed studies and for friction test procedures.

This investigation was conducted for urea-doped, columnar ice and various materials (steel, aluminium, and Inerta 160 coated steel) at ambient temperatures of $-1.5 \pm 1^\circ\text{C}$, and yielded the following results:

- a) The basic test configuration of the friction experiment (configurations a and c versus b and d of Fig. 1) significantly influences the behavior of the kinetic friction factor with varying relative velocity between ice and smooth stainless steel.

The kinetic friction factor between loaded ice samples travelling over a smooth stainless steel sheet increases as velocity is increased from 5 to 25 cm/s. There is no significant influence of velocity over the range 5-25 cm/s on the kinetic friction coefficient between a smooth stainless steel sample and an ice sheet (Fig. 2).

- b) The frictional shear stress, τ , of ice sliding over smooth stainless steel is a linear function of the normal pressure, P , applied to the ice sample, i.e.

$$\tau = \alpha P + \tau_0$$

where both α and τ_0 were found to be decreasing functions of the ice hardness H_i (Figures 3 and 4). When the ice hardness exceeded a critical value, the adhesion stress, τ_0 , became practically nil and α became constant. It is judged premature to quantify this critical hardness since it may depend not only on its measurement methods but also on the material surface characteristics and type of ice.

This result implies that for ice hardness below its critical value, the kinetic friction coefficient defined as $f_{ID} = \tau / P$ is a decreasing function of both P and H_i . For H_i (H_i) critical, f_{ID} is independent of both P and H_i .

- c) A large increase in the kinetic friction factor between ice materials of stainless steel or aluminium was observed when the roughness average of the material is increased slightly from 0.3 to 1.5 μm . Further increase in roughness up to 10 μm RA had only minor effects on the friction factor.

- d) The kinetic friction coefficient between a sample of rough stainless steel (1.5 μm RA) and an ice sheet decreases significantly as velocity is increased from 5 to 25 cm/s, as opposed to the negligible effect observed with a smooth stainless steel sample (see Conclusion a2).
- e) The friction coefficients between ice and samples of bare stainless steel and aluminum for three roughnesses (0.3, 1.3, 3.2 μm RA) did not vary significantly from each other. On the other hand, the friction factor between ice and Inerta 160 coated steel with an intermediate roughness of 1.6 μm RA was lower than that for the smoothest bare steel and aluminum (0.3 μm RA). These results indicate that the friction coefficient is not only affected by the magnitude of the surface roughness but also by surface and material properties such as roughness morphology and thermal conductivity.
- f) For the type of ice used in this investigation, no effect of ice orientation on the friction coefficient between samples of ice and stainless steel was detected.
- g) The testing procedure and apparatus used during this investigation yielded repeatable results of the influence of various parameters on the kinetic friction coefficient of ice.

Investigator	TEST CONFIGURATION	MATERIALS INVESTIGATED	CONTACT SURFACE SUBMERGED OR WET	EFFECTS OF VARYING...			SURFACE ROUGHNESS, R	THERMAL CONDUCTIVITY, K	HARDNESS, H
				NORMAL LOAD, N, OR NORMAL PRESSURE, P	SAMPLE SIZE S.S	VELOCITY, v			
BOWDEN & HUGHES (1939)	sample of material on rotating ice table	none applicable to this study	-	no effect with low loads. heavy loads: μ_k when $T=0^\circ\text{C}$ μ_k when $T < -1^\circ\text{C}$	none $0.02 \leq S.S. \leq 3.1$ cm $v=400$ cm/s	certain range had no effect but μ_k for low velocities	-	μ_k as k \uparrow	-
ENKVIST (1972)	(a) towing sleds (b) metal plates over ice (c) towing ice surface test	aluminum and various steels	-	μ_k as P \uparrow (a) & (b): $v=0.6$ m/s (c): μ_k constant when $P > 1.3$ kPa	-	none when $0.25 \leq v \leq 1.75$ m/s	(c) μ_k depended on type of R, not degree of R	-	-
RYVIM (1973)	Steel specimen towed on fresh water ice (field tests)	Polished and rusty steel	no effect	no effect if $P > 10$ kPa μ_k with P \uparrow for $P < 10$ kPa	-	no effect (all tests run at $v \geq 0.5$ m/s)	μ_k as R \uparrow	-	no effect
EVANS ET AL (1976)	pendulum-type apparatus. sliders on rotating drum of ice	copper, Perspex and mild steel	-	-	affects μ_k but specific relationship not mentioned	μ_k as v^{-3} for $0.2 \leq v \leq 10$ m/s $T=11.5^\circ\text{C}$	affects μ_k but specific relationship not mentioned	μ_k as k \uparrow	theory: μ_k as H \uparrow
SAEKI ET AL (1979)	sample of cylindrical ice moving over test surfaces	concrete plates and various steel plates	-	none when $100 \leq P \leq 1000$ kPa $-3.8 \leq T \leq -2.3^\circ\text{C}$ $1.3 \leq v \leq 1.4$ cm/s rough carbogreen?	-	none when $0.07 \leq v \leq 8$ cm/s $-5^\circ\text{C} \leq T \leq -4^\circ\text{C}$ $P=196$ kPa painted carbogreen	influences friction factor	-	-
VANCE (1980)	towing ice block over test surface	steel: uncoated and coated with Inerta 160	-	μ_k as P \uparrow $9 \leq P \leq 25$ kPa	-	μ_k as v \uparrow $v=6.86$ or 15.8 cm/s	μ_k as R \uparrow	-	-
TUSIMA & TABATTA (1979-1981)	table of test material moving beneath ice sample	carbon and stainless steel, aluminum and Inerta 160	no effect on μ_k	none when $2.9 \leq P \leq 226$ kPa $T=-5^\circ\text{C}$ $v=10^{-4}$ or 2×10^{-3} m/s	none	μ_k as v \uparrow 3.5×10^{-2} to 5×10^{-2} m/s $T=-5^\circ\text{C}$	μ_k as R \uparrow	-	-
CALABRESE & BUXTON (1980)	ring of material rotating on plate of ice	steel	-	none	-	μ_k as v \uparrow $1 \leq \mu_k \leq 100$ cm/s $P=275$ kPa $T=-18^\circ\text{C}$ 1018 steel	slight μ_k as R \uparrow $T=-22^\circ\text{C}$ $P=310$ kPa	-	-
CALABRESE & MURRAY (1982)	ring of material rotating on plate of ice	steel	-	none	-	μ_k as v \uparrow $1 \leq \mu_k \leq 100$ cm/s $P=275$ kPa $T=-18^\circ\text{C}$ 1018 steel	slight μ_k as R \uparrow $T=-22^\circ\text{C}$ $P=310$ kPa	-	-
OKSANEN (1980, 1983)	fixed, loaded slider on rotating table of ice	ice, steel, concrete and Inerta 160	μ_k for wet ice five times μ_k for dry ice	μ_k as P \uparrow $0.82 \leq P \leq 4.1$ kPa	-	μ_k as v^{-3} at -15°C , μ_k as v^{-1} at -1°C ice on ice tests	-	theory: at low temperature μ_k as k \uparrow	Theory: μ_k as H $-3/4$

TABLE 1.

Summary of Results of Previous Studies

Note $\mu_k = fID$

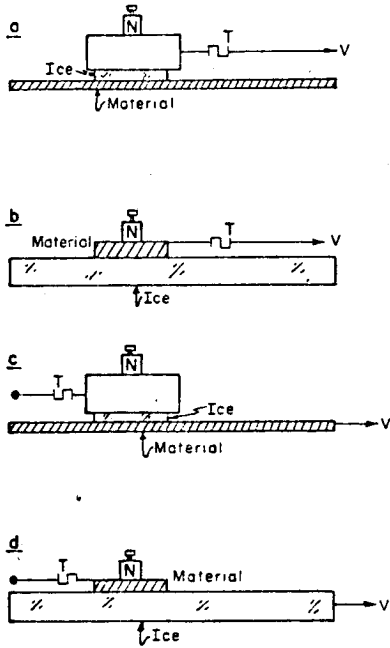


FIGURE 1. Test Configurations:

- a) loaded ice sample moving on stationary surface;
- b) loaded surface specimen moving on stationary ice sheet;
- c) stationary loaded ice sample on moving surface;
- d) stationary loaded surface specimen on moving ice sheet.

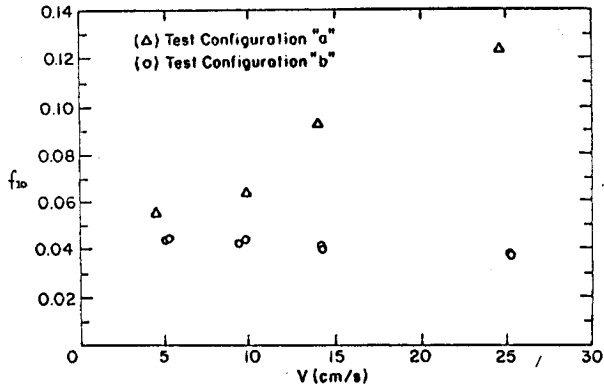


FIGURE 2. Effect of test configuration on variation of f_D with velocity.

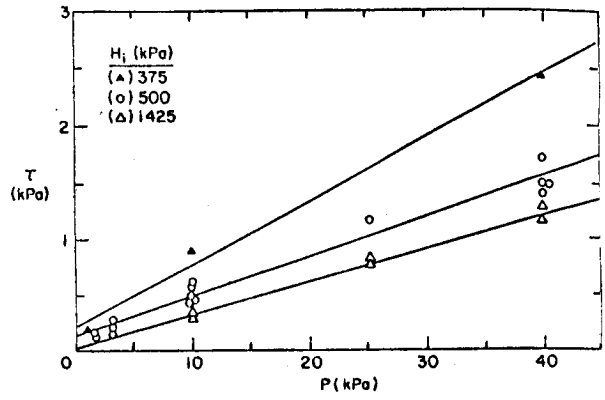


FIGURE 3. Variation of frictional shear stress with normal pressure and ice hardness ($V = 10 \text{ cm/s}$, $R = 0.36 \mu\text{m RA}$, stainless steel)

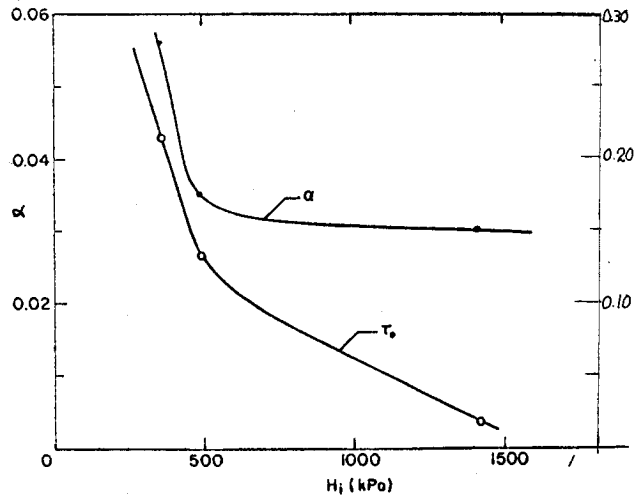


FIGURE 4. Plot of α and τ_0 (Eq.3) vs. ice hardness

CALABRESE AND MURRAY ON ICEBREAKER HULL COATINGS'

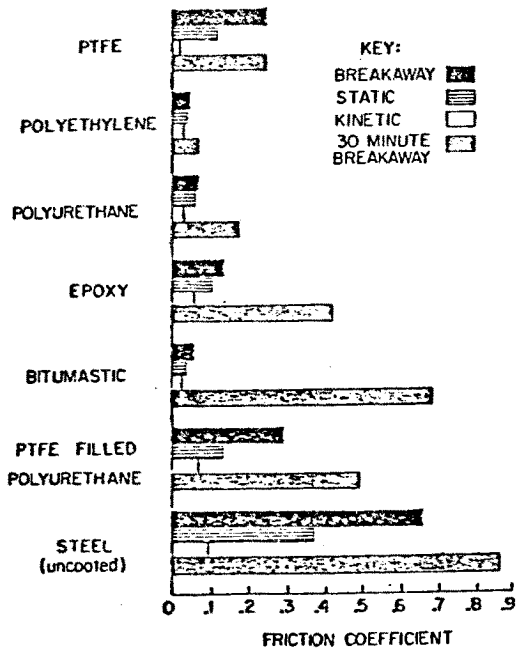


FIGURE 5. Example of friction coefficient results from rotation tests, ref. 10.

2.1 Recommendations

Based on the above results, recommendations are proposed for conducting friction tests so that meaningful comparison between different model studies, whether it be in the same laboratory or in different ones, may be made.

2.1.1 Recommendations for Future Studies.

Based on the experience gained through this study, it is highly recommended that in any future investigation of the effects of various parameters on the kinetic friction coefficient of ice tests be conducted in the two configurations (a) and (c) of loaded ice sample on material and loaded material sample on ice, respectively.

In addition, any series of tests designed to investigate the effects of a parameter other than velocity or pressure or both should be repeated for two extreme velocities (e.g. 5 and 25 cm/s) and/or two extreme pressures (e.g. 5 and 40 kPa). If significant variations in f_{ID} are noted between the extreme values of either parameter, tests at intermediate values should be made.

Specific parameters which need further investigation are the following:

- Tests ought to be made over a wider range of roughness, exceeding $10 \mu\text{m}$ RA. The actual roughness profile should also be measured.
- This study, and in particular the effect of velocity and test configuration, should be repeated at lower temperatures where heat dissipation is thought to take place more by conduction than by ice melting.
- Since some of the trends observed during this study may be due to the properties of urea-doped ice, this investigation should be repeated with ice of radically different structure, such as freshwater ice or snow ice, to eliminate the possible influence of urea concentration and "brine" drainage on the behavior of the kinetic friction coefficient with various parameters.

2.1.1 Recommendations for Friction Test Procedure in Model Studies.

The following general procedure is proposed for the determination of the kinetic friction coefficient between ice and structure surfaces during model tests of ice-structure interaction. It is based on the limited results obtained so far and is likely to be altered when more studies are completed.

- (a) It is recommended that the characteristics of the ice and test surface be as well documented as possible, in particular, type of ice, ice hardness, strength and crystal-line structure, type of test surface, surface roughness and surface treatment.
- (b) The friction test configuration (a or c in Fig. 1) should be selected to duplicate the loading and relative motion of the test. For example, in icebreaker tests, the ship hull is exerting pressure on surrounding ice and configuration (c) may be preferred, while in ice ride-up tests configuration (a) may be more appropriate. In case of doubt, both configurations should be used.
- (c) At least two loading pressures (e.g. 5 kPa and 20 kPa) ought to be used during friction tests to determine whether ice adhesion to the test surface influences the friction factor, especially when the model tests are to be conducted using weak, and thus "soft", ice.
- (d) Finally, in order to bring to light any variation of the frictional resistance with velocity, friction tests ought to be conducted at a minimum of two extreme velocities or, preferably, over a range of velocities.

The above procedure may appear overly cautious and time consuming. However, since the number of model tests in ice for particular structure are usually kept to a minimum because of their high cost and since frictional forces between ice and test structures are usually significant, it is considered worthwhile to invest sufficient time and effort in as thorough friction investigations as feasible.

The Committee recommends that full scale friction testing with icebreaking ships shall be continued and that the possibility of using friction panels in the shell shall be investigated. Such panels may be used for simultaneous recording of normal forces and tangential forces.

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3. ANALYTICAL AND SEMI-EMPIRICAL METHODS FOR THE PREDICTION OF SHIP RESISTANCE IN LEVEL ICE

Simple formulas for predicting the open water resistance of ships were more or less abandoned at the turn of the century. Instead, data from systematic model test series, such as Taylor's series, became the standard tool for ship powering purposes in basic design. Where a substantial data bank on non-systematic test results has been available it has been possible to employ multiple regression analysis including the selection of significant form parameters and resulting in useful analytical expressions for resistance prediction purposes. Such data banks are not available in case of ice resistance.

Compared to open water resistance the ice resistance of ships is unquestionably a still more involved process to model by detail analysis. On the other hand, the full-scale experimental backing is relatively scarce and not fully controlled. Thus it is not difficult to devise any simplistic expression and adjust its coefficients to make it fit half a dozen of experimental results. This is exactly what has happened. The result is confusing, as can be seen from Fig. 1.

Recent overviews and contributions have been made by Bachér [1], Milano [2] and Kotras et al [3]. Table 1 is a simplified summary, where some older method by the same authors have been left out for simplicity.

TABLE 1

LIST OF PROPOSED EXPRESSIONS FROM WHICH A QUANTITATIVE ICE RESISTANCE MAY BE COMPUTED.

Method	Ref. No.	PARAMETERS										No of Comp.	Comments
		L	B	T	Bow Form	h	σ_s	σ_c	Snow	f	ID Friction		
Carter	4	x	x		x	x	x		x	x		2	
Döngeloh	5		x		x	x	x					3	
Enkvist	6		x	x	x	x	x			x		3	Not intended for Predictions
Joh-Mak. + Levine	7	x	x		x	x						2	Marad-Series
Kashteljan	8		x		x	x	x					3	
Lew Edw-72	9		x	x		x	x			x		3	*C _B
Lewis-82	10	x	x			x	x					3	
Makutsov	11		x		x	x	x					2	Cargo Ships
Milano	12	x	x	x	x	x	x	x		x		5	
Naegle - Kotras	13, B	x	x		x	x	x	x		x		6	
Poznjak - Ionov	14	x	x		x	x	x			x		6	
Segal	15	x	x		x	x						2	River Icebreakers
Sujev	16		x	x	x	x				x		2	River Icebreakers
Vance	17	x	x			x	x					3	For Model Test Expansion

Some methods are just attempts to group the forces into components to facilitate regression analysis or model test result expansion, [7] [8]. Other methods rely on basic physical detail analysis of all involved phenomena, such as bending, crushing, breaking, turning, submerging, sliding [13] [12] [6].

The gross divergencies between these attempts show how difficult they are. It has by far not been possible to obtain detail experimental backing for all the hasty assumptions behind the details of these methods.

In a special report to the ITTC Ice Committee Milano [2] describes several semi-empirical and purely theoretical methods of predicting the icebreaking resistance of ships. He also applies these methods to a number of different types of icebreaking ships and compares the calculated resistances with model test results obtained at HSVA. Compared with these model test results, it seems that Milano's theoretical model predicts the resistance of different types of icebreaking ships reasonably well.

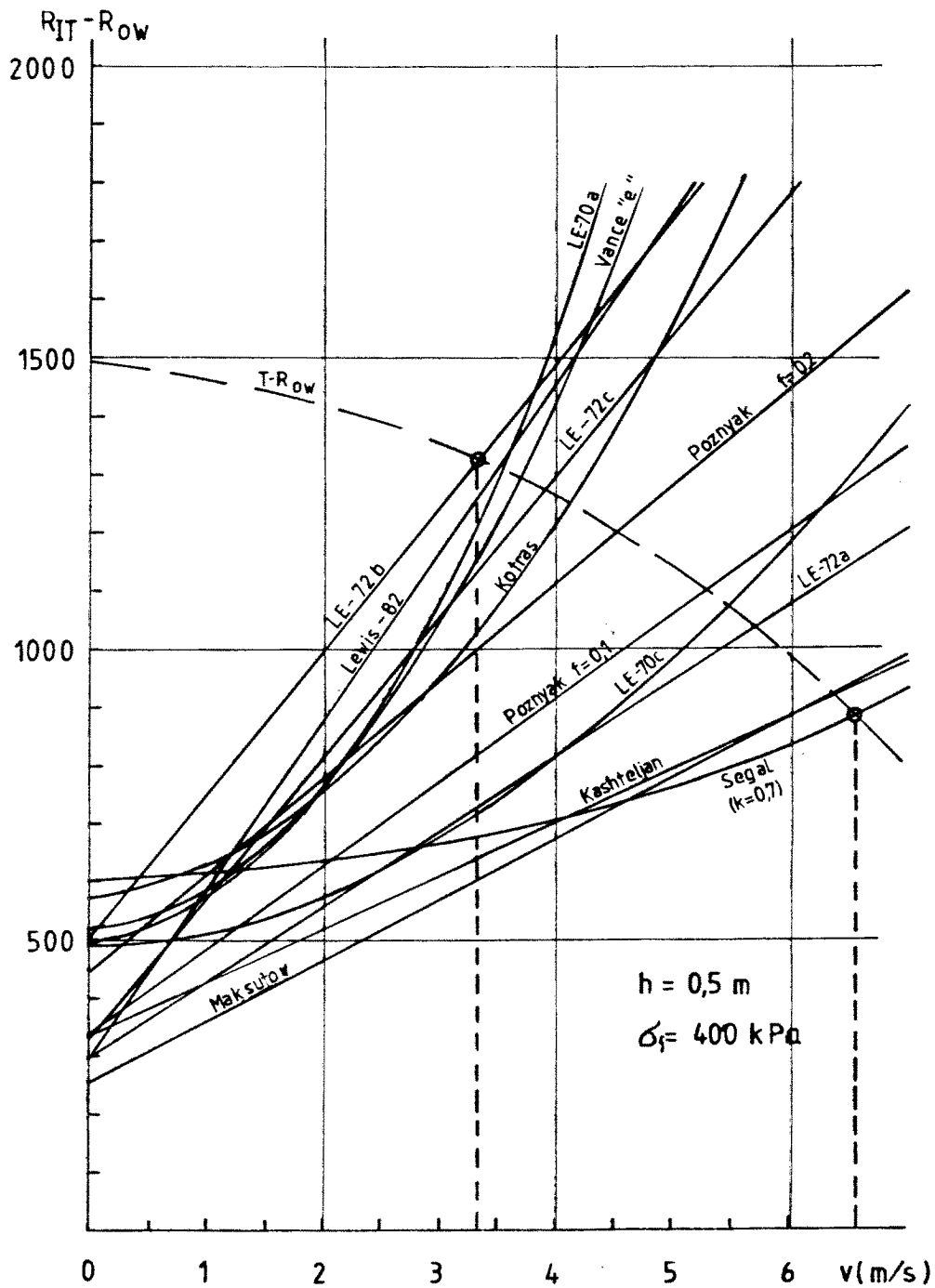


Fig. 1: Example of prediction according to various methods from ref. [1].
 The reference ship is a multi-purpose cargo vessel of 24 000 tons displacement, 24.4 m beam and 164 m length.
 T stands for net thrust.

The real value of the various theoretical methods for predicting the resistance of icebreaking ships can, however, be fully appraised by direct comparison with reliable full scale results.

As can be seen from figure 1, the gap between the different methods both in terms of resistance for a certain velocity and in velocity for a certain thrust may easily exceed 100 %. Figures 13-17 in [3] may be interpreted in the same way even after optimisation of the coefficients in the prediction method.

The Committee regards the main problem in the situation to be the scarcity of reliable full scale test data. Very few ship tests have been carried out with full control of environmental data, such as bending strength, compression strength and strain modulus of ice, density of snow and the hull roughness and mechanical friction.

In addition, changes in the propulsive coefficients due to the presence of ice around the hull and even in the disc are such that data from different tests with the same ship may diverge considerably, and therefore have to be taken into consideration. This fact limits the improvement of model test extrapolations as well as obtaining experimental backing to improve analytical prediction methods.

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4. MODELLING RIDGES

The Committee performed a State of the Art review on modeling ridges for ship tests.

4.1 Arctec Canada Limited - Modelling Ridges

A ridge may be modelled by partially refrozen rubble, which is piled into a screen suspended in the tank. The ridge profile is determined by the shape of the screen, and the type of ridge is determined by the amount of refreezing permitted. The degree of consolidation is determined after the model has penetrated the ridge by cutting a vertical section through the ridge, floating it on the water, and examining it in detail.

4.2 Model Simulation of Pressure Ridges at HSVA

Ice pressure ridges are simulated at HSVA by first growing a parental ice sheet, considerably thinner than the normal level ice. This parental ice sheet is cut into longitudinal strips by a cutting rake. These strips are further cut into pieces in order to achieve piece size dimensions of 3-6 times the parental ice sheet thickness. This fragmented ice is pushed by the carriage's pushing board into casts, the front side of which is held somewhat below and the other above the water surface. The cast is constructed of a pipe frame connected by strengthened plastic foil. The cast is adjusted in depth such as to produce the required ridge keel depth, (keel to sail ratio = 4.2:1).

After the ridge is built another level ice cover is frozen in the residual open water area of the ice tank. During the freezing period of the level ice cover the degree of consolidation of the upper layer of the ridge is controlled by covering the ridge with insulation materials over a certain time.

Immediately before the test starts, the cast is removed.

After the test is performed, the dimensions and the degree of consolidation of the ridge is measured and strength tests are carried out (bending strength, compression strength and shear strength of the fragmented ice).

A comparison of model and full scale test results of an icebreaker penetrating a ridge is given in the attached Fig 1.

4.3 Modelling Ridges at Wärtsilä

Natural ridges often have a cross profile which resembles two triangles with their bases connected (Fig. 2).

Similar ridges are possible to construct in the model basin but experience shows that it was difficult to find a reasonably good prediction method. One of the main problems is that the length of the ridge profile in nature often is much shorter than the ship. In model scale this leads to very small ridges and it was found that the repeatability of tests was rather poor.

In order to overcome these problems, Wärtsilä developed their own method for the simulation of ships in ridges. The main feature of the method is to construct a continuous ridge field of uniform thickness. The length of the field is at least 1.5 times that of the ship.

The model is towed through the ridge field at a constant speed and the ridge resistance is continuously recorded. In the analysis the ridge resistance is divided into three components, resistances of forebody, midbody and aftbody. Experience has shown that the ridge resistance of the aftbody of an icegoing ship is very small.

The forebody resistance is measured as the forebody penetrates into the ridge and the midbody resistance accordingly as the midbody enters the ridge field. Fig. 3 explains the theory.

The relationship between the natural triangular and the modelled uniform ridge cross-sections is determined from the integrated ridge thickness.

Full scale experience from correlating ridge resistance and ridge thickness has introduced the expression "integrated ridge thickness", which means that the triangular ridge profile is mathematically expanded as a uniform ridge. See ref. 1 for more information.

- ① bow penetrates the ridge
- ② bow leaves the ridge
- ③ propeller penetrates the ridge
- ④ propeller leaves the ridge

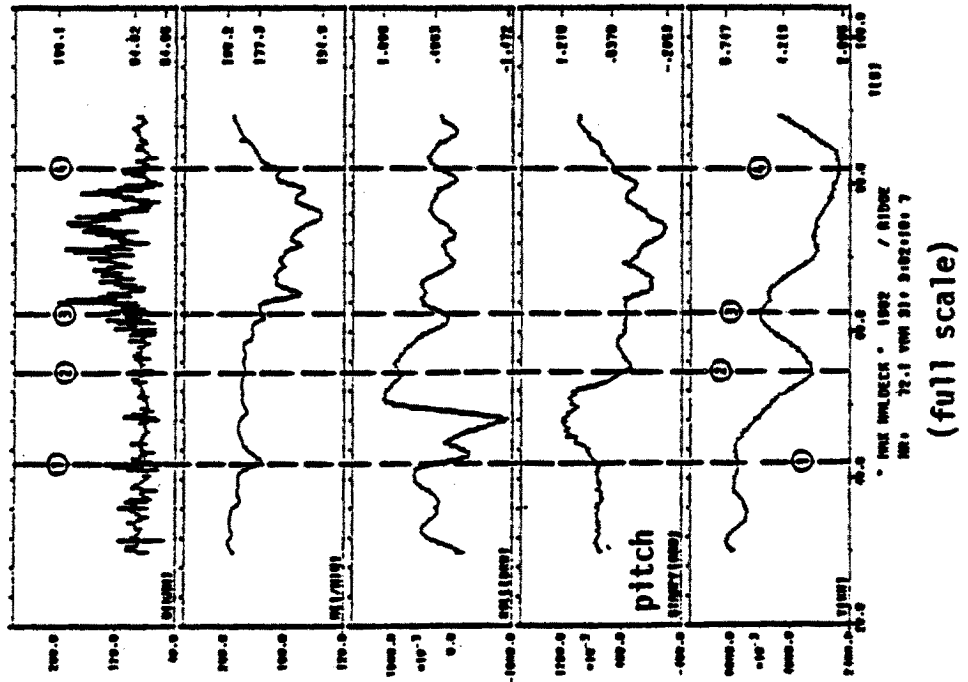
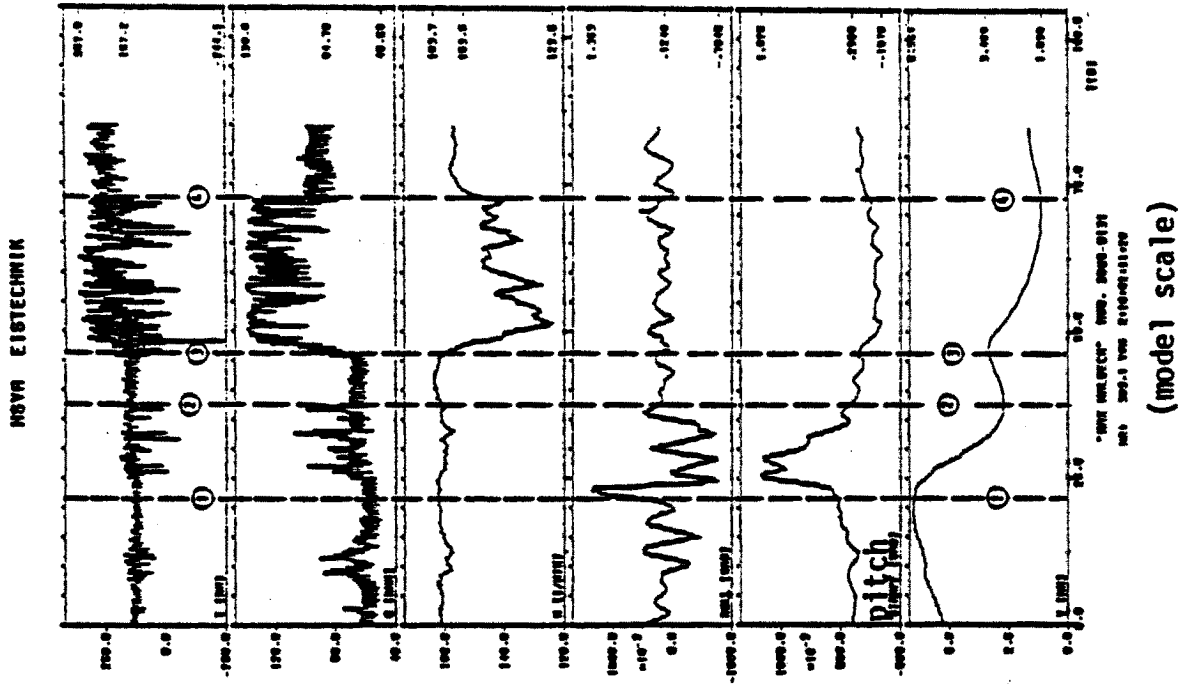
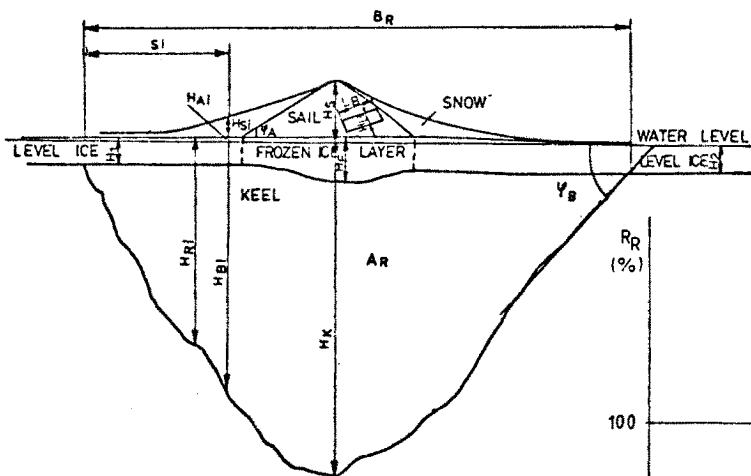


Fig. 7: Results of ridge breaking tests

FIGURE 2

A CROSS SECTION OF A RIDGE



NOHENCLATURE

- $A_R = \bar{H}_R \times B_R =$ Cross sectional area of ridge
- $B_R =$ Ridge breadth
- $C_B = L_B/H_B =$ Ice block aspect ratio
- $C_F = \rho_i / (\rho_w - \rho_i) =$ Ice floatation coefficient
- $C_K = H_K/H_S =$ Keel to sail ratio
- $C_L = B_R/(H_K + H_S) =$ Breadth to depth ratio
- $H =$ Thickness in general
- $H_A(i) =$ Ridge height above water surface
- $H_B(i) =$ Ridge depth below water surface
- $H_B =$ Ice block thickness (in sail or keel)
- $H_F(i) =$ Thickness of frozen ice layer (below sail)
- $H_K =$ Maximum depth of keel below water level
- $H_{R(i)} =$ Total ridge thickness
- $\bar{H}_R =$ Average thickness of a ridge or ridge field $\sum_{i=1}^N H_{R(i)}/N$
- $H_S =$ Maximum height of sail above water level
- $H_S(i) =$ Snow thickness
- $H_{1,2} =$ Level ice thickness left/right from a ridge or ridge field
- $L_B =$ Maximum dimension of ice blocks in sail or keel
- $N =$ Number of measuring points of a ridge or ridge field
- $S(i) =$ The distance from origin to a ridge measuring point
- $\mu_B =$ Porosity of ice block structure of sail or keel
- $\rho_i =$ Ice density ($\rho_A =$ above water level, $\rho_B =$ below water level)
- $\rho_w =$ Water density
- $\psi_A =$ Sail angle
- $\psi_B =$ Keel angle

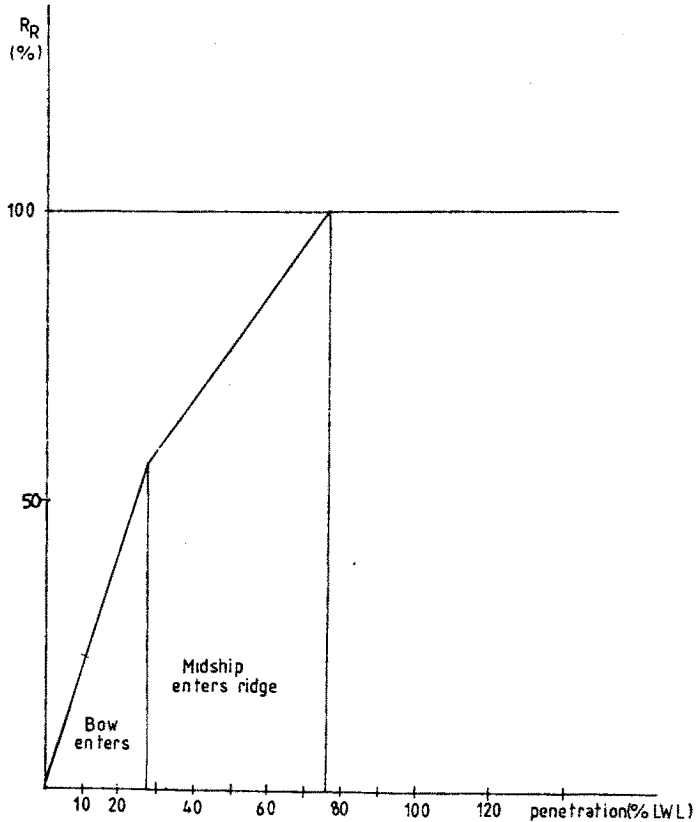


Fig. 3

Theoretical development of pure ridge-resistance as the model penetrates into the ridge field.

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(SRI)
6-38-1 Shinkawa, Mitaka, Tokyo - 181 Japan
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Kaanantie 1, 00650 Helsinki 65
Contact person: E Enkvist

5. MODEL ICE

A Questionnaire was sent out to active tanks.
The facilities were asked to answer questions
related to the preparation and the properties
of their model ice materials. The results are
summarized in Table 1.

3.1 Responding Organization

Arctic and Antarctic Research Institute (AARI)
34 Fontanka, Leningrad 191104, USSR
Contact person: D D Maksutov

Cold Regions Research and Engineering
Laboratories (CRREL)
72 Lyme Road, Hanover, N.H. 03755, USA
Contact persons: G F Frankenstein
J C Tatinclaux

TABLE 1

QUESTIONNAIRE ON MODEL ICE

	AARI	CRREL	HSVA	IHI	NKK	NRC	SRI	WARC
TYPE OF MODEL ICE	Salt 0 to 3.5% Columnar	Urea 0.9 to 1% Columnar	Urea 0.5 to 1.2% Columnar	Urea Columnar	Urea 0.4 to 1.2% Columnar	Urea 0.5% Columnar	Salt 0.5 to 1.3% Columnar	Salt 2% Fine Grained
SEEDING PROCEDURES								
Seeding Density (g/m ³)	50	-20	50	30		9.5	380-650	N.A.
Seed Water Temp.	-1 to +4°C	7 to 12°C	10°C	5 to 15°C	15°C	20°C	5°C (a nozzle)	N.A.
Air Temperature	-10 to -18°C	-7 to -10°C	-7 to -12°C	-15 to -20°C	-15°C	-18°C	-8 to -16°C	N.A.
Tank Water Temp.	0 to -1.8°C	0 to -0.2°C	-0.2 to -0.4°C	Freezing pt.	Freezing pt.	-1°C	0.2 to -1°C	
GROWTH CONDITIONS								
Ambient Air Temp.	-6 to -15°C	-15 to -20°C	-15 to -17°C	-10 to -25°C	-20 to -25°C	-18 to -20°C	-15 to -35°C	
Growth Rate	1 to 2.5 mm/hr	1 to 2mm/hr	2 mm/hr	2 to 3 mm/hr	3-4 mm/hr	2.8 mm/hr	4 mm/hr	
Final Ice Thickness	1 to 3.5 cm	2 to 8 cm	1.5 to 12 cm	2.5 to 5 cm	1.5 to 7 cm	1.4 to 6 cm	0.5 to 12 cm	
Top Layer Thickness	0.2 to 0.7 cm	3 to 7 mm	2 to 8 mm	5 to 6 mm	2 mm	1/5 of thickness	1 to 6 mm	
TEST CONDITIONS								
Ambient Air Temp.	-6 to -10°C	-2 to +1°C	+2 to +4°C	+5°C	-5 to +5°C	+2°C	-5 to +6°C	
Ice Tempering	no	yes	yes	yes	yes	yes	yes	
ICE PROPERTIES								
Density (g/cm ³)	0.84 to 0.98	0.93	0.92		0.94 (max)	0.93 to 0.95	0.92 to 0.96	
σ_f (kPa)	10 to 90	17 to 140	10 to 120	20 to 250	10 to 100	17 to 50	15 to 400	5 to 50
σ_c (kPa)	-	40 to 450	25 to 300			Horizontal: 60 to 310 Vertical: 120 to 400	400 (max)	5 to 90
τ (kPa)	-							
E (MPa)	0.2 to 4	14 to 400	20 to 300	10 to 570	2 to 250	30 to 60	1 to 750	5 to 50
f_{ID} (top/top)		0.08				30 to 180	0.1	10 to 100
f_{ID} (top/bottom)	0.08	0.15	0.25			0.35 (static)		
MEASUREMENT PROCEDURES								
σ_f	In situ Cant. beam	In situ Cant. beams Manual (1 to 2 sec)	In situ Cant. (0.01 to 0.015 sec)	In situ Cant. (2-20 mm/min)	In situ Cant. lever (≤ 1 sec)	In situ Cant. lever	In situ Cant. or 4-pt bending (1-1.5 sec)	In situ Cant.
σ_c	-	In situ-u-conf. v=1 to 2 cm/s	Comp. Test machine $t=10^{-1}$ to 15^{-1} sec			Reference Test Series	Comp. Test machine 1-50 mm/sec	Uniaxial Comp. $10^{-5} < \dot{\epsilon} < 10^{-2}$
τ	-					Shear Box on Service Carriage		Shear Apparatus
E	Plate-static (25g to 500g load)	Plate-Static	Plate-quasi Static	In situ Cant. or Plate	Plate 0.2-1.2kg/sec	Full Plate Static	Flexural	From Cant. beams and Plate
f_{ID}/W	Sample Surface towed over 1 m	Towed loaded in Sample (7-10m/s)	Standard Method		Standard Method	Ice Block Towed over Model Surface	Ice Block on moving Plate	

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6. PROPULSION TESTS

Until recently most model tests for icebreaking ships have been carried out in the towing mode only, by which the icebreaking resistance was established and optimized. In order to fully evaluate the icebreaking capability of ships, it is, however, necessary to perform propulsion tests, whereby the propeller-ice interaction is considered. By these propulsion tests the power-speed-ice thickness relationship can be established and the propeller safety can be addressed.

Up to now there are no answers to such significant problems as to

- a) how the propeller-ice interaction affects the ship propulsion system characteristics,
- b) how accurate the estimation of this effect can be during model experiments.

The main attempts of the investigators have been concentrated on the search of the answer to the first problem.

Accumulation of full-scale data on the characteristics of propeller-ice interaction allows some basis for an answer to the second problem.

Depending on the purpose of investigations all experiments on measuring ice loads acting upon the icebreaker propellers can be divided into two groups. The purpose of the first group of investigations is to estimate maximum ice loads acting upon the propeller and the shafting of the ship and to determine the reliability of these measurements in the most severe ice conditions [1], [2], [3], [4]. The purpose of the second group of investigations is to determine the amount of propulsion system efficiency loss during icebreaker performance, and their model tests in level ice [4], [5], [6], [7].

The analysis of full-scale propulsion test results made possible to establish common characteristic features for loads on propellers of icebreakers moving in ice.

Two types of loads were found to differ significantly in their magnitude and nature. The first type is relatively stable hydrodynamic loads during propeller gyration in water, and the second type corresponds to irregular ice loads during propeller-ice interaction. The characteristic feature of the second type of the loads is the presence of significant variable stress components in the propeller blade. While the icebreaker moves through ice both types of loads are alternating (Fig. 1). Under statistically stable ice conditions it is possible to determine the summed duration of the propeller-ice interaction time (t_I) for the period of observation (t_{Σ}) and the relative time of propeller-ice interaction

$$C_{TI} = t_I / t_{\Sigma} .$$

The C_{TI} value depends on the position of the propeller with respect to the hull (side propeller, or center one; bow or aft propeller), the direction of ship movement, the depth of propeller shaft immersion, the ice thickness, ice concentration etc. In similar ice conditions and for icebreakers with the same propeller position the C_{TI} values seemed to be almost the same [2].

Separate analysis of measurement data for each type of loads makes possible to determine a change of the propeller hydrodynamic characteristics when it is not interacting with ice, in comparison with the hydrodynamic characteristics of a ship moving in clear water and to determine the values of ice loads during interaction with ice.

Maximum ice loads several times exceed hydrodynamic ones. For example, ice forces may be four times as high as thrust in bollard conditions [4]. The amplitude of the variable shaft torque can be 6-10 times as high as the nominal torque of the power unit, and the ice bending moment at the shaft neck can be 8-15 times as high as the value measured during ship movement in clear water [2].

These ice load values, however, are extremely rare. While an icebreaker moves in various ice conditions the frequency of propeller-ice interaction as well as stresses in the propeller and the shaft are random values. Distribution of probability density of random values of stresses appearing in the blade root section [3] and in various parts of the shaft [2] is subject to exponential law. The relative time of propeller-ice interaction, the standard deviation of different measured stress components in various points of the shaft and the law for probability density distribution of random values of stresses characterize the amount of loads in the propeller-shaft system with sufficient completeness.

Measurement of the thrust and the torque at the icebreaker shaft show that during movement in level ice the relative time of the propeller-ice interaction and the intensity of interaction are not large. Thus it is possible to conclude that the effect of the propeller-ice interaction upon the propulsion system efficiency is relatively small [4], [5], Fig. 2.

Among the small amount of data published on propulsion tests of full scale and model icebreakers reasonable agreement has been reported in some cases (HSVA), but not so in others, [3].

Significant additional work is needed before reliable model propulsion tests can be achieved, and standardized modeling techniques and methods of model-to-ship correlation can be recommended. Among the research efforts to be undertaken, special attention should be directed to:

- simulation of propulsion system characteristics
- simulation of piece size of broken ice and its kinematics around ship hull
- correlation between model and full scale test results.

An important feature of propulsion model tests in ice is the possibility to make visual observations on the flow of ice into the propeller disc area, especially in case of novel design.

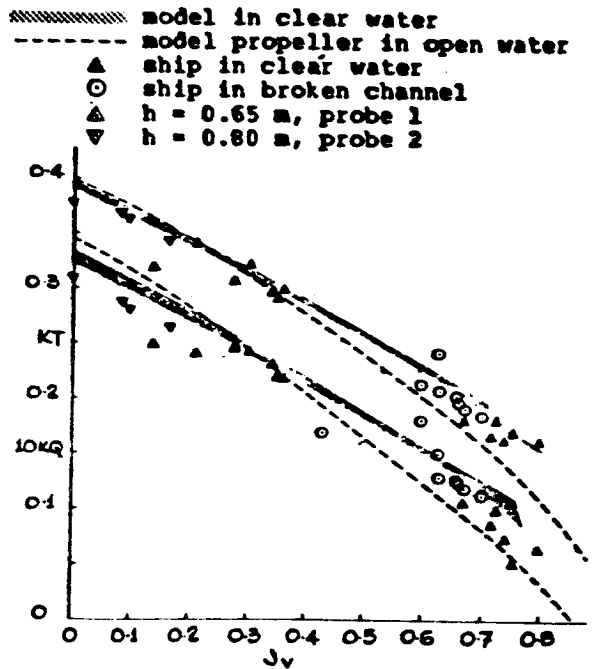


FIGURE 2. Torque and Thrust Coefficients from Model and Full Scale Tests with the R-Class Icebreaker, Ref. [9] Cap. 1

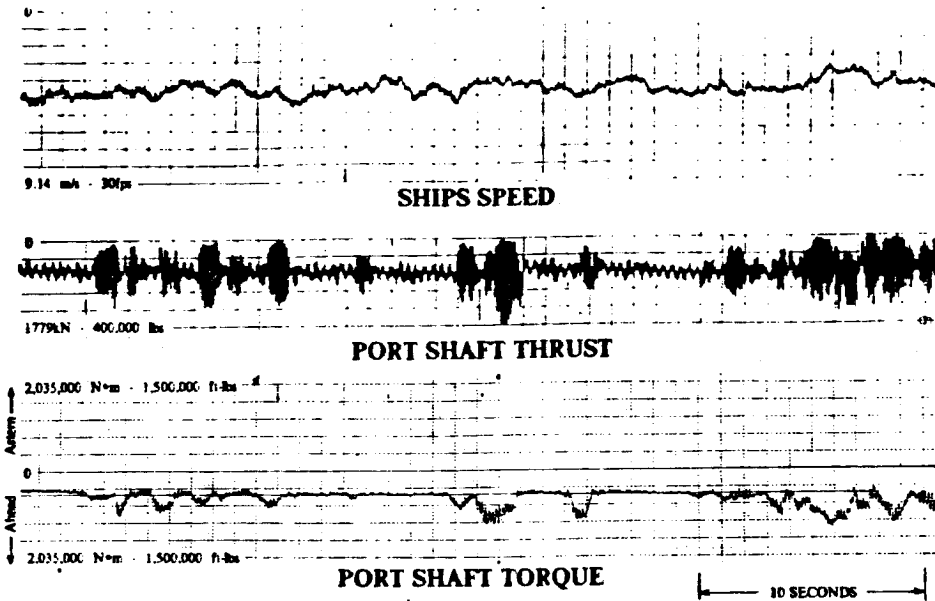


FIGURE 1. Typical Continuous Icebreaking Data

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III. RECOMMENDATIONS OF THE COMMITTEE

1. GENERAL RECOMMENDATIONS

1.1 List of Symbols

The list proposed by the 16th ITTC has been thoroughly reviewed and discussed. The Committee agreed to abbreviate the list and excluded all controversial symbols in order not to create confusion. The new list is presented in Appendix A. Its use is recommended

1.2 Continue full scale testing of ships in all ice conditions. Every effort must be made to collect all necessary data on ice and snow properties. Attention to hull roughness should be paid and measured if possible.

2. IMMEDIATE TASKS FOR THE COMMITTEE

2.1 To retest the Standard Model at another friction value.

2.2 Further investigations on propulsion testing techniques, in particular the propulsion test data for the Standard Model should be reanalyzed and compared to reanalyzed and new full scale data.

2.3 Review the testing techniques for offshore structures in various ice conditions.

2.4 Initiate work on establishing standard methods for friction testing on model and full scale hulls as well as a definition for the roughness of the hull.

APPENDIX

28.10.1983

1 (3)

RESISTANCE AND PROPULSION TESTS IN ICE

<u>Symbol</u>	<u>c.c. Symbol</u>	<u>Title</u>	<u>Definition</u>	<u>Dimension</u>
1	2	3	4	5
C_I	CI	Coefficient of net ice resistance	$\frac{R_I}{\rho_I g h^2 B}$	-
C_{IW}	CIW	Coefficient of water resistance in the presence of ice	$\frac{R_{IW}}{\frac{\rho_W}{2} S V^2}$	-
F_{IN}	FIN	Normal ice force on a body	Projection of the hull-ice interaction force on the external normal	LMT^{-2}
F_{IT}	FITA	Tangential ice force on a body	Projection of the hull-ice interaction force on the direction of motion	LMT^{-2}
F_{NI}	FNI	Froude number based on ice thickness	$F_{NI} = v / \sqrt{gh_I}$	-
F_{XI}	FXI	Components of the local ice force		LMT^{-2}
F_{YI}	FYI			LMT^{-2}
F_{ZI}	FZI			LMT^{-2}
f_{ID}	CFRD	Coefficient of friction between surface of body and ice (dynamic)	Ratio of tangential force to normal force between two bodies	-
f_{IS}	CFRS	- " - (static)		-
h_I	HI	Thickness of ice		L
h_{SN}	HSNOW	Thickness of snow cover		L
K_{QIA}	KQIA	Average coefficient of torque in ice	$K_{QA} = Q_{IA} / \rho_W n_A^2 D^5$	-
K_{TIA}	KTIA	Average coefficient of thrust in ice	$K_{TA} = T_{IA} / \rho_W n_A^2 D^4$	-
n_{IA}	NIA	Average rate of propeller revolution in ice		REVS T^{-1}
P_{DI}	PDI	Delivered power at propeller in ice	$P_{DI} = 2\pi Q_A n_A$	$L^2 MT^{-3}$
Q_{IA}	QIA	Average torque in ice		$L^2 MT^{-2}$
R_I	RI	Net ice resistance	$R_I = R_{IT} - R_{IW}$	LMT^{-2}

1	2	3	4	5	2.	
R_{IT}	RIT	Total resistance in ice	Ship towing resistance in ice	LMT^{-2}		
R_{IW}	RIW	Hydrodynamic resistance in presence of ice	Total water resistance of ship in ice	LMT^{-2}		
S_I	SALTI	Salinity of ice	Weight of salt per unit weight of ice	-		
S_W	SALTW	Salinity of water	Weight of dissolved salt per unit weight of saline water	-		
t°_A	TEMA	Temperature of air	} °C			
t°_I	TEMI	Local temperature of ice				
t°_W	TEMW	Temperature of water				
T_{IA}	TIA	Average total thrust in ice		LMT^{-2}		
X_I	} FIX	Ice force components on body relative to body axes		LMT^{-2}		
Y_I			FIY		LMT^{-2}	
Z_I			FIZ		LMT^{-2}	
δ_I	DELI	Deflection of ice sheet	Vertical movement of ice surface	L		
ϵ_I	STI	Ice strain	Elongation per unit length	-		
$\dot{\epsilon}_I$	STRAT	Strain rate	$\dot{\epsilon}_I = \partial \epsilon / \partial \tau$	T^{-1}		
η_{ICE}	ETICE	Relative propulsive efficiency in ice	$\eta_{ICE} = \eta_{ID} / \eta_D$	-		
η_{ID}	ETAID	Propulsive efficiency in ice	$\eta_{ID} = VR_{IT} / 2\pi n_{IA} Q_{IA}$	-		
μ_I	POISI	Poisson's ratio of ice		-		
v_A	NUA	Relative air volume in ice	Volume of gas pores per unit volume of ice	-		
v_B	NUB	Relative brine volume of dopant	Volume of liquid phase per unit volume of ice	-		
v_O	NUO	Total porosity	$v_O = v_A + v_B$	-		

3.

1	2	3	4	5
ρ_I	RHOI	Mass density of ice	Mass of ice per unit volume	ML^{-3}
ρ_{SN}	RHOSN	Mass density of snow	Mass of snow per unit volume	ML^{-3}
ρ_W	RHOW	Mass density of water		ML^{-3}
ρ_Δ	RHOD	Density difference	$\rho_\Delta = \rho_W - \rho_I$	ML^{-3}
σ_c	SIGCS	Compressive strength of ice		$L^{-1}MT^{-2}$
σ_F	SIGF	Flexural strength of ice		$L^{-1}MT^{-2}$
σ_T	SIGT	Tensile strength of ice		$L^{-1}MT^{-2}$
τ_S	TAUS	Shear strength of ice		$L^{-1}MT^{-2}$