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LM-2005-02

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S. J. Jones

April 2005

Canada

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SUMMARY

Following the successful full-scale trials of the USCGC Healy in 2000, it was decided to conduct a complete set of resistance and propulsion, and maneuvering, model tests of the vessel for correlation with the full-scale data. The proceedings of the POAC '01 conference (Frederking et al. 2001) contain several papers outlining the results of the full-scale trials. Jones and Moores (2002) have summarized the results of the resistance tests conducted at IOT. This report details both the resistance and propulsion model tests conducted at IOT; a second report will discuss the maneuvering tests. This report can be read in conjunction with IOT's Standard Test Methods TM 7, Resistance in Ice, and TM 8 D1, Model Propulsion in Ice, as an example of an application of these Standards.

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RESISTANCE AND PROPULSION MODEL TESTS OF THE USCGC HEALY (MODEL546) IN ICE

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December 2004

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RESISTANCE AND PROPULSION MODEL TESTS OF THE USCGC HEALY (MODEL 546) IN LEVEL ICE

1.0 INTRODUCTION

Following the successful full-scale trials of the USCGC Healy in 2000, it was decided to conduct a complete set of resistance and propulsion, and maneuvering, model tests of the vessel for correlation with the full-scale data. The proceedings of the POAC ’01 conference (Frederking et al. 2001) contain several papers outlining the results of the full-scale trials. Jones and Moores (2002) have summarized the results of the resistance tests conducted at IOT. This report details both the resistance and propulsion model tests conducted at IOT; a second report will discuss the maneuvering tests. This report can be read in conjunction with IOT’s Standard Test Methods TM 7, Resistance in Ice, and TM 8 D1, Model Propulsion in Ice, as an example of an application of these Standards.

2.0 USCGC HEALY

The USCGC Healy was launched on 15 November 1997 from Avondale Industries in New Orleans. She was delivered to the US Coast Guard on 10 November 1999, departed New Orleans on 26th January 2000, and proceeded north for extensive full-scale ice trials before arriving in Seattle on 9th August 2000.

The essential details of the Healy are shown in Table 1.

Table 1. Characteristics of USCGC Healy

Length, Overall	420ft 128 m
Beam, Maximum	82’ 25 m
Draft, Full Load	29’3’ 8.9 m at delivery
Displacement, Full Load	16,000 LT at delivery
Propulsion	Diesel Electric, AC/AC Cycloconverter
Generating Plant Drive Motors	4 Sultzer 12Z AU40S 2 AC Synchronous, 11.2 MW
Shaft Horsepower	30,000 Max
Propellers	2 fixed pitch, 4 bladed
Fuel Capacity	1,220,915 gal. 4,621,000 l
Speed	17 knots @ 147 RPM
Endurance	16,000 NM @ 12.5 knots
Icebreaking Capability	4.5 ft (1.4 m) @ 3 knots (continuous) 8 ft (2.44 m) Backing and Ramming
Accommodations	19 Officer, 12 CPO, 54 Enlisted, 35 Scientists, 19 Surge, 2 Visitors

The design icebreaking capability of the Healy was for continuous icebreaking at 3 knots through 4.5 ft (1.37 m) of ice of 100 psi (690 kPa) strength. The full-scale trials were designed to test this capability. Unfortunately, the ice strength found on the trials was approximately half of that specified. One of the objects of the model tests was to determine the effect of ice strength on the delivered power necessary for the Healy to meet her icebreaking specification.

2.1 Model Construction

Model 546 was constructed, in accordance with IMD's standard method, at a scale of 1:23.7. This scale was chosen so that we could use an existing set of propellers, namely our R-Class propellers 66L and 66R. The model's principal dimensions were:-

Table 2. Particulars of Model 546

Overall length (LOA)	5.40 m
Length between perpendiculars (LBP)	5.10 m
Maximum beam	1.05 m
Depth at midships (D)	0.54 m
Design waterline (DWL)	0.36 m
Draft at even trim	0.37 m
Vertical C. of G. (VCG)	0.416 m
Displacement	1240 kg

A non-removable ice knife and two bossings, also non-removable, were fitted, together with the twin rudders and propellers. The model's lines plan is shown in Fig. 1 and the

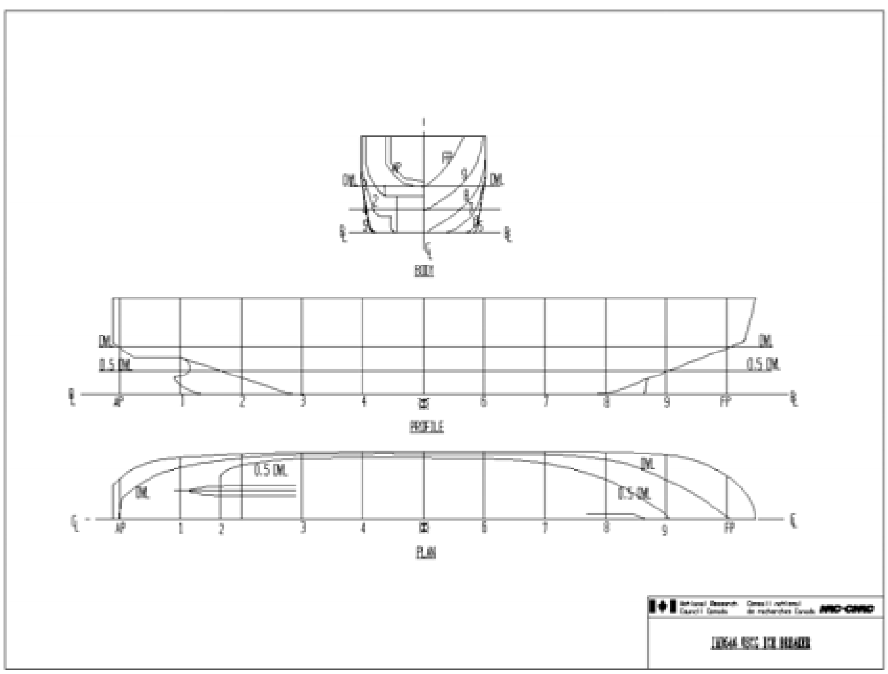

Fig. 1. Lines plan of USCGC Healy.

model is shown in the ice tank in Fig.2, and the stern arrangement is shown in Fig. 3.

Fig. 2. The Healy model 546 shown in the ice tank

Fig. 3. The stern arrangement of the *Healy* model 546.

The ice-hull friction coefficient requested was 0.05. However, for unknown reasons, it was much smaller at 0.014 (Low friction) so the resistance tests were repeated after re-painting, at a friction coefficient of 0.034 (High friction). The ice density was maintained constant for the different ice sheets at 870 ± 30 kg/m^3.

Table 3. Details of ice sheets used

Name	Date	Thick.	Strength	Test type
		Mm	Kpa	
Healy1	20 Dec 00	39	35	R, low frict.
Healy2	04 Jan 01	39	36	R, low frict.
Healy3	05 Jan 01	27	32	R, low frict.
Healy4	09 Jan 01	28	33	R, low frict.
Healy5	12 Jan 01	59	34	R, low frict.
Healy6	21 Mar 01	29	32	R, high frict.
Healy7	23 Mar 01	40	34	R, high frict.
Healy8	28 Mar 01	58	36	R, high frict.
Healy9	30 Mar 01	27	30	R, high frict.
Healy10	06 Apr 01	39	35	R, high frict.
Healy11	12 Apr 01	76	37/26	R, high frict.
Healy12	18 Apr 01	27	59/38/16	R, high frict.
Healy13	24 Apr 01	41	34	SP, high frict.
Healy14	25 Apr 01	28	32	SP, high frict.

3.0 TEST PLAN METHOD

Table 3 above shows the sheets that were used for the tests. In addition, open water resistance and propulsion tests, including overload tests, were conducted. The resistance tests were analyzed in accordance with IMD's standard method (Standard # TM7). The propulsion tests were analyzed in accordance with a draft standard method. Performance predictions were then made and compared to the full-scale data previously collected.

4.0 RESULTS

The detailed test run results are given in Appendix 1 for each ice sheet. The ice sheet details are given in Appendix 2.

4.1 Open Water Results

Open water resistance tests were conducted. Since the open water term is a small contribution to the total icebreaking resistance, a least squares polynomial was fitted to the data and this was used to calculate the open water term as needed. Fig. 4 shows the result for the low friction model.

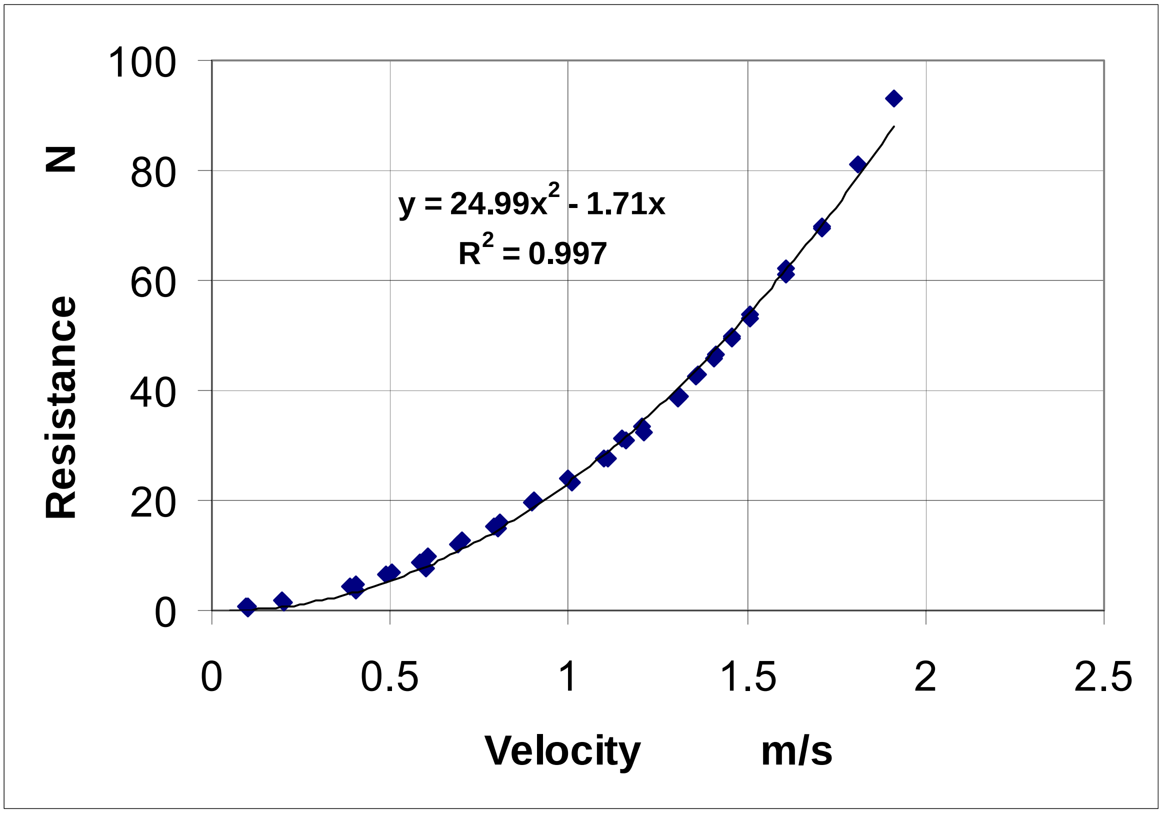

Fig. 4. Open water resistance of the USCGC Healy model 546, low friction.

4.2 Level Ice Resistance Analysis Method

4.2.1 Basis of analysis

As explained in IMD Standard Procedure TM7, the method uses a four component model for ice resistance given by:-

$$R_T = R_{BR} + R_C + R_B + R_{OW} \qquad \text{...............(1)}$$

where,

- R_T = total resistance in ice
- R_{BR} = resistance due to breaking the ice
- R_C = resistance due to clearing of the ice
- R_B = resistance due to buoyancy of the ice
- R_{OW} = resistance due to open water

Note that the breaking resistance, R_{BR}, is the only term that cannot be measured directly in the ice tank. The open water term, R_{OW}, is determined by first testing the model in open water at the same speeds as used in the ice tests. The level ice resistance test is then conducted to measures R_T. for different velocities. A pre-sawn test is then conducted as explained below.

4.2.2 Theory of pre-sawn test

The theory of the pre-sawn test is that it measures everything except the breaking term, i.e. it measures R_C+R_B+R_{OW}. Since R_{OW} is known, the pre-sawn test determines R_C+ R_B at each speed. By conducting a pre-sawn test at very low speed, V_M = 0.02 ms^{-1}, the dynamic forces associated with ice block rotation, ventilation, and acceleration are negligible, leaving only buoyancy, and a sliding friction term which is included in R_B. If the model is then stopped, the friction term reduces to zero and the only force remaining is the buoyancy. However, we do not separate out this friction term but include it in R_B. Having measured R_B, which is independent of velocity, it is subtracted from R_C+R_B to give R_C, which is velocity dependent. We have also measured R_{ow}, and R_T, for each velocity. Thus R_{BR} can be calculated from equation 1 above, and all components will have been determined.

4.2.3 Coefficients of resistance

In order to scale the model results to full-scale it is convenient to deal with non-dimensional coefficients for the resistance terms. These are defined as:-

$$C_{BR} = \frac{R_{BR}}{\rho_i B h_i {V_M}^2} \qquad \cdots\cdots\cdots\cdots\cdots (2)$$

where C_{BR} is the coefficient of the breaking resistance, R_{BR}
ρ_i is the density of the ice
B is the maximum beam of the model
h_i is the ice thickness
V_M is the model velocity

$$C_C = \frac{R_C}{\rho_i B h_i V_M^2} \qquad \cdots\cdots\cdots\cdots\cdots (3)$$

where C_C is the coefficient of the clearing resistance, R_C

$$C_B = \frac{R_B}{\Delta\rho_i g B h_i T} \qquad \cdots\cdots\cdots\cdots\cdots (4)$$

where C_B is the coefficient of the buoyancy resistance, R_B
$\Delta\rho_i$ is the difference in density between ice and the tank water.
g is the acceleration of gravity (9.808 $m.s^{-2}$)
T is the maximum draft of the model.

A non-dimensional strength number is defined as:-

$$S_N = \frac{V_M}{\left[\dfrac{\sigma_f h_i}{\rho_i B}\right]^{1/2}} \qquad \cdots\cdots\cdots\cdots\cdots (5)$$

or

$$S_N = \left[\frac{\rho_i B V_M^2}{\sigma_f h_i} \right]^{1/2} \qquad \cdots\cdots\cdots\cdots\cdots (6)$$

where σ_f is the flexural strength of the ice.

4.2.4 Basic analysis

Basic analysis begins by selecting time segments from the resistance data acquired on the carriage. From the position of the carriage during those time segments, the mean ice thickness and the flexural strength for that segment is calculated. This raw data is checked to see that it is internally consistent. If it is not, the time series is re-examined. Viewing the video record may show the reason for any anomalies, which is why it is important to have the videos synchronised with the data acquisition. This basic analysis gives mean total resistance at the different model speeds for known ice thickness and strength.

The steps in the following analysis can be summarised as follows. First, remove the open water resistance from the pre-sawn and the level ice data and analyse the pre-sawn data to obtain C_B and C_C. Following that, the level ice resistance data are analysed to obtain C_{BR}. Once this is done the resistance of the full-scale ship can be easily obtained from these coefficients, and by re-adding the open water resistance.

4.3 Low Friction Model – Level Ice Resistance Results

The low friction results are summarized in the spreadsheets below. Table 4 gives the results from the pre-sawn tests, and Table 5 gives the results from the level ice breaking tests.

Table 4. Summary of pre-sawn, low friction resistance results

USCGC Healy - Summary of Pre-sawn Ice Resistance Analysis-Model 546																
	$R_{OW} = 24.99V^2 - 1.71V$		Friction = 0.014			L=	5.4	B=	1.05	T=	0.37	Scale=	1/23.7			
Ice Sheet Name	Test Date	Pre-sawn Res. R_{ps} N	Open Water R_{ow} N	R_b+R_c $R_{ps}-R_{ow}$ N	R_b from Fig.1 N	Model Speed V_M m/s	Ice Thick. h_i mm	Ice Density kg/m^3	Ice Buoy. N	C_b from Fig. 2	R_b Recalc. Eqn. 4 N	R_c (R_c+R_b) $-R_b$ N	C_c Eqn. 3	F_n Eqn. 7	ln. C_c for Fig. 3	ln. F_n for Fig. 3
Healy1	20-Dec-00		0.08			0.101	38.5	906	14.16	1.29	18.26		0.000	0.164		
	20-Dec-00		3.21			0.394	38.5	906	14.16	1.29	18.26		0.000	0.641		
	20-Dec-00		7.72			0.591	38.5	906	14.16	1.29	18.26		0.000	0.962		
	20-Dec-00		14.25			0.79	38.5	906	14.16	1.29	18.26		0.000	1.286		
Healy2	4-Jan-01	20.4	0.51	19.89	15.99	0.181	38.2	913	13.03	1.29	16.81	3.09	2.572	0.296	0.945	-1.218
	4-Jan-01	49.9	13.50	36.40		0.77	38.2	913	13.03	1.29	16.81	19.59	0.902	1.258	-0.103	0.229
	4-Jan-01	80.45	33.35	47.10		1.19	38.2	913	13.03	1.29	16.81	30.29	0.584	1.944	-0.538	0.665
	4-Jan-01	17.2	-0.03	17.23		0.023	38.2	913	13.03	1.29	16.81	0.42	21.720	0.038		
Healy3	5-Jan-01	10.94	0.06	10.88	9.36	0.094	25	909	8.91	1.29	11.49	-0.61	-2.893	0.190		
	5-Jan-01	19.91	2.92	16.99		0.378	25	909	8.91	1.29	11.49	5.50	1.612	0.763	0.477	-0.270
	5-Jan-01	28.43	7.33	21.10		0.577	25	909	8.91	1.29	11.49	9.61	1.209	1.165	0.190	0.153
	5-Jan-01	39.72	13.87	25.85		0.78	25	909	8.91	1.29	11.49	14.36	0.989	1.575	-0.011	0.454
	5-Jan-01	10.35	-0.03	10.38		0.022	25	909	8.91	1.29	11.49	-1.11	-96.484	0.044		
Healy4	9-Jan-01	13.59	0.54	13.05	10.63	0.185	27.1	897	10.89	1.29	14.05	-1.00	-1.147	0.359		
	9-Jan-01	41.62	13.61	28.01		0.773	27.1	897	10.89	1.29	14.05	13.96	0.915	1.499	-0.089	0.405
	9-Jan-01	69.98	32.78	37.20		1.18	27.1	897	10.89	1.29	14.05	23.15	0.651	2.289	-0.429	0.828
	9-Jan-01	12.54	-0.03	12.57		0.022	27.1	897	10.89	1.29	14.05	-1.49	-120.444	0.043		
Healy5	12-Jan-01	32.51	0.55	31.96	29.18	0.186	56.8	910	20.02	1.29	25.83	6.14	3.269	0.249	1.184	-1.389
	12-Jan-01	52.16	2.91	49.25		0.377	56.8	910	20.02	1.29	25.83	23.43	3.037	0.505	1.111	-0.683
	12-Jan-01	61.44	7.31	54.13		0.576	56.8	910	20.02	1.29	25.83	28.31	1.572	0.772	0.452	-0.259
	12-Jan-01	32.75	-0.03	32.78		0.022	56.8	910	20.02	1.29	25.83	6.95	264.577	0.029		

In Table 4, the 3rd column is the measured pre-sawn ice resistance, the 4th column, Open Water, is the open water resistance calculated from the equation in Fig. 4 above, and column 5 is the pre-sawn minus the open water, which is equal to the clearing and buoyancy resistance. This is shown in Fig. 5 below. From the y-intercepts of Fig. 5, i.e. when v = 0, the measured buoyancy resistance is obtained. This is then plotted against the calculated buoyancy, which is given by $\Delta\rho_i gBh_i T$, where $\Delta\rho_i$ is the difference in density between the model ice and water, g is gravity, B is maximum width of model, h_i is the ice thickness, and T is the maximum draft of the model, as shown in Fig. 6. The slope of the line in Fig. 6 gives the coefficient of buoyancy resistance, C_B, in column 11 above.

Using C_B, the buoyancy resistance is re-calculated for each thickness, and subtracted from the total R_C+R_B to give R_C. This term depends on speed and is forced to go to zero at zero speed by the method we have used. The clearing coefficient, C_C, is now calculated from R_C and the model speed, according to equation 3 above. A thickness Froude number, F_N, is also calculated from

$$F_N = \frac{V_M}{\sqrt{gh_i}} \qquad \ldots\ldots\ldots\ldots\ldots (7)$$

The calculated C_C is then plotted against F_N on a ln-ln graph, as shown in Fig. 7, which can then be used to determine C_C for any speed V_M by using the regression equation shown on the graph.

Table 5. Summary of breaking resistance results for low friction model

USCGC Healy - Summary of Breaking Resistance Analysis																			
	Friction = 0.014			L=	5.4	B=	1.050	T=	0.37		Scale=	1/23.7							
	$R_{OW} = 24.99V^2 - 1.71V$																		
Ice	*Test*	*Model*	*Ice*	ln. F_h	*Ice*	*Ice*	S_n	ln. S_n	*Total*	R_{TOT}	ln. C_c	C_c	R_c	C_b	R_b	R_{ow}	R_{br}	C_{br}	ln. C_{br}
Sheet	*Date*	*Speed*	*Thick.*		*Strgth*	*Dens.*			*Resis.*	$- R_{OW}$	from		from	from	from				
Name				Eqn. 7			Eqn. 6		R_{TOT}		Fig. 3		Eqn. 3	Fig. 2	Eqn. 4		Eqn. 1	Eqn. 2	for
		m/s	*mm*		*kPa*	*kg/m³*			*N*	R_{IT}			N		N	N	N		Fig. 4
Healy1	20-Dec-00	0.103	39.4	-1.798	35.5	836					1.600	4.953	1.817	1.290	32.25	0.09	-34.15	-93.08	
	20-Dec-00	0.400	39.4	-0.441	35.5	836	0.317				0.554	1.740	9.629	1.290	32.25	3.31	-45.19	-8.17	
	20-Dec-00	0.598	39.4	-0.039	35.5	836	0.474				0.244	1.276	15.784	1.290	32.25	7.91	-55.94	-4.52	
	20-Dec-00	0.797	39.4	0.248	35.5	836	0.631				0.022	1.023	22.467	1.290	32.25	14.51	-69.22	-3.15	
Healy2	04-Jan-01	0.170	39.1	-1.293	36.4	847	0.134	-2.007	62.51	62.08	1.211	3.356	3.372	1.290	29.89	0.43	28.82	28.68	3.36
	04-Jan-01	0.777	39.1	0.227	36.4	847	0.614	-0.487	105.00	91.24	0.039	1.040	21.830	1.290	29.89	13.76	39.53	1.88	0.63
	04-Jan-01	1.200	39.1	0.662	36.4	847	0.949	-0.053	146.50	112.57	-0.296	0.744	37.243	1.290	29.89	33.93	45.44	0.91	-0.10
Healy3	05-Jan-01	0.093	27.0	-1.711	31.9	824	0.093	-2.373	32.10	32.04	1.533	4.632	0.936	1.290	23.69	0.06	7.42	36.71	3.60
	05-Jan-01	0.376	27.0	-0.314	31.9	824	0.377	-0.976	45.90	43.01	0.456	1.578	5.210	1.290	23.69	2.89	14.11	4.27	1.45
	05-Jan-01	0.580	27.0	0.120	31.9	824	0.581	-0.542	55.53	48.12	0.122	1.129	8.876	1.290	23.69	7.41	15.55	1.98	0.68
	05-Jan-01	0.784	27.0	0.421	31.9	824	0.786	-0.241	68.12	54.10	-0.111	0.895	12.855	1.290	23.69	14.02	17.56	1.22	0.20
Healy4	09-Jan-01	0.177	28.3	-1.091	32.7	833	0.172	-1.760	38.62	38.14	1.055	2.872	2.227	1.290	23.58	0.48	12.33	15.91	2.77
	09-Jan-01	0.770	28.3	0.379	32.7	833	0.749	-0.290	71.70	58.20	-0.079	0.924	13.567	1.290	23.58	13.50	21.05	1.43	0.36
	09-Jan-01	1.180	28.3	0.806	32.7	833	1.147	0.137	105.60	72.82	-0.408	0.665	22.926	1.290	23.58	32.78	26.32	0.76	-0.27
Healy5	12-Jan-01	0.184	58.5	-1.415	34.1	858	0.124	-2.090	111.77	111.24	1.305	3.688	6.580	1.290	41.55	0.53	63.11	35.37	3.57
	12-Jan-01	0.380	58.5	-0.690	34.1	858	0.255	-1.365	134.60	131.64	0.746	2.108	16.044	1.290	41.55	2.96	74.05	9.73	2.28
	12-Jan-01	0.586	58.5	-0.257	34.1	858	0.394	-0.932	155.04	147.46	0.412	1.510	27.322	1.290	41.55	7.58	78.59	4.34	1.47

The clearing resistance is now determined for the conditions that existed during the level ice resistance tests by using the plot of C_C against F_N in Fig. 7 and its regression line and equation. The buoyancy resistance is calculated for the test conditions from equation 4 above, given that C_B was determined in Fig. 6. By subtracting both these from the total ice resistance, R_T, given in Table 5, we are left with the breaking resistance only $R_{BR.}$ C_{BR} is then calculated from equation 2 and plotted against the strength number, S_N, given by equation 5 above, on a ln-ln basis, as shown in Fig. 8. From the resulting linear regression line, the slope and intercept can be used later in calculating C_{BR} for any value of S_N.

The end result of this analysis is an equation for the total ice resistance of the low friction (0.014) model given by:-

$$R_t = R_{OW} + 1.290\Delta\rho_i g B h_i T + 1.239\left(\frac{V_M}{\sqrt{g h_i}}\right)^{0.771}\left(\rho_i B h_i V_M^2\right) + 0.866 S_N^{1.6845}\left(\rho_i B h_i V_M^2\right) \ldots (8)$$

As a check that this equation is a good representation of the model data, calculated resistance is plotted against measured resistance as shown in Fig. 9. If the data were to fit the equation exactly, they would all lie on a line of slope 1:1. Fig. 9 shows a good correlation. From this equation (8), it is possible to calculate a resistance for the Healy at model or full-scale, for any ice condition and speed.

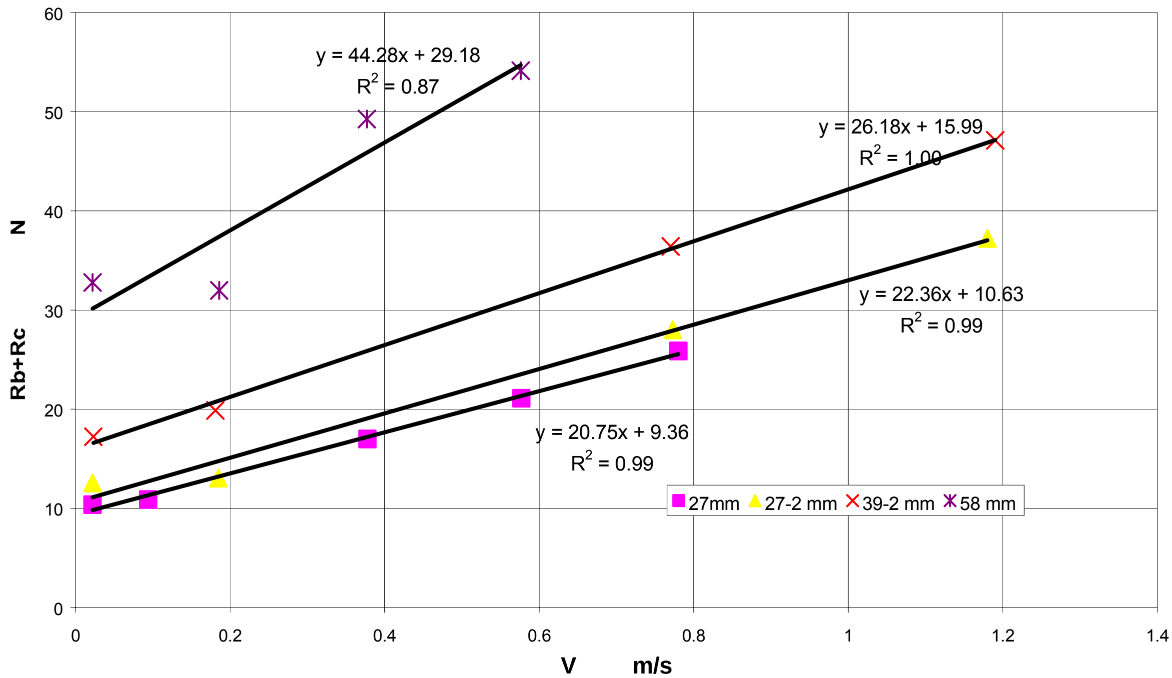

Fig. 5. Pre-sawn minus open water resistance, or buoyancy plus clearing resistance, for the Healy model 546, low friction 0.014.

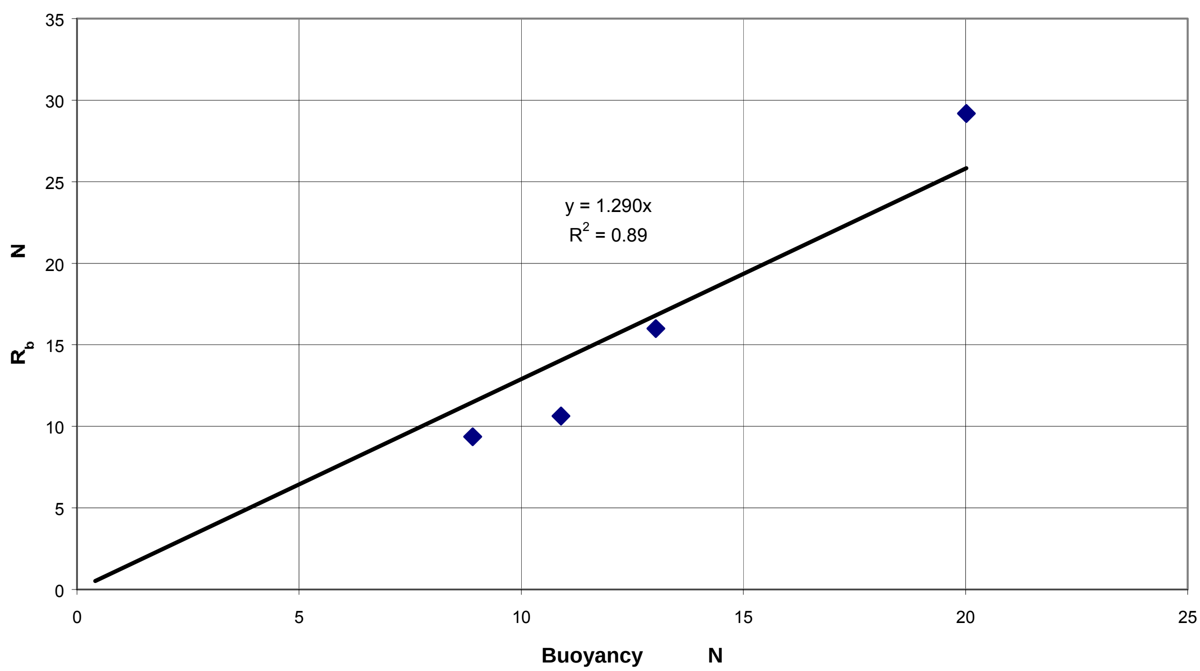

Fig. 6. The buoyancy resistance from the y-intercepts of Fig. 5 above, plotted against the calculated buoyancy, for the low friction Healy model.

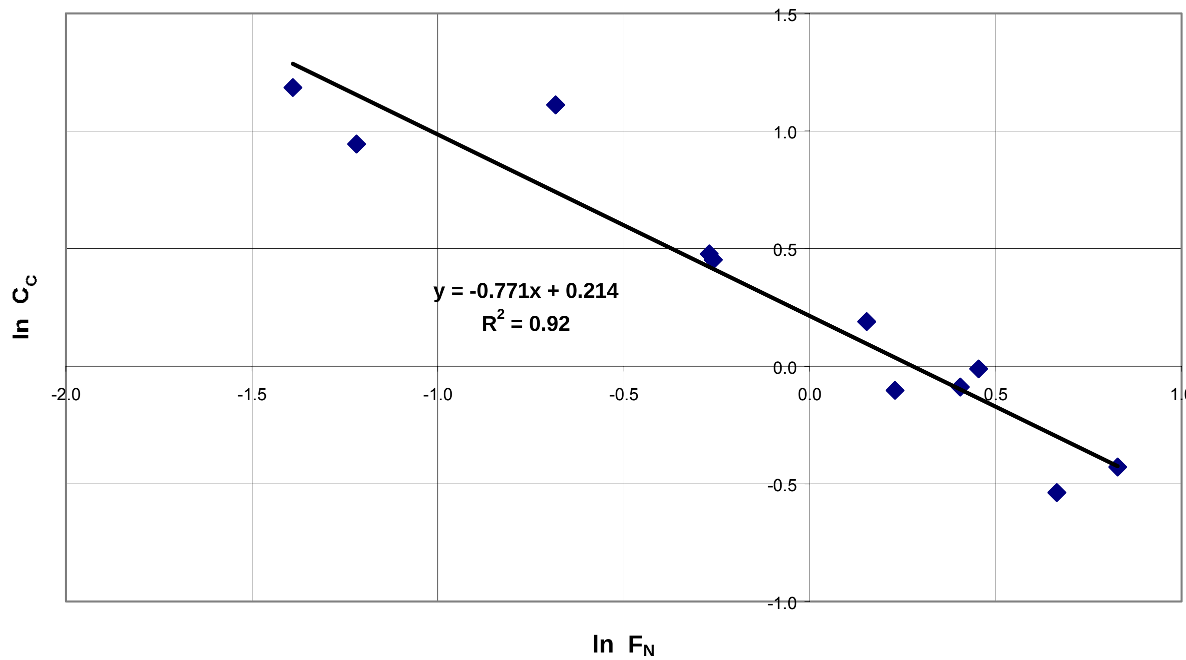

Fig. 7. Clearing coefficient plotted against Froude number on a ln-ln scale, for the low friction Healy model.

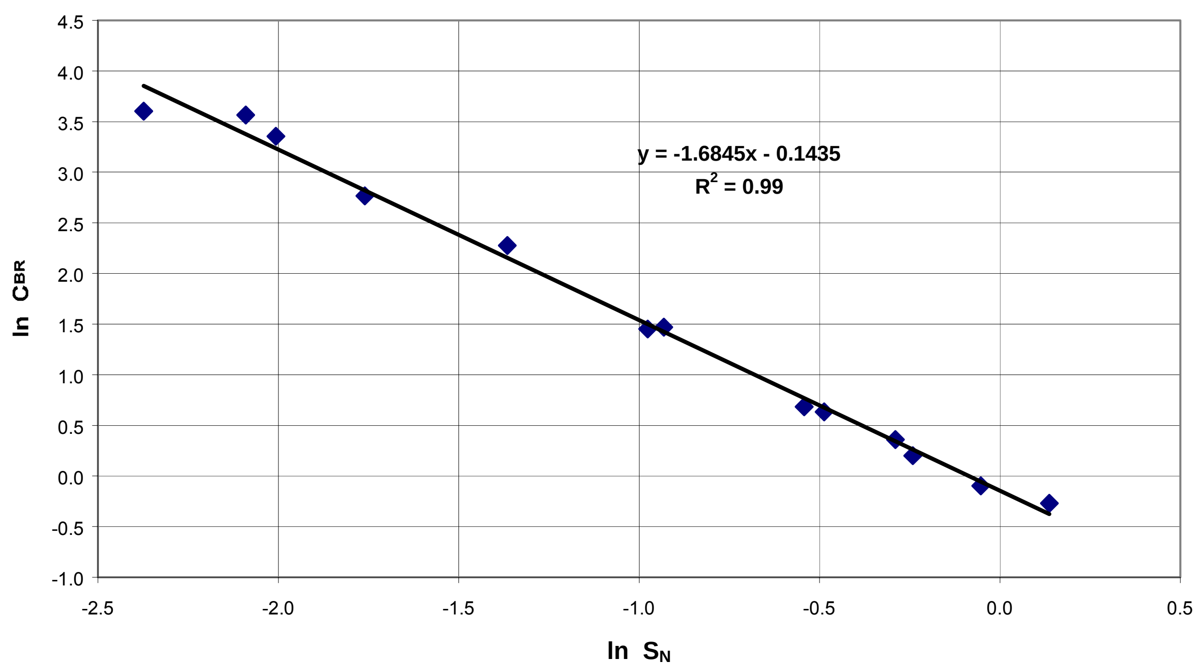

Fig. 8. Breaking coefficient plotted against “Strength Number” on a ln-ln scale, for the low friction Healy model.

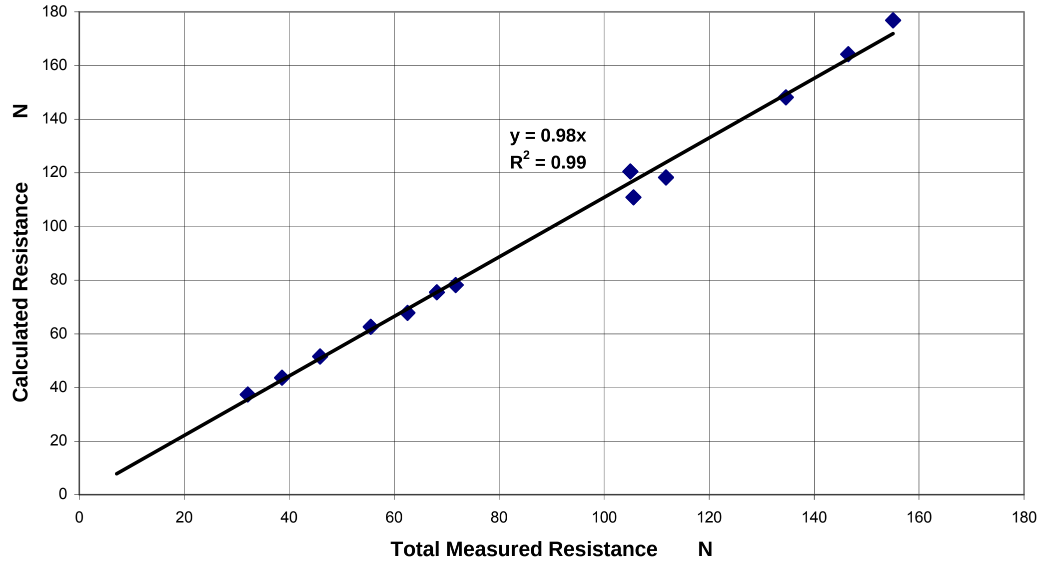

Fig. 9. Calculated versus measured total resistance for the low friction, 0.014, Healy model. The data would lie on a line of slope 1:1 if equation (8) were a perfect representation of the data.

4.4 High Friction Model – Level Ice Resistance Results

Similar results were also obtained for the high friction 0.034 Healy model. Tables 6 and 7 give the basic data for the pre-sawn and breaking resistance corresponding to Tables 4 and 5 above.

Table 6. Summary of pre-sawn, high friction resistance results

USCGC Healy - Summary of Pre-sawn Ice Resistance Analysis-Model 546																
$R_{OW} = 22.27 V^2 + 0.86 V$			Friction = 0.034			L=	5.4	B=	1.05	T=	0.37	Scale=	1/23.7			
Columns in italics are experimental data.																
Columns in red must be changed if ice conditions are changed																
Ice	*Test*	*Pre-sawn*	Open	R_b+R_c	R_b	*Model*	*Ice*	*Ice*	Ice	C_b	R_b	R_c	C_c	F_h	In. C_c	In. F_h
Sheet	*Date*	*Res.*	Water	=	from	*Speed*	*Thick.*	*Density*	Buoy.	from	Recalc.	(R_c+R_b)			for	for
Name		R_{ps}	R_{ow}	$R_{ps}-R_{ow}$	Fig.1	V_M	h_i			Fig. 2	Eqn. 4	$-R_b$	Eqn. 3	Eqn. 7	Fig. 3	Fig. 3
		N	N	N	N	*m/s*	*mm*	*kg/m^3*	N		N	N				
Healy6	21-Mar-01	16.9	0.3029	16.56	14.29	0.099	29.5	899	11.63	1.138	13.24	3.32	12.18	0.1839		
	21-Mar-01	28.8	3.8514	24.96	14.29	0.397	29.5	899	11.63	1.138	13.24	11.72	2.67	0.7381	0.982	
	21-Mar-01	42.0	8.3958	33.56	14.29	0.595	29.5	899	11.63	1.138	13.24	20.32	2.06	1.1062	0.724	
	21-Mar-01	49.7	14.759	34.93	14.29	0.795	29.5	899	11.63	1.138	13.24	21.69	1.23	1.478	0.209	0.39
	21-Mar-01	14.4	0.0259	14.38	14.29	0.020	29.5	899	11.63	1.138	13.24	1.14	103.78	0.037		
Healy7	23-Mar-01	21.3	0.2878	21.00	18.93	0.096	40.1	889	17.34	1.138	19.74	1.27	3.67	0.1531		
	23-Mar-01	33.6	3.7045	29.85	18.93	0.389	40.1	889	17.34	1.138	19.74	10.11	1.78	0.6203	0.579	-0.48
	23-Mar-01	42.5	8.1784	34.31	18.93	0.587	40.1	889	17.34	1.138	19.74	14.58	1.13	0.936	0.122	-0.07
	23-Mar-01	56.4	14.506	41.84	18.93	0.788	40.1	889	17.34	1.138	19.74	22.11	0.95	1.2565	-0.050	0.23
	23-Mar-01	20.3	0.0254	20.29	18.93	0.020	40.1	889	17.34	1.138	19.74	0.56	38.86	0.0313		
Healy8	28-Mar-01	43.0	0.8942	42.11	37.65	0.182	57.9	856	32.32	1.138	36.78	5.32	3.09	0.2415	1.128	-1.42
	28-Mar-01	58.0	3.4367	54.56	37.65	0.374	57.9	856	32.32	1.138	36.78	17.78	2.44	0.4963	0.893	-0.70
	28-Mar-01	69.0	7.884	61.12	37.65	0.576	57.9	856	32.32	1.138	36.78	24.33	1.41	0.7644	0.343	-0.27
	28-Mar-01	40.0	0.0244	39.98	37.65	0.019	57.9	856	32.32	1.138	36.78	3.19	170.02	0.0252		
Healy9	30-Mar-01	18.3	1.0628	17.24	13.23	0.200	27.3	892	11.49	1.138	13.08	4.16	4.06	0.3865	1.402	
	30-Mar-01	46.8	14.977	31.82	13.23	0.801	27.3	892	11.49	1.138	13.08	18.74	1.14	1.548	0.133	0.44
	30-Mar-01	76.1	33.21	42.89	13.23	1.202	27.3	892	11.49	1.138	13.08	29.81	0.81	2.3229	-0.215	0.84
	30-Mar-01	14.7	0.0261	14.67	13.23	0.020	27.3	892	11.49	1.138	13.08	1.59	155.75	0.0387		
Healy10	6-Apr-01	24.3	0.958	23.31	17.83	0.189	39.3	888	17.15	1.138	19.51	3.80	2.90	0.3044	1.066	-1.19
	6-Apr-01	59.9	14.255	45.64	17.83	0.781	39.3	888	17.15	1.138	19.51	26.13	1.17	1.258	0.156	0.23
	6-Apr-01	90.3	32.56	57.74	17.83	1.190	39.3	888	17.15	1.138	19.51	38.23	0.74	1.9167	-0.306	0.65
	6-Apr-01	18.9	0.0244	18.88	17.83	0.019	39.3	888	17.15	1.138	19.51	-0.64	-48.14	0.0306		

Table 7. Summary of breaking resistance results for high friction model

USCGC Healy - Summary of Breaking Resistance Analysis																						
R_{OW} = 22.27 V^2+0.86 V			Friction = 0.034			L=	5.4	B=	1.1	T=	0.37	Scale=	1/23.7									
Columns in italics are experimental data.																						
Columns in red must be changed if ice conditions are changed																						
Ice Sheet Name	*Test Date*	*Model Speed V m/s*	*Ice Thick. mm*	In. F_h Eqn. 7	*Ice Strgth kPa*	*Ice Dens. kg/m³*	S_n Eqn. 6	In. S_n for Fig. 4	*Total Resis. N*	In. C_c from Fig. 3	C_c	R_c from Eqn. 3 N	C_b from Fig. 2	R_b from Eqn. 4 N	R_{ow} N	R_{br} Eqn. 1 N	C_{br} Eqn. 2	In. C_{br} for Fig. 4	Calc. In C_{br} from Fig. 4	Calc. C_{br}	Calc. R_{br}	Calc. Total Resis. N
Healy6	21-Mar-01	0.099	29.5	-1.693	31.5	852	0.097	-2.329	43.0	1.353	3.868	1.01	1.138	19.34	0.303	22.38	86.12	4.46	4.28	72.18	18.76	39
	21-Mar-01	0.397	29.5	-0.304	31.5	852	0.390	-0.940	60.1	0.461	1.586	6.63	1.138	19.34	3.851	30.23	7.23	1.98	1.82	6.17	25.78	56
	21-Mar-01	0.596	29.5	0.103	31.5	852	0.586	-0.534	67.5	0.200	1.222	11.51	1.138	19.34	8.423	28.24	3.00	1.10	1.10	3.00	28.29	68
	21-Mar-01	0.796	29.5	0.392	31.5	852	0.783	-0.245	83.9	0.014	1.014	17.04	1.138	19.34	14.795	32.68	1.95	0.67	0.59	1.80	30.23	81
Healy7	23-Mar-01	0.097	40.1	-1.866	34.1	844	0.078	-2.548	58.4	1.464	4.324	1.45	1.138	27.69	0.293	28.96	86.20	4.46	4.67	106.25	35.69	65
	23-Mar-01	0.39	40.1	-0.475	34.1	844	0.315	-1.156	87.4	0.571	1.770	9.61	1.138	27.69	3.723	46.35	8.53	2.14	2.20	9.04	49.08	90
	23-Mar-01	0.586	40.1	-0.068	34.1	844	0.473	-0.749	101.3	0.310	1.363	16.71	1.138	27.69	8.151	48.75	3.98	1.38	1.48	4.39	53.88	106
	23-Mar-01	0.788	40.1	0.228	34.1	844	0.636	-0.453	124.7	0.119	1.127	24.98	1.138	27.69	14.506	57.52	2.59	0.95	0.96	2.60	57.66	125
Healy8	28-Mar-01	0.091	57.9	-2.114	36.0	843	0.059	-2.823	115.0	1.623	5.069	2.16	1.138	40.23	0.263	72.34	169.67	5.13	5.15	172.98	73.76	116
	28-Mar-01	0.180	57.9	-1.432	36.0	843	0.118	-2.141	134.0	1.185	3.272	5.46	1.138	40.23	0.876	87.43	52.41	3.96	3.95	51.69	86.23	133
	28-Mar-01	0.375	57.9	-0.698	36.0	843	0.245	-1.407	144.0	0.714	2.042	14.79	1.138	40.23	3.454	85.53	11.81	2.47	2.65	14.09	102.01	160
	28-Mar-01	0.578	57.9	-0.265	36.0	843	0.378	-0.974	168.0	0.436	1.547	26.61	1.138	40.23	7.937	93.22	5.42	1.69	1.88	6.55	112.63	187
Healy9	30-Mar-01	0.200	27.3	-0.951	29.8	822	0.206	-1.578	43.4	0.876	2.402	2.27	1.138	21.47	1.063	18.60	19.64	2.98	2.95	19.06	18.05	43
	30-Mar-01	0.801	27.3	0.437	29.8	822	0.827	-0.190	77.9	-0.015	0.986	14.97	1.138	21.47	14.977	26.49	1.74	0.56	0.49	1.63	24.80	76
	30-Mar-01	1.205	27.3	0.845	29.8	822	1.244	0.218	114.5	-0.277	0.758	26.06	1.138	21.47	33.373	33.60	0.98	-0.02	-0.23	0.79	27.24	108
Healy10	6-Apr-01	0.195	39.3	-1.158	35.0	845	0.157	-1.852	65.6	1.009	2.744	3.66	1.138	26.97	1.015	33.96	25.50	3.24	3.43	30.98	41.26	73
	6-Apr-01	0.79	39.3	0.241	35.0	845	0.636	-0.453	112.5	0.111	1.118	24.44	1.138	26.97	14.578	46.52	2.13	0.76	0.96	2.60	56.85	123
	6-Apr-01	1.19	39.3	0.651	35.0	845	0.958	-0.043	166.3	-0.152	0.859	42.63	1.138	26.97	32.560	64.15	1.29	0.26	0.23	1.26	62.44	165
Healy11	12-Apr-01	0.043	75.5	-2.996	37.0	850	0.024	-3.715	170.5	2.190	8.932	1.12	1.138	50.16	0.078	119.14	951.83	6.86	6.73	839.50	105.08	156
	12-Apr-01	0.083	75.5	-2.339	37.0	850	0.047	-3.057	179.2	1.767	5.856	2.73	1.138	50.16	0.225	126.08	270.35	5.60	5.57	261.94	122.16	175
	12-Apr-01	0.172	75.5	-1.610	37.0	850	0.097	-2.328	207.1	1.300	3.668	7.35	1.138	50.16	0.807	148.79	74.29	4.31	4.28	72.07	144.35	203
	12-Apr-01	0.269	75.5	-1.163	37.0	850	0.152	-1.881	209.6	1.013	2.753	13.48	1.138	50.16	1.843	144.11	29.42	3.38	3.49	32.64	159.91	225
					0.0									50.16								
	12-Apr-01	0.09	76.4	-2.264	26.0	856	0.061	-2.802	163.2	1.719	5.580	3.12	1.138	48.76	0.258	111.06	198.75	5.29	5.12	166.76	93.19	145
	12-Apr-01	0.183	76.4	-1.554	26.0	856	0.123	-2.092	174.4	1.264	3.538	8.17	1.138	48.76	0.903	116.56	50.45	3.92	3.86	47.45	109.63	167
	12-Apr-01	0.28	76.4	-1.129	26.0	856	0.189	-1.667	186.1	0.991	2.693	14.57	1.138	48.76	1.987	120.79	22.33	3.11	3.11	22.34	120.85	186
					0.0									48.76								
Healy12	18-Apr-01	0.569	26.9	0.102	59.0	820	0.420	-0.867	74.3	0.200	1.222	9.20	1.138	21.39	7.699	36.01	4.78	1.56	1.69	5.42	40.83	79
	18-Apr-01	0.57	27.3	0.097	38.0	819	0.520	-0.654	64.7	0.204	1.226	9.40	1.138	21.82	7.726	25.75	3.36	1.21	1.31	3.71	28.44	67
	18-Apr-01	0.574	28.5	0.082	16.0	845	0.803	-0.220	56.7	0.213	1.238	10.36	1.138	19.56	7.831	18.95	2.26	0.82	0.54	1.72	14.41	52

The graphs corresponding to Figs. 5-9 are shown below in Figs. 10-14 for the high friction model.

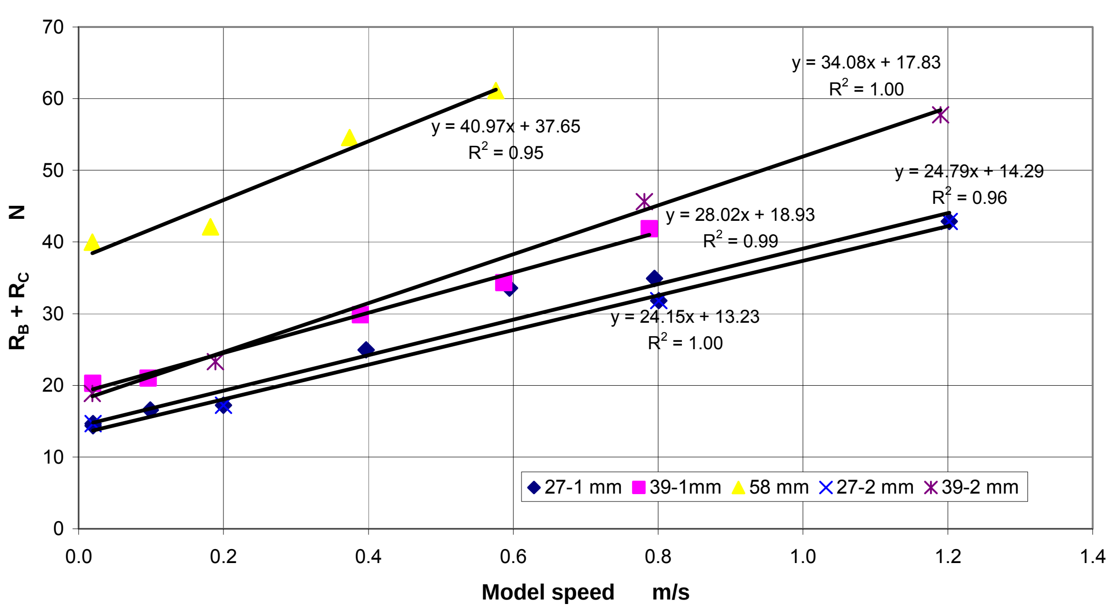

Fig. 10. Pre-sawn minus open water resistance, or buoyancy plus clearing resistance, for the Healy model 546, high friction 0.034

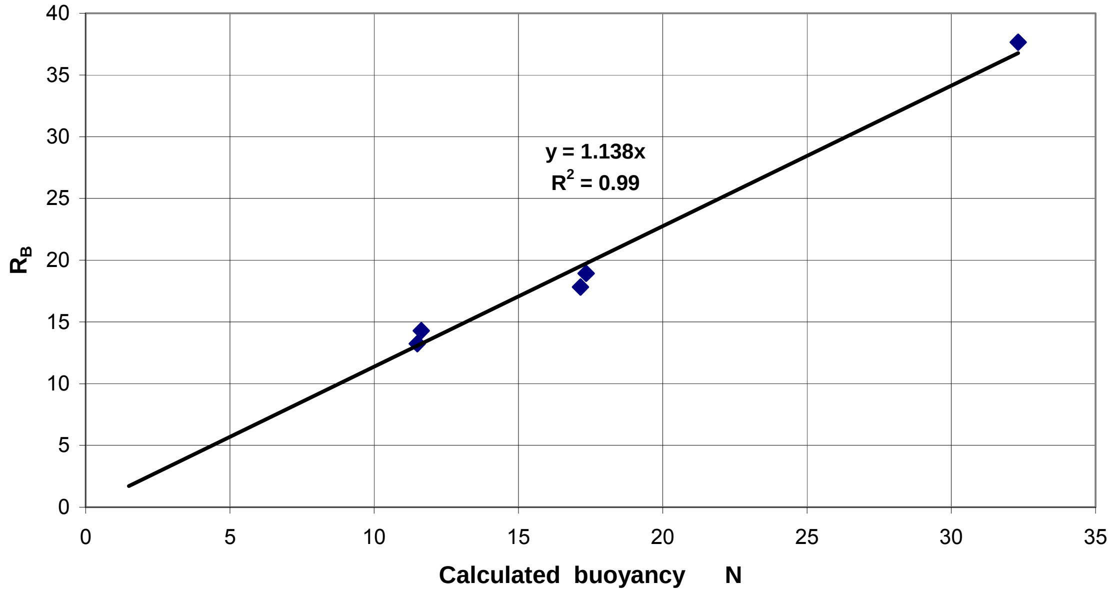

Fig. 11. The buoyancy resistance from the y-intercepts of Fig. 10 above, plotted against the calculated buoyancy, for the high friction Healy model.

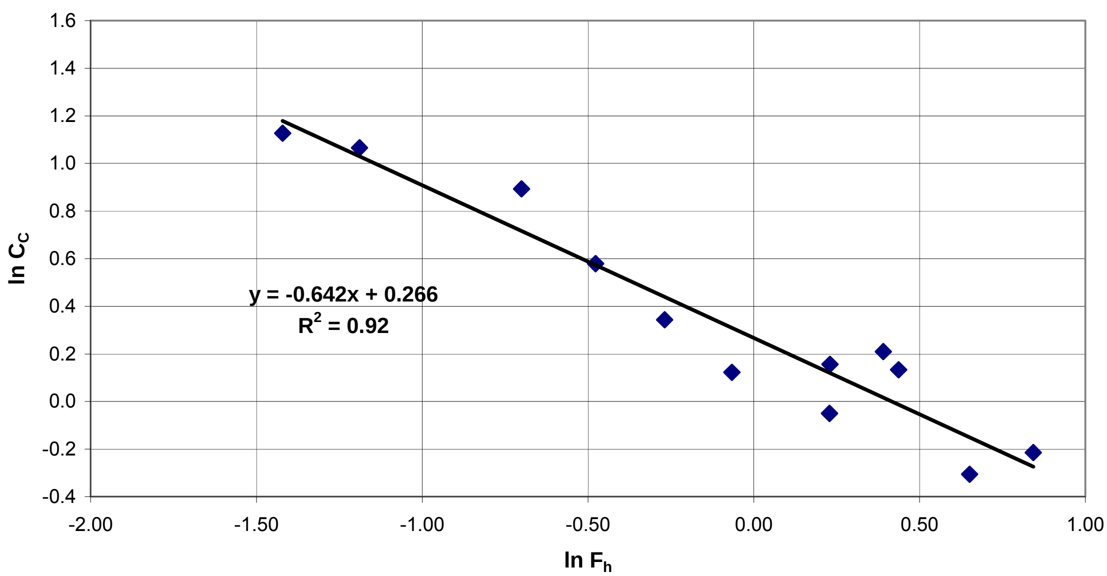

Fig. 12. Clearing coefficient plotted against Froude number on a ln-ln scale, for the high friction Healy model.

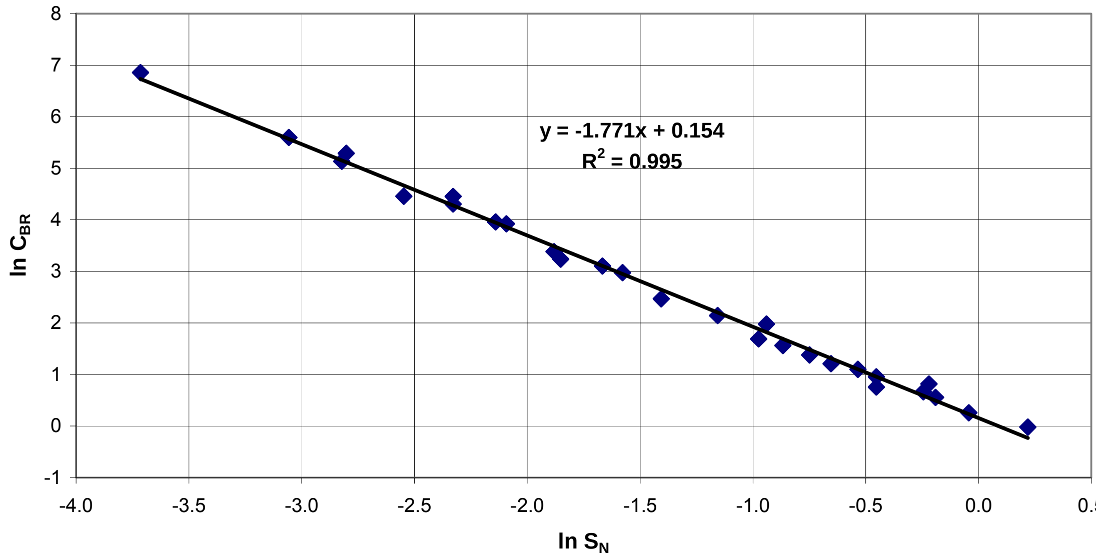

Fig. 13. Breaking coefficient plotted against "Strength Number" on a ln-ln scale, for the high friction Healy model.

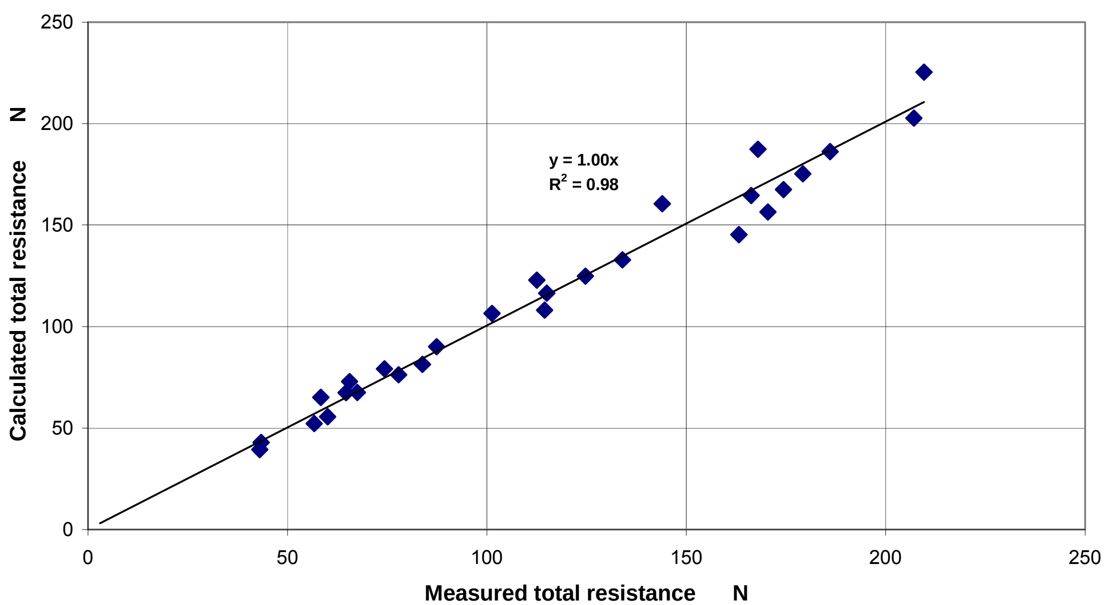

Fig. 14. Calculated versus measured total resistance for the high friction, 0.034, Healy model. The data would lie on a line of slope 1:1 if equation (8) were a perfect representation of the data.

The resistance equation obtained for the high friction (0.034) model was:-

$$R_t = R_{OW} + 1.138\Delta\rho_i g B h_i T + 1.035\left(\frac{V_M}{\sqrt{gh_i}}\right)^{-0.642}\left(\rho_i B h_i V_M^2\right) + 1.167 S_N^{-1.771}\left(\rho_i B h_i V_M^2\right) \ldots (9)$$

4.5 Other Results of Resistance Tests

The following results are taken from Jones and Moores (2002) and are repeated here for completeness. The open water resistance (Fig. 4) was first subtracted from the total resistance in ice to give R_{IT}, the total ice resistance. This was then used for the analysis in the figures below.

4.5.1 Effect of velocity

Fig. 15 below shows the total ice resistance results for the high friction (0.034) model as a function of velocity for different ice thicknesses, all for constant ice strength of 33±3 kPa. There is a linear dependence of ice resistance on velocity in Fig. 15. For example, when h_i=39 mm, ice flexural strength σ_f = 33kPa, and ice-hull friction coefficient = 0.034, the total ice resistance was given by:-

$$R_{IT} = 68.5v + 49.1$$

where v is the velocity in m/s and R_{IT} is in Newtons. Data are also shown for two different ice sheets of the same nominal thickness, 27 and 39 mm, and the resistance results are seen to be in good agreement even before any “corrections” of the data for slight differences in ice thickness or strength are made.

4.5.2 Effect of ice thickness

Fig. 16 below shows the total ice resistance as a function of ice thickness for different velocities, at constant ice strength. It can be seen that the effect of ice thickness is non-linear and the resistance increases approximately as the square of the ice thickness. The equation shown on Fig. 16 is a best fit to the 0.1 m/s data, and the best fit to the data at 0.4 m/s is:-

$$R_{IT} = 0.02h_i^2 + 1.35h_i$$

where h_i is in mm, and R_{IT} in Newtons.

4.5.3 Effect of friction

We investigated the effect of hull-ice friction coefficient on the ice resistance. Fig. 17 below shows the effect of changing the friction coefficient from 0.015 to 0.034 on the total ice resistance, for three different ice thicknesses. Fig. 17 shows that in thin ice of 27mm thickness, the effect of approximately doubling the friction coefficient from 0.015 to 0.034, increased the total ice resistance by about 10N or about 15% depending on speed. In thick ice of 58 mm, the resistance was also increased by about 15%. This result is consistent with our earlier correlation studies of the R-Class icebreaker (Spencer and Jones, 2001), and of other ships.

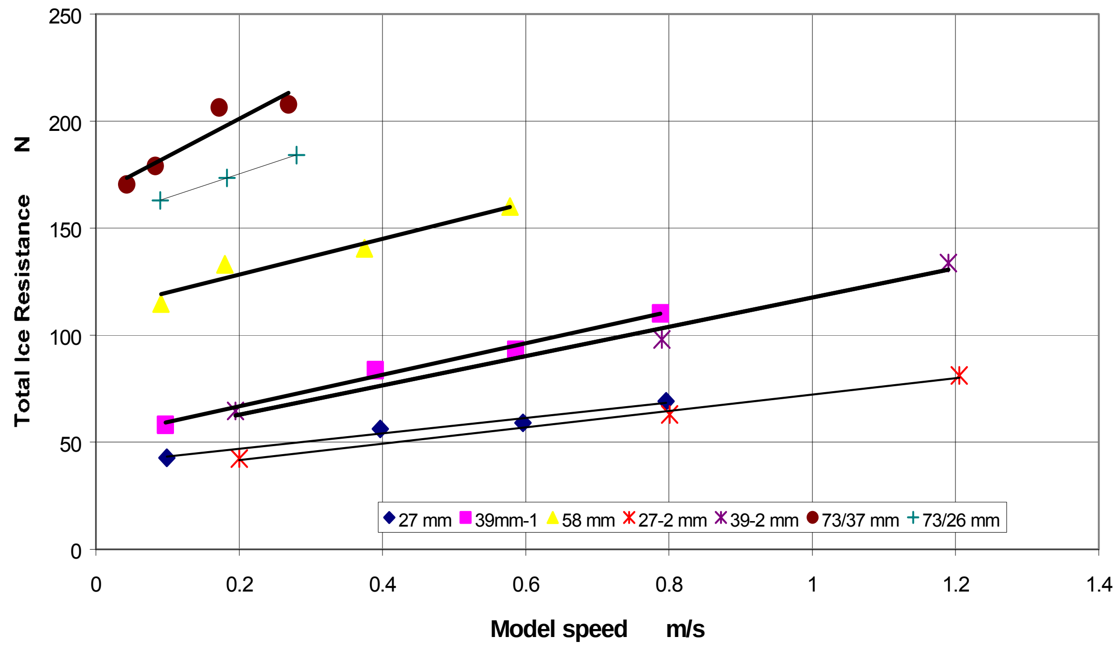

Fig. 15. Total ice resistance for the high friction Healy model as a function of velocity for different ice thicknesses. Ice strength was maintained constant at 33 ± 3 kPa.

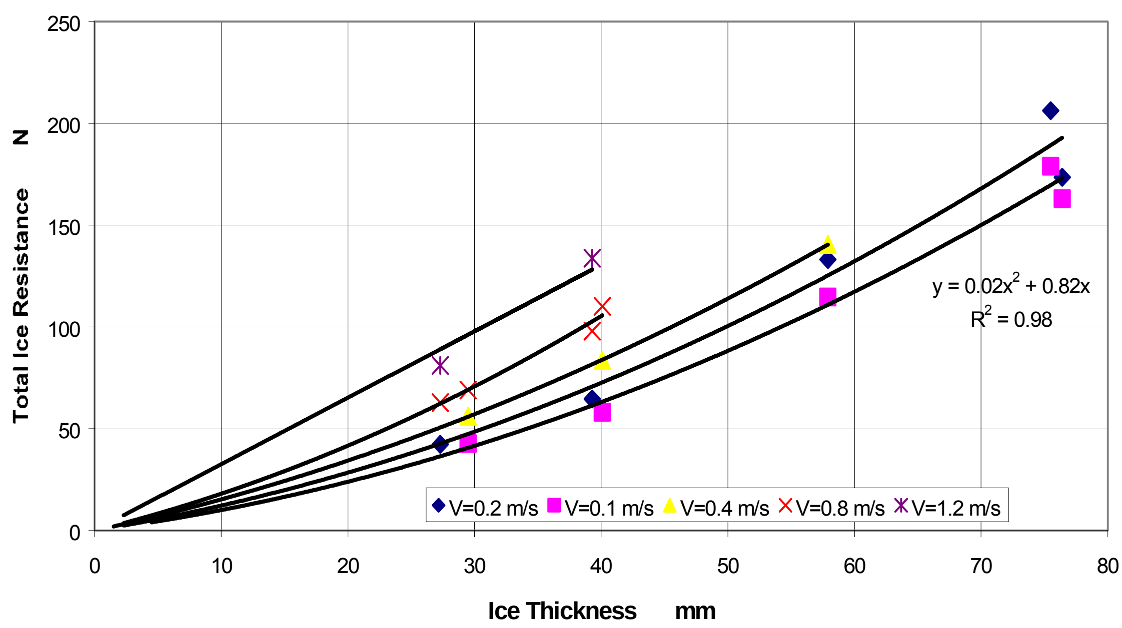

Fig. 16. Total ice resistance for the high friction Healy model as a function of ice thickness for different velocities as shown. Ice strength constant at 33±3 kPa.

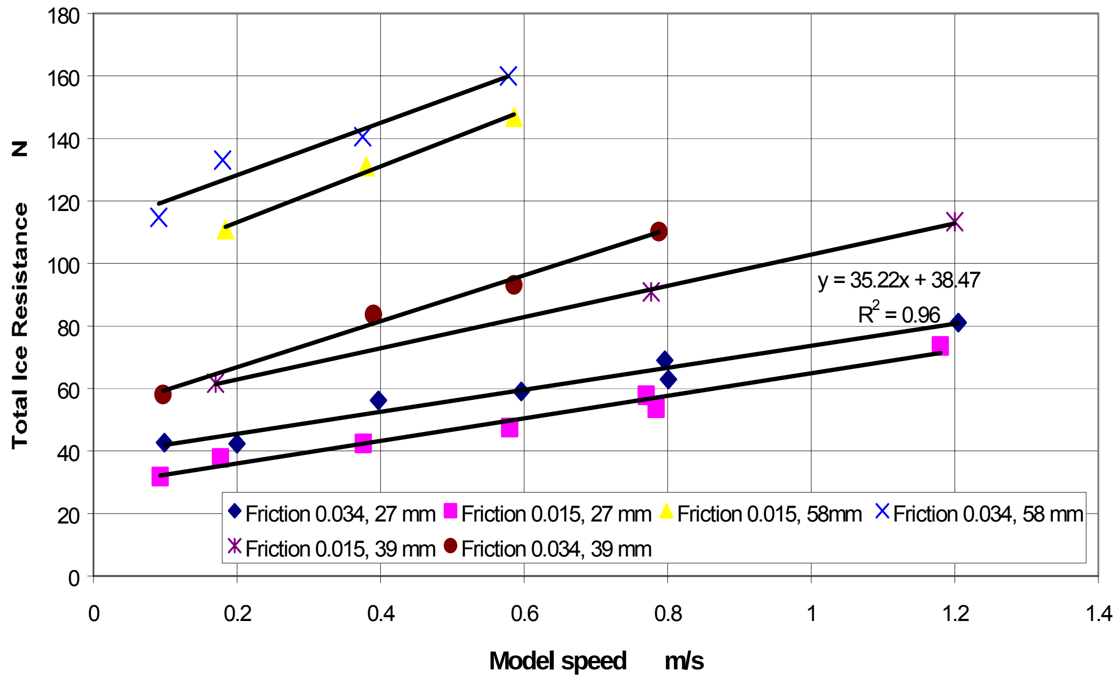

Fig. 17. Effect of ice-hull friction coefficient on the total ice resistance for the Healy model as a function of velocity.

4.5.4 Effect of ice strength

Fig. 18 below shows the effect of ice strength on the resistance of the Healy model. The results showed a significant effect, which increased considerably with ice thickness, as shown by the slope of the lines in Fig. 18. At 27 mm ice thickness, doubling the ice strength caused R_{IT} to increase by about 25%; at 76 mm ice thickness, doubling the ice strength caused a 40% increase in R_{IT}.

This result is significant because the full-scale trials were conducted in ice of about 315 kPa, when the design condition for the ship had specified 690 kPa. The ship had been designed for "continuous icebreaking at 3 knots through 4.5 ft (1.37 m) of ice of 100 psi (690 kPa) strength". The mean strength during the full-scale trials was 315kPa (Jones et al., 2001) a factor of 2.2 weaker than the design strength. These resistance results show that the power requirements of the ship would have had to be between 25% and 40% higher than those measured on the full-scale trials, for the ship to have broken the same thickness of ice of the design strength. On the trials, the ship broke 1.37 m of ice of 315 kPa flexural strength while traveling at 3 knot, using 20,000 hp. Our present results suggest that had the ice had a flexural strength of 690 kPa , the power required would have been about 30% greater or 26,000 hp. This is still within the capability of the Healy, which can generate a maximum power of 30,000 hp. This topic is discussed again later in this report, after the propulsion test results.

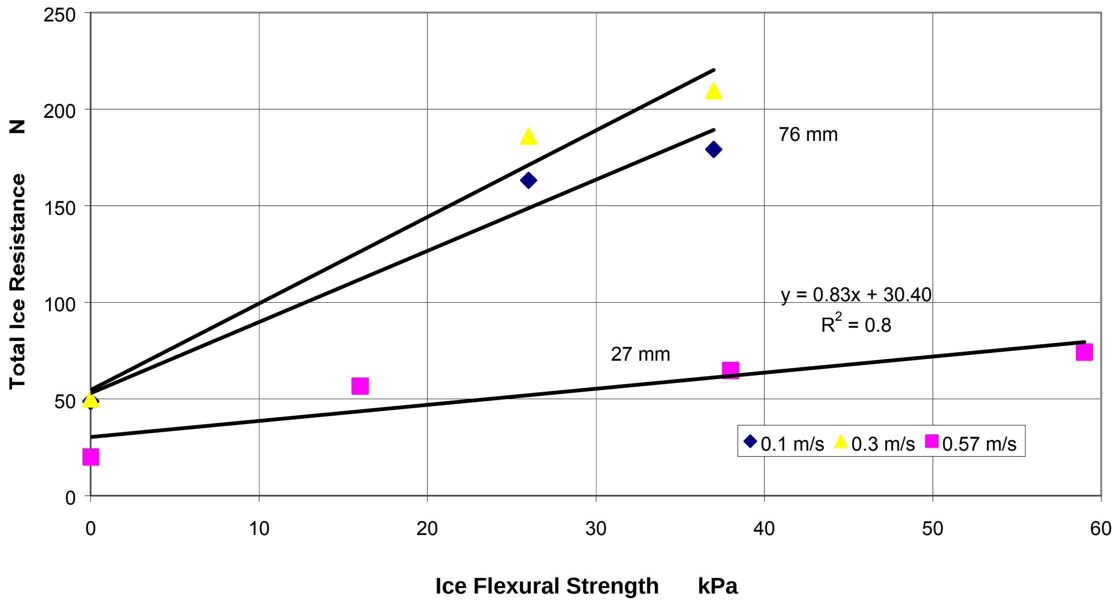

Fig. 18. Ice resistance as a function of ice flexural strength for two ice thicknesses and three velocities.

5.0 PROPULSION TESTS

Propulsion tests were conducted according to IOT's Standard Method (IOT Standard test method TM8 Draft1).

5.1 Background and Theory of the Method

The principle of this method is that overload experiments in open water are used to predict the hydrodynamic torque required to develop a thrust sufficient to move the hull against a force equal to the hull resistance in ice. Because such open water tests cannot take account of any ice-propeller interaction, it is necessary to conduct a corresponding experiment in ice to determine the increase in torque due to propeller-ice interaction. It is assumed in this method that propeller-ice interaction has a negligible effect on the thrust developed by the propulsion system. This has been shown to be true for small values of h_i/D where h_i is the ice thickness and D is the diameter of the propeller (Molyneux, 1989).

This method has certain advantages. If hydrodynamic effects can be separated from ice effects, some aspects of propulsive performance, for example, the effects of propeller pitch variation on tow force, can be investigated using only open water experiments. The torque due to ice can be considered as a function of the ice parameters (thickness, strength etc.) and added to the open water values. This method has the practical advantage that, because the towing carriage arrangement for resistance in ice tests and overload propulsion in ice tests are similar, it is possible to change quickly from one to the other. Thus, resistance and propulsion experiments in the same ice sheet are possible, provided that the propellers can be fitted or removed easily.

5.2 Self-propulsion Tests in Open Water using an Overload Method

The *Healy* model was equipped with the *R-Class* propellers, 66L and 66R. First, overload tow force tests were conducted in open water to give equations relating the tow force to rps for a given speed. The model was towed at a constant speed given by the carriage, and the rps was varied from 0 to between 12 and 18 rps depending on the speed. For a speed of 0.02 m/s the maximum rps was 12, for 1.2 m/s the maximum was 18 rps. The data were fitted to second order equations with high levels of accuracy. The results are shown in Fig. 19 below for the port side propeller. Similar equations were derived for the torque, Q, and thrust, T, as a function of RPS, during these overload tests as shown in Figs. 20 and 21. Neglecting ice-propeller interaction for the moment, it is now possible, therefore, to determine delivered power by:-

1. Equating resistance in ice for a specific ice thickness, strength, and speed to tow force from the open water overload tests
2. Determine an rps value from this tow force and Fig. 19.
3. Determine Q for this tow force from Fig. 20.
4. Calculate P_D from (2.π.Q.rps) and scale up for comparison with full-scale.
5. Repeat for different values of ice thickness, strength, and ship speed.

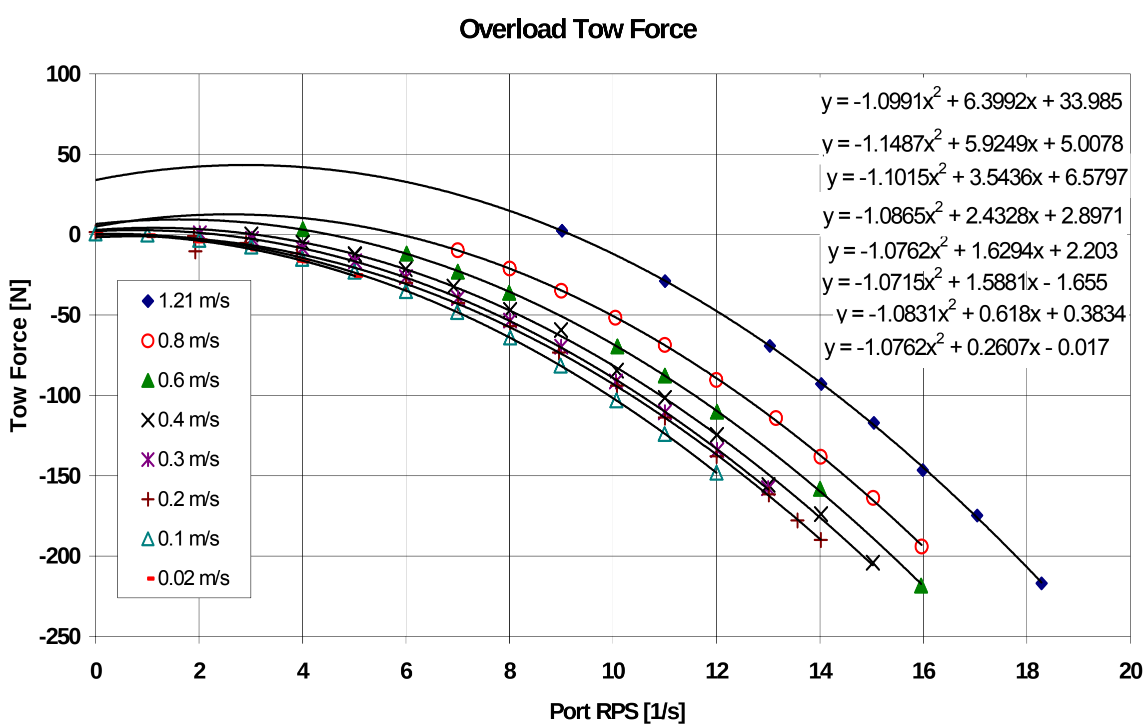

Fig. 19. Tow force in overload tests in of Healy model in open water

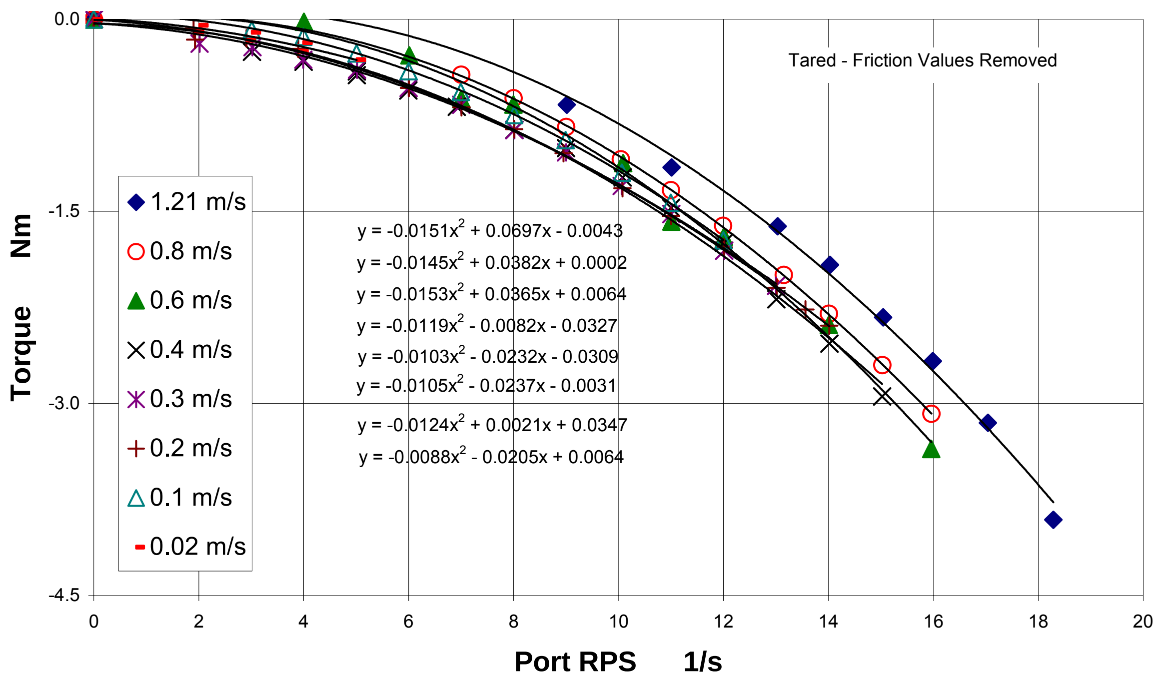

Fig. 20. Torque of port side propeller as a function of RPS for the water overload tests.

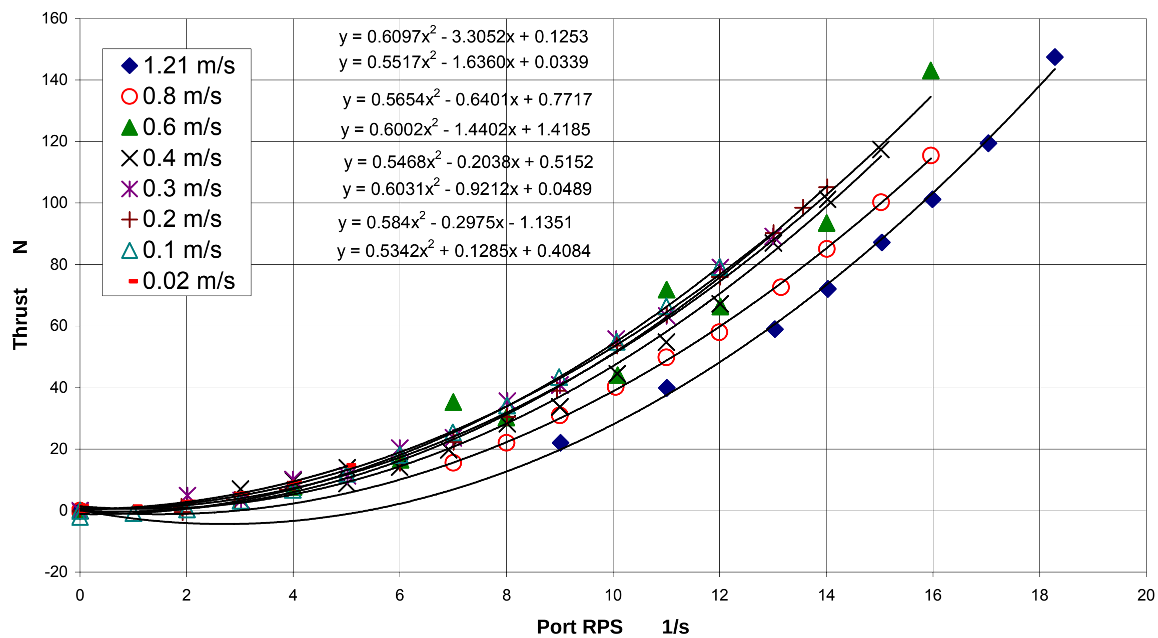

Fig. 21. Port side propeller thrust as a function of RPS for the water overload tests.

To take account of propeller-ice interaction we did the following. Two ice sheets were used for overload tests, one 39 mm thick and one 27 mm thick. Four speeds were used at five different rps. From these tests two graphs were drawn as shown in Fig. 22 and 23. They show thrust, T_i, and torque, Q_i, plotted against rps. For a given set of ice thickness, strength and ship speed, resistance can be calculated, equated to tow force and an rps found from Fig. 19 above. From this rps, Q and Q_i can be calculated from Figs 20 and 23, and the ratio Q_i/Q determined. A mean value of this ratio is then determined and used to convert Q to Q_i. From this value of Q_i, a value of Delivered Power is obtained and compared to full-scale. This is demonstrated in the Excel

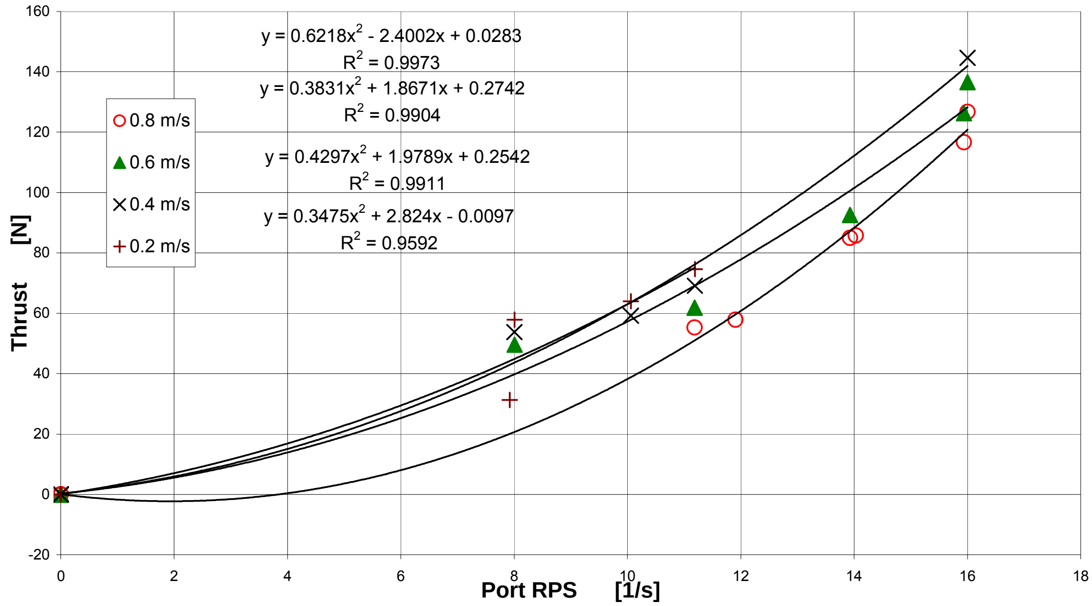

Fig. 22. Thrust developed during overload tests in ice, port side.

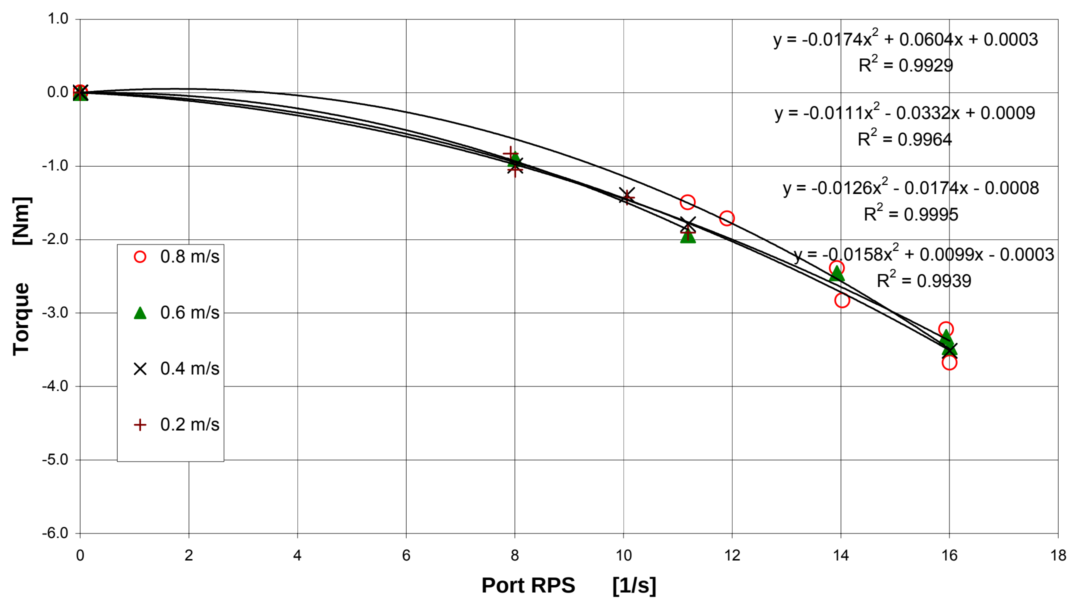

Fig. 23. Torque developed during overload tests in ice, port side.

spreadsheet shown in Fig. 24 below.

$h_{i\ Model}$ [m]	0.057	σf ice [Pa]	14810												
$h_{i\ Ship}$ [m]	1.36													**0.014**	**0.034**
Model Speed	**Ship Speed**	**R_T - $R_{OW\ Model}$**	**Model RPS**	**R_T - $R_{OW\ Ship}$**	**$R_{OW\ Ship}$**	**$Q_{OL\ Model}$**	**Qi/Q**	**Q_{Ice}**	**$R_{TS\ Ice}$**	**Eff. Power**	**Del. Power**	**Ship Speed**	**P_D Model**	**P_D Ship**	**P_DShip**
[m/s]	**[knot]**	**[N]**	**[1/s]**	**[kN]**	**[kN]**	**[Nm]**		**[N.m]**	**[kN]**	**R_{TS} [kW]**	**from Q_{Ice} [kW]**	**[knot]**	**[W]**	**HP**	**Hi Frict. HP**
0.01	0.09	54.79	8.45	729.34	77.79	1.59	1.067	1.695	807	39	5833	**0.09**	90.0	**7819**	**8915**
0.02	0.19	57.46	8.60	764.93	79.43	1.62	1.068	1.732	844	82	6062	**0.19**	93.5	**8126**	**9252**
0.10	0.95	68.25	8.76	908.54	93.07	1.88	1.077	2.028	1002	488	7235	**0.95**	111.6	**9699**	**11017**
0.20	1.89	77.32	9.18	1029.24	111.42	2.21	1.087	2.401	1141	1111	8973	**1.89**	138.5	**12029**	**13663**
0.30	2.84	85.36	9.39	1136.26	131.22	2.54	1.097	2.789	1267	1851	10661	**2.84**	164.5	**14290**	**16145**
0.40	3.79	93.03	10.58	1238.43	152.47	2.90	1.107	3.216	1391	2709	13857	**3.79**	213.8	**18575**	**20778**
0.60	5.68	108.03	11.93	1438.06	199.33	3.47	1.128	3.919	1637	4783	19043	**5.68**	293.8	**25527**	**28658**
0.80	7.57	122.97	13.44	1637.02	251.99	4.21	1.148	4.839	1889	7357	26492	**7.57**	408.8	**35512**	**39635**
1.00	9.46	138.05	15.62	1837.78	310.45	4.85	1.169	5.665	2148	10458	36035	**9.46**	556.0	**48304**	**53794**
1.20	11.36	153.34	18.03	2041.22	374.71	5.51	1.189	6.547	2416	14114	48052	**11.36**	741.5	**64413**	**71612**

Fig. 24. Spreadsheet used to determine Delivered Power.

In the above Fig. 24:-

Col. 1 is the experimental model speed in m/s.
Col. 2 is the corresponding ship speed in knots.
Col. 3 is the ice resistance, R_T-R_{OW}, calculated previously. This is equated to F_D, the tow force in the water overload tests.
Col. 4 is the model rps for this tow force. Where this is not available (because a particular speed was not used in the overload tests) values of rps are extrapolated from the other data in col. 4.
Col. 5 is the data of col. 3 scaled up to full-scale.
Col. 6 is the open water resistance of the full-scale ship calculated from the model open water resistance.
Col. 7 is torque, Q, of the model corresponding to the rps in col. 4. If it is not available it is extrapolated from the other data in the column.
Col. 8 is the ratio of torque from the ice overload test to the water overload test, Q_i/Q.
Col. 9 is the product of cols. 7 and 8, thus giving the torque, Q_i, in ice.
Col. 10 is the total resistance of the full-scale ship obtained by adding Cols. 5 and 6.
Col 11 is the Effective Power P_E, equal to R_{TS} (col. 10) multiplied by V_S (col. 2).
Col. 12 the Delivered Power, $P_D = 2\pi Q_i rps$, scaled up to full-scale. Q_i is col. 9 and rps is col. 4. The model scale factor for the *Healy* is 23.7.
Col. 13 is a repeat of col. 2
Col. 14 is Delivered Power at model scale, i.e. $2\pi Q_i rps$, not scaled up.
Col. 15 is col. 12 in units of HP rather than KW.
Col. 16 is Delivered Power in HP for a ship with the high friction coefficient, 0.034, for comparison.

Fig. 25 below shows the results of these calculations for the specific ice conditions of 1.36 m thickness and 351 kPa strength, which was the mean strength found during the full-scale trials for this thickness. The three "model" lines correspond to three friction coefficients; 0.014 and 0.034 as model tested, and 0.05 as extrapolated from the two others. The friction value 0.05 is the value that IOT has found gives best agreement between model-scale and full-scale, for a new hull in ice with little snow. The full-scale data was taken from Sodhi et al (2001) and was the delivered power measured independently on the propeller shafts by both torsion meters and strain gauges. A shaft speed measurement system was also installed on each shaft. The shaft speed and torque measurements were then combined to determine the power delivered to each shaft. The two measurements of shaft torque agreed with each other within 1%.

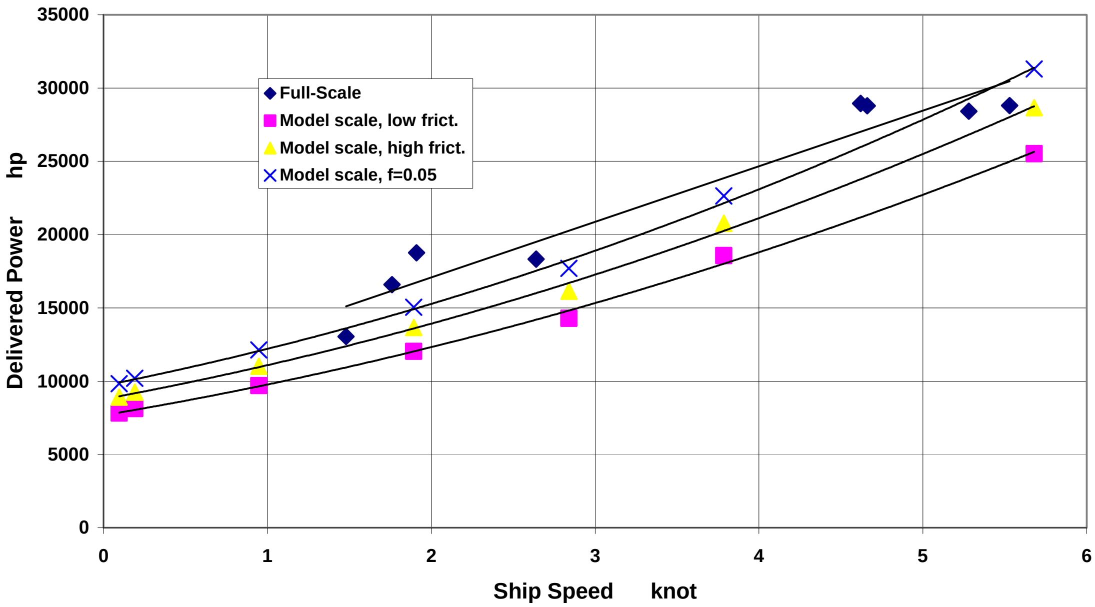

Fig. 25. Delivered power for the Healy calculated from the model tests for three friction coefficients, the two experimental ones, 0.014 and 0.034 and extrapolated to 0.05, compared to the measured full-scale power. Ice conditions, 1.36 m thick of strength 351 kPa.

Good agreement can be seen in Fig. 25 between the model scale data for a friction coefficient of 0.05 and the full-scale data. The following Figures 26-28 show similar results for the other ice thicknesses and strengths measured on the full-scale trials. While agreement between model and full-scale is always good it is clearly better at the higher ice thicknesses. Also note that the results for the two experimental friction coefficients show a larger effect of friction coefficient in thicker, and somewhat stronger, ice. This is consistent with the effect on resistance discussed earlier in Section 4.5.3 and Fig. 17. The power predicted from the model tests is always slightly lower than that measured at full-scale. Possible reasons for that are frictional losses in the ship's shaft bearings aft of the point at which the power was actually measured, and the fact that we were not using true *Healy* propellers in the model tests, but stock R-Class propellers.

The *Healy* was designed for "continuous icebreaking at 3 knots through 4.5 ft (1.37 m) of ice of 100 psi (690 kPa) strength". We have calculated, therefore, the delivered power required to do this, based on the model tests. The result is shown in Fig. 29 for the two friction coefficients tested and the 0.05 value extrapolated from them, in which it can be seen that the power required is just slightly greater than the 30,000 HP available on the *Healy*. Given the errors expected in both the full-scale and model-scale measurements, we conclude that the *Healy* is capable of its design requirement.

Purely for the sake of interest, we calculated the power required for an imaginary "Polar 8" icebreaker, assuming it to be identical in design to the *Healy*, as was proposed some

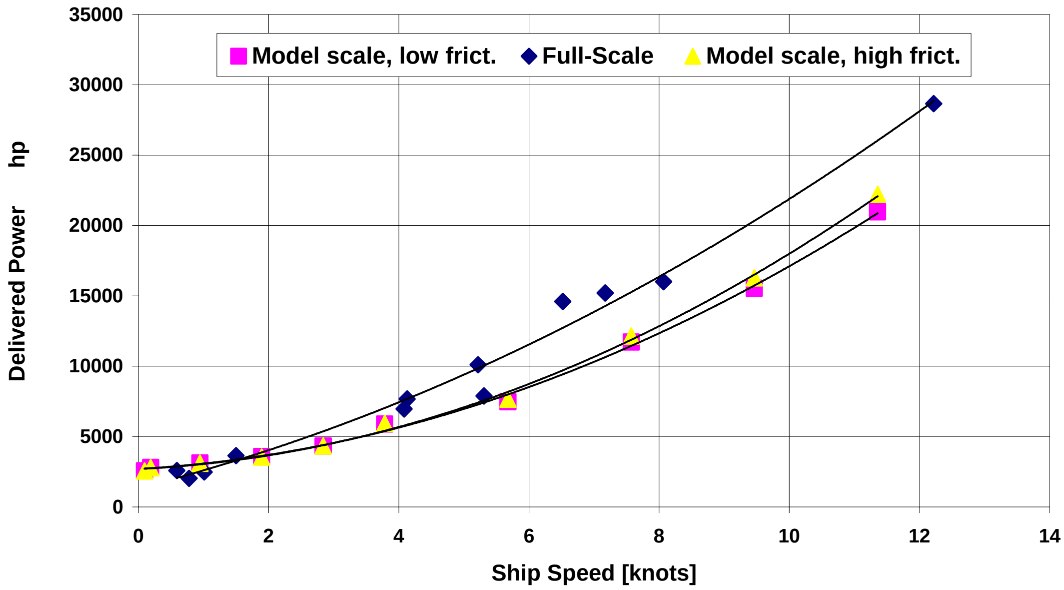

Fig. 26. Results for ice conditions of 0.66 m thickness of 272 kPa strength.

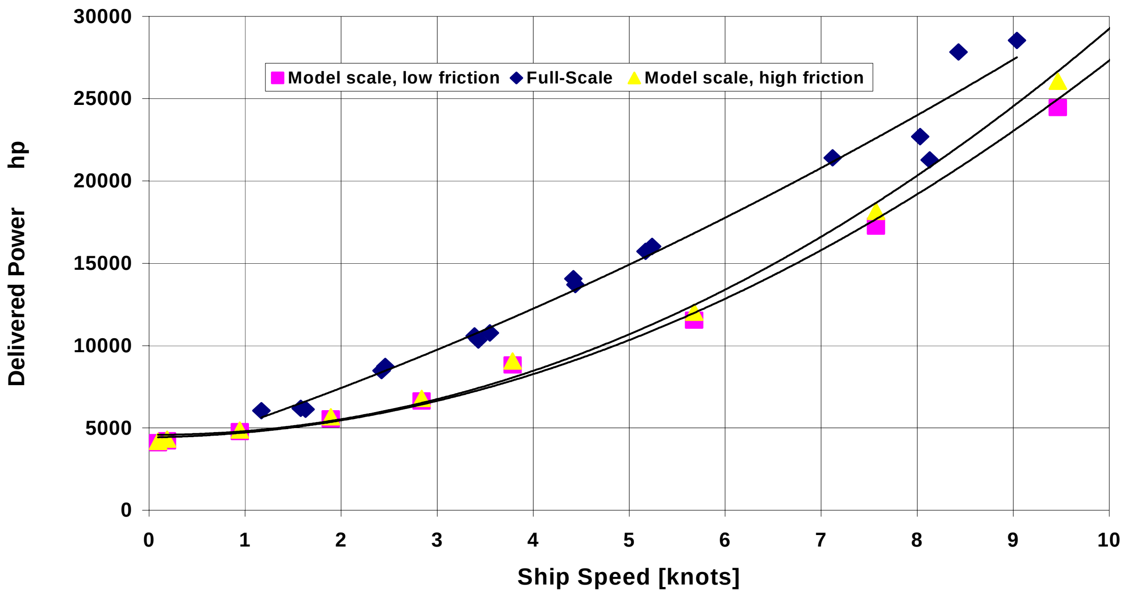

Fig. 27. Results for ice conditions, 0.89 m thickness, 259 kPa strength.

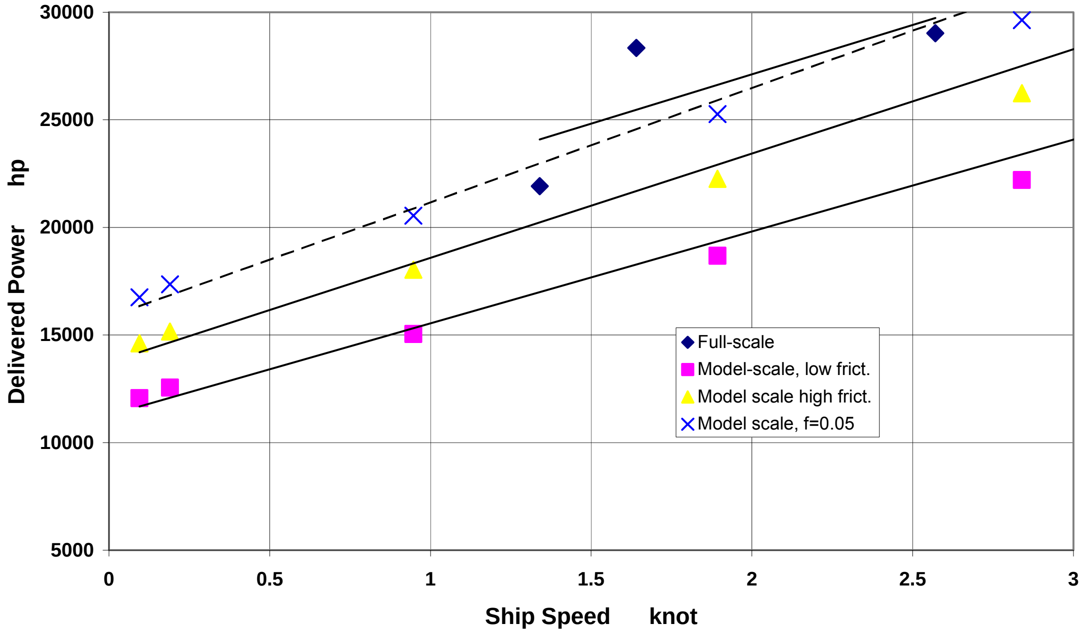

Fig. 28. Results for ice conditions 1.74 m thickness, 359 kPa strength.

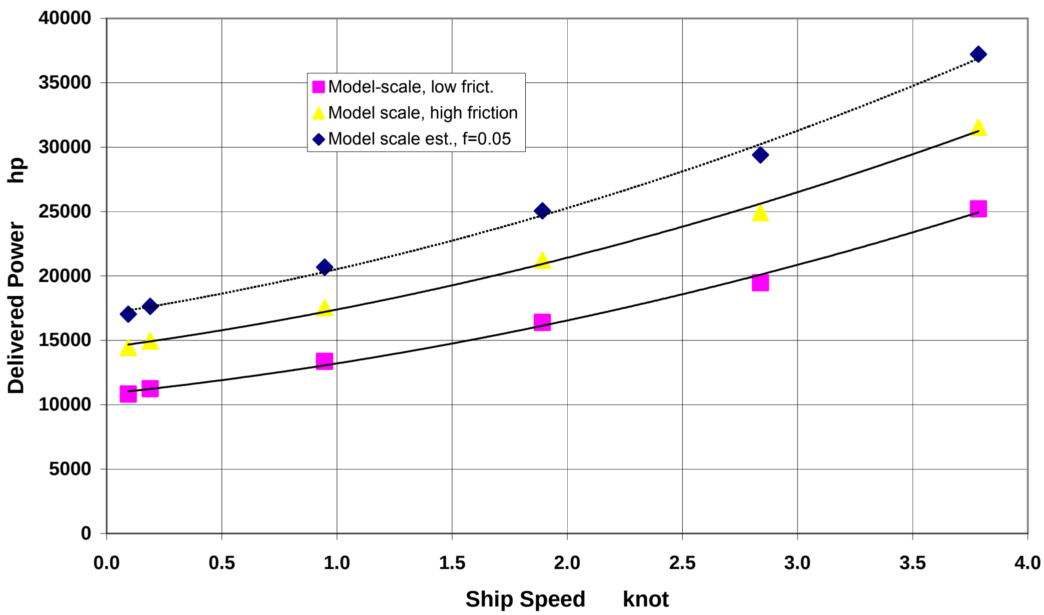

Fig. 29. Delivered power required for the Healy to break 1.37 m ice of 690 kPa strength calculated from the model tests.

years ago in Canada. Fig. 30 shows the result for ice conditions of 2.44 m (8ft) of strength 500kPa. This shows that for continuous icebreaking at 3 knot in these ice conditions, a delivered power of about 85,000HP would be required.

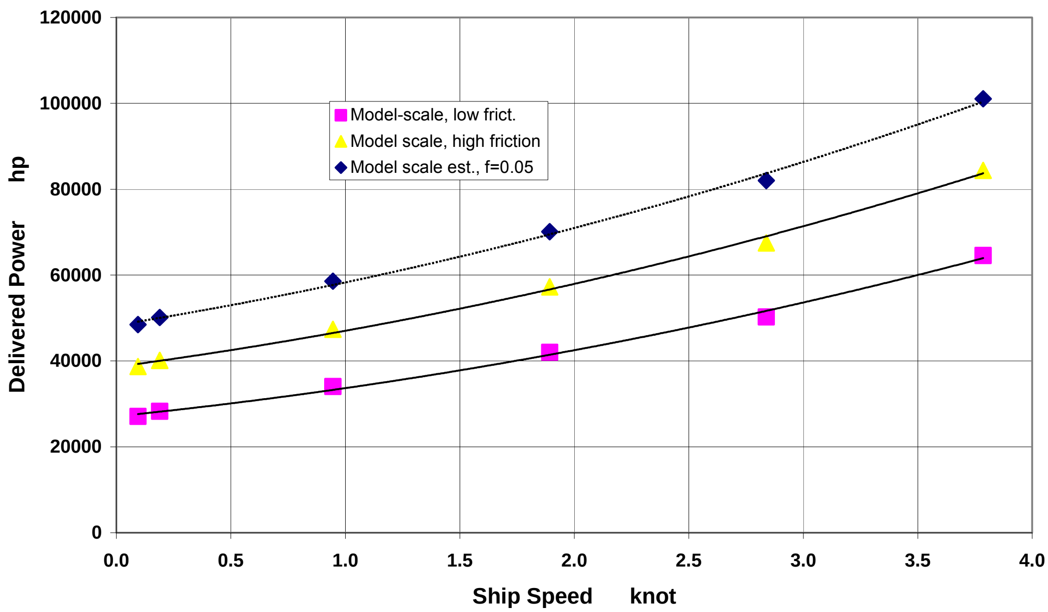

Fig. 30. An imaginary "Polar 8" icebreaker of the Healy design for ice conditions 2.44 m thick and 500kPa strength.

6.0 DISCUSSION AND CONCLUSIONS

Resistance tests on a 1:23.7 model scale of the USCGC Healy have shown that the ice resistance, excluding open water resistance, is directly proportional to velocity, and to ice thickness squared. The effect of hull-ice friction coefficient is significant as is the effect of ice strength.

Propulsion overload tests in open water combined with limited ice tests have demonstrated that the IOT Standard Method for analyzing propulsion tests in ice gives consistent results for delivered power, which agree well with the available full-scale data of the *Healy*. A correlation friction coefficient of 0.05 is again shown to be correct.

From the analysis of the resistance and propulsion tests, the *Healy* is shown to be capable of its design requirement of "continuous icebreaking at 3 knots through 4.5 ft (1.37 m) of ice of 100 psi (690 kPa) strength".

An imaginary "Polar 8" icebreaker of the *Healy* design would require 85,000 HP to continuously break ice of 2.44 m (8 ft.) thickness, of 500 kPa strength, at 3 knots.

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