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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

POWERING PREDICTIONS FOR THE R/V ATHENA (PG 94) REPRESENTED BY MODEL 4950-1 WITH DESIGN PROPELLERS 4710 AND 4711

L. Bruce Crook

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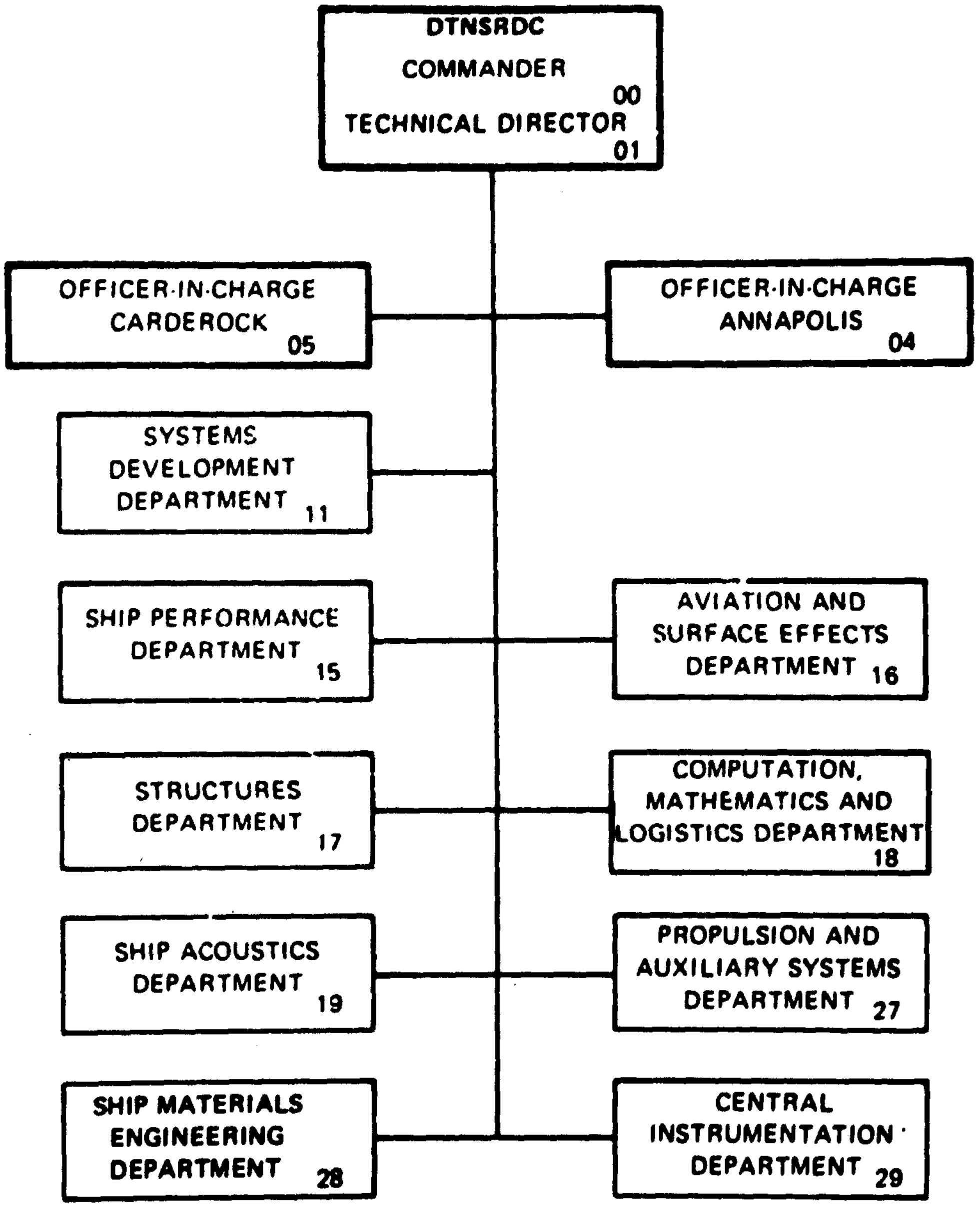

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As part of its overall project to adapt controllable pitch propellers to the needs of high speed combatant ships, the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) conducted a series of resistance and propulsion experiments on a model of the R/V ATHENA. These experiments were conducted to provide estimates of power requirements with design propellers for blade loading calculations. This report provides experimental conditions for setting up the blade loading model experiments. The estimated

correlation allowance between full-scale data and model data with design propellers was found to be 0.00065.

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NOTATION

C_A	Correlation allowance
D	Propeller diameter
EHP	Effective power in horsepower
SHP	Shaft power in horsepower
ETAD	Propulsive efficiency, $\eta_D = P_E/P_D$
ETAH	Hull efficiency, η_H
ETAO	Propeller open water efficiency, η_O
ETAR	Relative rotative efficiency, η_R
J_T	Advance coefficient based on thrust
LWL	Load waterline
P	Propeller pitch
P_D	Delivered power
P_E	Effective power
R_T	Hull towed resistance (total)
RPM	Propeller rotation speed, revolutions per minute
T	Propeller thrust
t	Thrust deduction fraction
w_Q	Torque wake fraction
w_T	Thrust wake fraction
S	Wetted surface
Δ	Ship displacement

η_D Propulsive efficiency

η_H Hull efficiency

η_O Propeller open water efficiency

η_R Relative rotative efficiency

METRIC CONVERSIONS

1 degree (angle)	= 0.01745 rad (radians)
1 foot	= 0.3048 m (meters)
1 fps foot per second	= 0.3048 m/s (meters per second)
1 inch	= 25.40 mm (millimeters)
1 knot	= 0.5144 m/s (meters per second)
1 lb (force)	= 4.448 N (Newtons)
1 lb (force) - inch	= 0.1130 N•m (Newton-meter)
1 long ton (2240)	= 1.016 metric tons, or 1016 kilograms
1 horsepower	= 0.7457 kW (kilowatts)

ABSTRACT

As part of its overall project to adapt controllable pitch propellers to the needs of high speed combatant ships, the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) conducted a series of resistance and propulsion experiments on a model of the R/V ATHENA. These experiments were conducted to provide estimates of power experiments with design propellers for blade loading calculations. This report provides experimental conditions for setting up the blade loading model experiments. The estimated correlation allowance between full-scale data and model data with design propellerswas found to be 0.00065.

ADMINISTRATIVE INFORMATION

The work reported herein was initiated and funded by the Naval Sea Systems Command (NAVSEA 05R) under Task Area S0379001. The experimental phase of this task was performed at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) under work unit number 1524-641. The data analysis and report preparation were performed by Chi Associates, Inc. (CAI) under contract to DTNSRDC, Contract No. (N00167-78-C-0089).

INTRODUCTION

The experiments reported herein were part of the Controllable Pitch Propeller Research Program at the Center. Full-scale and model measurements of alternating loads on the propeller have been made for the R/V ATHENA and its geosim model. In order to provide adequate information on the operating conditions for model experiments using the six-component dynamometer to measure propeller loads, resistance and propulsion experiments were performed. The results of those resistance and model propulsion experiments are reported herein.

In addition to alternating loads on the propeller, model and full-scale propeller disk wakes have been measured for the R/V ATHENA. These wake experiments were performed with the ship propelled by the port propeller while the starboard propeller was replaced by a pitot tube rake. Propulsion information was needed for the operating condition of single delivered propulsion. Such an experiment was performed and the results are reported herein.

Finally, it is possible to perform a ship-model correlation with the existing standardization trial data for PG 87[1] and PG 92[2] using the twin shaft model propulsion data. The resulting correlation allowance and comparisons of model and full-scale self propulsion data are also presented in this report.

EXPERIMENTAL PROCEDURE

DTNSRDC Model 4950-1, representing the PG 94 (now designated the R/V ATHENA) was constructed to a linear ratio of 8.250 in accordance with Naval Ship Engineering Center (NAVSEC) model plans. The model was fitted with rudders, shafts and struts, a centerline drag keel, skeg and stabilizer fins. Profile, lines and body plan drawings for the R/V ATHENA represented by Model 4950-1 are shown in Figure 1. Ship and model characteristics are listed in Table 1.

Model Propellers 4710 (right hand rotation, starboard side) and 4711 (left hand rotation, port side) representing the design propellers for the PG 84 class, were used for the powering experiments. The details of the propeller model geometry are presented in Figure 2. Open-water characteristics are presented as curves in Figure 3 and tabulated in Table 2.

[1] References are listed on page 6.

All model experiments were conducted on DTNSRDC Towing Carriage 2, using a block gauge to measure the towing force after an initial check was made with girder balance system. Four different experiments are reported here, numbers 30, 31, 35 and 36, as detailed in Table 3. Experiments 30 and 31 were (respectively) conventional resistance and propulsion evaluations using twin-screw propulsion. Experiment 35 was an additional resistance evaluation conducted because the rudder angles, displacement and trim were different from those in the previous evaluation. Experiment 36 was a propulsion experiment with the port propeller operating and the starboard propeller removed.

The full-scale resistance and propulsion predictions were calculated using the 1957 ITTC Ship-Model Correlation line, with a correlation allowance of 0.0005.

PRESENTATION AND DISCUSSION OF RESULTS

Resistance and propulsion data from Experiments 30 and 31 are presented in Figures 4 and 5 and in Tables 4 and 5, and for Experiments 35 and 36 in Figures 6 and 7 and Tables 6 and 7. Effective power, delivered power and RPM are shown in the figures together with the propulsive efficiency (P_E/P_D), thrust deduction fraction (t) and thrust wake fraction (w_T). Figure 8 shows the rise, sinkage and trim for Experiment 31, and Figure 9 shows the same data for Experiment 36. Note that, over the same speed range, slightly more bow rise and more stern trim are predicted for single-screw than for twin-screw propulsion, although the differences between the trim for the two conditions are small.

Blade Loading Experimental Conditions

The propulsion conditions for the blade loading experiments, summarized from the resistance and propulsion predictions listed above, are presented in Table 8. Note that the twin-screw propulsion prediction is at 20 knots (10.3 m/s), whereas the single-screw propulsion condition is at 15 knots (7.7 m/s). Also, the displacement and trim for the two conditions are different. These differences come about since Experiment 31 was run to obtain 20-knot conditions for blade loading experiments and Experiment 36 was run to obtain correlation with full-scale wake survey conditions. Table 8 also makes a comparison of single and twin-screw propulsion experiments at the same speed.

Comparison with Full-Scale Trial Data

The propulsion predictions from Model 4950-1, at two correlation allowances can be compared with previous full-scale trial data on the twin-screw PG 87[1] and PG 92[2]. Table 9 shows this comparison for four different speeds. In spite of the differences in displacement and propeller pitch ratio, the delivered power and RPM compare to within two and a half percent, except at 35 knots (18.0 m/s) where the differences are more than five percent. These differences may be due in part to the inacurracy of the full-scale measurement of the propeller pitch ratio. The correlation allowance should be 0.00065 for both hulls based upon the top three trial speeds. The data for a correlation allowance of 0.00065 is presented in Table 10, Also correlating on RPM from the model side to full-scale the RPM ratio of model to trial for the top three trial speeds varies from 0 to 5 percent for a C_A of 0.00065.

Single and Twin-Screw Propulsion Comparison

In addition to providing the propulsion conditions for the blade loading experiments and a correlation with full-scale data, the results of the resistance and propulsion experiments can be compared with each other. As shown in Table 11, the twin-screw propulsive efficiency and advance coefficient were always higher than for the single-screw case, and the EHP/Ton, the thrust deduction and the wake fraction were consistently lower for the twin-screw case. At 16 knots (8.2 m/s), the EHP/Ton of single-screw propulsion was more than five percent greater than for twin-screw, and the propulsive coefficient was almost four percent less due to single-screw's propulsion experiment having a heavier displacement and greater trim. The increase in effective power results from the added drag due to the rudder angle necessary to compensate for the turning moment of the single driving propeller offset from the ship centerline, along with the increase in drag due to heavier displacement and greater trim.

Comparison with Previous Model Data

The experimental resistance and propulsion results can also be compared with previous data obtained from a twin-screw model. Hoekzema[3] has reported on the powering charcteristics of Model 4950, which is similar to the ATHENA model. Model 4950 has a lighter displacement by 18%, a wedge on the transom line, larger V-struts, rudders farther outboard with trailing edges aft of the transom, and less rudder clearance. Model 4950-1 does not have a true wedge but reverse buttock lines which essentially act as a faired wedge, and is fitted with design propellers instead of stock propellers.

The propulsion charcteristics of the two hulls are compared in Table 12. The propulsive coefficient, thrust deduction, wake fraction and advance coefficient are consistently lower for the ATHENA and the effective power per ton of displacement is higher for the ATHENA. For example, at 15 knots (7.7 m/s), the EHP/Ton predicted for the ATHENA was more than 10 percent greater than that for Model 4950, although the ATHENA propulsive coefficient was only about two percent less. These differences are due in part to the different drafts and correspondingly different transom immersion of the two hulls, and to the different propeller designs. In addition, propulsion predictions for Model 4950 were made using the ATTC friction line and a correlation allowance of 0.0004, whereas the ATHENA predictions used the ITTC friction line and a correlation allowance of 0.0005.

CONCLUSIONS

1. R/V ATHENA model predictions resemble full-scale measurements on two similar twin-screw hulls (PG 87 and PG 92) at the correlation allowance of 0.0005. However, a correlation allowance (C_A) of 0.00065 for these two type hulls represents a better model-ship full-scale powering scaling.
2. For the speed range of 14 to 19 knots (7.2 to 9.8 m/s), twin-screw propulsion is predicted to be more efficient than single-screw propulsion with the starboard propeller removed.
3. Based on effective power per ton of displacement, the ATHENA propulsion characteristics vary from those in a similar earlier twin-screw design (Model 4950). These differences are attributed in part to variations in drafts, transom immersion, stock or design propellers used and prediction parameters (friction coefficient and correlation allowance).
4. The propeller RPM correlation at a C_A of 0.00065 shows from zero to 5 percent difference between model and full-scale RPM with the model RPM under predicting the full-scale value.

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1. Hundley, L. L. Jr., "USS READY (PG 87) STANDARDIZATION TRIAL RESULTS (U)," NSRDC Department of Hydromechanics Evaluation Report C-352-H-01, September 1969. Declassified on 8/2/77.

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3. Hoekzema, D.R., "POWERING CHARACTERISTICS FOR A 154-FOOT HIGH SPEED PGM FROM TESTS OF MODELS 4932, 4942 and 4950 (U)," Hydromechanics Laboratory Research and Development Report C-1652, April 1964. Declassified on 8/2/77.

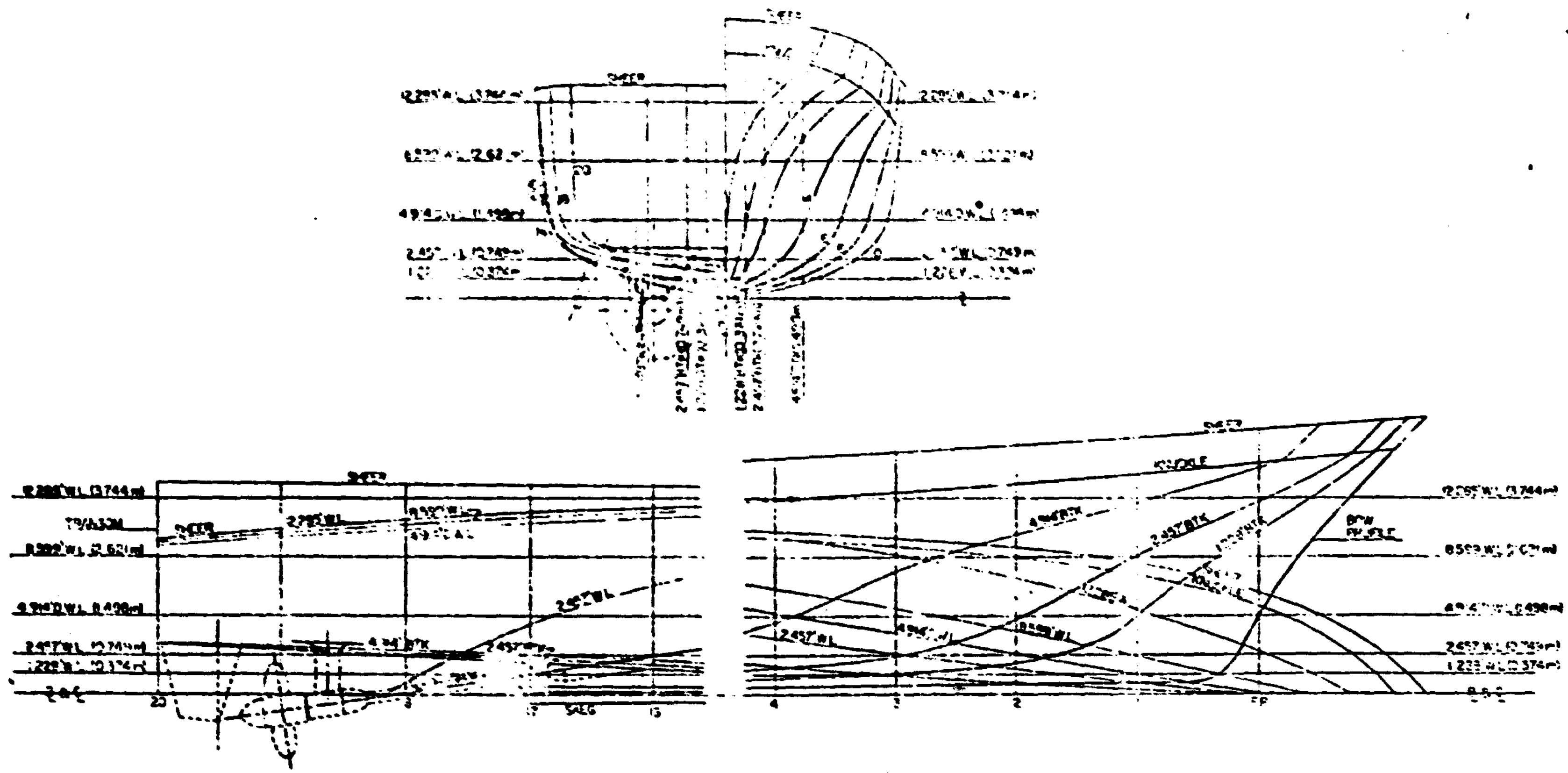

Figure 1 - Profile Lines and Body Plan for the R/V ATHENA Represented by Model 4950-1

	PROP. NO.	[illegible]	DIA. MODEL	DIA. SHIP	PITCH MODEL AT 70 PCT.	PITCH SHIP AT 70 PCT.	PITCH RATIO AT 70 PCT.	NUMBER OF BLADES	EXP. AREA	[illegible]	[illegible]	PROJ. AREA	[illegible]	[illegible]	RAKE ANGLE OF TIP	ROTATION	[illegible]	SECTION LENGTH [illegible] AT 70 PCT.
INCHES MM	4710	0.250	0.727 221.67	72.000 1020.00	9.697 246.30	80.000 2032.00	1.111	4	46.350 29900.6	0.775	0.443	40.100 25871.1	0.670	0.048	0.000	R.H.	4950	4.800 110.33
INCHES MM	4711	0.250	0.727 221.67	72.000 1020.00	9.697 246.30	80.000 2032.00	1.111	4	46.350 29900.6	0.775	0.443	40.100 25871.1	0.670	0.048	0.000	L.H.	4950	4.800 110.33

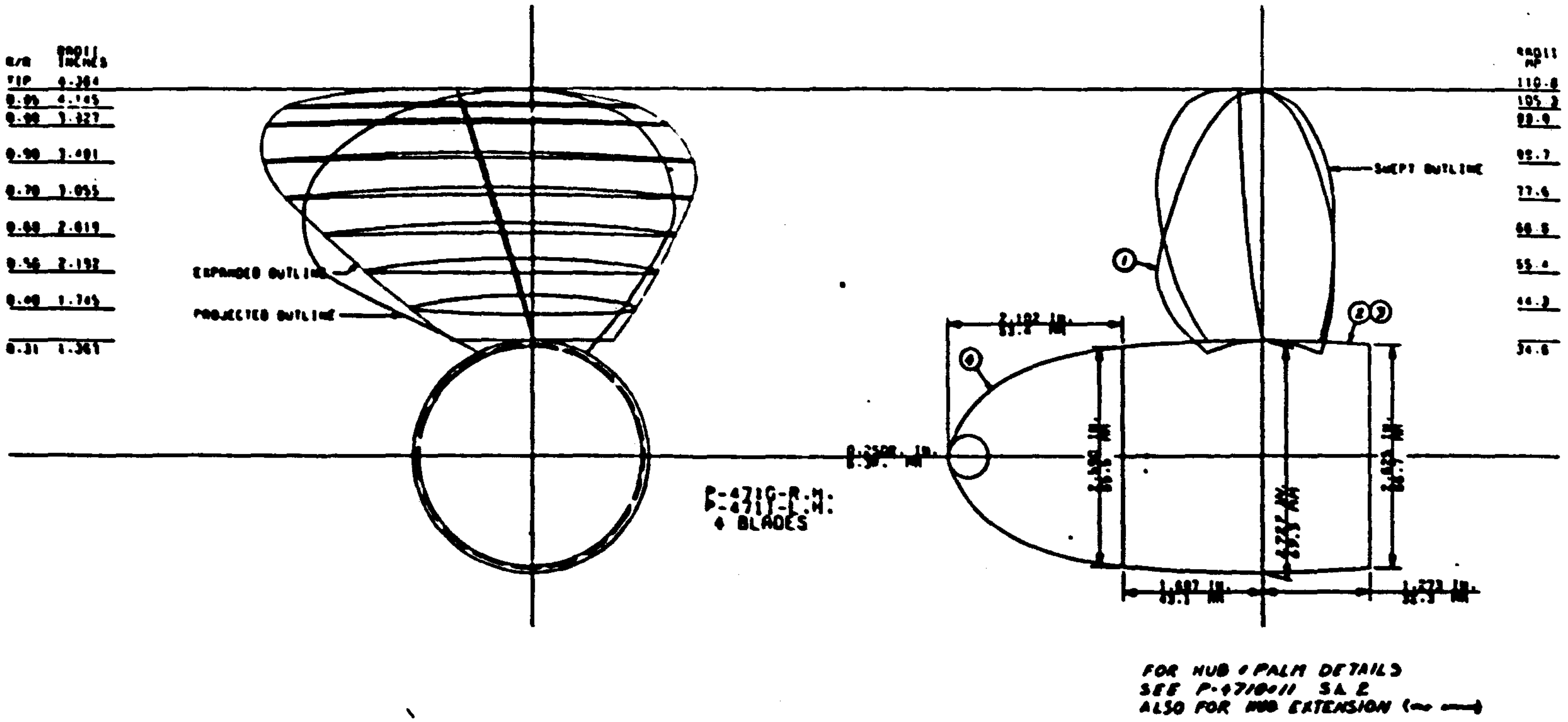

Figure 2 - Sketch of Model Propellers 4710 and 4711 Details

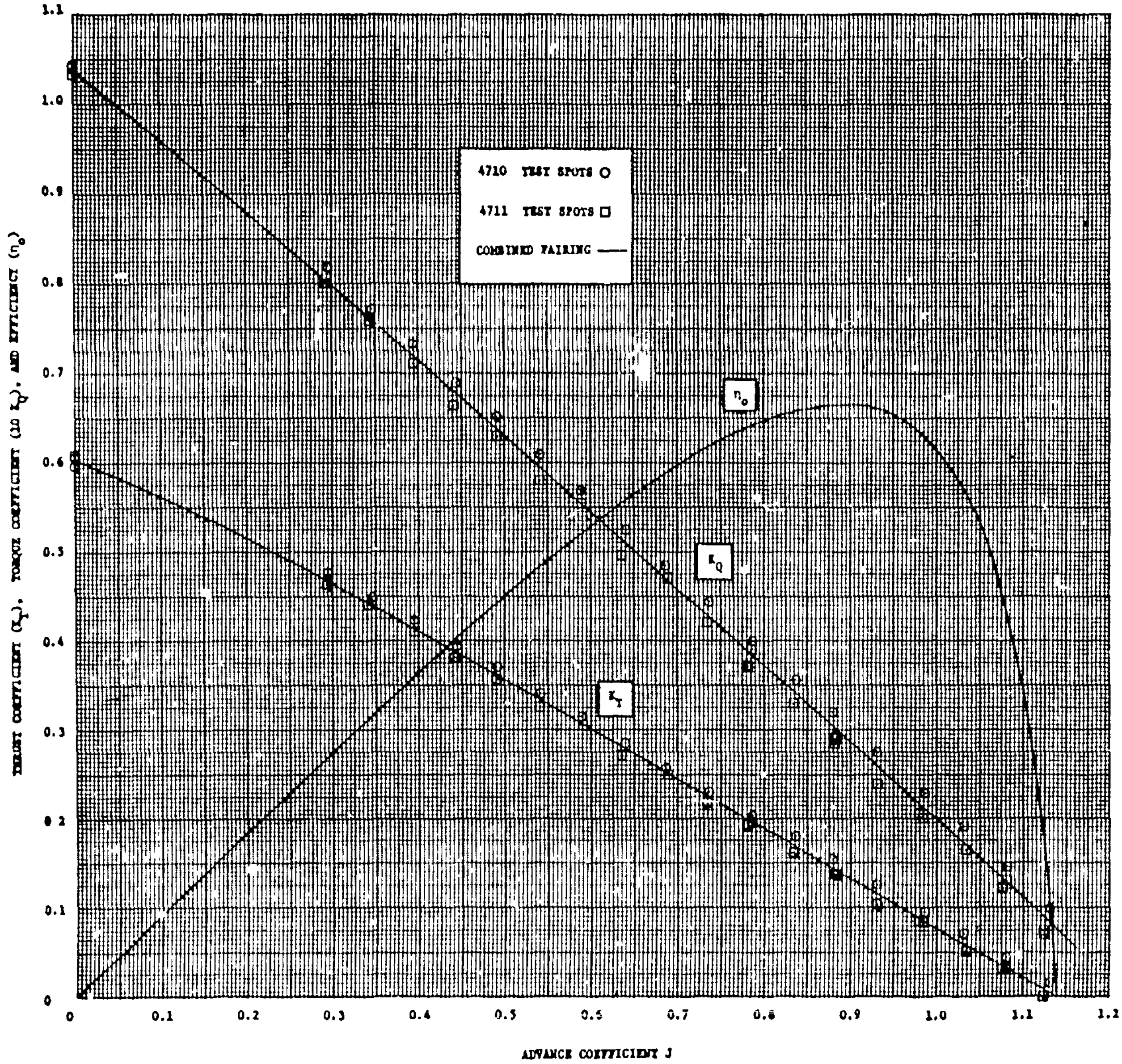

Figure 3 - Open-Water Characteristics Curves for Propellers 4710 and 4711

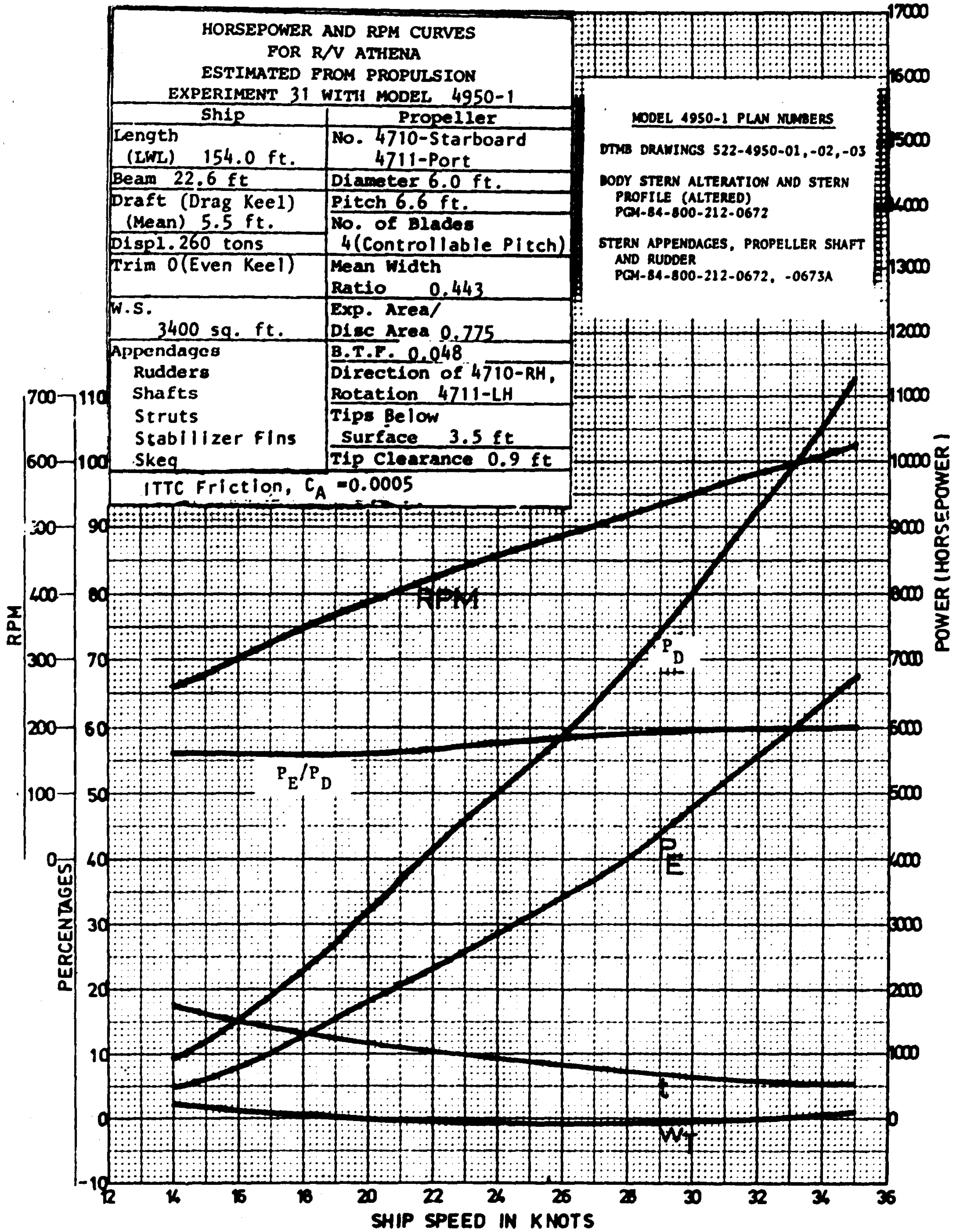

Figure 4 - Predicted Twin-Screw Propulsion Characteristics for the R/V ATHENA from Experiment 31

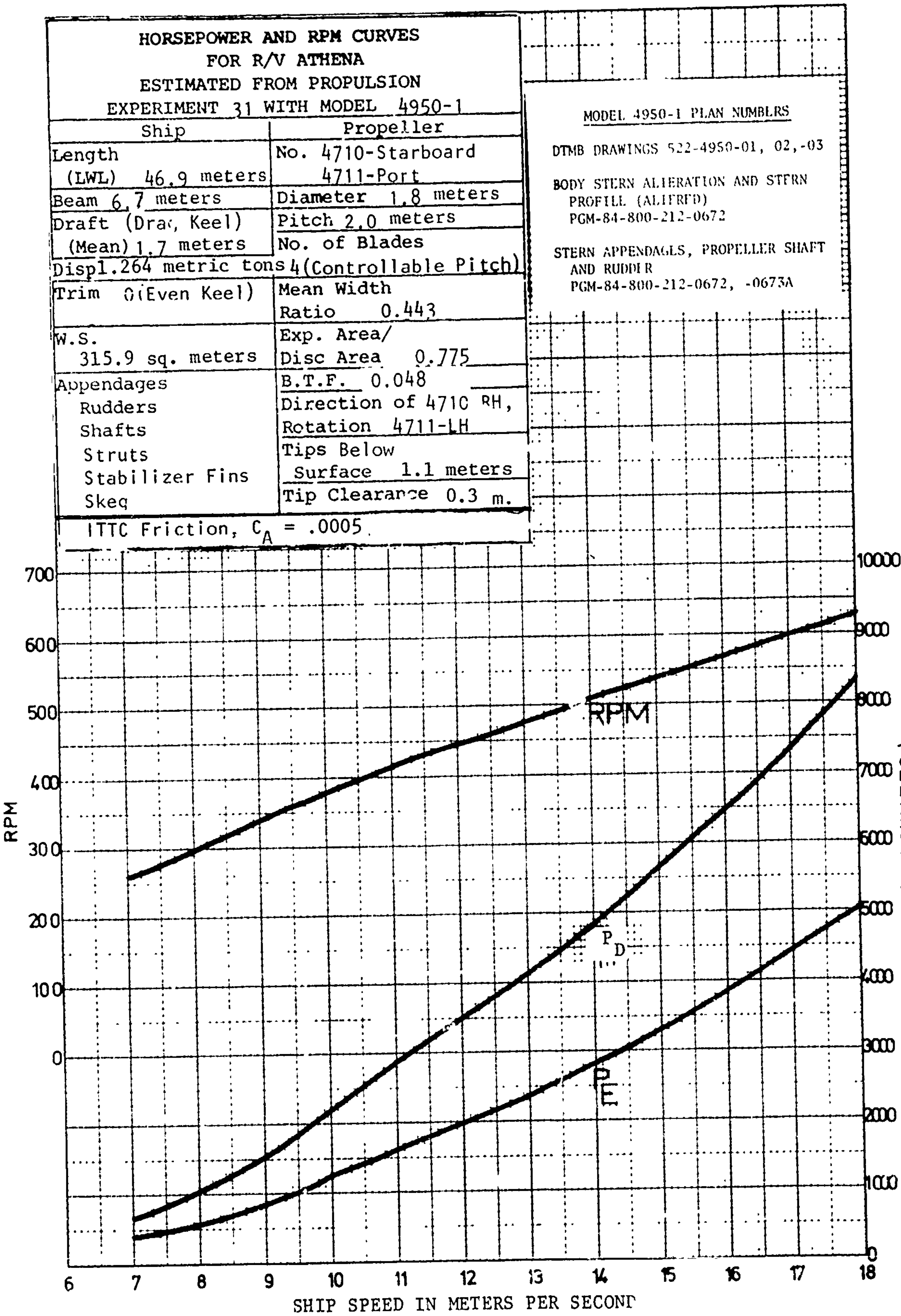

Figure 5 - Predicted Metric Twin-Screw Propulsion Characteristics for the R/V ATHENA from Experiment 31

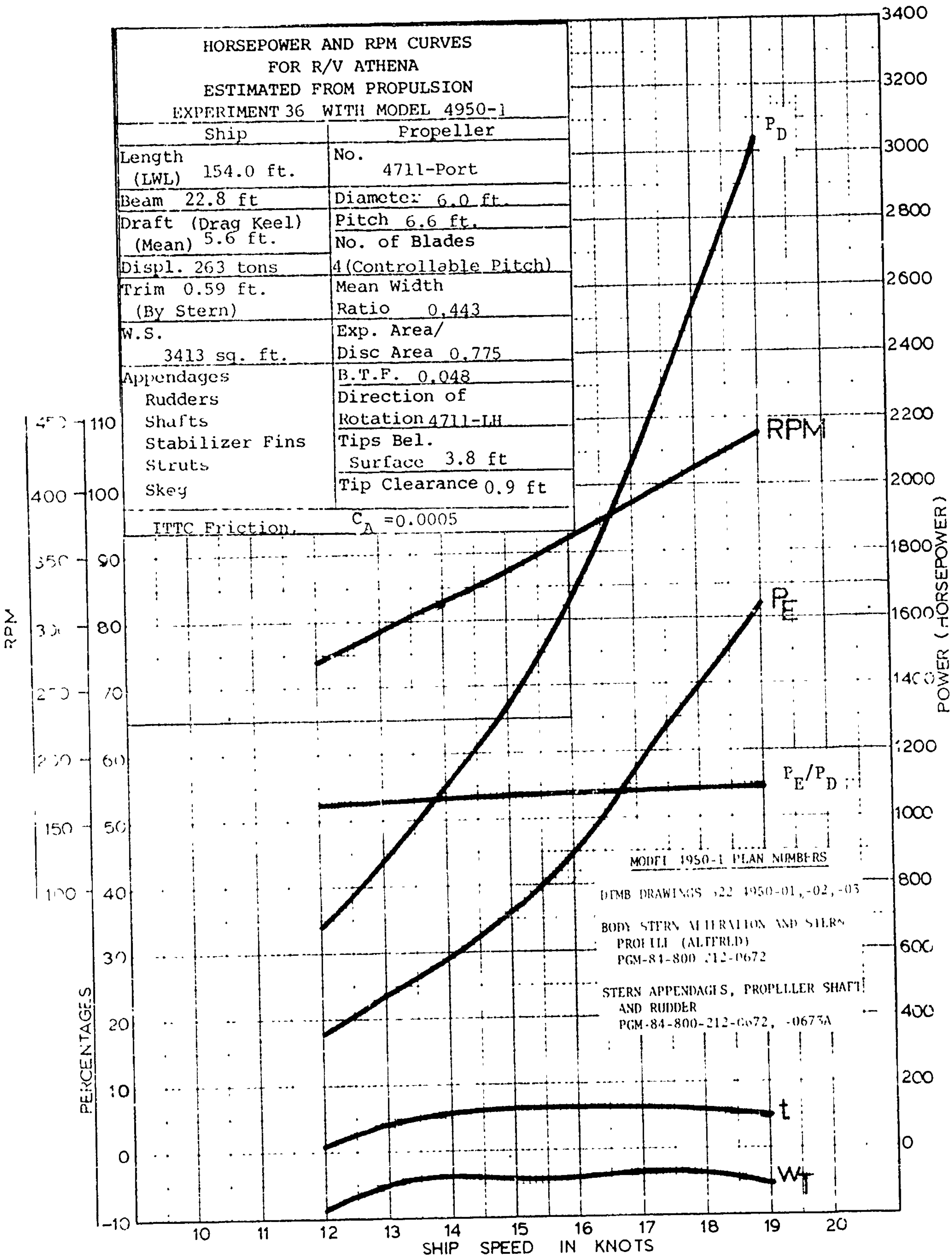

Figure 6 - Predicted Single-Screw Propulsion Characteristics for the R/V ATHENA from Experiment 36

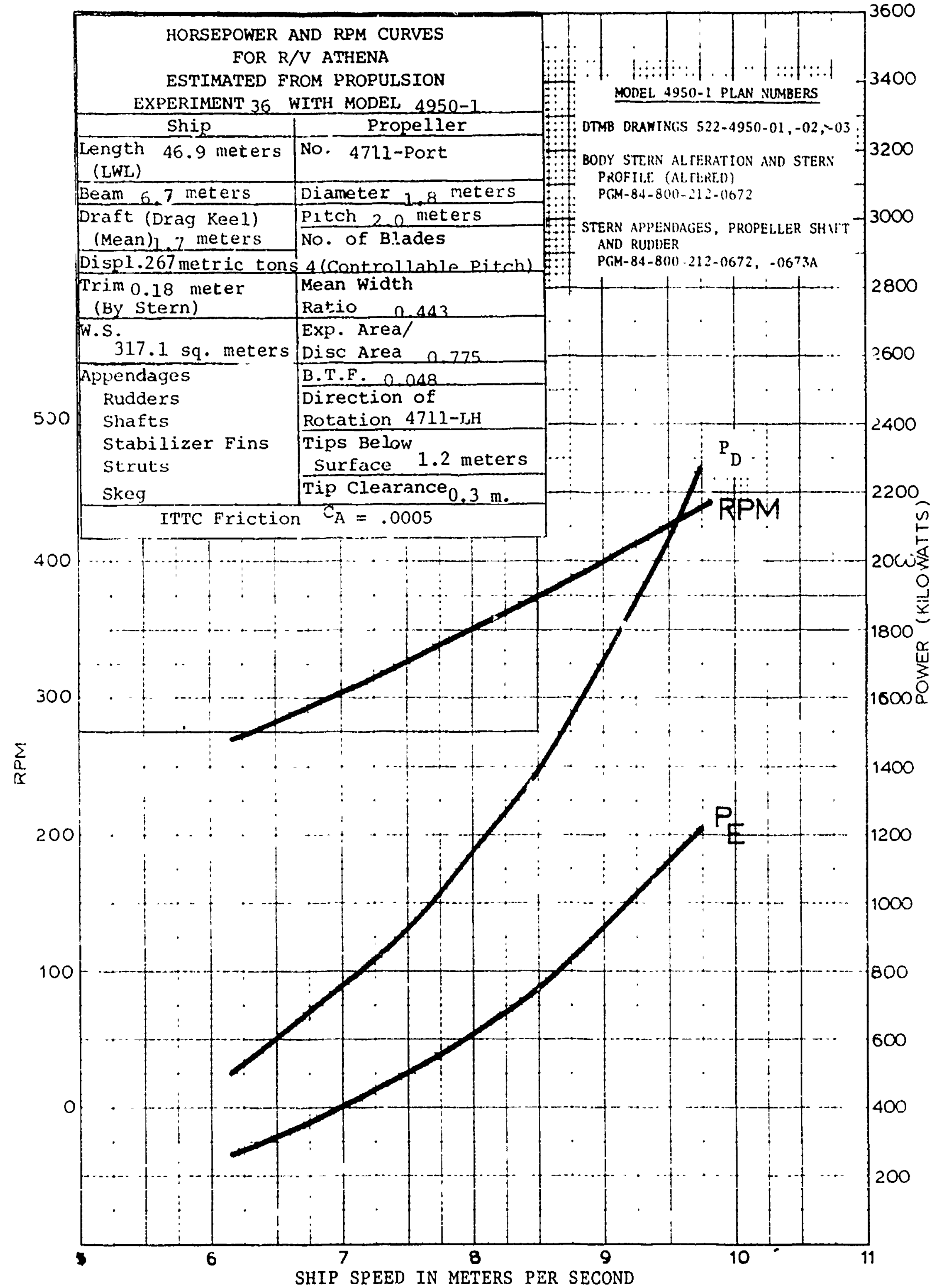

Figure 7 - Predicted Metric Single-Screw Propulsion Characteristics for the R/V ATHENA from Experiment 36

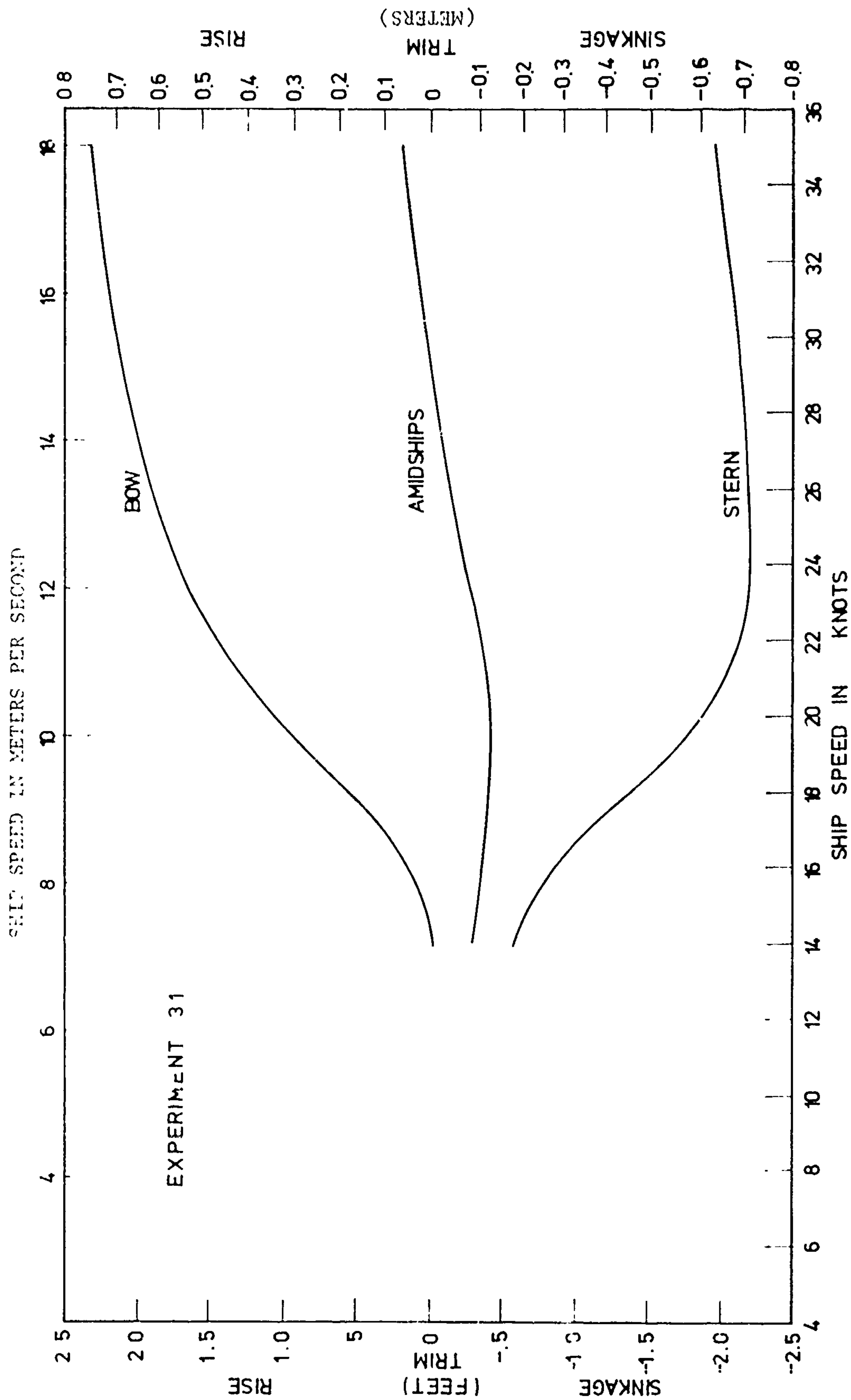

Figure 8 - Twin-Screw Rise, Sinkage and Trim Predictions for the R/V ATHENA from Experiment 31

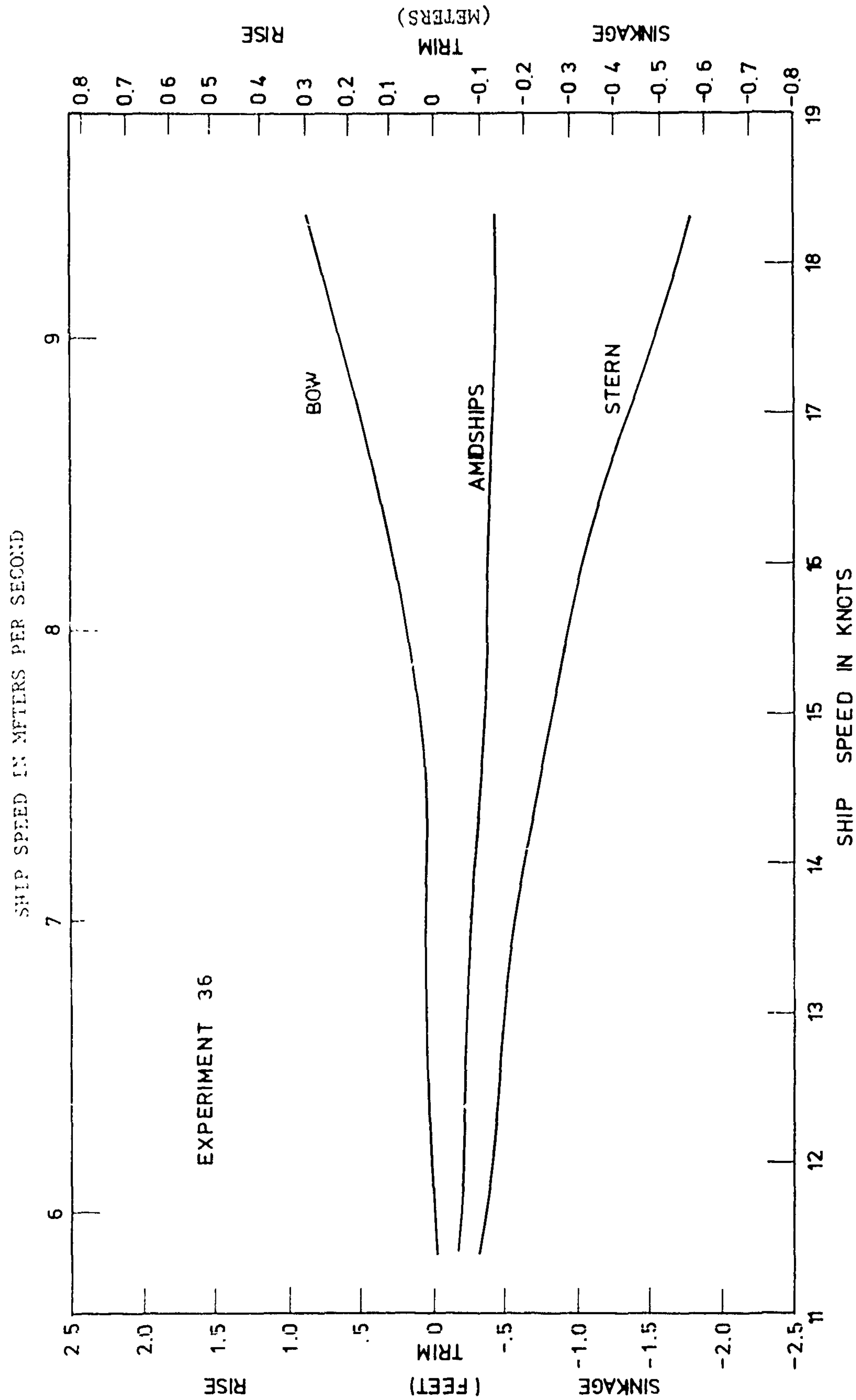

Figure 9 - Single-Screw Rise, Sinkage and Trim Predictions for the R/V ATHENA from Experiment 36

TABLE 1

Ship and Model Characteristics

R/V ATHENA Represented by Model 4950-1

		Ship	Model
Length Between Perpendiculars		154.0 ft (46.94 m)	18.67 ft (5.69 m)
Length Overall		164.5 ft (50.14 m)	19.94 ft (6.08 m)
Maximum Beam	(twin-screw)	22.6 ft (6.87 m)	2.73 ft (0.83 m)
	(single-screw)	22.8 ft (6.96 m)	2.77 ft (0.84 m)
Displacement	(twin-screw)	260 tons (264 metric tons)	1009 lbs (458 kg)
	(single-screw)	263 tons (267 metric tons)	1020 lbs (463 kg)
Wetted Surface	(twin-screw)	3400 ft^2 (315.9 m^2)	49.95 ft^2 (4.640 m^2)
	(single-screw)	3413 ft^2 (317.1 m^2)	50.15 ft^2 (4.659 m^2)
Draft	(twin-screw)	5.58 ft (1.70 m)	0.676 ft (0.206 m)
	(single-screw)	5.65 ft (1.72 m)	0.682 ft (0.208 m)
(Drafts measured at midships due to drag keel)			
Trim by Stern	(twin-screw)	even keel	even keel
	(single-screw)	0.59 ft (0.18 m)	0.072 ft (0.022 m)
Propeller Diameter		6.0 ft (1.83 m)	8.73 in (222 mm)
Linear Scale Ratio		8.25	1.0

Propellers: Twin-screw, controllable pitch, 4 blades each. Only port propeller operating for single screw experiments.

Appendages: Twin stabilizers, main shafts and V-struts, twin rudders, centerline skeg.

TABLE 2

FAIRED OPEN-WATER CHARACTERISTICS FOR PROPELLERS 4710 and 4711

J	K_T	10 K_Q	E
.050	.585	1.002	.046
.100	.563	.962	.093
.150	.538	.921	.139
.200	.514	.881	.186
.250	.489	.840	.232
.300	.464	.799	.277
.350	.438	.757	.322
.400	.411	.716	.365
.450	.385	.673	.410
.500	.358	.631	.451
.550	.330	.588	.491
.600	.302	.546	.528
.650	.274	.503	.563
.700	.246	.460	.596
.750	.218	.417	.624
.800	.189	.374	.643
.850	.161	.330	.660
.900	.133	.287	.664
.950	.105	.243	.653
1.000	.077	.199	.616
1.050	.050	.156	.536
1.100	.022	.112	.344
1.125	.009	.089	.181

4710 Test 2 June 1978

4711 Test 1 January 1978

TABLE 3

Experimental Program

Model 4950-1 Representing the R/V ATHENA (PG 94)

Experiment Number	Type of Experiment	Displacement Ship	Displacement Model	Draft Ship	Draft Model	Wetted Surface Ship	Wetted Surface Model	Trim by Stern Ship	Trim by Stern Model	Correlation Allowance	Water Density Ship	Water Density Model	Water Viscosity x10^5 Ship	Water Viscosity x10^5 Model	Rudder Angle
30	P_E	260 tons (264 metric tons)	1009 lbs (458 kg)	5.58 ft (1.70 m)	8.12 in (20.6 cm)	3400 ft² (315.9 m²)	49.95 ft² (4.64 m²)	even keel		--	1.9886 slugs/ft³ (1024.9 kg/m³)	1.9367 slugs/ft³ (998.1 kg/m³)	1.1960 ft²/sec (1111.1 cm²/sec)	1.0836 ft²/sec (1006.7 cm²/sec)	2° t.e. inboard (port and starboard)
31	P_D (twin screw)	260 tons (264 metric tons)	1009 lbs (458 kg)	5.58 ft (1.70 m)	8.12 in (20.6 cm)	3400 ft² (315.9 m²)	49.95 ft² (4.64 m²)	even keel		0.0005	1.9886 slugs/ft³ (1024.9 kg/m³)	1.9367 slugs/ft³ (998.1 kg/m³)	1.1960 ft²/sec (1111.1 cm²/sec)	1.0836 ft²/sec (1006.7 cm²/sec)	2° t.e. inboard (port and starboard)
35	P_E	263 tons (267 metric tons)	1020 lbs (463 kg)	5.63 ft (1.72 m)	8.19 in (20.8 cm)	3413 ft² (317.1 m²)	50.15 ft² (4.66 m²)	0.59 ft (0.18 m)	0.86 in (2.18 cm)	--	1.9867 slugs/ft³ (1023.9 kg/m³)	1.9371 slugs/ft³ (998.3 kg/m³)	0.9365 ft²/sec (870 cm²/sec)	1.1133 ft²/sec (1034.3 cm²/sec)	1° t.e. outboard port, 2° t.e. inboard starboard
36	P_D (single screw)	263 tons (267 metric tons)	1020 lbs (463 kg)	5.63 ft (1.72 m)	8.19 in (20.8 cm)	3413 ft² (317.1 m²)	50.15 ft² (4.66 m²)	0.59 ft (0.18 m)	0.86 in (2.18 cm)	0.0005	1.9867 slugs/ft³ (1023.9 kg/m³)	1.9371 slugs/ft³ (998.3 kg/m³)	0.9365 ft²/sec (870 cm²/sec)	1.1133 ft²/sec (1034.3 cm²/sec)	1° t.e. outboard (port), 2° t.e. inboard (starboard)

TABLE 4

Calculation of Twin-Screw Effective and Delivered Power

From Faired Coefficients

Model 4950-1 Representing the PC 94

Data from Experiments 30 and 31

Propellers: Twin-screw, design propellers represented by models 4710 and 4711, outboard rotation

Appendages: Twin stabilizers, main shafts and V-struts, twin rudders 2° trailing edge inboard

ITTC friction, no turbulence stimulation, $C_A = 0.0005$
Displacement 260 tons (264 metric tons)
Draft 5.58 ft (1.70 m) (Drag Keel)
Trim (even keel)
Wetted Surface 3400 ft^2 (315.9 m^2)

EXPERIMENT 31 ATHENA MODEL 4950-1

SHIP SPEED		EFFECTIVE POWER(PE)		DELIVERED POWER (PD)		REVOLUTIONS
(KNOTS)	(M/SEC)	(HORSE-POWER)	(KILO-WATTS)	(HORSE-POWER)	(KILO-WATTS)	PER MINUTE
14.0	7.20	550.	410.	980.	730.	266.1
15.0	7.72	675.	505.	1210.	900.	285.8
16.0	8.23	840.	630.	1500.	1120.	306.2
18.0	9.26	1290.	960.	2290.	1710.	349.6
19.0	9.77	1550.	1160.	2750.	2050.	370.7
19.5	10.03	1690.	1260.	2990.	2230.	380.9
20.0	10.29	1820.	1360.	3220.	2400.	390.7
20.5	10.55	1960.	1460.	3460.	2580.	400.0
21.0	10.80	2130.	1570.	3700.	2760.	408.8
22.0	11.32	2350.	1760.	4140.	3080.	426.3
24.0	12.35	2880.	2150.	5010.	3740.	459.3
26.0	13.38	3430.	2550.	5900.	4400.	489.8
28.0	14.40	4060.	3030.	6890.	5140.	520.5
30.0	15.43	4790.	3570.	8050.	6000.	551.0
32.0	16.46	5550.	4140.	9300.	6930.	582.6
34.0	17.49	6360.	4750.	10550.	7870.	613.8
35.0	18.01	6780.	5060.	11210.	8360.	629.1

TABLE 5

Calculation of Twin-Screw Efficiencies, Thrust Deduction

and Wake Factors from Faired Coefficients

Model 4950-1 Representing the PG 94

Data from Experiments 30 and 31

Propellers: Twin-screw, design propellers represented by models 4710 and 4711, outboard rotation

Appendages: Twin stabilizers, main shafts and V-struts, twin rudders 2° trailing edge inboard

ITTC friction, no turbulence stimulation, $C_A = 0.0005$
Displacement 260 tons (264 metric tons)
Draft 5.58 ft (1.70 m) (Drag Keel)
Trim (even keel)
Wetted surface 3400 ft^2 (315.9 m^2)

SHIP SPEED (KNOTS)	EFFICIENCIES(ETA)				THRUST DEDUCTION AND WAKE FACTORS			ADVANCE COEF.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
14.0	.560	.655	.840	1.020	.820	.980	.985	.870
15.0	.560	.655	.845	1.010	.835	.985	.990	.875
16.0	.560	.655	.855	1.005	.845	.990	.990	.875
18.0	.565	.655	.865	.990	.865	1.000	.995	.870
19.0	.565	.655	.875	.990	.875	1.000	.995	.865
19.5	.565	.655	.875	.985	.880	1.005	.995	.865
20.0	.565	.655	.880	.985	.885	1.005	.995	.870
20.5	.565	.655	.885	.980	.885	1.005	.995	.870
21.0	.565	.655	.890	.975	.890	1.005	.995	.870
22.0	.570	.655	.890	.975	.895	1.005	.995	.875
24.0	.575	.655	.900	.970	.905	1.005	.995	.890
26.0	.580	.655	.915	.970	.915	1.005	.990	.900
28.0	.590	.655	.925	.970	.925	1.000	.990	.910
30.0	.595	.655	.940	.965	.935	.995	.985	.915
32.0	.595	.655	.945	.965	.940	.995	.985	.925
34.0	.605	.655	.950	.970	.945	.995	.985	.930
35.0	.605	.655	.955	.970	.950	.995	.985	.935

TABLE 6

Calculation of Single-Screw Effective and Delivered Power

from Faired Coefficients

Model 4950-1 Representing the PG 94

Data from Experiments 35 and 36

Propellers: No starboard propeller, design port propeller represented by model 4711, outboard rotation

Appendages: Twin stabilizers, main shafts and V-struts, port rudder 3° to port (= 1° trailing edge outboard) starboard rudder 2° trailing edge inboard

ITTC friction, no turbulence stimulation, $C_A = 0.0005$
Displacement 263 tons (267 metric tons)
Draft 5.63 ft (1.72 m) (Drag Keel)
Trim by stern 0.59 ft (0.18 m)
Wetted surface 3413 ft² (317.1 m²)

SHIP SPEED (KNOTS)	SHIP SPEED (M/SEC)	EFFECTIVE POWER (PE) (HORSE-POWER)	EFFECTIVE POWER (PE) (KILO-WATTS)	DELIVERED POWER (PD) (HORSE-POWER)	DELIVERED POWER (PD) (KILO-WATTS)	REVOLUTIONS PER MINUTE
12.0	6.17	360.	265.	680.	505.	270.4
13.0	6.69	470.	355.	880.	655.	291.4
14.0	7.20	585.	440.	1100.	820.	313.4
15.0	7.72	725.	540.	1340.	1000.	337.1
16.0	8.23	895.	670.	1660.	1240.	361.5
17.0	8.75	1130.	840.	2080.	1550.	386.7
18.0	9.26	1380.	1030.	2540.	1900.	412.9
19.0	9.77	1640.	1220.	3030.	2260.	439.9

TABLE 7

Calculation of Single-Screw Efficiencies, Thrust Deduction and Wake Factors from Faired Coefficients

Model 4950-1 Representing the PG 94

Data from Experiments 35 and 36

Propellers: No starboard propeller, design port propeller represented by model 4711, outboard rotation

Appendages: Twin stabilizers, main shafts and V-struts, port rudder 3° to port (= 1° trailing edge outboard) starboard rudder 2° trailing edge inboard

ITTC friction, no turbulence stimulation, $C_A = 0.0005$
Displacement 263 tons (267 metric tons)
Draft 5.63 ft (1.72 m) (Drag Keel)
Trim by stern 0.59 ft (0.18 m)
Wetted surface 3413 ft^2 (317.1 m^2)

SHIP SPEED (KNOTS)	EFFICIENCIES (ETA)				THRUST DEDUCTION AND WAKE FACTORS			ADVANCE COEF.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
12.0	.530	.650	.905	.895	.985	1.085	1.020	.815
13.0	.530	.640	.910	.910	.955	1.050	.990	.790
14.0	.535	.635	.905	.930	.940	1.040	.990	.780
15.0	.540	.635	.895	.945	.935	1.040	1.005	.790
16.0	.540	.635	.895	.950	.930	1.040	1.010	.780
17.0	.540	.630	.905	.950	.935	1.030	.995	.765
18.0	.540	.630	.905	.950	.940	1.035	1.000	.765
19.0	.545	.630	.900	.955	.945	1.055	1.025	.770

TABLE 8

Propulsion Conditions for Blade Loading Experiments

	Twin-Screw Propulsion (Experiments 30, 31)		Single-Screw Propulsion (Experiments 35, 36)	
Displacement, tons (metric tons)	260	(264)	263	(267)
Draft, ft (m)(Drag Keel)	5.58	(1.70)	5.63	(1.72)
Trim by stern, ft (m)	Even Keel		0.59	(0.18)
Speed, knots (m/s)	20.0	(10.3)	15.0	(7.72)
RPM	390.7		337.1	
Delivered power, hp (KW)	3220	(2401)	1340	(999)
$1 - t$	0.885		0.935	
$1 - w_T$	1.005		1.040	
$1 - w_Q$	0.995		1.005	
J_T	0.870		0.780	
η_D	0.565		0.540	
η_O	0.655		0.635	
η_H	0.880		0.895	
η_R	0.985		0.945	

TABLE 8
(continued)

Propulsion Conditions for Blade Loading Experiments

	Twin-Screw Propulsion (Experiments 30, 31)		Single-Screw Propulsion (Experiments 35, 36)	
Displacement, tons (metric tons)	260	(264)	263	(267)
Draft, ft (m) (Drag Keel)	5.58	(1.70)	5.63	(1.72)
Trim by stern, ft (m)	Even Keel		0.59	(0.18)
Speed, knots (m/s)	19.0	(9.77)	19.0	(9.77)
Effective power, hp (kW)	1550	(1156)	1640	(1223)
RPM	370.7		439.9	
Delivered power, hp (KW)	2750	(2051)	3030	(2259)
1-t	0.875		0.945	
$1-w_T$	1.000		1.055	
J_T	0.865		0.770	
η_0	0.655		0.630	
K_T/J_T^2	0.104		0.182	
η_D	0.565		0.545	

TABLE 9

Comparison of Twin-Screw Shaft Power and RPM from Full-Scale Measurements and

Predictions from Model Experiments

Speed		Experiment 31: P/D = 1.11, Δ = 260 tons (264 metric tons), C_A = 0.0005			PG 87*: P/D = 1.15, Δ = 260 tons (264 metric tons)			PG 92**: P/D = 1.14, Δ = 250 tons (254 metric tons)			Experiment 31: P/D = 1.11, Δ = 260 tons (264 metric tons), C_A = 0.00065		
		RPM	Delivered Power		RPM	Delivered Power		RPM	Delivered Power		RPM	Delivered Power	
knots	(m/s)		hp	(kW)		hp	(kW)		hp	(kW)		hp	(kW)
20	(10.3)	391	3220	(2401)	385	3250	(2424)	393	3300	(2461)	391	3290	(2450)
25	(12.9)	481	5460	(4073)	470	5450	(4064)	472	5500	(4101)	475	5570	(4150)
30	(15.4)	551	8050	(6003)	560	8100	(6040)	560	8250	(6152)	551	8250	(6150)
35	(18.0)	629	11210	(8359)	663	11850	(8836)	662	11950	(8911)	629	11530	(8600)

* Figure 2 of Reference 1
** Figure 3 of Reference 2

TABLE 10

CALCULATION OF TWIN-SCREW EFFECTIVE AND DELIVERED POWER, EFFICIENCIES, THRUST DEDUCTION, AND WAKE FACTORS FROM FAIRED COEFFICIENTS

Model 4950-1 Representing PG 87.

Data from Experiments 30 and 31

Propellers: Twin-screw, design propellers represented by models models 4710 and 4711, outboard rotation

Appendages: Twin stabilizers main shafts and V-struts, twin rudders 2° trailing edge inboard

ITTC friction, no turbulence stimulation, C_A = 0.00065
Displacement 260 tons (264 metric tons)
Draft 5.58 ft (1.70 m) (Drag Keel)
Trim (even keel)
Wetted surface 3400 ft^2 (315.9m^2)

SHIP SPEED		EFFECTIVE POWER(PE)		DELIVERED POWER (PD)		REVOLUTIONS PER MINUTE
(KNOTS)	(M/SEC)	(HORSE-POWER)	(KILO-WATTS)	(HORSE-POWER)	(KILO-WATTS)	
14.0	7.20	560.	420.	1000.	750.	266.1
15.0	7.72	690.	515.	1230.	920.	285.8
16.0	8.23	860.	640.	1540.	1140.	306.2
18.0	9.26	1310.	980.	2340.	1740.	349.6
19.0	9.77	1580.	1180.	2810.	2090.	370.7
19.5	10.03	1720.	1280.	3050.	2270.	380.9
20.0	10.29	1860.	1380.	3290.	2450.	390.7
20.5	10.55	2000.	1490.	3530.	2630.	400.0
21.0	10.80	2140.	1600.	3770.	2810.	408.8
22.0	11.32	2400.	1790.	4220.	3150.	426.3
24.0	12.35	2940.	2190.	5120.	3820.	459.3
26.0	13.38	3500.	2610.	6030.	4500.	489.8
28.0	14.40	4160.	3100.	7060.	5260.	520.5
30.0	15.43	4910.	3660.	8250.	6150.	551.0
32.0	16.46	5700.	4250.	9540.	7110.	582.6
34.0	17.49	6540.	4880.	10840.	8090.	613.8
35.0	18.01	6970.	5200.	11530.	8600.	629.1

SHIP SPEED (KNOTS)	EFFICIENCIES(ETA) ETAD	ETAO	ETAH	ETAR	THRUST DEDUCTION AND WAKE FACTORS 1-T	1-WT	1-WQ	ADVANCE COEF. JT
14.0	0.560	0.655	0.845	1.010	0.820	0.970	0.975	0.865
15.0	0.560	0.655	0.850	1.005	0.835	0.980	0.980	0.870
16.0	0.560	0.655	0.860	0.995	0.845	0.985	0.980	0.865
18.0	0.560	0.655	0.875	0.985	0.865	0.990	0.985	0.860
19.0	0.565	0.650	0.880	0.985	0.875	0.995	0.990	0.860
19.5	0.565	0.650	0.880	0.980	0.880	0.995	0.990	0.860
20.0	0.565	0.655	0.885	0.980	0.885	1.000	0.990	0.865
20.5	0.565	0.655	0.890	0.975	0.885	1.000	0.990	0.865
21.0	0.565	0.655	0.895	0.970	0.890	0.995	0.985	0.865
22.0	0.570	0.655	0.895	0.970	0.895	1.000	0.985	0.870
24.0	0.575	0.655	0.905	0.965	0.905	1.000	0.985	0.880
26.0	0.580	0.655	0.920	0.965	0.915	0.995	0.985	0.895
28.0	0.590	0.655	0.930	0.965	0.925	0.995	0.980	0.900
30.0	0.595	0.655	0.945	0.960	0.935	0.990	0.975	0.910
32.0	0.595	0.655	0.950	0.960	0.940	0.990	0.975	0.915
34.0	0.605	0.655	0.955	0.965	0.945	0.990	0.975	0.925
35.0	0.605	0.655	0.960	0.965	0.950	0.990	0.975	0.930

TABLE 11

Comparison of Resistance and Propulsion Factors for Single and Twin-Screw Propulsion for the R/V ATHENA Represented by Model 4950-1

SPEED		EHP/TON		P_E/P_D		1-t		$1-w_T$		J_T	
KNOTS	M/S	SINGLE	TWIN	SINGLE	TWIN	SINGLE	TWIN	SINGLE	TWIN	SINGLE	TWIN
14.0	7.20	2.22	2.12	0.535	0.560	0.940	0.820	1.040	0.980	0.780	0.870
16.0	8.23	3.40	3.23	0.540	0.560	0.930	0.845	1.040	0.990	0.780	0.875
18.0	9.26	5.25	4.96	0.540	0.565	0.940	0.865	1.035	1.000	0.765	0.870
19.0	9.77	6.24	5.96	0.540	0.565	0.945	0.875	1.055	1.000	0.770	0.865

TABLE 12

Comparison of Resistance and Propulsion Factors for Twin-Screw Propulsion for the R/V ATHENA Represented by Models 4950-1* and 4950**

SPEED		EHP/TON		P_E/P_D		1-t		$1-w_T$		J_T	
KNOTS	M/S	ATHENA	4950	ATHENA	4950	ATHENA	4950	ATHENA	4950	ATHENA	4950
15.0	7.72	2.60	2.34	0.560	0.570	0.835	0.915	0.985	1.030	0.875	1.060
20.0	10.29	7.00	6.18	0.565	0.590	0.885	0.930	1.005	1.040	0.870	1.045
25.0	12.87	12.15	11.24	0.580	0.600	0.910	0.930	1.005	1.035	0.895	1.060
30.0	15.43	18.42	17.10	0.595	0.610	0.935	0.925	0.995	1.020	0.915	1.080
35.0	18.01	26.08	25.18	0.605	0.620	0.950	0.930	0.995	1.015	0.935	1.100

* Model 4950-1
Experiment 31
260 Ton Displacement (264 metric tons)
Design Propellers
ITTC Friction
$C_A = 0.0005$

** Model 4950
Experiment 8
213.5 Ton Displacement (217 metric tons)
Michigan Wheel Propellers
Schoenherr Friction
$C_A = 0.0004$

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