THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

RESULTS OF FULL-SCALE PROPELLER TESTS ON S.S. TANNENBERG

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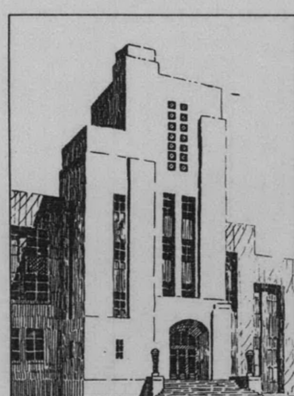

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RESULTS OF FULL-SCALE PROPELLER TESTS
ON S.S. TANNENBERG

(ERGEBNISSE NATURGROSSER SCHRAUBENVERSUCHE AUF DAMPFER "TANNENBERG")

by

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The David W. Taylor Model Basin
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RESULTS OF FULL-SCALE PROPELLER TESTS ON S.S. TANNENBERG*

I. PROBLEM AND METHOD OF SOLUTION

The applicability of the results of tests with hull and propeller models to full-scale ships and propellers is limited by three uncertain factors:

1. The degree of roughness of the hull surface and the friction coefficient to be used to represent it;

2. Applicability to the full-scale ship of the wake factor obtained by model test;

3. Applicability to the ship propeller of thrust and torque coefficients measured on the model.

It is because of these uncertainties that ship data still occasionally deviate from those predicted from model tests, and that the empirical correction factors fluctuate within certain limits.

It has been our endeavor in recent years to limit and to clear up as far as possible the first and greatest uncertainty arising from the degree of roughness of the ship's surface.

This has been achieved by various means. First, resistance research has been carried out in Göttingen and Hamburg and coefficients have been set up for various types of surface roughness. Furthermore, full-scale tests have been carried out on sister ships having different surface conformations (riveted and welded plates), but with other conditions equal and with propellers of the same design. Finally, exact measurements have been made on a series of ships on trial runs. These have yielded much material for comparison with model test data.

Thus it has been possible to set up definite roughness factors for the surface conformation of ships and to establish corresponding resistance coefficients which give some fairly reliable values for calculating ship resistance.

The second source of uncertainty lies in the applicability of the wake determined by model test. The uncertainties lie in the method of measuring wake on the model, and in the question as to what part of the total wake in individual cases is made up of frictional wake.

The third source of uncertainty lies in the applicability of the model thrust and torque coefficients to the full-scale structure. These uncertainties may be caused by the occurrence of subcritical flow conditions on the model propeller, or by differences in the friction coefficients for the smooth blade surfaces of the

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* This paper appears in condensed form in Zeitschrift d. VDI, No. 18, 6 May 1939, pp 530-531.

full-scale propeller with the corresponding Reynolds' numbers.

Usually all three of the influences mentioned in the foregoing occur simultaneously, so that analysis is rendered most difficult. However, special procedure and tests with the S.S. TANNENBERG made it possible to investigate separately the various influences and thus to obtain definite information concerning the applicability of model data to the full-scale ship and its propellers. For the purpose of making these tests the Hamburg Model Basin chartered the vessel twice; in 1937 and in 1938.

The S.S. TANNENBERG is a twin-screw vessel driven by steam turbines. It was built in 1934 by the Stettiner Oderwerke for the Reich Ministry of Communications, for service with the East Prussian Division. The engines were furnished by the firm of Schichau, Elbing; the propellers by the Atlaswerke, Bremen. The propellers are mounted on short shaft bossings and struts. The ship has a centerline rudder at the stern, and a bow rudder. All this rendered it particularly suitable for the tests.

Because of the uniform torque, the turbine drive assured good torsion data. The Mitchell thrust block was adapted for thrust measurements. The fact that the propellers were carried by struts assured a relatively uniform wake distribution. The type of steering gear already installed assured good steering qualities both while running ahead and astern.

It was required, for comparison with model test data, to determine the propeller coefficients on the prototype in a condition free of frictional wake. This is possible only with the ship running astern, when there is no frictional wake in the region of the propeller.

It was also necessary to apply the thrust and torque coefficients thus determined for the backing propeller to the propeller running forward, in order to determine the effect of wake while running ahead.

It was necessary, therefore, that the propeller be so designed as to possess the same characteristics running ahead and astern; i.e., the blade sections and profiles had to be perfectly symmetrical.

Finally, it was not sufficient to measure the propeller coefficients only under normal load. Provision had to be made to bring about the greatest possible variations in load on the propellers.*

The following test apparatus was installed:

1. Speed measuring devices: One static pressure log (HSVA) at the bow, one static pressure log (HSVA) at the stern, one resistance log (HSVA) amidships on the starboard side for measurements while running ahead and astern;

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* Translator's note.- The author does not mention the fact at this point that the port and starboard propellers had different characteristics.

2. A thrustmeter (Deutsche Werft, Hamburg) on the Mitchell thrust block on each shaft, each with two pressure dials and recorders for ahead and astern runs;

This adaptation of the apparatus, requested by the HSVA, assured a constant check on reliability, because thrust could be recorded as the difference between the readings of two recording pressure meters, and because under constant thrust the pressure curve of each gage could be shifted by pumping on the opposite side.

3. Torsionmeters, three on each shaft: (1) Torsionmeter (HSVA) with scratch extensometer, (2) Torsionmeter (Blohm and Voss) with mirror indicator, (3) Torsionmeter (Maihak) with Schaefer singing wires and oscillograph.

4. Revolution counters (HSVA) with cam contacts.

All four of these measurements were recorded in continuous curves and properly synchronized.

The runs in the spring of 1937 yielded no adequate data, as they were marked by temporary breakdowns of one or the other of the instruments. In the light of this experience, all tests during 1938 were carried out, whenever possible, with at least two different instruments in each group. This was unfortunately not possible in the case of thrust measurements, and for this reason three measurements are lacking on one trip.

Much experience was also gained in other respects on the 1937 trip, and later utilized on the 1938 voyage. The weather was unusually favorable, particularly on the second trip in 1938.

It should be pointed out that none of the usual propulsion tests were carried out; runs were made only to determine the propeller coefficients of the two different types of propellers running ahead and astern under various load factors.

Propulsion tests of the orthodox type would have been useless because the port and starboard propellers were different from each other and neither the powers absorbed nor the thrusts were equal for equal RPM.

The runs were consequently arranged so that the RPM's of the propellers were changed with respect to each other, to permit investigation of various load factors for each propeller over the widest possible range. By tests of 1:20-scale models the thrust and torque coefficients of the model propellers were measured in open-water condition as well as behind the model for various load factors, including astern operation. Moreover, the wake distribution in the region of the model propeller was measured by a double pitot tube while running ahead as well as astern.

After the coefficients of the full-scale propeller and the wake of the ship have been ascertained, it is an easy matter to determine the friction coefficient for the roughness factor of the ship's surface from the usual progressive speed trials of the ship in comparison with the model tests.

Thus all three of the remaining uncertainties in transferring model test data to the prototype, mentioned at the beginning of this paper, have been clarified, at least in the present instance.

Furthermore, a method has been found for carrying out this clarifying process, and it has been learned whether the proposed classification of roughnesses of ship and propeller is valid.

The details of this process will be described by means of the results of the tests.

II. TEST RESULTS

(a) Design Data

The S.S. TANNENBERG, used for the tests, is equipped with two 4000 horsepower steam turbines with reduction gears, and has the following dimensions:

Length	L	=	120.00 meters (393.69 feet)
Beam	B	=	15.50 meters (50.85 feet)
Draft	T	=	4.50 meters (14.76 feet)
Displacement	D	=	4664 cubic meters (4705.3 tons)*
Block coefficient	δ	=	0.558

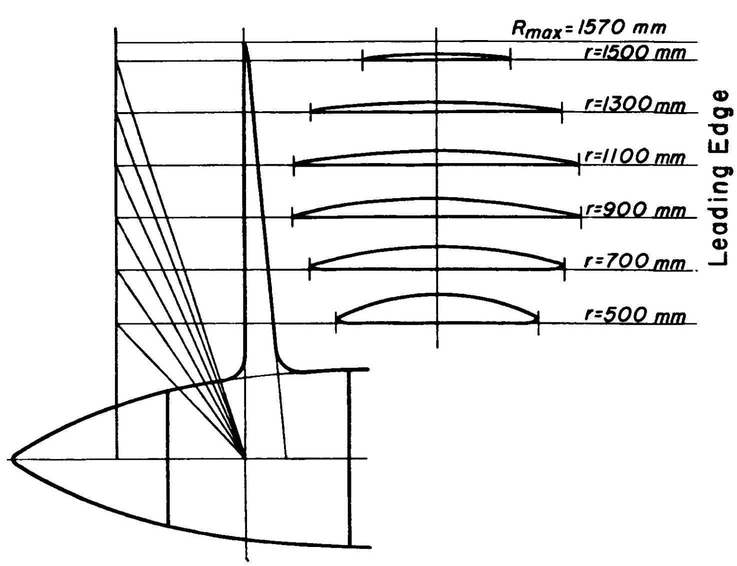

Figure 1 – Port Propeller

* Translator's note.- Elsewhere in this paper, displacement is given in metric tons, where one cubic meter of fresh water is equal to one metric ton.

The port propeller, Figure 1, was made of bronze, and had the form customary in such vessels. The propeller had the following dimensions:

Diameter	D	=	3140 millimeters (10 feet 4 inches)
Pitch	H	=	3140 millimeters (10 feet 4 inches)
Number of blades	Z	=	3
Projected area ratio	A_a/A	=	0.42

Perpendicular generatrices, symmetrical blade profiles, ogival blade sections.

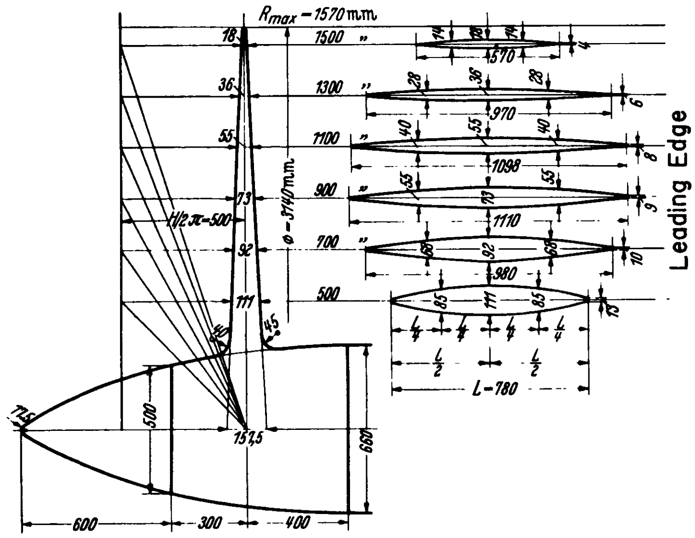

Figure 2 – Starboard Propeller

The starboard propeller was built as a completely symmetrical test wheel to the same dimensions. The blades had symmetrical lens-shaped sections, Figure 2, and were of bronze. Its dimensions were as follows:

Diameter	D	=	3140 millimeters (10 feet 4 inches)
Pitch	H	=	3140 millimeters (10 feet 4 inches)
Number of blades	Z	=	3
Projected area ratio	A_a/A	=	0.42

Perpendicular generatrices, symmetrical blade profiles, lens-shaped blade sections.

The models of ship and propellers were built on a scale of 1:20 and tested in the Hamburg Model Basin. The model propellers were 157mm (6.18 inches) in diameter.

(b) Model Tests

In 1937 and 1938, the model propellers were tested several times in open water, running ahead and astern, and at various RPM's. The no-load torque of the starboard propeller at zero thrust has the same values running ahead and astern, since its sections are perfectly symmetrical.

The model test data are given in Figures 3 and 4. The resistance coefficient of the test propeller with lens-shaped sections is calculated from the no-load

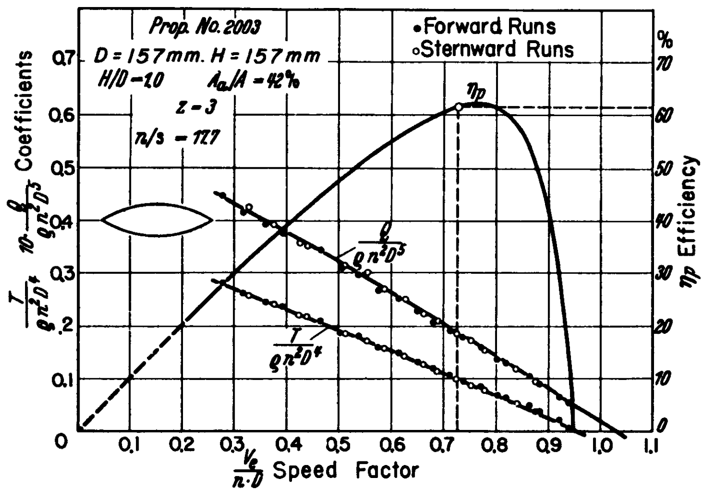

Figure 3 – Characteristic Curves, Starboard Propeller (Open-Water)

torque at zero thrust and corresponds exactly to the value, C = 0.455 (log R)$^{-2.58}$ to be expected from the Prandtl-Schlichting formula for smooth surfaces. The friction coefficient of the standard propeller with circular (ogival) section is about 30 per cent higher.

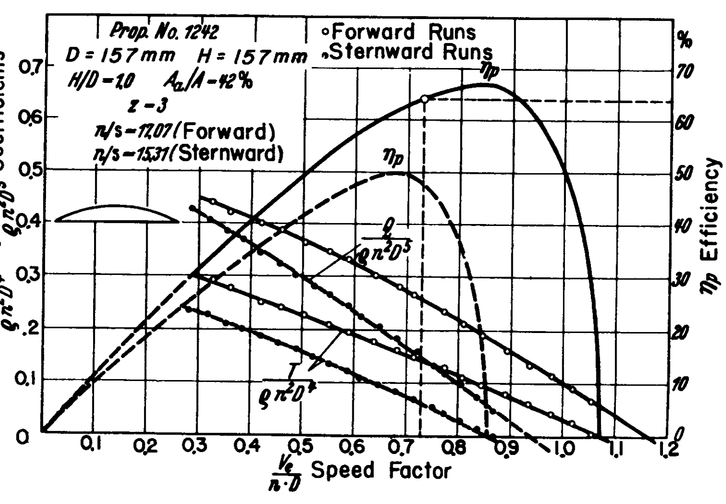

Figure 4 – Characteristic Curves, Port Propeller (Open-Water)

The two models were also self-propelled several times in 1937 and 1938. These tests were carried out on the ship model in the same way as in the ship trials, with the propellers running ahead and astern at various speeds and RPM's, i.e., at various speed factors and load factors.

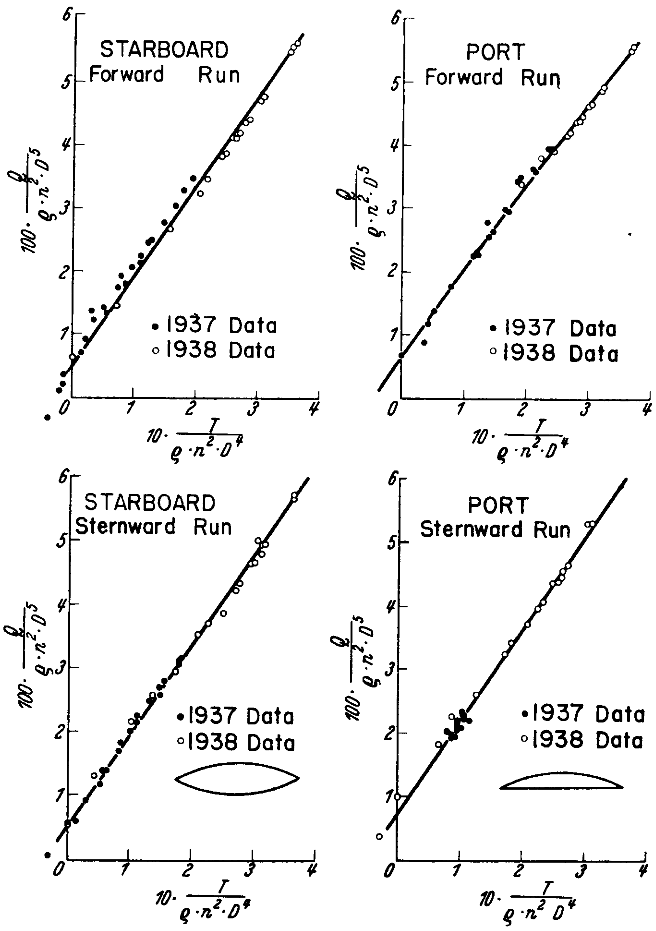

Figure 5 – Model Propellers with Ship Model

The test data are given in Figure 5 where the torque coefficients are plotted against the thrust coefficients. The starboard propeller has the same characteristics running ahead as astern. Deviation occurred only at small RPM's in the sub-critical range.

In Figures 6, 7, 8, and 9 the coefficient curves are plotted over the speed factor. Solid lines are used for the self-propelled model data, and broken lines for the open-water propeller data. The horizontal distance between curves of corresponding coefficients is the measure for the wake effect on the self-propelled model, which is practically the same in both propellers in spite of the differences between them.

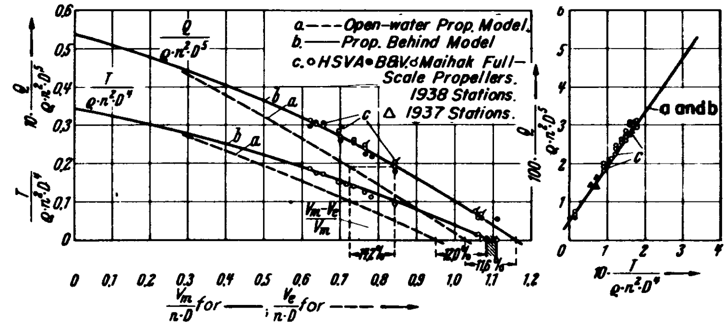

Figure 6 – Starboard Propeller Running Forward

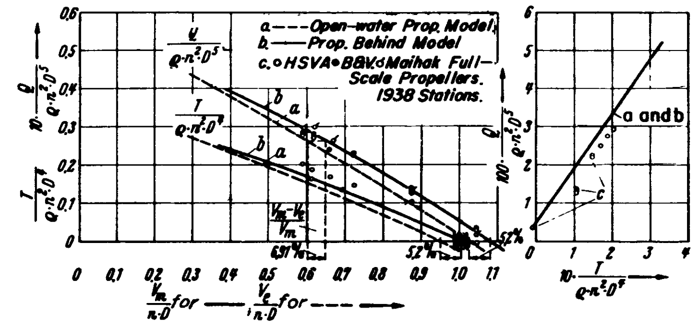

Figure 7 – Starboard Propeller Running Sternward

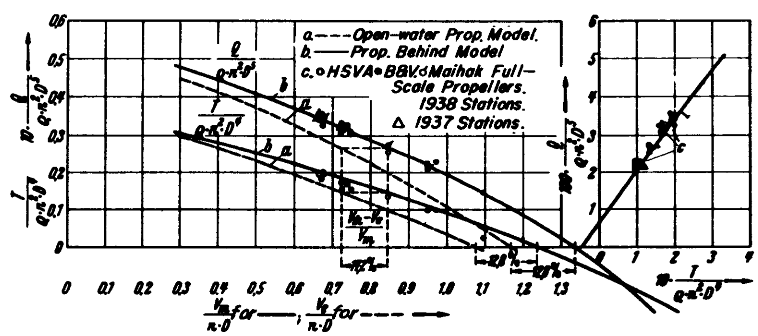

Figure 8 – Port Propeller Running Forward

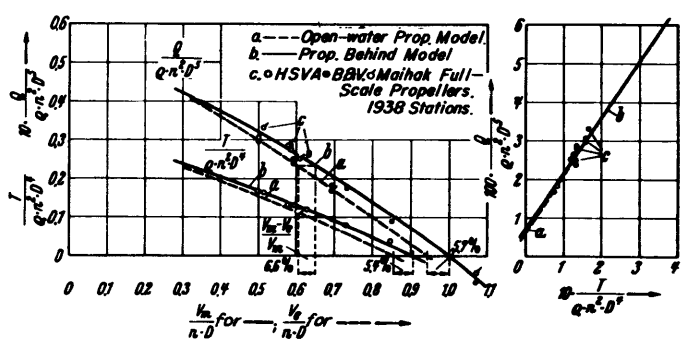

Figure 9 – Port Propeller Running Sternward

These wake values obtained from the horizontal distance between curves, i.e., for the same coefficients, are all somewhat higher than they should be, judging by the mean entrance velocity in the propeller disk, as measured with the double pitot tube.

This can be explained by the fact that the propeller behind the model operates under fluctuating entrance velocity and thus generates a smaller thrust than the open-water propeller which operates in uniform mean entrance velocity. This is because the mean generated thrust is lower when the coefficient curve is arched than the thrust at uniform entrance velocity and uniform speed factor, and the speed fluctuations reduce the thrust of the blades at each revolution, so that the thrust equal to that of the open-water propeller can be generated only at a smaller speed factor. This causes an apparent increase in the wake determined by this method with respect to the wake determined from direct speed measurements.

Aside from this, the variations in wake that accompany changes in ship speed cannot be neglected in exact analyses of tests.

In the case of the TANNENBERG model these variations were determined by measuring zero thrust at various speeds; see Figure 10. These measurements could be made with great accuracy, while the measurements of zero torque, even when carried out with the greatest care and the most accurate apparatus devised for the purpose were, too uncertain, due to variations of friction in the shaft bearings.

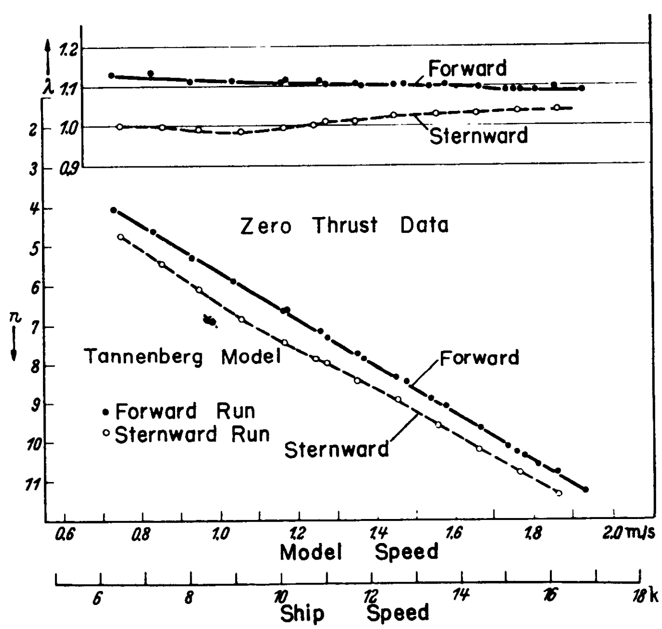

Figure 10

In the ahead runs zero thrust fluctuated from speed factors of 1.12 at low speeds to 1.084 at the service speed. This represents wake variations of 14.9 to 12.4 per cent.

On the astern runs, in which the wave formation is considerably greater because of the unfavorable shape of the advancing stern, the speed factors varied from a minimum of 0.985 at 9 knots to 1.02 at 12 knots, corresponding to wake factors of 3.5 and 7 per cent.

The highly reliable propeller model measurements, made at equal Reynolds' numbers in open water and behind the model, offer no cause to assume that the wake determined from thrust differs from that calculated from the torque coefficient. As long as there are no tangential components or excessive irregularities in the inflowing stream and no thrust-producing deflecting structures in the way of the propeller, there is no conceivable reason to assume that there is such a difference. Similarly there is no difference between the propeller characteristics C_1/C_2 of the open-water propeller and the propeller behind the model beyond the degree of test accuracy.

The bare-hull wake (Grundnachstrom) was measured in the region of the propeller circle by a double pitot tube with the ship model running ahead as well as astern for a ship speed of 13 knots. The contours of equal wake are plotted in Figures 11 and 12. This gives a mean entrance velocity of 0.88 times ship speed when going

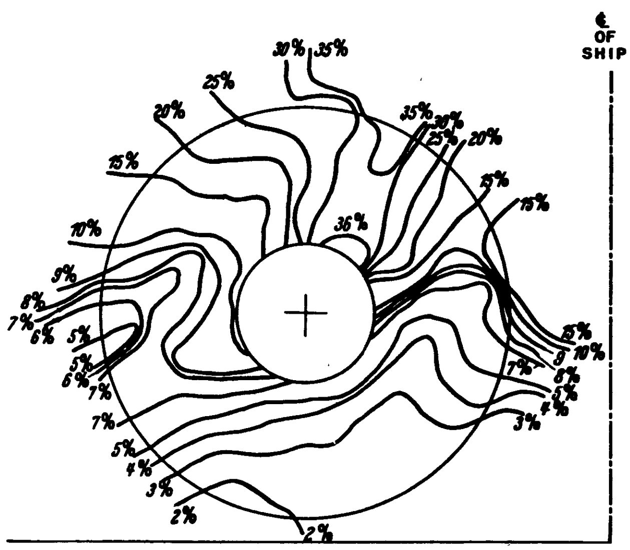

Figure 11 – Curves of Equal Wake in Percent of the Corresponding Ship Velocity. Running Forward

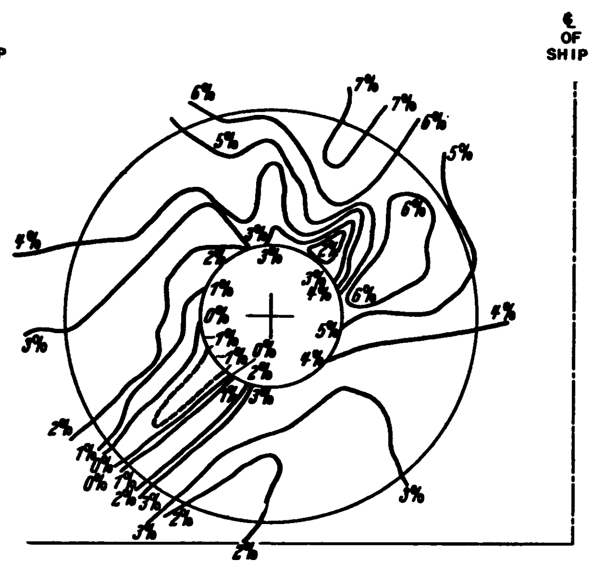

Figure 12 – Curves of Equal Wake in Percent of the Corresponding Ship Speed. Sternward run.

ahead, and 0.96 times ship speed when going astern; see Figure 13. The wake found from the open-water thrust and torque coefficients going ahead is about 14 per cent, going astern it is about 6 per cent. This applies to both port and starboard propellers.

To obtain an idea of the wake variation at various model speeds, the exact draft of the ship on the 1938 trials was re-checked in March 1939 with a double pitot tube on a diagonal through the propeller circle. Comparison with the earlier data showed only small differences of about ± 1 per cent absolute, which may also be explained by the slightly different trim in the earlier tests; see Figures 14, 15, and 16.

On the ahead runs wake measurements at speeds less than 1.0 meters per second, corresponding to 8.5 knots, brought to light a highly noteworthy phenomenon. While it should be expected that because of decreasing wave formation at decreasing speed the wake would grow constantly more uniform and independent of velocity

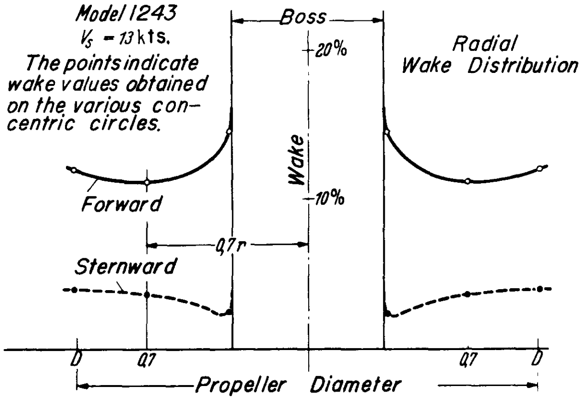

Figure 13

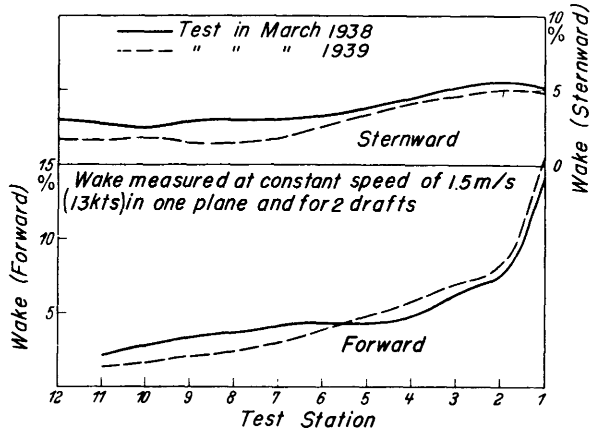

Figure 14

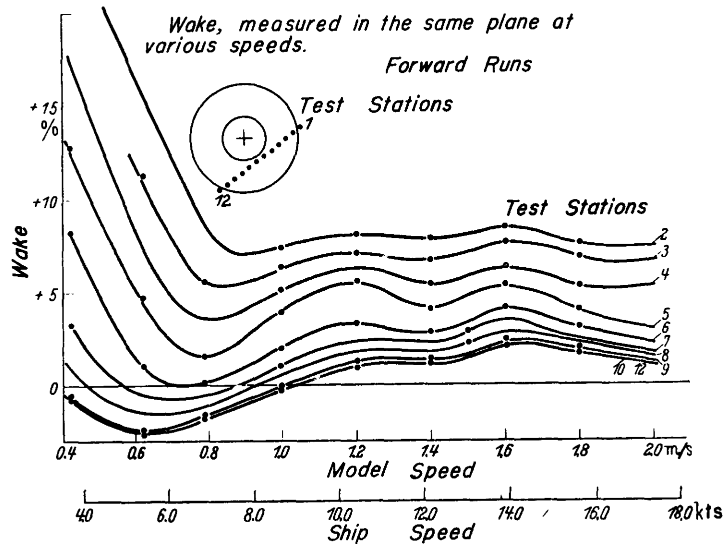

Figure 15

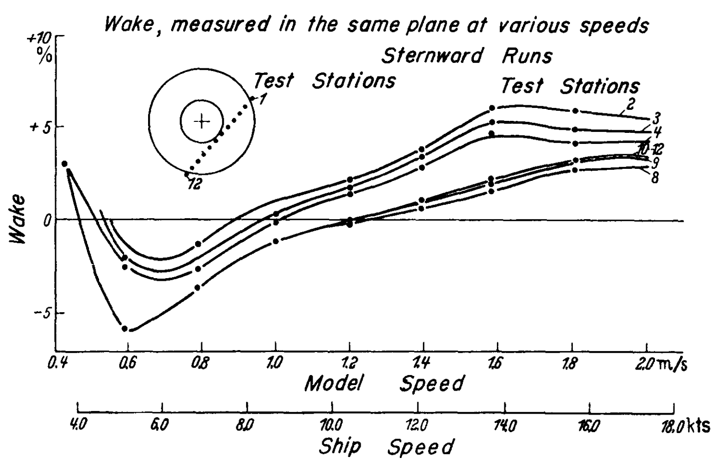

Figure 16

influences, the wake values, on the contrary, increased greatly at speeds less than 0.6 meters per second (1.16 knots). This can indicate only flow anomalies, such as occur in the critical range in the case of a sphere. If we now compare the Reynolds' number for the model by introducing the width of the model as the measure of length, we get a Reynolds' number of 0.5 x 0.775 x 10 / 1.15, or $R = 3.36 \times 10^5$, which is within the critical range of such bodies. This shows that this range must be avoided with great care in order to obtain correct data from model tests, and demonstrates how easily such conditions may be determined by wake measurements.

Although the same phenomenon occurred on the astern runs, this is the natural consequence of the condition of flow resulting from formation of a bow wave, which exists also in the case of the ship. In any event, this test result shows that backing tests are not such an ideal method of comparing the model with the ship as had previously been supposed, because the velocities of flow at the location of the propeller are affected by the orbital velocities.

(c) Ship Tests

The ship tests now to be discussed were planned to permit measurement of the greatest possible slip range for each propeller. All the test data of the 27 runs are given in Table 1. In general, there are three values for each run, each set composed of data obtained independently by one of the three test groups representing HSVA, Blohm and Voss, and H. Maihak. The tests lasted from 12:50 p.m. to 10:25 p.m., or nearly ten hours. The runs were made off the Island of Bornholm under good weather conditions.

Sea:	smooth
Wind:	0 – 1 (Beaufort Scale)
Water:	10°C (50°F.)
Air:	$15^{\circ} - 12^{\circ}$C ($75^{\circ} - 60^{\circ}$F.)
Atmospheric pressure:	760 millimeters (19.9 inches of Hg)

The revolutions of the starboard and port propellers on each test run are plotted in Figure 17, and the curves of equal ship speeds on ahead and astern runs are included, all of which data give some idea of the scope of the tests.

Since analysis of the ship trials of 1937 showed that the intervals between successive runs had not been long enough to obtain constant conditions, considerably longer intervals were allowed in 1938 – about 20 minutes on the average. These intervals were used even on straight runs in order to assure that the thrusts and torques corresponded to the new constant velocity after a change in RPM.

The thrust and torque coefficients were calculated from the ship trial data and plotted on the model test charts. As expected, there was considerable scattering of the data in the range of small or negative thrusts and torques, because trial instruments had not been designed to measure small values. With the shaft rotating

Table 1 - Test Trip of the S.S. TANNENBERG, 17 May 1938.

				Port						Forward Runs				Starboard				
Run No.	Time	Measured by	V_s in kts	RPM	Thrust	SHP	C_1	$10 \cdot C_2$	λ_m	Time	Measured by	V_s in kts	RPM	Thrust	SHP	C_1	$10 \cdot C_2$	λ_m
									Forward Runs									
1	12.50	HSVA Blohm&Voss Maihak	4.3	35 35 —	—0.25 —.025	29 10 —	—0.0723 —0.0723 —	0.55 0.19 —	1.205 1 205 —	12.50	HSVA Blohm&Voss Maihak	4.3	60 60 —	1.4	79 85 —	0.138 0.138 —	0.298 0.321 —	0.705 0.705 —
2	13.10	,,	8.6	78 78 —	0.85	122 108 —	0.0495 0.0495 —	0.209 0.185 —	1.085 1.085 —	13.10	,,	8.6	115 115 —	5.2	485 473 —	0.140 0.140 —	0.260 0.254 —	0.735 0.735 —
3	13.30	,,	11.10	112 112 —	3.20	390 440 —	0.092 0.092 —	0.226 0.255 —	0.972 0.972 —	13 30	,,	11.1	140 140 —	6.4	663 720 —	0.111 0.111 —	0.197 0.214 —	0.779 0.779 —
4	13 50	,,	7.8	114 114 113	6 60	643 609 617	0.182 0.182 0.184	0.354 0.335 0.347	0.672 0.672 0 678	13.50	,,	7.8	46 46 43	—2.65	—49 —41 —39	—0.444 —0.444 —0.508	—0.410 —0.343 —0.400	1.666 1.666 1.782
5	14.10	,,	9 9	146 146 146	11.10	1336 1290 1313	0.189 0 189 0.189	0.35 0.338 0.343	0.665 0.665 0.665	14.10	,,	9.9	59 59 60	—3.50	—125 —106 —128	—0.355 —0.355 —0.343	—0.495 —0.420 —0.482	1.645 1.645 1.618
6	14.30	,,	13 1	190 190 194	18.70	2750 2970 3153	0.181 0.187 0.183	0.324 0.35 0.351	0.676 0.676 0.663	14 30	,,	13.1	80 80 80	—5.80	—284 —257 —244	—0.321 —0.321 —0.321	—0.452 —0.409 —0.387	1.607 1.607 1.607
7	14.50	,,	11.75	152 152 155	9.68	1326 1320 1328	0.157 0.151 0.149	0.308 0.3065 0 29	0.748 0.748 0.744	14.50	,,	11.75	109 109 110	0.50	92 103 121	0.0149 0.0149 0.0146	0.057 0.065 0.074	1.059 1.059 1.05
8	15.10	,,	8.7	118 118 117	5.85	656 618 618	0.151 0.151 0.153	0.326 0.306 0.314	0.723 0.723 0.730	15 10	,,	8.7	77 77 80	—0.20	50 30 43	—0.012 —0.012 —0.010	0.089 0.054 0.068	1.11 1.11 1.068
9	15.30	,,	7.65	44 44 42	—2.30	—37 —33 —33	—0.420 —0 420 —0.440	—0.354 —0.316 —0.363	1 705 1.705 1.787	15.30	,,	7.65	121 121 124	7.60	677 622 764	0 184 0.184 0.175	0.311 0.286 0.326	0.62 0.62 0.605
10.	15.50	,,	9 7	59 59 60	—3.25	—53 —60 —62	—0.335 —0.335 —0.333	—0.21 —0.238 —0.234	1.615 1.615 1.585	15.50	,,	9.7	149 149 152	10.70	1218 1230 1440	0.171 0.178 0.164	0.300 0.303 0.333	0.639 0.639 0.626
11	16.10	,,	12 5	82 82 75	—4.1	—55 —114 —95	—0.220 —0.220 —	—0.081 —0.168 —0.114	1.495 1 495 1.635	16 10	,,	12.5	187 187 188	16.80	2358 2400 2654	0.170 0.170 0.168	0.297 0.303 0 325	0.656 0.656 0.652
12.	16.30	,,	13.4	120 120 123	0.70	307 302 312	0.0175 0.0175 —	0.145 0.143 0 136	1 095 1.095 1 070	16.30	,,	13.4	188 188 189	15.00	2170 2100 2358	0.151 0.151 0.150	0.266 0.258 0.284	0.700 0.700 0.696
13	16 50	,,	14 8	152 152 152	5.60	930 926 893	0 088 0.088 0.088	0.216 0.215 0.207	0.95 0.95 0 95	16.50	,,	14.8	190 190 190	12.55	2010 1870 2076	0.123 0.123 0.123	0.239 0.222 0.246	0.764 0.764 0.764
14	17.10	,,	16.8	195 195 195	14.00	2475 2430 2296	0.132 0.132 0.132	0.272 0.267 0.252	0.846 0.846 0.8467	17.10	,,	16.8	196 196 196	10.10	1760 1660 1853	0.093 0.093 0.093	0.190 0.179 0.200	0.842 0.842 0.842
15.	17.30	,,	14 3	190 190 194	16.40	2700 2730 2885	0.164 0.164 0.158	0.320 0.323 0.322	0.739 0.739 0.724	17.30	,,	14.3	132 132 130	—0.70	100 85 66	—0.014 —0.014 —0.015	0.036 0.030 0.025	1.065 1.065 1.081
									Sternward Runs									
16	18.10	HSVA Blohm&Voss Maihak	3.56	59 59 59	1.3	24 60 63	0.132 0.132 0.132	— 0.238 0.250	0.593 0.593 0.593	18.10	HSVA Blohm&Voss Maihak	3.56	59 59 57	1.5	52 45 40	0.153 0.153 0.164	0.206 0.178 0.176	0.592 0.592 0.613
17	18.30	,,	6.50	92 92 96	2.16	110 174 184	0.092 0.092 0.083	— 0.182 0.169	0.694 0.694 0.664	18.30	,,	6.50	92 92 92	3.2	185 187 187	0.134 0.134 0.134	0.194 0.196 0.196	0.694 0.694 0.694
18	18.50	,,	9.28	125 125 130	3.45	235 419 455	0.078 0.078 0.072	— 0.175 0.169	0.729 0.729 0.701	18.50	,,	9.28	126 126 128	6.65	538 550 551	0.148 0.148 0.144	0.219 0.224 0.214	0.723 0.723 0.712
19	19.10	,,	—	137 137 142	7.15	367 664 752	—	—	—	19.10	,,	—	136 136 138	7.75	674 700 759	—	—	—
20	19.40	,,	4.42	34 34 35	2.70	—17 —15 —12	0.826 0.826 0.780	—0.353 —0.311 —0.228	1.262 1.262 1.240	19.40	,,	4.42	80 80 80	3.85	169 169 256	0.213 0.213 0.213	0.268 0.268 0.406	0.542 0.542 0.542
21	20.00	,,	7.40	50 50 53	1.50	—76 —63 —63	—0.213 - 0.213 —0.190	—0.494 —0.410 —0.344	1.453 1.453 1.370	20.00	,,	7.40	124 124 123	8.80	655 668 678	0.202 0.202 0.205	0.279 0.284 0.296	0.587 0.587 0.590
22	20.20	,,	8.49	78 78 82	—	—63 —43 —25	—	—0.108 —0.074 —0.037	1.069 1.069 1.015	20.20	,,	8.49	135 135 135	9.65	827 850 929	0.188 0.188 0.188	0.273 0.281 0.307	0.617 0.617 0.617
23.	20.40	,,	9.28	108 108 108	1.30	70 137 143	0.0396 0.0396 0.0396	— 0.088 0.092	0.843 0.843 0.843	20.40	,,	9.28	138 138 136	9.10	779 767 821	0.169 0.169 0.174	0.241 0.237 0.266	0.661 0.661 0.670
24	21.25	,,	8.32	140 140 141	7.55	937 950 987	0.1355 0.1355 0.1335	0.278 0.282 0.286	0.584 0.584 0.578	21.25	,,	8.32	78 78 78	—0.6	16 20 9	—0.036 —0.036 —0.036	0.028 0.0344 0.0154	1.047 1.047 1.047
25	21.45	,,	8.89	138 138 143	6.75 7.10	855 848 902	0.125 0.125 0.123	0.264 0.262 0.252	0.633 0.633 0.610	21.45	,,	8.89	100 100 100	3.00	155 167 158	0.106 0.106 0.106	0.126 0.136 0.129	0.873 0.873 0.873
26	22.10	,,	—	140 140 142	5.40	700 660 728	—	—	—	22.10	,,	—	122 122 125	6.20	441 423 479	—	—	—
27	22.25	,,	6.28	123 123 120	6.75 7.0	701 628 707	0.158 0.158 0.172	0.306 0.298 0.332	0.501 0.501 0.514	22.25	,,	6.28	31 31 30	—1.40	—42 —40 —46	—0.520 —0.520 —0.555	—1.150 —1.095 —1.390	1.980 1.980 2.054

slowly, frictional effects become noticeable in the torque; this is also the case in torque tests with the model.

The most important tests were those with the starboard propeller, the test wheel with symmetrical blade sections. These data for the full-scale propeller running ahead show no deviations either in torque or thrust from the curve obtained with the model, beyond the limits of test accuracy. The data fluctuate about this model curve, and at the same time give an idea of the test accuracy obtainable. Several values obtained in 1937 were also included in the C_1/C_2 curves. They showed good agreement with the 1938 data, while the 1937 speed data had been vitiated by ice formation on the log line.

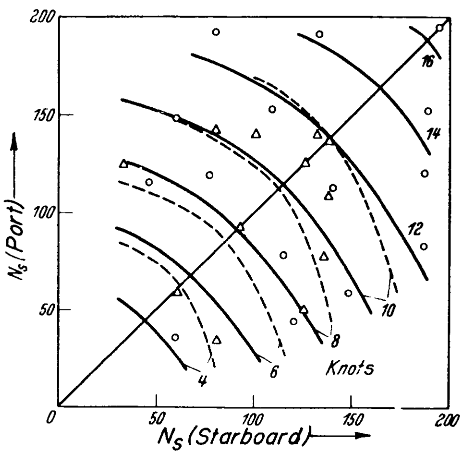

Figure 17 – Revolutions of Port and Starboard Propellers in the 1938 Test Runs
Curves of Equal Ship Speeds Ahead —o—
Curves of Equal Ship Speeds Astern --Δ--

The measured torques for the same starboard ship propeller running astern likewise fair well with the model curve, while the thrusts measured on the astern runs were usually too high.

In the case of the port propeller the torque values for the ahead runs are also satisfactory. Thrust measurements on these runs yielded values obviously too low, while those on the astern runs fair well with the curve.

It may be said in this regard that for safety, the thrustmeter springs were designed for thrusts up to 32 tons, but in no case did the thrusts measured exceed 16 tons. A deflection of 2.09 millimeters (0.082 inch) on the indicator recorded one ton. Therefore it is understandable that the accuracy was of the order of only ± 0.5 tons at the best, and was even less for small thrusts. Variations in readings during the tests were very small, and the thrust recordings were constant.

By adding the thrusts, a curve of the total thrust for the ship can be plotted. However, since the recorded port thrusts were too low, this value may be about 500 kilograms (1102.3 pounds) too low (Figure 18).

This is found by comparing the total thrusts at approximately equal speeds,

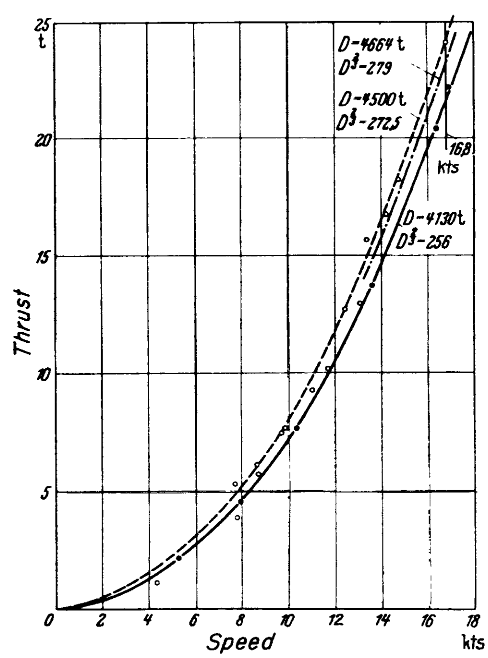

Figure 18 – Comparison of Thrust Data of S.S. TANNENBERG o----o with Model Data of 1934 —·—·— and 1937 •—•—•—•— for Model 1243 in the Hamburg Model Basin

when either the starboard propeller or the port propeller had to supply the major part of the thrust. In this way the tests are used to check each other.

(d) Comparison of Ship and Model Efficiencies

For the TANNENBERG Model 1234 which was built of wood on a scale of 1:20 (about 19.7 feet long), there are two series of propulsion data available with Froude friction corrections, viz.:

1. For a ship draft of 4.50 meters (14.76 feet), at zero list, a displacement of 4664 cubic meters (4705.3 tons), with two similar propellers, 1242, of the year 1934;

2. For a mean draft of 4.076 meters (13.37 feet), with a list of 0.05 meters (0.164 feet) to starboard, for a displacement of 4130 cubic meters (4166.5 tons) with propeller 1242 on the port side and 2003, the symmetrical test wheel of 1937, on the starboard side.

For the ship, the data of the trial runs of 17 May 1938 are available for a mean draft of 4.375 meters (14.35 feet) with a list to starboard, for a displacement of 4500 cubic meters (4539.8 tons) with propeller 1242 on the port side and 2003, the symmetrical test wheel, on the starboard side. These give

(a) The test data for a propulsive run at 195.5 RPM and a speed of 16.8 knots in smooth water without wind;

(b) The required total thrusts for speeds from 8 to 10 knots, which correspond to the ship resistances, including wake, which for this ship is a constant 4-1/2 per cent according to model test. These are to be compared with the total thrusts of the 1934 and 1937 model tests, making allowance for the difference in displacement and in the effects of wind and temperature.

The apparent speed factor v/nD is calculated according to the ship data by means of

Speed	v = 16.8 knots
Propeller revolutions	n = 195.5 RPM
Propeller diameter	D = 3140 millimeters (10 feet 4 inches)
	v/nD = 0.844

The actual speed factor according to the open-water curves for model propellers for equal C_1 and C_2 values of the propellers is calculated from v/nD = 0.725.

Propeller efficiencies from the C_1 and C_2 values for the port propeller

$$\eta_p = \frac{v_e}{2\pi n \cdot D} \cdot \frac{C_1}{C_2} = \frac{0.725}{6.28} \cdot \frac{0.145}{0.0262} = 0.637,$$

and for the starboard propeller

$$\eta_p = \frac{v_e}{2\pi n \cdot D} \cdot \frac{C_1}{C_2} = \frac{0.725}{6.28} \cdot \frac{0.100}{0.019} = 0.608,$$

and for both propellers (port + starboard)

$$\eta_p = 0.625\,.$$

Loss in total efficiency through the starboard propeller 0.625/0.637 = 0.98, i.e., 2 per cent;

Friction effect of stuffing box 0.99, i.e., 1 per cent;

Wind effect at wind force B = 0, 0.975, i.e., 2-1/2 per cent;

Effect of water temperature of 10 degrees Centigrade, 0.988, i.e., 1.2 per cent as compared to 15 degrees Centigrade (59 degrees Fahrenheit).

SHP measured on the ship forward of the stern tube, 4155 HP:

SHP measured on the propeller, 4155 x 0.99 x 0.975 x 0.988 = 3970;

$$C_w = \frac{D^{2/3} \cdot V^3}{SHP} \;;\; D = 4500,\; D^{2/3} = 272.5$$

$$V = 16.8 \text{ kn}, \qquad V^3 = 4750.$$

$$C_w = \frac{272.5 \cdot 47500}{3970} = \cdot 326.$$

C_w in the 1937 model test for D = 4130 tons, $D^{2/3}$ = 256, C_w = 326;

C_w in the 1934 model test for D = 4664 tons, $D^{2/3}$ = 279, C_w = 370.

In the 1934 model test, however, two similar propellers were used, having a total efficiency of 0.637. Therefore the C_w-value must be reduced 2 per cent to permit comparison, making it C_w = 0.98 x 370 = 362.

The equivalent C_w-value for D = 4500 tons for the model tests is calculated as C_w = 351. The value obtained by measurement on the ship is C_w = 326. The difference, 326/351 = 0.928 or 7.2 per cent, is now to be ascribed only to the fact that the outputs calculated with Froude's friction correction are small with respect to the roughness of the ship's surface.

Comparison of Thrust Data.

The difference between the $D^{2/3}$-values of the model tests of 1937 and 1934 is 256/279, which is 8 per cent.

This also agrees approximately with the difference in thrusts in the two model tests. The thrust measured on the ship must first be decreased by a correction for the temperature and the wind effect, after which the equivalent thrust at 16.8 knots becomes 24.1 x 0.975 x 0.988 = 23.2 tons. For comparison with the model thrust curve for 1937, this must be increased by the ratio between the $D^{2/3}$-values, i.e., by

$$\frac{279}{272.5} = 1.025\,,$$

which gives 23.2 x 1.025 = 23.8 tons.

The difference in thrust then is

$$\frac{23.0}{23.8} = 0.965 ,$$

which is 3-1/2 per cent. Considering that the port thrusts as measured were almost certainly too small and that the inaccuracy of measurement is about ± 0.5 tons, the roughness calculated from the thrust data must also be taken as at least 6 per cent.

If the added roughness of the TANNENBERG is accordingly taken as 7 per cent with respect to the total resistance, it will amount to 11 per cent with respect to the frictional resistance.

With an equivalent sand roughness of 0.1 millimeters, the correction according to Weitbrecht's tables would be 5 per cent, and for 0.2 millimeters, 20 per cent. Thus the measured value for an 11 per cent correction corresponds to an equivalent sand roughness of 0.14 millimeters.

From measurements by Schoenherr in America on trial runs of the CLAIRTON in completely new condition*, an equivalent sand roughness of 0.16 millimeters was obtained.

III. CONCLUSIONS

On the basis of these test data with the S.S. TANNENBERG and her 1:20 scale model we are enabled to make a reliable determination of the friction coefficient of the ship's surface. An average of 0.15 millimeters for carefully built merchant ships in new condition appears to be a value that can be reliably used for calculations.

The test data for full-scale propellers confirm to a large extent the model propeller curves. This means that no scale effect was noticeable in the wake effect of the ship as compared to that of the model, either on astern runs in which there is no frictional wake, or on ahead runs; scale effect would necessarily have caused a reduction of the ship wake with respect to model wake.

This may be further explained by the fact that on ahead runs the major portion of the frictional wake flows along the hull of the ship and extends into the range of the propeller disk to a scarcely noticeable extent (on a twin-screw ship such as this one).

It means further that there will be no noticeable scale effect in the thrust and torque values. This is explained on the one hand by the fact that the model propellers are studied in the super-critical range, and on the other hand the roughness factor of the blade surfaces of the full-scale bronze propellers corresponds approximately to an equivalent sand roughness which has the same friction coefficient as the smooth model propellers with their smaller Reynolds' number.

Thus the last obscure and doubtful factors in transferring model data to the ship and its propellers have been cleared up and explained by these comparative

* Translator's note: CLAIRTON'S bottom was freshly painted but not new.

tests of a ship model and a full-scale ship and its propellers, now carried out for the first time on so large a scale. A reliable and theoretically satisfactory basis is now available for applying model test data to the full-scale prototype, at least for twin-screw vessels with shaft bossings of such a type as the S.S. TANNENBERG.

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(2) Kempf, G.: Rauhigkeits und Kennzahleinfluss bei Schiffsschrauben (Roughness and Scale Effect in Marine Propellers). Werft-Reederei-Hafen 1938, No. 11, (U. S. Experimental Model Basin Translation 54.)

(3) See Berendt, E.: Zeitschrift des Vereins Deutscher Ingenieure, vol. 79 (1935) page 587.