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NEW SEA TRIALS ON THE SANDBLASTED *LUBUMBASHI*

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Summary

In a previous paper[1] a review was given of the increase of frictional resistance of M.V. *Lubumbashi* during the first three years of the life of this vessel.

After some five years' service the hull surface had roughened so far that sandblasting was decided.

The surface roughness was measured before and after sandblasting. Again measured mile trials were carried out, where power and thrust were measured, and a comparison with the results of the newly-built ship enabled the author to establish the effect of sandblasting.

Further information on the frictional resistance of the hull surface is given by pitot traverses taken over the bottom in the centreline, fore and amidships.

Summary of Nomenclature

V = Ship's speed through the water in knots.
U = Free stream velocity at edge of boundary layer in knots.
u = Velocity in boundary layer in knots.
δ = Thickness of boundary layer in inches.
ρ = Mass density
l = Distance from foot of stem to pitot log.
γ = Kinematic viscosity.
R_n = $V\,l/\gamma$ = Reynolds number at pitot log.
C_f = Frictional resistance coefficient.
N = *rpm* = Propeller revolutions per minute.
dhp = Delivered horsepower at screw.
T = Thrust in tons.
t = Thrust deduction coefficient.
ehp = $T(1 - t)\,V/0{\cdot}1455$ = Effective horsepower.
ehp/dhp = Propulsive efficiency.
V_w = Ship's speed with wind (measured mile trials).
V_a = Ship's speed against wind (measured mile trials).
dhp_w = Delivered horsepower at screw with wind (measured mile trials).
dhp_a = Delivered horsepower at screw against wind (measured mile trials).
dhp_s = Delivered horsepower at screw still air.
T_w = Thrust with wind (measured mile trials).
T_a = Thrust against wind (measured mile trials).
T_s = Thrust still air.

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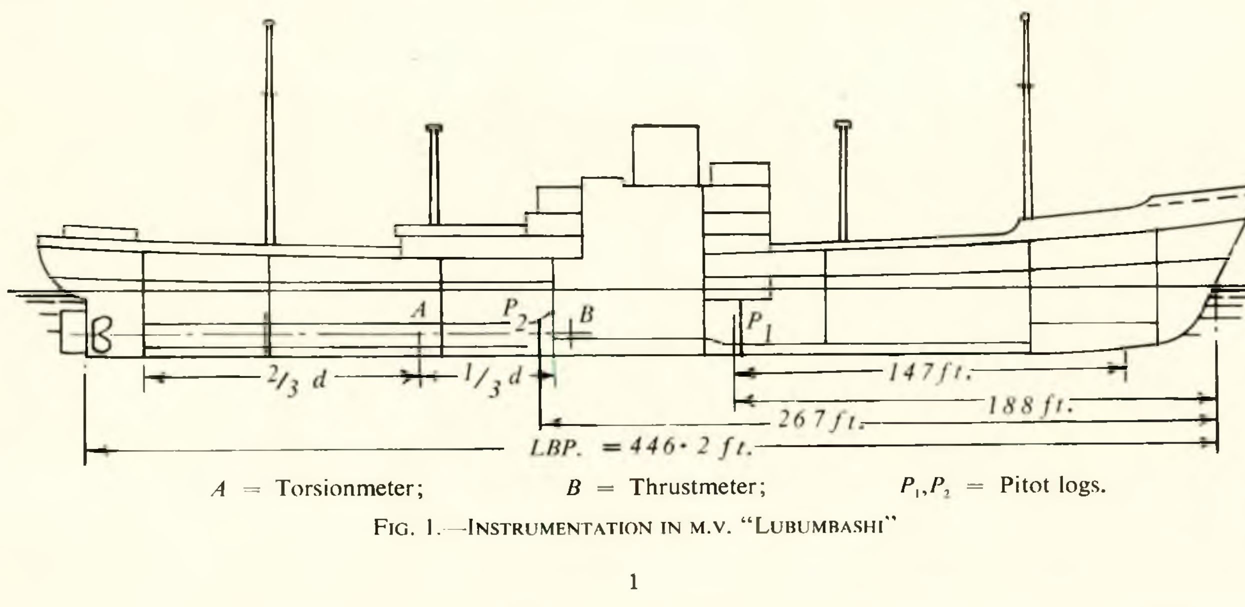
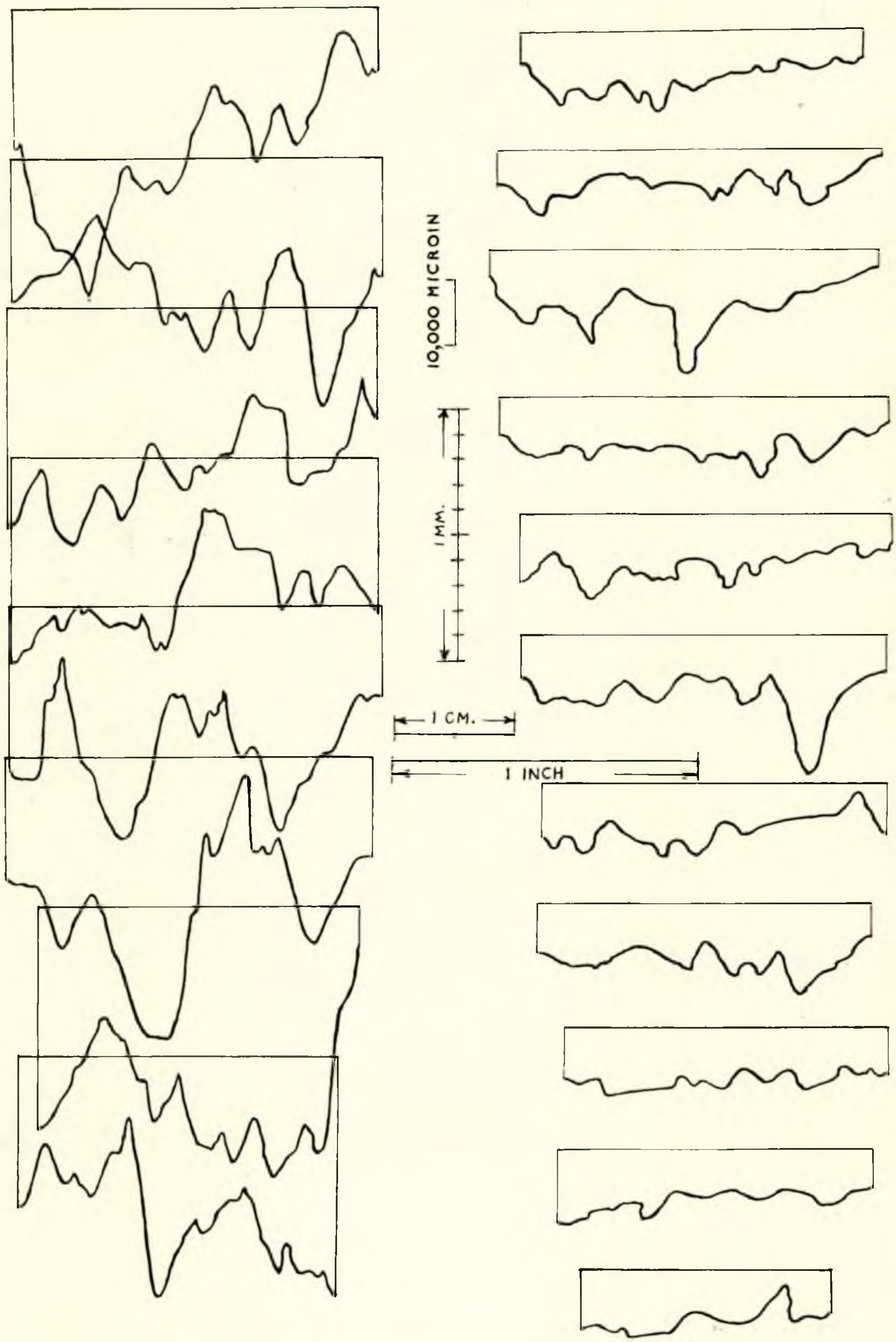


A = Torsionmeter; *B* = Thrustmeter; P_1, P_2 = Pitot logs.

FIG. 1.—INSTRUMENTATION IN M.V. "LUBUMBASHI"



A. Before sandblasting. B. After sandblasting.

FIG. 2.—PROFILES OF THE HULL BEFORE AND AFTER SANDBLASTING

FIG. 3.—PHOTOGRAPH RELATIVE TO THE PROFILES A (FIG. 2) BEFORE SANDBLASTING (FULL SCALE)

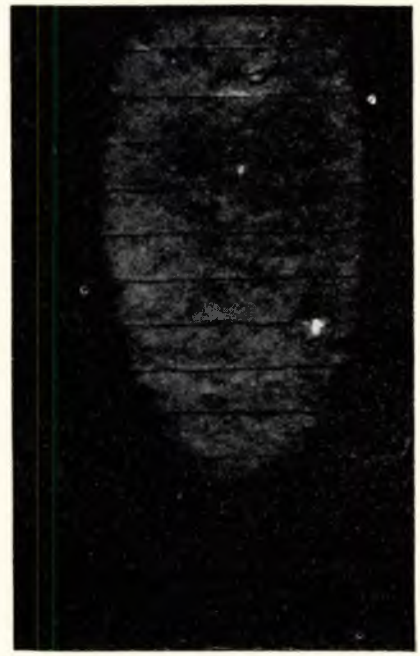


FIG. 4.—PHOTOGRAPH RELATIVE TO THE PROFILES B (FIG. 2) AFTER SANDBLASTING (FULL SCALE)

1. Instrumentation for the Trials

In August 1958, four years and eight months after her first trials, the *Lubumbashi* was dry-docked and the hull sandblasted. This sandblasting was carried out by the dry system. Advantage was taken of the instrumentation of this ship, especially the torsionmeter, the thrustmeter, and the pitometer log, to make an investigation on the behavicur of this vessel in this new hull condition (Fig. 1).

The Siemens–Ford torsionmeter and the Michell thrustmeter were given the same location as for the previous trials. The thrustmeter was installed on the thrust bearing, the torsionmeter was installed at the first third of the shaft, there being in the tunnel four bearings before and nine bearings after torsionmeter.

Two pitometer logs were fitted in the bottom of the hull near the centreline: one log was fitted before the engine-room, 188 ft. from the forward perpendicular, the second log was fitted after the engine-room in the tunnel, 267 ft. from the forward perpendicular.

The torsionmeter was calibrated, fitted on the shaft. The shaft losses from torsionmeter to propeller are calculated in the same way as for the newly-built ship[2]; the shaft loss being 1 hp per revolution, the horsepower at screw dhp is calculated by subtracting from the measured horsepower at torsionmeter mhp the *rpm*. The motor horsepower is obtained by adding to mhp half the *rpm*. This gives a complete loss from motor to propeller of 3 per cent at full power.

The accuracy of measurements is within the following limits of error:

Speed through the water, the pitot logs being calibrated on the measured mile, 1 per cent. This 1 per cent relates only to normal service. The combined measurement of speed over ground with the beacons on the measured mile and of speed through the water with the pitot logs gave a much higher accuracy of the obtained value of speed on the measured mile.

Torque, the torsionmeter being calibrated fitted on the shaft in the engine shop, 2 per cent.

Thrust: 3 per cent.

These limits of error relate to measurements made in a sea where waves are not higher than 4 ft. Waves of this height do not give the ship any appreciable motion.

2. The Trials

It was the aim of the trials to establish the effect of sandblasting the hull on the resistance of the ship.

Three series of measurements must be carried out:

(1) The measurement of the roughness of the hull surface, before and after sandblasting.

(2) The measurement of velocity distribution in the boundary layer by means of both pitot logs. It is known that the roughness of the surface is described by the shape of the velocity curve in the friction belt.

(3) As a conclusion of the investigation, measured mile trials must be carried out and the results compared with the results of the measured mile trials of the newly-built ship.

The measurement of the hull surface roughness could be made in dry-dock.

As the outward passage after sandblasting was from Antwerp to New York, it was decided to deviate the ship from her route and to carry out measured mile trials at Polperro in loaded condition. On the way from Antwerp to Polperro there was an opportunity for many traverses being taken with both pitot logs. So the experimenters embarked in Antwerp, made the trip to Polperro, and disembarked in Plymouth after the measured mile trials.

3. The Measurement of Hull Roughness

In the second *Lubumbashi* paper[1] a description was given of the hull roughness after three years' service. The mean height of the asperities was 0·05 in. After nearly five years' service, the surface roughness was even worse. Corrosion cavities of a depth of some 0·1 in. and a surface of 2 × 2 in. were spread over the bottom, especially fore. Furthermore, many rust scales 0·05 to 0·1 in. thick covered the hull. Small blisters of 0·5 to 1·5 in. diameter, 0·1 to 0·2 in. height, were spread over the whole surface. In many places the paint had disappeared, on the bottom and on the ship's side between light and loaded waterline. The remaining paint was rough with asperities of 0·02 to 0·07 in., and where paint covered corrosion the asperities were even higher.

In the ship's side, thickly spread corrosion cavities of a depth nearly 0·1 in. were visible between light and loaded waterline, even after sandblasting and painting.

It had been stated during the measurements of the three-year-old *Lubumbashi* that the roughness was at the limit of what could be measured with a reasonable accuracy by means of the pneumatic feeler. And now the hull surface was even rougher.

It was the owner's wish to have roughness measurements carried out in two conditions of the hull: (1) in the crude condition of the hull as the ship entered dry-dock; (2) in the condition as the ship left dry-dock, sandblasted and painted.

It was then decided to make the roughness measurements in the same manner as was done on the hull of M.S. *Arabia*.[3] By means of a camera especially designed by the Geodesy Laboratory of the Technical University of Delft, photographs were taken of the uneven surface of the hull of the ship. The photographs were worked out to profiles by means of the pantograph of a photogrammatic calculating instrument.

As many samples as possible were taken of the hull surface in both conditions, before sandblasting, the ship being in dry-dock, and after sandblasting and painting. Some 100 profiles were worked out in the crude condition of the hull against some 200 profiles in the condition after sandblasting. Out of these profiles the group A of Fig. 2 (derived from photograph, Fig. 3) and the group B of Fig. 2 (derived from photograph, Fig. 4) are representative of the mean hull surface condition, group A, before sandblasting, group B after sandblasting and painting.

It might be of interest, however, to mention that, even after sandblasting, the hull surface, owing to corrosion, remains in some parts of the ship rather bad, as can be seen on photograph, Fig. 5. No account, however, is taken of these odd profiles in the analysis of the hull roughness, as they are not regularly distributed over the whole surface of the hull. The profiles of parts that are located above the loadline of the Polperro trials are also disregarded.

FIG. 5.—VIEW OF A PART OF THE SHIP ESPECIALLY AFFECTED BY CORROSION, AFTER SANDBLASTING (FULL SCALE)

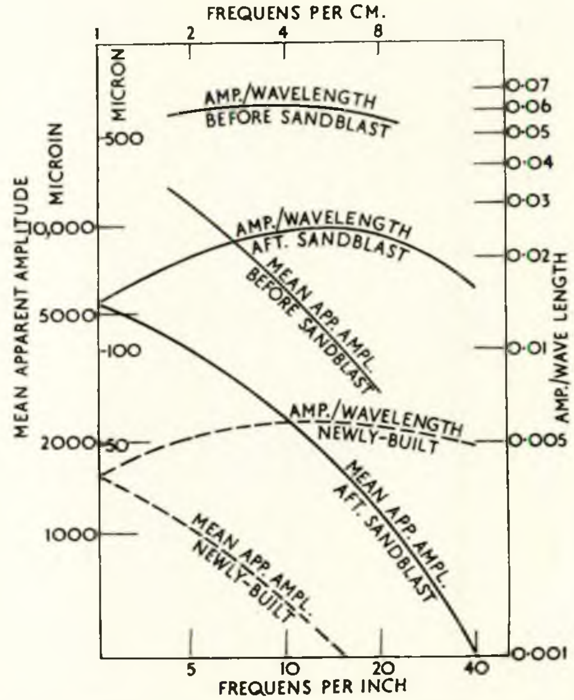


FIG. 6.—ANALYSIS OF THE HULL ROUGHNESS ACCORDING TO THE B.S.R.A. METHOD

Fig. 6 shows in a logarithmic scale the results of the analysis of the profiles of Fig. 2 according to the B.S.R.A. method.[5]

The data of the newly-built ship are repeated in this figure in order to obtain a good picture of the progression of the roughness of the hull surface of the ship when in service.

It must be said that the roughness analysis of the newly-built ship was made of profiles taken in a laboratory by means of a Talysurf on sample plates distributed around the new ship when sandblasting and painting this ship. But the Talysurf data are confirmed by the measurements made with the pneumatic feeler.

It is remarkable that in the logarithmic scale of Fig. 6 the three amplitude-wavelength lines are nearly equidistant and parallel. The amplitudes are brought back to one-third of their values by sandblasting the hull, but even then they remain three times larger than the amplitudes of the newly-built ship.

4. Velocity Distribution in the Boundary Layer

The roughness of the hull surface was furthermore described by the shape of the velocity curve in the friction belt. Two pitometer logs were installed in the bottom of the ship, in P_1 and in P_2 (Fig. 1). The pitot log in P_1 is the same as was installed in the newly-built ship, when at the beginning of 1954 the measured mile trials were conducted at Polperro, and the position is the same, too. The second pitot log in P_2 was given also the same position as it had in August 1954, when the vessel left Antwerp for her fourth voyage, after having been cleaned and painted in dry-dock.

Obviously pitot log P_1 allows the best comparison to be made between the surface conditions, when the ship was new and some five years later after she was sandblasted and painted. The second pitot log, however, can give more information on surface roughness as the traverses taken with this instrument are affected by a much greater part of the bottom. This pitot log was installed in July 1954, just before the fourth voyage, and many very accurate measurements were made in August with this log in a calm sea. When comparing these traverses with the traverses of September 1958, it must be considered that the ship, although cleaned and painted in July 1954, had already

TABLE IA

PITOT P_1: NEWLY-BUILT SHIP
DATE: JANUARY 13, 1954

Distance out from shell in cm.	Velocity in knots u	Velocity ratio u/U
60·5	16·10	1·000
50·5	16·00	0·994
40·5	15·80	0·982
30·5	15·40	0·957
25·5	15·00	0·932
20·5	14·60	0·907
17·5	14·40	0·895
15·5	14·20	0·882
13·5	13·90	0·864
12·5	13·80	0·857
11·5	13·50	0·838
10·5	13·40	0·832
9·5	13·40	0·832
8·5	13·10	0·814
7·5	13·00	0·807
6·5	12·80	0·795
5·5	12·70	0·789
4·5	12·20	0·758
3·5	11·80	0·733
2·5	11·60	0·721
1·5	11·50	0·714
0·5	9·70	0·603
0·0	7·20	0·450
Ship's speed in knots, V ..		16·00
Velocity potential flow, U ..		16·10
Reynolds number R_n ..		3×10^8
Frictional resistance coefficient C_f		0·00180

TABLE IB

PITOT P_1: SANDBLASTED HULL
DATE: SEPTEMBER 7, 1958

Distance out from shell in cm.	Velocity in knots u	Velocity ratio u/U
52·3	15·60	1·000
47·3	15·55	0·997
42·3	15·50	0·996
37·3	15·20	0·974
34·3	15·20	0·974
32·3	15·10	0·968
30·3	15·10	0·968
28·3	15·00	0·961
26·3	15·00	0·961
24·3	14·70	0·945
22·3	14·60	0·936
20·3	14·25	0·914
18·3	14·00	0·897
16·3	13·80	0·885
14·3	13·70	0·878
12·3	13·20	0·846
10·3	13·00	0·834
8·3	12·55	0·805
6·3	12·10	0·776
5·3	11·90	0·763
4·3	11·70	0·750
3·3	11·40	0·731
2·3	10·85	0·696
1·3	10·25	0·657
0·9	9·85	0·632
0·5	9·25	0·593
0·0	6·75	0·433
Ship's speed in knots, V ..		15·50
Velocity potential flow U ..		15·60
Reynolds number R_n ..		3×10^8
Frictional resistance coefficient C_f		0·001 74

suffered from corrosion which had given the hull surface a rather appreciable deterioration. But the effect of that deterioration was very well known by the comparison of the propulsion data of January and October 1954, and by the comparison of the traverses of pitot log P_1, taken when the ship was new, and in October after more than a half-year's service.

In conclusion, the information given by both logs is very useful when comparing the hull surface roughness in both conditions of the ship, newly-built and after some five years' service, the ship being sandblasted and painted.

The data of the traverses are given in the Appendix. During the measured mile trials of September 8, 1958, the accuracy of both pitot logs was checked. Pitot log P_2, which always had proved to be a reliable instrument, gave measurements 0·05 knot high as compared with the actual speed on the mile: there is much evidence that this 0·05 knot is the effect of the potential flow. Pitot log P_1, however, gave measurements 0·5 knot high: this 0·5 knot is due for one part 0·1 knot to the effect of potential flow[2]; for the most important part, however, 0·4 knot to an inaccuracy in the adjustment of the instrument. All the data given by this instrument are to be corrected for 0·4 knot to obtain the actual velocity in the boundary layer.

From the data of Tables IA and IB, IIA and IIB, the loss of momentum $\int \rho\, u\,(U - u)\, dy$ of the water along the bottom over a breadth equal to unit can be calculated in the usual way. Dividing this loss of momentum by $1/2\, \rho\, V^2\, l$, where V is ship's speed and l the distance from the foot of the stem to the pitot log, gives the frictional resistance coefficient C_f.

The frictional resistance coefficient is first calculated, taking the data of pitot log P_1, from the foot of the stem to this log.

There is no appreciable difference between the values of the frictional resistance coefficient, 0·00180 for the newly-built ship, and 0·00174 for the sandblasted ship some five years later. The difference is within the limit of error of measuring and computing.

TABLE IIA

PITOT P_2 TRAVERSES 4TH VOYAGE (CLEAN HULL)

Distance out from shell in cm.	Velocity in knots in boundary layer *u*					
	1 (up)	2 (down)	3 (up)	4 (down)	5 (up)	6 (down)
0·00	—	—	1·80	1·80	0·00	0·00
0·05	—	—	—	—	—	1·90
0·10	—	—	—	—	4·80	—
0·15	—	—	—	—	—	3·20
0·20	—	—	—	4·40	5·80	5·20
0·30	—	—	—	6·00	6·30	6·00
0·40	—	—	—	—	6·90	—
0·50	—	—	—	7·00	—	6·90
0·60	—	—	—	—	7·70	—
0·65	—	—	—	—	—	7·30
0·80	—	—	—	7·30	—	7·90
1	8·40	8·30	8·50	7·90	8·20	8·30
2	9·30	9·30	9·35	8·80	9·60	9·40
3	9·70	9·80	9·80	9·50	10·20	10·10
4	10·00	10·10	10·10	10·00	10·50	10·40
5	10·40	10·40	10·40	10·30	10·90	10·90
6	10·80	10·70	10·70	10·50	11·10	11·20
7	10·90	10·90	10·80	10·70	11·20	11·30
8	10·90	11·00	10·80	11·00	11·40	11·50
9	11·00	11·10	10·90	11·30	11·70	11·70
10	11·10	11·20	11·20	11·30	11·90	11·90
11	11·30	11·30	11·30	11·30	12·00	12·00
12	11·40	11·50	11·50	11·50	12·20	12·20
13	11·60	11·60	11·70	11·70	12·30	12·50
14	11·70	11·80	11·70	12·10	12·50	12·60
15	11·90	11·90	12·00	12·20	12·60	12·70
16	12·00	12·10	12·10	12·20	12·80	12·90
17	12·10	12·10	12·20	12·20	12·90	13·00
18	12·20	12·20	12·30	12·40	13·00	13·20
19	12·30	12·30	12·50	12·60	13·15	13·10
20	12·40	12·50	12·40	12·70	13·30	13·20
25	13·00	13·10	13·20	13·00	13·70	13·70
30	13·30	13·40	13·40	13·20	14·15	14·15
35	13·50	13·70	13·60	13·80	14·40	14·60
40	13·70	13·90	13·90	14·00	14·70	14·90
45	14·10	14·30	14·20	14·20	15·10	15·30
50	14·40	14·70	14·50	14·40	15·20	15·40
55	14·60	14·80	14·80	14·70	15·40	15·50
60	14·80	15·00	14·95	14·80	15·60	15·60
70	14·90	15·20	15·15	15·00	15·70	15·80
Ship's speed V ..	14·85	15·15	15·10	14·95	15·65	15·75
Potential flow U ..	14·90	15·20	15·15	15·00	15·70	15·80
Reynolds number R_n	$4{\cdot}8 \times 10^8$	$4{\cdot}8 \times 10^8$	$4{\cdot}8 \times 10^8$	$4{\cdot}8 \times 10^8$	5×10^8	5×10^8
Frictional coefficient C_f	0·001 88	0·001 98	0·001 99	0·001 88	0·001 81	0·001 81
Date	2.8.54	2.8.54	3.8.54	3.8.54	4.8.54	4.8.54

The data obtained by pitot log P_1 are plotted in Fig. 7. Only one single curve can be drawn through the data relating to both hull conditions. In conclusion, for the part of the ship affecting this pitot log, the surfaces are to be considered as hydraulically equivalent.

Considering now the P_2 data, it is somewhat more difficult to have a comparison made of the roughness in both conditions, September 1958 and newly built, because the pitot log was installed in July 1954. A correction has to be made for the first six months.

Again the frictional resistance coefficient is computed in the usual way from the data of August 1954 (Table IIA). This gives on the bottom of the ship from stem to pitot log P_2 a mean value of $C_f = 0{\cdot}00189$. Establishing the frictional resistance coefficient from the data of September 1958 (Table IIB) gives a mean value of $C_f = 0{\cdot}001708$. This means for August

TABLE IIb

Pitot P_2: Sandblasted Hull

Date: September 7, 1958
Hour: 13h. to 15h.

Distance out from shell in cm	Velocity in knots u	Velocity ratio u/U
70	15·50	1·000
65	15·45	0·996
60	15·35	0·990
55	15·30	0·987
50	15·10	0·974
45	14·90	0·961
40	14·55	0·938
38	14·45	0·931
36	14·40	0·928
34	14·25	0·920
32	14·05	0·906
30	13·95	0·900
28	13·85	0·893
26	13·65	0·880
24	13·45	0·867
22	13·25	0·854
20	13·20	0·851
19	13·10	0·844
18	12·95	0·835
17	12·95	0·835
16	12·80	0·826
15	12·70	0·819
14	12·70	0·819
13	12·60	0·813
12	12·40	0·800
11	12·30	0·794
10	12·00	0·774
9	11·70	0·755
8	11·60	0·750
7	11·40	0·739
6	11·10	0·716
5	10·90	0·703
4	10·50	0·676
3	9·90	0·640
2	9·10	0·590
1	7·00	0·450
0	1·50	0·097
Ship's speed in knots, V ..		15·45
Velocity potential flow, U ..		15·50
Reynolds number R_n ..		5×10^8
Frictional resistance coefficient C_f		0·001 734

Date: September 7, 1958
Hour: 21h. to 22h.

Distance out from shell in cm.	Velocity in knots u	Velocity ratio u/U
70	15·30	1·000
60	15·20	0·993
50	15·00	0·981
45	14·65	0·956
40	14·40	0·941
38	14·25	0·931
36	14·10	0·921
34	14·05	0·918
32	13·95	0·911
30	13·95	0·911
28	13·90	0·908
26	13·75	0·898
24	13·60	0·889
22	13·40	0·875
20	13·20	0·863
19	13·00	0·850
18	12·95	0·846
17	12·90	0·843
16	12·75	0·833
15	12·50	0·817
14	12·50	0·817
13	12·35	0·807
12	12·25	0·800
11	11·95	0·781
10	11·95	0·781
9	11·85	0·775
8	11·60	0·758
7	11·30	0·738
6	11·00	0·719
5	10·65	0·696
4	10·35	0·676
3	10·00	0·653
2	9·00	0·590
1	7·00	0·460
0	1·50	0·098
Ship's speed in knots, V ..		15·25
Velocity potential flow, U ..		15·30
Reynolds number R_n ..		5×10^8
Frictional resistance coefficient C_f		0·001 682

1954 an increase of the frictional resistance coefficient of 11 per cent as compared with the frictional resistance coefficient of September 1958. On the other hand, it has been stated in the previous *Lubumbashi* paper[1] that the increase of frictional resistance from January (newly built) to October 1954 was 11 per cent. This was obtained from P_1 traverses as well as from power data. Thus it is established again from the P_2 data that, for the part of the bottom affecting this pitot log, the surface roughness is hydraulically the same for the newly-built ship and after sandblasting and painting some five years later.

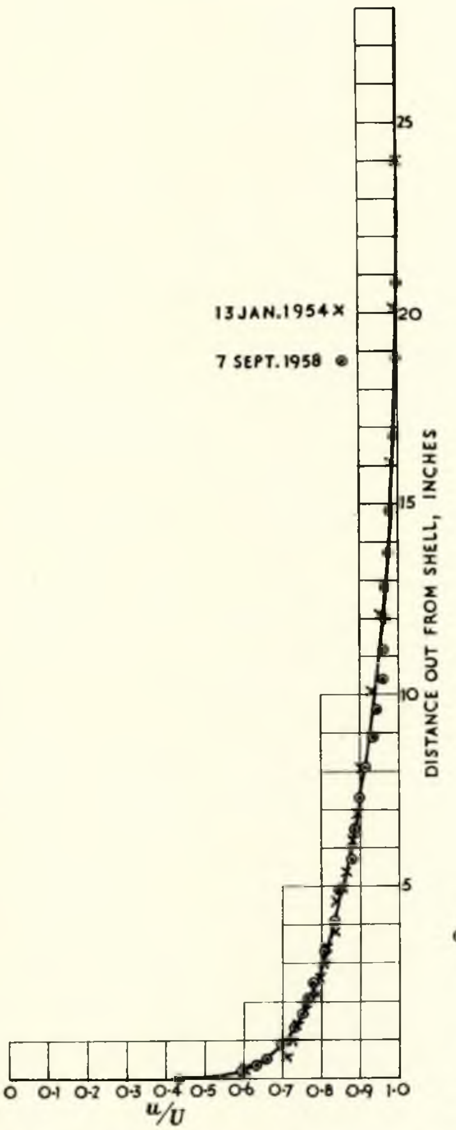


Fig. 7.—Velocity distribution in the boundary layer. (Pitot log P_1)

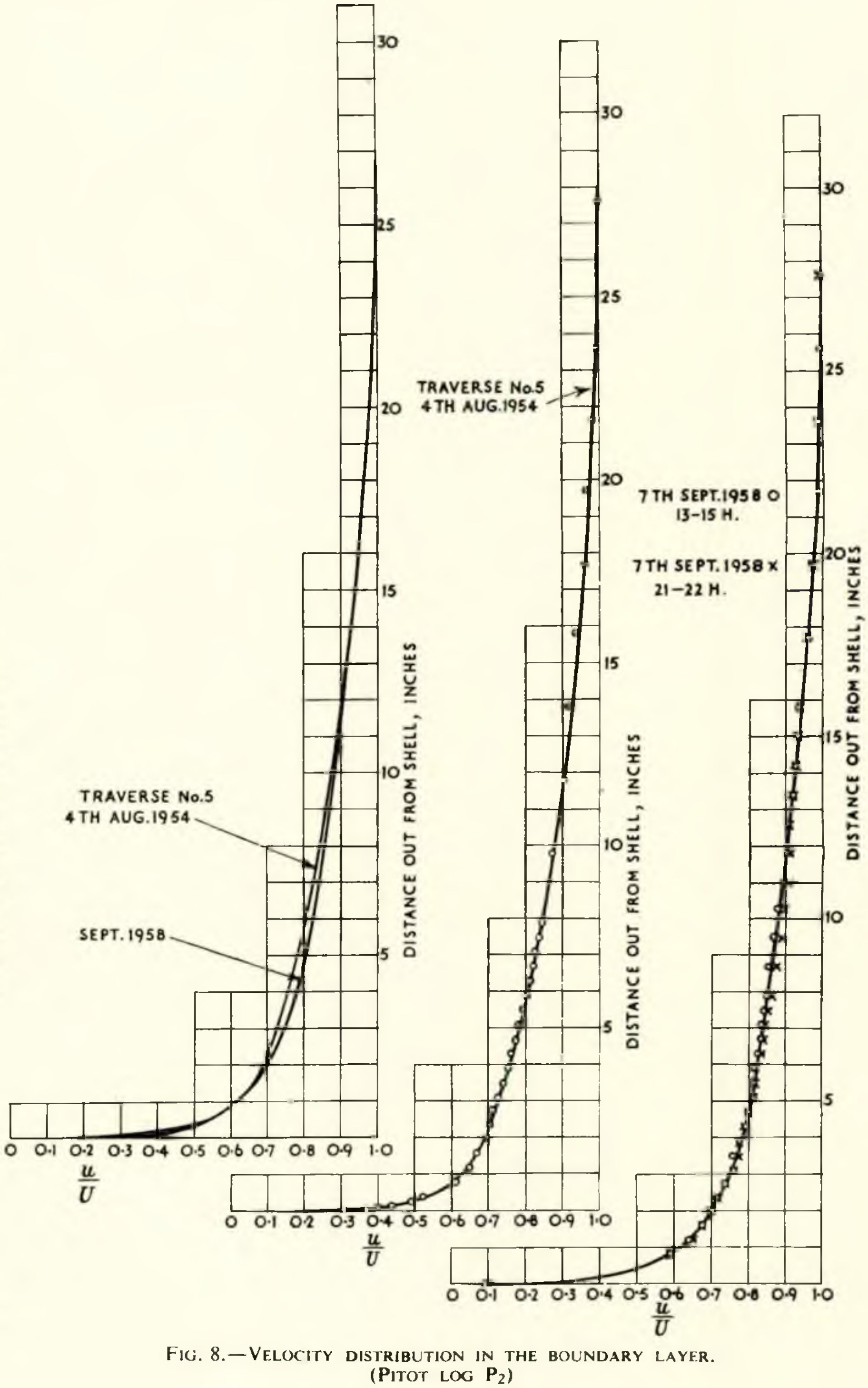


Fig. 8.—Velocity distribution in the boundary layer. (Pitot log P_2)

Again, the velocity curves P_2 are given for August 1954 and September 1958 (Fig. 8). In Table IIA the traverse 5 is taken, giving the lowest frictional resistance coefficient, the most unfavourable to be compared with the traverses of September 1958. For the traverses of September 1958 the mean curve is drawn and from the relative position of the curves September 1958 and August 1954 it is obvious that the roughness was higher in August 1954.

Incidentally, it could be remarked that the I.T.T.C. 1957 line gives for a Reynolds number 3×10^8 a $C_f = 0{\cdot}001788$ and for a Reynolds number 5×10^8 a $C_f = 0{\cdot}001671$. These values are very close to the values obtained from the traverses of P_1 and P_2 for the newly-built and the sandblasted ship.

5. The Measured Mile Trials

The measured mile trials of the newly-built ship were carried out in ballast and in fully loaded condition. Unfortunately, when the *Lubumbashi* left Antwerp September 6, 1958, she was medium loaded.

On the other hand, Dr. Allan, Superintendent of the National

TABLE III

SHIP TRIAL RESULTS. SHIP: M.V. "LUBUMBASHI." MEASURED MILE: POLPERRO, SEPTEMBER 8, 1958

Group and run	Direction	Time at start, G.M.T.	Ground speed, knots	Reading pitot P_1, knots	Reading pitot P_2, knots	Actual water speed V, knots	N *rpm*	dhp at screw	Thrust T, tons
I. 1	E.W.	5·48	14·15	14·93	14·41	14·37	101·10	4,053	36·90
2	W.E.	6·23	15·85	16·10	15·69	15·62	103·50	4,171	36·50
3	E.W.	6·59	14·38	15·19	14·75	14·67	101·76	4,118	37·30
II. 4	W.E.	7·30	16·80	17·31	16·98	16·89	114·12	5,852	46·65
5	E.W.	8·02	15·82	16·68	16·21	16·17	112·86	5,688	46·75
6	W.E.	8·28	16·82	17·33	16·97	16·90	113·82	5,844	46·25
III. 7	E.W.	9·00	16·33	16·91	16·51	16·45	116·28	6,432	49·90
8	W.E.	9·38	17·43	17·70	17·33	17·28	117·42	6,475	49·30
IV. 9	E.W.	10·25	11·96	12·80	12·35	12·22	85·20	2,312	—
10	W.E.	10·57	13·42	13·73	13·33	13·20	87·12	2,335	25·20
11	E.W.	11·30	12·06	12·75	12·35	12·19	84·84	2,309	—

For group II visibility was poor, ground speed is questionable for this group.

Course W.E. 86 deg., course E.W. 266 deg. On the straight course the range of rudder angles was 0 to 2 deg. port, 0 to 3 deg. starboard. The depth under keel varied from 20 to 23 fathoms, except for run 3 where it was 16 fathoms, and run 6 where it was 14 fathoms.

Wind was nearly constant during the trials, about 16 knots westerly.

State of sea: moderate. True direction of waves: 250 deg. Height of waves: 3 to 4 ft.

Thrust is corrected for shaft obliquity and for static head.

For runs 7 and 8 power is computed from indicator diagrams on a basis of mechanical efficiency calculated from the other runs, where power was measured with the torsionmeter.

Physical Laboratory, who ran the model and made the comparison with the trials, did not make tests at an intermediate draught.(2)

Nevertheless, an attempt was made to compare the results of the new measured mile trials with the data obtained for the newly-built ship.

Table III gives the results of the measured mile trials conducted at Polperro, September 8, 1958.

The particulars of M.V. *Lubumbashi* are recalled here:

446·2 ft. *LBP*; 61·35 ft. breadth moulded; draught for'ard 19·83 ft., draught aft 23·67 ft.; extreme displacement 11,640 tons; water temperature 61° F.

Propeller, 4 blades: Single screw (R.H.), 17·62 ft. diameter; mean designed face pitch = 14·50 ft.; developed blade surface area = 107·2 ft.^{2}

This was a new propeller with characteristics slightly different from the characteristics of the propeller of the newly-built ship.

Hull surface: riveted seams, welded butts, ship four years and eight months old, sandblasted and painted before the trials.

A first step is to correct the results of the measured mile trials to still air condition. This has been done as given in Taylor's book.(4)

There is, however, a deviation from Taylor's method in that the effect of current is eliminated first of all by means of the readings of the pitot logs.

Both pitot logs are calibrated by comparing the mean of means of their readings for each group with the mean of means of ground speeds. This gives for each pitot log an error line. Both lines are fairly well parallel except for the runs of group II, where the deviations are important and quite the same for both pitot logs; because of that, the ground speeds of group II are ignored, and the error lines of the pitot logs are based only upon the ground speeds of groups I, III, and IV.

Corrected then for this error, each pitot log gives for each run a speed relative to water v. The values v_1 and v_2 given by each pitot log for a run are very close and their mean $V = v_1 + v_2/2$ is an accurate value for the "water speed" of the ship.

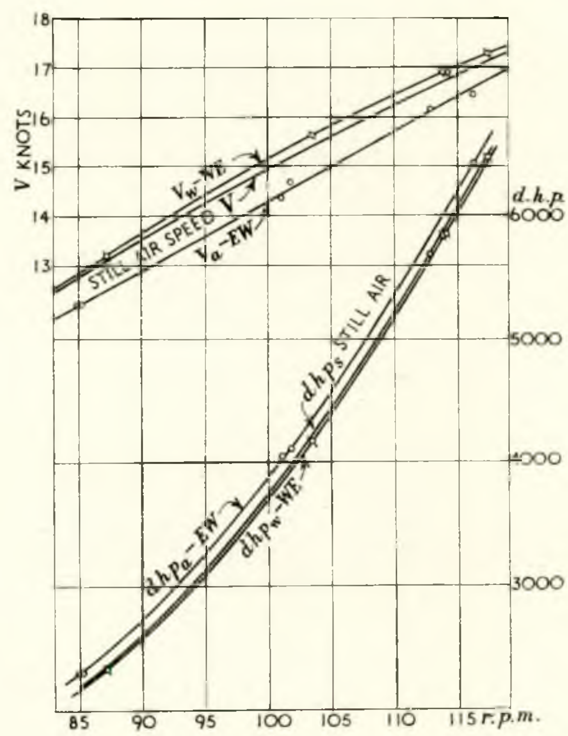


FIG. 9.—ANALYSIS OF THE RESULTS OF THE MEASURED MILE TRIALS: RELATION DHP–SPEED

For each run the group of simultaneous values of speed V, *rpm*, and dhp (resp. T) are then plotted, and this gives Fig. 9 and Fig. 10. V_a, dhp_a, and T_a refer to runs against the wind, V_w, dhp_w, and T_w refer to runs with the wind.

It is remarkable that the groups of values obtained respectively with and against wind are well in line, as well for dhp as for thrust T.

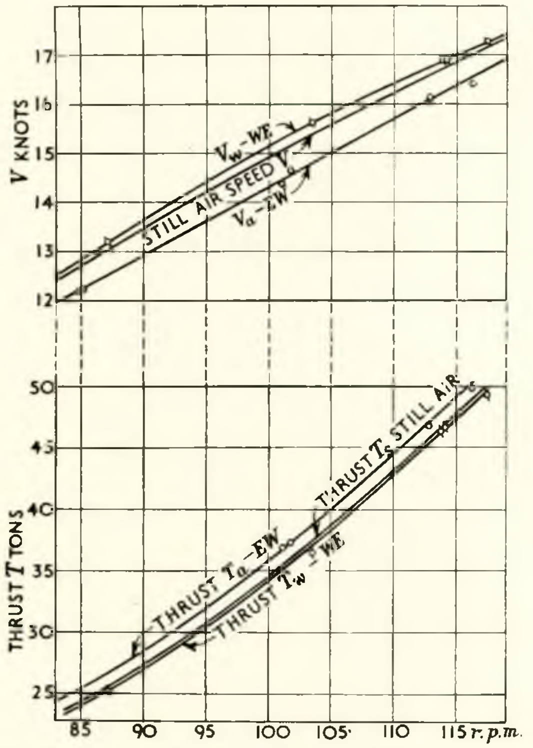


FIG. 10.—ANALYSIS OF THE RESULTS OF THE MEASURED MILE TRIALS: RELATION THRUST–SPEED

The necessary corrections to obtain the still air values are then made and they are given in Tables IV and V.

Correcting in both Fig. 9 and Fig. 10, the V lines with and against wind for the Δ V of the Tables gives new V lines: these new V lines are very close and the mean line between them gives definitely the "still air speed V" for the interpolated dhp and T values in still air.

It must be remarked that a correction has been made for wind effect, but not for the effect of waves. This objection can be met by the following considerations.

The wave height, 3 to 4 ft., was small compared with the dimensions of this cargo liner. Ship motions were slight and the effect of waves on ship resistance must have been very small. Moreover, during previous trials, in many circumstances the effect of a following sea has been determined on this ship,[1,2] and it was of the same order as now found by the Taylor method.

Finally, the still air values of dhp and thrust T of the September 1958 trials are compared with the values obtained for the trials carried out on the newly-built ship, in ballast in December 1953 and loaded in January 1954.

The displacement, 11,640 tons, of the September 1958 trials is half way between the ballast displacement, 8,945 tons, and the loaded displacement, 14,192 tons, of the trials on the newly-built ship. This makes the comparison rather difficult.

In Figs. 11 and 12, dhp and T of the trials on the newly-built ship are corrected for the displacement, 11,640 tons, of September 1958, for the ballast condition up to this displacement, for the loaded condition down to this displacement. This gives two different lines of which the mean line is supposed to give dhp and thrust T in the newly-built condition of the ship for a displacement of 11,640 tons.

It must be said that for the trials in newly-built condition thrust was not corrected for static head, as was remarked in a footnote.[2] T has been corrected now for static head.

Again, dhp and T, still air condition, of the September 1958 trials are plotted in these diagrams, as they were obtained from Figs. 9 and 10, for five values of dhp and five values of T.

It is remarkable that the dhp values of 1958 are with precision on the dhp line deduced from the trials, on the newly-built ship. The T values of 1958 are somewhat below the line of the newly-built ship.

TABLE IV

dhp CORRECTIONS FOR STILL AIR CONDITION, SEPTEMBER 1958 TRIALS

rpm	V_1	dhp_s	dhp_w	dhp_a	V_w	ΔV_w	V_a	ΔV_a
85	12·55	2,200	2,180	2,315	12·66	0·11	11·92	0·63
90	13·28	2,615	2,590	2,740	13·40	0·12	12·67	0·61
95	14·02	3,130	3,100	3,270	14·15	0·13	13·41	0·61
100	14·75	3,730	3,700	3,880	14·86	0·11	14·17	0·58
105	15·40	4,435	4,400	4,580	15·52	0·12	14·91	0·49
110	16·07	5,220	5,180	5,360	16·19	0·12	15·65	0·42
115	16·70	6,060	6,020	6,200	16·81	0·11	16·32	0·38

V_1 is the provisional "Still air speed," mean of V_w and V_a

TABLE V

THRUST T CORRECTIONS FOR STILL AIR CONDITION, SEPTEMBER 1958 TRIALS

rpm	V_1	T_s	T_w	T_a	V_w	ΔV_w	V_a	ΔV_a
85	12·55	24·4	24·1	25·4	12·70	0·15	12·05	0·50
90	13·28	27·3	27·0	28·4	13·42	0·14	12·76	0·52
95	14·02	30·7	30·4	31·8	14·15	0·13	13·53	0·49
100	14·75	34·5	34·2	35·7	14·87	0·12	14·25	0·50
105	15·40	38·6	38·3	39·9	15·52	0·12	14·89	0·51
110	16·07	43·1	42·8	44·3	16·18	0·11	15·63	0·44
115	16·70	47·7	47·4	49·0	16·80	0·10	16·25	0·45

V_1 is the provisional "Still air speed," mean of V_w and V_a

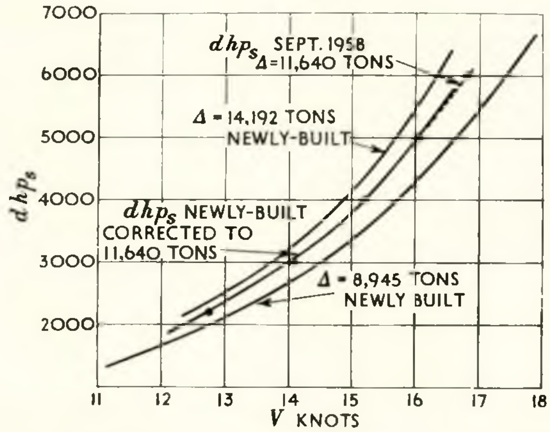


FIG. 11.—DHP COMPARISON OF THE SANDBLASTED SHIP WITH THE NEWLY-BUILT SHIP

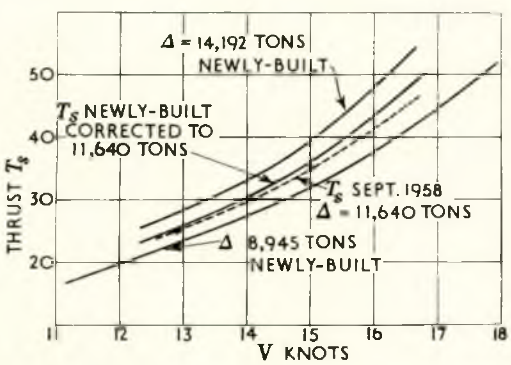


FIG. 12.—THRUST COMPARISON OF THE SANDBLASTED SHIP WITH THE NEWLY-BUILT SHIP

If it is considered that the thrustmeter had not the same accuracy as the torsionmeter, the conclusion is evident: the hull surface of September 1958 is hydraulically equivalent to the surface of the newly-built ship.

There is an argument against this method of comparison of the trial results. The discrepancy between the Admiralty coefficients in light and loaded condition is important. That difference, however, is slight at the higher speeds and the experimenters fortunately had a group of runs at a speed of nearly 17 knots. In the higher part of the curves dhp and T, obtained by correcting the results of the trials in ballast and loaded condition of the newly-built ship to the displacement of 11,640 tons, these curves converge, so far that the discrepancy in the corrected dhp and T values is here not more than 4 per cent. This validates the interpolation.

Finally, the propulsive efficiency ehp/dhp is calculated for the new trials. Table VI gives this propulsive efficiency, it being assumed that the thrust deduction coefficient is the same as given by the 1954 N.P.L. model tests. There is further an error in that the speed used for the calculation is the computed still air speed, not the actual speed.

TABLE VI

PROPULSIVE EFFICIENCY ehp/dhp, SEPTEMBER 1958 TRIALS

V, knots	T, tons	t	dhp	ehp/dhp
13	25·3	0·213	2,320	0·794
14	29·6	0·217	2,940	0·785
15	34·9	0·221	3,800	0·763
16	41·3	0·226	4,910	0·741
17	48·8	0·230	6,300	0·721

ehp/dhp must be reduced by 3·5 per cent

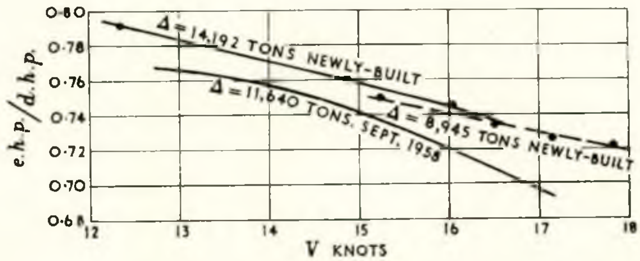


FIG. 13.—PROPULSIVE EFFICIENCY COMPARISON OF THE SANDBLASTED SHIP WITH THE NEWLY-BUILT SHIP

In Fig. 13 this propulsive efficiency is compared with the propulsive efficiency obtained during the 1953–54 trials. There is no deterioration of propulsive efficiency. Hence, comparing dhp, results in comparing the resistance values.

In conclusion, it is evident, from the pitot traverses as well as from the measured mile trials, that both hull conditions, newly-built and five years old but sandblasted, are hydraulically equivalent.

There is an apparent inconsistency between this conclusion and the roughness measurements. Comparing the curves of the mean apparent amplitudes and the curves of the ratios amplitude-wavelength in these two conditions (Fig. 6), one would be inclined to conclude for a substantial difference in resistance.

It must be said that the roughest part of the ship is located between light and loaded waterline, and this part was only a little immersed during the measured mile trials at Polperro. When fully loaded the effect of hull roughness on ship resistance might be more evident than at the present trials.

But it is clear from the Polperro trials of this sandblasted ship that the aspect of the roughness of hull surface is more important than the absolute value of the height of the asperities. Allan and Cutland, in their study of artificial roughnesses,[6] have shown that the roughness resistance coefficient of a corrugation is maximum for a ratio amplitude-wavelength 0·06. This is exactly the ratio amplitude-wavelength of the hull surface of the *Lubumbashi* after five years' service before sandblasting (Fig. 6). This means that, due to the aspect of the asperities of the hull surface, the roughness of this ship became critical, and any operation, altering thoroughly this aspect, could not but lower substantially the ship's resistance.

6. Service Performance before and after Sandblasting

It has been shown, on the basis of the measured mile trials run at Polperro when the ship was new and these trials run again five years later but with a sandblasted hull, that both hull surfaces were hydraulically equivalent and induced the same resistance. Thus sandblasting of the hull of the five-year-old ship was fully effective.

As there might remain some doubt about this statement, due to the apparent roughness of the surface after sandblasting, it is certainly of interest to give the analysis of the service performance data of this ship—

(i) when she was newly built, during her maiden voyage;
(ii) when she was five years old, before sandblasting;
(iii) when she was five years old, after sandblasting.

The author was fortunate enough to make the maiden voyage with the *Lubumbashi* and an analysis of the performance data of this first voyage[2] showed a very good correlation of the performance of the newly-built ship with the results of the Polperro measured mile trials. During this first voyage, from Antwerp to Teneriffe, the weather was generally fine, and the power and thrust data in calm weather were practically—with a very small scattering—on the still air line deduced from the measured mile trials.

In the second *Lubumbashi* paper[1] a detailed account was given of the effect of fouling and deterioration of the hull on ship's resistance during the first three years of the life of the vessel. The author is now in a position to complete this picture and the best way to do this consists in analysing the service performance data of the last voyage of the ship before the hull was sandblasted in 1958.

This last voyage, from New York to Rotterdam, in July 1958, happened in ideal weather conditions. In the beginning of the voyage, during three days, wind was south-easterly, force 2 in the scale of Beaufort the first and the second day, force 3 to 4 the third day. The fourth day wind was north-easterly, force 2. Then during six days the wind and sea were following, varying from west-north-west to west-south-west, force 2 to 5.

The mean displacement during the voyage was 14,050 tons, the mean speed 15·03 knots, the mean revolutions 106·9 *rpm*.

Two series of diagrams were taken:

(i) V = 15 knots, dhp = 5,003, *rpm* = 107·5;
(ii) V = 14·5 knots, dhp = 5,009, *rpm* = 106·2.

dhp is obtained from ihp, the mechanical efficiency being deduced from the results of the measured mile trials of September 1958.

Interpolation on a base of dhp/*rpm*^{3} gives for the whole voyage a mean dhp = 4,982 for a mean speed V = 15·03 knots and a mean *rpm* = 106·9.

Comparing these data with the data of the measured mile trials in loaded condition January 1954, corrected to still air condition, results in an increase of power of 20·6 per cent, say 20 per cent if some allowance is made for the third day, when the wind was Beaufort 3 to 4 south-easterly.

This 20 per cent consists of a part due to deterioration and a part due to fouling. The ship was three months out of dock and had suffered from some fouling. It is somewhat difficult to estimate this effect of fouling.

The first year of the life of the vessel, this effect of fouling for three months out of dock is 6 per cent. Later, after five years, this effect is certainly less, probably about 3 per cent, because the hull surface is already deteriorated. With an allowance of 3 per cent for this fouling, the effect of the deterioration of the hull surface on ship's resistance is estimated to be 17 per cent. This increase of resistance is calculated on the engine developing her full rate of service power, say 5,000 dhp.

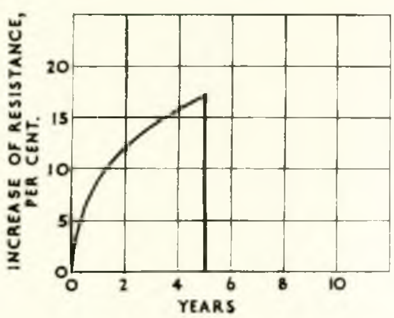


FIG. 14.—EFFECT OF DETERIORATION OF THE HULL ON SHIP'S RESISTANCE

A new diagram showing the increase of resistance due to hull surface deterioration during five years is now given in Fig. 14. This new diagram completes the diagram which was given before and it is now established:

(1) That the effect on ship's resistance of the deterioration of the hull surface does not increase in a linear relation to the number of years' service of the ship, but that the relation is parabolic;

(2) That the results of the measured mile trials run in 1958 showed that sandblasting brings the hull surface again to the newly-built condition, hence that for this ship the effect of deterioration of 17 per cent as well as the effect of fouling of 3 per cent were taken off by sandblasting.

Again, an analysis of the service performance data could be made for the first voyage after sandblasting the hull in 1958. Unfortunately, the only part of this voyage that took place in good weather conditions was the trip New York-Rotterdam and no diagram was taken during this trip. That is why the comparison with the maiden voyage of the ship in 1954 is to be made on a basis of the fuel coefficient $\Delta^{2/3} V^3/T$, where Δ is the displacement in tons, V the mean speed in knots, T the mean daily fuel consumption in tons.

During the maiden voyage of the ship Antwerp-Congo-Antwerp in 1954, as well as during the trip New York-Rotterdam in 1958, the sea was mainly moderate and following, the mean of sea state being 4 in the scale of Beaufort. It is known that this state of sea is very near the ideal sea condition. The mean displacement was 14,550 tons during the maiden voyage and 13,100 tons during the voyage New York-Rotterdam. The fuel coefficient was 92,500 for the maiden voyage against 92,000 for the voyage New York-Rotterdam. This means that on a basis of the fuel coefficient the *Lubumbashi*, after sandblasting the hull, came back to the newly-built condition.

Acknowledgments

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The author is very much indebted to all those who helped him, especially the Compagnie Maritime Belge, shipowners, the Mercantile Marine Engineering and Graving Docks Co., who installed most of the instruments, and Mr. J. Verhoest, his assistant.

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DISCUSSION

The Chairman, Mr. J. M. Murray, M.B.E., B.Sc. (*Vice-President, R.I.N.A.*): This is a very important paper and one which I am sure many people will read and will refer to quite often in the future. This series of papers on the *Lubumbashi* provides the basis documentation of the propulsion results for the ship; and it says very much for the public spirit of the owners, the Compagnie Maritime Belge, S.A., that they have taken all these particulars.

There are a number of questions which come to mind immediately, and I have no doubt that they will be posed in the course of the discussion.

M. G. Dufour (*Member*) (*Read by the Secretary*): When it was suggested to carry out new sea trials with the M.V. *Lubumbashi*, after sandblasting her hull, the owners agreed immediately with this proposal as they expected this would give them more reliable information about the efficiency of the hull treatment than could be gathered by the statistical analysis of the performances of several other ships which were already sandblasted.

It must be said that trials were run indeed with all these ships after sandblasting of their hulls and that their performances on the measured mile were compared with those obtained with the newly-built ships. However, since they were not fitted with torsiometer, nor thrustmeter, nor Pitot log, and that power had to be computed from indicator diagrams on a basis of estimated mechanical efficiency the results of these trials could not have the degree of accuracy obtained by Professor Aertssen's new experiments.

Nevertheless, our trials showed, within a limit of accuracy estimated at 2 to 3 per cent that, after sandblasting, the hull condition is comparable to what it was for the newly built ship. This was further confirmed by the statistical analysis of voyage records from whom it appeared that, for the first year of operation after hull treatment, the mean power allowance on tank predictions was nearly the same as for the first year the ships went to sea. It appeared also from this analysis that the benefit of fuel consumption amounted to 13 per cent for this first year and that for the further years this benefit was slowly decreasing. The effect of sandblasting should disappear after about five years. Calculated on the whole of this period the benefit of fuel consumption should largely offset the cost of sandblasting.

After her hull was treated in the same manner the logbook records of the M.V. *Lubumbashi* were also analysed and, again, it was found that, for the three voyages she performed after sandblasting, the mean value of the power allowance on tank predictions compares very closely with that obtained for the three first voyages of the newly-built ship.

This conclusion might appear questionable as it is based on records of routine measurements which are not accurate and are influenced by weather effect which gives rise to a considerable scattering of the recorded figures, especially when it concerns the actual voyages of the M.V. *Lubumbashi*, comprising two crossings of the North Atlantic. Table VII related to the first voyage after sandblasting should emphasize this.

Considering the crossing New York–Rotterdam, which was performed in a following sea, it appears that the hull must have been very clean. For the other performances the power allowance is affected by weather effect, especially for the westbound crossing of the Atlantic which was performed in a nearly head sea.

It might be interesting to give here also the performances of the ship on her maiden voyage: for a displacement of 15,550 LT she realized 15·12 knots with a mean power of 4,785 dhp and a fuel consumption of 22·20 tons for propulsion only. This corresponds to a C_{Adm} of 429 and an allowance on tank predictions of 9 per cent.

It must be considered that the weather effect on the Congo route is less than on the voyages with North Atlantic crossings.

TABLE VII

	Weather conditions (mean wind strength in Beaufort scale)	Mean draught (ft. in.)	Mean displacement (LT)	Mean speed (knots)	Mean *rpm*	Mean slip (per cent)	Consumption per 24 hours (prop. only), tons	Mean power, dhp	C Fuel	C Adm.	Power allow., per cent
Plymouth–New York	Bft. 3/4–N.W./S.W.	20 8	10,950	14·70	108·8	6·7	25·85	5,570	60,400	280	61
Philadelphia–Boma . .	Bft. 3–E./S.E.	17 9	9,250	16·25	110	−1·9	24·1	5,185	78,500	365	9
Luanda–Philadelphia	Bft. 3/4–S./E.	28 6	15,800	15·36	109·8	3·6	25·0	5,390	90,600	421	10
New York–Rotterdam	Bft. 5–N.W.	24 5	13,300	15·91	109·4	−0·2	24·3	5,230	92,800	432	0
Mean for round trip		23 0	12,350	15·62	109·5	1·7	24·58	5,290	83,100	384	16

TABLE VIII

	Weather conditions (mean wind strength in Beaufort scale)	Mean draught (ft. in.)	Mean displacement (LT)	Mean speed (knots)	Mean *rpm*	Mean slip (per cent)	Consumption per 24 hours (prop. only), tons	Mean power, dhp	C Fuel	C Adm.	Power allow., per cent
Antwerp–New York	Bft. 5–N.N.W./S.S.W.	21 3	11,350	15·04	107·04	3·4	26·55	5,710	64,700	301	51
Halifax–Matadi . .	Bft. 3–S.S.E./S.W.	19 9	10,400	15·80	109·2	0·25	27·21	5,875	68,900	320	33
Matadi–New York . .	Bft. 3–N.E./N.N.E.	26 4	14,450	15·66	109	0·95	26·45	5,690	86,200	401	13
New York–Rotterdam	Bft. 3–N.E./N.N.E.	19 11	10,500	16·52	109·2	−4·3	26·47	5,690	81,700	380	5
Mean for round trip		21 9	11,650	15·71	108·3	−0·06	25·92	5,580	77,500	358	21

According to our experience the difference should amount to 8–10 per cent. Hence the power allowance on this route should have been 9 + 8 (10) = 17 (19) per cent, which corresponds nearly to the 16 per cent recorded for the first voyage after sandblasting. We may conclude again that the hull condition was nearly the same as for the newly-built ship.

Voyage 3 after sandblasting gave the results shown in Tables VII and VIII.

The mean weather conditions were nearly the same as for the first voyage shown in Table VII. Hence it may be concluded that, within an interval of 6 months, there is a deterioration of 5 per cent due to fouling of the hull.

Obviously these conclusions cannot be considered as definite. The statistical way of analysing voyage performances is a long one and it is only after collecting data for numerous voyages that a reliable figure can be reached.

Therefore we appreciate very much the work done by Professor Aertssen as it permits us to have a more precise idea of the behaviour of our ship before and after sandblasting.

It might appear somewhat surprising that the performances after sandblasting compare so closely with those obtained with the newly-built ship since, according to the roughness measurements, the hull surface was not the same as in the initial condition. Owing to corrosion inegalities remained on the surface and Professor Aertssen relates that their amplitudes were three times larger than for the new ship. This seems, however, not to have influenced the hydrodynamic quality of the hull. One must conclude that these small asperities due to corrosion pitting are softened by the hull painting and that their effect on resistance is not so severe as some people suggest. What seems more important to consider is the deterioration due to local rust-blisters and to disappearance of paint, which creates inegalities on the hull surface having a ratio amplitude-length exceeding sometimes the limit of 0·6 indicated by Allan and Cutland as being a permissible maximum. Therefore we believe that, from the point of view of ship's resistance, the quality of paint and the care taken by its application is just as important as all attempts to reduce corrosion. However, this does not invalidate the usefulness of anti-corrosion devices as a means of preventing premature thinning of hull plating and leakage at riveted joints.

Mr. F. H. Todd, B.Sc., Ph.D. (*Vice-President, R.I.N.A.*): Professor Telfer has said that further important information might be gleaned from these trials if further model tests were carried out and has suggested that this might be done at N.P.L. We are, of course, very good friends of Professor Aertssen, who has made observations of the full-scale performance of some Belgian cross-Channel ships for which we have tested models of the ships and have provided him with the results. If he thinks there is more to be learned from further model tests on the *Lubumbashi* I should be very glad to discuss such possibilities with him.

It is one of my responsibilities as the Superintendent of a towing tank to predict the power for a ship from the results of model tests. Usually when the latter are carried out all that is known of the finished ship is that she will have a riveted, a welded, or a partly welded hull. We know nothing about the roughness of the final paint nor any details as to the time elapsing between the docking and the trials. In other words, with such rather meagre knowledge we have to predict what the condition of the ship's hull surface will be in three years' time. For this reason we are very interested to hear from anyone who can tell us how to improve the power prediction.

There are a number of things which affect the roughness of the hull of a new ship. The structural roughness will depend upon whether the hull is riveted or welded, while the paint roughness will depend both upon the preparation of the plating before and during the building and upon the care with which the paint is applied. This is the condition in which we are primarily interested because in general the shipbuilder is interested in what the ship will do on the trial trip. The owner, however, is more interested in what happens afterwards during the ship's life and the performance is then affected by the corrosion of the plating, the fouling of the ship's surface, and the treatment on successive dockings. Over the last ten or twelve years, in conjunction with the British Shipbuilding Research Association, we have carried out research into the correlation between the ship's power as predicted from the model test and the power as measured on trial. The results of some of this work were given to The Institution last year by Mr. Clements. This correlation emphasized the magnitude of the differences which can occur among new ships and even among sister ships. In one group of six sister ships, all tankers, all new, which had been out of dock for less than 20 days and were run in good weather, the power for the same speed varied as much as 25 per cent. These differences do not cover deterioration of the surface itself due to corrosion or fouling and it is in this area that Professor Aertssen has given us some most valuable information.

I would like to comment upon Fig. 14 in the paper. I think one might get the impression that the deterioration of the ship's surface was very rapid at first but was gradually falling off and that its effect on the ship's resistance was only 17 per cent at the end of five years. This, of course, is not the case because the ship was, in fact, docked, cleaned, and painted several times during this period, and the curve shown in the figure is really a curve joining up the performance figures for the ship immediately following each docking and cleaning. The 17 per cent deterioration therefore represents the difference between the clean, freshly painted new ship and the cleaned, repainted ship at the end of five years. It is therefore to a large extent a measure of the corrosion effect.

One of the surprising conclusions we can draw from the paper is that when the measured roughness was some three times as great as on the new ship the power absorbed was the same. In trying to find the reason for this I would like to mention some work done on this subject in the United States by Mr. C. J. Posey of the State University of Iowa. If we imagine a roughness having a cross-section like a north light roof it will at once be obvious that the resistance will be different if we run it in different directions because the slope of the roughness facing the flow will be different in these two cases. Thus the resistance is not going to depend only on the amplitude of the roughness y, but also on the slope dy/dx. Also one might expect that if the tops of the roughnesses are rounded off instead of being sharp the resistance would again be different and the roundness of the roughness would be a function of d^2y/dx^2. For any given roughness record the profile can be analysed by means of an electronic computer and histograms prepared showing the distribution of the different values of dy/dx and dy/dx^2. Mr. Posey showed that by means of such histograms he could correlate the roughness with the appropriate specific resistance. I would like to suggest that perhaps this is the reason for the differences which Professor Aertssen has found in his trials. After the ship has been in service for a long time, the roughness record is likely to be one of considerable amplitude and having some rather sharp edges and points. Perhaps the effect of sandblasting is to round off these angles and points and thus reduce the resistance although the surface is still far from what we may call smooth.

I should like to thank Professor Aertssen for his persistence in following up his earlier work on the *Lubumbashi* and for the very great amount of data he has given the profession in this field. Obviously there is a great deal in the paper which one can only absorb after much study and it will remain a valuable source of reference.

Mr. H. J. S. Canham (*Associate-Member, R.I.N.A.*): The paper describes what at first sight appears to be a remarkable piece of work. There is apparently good correlation between the performance of the *Lubumbashi* at the end of five years in service, immediately after the hull surface had been sandblasted and repainted, and the trial performance of the newly-built ship. This correlation is indicated by comparison of trial performance data, surface roughness data and pitot log traverses. This could be a very significant result because it implies that the attainment of a hydrodynamically smooth ship is well within practical capabilities. Unfortunately, there are inconsistencies in the data, in common with so many trial performance results.

Fig. 6 indicates an important inconsistency between the measured roughness and the performance of the ship, unless it is accepted that the difference in mean apparent amplitude of roughness between that for the new hull condition and that after sandblasting would not, in fact, materially alter the resistance of the hull. Unfortunately, the range of frequency covered in Fig. 6 does not include the frequencies used at B.S.R.A., where efforts have been concentrated so far on frequencies of ½ and 2 per inch. Assuming that it is permissible to do so, extrapolation of the curve of mean apparent amplitude against the frequency for the sandblasted hull to a frequency of ½ per inch gives a mean apparent amplitude of 8,000 microin. Roughness and trial performance data obtained by B.S.R.A. suggest that with a mean apparent amplitude of this order the ships concerned have greater resistance than for the hydrodynamically smooth condition.

Presumably the purpose of changing the propeller was to obtain a more efficient propeller, in which case a somewhat higher propulsive efficiency might be expected, everything else being equal. For a given condition of the hull surface any increase in propulsive efficiency should be shown by a reduction in dhp. Such a reduction in dhp could well be masked by an increase due to the increased roughness of the hull after sandblasting.

The figures given in Table VI for propulsive efficiency do not appear to be correct. For example, with values of V, T, *t*, and dhp given, the propulsive efficiency at a speed of 15 knots has the value 0·738 and at 17 knots has the value 0·697. These values are significantly lower than those for the new ship at the same speed. Perhaps the author will look into this point. This may not be a matter of great significance, since the values of *t* are only assumed to apply to the ship, but the smaller propulsive coefficient indicates a lower ehp for a given dhp and hence a less resistful hull after sandblasting than for the newly-built ship. It seems highly unlikely that this was the case.

Referring back to the data which the author originally gave for this ship in 1955, it is noted that a Froude correlation factor of 1·00 was derived from the trial results of the new ship. This value is somewhat higher than the average for a ship with welded butts and riveted seams and frames, which is about 0·95. Thus the newly-built *Lubumbashi* had a trial performance rather worse than the average. Here again there is evidence to suggest that the new ship was not hydrodynamically smooth.

It therefore seems advisable to obtain more performance and surface roughness data from other ships before drawing any firm conclusions about the practicability or otherwise of achieving a hydrodynamically smooth surface on a new or old ship by means of sandblasting or other special bottom treatment. Thanks are due to the author for the significant lead which he has taken in this work.

More details of the new propeller would be welcomed, and it is hoped that it will be possible for new model tests to be carried out at N.P.L.

Mr. T. Macduff (*Associate-Member, R.I.N.A.*): The fundamental consideration concerning the shipowner is the economics of sandblasting and painting in dry-dock, weighed against the cost of fuel saved by the resulting smooth hull, over a period of time, and from the results of this valuable investigation it should be possible to determine the desirable economic interval between sandblasting operations for the *Lubumbashi*. It would be much appreciated if Professor Aertssen could give an economic analysis on the above lines.

Concerning this investigation, the particulars of the new propeller, also any significant gain in open efficiency over that of the original propeller, would help to eliminate a possible variable. It is considered that pitot measurements in the vicinity of the propeller, might have permitted an assessment of the change in frictional wake arising from change in hull surface roughness. Professor Aertssen's opinions on the resulting wake gain in propulsion due to hull roughness would be appreciated.

Due to the abrasive nature of the sandblasting process, the possibility of accelerated hull surface deterioration from sandblasting cannot be discounted entirely, and thus suggests the desirability of still further sea trials for the *Lubumbashi* which would be of great interest.

Mr. A. Simpson (*Associate-Member, R.I.N.A.*): Reference has been made to the effects of sandblasting on the roughness of the hull. Were measurements made of the mean thickness after the first five years of fouling, corrosion, and sandblasting? If there were any serious reduction of total thickness, the initial thickness would have to be corrected to allow for this.

Mr. A. E. Franklin (*M.I.Mar.E.*): A point occurs to me which the author has not raised in his paper. If one assumes that the hull had not been sandblasted at the end of five years' service, it could be expected that subsequent deterioration between dry-dockings would be more rapid owing to the poor adhesion of anti-corrosive and anti-fouling paints on the roughened surface. In addition to giving the underwater surface, what is, in fact, a new lease of life, sandblasting would also decrease the rate of deterioration between subsequent dockings.

Mr. F. Wellman (*Stud. R.I.N.A.*): In the text of the paper, above Fig. 5, the author states that he took some 100 profiles of the hull before sandblasting and some 200 profiles after sandblasting.

This brings to mind two important points. Firstly, for the purpose of a statistical analysis, one would assume that it is necessary to have more profiles for the rougher hull. From what is stated in the paper it appears that a considerably greater number of profiles were taken after sandblasting, which is a reversal of normal procedure.

Secondly, an examination of the photographs reproduced in the text reveals that there are approximately ten profiles on each photograph. This suggests that only ten photographs were taken of the hull before sandblasting. The areas chosen may have been representative of the whole surface, but it does seem a rather small number. Perhaps Professor Aertssen would comment on this and tell us how the areas were selected.

Mr. D. W. Webb (*Associate-Member, R.I.N.A.*): Professor Aertssen has devoted a lot of study to ship performance personally. In his comparison, on the last page of the paper, he refers to the service performance data of the ship on the last voyage, from New York to Rotterdam. Will he give his opinion of the value of that data as compared with that of his own data? He visits and sails on these ships, but now he is speaking, I presume, from observations which the staff of the *Lubumbashi* have made.

Mr. J. M. Murray, M.B.E., B.Sc. (*Vice-President, R.I.N A.*): I would like to ask Professor Aertssen a question about Fig. 6.

I have looked up the paper by Allen and Cutland and have found that the reduction of the amplitude/wavelength ratio from 0·06 to 0·02 would halve the excess resistance, on the assumption that the amplitude remained constant. Allen and Cutland showed from experiments on the resistance of a surface with regular corrugations that C_f is proportional to $h\,t/a$ for constant speed, when h/a is the amplitude/wavelength ratio, and t is the distance affected by the transverse oscillations set up by the irregularities. The effect of sandblasting is to reduce h and with it t, so the reduction of resistance on this basis is much greater than the amplitude/wavelength ratio parameter would suggest. In addition, the sandblasting has removed the asperity of the surface, thus giving a further improvement. On this basis the effect of sandblasting on the *Lubumbashi* seems reasonable, and I would like Professor Aertssen's comments on this aspect.

I trust the trials on this ship will continue.

Mr. R. Cook, M.Sc. (*Chairman of Council, I.Mar.E.*): Having seen something of this type of investigation at fairly close quarters in the British Shipbuilding Research Association I am, although a mere engineer, well acquainted with the many pitfalls and possible sources of error in this type of work. Indeed, on a number of occasions I have watched Mr. Canham and his colleagues making an agonizing re-appraisal of their results in an endeavour to make them fall into line.

I am therefore full of admiration for the manner Professor Aertssen has managed to obtain results which fall into line with each other, and I must congratulate him on his work. It seems to me that on all counts our two Institutions are fortunate to have his paper presented to us at this joint meeting, and I am sure it will form a very valuable addition to our TRANSACTIONS.

It gives me great pleasure to propose a hearty vote of thanks to Professor Aertssen.

Written Discussion

M. Jourdain (*M.I.Mar.E.*): Professor Aertssen mentions that the propeller fitted before the last sea trials of the *Lubumbashi* was a new one, but it does not appear from the paper that he considers this fact as important.

In my opinion, supported by one shipowner at least, there is some probability that the overall deterioration previously measured would not be due to the hull roughness only, but also to some extent to the propeller roughness; I should like to know if Professor Aertssen shares this view.

The question has not only a theoretical interest, because if the propeller is responsible for a fair amount of the deterioration, this one can be reduced by repolishing it, an operation which is not too expensive to be repeated at shorter intervals than sandblasting.

Professor E. V. Telfer, D.Sc., Ph.D. (*Vice-President, R.I.N.A.*): Once more we are indebted to Professor Aertssen for an excellent and informative paper.

I have been particularly intrigued by the lines running across the paint photographs in Figs. 3 to 5. Presumably these are the profile bases of Fig. 2. Could Professor Aertssen enlighten us?

Professor Aertssen: A glass set upon the hull surface is marked by a series of parallel lines. A bundle of rays falling obliquely on these lines enlarges the height of the roughness asperities, the amplification factor being 2·09. The asperities, traced in this way on the photograph, Fig. 3, are then worked out by microphotogrammetry to the profiles A of Fig. 2.

Professor Telfer: Thank you. Now I understand the photographs. This work is undoubtedly extremely useful and is worthy of much emulation. I would strongly recommend the British Shipbuilding Research Association to consider similar pitot tube tests on their ship trials generally, since the information they give should certainly enable us to reduce the gap in our knowledge between ship and model. It should be appreciated, nevertheless, that this very useful method does not as yet tell us anything about structural roughness. The pitot tubes are installed away from the riveted plate seams and the paint appears to be sufficiently thick either to cover or at least effectively reduce the frame riveting projection. It follows, therefore, that the pitot specific resistance is only a sample of the actual frictional resistance; and this is likely to be distinctly higher than the measured value. This latter will be a correct value, however, for an all-welded ship and therefore offers a very valuable means of quantifying *minimum* ship specific frictional resistance. An analysis of Allan, Canham, and Clements's (B.S.R.A.) work suggests that this is not likely to be less than $(1{\cdot}2 + 3{\cdot}5/L^{\frac{1}{3}})$ and will be independent of Reynolds number. Corresponding to the 3·5 constant, Professor Aertssen's data give an average value of 3·18 for the sandblasted ship, 3·44 for the new ship, and 4·45 for the clean ship (August 1954). There is, of course, a question as to the intrinsic accuracy of these results, but in any case their mean is not far from the 3·5 value deduced from the B.S.R.A. data. This value presumes that the ship surface, although apparently commercially smooth, is actually technically rough. In Professor Aertssen's earlier work his data seemed to show a Reynolds number effect. I wonder if he now still feels the data are in fact influenced by Reynolds number?

So far as fouling influence is concerned a recent re-examination of the very extensive tests carried out by Hiraga on the old Japanese destroyer *Yadachi* clearly shows that fouling resistance increases directly as time out of dock, beyond a certain initial time out of dock, depending upon the surface deterioration before painting. The worse this deterioration the higher of course will be the added resistance, but curiously enough painting does not appear to have any effect until the fouling is actually rougher than the surface deterioration. Actually, if the slope of the ultimate fouling resistance line is extrapolated back to zero days out of dock it is found to start from the original smooth hull condition. The *Yudachi* tests, already nearly thirty years old, certainly have lessons very valid today. They clearly show, for example, as Professor Aertssen's tests also show, that the original smoothness cannot be regained by painting but only by removing the surface deterioration as, for example, by sandblasting. The *Yudachi* data do not show the increase varying as some frictional power of the time out of dock. The actual resistances increase itself is, at constant speed, linear with time. As the *Yudachi* data are explicit, I feel that they must be respected. In the absence of the *Yudachi* my own experience suggests an Admiralty constant or power loss varying as the square root of the days out of dock. Further data are undoubtedly required to decide the issue, but in any case surface deterioration is a real thing and can take place initially very rapidly. Painting at more frequent intervals than usual may slow down the rate of deterioration just as Professor Aertssen has shown. I believe that this probably explains the *Yudachi* contradiction.

In connection with the *Lubumbashi* trials Professor Aertssen states that he derives his average speeds by applying the mean of means method both to the sighted speeds over the ground and to the pitot speeds. This method is not correct. The mean of means is only accurately applied under a linearly varying tidal condition, the basic idea being that by taking the mean of the first and third runs this is very nearly simultaneous in time with the second run and can be justifiably averaged with it. The pitot readings are not subject to such tidal influence. All results carry equal weight and should therefore be simply averaged.

One point in conclusion. Professor Aertssen states that for the last trials a new propeller was fitted. As this was slightly but I suppose deliberately, different from the original it would undoubtedly add to the value of an already splendidly informative paper if Professor Aertssen could include a plan of a new propeller in his reply. If the new propeller is a proprietary design the comparative issues raised by Professor Aertssen may not be so clear cut as they now appear to be.

Author's Reply

In the first place I must say that I was very pleased to obtain from Monsieur Dufour, General Manager of the Compagnie Maritime Belge, some more statistical information on the performance of the sandblasted *Lubumbashi*, which I think is conclusive in this matter.

From Table VII it may be concluded that the *Lubumbashi*, after sandblasting, was refreshed so far that her performance was again that of the newly-built ship. It is perhaps somewhat hazardous to conclude from a comparison of two single voyages, the maiden voyage of this ship and the voyage taking place five years later, immediately after sandblasting, two voyages with quite different types of weather, that the hull surface came back to its newly-built condition. But, as Mr. Dufour emphasizes, the crossing New York–Rotterdam, which was part of the first voyage after sandblasting the hull, took place in a following wind and sea, 4 to 5 in the Beaufort scale, which represents an ideal sea state without gain or loss of speed. Now the Admiralty coefficient C_a for that crossing is exactly the same as C_a for the newly-built ship in still air. That means that the ship has regained her original performance as when newly built.

The remarks of Professor Telfer concerning the information on roughness and minimum ship specific frictional resistance to be gained from pitot traverses are to the point. The hull surface of the *Lubumbashi*, as well in the newly-built condition as five years later when she was sandblasted, was remarkably smooth: this is shown by the pitot tube tests as well as by the propulsion data. But there remained indeed a certain roughness on this hull as compared with the hydraulically smooth surface. No effect of Reynolds number can be deduced from the last measured mile trials. This Reynolds number is 3×10^8 for pitot log P_1 against 5×10^8 for pitot log P_2, while the computed frictional resistance data from the traverses are practically the same for both logs: 0·00174 for pitot log P_1 against 0·00171 for pitot log P_2.

It is difficult to say whether there is an appreciable effect of the roughness of the seams on the traverses of the pitot tubes. There must be some effect of this roughness, as the traverse does not give the local frictional resistance but integrates the resistance over the whole of the surface from stem to the place where the pitot tube is installed. A great number of pitot tubes distributed around the hull must certainly give a more reliable figure of the overall smoothness. The traverses indeed are a good means of comparison of hull surface state and mainly therefore they were used in this work.

Professor Telfer's comments on the fouling and the deterioration of the hull surface are welcome. The effect of surface deterioration, by corrosion essentially, and further the effect of fouling, by barnacles and sea grass, were treated somewhat concisely in Section 6. And I am glad that Professor Telfer and after him Dr. Todd have clarified our ideas on these sources of resistance increase, which are really separate but which converge to the same effect. In the beginning of a ship's life, the effect of fouling is important, some 6 per cent for the first three months' service, but later on this effect goes down; it is 9 per cent after six months and 12 per cent after a year's service. This is roughly 1 per cent for a month's service. When after that year the ship is dry-docked, cleaned and painted, the surface does not resume its newly-built condition: there remains an unevenness which is due partly to corrosion, partly to broken paint coats, and partly to imperfect cleaning. Hence the resistance is increased as compared to the resistance of the newly-built ship, and that is what is called here the effect of deterioration of surface. When now, let us say after the second year the ship is dry-docked, cleaned, and painted again, the hull surface does not come back to its condition after the first dry-docking and painting, but there is again an increase of resistance, due to further deterioration of the surface. The rate of increase of resistance due to the deterioration that second year, however, will be smaller than the increase of the first year; we learned that peculiarity from Kempf's work on the effect of roughnesses: adding a same amount of deterioration to a hull surface does not double the increase of resistance. This explains the parabolic form of the curve of Fig. 14.

On the other hand, once the hull surface deteriorated, the effect of fouling on ship's resistance will be less than for the newly-built ship. And this effect will be very small when, as on the *Lubumbashi* after five years' service, the hull roughened so far that sandblasting could no longer be avoided.

I thank Dr. Todd for having brought out more clearly than I did in the paper, the relative importance of deterioration and fouling of the hull surface. His explanation gives the true meaning of Fig. 14.

It is a disturbing conclusion that after sandblasting the measured roughness was still three times as great as on the new ship and that the power absorbed was the same. Dr. Todd draws attention to the work of Mr. C. J. Posey on the shape of roughness and its effect on resistance. This work is to be compared with the work of Allan and Cutland on the same subject. It is confirmed that the shape of the asperities of a roughness is perhaps more important than the height of these asperities.

It is very interesting to hear from Mr. Canham that it is suggested that, in view of the mean apparent amplitude of a frequency of 1/2 per inch of the sandblasted hull measuring somewhat as 8,000 microin., this ship must have a greater resistance than for the hydrodynamically smooth condition. But this does not mean that the sandblasted hull is worse than the hull of the newly-built ship. And Mr. Canham. from the measured mile trial data of the newly-built *Lubumbashi*, deduces that there is evidence that the new ship was not hydrodynamically smooth.

Mr. Canham, as well as Professor Telfer, Mr. Macduff, and Mr. Jourdain, insist upon more knowledge on the new propeller. There must be a misunderstanding. The propeller was renewed after two years' service, and at the moment of the sandblasting was more than two years on the ship and was left in its place. It was a Zeise propeller, the design of which is not completely known.

It is very difficult to give a definite answer to the question of Mr. Macduff concerning the desirable economic interval between sandblasting operations on a ship. This interval certainly must depend upon the route followed normally by the ship. Southern routes are more fouling than northern routes and conseqeuntly require a more frequent sandblasting. For a ship sailing frequently in warm waters the normal interval must be five years.

The economic side of the question has been explained clearly by Mr. Dufour, general manager of the shipping company, where in his contribution he said that, calculated over the whole of the period where sandblasting from experience must have a decreasing effect on power—for this type of ship and this route about five years—the benefit of fuel consumption should largely offset the cost of sandblasting.

Concerning the wake in the vicinity of the propeller, it is without doubt that much could be learned from a study of the wake distribution in the vicinity of the propeller. Many pitot tubes, however, are needed then, and Mr. Macduff can believe me when I tell him that it takes a lot of trouble to install a pair of such instruments on a ship as was done on the *Lubumbashi*. The principal effect of fouling or deterioration, which represents an increase of roughness, is a resistance increase. But a certain amount of power can be gained from an increasing hull efficiency due to the increase of wake. Finally, that increase of roughness results in an increase of power. We have, however, still much to learn about a propeller working behind a ship, its efficiency in open water, and its scale effect, as well as about thrust deduction and wake.

Mr. Macduff fears an accelerated hull surface deterioration and is interested about further data from the voyages of this ship. In his contribution Mr. Dufour has fortunately given the answer to that question. It can be read there that, from an analysis of the voyage data, it is concluded that, within an interval of six months after sandblasting, the increase of power due to fouling is 6 per cent. That increase of power was 9 per cent for the newly-built ship. It is known that the season of the year, the temperature, and time spent in harbour have an influence, but from these figures of 6 and 9 per cent it can be concluded that there is no risk for the sandblasted ship fouling more quickly than a well-painted newly-built ship.

Mr. Simpson questions the thickness of plating after the first five years of the life of this ship. Corrosion cavities of a depth of some $0 \cdot 1$ in. and a surface of 2×2 in. were spread over the bottom. These cavities remained after sandblasting.

I fully agree with Mr. Franklin where he emphasizes that sandblasting gives the underwater surface a new lease of life and is a good protection against further corrosion. But one thing is curious: the further rate of increase of power would have been less were the ship not sandblasted. The rate of increase is worse on the smooth surface of a newly-built or, what is practically the same, on a sandblasted ship than on a very fouled and deteriorated ship. The increase of power after six months was 9 per cent on the newly-built *Lubumbashi* and 6 per cent on the sandblasted ship five years later; it was no more than 3 or 4 per cent after eight months' service when the hull surface had deteriorated by three years' service.

Mr. Wellman questions on the number of photographs. It must be said that 18 photographs were taken before, and 22 photographs after sandblasting, whereas 100 profiles were worked out in the crude condition and 200 profiles in the sandblasted condition. The chosen profiles represent the mean surface condition for both states of the hull.

I was very pleased by the remarks of Mr. Webb on the data of the New York voyage prior to the sandblasting. This gives me the opportunity to mention the high quality of these data which came indeed from the staff of the *Lubumbashi*. Fortunately, two series of diagrams were taken and it can be said that the data are in line with the whole of the data taken with torsionmeter, thrustmeter, and pitot log.

I thank Mr. Murray for having drawn attention to the factor t of Allan and Cutland which certainly decreases after sandblasting. That decrease must have, I agree, a diminishing effect on frictional resistance.

It was indeed gratifying to hear from Mr. Cook that this whole work might have been of some use, and that it is honoured by inclusion in the TRANSACTIONS of both Institutions.