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TOWARDS WEAR REDUCTION IN ENGINES USING RESIDUAL FUEL

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Although this paper describes an investigation into the causes of wear in direct drive marine Diesel engines, it is equally applicable to medium speed four-cycle engines. For reasons of convenience and cost the work was carried out on two Crossley H.H.9 235 × 406 mm, (9·25 × 16 in) horizontal four-cycle trunk piston open crankcase mono-cylinder engines. The programme was sponsored by the British Ship Research Association, and took place between 1959 and 1968.

The operating factors investigated were jacket temperature, the comparison of a lubricating oil of high alkalinity as compared with a straight mineral oil, fuel composition and the degree of centrifuging of the fuel.

Trial of different carefully selected liner materials was made, as well as liners banded over the upper portion with hard surface materials. Ring materials included unhardened and hardened plain rings and inlaid rings sprayed with molybdenum and chromium.

Results showed that a high jacket temperature was important, irrespective of whether or not an alkaline oil was employed.

The sulphur content of the fuel had usually the most influence on wear but Conradson carbon value and ash content could also be important. Fifteen fuels of widely ranging composition were tested.

Centrifuging only reduced wear in the case of one especially dirty fuel out of seven fuels regarded as typical of those bunkered in representative areas of the world.

High basicity additive lubricating oil reduced liner wear to about one tenth and top ring wear to about one sixth of that measured using a straight oil.

In comparison with the standard build consisting of a vanadium titanium liner and unhardened rings, the following liner and ring combinations gave useful wear reductions:

hardened top ring in standard liner;
austenitic liner with unhardened rings;
2 per cent nickel/copper liner and unhardened rings;
molybdenum banded liner, especially when used with hardened top ring.

An outline of present rates of wear of liners, rings and ring grooves in direct drive and medium speed engines is given, together with suggestions for improvement arising out of the investigation.

INTRODUCTION

Some ten years ago, when the investigation into the causes of wear in engines running on residual fuel, which is the subject of this paper, had only just begun, the situation as regards liner and ring wear in the then mostly two-cycle direct drive engines was much worse than it is now. The main improvement in liner and ring wear since then has undoubtedly been brought about by the general acceptance and use of cylinder oils of high basicity which at that time were comparatively new innovations.

The geared medium speed engine had also at that time only just begun to win some acceptance and it was not without some surprise that it was found that these engines would run on residual fuels at b.m.e.p.'s of 13·8 bar (200 lb/in²) at some 500 rev/min without difficulty, in spite of the fact that they were trunk piston engines. However, a lubricating oil of suitable alkalinity in the crankcase was essential.

Nevertheless, an examination of the present wear rates of the direct drive two-cycle engines and the geared four-cycle medium speed engines shows that there is still room for further reduction, in spite of some improvement by better liner materials along with the use of oils of sufficient basicity.

Table 1 gives such figures, and also includes those for the medium speed engines running on marine Diesel fuel. These reflect the gain achieved by using a distillate fuel or near distillate fuel.

Examination of the liner wear figures makes it clear that the direct drive engines do not generally attain the figure of 0·030 to 0·050 mm (0·0013 to 0·002 in) per 1000 hours diametral wear which is necessary for a liner to last the life of a ship. (Taken as 20 years with running hours 5 to 8000/year, and assuming also that in both direct drive and medium speed engines liner wear can be allowed up to 0·5 per cent of the bore, i.e. 5 mm (0·2 in) in a 1000 mm bore, and 2·5 mm (0·1 in) in a 500 mm bore). Liner wear rates on the medium speed engines are just able to fulfill such a requirement. The above assumes that liner life is not ended by thermal cracking or water side attack which does still occur too frequently.

Top ring peripheral wear, in the direct drive engine is about ten times the liner wear rate. Hence in one year's operation the ring gap has increased by 15 to 24 mm (0·6 to 0·96 in), and so the top ring must be changed yearly, or the blast of high temperature gas past this increased gap will become excessive and harmful. Ring breakage is also troublesome in direct drive engines and yearly piston examinations are desirable. Medium speed

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TABLE I—GENERAL WEAR RATES AND MAINTENANCE PERIODS IN 2 CYCLE DIRECT DRIVE AND 4 CYCLE MEDIUM SPEED ENGINES

Component wear	Direct drive 2 cycle		Medium speed 4 cycle			
	Using bunker fuels at around 1500 sec Red. 1 at 100°F		Using bunker fuels 200–1500 sec Red. 1 at 100°F		Using marine Diesel fuel	
	in	mm	in	mm	in	mm
Liner wear on diameter per 1000 hours	0·002 to 0·006	0·05 to 0·15	0·0002 to 0·0008	0·005 to 0·02	below 0·0002	below 0·005
			chrome periphery			
Top ring radial wear per 1000 hours	0·010 to 0·030	0·25 to 0·75	0·001 to 0·002	0·025 to 0·05	below 0·001	below 0·025
	plain groove		*cast iron insert or steel crown*			
Top ring groove wear per 1000 hours	0·002*	0·05*	0·0005 to 0·001	0·012 to 0·025	below 0·0005	below 0·012
	chromed lower side					
	0·0008	0·02				
	chromed both sides					
	0·00025	0·0063				
Piston withdrawal period, hours (top ring usually changed at this time)	7000		12 000		15 000	
Exhaust valve reconditioning period, hours	3000		2000 to 6000		above 6000	

* Varies with engine type.

engines do not suffer from this trouble. The peripheral wear rate of the top ring in medium speed engines is also at about ten times the liner wear rate, and so in two years operation the ring gap increases by 3·7 to 6·0 mm (0·150 to 0·240 in), and thus piston withdrawals can be every two years.

The table shows that the top ring groove wear is high in direct drive engines without resort to some kind of groove arming such as chrome plating of the sides. This is claimed to markedly increase the life of the piston between regrooving operations from some 20 000 to some 40 000 hours. However, it is often piston crown burning that limits piston life and not the ring groove wear. The medium speed engine does not suffer from such piston crown burning, and so far it has not been necessary to arm the grooves by chrome plating. Piston life is around 20 000 hours before regrooving or crown renewal in two part pistons with steel or iron crowns becomes necessary.

The direct drive engines which use exhaust valves usually recondition their valves every 2000 to 3000 hours. Trouble in medium speed engines can occur in half this time, on the other hand they may run for as long as 6000 hours. The longer valve life achieved with marine Diesel fuel reflects the beneficial effect of eliminating sodium and vanadium from the fuel.

In medium speed engines it appears that main and big end bearings may require replacement after 30 000 to 50 000 hours, whereas the direct drive engines may go their whole life without replacement of crankshaft or crosshead bearings, except in a few individual cylinders.

Cracked cylinder covers are not related to wear but are a trouble more particularly in direct drive engines, although they also occur in medium speed engines.

Wear of the injection pump plungers and nozzles will not be considered in this paper, although without doubt nozzle life could be extended with advantage.

The conclusions that may be drawn from the wear table are that it is radial ring wear that is most in need of reduction in direct drive engines. To this must be added ring breakage, which is in some cases caused by a high rate of ring and groove side wear. Next to ring and groove wear comes liner wear, which still needs further reduction in many direct drive engines if liners are to be expected to last the life of the ship.

In the case of medium speed engines, prolongation of exhaust valve seat life between reconditioning is the main need.

The investigation carried out at Shoreham was concerned in the main only with ring and liner wear.

THE INVESTIGATION

Engine Details

The tests were run on a Crossley H.H.9 single cylinder horizontal four stroke compression ignition engine of 235 mm ($9\frac{1}{4}$ in) bore and 406 mm (16 in) stroke, rated at 28·4 kW (38 bhp) 5·87 bar (85 lb/in^2 b.m.e.p.) at 330 rev/min. The engine was lubricated by a spot feed total loss system with separate feeds to the piston and bearings. The combustion chamber was a clerestory type with the inlet valve vertically over the exhaust valve, and with a compression ratio of 15·5:1.

The engine was equipped with a Crossley timed jerk fuel injection pump with spill valve control, and C.A.V. T-size injector to which water cooling had been added to the injector nozzle tip, as is normal practice when running on heated residual type fuels.

A special sand-cast vanadium-titanium cylinder liner and sand-cast piston rings were used for this work, in order that the material of these components should be as representative as possible of large marine engine practice. Since the structure of the material is related to the cooling time of the casting, the silicon content of the liner material was adjusted to compensate as far as possible for the faster rate of cooling of the relatively small liner castings used for this engine.

The engine was operated at a test load of 4·14 bar (60 lb/in^2) b.m.e.p. at 330 rev/min and a jacket coolant outlet temperature of 70°C.

Fuel System

A fuel system generally representative of marine practice was employed. Two De Laval type 4000 centrifuges were arranged in series: the first acting as a purifier and the second as a clarifier. The fuel was supplied to the injector pump at a temperature of 90°C, and the high-pressure pipe was heated to give a temperature of 120°C at the injector. Fuel consumption was measured by weighing. The effect of residual-fuel temperature on viscosity and performance is shown in Fig. 1, which shows that so long as the residual fuel is heated until its viscosity is similar to that of gas oil, it gives a similar performance in this engine.

Fuel

The reference fuel was chosen to have a viscosity of 370cSt at 37·8°C (1500 sec Red. no. 1 at 100°F), which is a generally representative figure for bunker fuels. Table II—fuels 1, 2 and

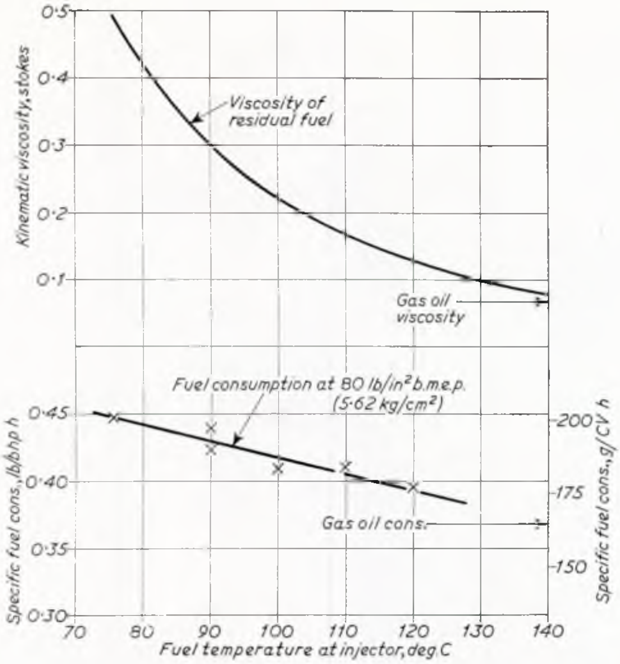

FIG. 1—*Effect of fuel temperature on fuel viscosity and engine performance*

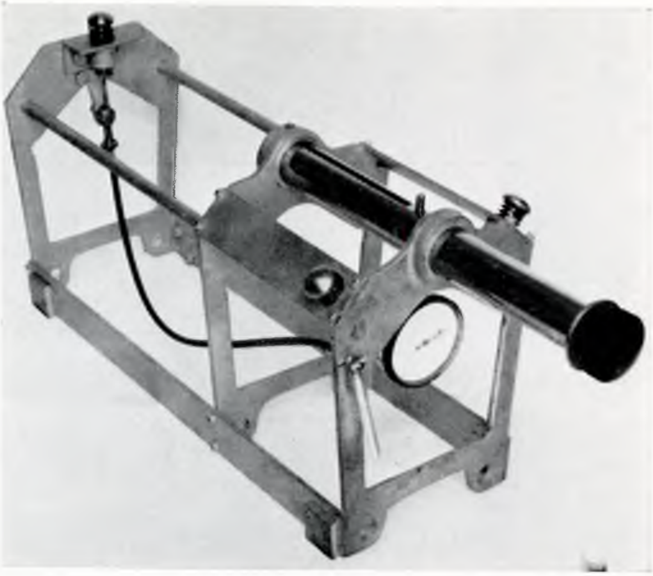

FIG. 2—*Instrument used for measurement of radial wear*

3—gives the specification for three batches of this fuel, and shows that different batches have not changed significantly in this respect throughout the programme. The sulphur content lay between 3·1 and 3·5 per cent for all but the early work.

Lubricating Oil

The straight oil used at first was Shell Trochus J.37 (C.I.A.), but since it later became unobtainable the Shell Company supplied a matching oil ref: R.445. These oils were 30 grade. The high basicity oil was Shell Alexia 40 (i.e. 40 grade) having a TBN of 70.

Wear Measurement

When build changes were involved (as was the case when comparing ring and liner combinations), it was necessary to rely on direct measurement. The liner was gauged with a dial-type comparator, but a special instrument was also used to measure the radial wear at eight stations round the liner (see Figs. 2, 3 and 4). Ring wear was assessed by weighing.

For wear comparisons that did not involve changes of engine build (for example, changes in fuel, lubricating oil, and jacket temperature), the rate of wear was assessed by measuring the iron content of the used piston lubricating oil discharged as 'sludge' from the open end of the cylinder bore by the total loss piston lubrication system.

In common with the well established radio-active tracer wear measurement technique, experience with this test procedure demonstrated that iron was discharged into the used piston lubricating oil in direct proportion to the rate of cylinder bore and piston ring wear.

However, since the quantity of sludge recovered varied considerably from build to build, it was necessary, before placing any reliance on the iron-recovery method, to confirm that the iron content in the sludge remained a constant proportion regardless of the amount of sludge recovered. In other words, it was necessary to confirm that the total iron worn off the rings and liner was evenly distributed throughout the oil supplied to the cylinder, regardless of how much of this supply was passed inwards and out of the exhaust valve, and how much was passed outwards and collected from the mouth of the cylinder for iron-recovery assessment. Figure 5 shows a plot of many tests under standard conditions of engine injection with sludge-recovery percentages varying from 20 to 60 per cent. These confirm such a direct relationship. Hence iron-recovery wear figures are all compared in the results that follow after correction to 100 per cent recovery. However, since the liner

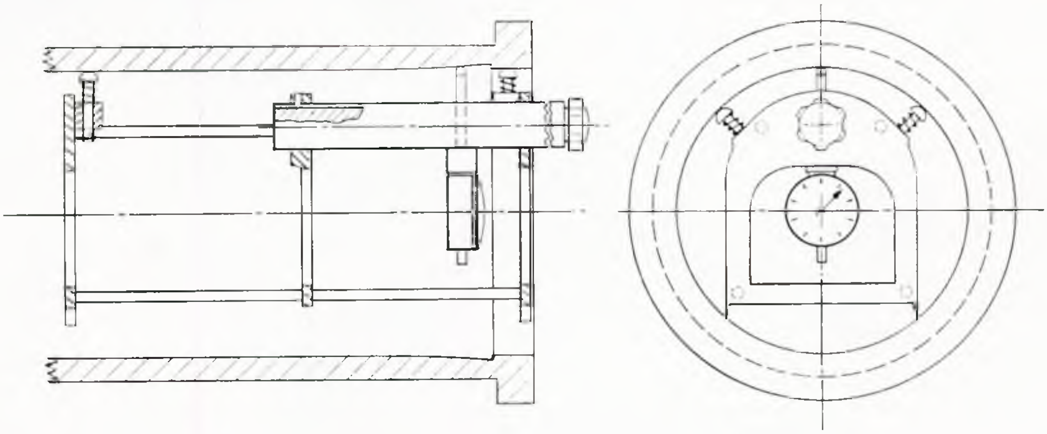

FIG. 3—*Instrument for measurement of radial wear in use*

TABLE II—FUEL-INSPECTION DATA

Fuel reference no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Designation	Standard 1500 sec	Standard 1500 sec	Standard 1500 sec	Nigerian high-ash low-sulphur	Ashless heavy	Western DR71A	Gas oil r.v. (road vehicle)	High-sulphur gas oil	Medium high-viscosity 2740 sec	Middle East	Far East	Western	Western	Las Palmas	Doxford
Supplied by	BP	BP	BP	BP	BP	Shell	Shell Mex and BP	Shell	BP	mv *Radnorshire*	mv *Paparoa*	mv *Ruahine*	Ellerman Lines	mv *Athlone Castle*	Doxford
Specific gravity at 60°F/60°F	0·952	0·957	0·954	0·979	0·944	0·953	0·835 0·840	0·926	0·965	0·944	0·949	0·958	0·950	0·976	0·982
Flash point (PM closed), °F	210	360	240	225	245	216		184	240	214	225	186	186	188	225
Calorific value, Btu/lb	18 360	18 350	18 400	18 530	18 500				18 280						
Total sulphur content, per cent wt	3·5	3·08	3·37	0·96	3·61	2·6	0·5	2·91	3·44	2·81	2·80	2·58	2·17	2·75	2·97
Kinematic viscosity at 100°F, cs	368·3	356·3		376	401–405				677	266·2	196	369·4	154·6	740·7	890·1
Viscosity Red. No 1 sec at 100°F	1500	1440	1420	1520	1622–1640	1680		30 @ 122°F	2740	1080	795	1500	625	3000	3600
Pour point, °F	10	30	55		50	40		20	35		70			25	
Carbon residue (Conradson), per cent wt	11·1	10·3	9·4	7·9	3·05	8·5	0·1	0·20	11·3	8·9	7·5	11·6	9·14	13·0	13·2
Asphaltenes, per cent wt	3·3	1·54	2·52	1·3	0·05	6·3			5·0	3·29	2·0	7·77	5·61	7·7	6·05
Acidity, mg KOH/g	0·21	0·33	0·3		0·06				0·32		0·23			0·86	
Ash content 550°C, per cent wt	0·039	0·042	0·05	0·096	0·001	0·06			0·083	0·030	0·031	0·128	0·068	0·137	0·132
Water content, per cent vol	trace	0·1	0·05	trace	trace				nil	nil	nil	nil	0·8	3·8	0·4
Water and sediment, per cent vol	trace	—	—	0·2	0·01				0·1		0·1			4·8	
Sediment by extraction, per cent wt	0·01	0·01	0·01	0·03											
Vanadium content, ppm	72		198	48					107	76	41	412	221	406	86

See conversion table on p. 410.

and rings were measured at each 100 hours sandwich test, it enabled a check computation to be made to see if the total sum of the iron figures corrected to 100 per cent recovery, agreed with the total weighed ring wear plus calculated liner wear.

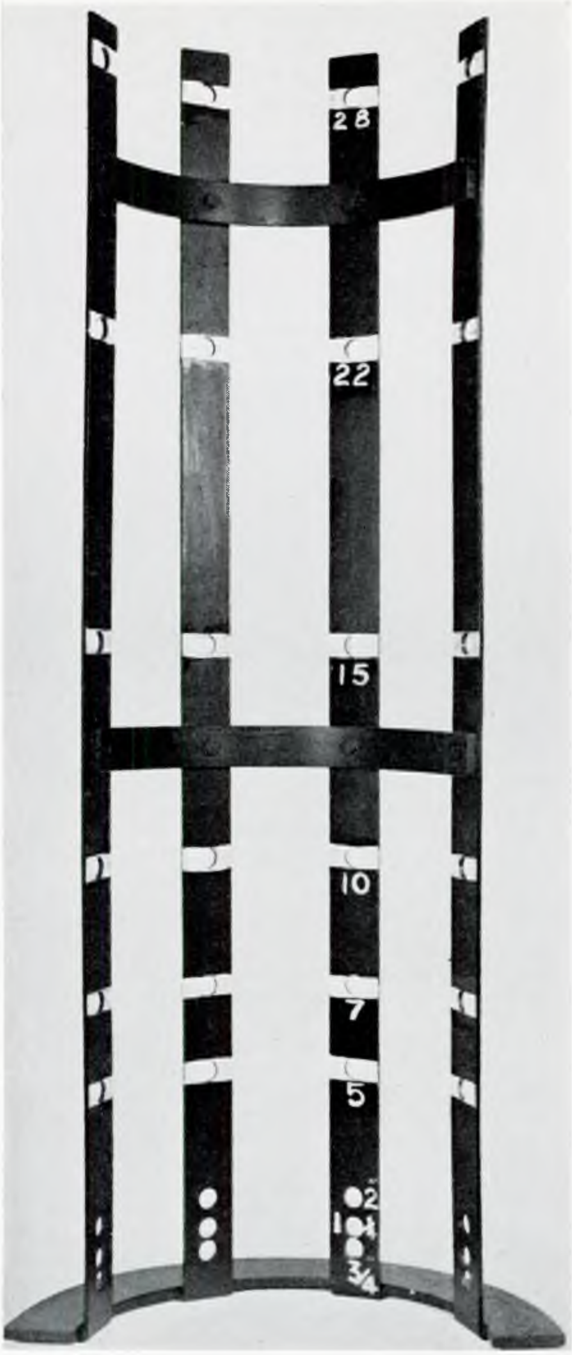

FIG. 4—*Jig for mercer gauging positions for diametral wear measurement*

Such an iron balance over nearly 1000 hours of running is shown in Table III and agreed well with iron-recovery figures.

As a result of extensive exploratory work with the iron-recovery method, wear comparisons between two variables were made using a sandwich test procedure, shown in Fig. 6, which involved runs of approximately 100-hour duration. After rebuild the engine was run in for some 24 hours.

A 24 hour test was then made using a first set of conditions, which were changed for another set during the following 24 hours. Finally a check run was made with the original set in the final 24 hours. After each sandwich test the piston was removed and cleaned before the next test. One new ring was fitted in the lowest groove (No. 1 ring), and all the used rings were moved up one groove, the top ring (No. 4) being discarded.

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The sulphur content of the fuel had usually the most influence on wear but Conradson carbon value and ash content could also be important. Fifteen fuels of widely ranging composition were tested.

Centrifuging only reduced wear in the case of one especially dirty fuel out of seven fuels regarded as typical of those bunkered in representative areas of the world.

High basicity additive lubricating oil reduced liner wear to about one tenth and top ring wear to about one sixth of that measured using a straight oil.

In comparison with the standard build consisting of a vanadium titanium liner and unhardened rings, the following liner and ring combinations gave useful wear reductions:

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austenitic liner with unhardened rings;
2 per cent nickel/copper liner and unhardened rings;
molybdenum banded liner, especially when used with hardened top ring.

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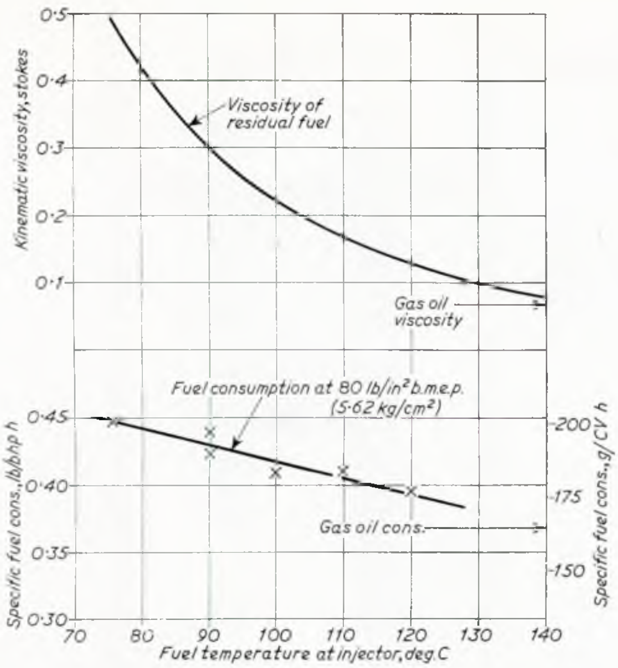

FIG. 1—*Effect of fuel temperature on fuel viscosity and engine performance*

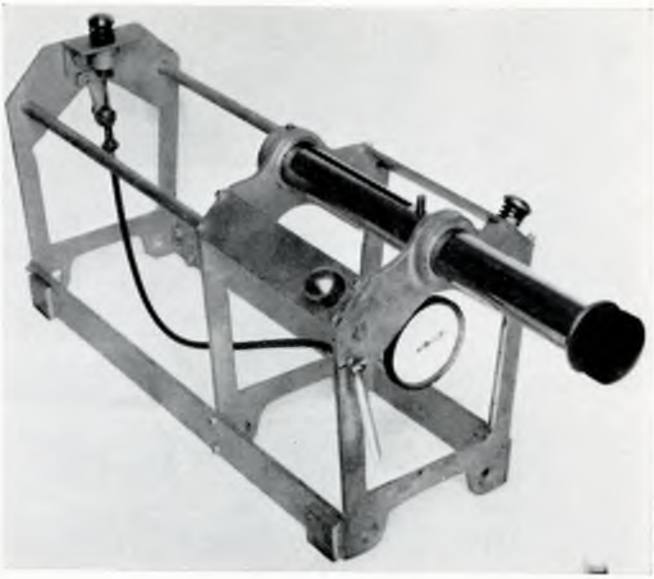

FIG. 2—*Instrument used for measurement of radial wear*

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For wear comparisons that did not involve changes of engine build (for example, changes in fuel, lubricating oil, and jacket temperature), the rate of wear was assessed by measuring the iron content of the used piston lubricating oil discharged as 'sludge' from the open end of the cylinder bore by the total loss piston lubrication system.

In common with the well established radio-active tracer wear measurement technique, experience with this test procedure demonstrated that iron was discharged into the used piston lubricating oil in direct proportion to the rate of cylinder bore and piston ring wear.

However, since the quantity of sludge recovered varied considerably from build to build, it was necessary, before placing any reliance on the iron-recovery method, to confirm that the iron content in the sludge remained a constant proportion regardless of the amount of sludge recovered. In other words, it was necessary to confirm that the total iron worn off the rings and liner was evenly distributed throughout the oil supplied to the cylinder, regardless of how much of this supply was passed inwards and out of the exhaust valve, and how much was passed outwards and collected from the mouth of the cylinder for iron-recovery assessment. Figure 5 shows a plot of many tests under standard conditions of engine injection with sludge-recovery percentages varying from 20 to 60 per cent. These confirm such a direct relationship. Hence iron-recovery wear figures are all compared in the results that follow after correction to 100 per cent recovery. However, since the liner

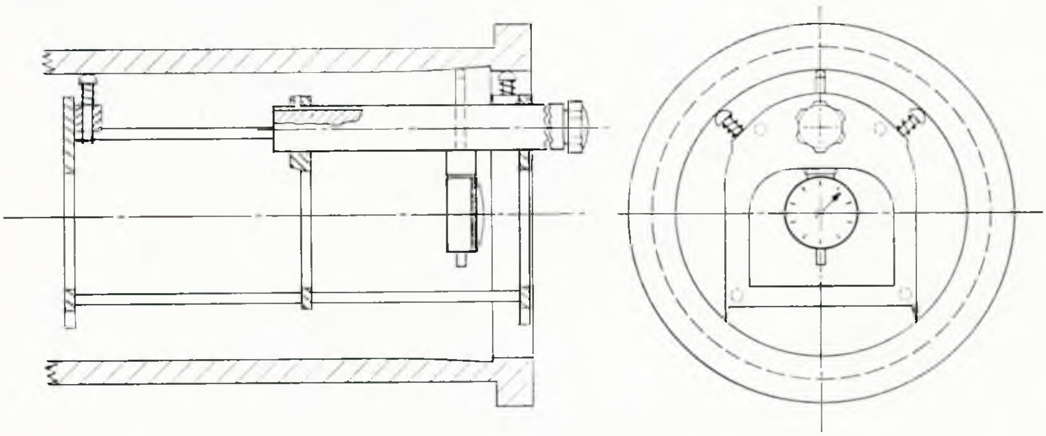

FIG. 3—*Instrument for measurement of radial wear in use*

TABLE II—FUEL-INSPECTION DATA

Fuel reference no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Designation	Standard 1500 sec	Standard 1500 sec	Standard 1500 sec	Nigerian high-ash low-sulphur	Ashless heavy	Western DR71A	Gas oil r.v. (road vehicle)	High-sulphur gas oil	Medium high-viscosity 2740 sec	Middle East	Far East	Western	Western	Las Palmas	Doxford
Supplied by	**BP**	**BP**	**BP**	**BP**	**BP**	Shell	Shell Mex and BP	Shell	BP	mv *Radnorshire*	mv *Paparoa*	mv *Ruahine*	Ellerman Lines	mv *Athlone Castle*	Doxford
Specific gravity at 60°F/60°F$_1$	0·952	0·957	0·954	0·979	0·944	0·953	0·835 0·840	0·926	0·965	0·944	0·949	0·958	0·950	0·976	0·982
Flash point (PM closed), °F	210	360	240	225	245	216		184	240	214	225	186	186	188	225
Calorific value, Btu/lb	18 360	18 350	18 400	18 530	18 500				18 280						
Total sulphur content, per cent wt	3·5	3·08	3·37	0·96	3·61	2·6	0·5	2·91	3·44	2·81	2·80	2·58	2·17	2·75	2·97
Kinematic viscosity at 100°F, cs	368·3	356·3		376	401–405				677	266·2	196	369·4	154·6	740·7	890·1
Viscosity Red. No 1 sec at 100°F	1500	1440	1420	1520	1622–1640	1680		30 @ 122°F	2740	1080	795	1500	625	3000	3600
Pour point, °F	10	30	55		50	40		20	35		70			25	
Carbon residue (Conradson), per cent wt	11·1	10·3	9·4	7·9	3·05	8·5	0·1	0·20	11·3	8·9	7·5	11·6	9·14	13·0	13·2
Asphaltenes, per cent wt	3·3	1·54	2·52	1·3	0·05	6·3			5·0	3·29	2·0	7·77	5·61	7·7	6·05
Acidity, mg KOH/g	0·21	0·33	0·3		0·06				0·32		0·23			0·86	
Ash content 550°C, per cent wt	0·039	0·042	0·05	0·096	0·001	0·06			0·083	0·030	0·031	0·128	0·068	0·137	0·132
Water content, per cent vol	trace	0·1	0·05	trace	trace				nil	nil	nil	nil	0·8	3·8	0·4
Water and sediment, per cent vol	trace	—	—	0·2	0·01				0·1		0·1			4·8	
Sediment by extraction, per cent wt	0·01	0·01	0·01	0·03											
Vanadium content, ppm	72		198	48					107	76	41	412	221	406	86

See conversion table on p. 410.

and rings were measured at each 100 hours sandwich test, it enabled a check computation to be made to see if the total sum of the iron figures corrected to 100 per cent recovery, agreed with the total weighed ring wear plus calculated liner wear.

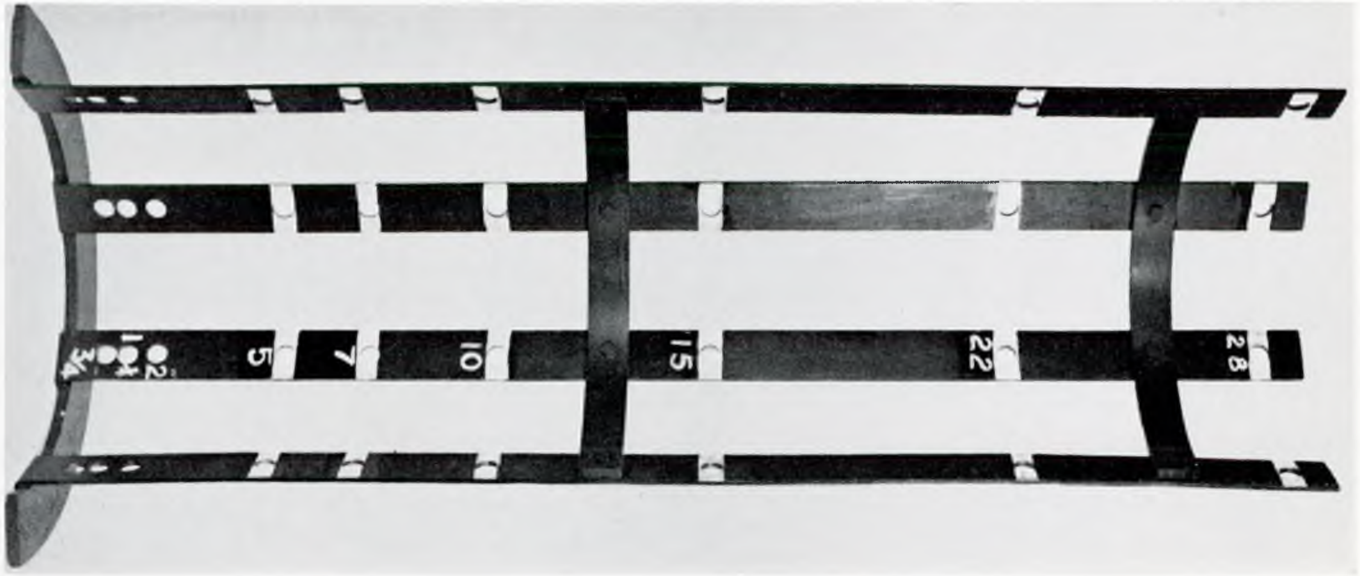

FIG. 4—*Jig for mercer gauging positions for diametral wear measurement*

Such an iron balance over nearly 1000 hours of running is shown in Table III and agreed well with iron-recovery figures.

As a result of extensive exploratory work with the iron-recovery method, wear comparisons between two variables were made using a sandwich test procedure, shown in Fig. 6, which involved runs of approximately 100-hour duration. After rebuild the engine was run in for some 24 hours.

A 24 hour test was then made using a first set of conditions, which were changed for another set during the following 24 hours. Finally a check run was made with the original set in the final 24 hours. After each sandwich test the piston was removed and cleaned before the next test. One new ring was fitted in the lowest groove (No. 1 ring), and all the used rings were moved up one groove, the top ring (No. 4) being discarded.

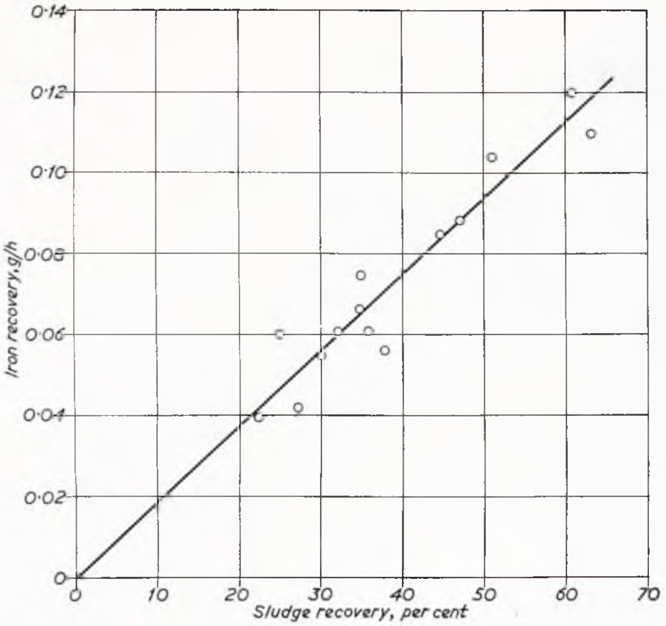

FIG. 5—*Relationship between iron and sludge recovery 'standard' conditions: 70°C coolant*

TABLE III—IRON BALANCE. TESTS 13 TO 46

Total liner life 914 h

Summation of loss, g, from:	
Top rings	43·68
2nd rings	11·30
3rd rings	9·34
4th rings	9·36
Total loss from rings	74
Total loss from liner, based on estimate from liner-wear profile	124
Total loss from ring and liner	198 g
Summation of $\frac{\text{iron recovered}}{\text{per cent of sludge recovered}}$ × 100 for all tests	192 g
Discrepancy in balance = 6 g = 3 per cent	

TEST RESULTS

Influence of Jacket Temperature

To compare the liner temperature distribution in the Crossley engine with that in a marine engine, measurements were made using eleven traversing thermocouples installed along the length of the cylinder. The results at various jacket temperatures are shown in Fig. 7 and the Doxford-engine temperatures compared at similar fractions of the top-ring travel. It will be clear that temperatures on the Crossley engine are similar to those of the Doxford engine when the jacket temperature is 30°C. The Doxford-engine measurements have been described by Millington(1).

A series of sandwich tests was then run in which the effect of coolant jacket temperature on wear was assessed. The results of the first of these tests are shown plotted in Fig. 6 from which it may be seen that the first 25 hours or so of the test were devoted to running-in the piston ring pack, the second period of the test to confirming the wear rate at the standard test operating conditions, the third to establishing the wear with the jacket temperature reduced to 30°C, and the final period to checking back on the wear rate at the standard jacket temperature of 70°C. Ignoring the running-in period, which was of course carried out under progressively increasing engine loads, iron recovery figures of 0·06 and 0·075 g/h were recorded at the 70°C jacket condition, and 0·138 g/h at 30°C. Applying the 100 per cent sludge recovery correction to these figures gave results of 0·191 and 0·214 g/h for 70°C and 0·353 for 30°C—a very significant increase at the lower temperature. Similar tests in this series yielded corrected iron recovery values of 0·213 g/h for a 50°C jacket temperature, and 0·133 g/h at 95°C, i.e.

Jacket Temperature °C	*Indicated Wear Rate g Fe/h*
30	0·353
50	0·213
70	0·192
95	0·133

These wear rates are shown plotted in Fig. 8 against both coolant temperature and bore surface temperature at the top of the piston ring travel.

The tests showed a remarkable diminution in rate of wear as the temperature of the liner was increased by raising the coolant temperature, suggesting that the liner was normally

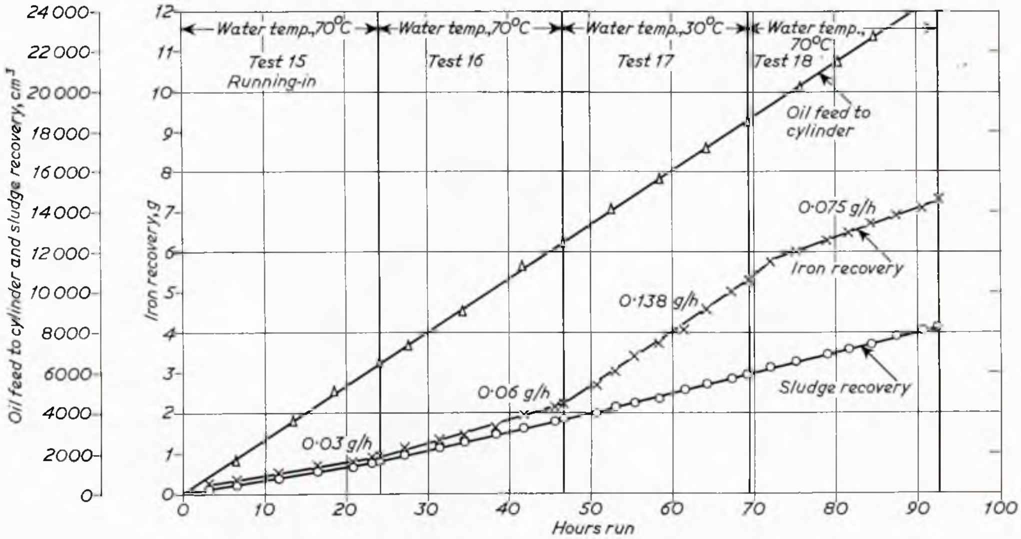

FIG. 6—*Sandwich test for 30°C coolant temperature*

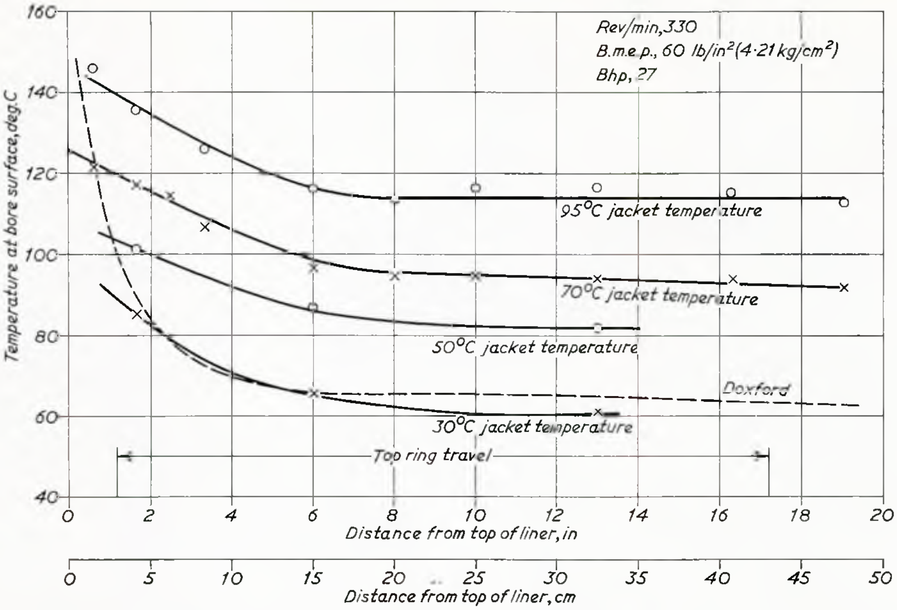

FIG. 7—*Bore-surface temperature. Crossley H.H.9. 9¼in bore × 16in stroke*

over cooled, but it was not clear whether it was the whole liner that was over cooled or only parts of it—the outer end for instance. In an attempt to clarify this, the liner coolant space was divided into two completely separate sections. The topmost 3 in of the liner jacket was separated from the remainder by a diaphragm plate. This upper section of the liner jacket and the cylinder head together formed one cooling-water circuit, while the lower section of the liner formed a completely separate circuit. These two coolant circuits were fitted with independent water pumps and heat exchangers, so that they could operate separately.

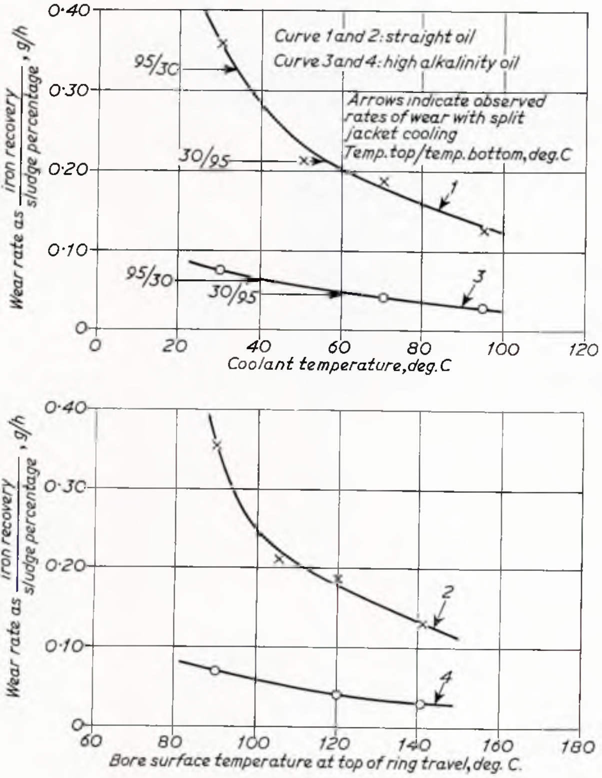

FIG. 8—*Effect of jacket temperature and lubricant on wear*

Tests were run using entirely different levels of temperature in the two halves with the object of elucidating more exactly the role of liner temperature in the wear problem. Sandwich tests were made using the extremes of coolant temperature so far explored, 30°C and 95°C, in one case the upper section of the jacket being maintained at 30°C and the lower half at 95°C, and in the other the temperatures being reversed. The results obtained have been marked in on the curves of Fig. 8.

The foregoing tests suggested very strongly that corrosion was playing a large part in the wear; this, coupled with the widespread use of high-alkalinity oils in service, made it desirable to evaluate this type of lubricant on the test engine. Further sandwich runs were therefore made using a high-alkalinity lubricant of a non-emulsion single phase type at coolant temperatures of 30, 70, and 95°C respectively, together with split-jacket temperatures of 30/95 and 95/30°C. Again the results are included in Fig. 8 and show the same trends as with the straight oil but at a lower level of wear.

These results do show the very strong influence that liner temperature has on wear. Other workers have demonstrated this from time to time but mostly on small engines burning distillate fuels with the relatively low sulphur content of 0·7 to 1·0 per cent. In these cases it has usually been shown that there is a limiting coolant temperature, generally of 70 to 80°C, above which the improvement in wear rate becomes small. The tests on the Crossley engine differ in this respect in that there is a continuing gain up to the highest temperature so far used. This difference is probably because of the higher sulphur content of the residual fuel and the greater tendency to form acids of sulphur in the combustion process; higher temperatures of the internal surfaces of the engine are therefore necessary to avoid condensation of acid.

The importance of corrosion in the mechanism of wear of marine propulsion engines burning residual fuel has been a matter of debate for a number of years, but the temperature measurements of the liner in both the Crossley and the Doxford engines already referred to indicate that the condensation of acid will occur, as was described by Millington(1). The results of the present tests, as represented for instance in Fig. 8, indicate strongly that corrosive wear is playing an important part. That this is so is further indicated by the undoubted reduction in wear rate, which occurs in marine service when a highly-alkaline oil is used for cylinder lubrication and which also occurred in the Crossley-engine tests.

The process by which acid deposited on the liner causes wear concentrated near the top of the ring travel is not fully understood, but the interesting feature of the tests with the divided jacket is that a high rate of wear occurs when the outer sections of the liner are cool although the point of maximum wear, the top of the ring travel, is in the hot zone. This suggests that acid products of combustion condense on the cooler sections of the liner and are swept up to the top of the ring travel by the piston rings where the combination of high loading between ring and bore surface and the poor lubrication at this point encourages a rapid corrosive attack.

Cotti and Simonetti(2) have also pointed out the importance of high liner temperature from results on direct drive and medium speed engines. They show that there is some correlation between the calculated acid condensate intensities along the liner and the observed wear patterns, although they do not appear to take into account the likely sweeping up action of the rings on this condensate as the piston moves up.

A practical outcome of these observations is that, although an engine designer may be unwilling to raise the temperature of the whole length of the jacket because of lubrication and thermal problems around the inner zone of the liner and combustion space, he might well accept a higher temperature in the outer sections where both lubrication and heat flow are less troublesome. A material gain in wear could result thereby.

In regard to the work with the alkaline-additive oil the first point to be noted is that the rate of wear has been reduced by a factor of 4·5 : 1 at 70°C jacket temperature. This is in broad agreement with published data from marine service including the original records of van der Zijden(3) and gives additional confidence in the results obtained from the Crossley unit. It will also be seen that the changes of wear with coolant conditions, including the split-jacket conditions, are again reproduced very closely but at the reduced level. Thus the rate of wear falls progressively with rising jacket temperature, and the wear rate observed with the cool outer and hot inner section is relatively high. These results indicate that although the high-alkalinity oil has greatly reduced wear, the remaining wear is still in some measure associated with corrosion.

Effect of Centrifuging the Fuel

The initial intention was to run the engine and measure rates of wear when using residual fuel which had been centrifuged to a varying degree. It was hoped that it would be possible to prepare a curve of engine wear versus degree of cleaning from which a limited cleaning could be selected, and subsequently to express this degree of cleaning in terms of a limited particle size of insoluble ash which it would be permissible for the centrifuges to pass.

A preliminary test was made to compare engine-wear rates when using the full two-centrifuge cleaning arrangement with those obtained when using fuel from the same batch without cleaning treatment of any kind. The fuel used for this test was the 370cSt (1500 sec Red. 1) residual fuel employed as the

TABLE IV—GENERAL INFORMATION ON FUELS USED FOR THE INVESTIGATION

Fuel reference no.	Designation	Source	Supplied by	Remarks
1 2 3	standard 1500 sec	Middle East	BP	Standard fuel for all running not carried out on alternative named fuels.
4	Nigerian, high-ash low-sulphur	Nigeria	BP	Fuels obtained for this investigation solely on account of their sulphur and ash contents.
5	ashless heavy, low-ash, high-sulphur	Middle East	BP	
6	western DR71A medium ash and sulphur	Venezuela	Shell	
7	gas oil r.v. (road vehicle)		Shell Mex	
8	gas oil, high sulphur		Shell	
9	medium high viscosity, 2740 sec	probably Middle East	BP	
10	Middle East	Aden	Glen Line	Shipboard sample of fuel of Middle East origin, Bunkered Aden. m.v. *Radnorshire*
11	Far East	Borneo	Eastern and Australian Steamship Co.	Shipboard sample of fuel of Far Eastern origin. Bunkered Tarakan. m.v. *Paparoa.*
12	western	Venezuela	New Zealand Shipping Co.	Shipboard sample of fuel of Western origin. Bunkered Curacao, m.v. *Ruahine.*
13	western	Curacao	Ellerman Lines	Shipboard sample from m.v. *City of Johannesburg.*
14	Las Palmas	believed Venezuela	British and Commonwealth Group	Shipboard sample from m.v. *Athlone Castle.*
15	Doxford	San Pedro	Doxford	Sample of 'difficult' fuel offered by Doxford, primarily for fuel-cleaning tests.

standard for wear tests on the Crossley engines; the inspection data are shown in Table II, and more general information is given in Table IV, fuel ref. no. 2.

These initial runs showed no increase of wear when using uncleaned fuel, and a series of check tests were made with similar results.

The standard fuel, which the British Petroleum Co. had supplied to a substantially constant specification for the wear tests on the Crossley engines, was thought to have received appreciably cleaner handling than in ships' bunkers. Therefore random samples of uncleaned residual fuels were obtained from the bunkers of various vessels. To be as comprehensive as possible, the samples were obtained from ships which bunkered in the Middle East, the Far East, and in the western hemisphere.

Sandwich tests carried out comparing the wear rate obtained with each of these fuels untreated and double-centrifuged, again confirmed the results of the earlier tests by indicating no reduction in wear rate between the untreated and double-centrifuged states.

As an additional precaution against drawing incorrect conclusions from this investigation by employing fuels that may have been cleaner than commonly encountered in service, owners were invited to submit samples of fuels for further tests, the investigation specifically requesting "dirty" fuels for this purpose. Three companies were kind enough to submit a fuel each, reference nos. 13, 14, and 15, Tables II and IV. Two came direct from the bunkers of vessels and the third from Doxford and Sons, this last being a sample from a batch of fuel which had been off-loaded as unfit for normal use in a marine engine. Each of the three fuels was run in a four-layer sandwich test as before.

The first fuel (13) was offered, not because it was a dirty fuel, but because it was said to be unsatisfactory by promoting ring sticking owing, it was suggested, to a high asphaltene content. No unusual behaviour of the Crossley engine was observed when testing the fuel, and at the conclusion of the run, the internal condition of the engine was in no way different from that found on any other routine strip, although, of course, it should be realized that much more prolonged running than was required for these wear tests might have been necessary to promote ring sticking or other similar troubles. As in all the previous tests, no change in wear rate was observed between the untreated and cleaned fuel tests.

The second of this group of service fuels (14) was offered because the engines of the vessel from which it was obtained had been running in an unsatisfactory manner, with high rates of piston-ring wear being observed. It was also understood that some difficulty had been experienced when centrifuging this fuel on board, large quantities of sludge being separated from the fuel by the separators. Ricardo and Co. also found this fuel very bad as far as the centrifuges were concerned. Owing to the extremely rapid accumulation of sludge, the purifier bowl filled quickly enough to necessitate shutting down for sludge removal after approximately every 77 litres (17 gallons) or so of fuel had been passed. The rate of sludge removal was 22·9 kg per tonne (49·6 lb/ton) by the purifier and 4·25 kg per tonne (9·25 lb/ton) by the clarifier, a total of 27·0 kg per tonne (58·85 lb/ton). An examination of this sludge disclosed that it was an oil-water emulsion, the sludge extracted by the purifier having a water content of 35·4 per cent and that by the clarifier 18 per cent. This fuel was run in the same type of sandwich test as all the others in the series, but in this case an additional test was added in which fuel that had been treated in the ship's Gravitrol centrifuge was also compared with the untreated and Ricardo cleaned fuel. No significant difference in wear rate was observed between any of the three tests.

The third fuel from Doxfords was the only fuel in the whole series that showed a reduction in wear rate as a result of cleaning. As may be seen from Table V, the wear rate was reduced from 0·274 g of iron per hour uncleaned to 0·203 g per hour after purifying and clarifying, a reduction in wear of some 26 per cent. It is believed that this result is reliable, but it would have been more satisfactory to have been able to confirm this solitary test; unfortunately there was not enough of the fuel available to allow this.

The wear figures obtained from all the tests in this investigation are also shown summarized in Table V.

Centrifuged Sludge

In order to relate the foregoing wear-test observations as far as possible with material removed from the fuel by the centrifuges, all the material remaining in both centrifuge bowls after treating each individual fuel was collected, and the solids extracted by repeatedly washing in benzene, with generous settling periods between each change of benzene until it was only slightly discoloured. The residue, which varied in colour from dark brown to black, was then carefully dried and weighed. The weights of this solid material removed from the bowls of

TABLE V—ASH LEVELS OF FUELS

Fuel reference no.	2	10	11	12	13	14	15
Designation	1500 sec	Middle East	Far East	Western	Western	Las Palmas	Doxford
Ash, per cent wt	0·042	0·030	0·031	0·128	0·068	0·137	0·132
Solids removed by purifier, per cent wt	0·004	0·005	0·003	0·005	0·008	0·010	0·045
Ash after purifying, per cent wt by difference	0·038	0·025	0·028	0·123	0·060	0·127	0·087
Solids removed by clarifier, per cent wt	0·003	0·002	0·002	0·004	0·004	0·005	0·006
Ash after clarifying, per cent wt by difference	0·035	0·023	0·026	0·119	0·056	0·122	0·081
Measured ash after centrifuging, per cent wt		0·028	0·020	0·108	0·043	0·117	0·085
Percentage initial ash content removed by purifier	9·5	16·7	9·7	3·9	11·8	7·3	34·1
Percentage initial ash removed by clarifier	7·1	6·7	6·5	3·1	5·9	3·7	4·5
Percentage initial ash removed by both centrifuges	16·6	23·4	16·2	7·0	17·7	11·0	38·6
Wear rate, g/h							
cleaned	0·193	0·123	0·165	0·141	0·242	0·335	0·203
untreated	0·188	0·124	0·164	0·143	0·233	0·358	0·274

TABLE VI—MATERIAL REMOVED BY CENTRIFUGES

Fuel reference no.	2	10	11	12	13	14	15
Designation	1500 sec	Middle East	Far East	Western	Western	Las Palmas	Doxford
weight of damp sludge removed by centrifuges							
Purifier:							
grammes	137		55		26	3325	625
lb/ton*	0·89		0·437		0·275	49·6	8·72
Clarifier:							
grammes	68		17		too little to collect and weigh	620	389
lb/ton	0·44		0·135			9·25	5·41
Total:							
grammes	205		72		26	3945	1015
lb/ton	1·33		0·572		0·275	58·85	14·13
weight of benzene-washed material removed by centrifuges							
Purifier:							
grammes	13·1	11·5	8·2	15·7	17	15·2	81
lb/ton	0·085	0·111	0·065	0·116	0·180	0·226	1·13
per cent by weight	0·0038	0·005	0·0029	0·005	0·008	0·010	0·045
Clarifier:							
grammes	8·8	4·2	4·2	12·5	7·8	6·8	9·8
lb/ton	0·057	0·040	0·033	0·092	0·083	0·102	0·14
per cent by weight	0·0025	0·0018	0·0015	0·004	0·004	0·005	0·006
Total:							
grammes	21·9	15·7	12·4	28·2	24·8	22·0	90·8
lb/ton	0·142	0·151	0·098	0·208	0·263	0·328	1·27
per cent by weight	0·006	0·007	0·0045	0·009	0·012	0·015	0·057
per cent of damp sludge	10·7		17·1		96·7	0·56	9·0

* To convert lb/ton to kg/tonne, multiply by 0·46.

both the purifier and clarifier are shown in Table VI. expressed both in lb/ton and as a percentage by weight of the fuel from which it was extracted.

Shortly after the start of this work it was suggested that the weight of damp sludge removed by the centrifuges would also be of interest, and this has therefore been included in Table VI for the majority of the fuels tested.

The last line in Table VI shows the percentage of solid material present in the damp sludge, from which it is evident that the quantity of sludge removed from a fuel by centrifuging is no guide as to the "dirtiness" of the fuel as far as solid material is concerned, nor does it appear to bear any relationship to the relative wear rates observed with the various fuels. The quantity of damp sludge may therefore safely be ignored as far as bore wear is concerned.

However, considering the weights of benzene-washed material in Table VI, the Doxford fuel, which was the only sample to show a significant reduction in bore wear as a result of centrifuging, yielded a substantially larger weight of solid material than any of the other fuels. Furthermore, a substantially greater proportion of the original ash was removed by centrifuging, indicating that this particular fuel did in fact contain that much more true "dirt", and may in fact be considered a particularly badly contaminated fuel.

The benzene-washed solids may be assumed to represent the greater part of the insoluble ash content of the fuels; in Table V they are shown expressed as percentages by weight together with the original ash contents as quoted in the inspection data. The approximate ash content of the fuels after each centrifuging stage has been calculated, as has the percentage of the original ash removed by each stage.

In the case of the Doxford fuel, it will be seen that the purifier not only removed an appreciably larger quantity of solid material than from the other fuels but this quantity also represented a proportionately larger percentage of the initial ash content. The solids removed by the clarifier, however, were similar both in quantity and as a percentage of the original ash to that removed by the clarifier from the other fuels. This suggests very strongly that a single centrifuging stage would almost certainly have provided a degree of cleaning for the Doxford fuel that would have been entirely adequate from the point of view of bore wear. As already stated, there was not enough of this fuel available to carry out more than the basic test, otherwise a run with a single stage at centrifuging only, to establish this point, would have been of value.

The results suggest that only in exceptional circumstances would the complete abandonment of all centrifuging result in any deleterious effect as far as cylinder liner and rings are concerned. It is not expected that operators would in fact abandon all fuel treatment, as some protection is needed against the accidental ingress from time to time of excessive dirt or water, and a centrifuge appears to be the most satisfactory way of handling this in residual fuels. However, it does appear that the wider adoption of single centrifuging at throughputs higher than commonly employed would be justified, or alternatively the use of fuel filtering systems without centrifuges.

The Influence of the Composition of the Fuel

The object of this investigation was to study the effect of fuel composition on wear of cylinder liner, piston and piston rings, factors such as the amounts of sulphur, ash, Conradson carbon residue, etc., being of particular interest.

A problem immediately arises as to how these components in the fuel can be varied in a reasonably controlled manner. It would be possible to add these components in the form of oil-soluble compounds to a standard base fuel, but such an approach is open to the gravest suspicion. Residual fuel is an extremely complex material and full details of its molecular structure are not known. It is likely, for instance, that the sulphur in the fuel is associated with the larger molecules and consequently may tend to be concentrated in the combustion process into those parts of the fuel late to burn. If, therefore, sulphur is added to a base fuel in the form of the light molecule of hydrogen sulphide, as is sometimes done, there is no assurance that the sulphur will be burnt in the same way or deposited on the cylinder walls in a similar manner to sulphur in the natural state carried in the heavy molecules. Again the artificial augmentation of the ash content of the fuel could only be done with confidence if not only the composition of the ash was known in detail, but also the particle size distribution was known and satisfactorily reproduced for each component of the ash.

Because of the extreme difficulty in meeting these requirements it was decided to use samples of residual fuel, as bunkered, from as many different sources as reasonable, and furthermore ship operators were asked to supply samples of fuel which were believed to be particularly troublesome in service. As a result fifteen fuels of very considerably varying composition were examined in detail in an attempt to build up an overall picture of the relative importance of the several components of these fuels in relation to engine wear.

Only a limited amount of reliable information had been published on the effects of the fuel components on wear at the time these tests were made, and a brief comment on the position as it was understood then is given below.

a) *Sulphur Content of the Fuel*

The sulphur contained in hydrocarbon fuels burns to oxides of sulphur which in turn combine with water, formed by the combustion of hydrogen in the fuel, to give sulphuric acid which, unless the surface temperatures are above the dewpoint, will condense on the cylinder and combustion-chamber walls. In small engines running on distillate fuels there is ample evidence that high rates of wear are experienced under these conditions. As already related, wear with residual fuels was greatly reduced by operating the Crossley engine at higher temperatures of the combustion chamber and cylinder walls, and indeed it may be fairly assumed that the beneficial experience with lubricating oils of high alkalinity has also shown that wear arises from acid attack. There is no doubt that sulphur contributes strongly to the wear rate even though the exact mechanism may not be understood with certainty.

b) *Ash Content of the Fuel*

The ash content as quoted in the inspection data for fuels consists of both oil-soluble and insoluble impurities.

The soluble ash consists largely of vanadium and sodium compounds, and cannot of course be separated by centrifuging or filtering. The carbonaceous deposits in the cylinder are known to be rich in vanadium, but the effect of this material on wear is not known. Unfortunately, as is now well known, in engines using poppet valves, sodium and vanadium compounds, either unburned or imperfectly combusted, adhere to the exhaust valve seats if the seat temperature is above 530°C. This results in early seat deterioration, gas leakage, rise of exhaust temperature and performance deterioration.

The insoluble ash consists largely of iron oxide and silica, some of which no doubt has entered the fuel during transit and handling. It is almost universal practice to centrifuge the fuel to reduce the quantity of insoluble ash by removing the larger particles. Christie and Bailey(4) have quoted test results from a 230 mm bore four-cycle engine showing an almost linear relationship between ash content and wear.

c) *Carbonaceous Deposits*

Carbonaceous deposits and general fouling within the cylinder are greater with residual than with distillate fuels. The deposits have also been claimed, by Lyn(5) to be harder and more abrasive. The Conradson carbon number for the fuel may be a guide to the tendency of the fuel to form carbonaceous deposits.

d) *Asphaltene Content*

Little or nothing is known of the effect of asphaltene content on wear. Indiscriminate mixing of fuels can cause instability of the asphaltenes resulting in the formation of dry sludge in suspension in the fuel, which in turn may cause the precipitation of the asphaltenes as a result of repeated heating and cooling or centrifuging, sometimes in quantities large enough to overwhelm the centrifuges. Oil companies, however, take pains to ensure compatibility of the asphaltene contents of base residuals and the viscosity-controlling component fuel in each blend. While the asphaltenic material is largely organic and may therefore be passed through the engine safely on its own account, sight should not be lost of a possible effect on combustion, perhaps by promoting nozzle trumpeting, or on the formation of cylinder deposits.

e) *Combustion*

Combustion may well be interrelated with (c) and (d). While it is generally agreed that combustion can be as good with residual as with Diesel fuel, the margin between good and bad combustion would appear to be smaller, and therefore any nozzle fouling or poppet exhaust-valve seat fouling would be proportionately more liable to spoil combustion still further.

Details of Test Fuels

As in the previous series of tests a fuel of reasonably constant specification was supplied by British Petroleum and was regarded as a reference fuel. British Petroleum were also able to supply a residual fuel of Nigerian origin with the low sulphur content of 0·96 per cent, but with a relatively high ash content of 0·096 per cent; they also supplied an ashless residual fuel, 0·001 per cent ash, but with high sulphur, 3·61 per cent. Two distillate gas oils were obtained having of course negligible ash, but with sulphur contents of 0·5 and 2·9 per cent respectively. These five fuels were augmented by a number of other samples of residual fuels, five of which were actually obtained from vessels' bunkers, to give a total of fifteen covering as large a range of sulphur and ash content as possible. The inspection data for all these test fuels are shown in Table II and general information in Table IV.

Test Results

Table VII lists all the wear-rate measurements which are discussed below.

Discussion

While experience has shown that in wear testing some scatter of the results will be inevitable, yet unless any one fuel characteristic, and that characteristic alone, is responsible for wear, the plot of that characteristic against wear will also show a degree of scatter due to other wear-inducing agents present in the fuels investigated.

Such scatter is clearly present in the plot of fuel sulphur content against wear rate shown in Fig. 9, which indicates that while a marked increase in wear with increase in sulphur content is evident with the two distillate fuels, considerable scatter has occurred with the residuals. As would be expected, a general increase in wear with increase in sulphur is indicated. No residual fuel has shown a lower wear rate than the distillate fuels of a comparable sulphur level, although it is interesting to note that "good" residuals such as the Nigerian high-ash low sulphur (no. 4), the ashless heavy (no. 5), and the Middle East bunkered (no. 10) show wear rates that are comparable with the

TABLE VII—TEST RESULTS

Fuel reference no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Designation	standard 1500 sec	standard 1500 sec	standard 1500 sec	Nigerian high-ash low-sulphur	ashless heavy	western DR71A	gas oil r.v.	high-sulphur gas oil	medium high, viscosity 2740 sec	Middle East	Far East	western	western	Las Palmas	Doxford
Supplied by	B.P.	B.P.	B.P.	B.P.	B.P.	Shell	Shell Mex and B.P.	Shell	B.P.	m.v. *Radnorshire*	m.v. *Paparoa*	m.v. *Ruahine*	Ellerman Line	m.v. *Athlone Castle*	Doxford
Corrected wear rate, iron g/h	0·179	0·218	0·195	0·073	0·124	0·179	0·042	0·115	0·300	0·123	0·165	0·161	0·242	0·341	0·203

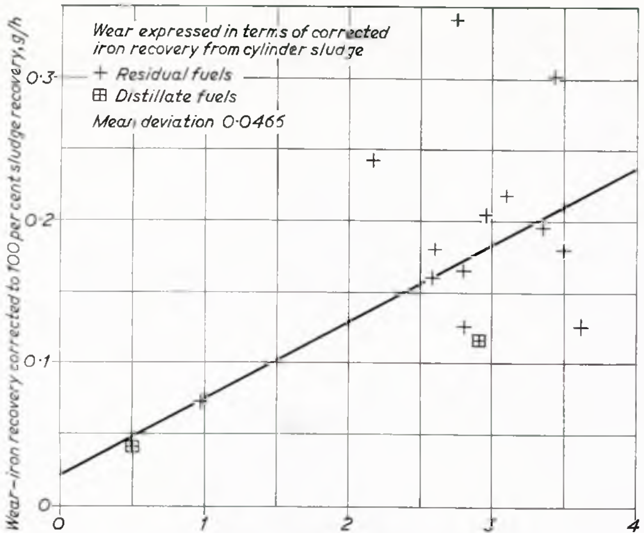

FIG. 9—*Effect of fuel sulphur content on cylinder bore and piston ring wear*

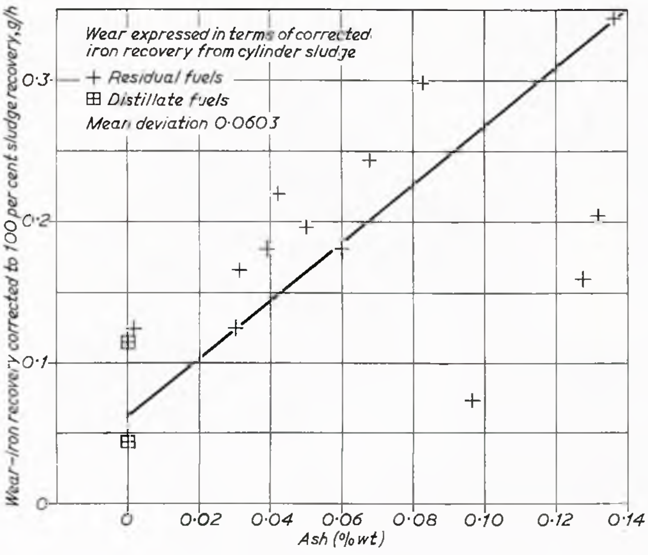

FIG. 10—*Effect of fuel ash content on cylinder bore and piston ring wear*

relevant gas oils. However, the majority of the residual fuels investigated exhibit wear rates higher to a greater or less extent than the gas-oil/sulphur wear line, thus indicating that at least one other wear-controlling factor is exerting an influence, which the degree of scatter suggests might be almost as large as that of the sulphur itself.

An obvious first choice for this additional factor is the ash content, which has been plotted against wear in Fig. 10.

In this case the test results obtained with twelve of the fuels involved do in fact fall within a satisfyingly narrow band indicating a progressive increase in rate with ash content. The wear rates of the three remaining fuels, however, are so much below this band that no precise simple relationship between ash and wear may justifiably be assumed.

The three fuels with the relatively low wear rates were nos. 4, 15, and 12, that is the low-sulphur Nigerian, the Doxford fuel, and the sample from m.v. *Ruahine*. No. 4 was one of the good residuals mentioned with reference to sulphur, the other two were not. The low relative wear of the Nigerian fuel may be attributed, in part at least, to the low sulphur content of 0·096 per cent. Alternatively, the ash of all three fuels may have contained a smaller proportion of wear-producing material than the remainder.

Furthermore, the practice of centrifuging residual fuels is designed primarily to remove as much as possible of the solid material, which would be most likely to affect wear. This of course would also affect the ash content, and since these tests were all carried out with centrifuged fuel, the wear rates have been plotted against the ash contents of the cleaned fuel. The general scatter, however, was then greater than when the untreated fuel ash contents were employed in Fig. 10.

As no marked improvement in correlation was obtained using the ash content of the centrifuged fuel, and as it would be more convenient in any case to relate wear with respect to the regular inspection data, the ash content of the untreated fuel was employed in all the additional analyses carried out.

In order to facilitate comparisons between the various plots, the mean deviation of all the experimental points in each figure from a mean line was determined. As shown in Figs. 9 and 10, the mean deviations for the sulphur and ash plots are 0·0466 and 0·0603 g per hour respectively. The mean deviation for the centrifuged ash plot was 0·0629.

The ash versus wear plots having confirmed the sulphur plot in indicating that more than one factor should be considered concurrently, an extensive survey of compound influences was made in which all the various factors in the inspection data likely to be involved in the wear mechanism were considered in joint relationship with each other. The following proved to be most interesting.

Combining the sulphur and ash contents and plotting against wear reduced the mean deviation from the 0·0466 and 0·0603 g per hour of the individual sulphur and ash plots to 0·0403, the actual form of this plot being wear against sulphur + 20 × the ash content.

The coefficient of 20, which was found by trial to be the optimum, is relatively large, but this is not surprising in view of the numerically very much smaller values of the ash than of the sulphur contents, the average ash contents of the fuels investigated being 0·060 per cent by weight, and the average sulphur value 2·69 per cent.

As has already been remarked, a mutual dependence between sulphur and carbon formation within the cylinder in the production of wear has been proposed by other investigators.

When carbon formation occurs at a relatively high rate, the probability of comparatively large fragments of combustion-chamber deposits becoming detached and being forced between the piston and liner bore is correspondingly increased. Such material, although not necessarily particularly hard, would almost certainly have a detrimental effect on wear either by local "packing" of the material or by locally impairing lubrication.

Support is lent to this theory by a consideration of the joint influence of sulphur and Conradson carbon residue in the expression: wear versus sulphur + $\frac{1}{4}$ Conradson, shown in Fig. 11, in which the mean deviation has been further reduced to 0·0364 g per hour. The optimum value of the Conradson coefficient of $\frac{1}{4}$ was again determined by trial.

McConnell and Nathan⁽⁶⁾ have suggested that particles of carbon formed during combustion convey the sulphuric acid produced from the fuel sulphur to the cylinder walls, and therefore the smaller the quantity of carbon produced the less the acid attack for a given sulphur content.

This would suggest that wear, in part, might be related to the product of sulphur and Conradson carbon values and an examination of the sulphur + sulphur × Conradson form yielded a minimum mean deviation of 0·0373, not quite as low as the 0·0364 of the sulphur plus Conradson series, but once again the optimum value of the Conradson coefficient was found to be $\frac{1}{4}$.

A similar examination of the sulphur + sulphur × ash series, however, yielded a lower mean deviation value than had been obtained in the case of sulphur + ash. As shown in Fig. 12 the mean deviation fell to 0·035 from the previous value of

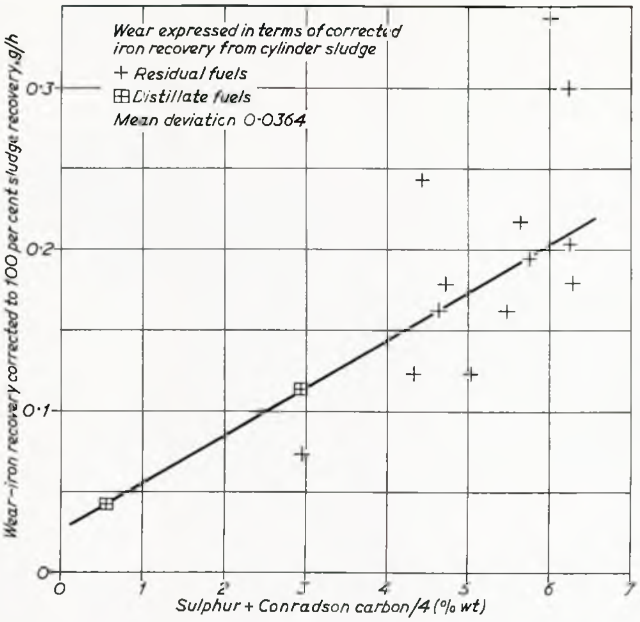

FIG. 11—*Joint influence of fuel sulphur and Conradson carbon residue on cylinder bore and piston ring wear*

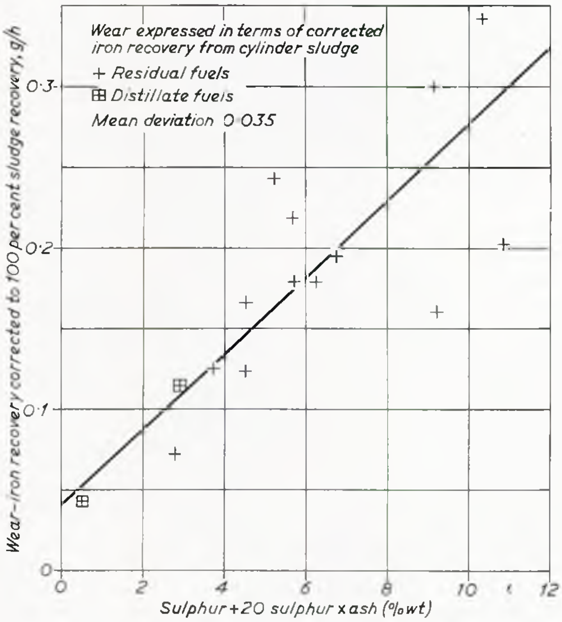

FIG. 12—*Joint influence of fuel sulphur and ash contents on cylinder bore and piston ring wear*

0·0403. Again the optimum value of the coefficient remained unchanged, in this relationship at 20.

A combination-expression including ash and Conradson carbon was also explored of the form

wear proportional to sulphur + sulphur (ash + carbon),

and the best fit appeared to be the formula

$$\text{wear} \propto \text{sulphur}\left(1 + 5\left(\text{ash} + \frac{\text{Conradson}}{100}\right)\right)$$

as shown in Fig. 13, but the mean deviation of 0·0363 showed no improvement.

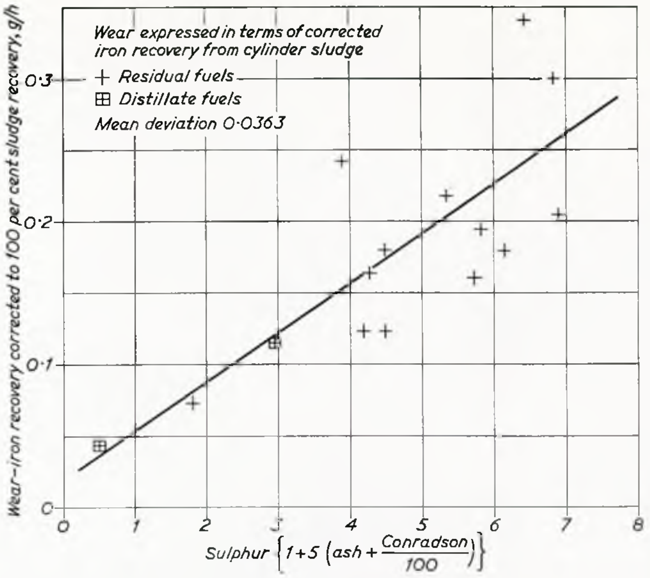

FIG. 13—*Joint influence of fuel sulphur, ash and Conradson carbon residue on cylinder bore and piston ring wear*

It is apparent from this discussion that the rate of wear is closely associated with the sulphur in the fuel, but in addition there is a factor associated with those characteristics of the fuel giving rise to cylinder deposits. Whether these deposits cause wear by direct abrasion or by acting as carriers of acidic material is not known, but direct observation of the engine suggests that wear, in part at least, arises from scoring of the rings, possibly together with local gas blow and deterioration of lubrication where these scores occur. Whether these cylinder deposits are more closely related to Conradson carbon values or ash levels is not clear from these experiments, and this is in part because within the group of fuels tested there was a cross relation between carbon and ash preventing a clear separation of these two variables.

In principle there appears to be some attraction to the expression relating wear to fuel components of the form

$$\text{wear} \propto \text{sulphur}\left(1 + 5\left(\text{ash} + \frac{\text{Conradson}}{100}\right)\right)$$

but the spread of the data scarcely justifies the adoption of this approach at the present time and the simpler form of

$$\text{wear} \propto \text{sulphur} + \frac{\text{Conradson}}{4}$$

could be regarded as a more practical formula.

Inspection of the test results does not suggest that other characteristics of the fuel, viscosity, vanadium content, etc. have a bearing on the rate of wear of the liner and rings.

Effect of Ring and Liner Materials

As previously stated rings wear quite rapidly, top-ring replacement being at least once a year, i.e. every 5000 to 8000 hours. Hence work on ring and liner materials to bring about a further reduction of wear was and still is considered very worthwhile. A wear rate of 0·05 mm or 0·002 in per 1000 hours would enable the liners to last 20 years or the life of the ship, assuming 5000 hours per annum of running, or if the running time is closer to 8000 hours per annum a lower wear rate of 0·03 mm or 0·00125 in is needed.

In choosing a suitable liner material for test, the following considerations were taken into account:

i) mechanical strength;
ii) resistance to thermal stress;
iii) good bearing properties;
iv) machinability;
v) low cost.

TABLE VIII—LIST OF LINER MATERIALS

	Liner	Approximate composition, per cent						Brinell hardness	Ring test		Notes
		Total carbon	Si	P	Ni	Cr	Other elements		Tensile ton/in²	En, lb/in² × 10⁶	
All standard sand-cast liners	Sand-cast	3·2	1·4	0·35	—	—	S 0·12 Mn 0·9 Ti 0·07 Va 0·17	200	17	—	
	Molybdenum banded	—	—	—	—	—	—	—	—	—	B
	Cermet banded	—	—	—	—	—	—	—	—	—	C
	Colmonoy banded	C 0·65	Bands Cr 11·50	Fe 4·25	Si 3·75	B 2·5	Ni balance	—	—	—	D
	Cobalt/tungsten carbide banded	Bands of Metco 439 50 per cent cobalt/tungsten-carbide aggregate						—	—	—	D
Centrifugally cast liners	No. 1. unhardened	3·2	2·2	0·1	—	0·35	S 0·08 Mn 0·8 Mo 0·65	207–255	23	18	
	No. 1. hardened							440+	—	—	A
	Austenitic	2·7	2·1	0·4	14·0	1·5	S 0·08 Mn 1·0 Cu 6·5	140–200	16	12	
	Low-silicon	3·3	1·0	0·1	—	—	S 0·08 Mn 0·80	180–240	30	—	
	No. 2.	3·3	1·8	0·2	0·15	—	—	179–241	16	14	
	2 per cent nickel/copper	3·15	1·8	0·2	1% Ni 1% Cu	—	Mn 0·8 Va 0·4	241	—	—	
	No. 1. plasma-hardened	3·2	2·2	0·1	—	0·35	S 0·08 Mn 0·8 Mo 0·65	490	—	—	

A Depth of hardened layer on these liners is not less than 1 mm (0·040 in).

B This is a sand-cast liners of standard specification in which grooves, 3-mm wide × 1-mm deep, spaced 2 mm apart, have been machined; the grooves being filled with molybdenum. The grooves extend from inside the inner ring travel to a point outside the wearstep region, covering a total distance of some 3 in (see Fig. 14).

C This a centrifugally cast No. 1. liner with grooves as described in B, but filled by spraying with a 30/70 alumina/nickel aluminide cermet.

D The grooves in these liners were much wider than in B, being 19-mm wide × 1-mm deep and not of rectangular section, but tapering upwards at the sides. Hence the number of bands was 4 instead of 16, and spaced ¼ in apart (see Fig. 14).

The use of very heavy sand-cast liners did tend to limit the possible choice of iron composition because of the lower cooling rate in the foundry, and prevented some of the liner irons developed for small engines being used. However, the current trend for smaller liner castings, coupled with the possibility of centrifugal casting, induction hardening, or the deposition of metal surfaces by electroplating or spraying, has opened up the field for alternative materials.

Choice of Materials

To assist in making the most useful selection, discussions were first held with several liner manufacturers and other experts in this field.

Table VIII lists all the liner materials and banded liners chosen and used, their composition and hardness, and also their tensile strength and modulus where known. As already stated, the standard reference liners were made of the Va/Ti iron in common use in marine direct-drive engines. They were sand-cast, and both rate of cooling and composition were adjusted to give them a microstructure similar to that of large liners.

Resulting from the initial discussions, the following centrifugally cast materials were chosen as being the best for the first tests:—

No. 1 cast iron—a hardenable high-duty material.

Austenitic cast iron—an austenitic material giving increased corrosion resistance.

Low-silicon cast iron—chosen as giving good results in some engines.

It was agreed to keep the hardness of these liners within the 200–250 Brinell range. The cooling rate of these centrifugally-cast liners was adjusted to match that of the large engine liners.

Table VIII shows two other centrifugally cast materials, namely no. 2 cast iron, and a 2 per cent nickel/copper iron. These were a later choice: the first because it was giving unexpectedly bad results in service and hence its behaviour needed confirmation in the Crossley engines; the second was a new material reputed to have increased resistance to corrosion.

Two hardened-bore liners were also tried: the first induction-hardened to 440 Brinell and the second hardened by plasma gun to 480 Brinell. It was hoped to reach 600 Brinell by the latter method, but it was not found possible.

Altogether four banded standard Va/Ti liners have been

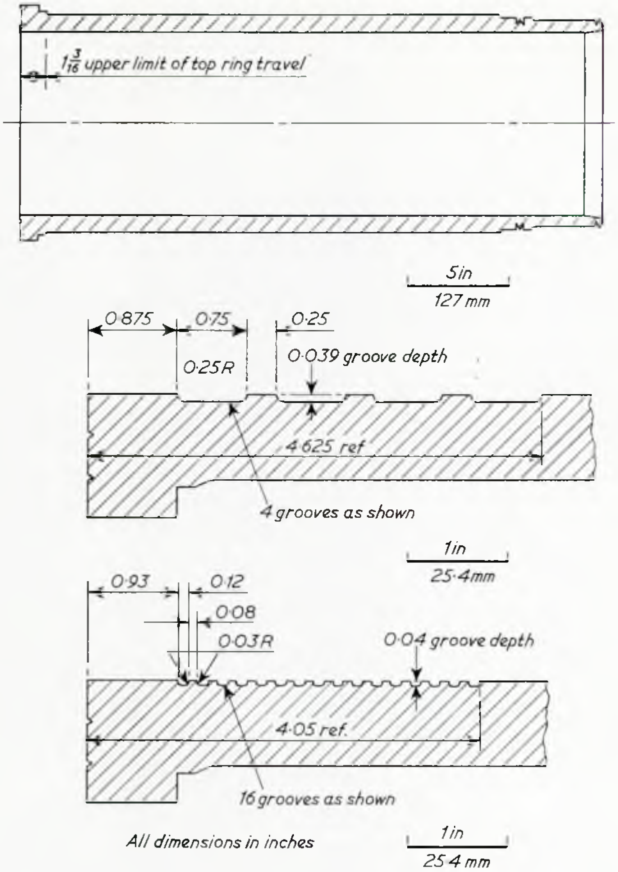

FIG. 14—*Grooves for banded liners*

tried. Two had sixteen narrow bands and two had four wide bands, as shown in Fig. 14. The narrow bands were satisfactory for filling with an oxy-acetylene spray gun, but the plasma gun with transferred arc for fusing the material on the liner required wider bands to avoid burning the cast iron.

The hard-facing materials tried were:—

Molybdenum	Sprayed on with an oxy-acetylene gun (narrow bands)
70/30 alumina/nickel aluminide cermet	Sprayed on with an oxy-acetylene gun (narrow bands)
Colmonoy 5 nickel/chrome alloy	Sprayed on with a plasma gun plus transferred arc (wide bands)
Cobalt/tungsten carbide	Sprayed on (wide bands)

The ring materials are listed in Table IX.

It will be seen that the reference sand-cast rings are of similar material to the B.S. 4.K.6 Specification; as also are the other rings, except for those with a bainitic structure.

The black-faced standard rings are simply the same rings with a phosphated running-in finish. There was no indication that this finish had any effect on wear after running-in, when the black had worn off.

The ring variations tried are therefore:—

1) normal-hardness sand-cast rings;
2) hardened ring pack, or hard top ring only;
3) molybdenum inlaid top rings;
4) plasma-sprayed chromium top ring;
5) bainitic ring pack.

Test Procedure

As will be seen from Table X the duration of test runs was either 100 or 500 hours. Most of the tests were carried out using a straight lubricating oil, R.445, and 100 hours of running was quite sufficient to give enough wear for accurate measurement. However, when running on Alexia 40, an oil of high basicity, the liner wear was much reduced. In the first tests on this oil five separate 100-hour runs were necessary to obtain measurable liner wear. The engine was dismantled for the cleaning of parts and for wear measurement at the end of each 100-hour run and a new bottom ring was fitted, the lower rings all being moved up one after discarding the top ring. However, after tests with two builds using Alexia 40, subsequent runs were carried out for the full 500 hours without any dismantling. Most of the 100-hour tests were carried out in daily runs of eight hours duration, but for the 500-hour runs this period was doubled to sixteen hours daily. No running was carried out at weekends.

With the early 100-hour tests, the running-in period after rebuild with new parts was included in the test. In a few cases the first run of several 100-hour runs with the same build,

TABLE IX—LIST OF PISTON-RING MATERIALS

Rings	Approximate composition, per cent						Brinell hardness	Notes
	Total carbon	Si	P	Ni	Cr	Other elements		
Standard	3·4	1·8	0·4 max	0·15	0·1	S 0·15 Mn 1·0	180	—
Black-faced							207–210	A
C.I.1 (hardened)	3·5	1·8–2·3	0·47–0·7		1·0 max	S 0·1 max Mn 0·7–1·0	372–448	—
Plasma-sprayed chromium	3·5	1·8–2·5	0·4–0·65		0·3–1·0	S 0·1 max Mn 0·6–1·0	—	
Bainitic iron	3·2–3·5	2·0–2·4	0·1	0·9–1·2	0·1–0·4	S 0·1 Mn 0·6–0·8 Cu 0·9–1·2 Mo 0·6–0·8	270	
Molybdenum inlaid	3·4	1·8	0·4 max	0·15	0·1	S 0·15 Mn 1·0	—	B
	—	—	—	—	—	—	—	C

A These rings are made to the same specification as the standard rings, but their peripheral surfaces are black. This is an anti-scuff finish for running-in and has no effect on later wear.

B These are black-faced rings with machined grooves 1-mm deep in the peripheral faces filled with molybdenum.

C Second set of molybdenum rings as it was thought spraying might have distorted the finished rings, B.

TABLE X—SUMMARY OF WEAR TESTS

Build			R.445 lubricating oil						Alexia 40 lubricating oil											
			100 h tests, 270 cm³/h						100 h tests, 270 cm³/h						500 h tests, 100 cm³/h					
no.	liner (all centrifugally cast except standard)	rings	liner wear, mm × 10² in × 10³ 1000 h on diameter	ring wear, g/1000 h					liner wear mm × 10² in × 10³ 1000 h on diameter	ring wear, g/1000 h					liner wear, mm × 10² in × 10³ 1000 h on diameter	ring wear, g/1000 h				
				top 4	3	2	1	total		top 4	3	2	1	total		top 4	3	2	1	total
1	standard Va/Ti	standard	50·8 20·0	31·0	8·1	4·2	8·4	51·7	5·1 2·0	4·72	2·54	2·00	4·36	13·6	3·0 1·2	3·86	1·64	1·06	2·40	8·96
2		hardened top ring													1·0 0·4	4·08	2·16	1·88	4·50	12·6
3		molybdenum-sprayed top ring	83·8 33·0	137	13·2	8·97	14·0	173												
4		plasma-sprayed chrome top ring	55·9 22·0	21·0	7·4	4·8	4·6	37·8												
5		all rings bainitic structure	29·7 11·7	37·0	6·1	4·7	4·7	52·5												
6	as above, but banded with molybdenum	standard	20·3 8·0	30·1	7·90	7·40	6·27	51·6	1·5 0·6	5·44	2·42	1·74	3·87	13·5						
7		all rings hardened	9·9 3·9	27·0	21·5	19·8	34·7	103												
8		hardened top ring only	11·9 4·7	21·6	9·55	10·3	10·7	52·2												
9	standard Va/Ti, but banded with a cermet	standard	ring and liner wear excessive due to cermet coming away and abrading.																	
10	standard Va/Ti with Colmonoy 5 bands		23·9 9·4	97·0	36·7	26·3	40·9	201												
11	standard Va/Ti, but with cobalt/tungsten-carbide bands		107 42·0	very excessive ring wear																
12	No. 1.		52·8 20·8	34·7	9·65	8·32	10·3	63·0							4·1 1·6	3·26	1·84	1·78	2·00	8·88
13	No. 1 induction-hardened		54·4 21·4	31·7	9·73	6·53	13·4	61·4												
14	No. 1 plasma hardened														2·5 1·0	3·76	2·50	1·76	2·44	10·5
15	low silicon		83·8 33·0	21·8	4·75	3·00	5·30	34·8												
16	Mk 18 austenitic		33·0 13·0	27·8	8·37	5·77	6·60	48·5												
17	No. 2.		74·1 29·2	35·4	6·0	3·40	6·40	51·2							8·1 3·2	5·40	1·98	1·66	3·04	12·1
18	2 per cent nickel/copper		52·8 20·8	31·6	10·6	7·50	10·2	59·9							2·0 0·8	2·38	0·66	0·46	0·62	4·12
19		hardened top ring													2·0 0·8	2·80	1·40	1·24	1·96	7·40

Average top ring radial wear (assuming all wear is radial) = g × 0·0197 mm. or g × 0·000777 in.

TABLE XI—RELATIVE LUBRICATING-OIL SUPPLY TO CYLINDERS OF DOXFORD 'P' AND CROSSLEY H.H. 9 ENGINES

Engine	Bore	Stroke	Rev/min	b.m.e.p. bar (lb/in^2)	kW (bhp)	Cylinder surface swept on firing stroke, m^2/h	Cylinder oil supply, g/h	Oil supply	
								g/kW/h (g/bhp/h)	cm^3/m^2 swept surface
Crossley H.H. 9 (4-cycle)	235 mm (9¼ in)	406 mm (16 in)	330	4·14 (60)	20·1 (27)	2970	270 × 0·9 = 243	12·05 (9·0)	0·091
							70 × 0·9 = 63	3·13 (2·33)	0·0236
							100 × 0·9 = 90	4·45 (3·33)	0·0337
Doxford 'P' (opposed-piston 2-cycle)	670 mm	730 mm (upper cylinder) 1370 mm (lower cylinder)	112	7·58 110	1042 (1400)	29 700	700	0·67 (0·5)	0·0262

showed a high rate of wear. Where this occurred the first 100-hour run was ignored.

It was not found possible to run-in the engine satisfactorily using Alexia 40 lubricating oil, hence when running on this oil it was necessary to carry out some 30 hours of running-in on the straight oil first, then to dismantle the engine, clean and measure up the liner, and weigh the rings before starting the test on Alexia 40. This separate running-in period for new liners was also extended to all later tests on the straight oil, particularly as reliance was often placed on a single 100-hour run.

The method of iron recovery for the wear tests with various liner and ring builds was found unsuitable because of the complication when using banded liners and hard surfaced rings. Hence all such wear measurements were made by direct methods. Figures 2 and 3 show the instrument used to obtain radial-wear measurements. These radial figures were also backed up by diametral-wear measurements as shown in Fig. 4. Ring wear was assessed by weighing.

Test Results

The results of the wear tests are summarized in Table X. It will be seen that altogether nineteen different builds have been tried and of the nineteen nearly half were run on Alexia 40 lubricating oil also.

It will be noted that all liner wear rates are quoted in hundredths of a millimetre and thousandths of an inch on diameter per 1000 hours of running. Ring weights are given in g per 1000 hours for each ring, plus a total ring-wear figure.

The reduction of lubricating-oil supply used in the 500-hour runs with Alexia 40 oil from 270 to 100 cm^3/h was made to bring this rate into a region more representative of the direct-drive marine engine, as prior to these longer tests there appeared to be a lack of correlation between Doxford and Crossley-engine results, which it was thought (at the time) might be due to:

a) the use of a straight oil;
b) the use of an unrepresentatively high lubricating-oil consumption;
c) differences of liner microstructure. (This was disproved after examination of liner specimens).

Table XI compares the lubricating-oil consumption of the Doxford "P" and Crossley engines. It will be clear that on the basis of cubic centimetres per square metre of cylinder wall surface swept on each firing stroke, the lubricating-oil supply is similar, taking the Crossley engine at a supply of 70 cm^3/h. However, before adopting such a reduced oil supply it was necessary to ensure that it would not prejudice satisfactory operation of the engine or markedly increase the rate of wear. Table XII summarizes the results of iron-recovery wear tests to clarify this point. It will be seen that the corrected-iron recovery rates are little affected by reduction of the oil supply down to 70 cm^3/h with either the standard Va/Ti liners or the no. 1 and no. 2 material liners. However, because at 70 cm^3/h there was occasional gas blow past the rings, 100 cm^3/h was used for the actual tests. These materials were those in service in Doxford engines, which had doubtful wear correlation with the Crossley-engine results.

TABLE XII—EFFECT OF CYLINDER LUBRICATING-OIL SUPPLY ON WEAR RATES AS MEASURED BY THE IRON-RECOVERY METHOD

Alexia 40 lubricating oil

Liner material	Wear rate, g/h over 25 hours		
	Oil feed, cm^3/h		
	=270	=135	=70
Vanadium/titanium sandcast	0·031	0·023	0·049
No. 2 cast iron	0·038	0·047	0·044
No. 1 cast iron	0·047	0·043	0·047

Referring again to Table XI, it is interesting to note that for a constant oil-supply value, in cm^3/m^2, of surface swept on the firing stroke, the g/kW h varies inversely as the bore diameter and brake mean effective pressure, i.e. the g/kW h of the Doxford "P" engine is 1/5 that of the Crossley engine.

Good correlation with the Crossley engines was obtained from the service results on the Doxford engine with the no. 2 material. The results showed a liner wear 2·67 times greater than with the standard Va/Ti liner in 500-hour tests (see Table X, builds 1 and 17). On a 100-hour test with straight oil, the liner wear rate was 1·46 times that of the Va/Ti liner. Doxford had been obtaining liner wear rates two to five times greater with the no. 2 as compared with the Va/Ti material.

The results of Table X are discussed in (a) to (d) under the following headings:

a) plain liner materials with standard ring pack;
b) banded liners with standard ring pack;
c) ring pack variations;
d) effect of additive oil on wear and wear correlation.

a) *Plain Liner Materials with Standard Ring Pack*

The relevant tests from Table X are extracted in Table XIII. It will be seen that with the straight oil the only material showing promise is the austenitic one which reduces liner wear to 65 per cent of that with the standard liner. No. 1 hardened or unhardened and 2 per cent nickel/copper materials give similar results to the standard liner, although ring wear is slightly increased. The no. 2 and low-silicon materials give a high liner wear, but the low-silicon material reduces total ring wear to 70 per cent of that occurring with the standard liner.

With Alexia 40 lubricating oil these results are modified in that the 2 per cent nickel/copper material gives 65 per cent lower liner wear and only 56 per cent of the total ring wear with the standard liner, i.e. similar liner-wear reduction to the austenitic liner on straight oil, but with reduced ring wear. It would have been interesting to run the austenitic material with the additive oil. The low wear with the austenitic liner may in

TABLE XIII—PLAIN LINERS AND STANDARD RING PACK (EXTRACTED FROM TABLE X)

Build			R.445			Alexia 40					
			100 h: 270 cm^3/h			100 h: 270 cm^3/h			500 h: 100 cm^3/h		
no.	liner (all centrifugally cast except standard)	rings	liner wear mm × 10^2 in × 10^3 / 1000 h	ring wear, g / 1000 h top ring	total	liner wear mm × 10^2 in × 10^3 / 1000 h	ring wear, g / 1000 h top ring	total	liner wear mm × 10^2 in × 10^3 / 1000 h	ring wear, g / 1000 h top ring	total
1	standard Va/Ti	standard	50·8 20·0	31·0	51·7	5·1 2·0	4·72	13·6	3·0 1·2	3·86	8·96
12	no. 1. unhardened		52·8 20·8	34·7	63·0				4·1 1·6	3·26	8·88
13	no. 1. induction-hardened		54·4 21·4	31·7	61·4						
14	no. 1. plasma-hardened								2·5 1·0	3·76	10·5
15	low silicon		83·8 33·0	21·8	34·8						
16	austenitic		33·0 13·0	27·8	48·5						
17	no. 2.		74·1 29·2	35·4	51·2				8·1 3·2	5·40	12·1
18	2 per cent Ni/Cu		52·8 20·8	31·6	59·9				2·0 0·8	2·38	4·12

part be due to a lower thermal conductivity raising the surface temperature of the bore.

Hence, out of these tests, the 2 per cent nickel/copper and austenitic materials show up as the best, with the low-silicon giving low ring wear at the expense of increased liner wear.

b) *Banded Liners with Standard Ring Pack*

Table XIV shows that the molybdenum bands reduce liner wear to 40 per cent with the straight oil and to 30 per cent with the additive oil. Ring wear is unaltered compared with the standard liner.

The cermet 70/30 alumina/nickel aluminide banded liner gave excessive wear, due to the filling coming away and causing rapid abrasion.

The Colmonoy 5 banded liner gave quite low liner wear, but excessive ring wear. The microstructure of this alloy consists of hard particles of chromium carbide and chromium boride dispersed in a softer matrix. For reasons not fully understood, there was a high coefficient of friction between the bands and the ring and piston surfaces, and a high rate of ring wear. It would appear therefore that this material is incompatible with cast-iron surfaces.

TABLE XIV—BANDED LINERS AND STANDARD RING PACK (EXTRACTED FROM TABLE X)

Build			R.445			Alexia 40					
			100 h: 270 cm^3/h			100 h: 270 cm^3/h			500 h: 100 cm^3/h		
no.	liner (sandcast)	rings	liner wear, mm × 10^2 in × 10^3 / 1000 h	ring wear, g / 1000 h top ring	total	liner wear, mm × 10^2 in × 10^3 / 1000 h	ring wear, g / 1000 h top ring	total	liner wear, mm × 10^2 in × 10^3 / 1000 h	ring wear, g / 1000 h top ring	total
1	standard Va/Ti	standard	50·8 20·0	31·0	51·7	5·1 2·0	4·72	13·6	3·0 1·2	3·86	8·96
6	standard, but banded with molybdenum		20·3 8·0	30·1	51·6	1·5 0·6	5·44	13·5			
9	standard, but banded with a cermet		ring and liner wear excessive due to cermet coming away and abrading								
10	standard, but wide bands of Colmonoy 5		23·9 9·4	97·0	201						
11	standard, but wide bands of cobalt/tungsten carbide		107 42·0	excessive ring wear							

TABLE XV—RING-PACK VARIATIONS (EXTRACTED FROM TABLE X)

Build			R.445			Alexia 40					
			100 h: 270 cm^3/h			100 h : 270 cm^3/h			500 h: 100 cm^3/h		
no.	liner	rings	liner wear, mm × 10^2 in × 10^3 / 1000 h	ring wear, g / 1000 h top ring	ring wear, g / 1000 h total	liner wear, mm × 10^2 in × 10^3 / 1000 h	ring wear, g / 1000 h top ring	ring wear, g / 1000 h total	liner wear, mm × 10^2 in × 10^3 / 1000 h	ring wear, g / 1000 h top ring	ring wear, g / 1000 h total
1	standard Va/Ti (sandcast)	standard	50·8 20·0	31·0	51·7	5·1 2·0	4·72	13·6	3·0 1·2	3·86	8·96
2		hardened top ring							1·0 0·4	4·08	12·6
3		molybdenum-sprayed top ring	83·8 33·0	137	173						
4		plasma-sprayed chrome top ring	55·9 22·0	21·0	37·8						
5		all rings bainitic structure	29·7 11·7	37·0	52·5						
6	standard, but banded with molybdenum (sandcast)	standard	20·3 8·0	30·1	51·7	0·6	5·44	13·5			
7		all rings hardened	9·9 3·9	27·0	103						
8		hardened top ring	11·9 4·7	21·6	52·2						
18	2 per cent Ni/Cu (centrifugally cast)	standard	52·8 20·8	31·6	59·9				2·0 0·8	2·38	4·12
19		hardened top ring							2·0 0·8	2·80	7·40

The cobalt/tungsten carbide banded liner gave enormous rates of ring wear because the very hard particles of tungsten carbide in a softer corrosion-resistant matrix almost machined the ring surfaces. The band surface finish was too coarse and results might have been better with a finer finish.

Thus, only the molybdenum-banded liner sprayed on with an oxy-acetylene gun shows a substantial gain in liner wear, with both straight and additive oils. This is a greater gain than given by either the austenitic or 2 per cent nickel/copper plain liners except as regards ring wear when using the additive oil with the 2 per cent nickel/copper liner.

c) *Ring Pack Variations*

Table XV gives the results of the ring pack variations extracted from Table X. These tests were carried out with the standard Va/Ti liners, the molybdenum-banded Va/Ti liner, and also a liner in the 2 per cent nickel/copper material.

The outstanding feature of these tests was the beneficial effect of a hardened top ring in the standard liner, plain or molybdenum-banded, and using straight or additive lubricating oil. The plain liner wear with a straight oil is reduced to 60 per cent with bainitic-structure rings of intermediate hardness, and to 33 per cent with the additive oil using a plain hardened top ring. Similarly if a hardened top ring is used, the Va/Ti molybdenum-banded liner wear is reduced to 59 per cent of the wear with a standard unhardened top ring (using the straight oil).

The molybdenum-banded liner wear using the hardened top ring, as compared with the wear of the plain standard Va/Ti liner with standard ring pack, is reduced to 25 per cent while using the straight lubricating oil. Had this combination been run on the Alexia 40 oil the improvement might have been even greater in view of the marked effect of the hardened top ring in the plain liner. However, the contradictory result is the lack of response of 2 per cent nickel/copper material to the hardened top ring using the additive oil. It must therefore be concluded that the gain due to the hardened top ring applies only to certain liner materials. It would have been interesting to try the austenitic material with a hardened top ring.

Rather unexpectedly, if all the rings were hardened the wear of the lower rings increased, but not that of the liner (see build 7).

The molybdenum-inlaid rings failed due to the filling coming away and causing additional abrasion. This was a little surprising since the liner temperature is not high at the limit of top ring travel, i.e. 120°C at 70°C jacket temperature (see Fig. 7). It is known that sprayed molybdenum may disintegrate if the top-ring temperature exceeds 250°C. For this reason a second batch of rings was tried, but there was no improvement.

Somewhat disappointingly, the plasma-sprayed chrome ring showed no liner-wear gain to match the reduced wear rate of the top ring.

It is interesting that the ring pack consisting of all bainitic-structure rings with a hardness of 270 Brinell, which is intermediate between the normal pearlitic-structure soft and hard rings, gives a result similar to that which might have been expected by fitting a normal pearlitic-structure hard top ring, i.e. liner wear reduced to 59 per cent with little change of ring wear, as compared with the standard ring pack. Not only the hardness, but the bainitic structure itself may be having an influence.

d) *Effect of Additive Oil on Wear and Wear Correlation*

Table XVI is an abstract from Table X of those builds with which running was carried out with both lubricating oils. It will be seen that the liner wear rate on the 500-hour tests with Alexia 40 when compared with the rate on the straight oil over a 100-hour test for the same build, varies from 1/9 with the no. 2 liner material to 1/26 with the 2 per cent nickel/copper material. The total ring wear ranges from 1/4 to 1/14 with the

TABLE XVI—EFFECT OF ADDITIVE OIL ON WEAR AND ON WEAR CORRELATION (EXTRACTED FROM TABLE X)

Build			R.445			Alexia 40					
			100 h: 270 cm³/h			100 h: 270 cm³/h			500 h: 100 cm³/h		
no.	liner (all centrifugally cast except standard)	rings	liner wear, mm × 10² in × 10³ / 1000 h	ring wear, g / 1000 h top ring	total	liner wear, mm × 10² in × 10³ / 1000 h	ring wear, g / 1000 h top ring	total	liner wear, mm × 10² in × 10³ / 1000 h	ring wear, g / 1000 h top ring	total
1	standard Va/Ti	standard	50·8 20·0	31·0	51·7	5·1 2·0	4·72	13·6	3·0 1·2	3·86	8·96
6	standard, but banded with molybdenum		20·3 8·0	30·1	51·6	1·5 0·6	5·44	13·5			
12	no. 1. unhardened		52·8 20·8	34·7	63·0				4·1 1·6	3·26	8·88
13	no. 1. induction-hardened		54·4 21·4	31·7	61·4						
14	no. 1. plasma-hardened								2·5 1·0	3·76	10·5
17	no. 2.		74·1 29·2	35·4	51·2				8·1 3·2	5·40	12·1
18	2 per cent Ni/Cu		52·8 20·8	31·6	59·9				2·0 0·8	2·38	4·12

same materials. The standard build lies in between, with a liner wear of 1/16 and a total ring wear of 1/6. These wear ratios are not valid except for comparison between builds because of the longer period of the run on the anti-corrosive oil which has the effect of giving a lower mean wear rate as compared with a 100-hour period. They are of interest however because they show that Alexia 40 has an effect which varies with the material combination.

For directly comparative 100-hour runs the standard build gives 1/10 the liner wear and 1/4 of the total ring wear, and the molybdenum-banded liner 1/13 the liner wear and 1/4 of the total ring wear. It is clear therefore that the standard build returns a slightly higher rate of wear on these shorter runs, in spite of the higher rate of lubricating-oil supply. This is supplementary evidence to that of Table XI, namely that the reduced 100 cm³/h rate of supply has no appreciable effect on the wear rate of the standard build running on Alexia 40 lubricating oil, since the reduction in wear rate resulting from the longer 500-hour runs is of the order expected from the longer duration of the run.

These results do show that the effectiveness of the additive oil varies considerably with the liner material and ring pack. Nevertheless the molybdenum-banded liner still remains the best and the no. 2 liner material the worst that was tested on either oil, bearing in mind that a 500-hour test on the molybdenum-banded liner would have yielded a lower liner wear rate of about 0·01 mm or 0·0004 in/1000 h.

Summary of Best Results with Comments

A comparison of the rates of liner and ring wear with the standard build shows that:

i) A molybdenum-banded liner with the standard ring pack reduced liner wear to 30 per cent (with Alexia 40 lubricating oil).

ii) A hardened top ring in the molybdenum-banded liner reduced liner wear to 59 per cent of the rate with the standard ring pack using the straight lubricating oil. Hence with the Alexia 40 oil a liner wear rate of the order of 59 per cent × 30 per cent, i.e. 18 per cent of the standard build, might be expected.

iii) A hardened top ring in the plain standard liner reduced liner wear to 33 per cent (with Alexia 40 lubricating oil). However, total ring wear increased by 41 per cent.

iv) A 2 per cent nickel/copper liner material reduced liner wear to 67 per cent and total ring wear to 46 per cent (with Alexia 40 lubricating oil).

v) An austenitic liner material reduced liner wear to 65 per cent (with straight lubricating oil).

vi) A bainitic-structure ring pack with peripheral surfaces of intermediate hardness, reduced liner wear to 59 per cent (with straight lubricating oil).

vii) A plasma-sprayed chrome top ring reduced top-ring wear to 68 per cent of the rate with the unhardened ring (with straight lubricating oil).

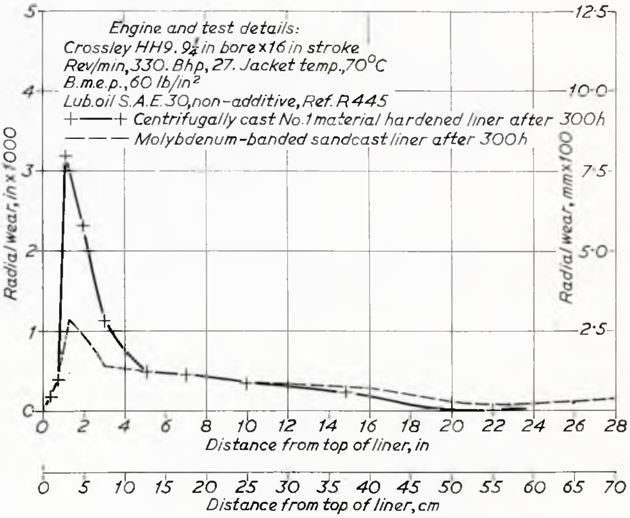

FIG. 15—*Curves showing radial wear profiles of centrifugally cast no. 1 material hardened, and molybdenum banded sand-cast liners*

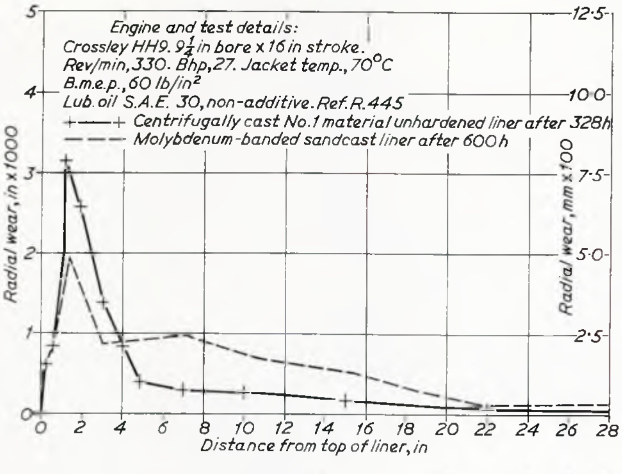

FIG. 16—*Curves showing radial wear profiles of centrifugally cast no. 1 material unhardened, and molybdenum banded sandcast liners*

These results show that the molybdenum-banded liner gives the best results. However, it must not be forgotten that the gain in reduced wear is limited to the banded portion, see the liner-wear profiles of Figs. 15 and 16. Since the cost of banding full-size liners would be high, it might be better to explore the cheaper solutions first.

CONCLUSIONS

Influence of Jacket Temperature

The tests show that the rate of wear is influenced strongly by the temperature of the coolant; the wear improves as the temperature is raised even up to the limit so far explored of 95°C (203°F). This suggests most strongly that corrosion by condensed acids of combustion is a very important factor in the mechanism of wear.

It is well established from service experience that high-alkalinity cylinder lubricating oils materially reduce wear, as was also the case in the Crossley engine. This further indicates that acid attack is a major factor in wear. The important finding in the Crossley tests was that even when using a high-alkalinity oil the rate of wear continued to diminish as the temperature of the coolant was raised, in the same way as when using a straight lubricant. This implies that the wear still occurring with these special oils remains in some measure corrosive and therefore the use of the elevated jacket temperatures or perhaps of still higher alkalinity levels in the lubricant would be advantageous.

Tests with split coolant jackets when using both straight and special oils have shown the importance of maintaining the outer sections of the liner at as high a temperature as possible, even though the maximum wear occurs in the inner section of the liner. The use of higher coolant temperatures in the outer sections where thermal, mechanical, and lubrication problems are light should be a practical possibility.

Influence of Fuel Composition

This series of wear tests on fifteen fuels having a wide range of composition has confirmed the importance of the sulphur content of the fuel in relation to cylinder wear. However, the tests also indicate that those characteristics of the fuel giving rise to cylinder deposits, Conradson carbon value, and ash content for instance also contribute to a marked extent to the wear. Thus with a poor quality residual fuel having a high Conradson number it is believed that nearly half the rate of wear may be associated with the carbonaceous and ash deposits.

There is some evidence to support a formula relating wear to fuel composition of the form

$$\text{wear} \propto \text{sulphur}\left(1 + 5\left(\text{ash} + \frac{\text{Conradson}}{100}\right)\right)$$

but the scatter of the results scarcely justifies this approach at the present time and the simpler formula

$$\text{wear} \propto \text{sulphur} + \frac{\text{Conradson}}{4}$$

gives a measure of the relative importance of these two components in typical residual fuels.

Influence of Centrifugal Cleaning of the Fuel

Of seven different fuels investigated, from widely different sources, and giving rise to widely differing wear rates, six showed no significant difference in cylinder-bore and piston-ring wear between their uncleaned and double-centrifuged states when tested in the Crossley H.H.9 engine.

The seventh fuel, which was an exceptionally dirty specimen, yielded a reduction in wear of some 26 per cent as a result of double centrifuging. However, the quantity of solid material removed by each individual centrifuge strongly indicates that a single stage would have provided a sufficient degree of fuel cleaning to have produced no further reduction in wear as a result of the second stage. This in turn leads to the conclusion that a single centrifuging stage or an equivalent system of filtration, would provide a degree of fuel cleaning entirely adequate on the score of cylinder-bore and piston-ring wear.

Influence of Ring and Liner Material Using Both Straight and Anti-Corrosive Lubricant (wear measured directly and not by iron recovery)

For directly comparative 100 hour runs, a high basicity lubricating oil reduced the liner step wear rate by 10 : 1, top ring wear rate by 6 : 1 and total ring wear rate by 4 : 1 with the standard sandcast vanadium/titanium liner and standard unhardened rings. (As was the case for all this work the reference fuel contained 3·2 to 3·4 per cent of sulphur).

This is a much greater wear reduction than the material changes from the standard build show. The molybdenum banded liner with a hardened top ring gives a liner wear rate reduction of 5 : 1 and plain liners with various other rings between 1·5 to 3 : 1. Top ring and total ring wear is not reduced by more than about 1·5 to 2 : 1 by any build.

However, what the direct drive engine needs is ring wear reduced by about 10 : 1 and liner wear by only 2 or 3 : 1.

Material changes may give the necessary liner wear rate reduction. Those the tests suggest as worthy of trial are a hardened top ring, a chrome top ring, an austenitic liner, or a hardened liner with unhardened rings. Costly recourse to liners banded with molybdenum does not seem justified if plain liner materials together with perhaps special rings will give the required wear rate reduction.

The 2 per cent nickel/copper liner shows some promise in these tests when used with the anti-corrosive oil, but Doxford(7) did not find any gain in their "J" engine when using this material.

It is clear from the ring wear tests that no build tried yielded the some 10 : 1 reduction in radial top ring wear that the direct drive engine ideally requires.

These conclusions led the authors to the following thoughts for future investigations.

POSSIBLE FUTURE LINES OF ATTACK ON PISTON RING AND CYLINDER LINER WEAR IN DIRECT DRIVE MARINE ENGINES

Hard or Hard Surfaced Top Rings

In the tests on materials a plasma sprayed chrome ring reduced both liner and top ring wear. However such rings have been tried in the large engines without much success because the chrome wears off rapidly at the horns of the ring. One explanation is that the horns become overheated as a result of the blast of hot gas through the gap which starts life at about 8 mm in width. It then softens and wears more quickly. The chrome thickness would not normally be more than 0·25 mm.

It would appear worth trying hardened flake cast iron or hardened nodular iron rings. Perhaps even hardened steel top rings or rings cast in a Stellite.

Various new hard surfacings are available for the piston rings of truck engines, and the most promising of these could be assessed on the direct drive engine top rings.

Hard Surfacing of the Grooves

One would imagine that any measure that reduces the rate of groove wear will help towards reducing ring radial wear. The latter might be expected to increase as the side clearance increases, although if the side clearance is inadequate in the erection of the engine, this can cause increased radial wear as Hosie and Schrakamp(8) have recorded.

The view of the authors is that chrome plating of the lower side or both sides of the grooves must help to reduce top ring radial wear.

Cylinder Lubrication

One of the causes of rapid ring wear is uneven lubrication. With eight quill points the distance between them is about 400 mm or 16 in. Oil may not spread to the mid positions, and the surfaces blacken with lacquer formation here which is the usual sign of corrosive wear occuring because there is not sufficient alkalinity present(8). The lacquer hides increased corrosive wear which can amount to anything up to ten times the wear at the oil feed points in severe cases. Suitable oil spreading grooves greatly improve this uneven wear.

Efforts to obtain more even lubrication have been made. Doxford used a timed system using higher pressure fuel type injectors as described in Butler's 1962 Cimac paper(9). However the benefit was marginal.

The position now is that some engines use timed feeds and some not. Some inject every revolution and some every so many revolutions, since it is easier to meter accurately a larger injection quantity every so many revolutions when using some eight to twelve quill points.

Perhaps the ideal method would be to use a timed injection through one of the ring grooves, the top if possible, with either the clearance adjusted to give an even supply of oil around the periphery, or using a minimum side clearance plus a large number of small radial grooves cut across the face of the ring.

While on this subject it must be said that the authors find it difficult to dismiss the probability that the lower wear rates in the four cycle medium speed trunk engines are related to the more evenly spread lubricating oil film resulting from the absence of scavenge ports and the copious splash lubrication flung at the piston from below, also the reversal that the rings get on the idle stroke probably gives better lubrication to the undersides of the top rings.

Elimination of Wear Rate Variation

As Table I indicates, in direct drive engines the liner step wear rate limits are given as from 0·05 to 0·15 mm, and the top ring radial wear rate limits from 0·25 to 0·75 mm.

This is a large variation, more effort could be put into reducing it. An investigation could be made into the causes of the variation and the sometimes wide differences in wear between the cylinder and rings of the same engine. This could yield information which would greatly help towards bringing the wear rate variations closer to the lowest figures.

Top Rings with Sealed Gaps

Baker, Casale and Sloan(10) have shown in a 203 mm (8 in) bore crosshead two cycle test unit that the liner temperature at T.D.C. rises 100°C or more at the gap as a result of the blast of gas here. There are certain types of ring gap which do hold gas pressure. These might materially improve the conditions of lubrication of the top ring. Top rings do rotate(11), so that the fully sealing gap would stop the high temperature blast from a top ring gap of some 25 mm (towards the end of the life of the ring) from rotating round the bore and scouring off the oil film locally. It is believed that fully sealing gaps unload the lower rings considerably, so that some gas leak paths from the top groove to the second ring might be found beneficial though not necessarily essential.

Reduction of Abrasive Wear from Combustion Products

While corrosive wear has been dealt with in some measure in the foregoing, one should not lose sight of the abrasive aspect.

The Crossley engine, when running on residual fuel and using the untreated lubricant, showed perfectly clear and very distinct evidence of abrasive wear of the piston rings, the peripheral faces of which were invariably liberally covered with longitudinal score marks.

Since centrifuging the fuel had, generally, no effect on wear rates, this abrasion was not the result of particulate contamination of the fuel.

On changing to alkaline lubricating oil the appearance of the ring peripheral faces changed to a more normal polished surface, with none of this bad scoring, thus confirming that it was not caused by abrasive material in the fuel that had passed through the centrifuges, and also establishing that abrasive material was being generated in the combustion zone. While this material may have been wear debris released as a by-product of corrosive attack, it is more likely that it was detached fragments of cylinder deposit.

The latter theory has some support from the fact that when attempting to run sandwich tests to compare wear rates with residual and distillate fuels, very high rates of wear were experienced in the latter parts of the tests, coupled with severe ring scuffing and sporadic audible ring blowing. Inspection of the piston immediately following such an incident of piston blow disclosed fresh scuffing directly in line with an area on the crown land where deposits had just broken away.

Cotti and Simonetti(2) reported a correlation between lubricant sulphated ash and wear on Fiat engined tankers operating on low sulphur (0·4 to 0·5 per cent) residual fuels, while Cook(12) demonstrated on a Petter AV-1 oil test engine running on 1·0 per cent sulphur reference gas oil that while a dramatic reduction in wear was achieved by increasing the lubricant total base number up to approximately 17, further increases in alkalinity produced an increase in wear rate.

The foregoing suggests that the effect of deposits on wear is worthy of closer study:

1) from the chemical standpoint;
2) by rethinking the engineering of the lubrication.

With regard to the latter, in the interest of reasonable economy, oil feed rates to the pistons of cross-head engines are low, and the cylinder drainings are normally discharged as a paste. It may in fact, be mild grinding paste due to the concentration of hard deposit material. A considerable increase in oil supply, with an appropriate reduction in alkalinity to preserve a satisfactory balance between basicity and fuel sulphur content, would help to wash abrasive matter clear.

Ring wear, at present rates, has a greater nuisance value than bore wear in these engines, and a possible attack on this problem would be to introduce the lubricant, not through cylinder quills as at present, but as has been suggested above, through a timed feed to the piston interior and thence from the backs, or preferably through the sealing faces, of the top ring grooves, in order to lubricate these rings with oil uncontaminated by abrasive material from the combustion chamber.

ACKNOWLEDGEMENTS

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CONVERSION FACTORS TO ASSIST COMPARISONS WITH DATA IN IMPERIAL UNITS

(Correct to 5 significant figures)

Length
1 km =0·53961 U.K. nautical mile
1 km =0·53996 International nautical mile
1 m =0·54681 fathom
1 m =3·2808 ft
1 mm =0·039370 in
1 µm =0·039370 mil

Area
1 m^2 =10·764 ft^2
1 mm^2 =0·0015500 in^2

Volume
1 m^3 =35·315 ft^3
1 l =0·21998 gal

Section Modulus
1 m cm^2 =0·50853 in^2 ft
1 cm^3 =0·061024 in^3

Second Moment of Area
1 m^2 cm^2 =1·6684 in^2 ft^2
1 cm^4 =0·024025 in^4

Frequency
1 Hz =1 c/s

Speed
1 km/h =0·53961 UK knot
1 km/h =0·53996 International knot
1 m/s =3·2808 ft/s

Acceleration
1 m/s^2 =3·2808 ft/s^2

Mass
1 tonne =0·984207 ton
1 kg =2·2046 lb

Specific Volume
1 m^3/tonne =35·881 ft^3/ton
1 l/kg =0·016018 ft^3/lb

Mass Flow
1 tonne/h =0·98421 ton/h
1 kg/h =2·2046 lb/h

Volume Flow
1 m^3/min =35·315 ft^3/min
1 m^3/h =3·6662 gal/min
1 l/h =0·21998 gal/min

Density
1 g/cm^3 =0·036127 lb/in^3
1 g/l =0·062428 lb/ft^3

Moment of Inertia
1 kg m^2 =23·730 lb ft^2
1 kg cm^2 =0·34172 lb in^2

Momentum
1 kg m/s =7·2330 lb ft/s

Moment of Momentum and Angular Momentum
1 kg m^2/s =23·730 lb ft^2/s

Force
1 kN =0·10036 tonf
1 N =0·22481 lbf

Moment of Force
1 kN m =0·32927 tonf ft
1 N m =0·73756 lbf ft

Pressure
1 bar =0·98693 atm
1 bar =14·504 lbf/in^2
1 mbar =0·029530 in Hg
1 mbar =0·40147 in wg
1 µbar =1 dyn/cm^2

Stress
1 hbar =0·64749 tonf/in^2
1 hbar =1450·4 lbf/in^2

Absolute or Dynamic Viscosity
1 cP =10^{-3}N s/m^2
1 kg/m s =0·67197 lb/ft s

*Kinematic Viscosity**
1 cSt =10^{-6} m^2/s
1 m^2/s =10·764 ft^2/s

Energy (Work, Heat)
1 kWh =1·3410 hp h
1 kJ =0·94782 Btu
1 J =0·73756 ft lbf

Power
1 kW =1·3410 hp
1 W =0·73756 ft lbf/s
1 W =3·4121 Btu/h

Fuel Consumption Rate
1 kg/kWh =1·6440 lb/hp h

Absolute Temperature
°F =9/5 K − 459·7
°R =9/5 K

Celsius Temperature
°F =9/5 °C + 32

Temperature Interval (°C)
1 °C =9/5 °F

Linear Expansion Coefficient
1 °C^{-1} =5/9 °F^{-1}

Heat Flow Rate
1 kW =0·94782 Btu/s

Specific Energy, Calorific Value, Specific Latent Heat
1 kJ/kg =0·42992 Btu/lb

Specific Heat Capacity
1 kJ/kg °C =0·23885 Btu/lb °F

Specific Entropy
1 kJ/kg K =0·23885 Btu/lb °R

Density of Heat Flow Rate
1 W/m^2 =0·31700 Btu/ft^2 h

Volumetric Heat Release Rate
1 W/m^3 =0·096622 Btu/ft^3 h

Coefficient of Heat Transfer
1 W/m^2 °C =0·17611 Btu/ft^2 h °F

Thermal Conductivity
1 W/m °C =6·9335 Btu in/ft^2 h °F

Prefixes (in order of magnitude)
tera T =10^{12}
giga G =10^{9}
mega M =10^{6}
kilo k =10^{3}
hecto h =10^{2}
deca da =10
deci d =10^{-1}
centi c =10^{-2}
milli m =10^{-3}
micro µ =10^{-6}
nano n =10^{-9}

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* *Diagrams for converting Redwood and Saybolt seconds, Engler degrees, and Barber fluidity are given in standard text books, e.g. H.M. Spiers' 'Technical Data on Fuel'.*

Unchanged Factors
Plane angle Angular velocity Time Angular acceleration Rotational speed

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Discussion

MR. B. TAYLOR, M.I.Mar.E., said that the subject of the evening's paper was one of great interest to all builders of marine engines and to all operators, but it was one which was complicated by many factors which could influence the wear rate of cylinder liners and piston rings. The authors had been successful in isolating a number of important factors, but there were others more elusive, as indicated by the wide variation in wear rates to be found from one engine to another of similar type, performing under similar conditions, or even in the same engine. The authors had done an excellent job, and were to be congratulated on the presentation of the results of a most systematic and comprehensive piece of research carried out over a period of more than ten years.

He agreed with the authors that in slow speed engines radial ring wear, and ring breakage, were the most important problems to be faced in regard to maintenance and reliability. Since the introduction of chromed grooves in the pistons, groove wear was no longer a serious problem. In the Doxford engine they found that they got a groove wear rate averaging about 0·003 in per 1000 hours for grooves which were chromed on the lower face only.

They also concurred with the authors in the figures given for liner wear, varying between 0·002 to 0·006 in per 1000 hours and confirmed the rate of top ring wear in the lower piston of Doxford engines, which approached ten times the rate of liner wear. In the upper piston the wear rate was only about half this figure, and also in the rings below the top ring in the lower piston the wear was very much reduced. These differences in wear rate between the firing rings of the upper and lower pistons could probably be accounted for by the fact that the upper piston of the "J" engine had only about one-third of the stroke of the lower one.

All the figures which he had mentioned were, of course, for standard cylinder liners with normal cast iron piston rings. It had been the practice to use a vanadium cast iron for many years, but at the same time they had carried out experiments with a variety of different liner materials and, as one could appreciate, to do this in service could be a very expensive exercise. It was a pity that the results of this investigation had not been available a few years earlier.

A first reaction, on reading the paper, had been some doubt as to the validity of the results obtained from a relatively small four stroke engine when considering the conditions in a large two stroke engine. On reading of the method of comparing wear by measurement of the iron content of the oil sludge from the cylinder, he had been even more doubtful. However, after studying the figures given in Table III and plotted in Fig. 5, he had been convinced that the findings of the investigation could be applied to the large slow speed engine, and in fact many of the conclusions drawn had been borne out in practice, e.g. the influence of jacket water temperature.

The authors had shown the importance of avoiding overcooling the lower end of the liner remote from the combustion zone and in this connexion a significant change in design which had been adopted in the "J" engine was to reduce the length of the water jacket. The latest Doxford engine had a shortened jacket so that only about 25 per cent of the lower liner was water cooled. The remaining part was not cooled, and consequently a more even temperature distribution along the length of the liner was maintained. So although the dotted line shown in Fig. 7 indicated the temperatures found in an early Doxford engine, the picture today was very different, and the temperatures in service approximated much more closely to the curve which showed the liner temperature of the experimental engine with a jacket water temperature of 70°C.

These changes, together with others, had made a significant improvement in liner wear.

There was no problem in maintaining the cylinder wall temperature at the inner zone, and in the large engine the problem was to avoid over-heating in this area because of the relatively thick wall which was required in the large cylinder liner. But over the years there had been improvements in the cooling arrangements and tests had now shown that the maximum temperature of the liner wall at the inner end of the stroke was of the order of 170/180°C.

Probably the most striking conclusion of this work was the one in which the authors had stated that centrifuging of normal residual fuels had no effect on the rate of wear. But he was pleased to note that they did not advocate dispensing entirely with treatment of the fuel. It was now common practice to dispense entirely with clarifying the fuel oil and to have single stage centrifuging. Quite a number of companies had adopted this practice for a number of years. This fell in line with the recommendation made by the authors but he considered that filtration or single centrifuging of the fuel was necessary to maintain satisfactory performance of the injection equipment and fuel pumps. Inadequate filtration of the fuel could lead to serious trouble by sticking of the fuel pump plungers or injectors, causing inefficient combustion which, in turn, led to fouling of the engine and to turbo-charger problems.

The results given for the centrifuging of the different fuels (Tables V and VI) needed some careful study. The very wide range in the proportion of insoluble material contained in the damp sludge removed from the various fuel samples was striking. It was therefore all the more remarkable that treatment of the fuel had had no apparent affect on wear. The authors concluded that the quantity of damp sludge removed by the purifier might safely be ignored in relation to wear in the engine. This might be true, but it could not be ignored in other respects, because there was a sufficient amount of evidence to suggest that when a greater amount of sludge was removed by the purifier there was a greater chance that fouling of the engine would be a problem. Water content of the fuel seemed to be a major factor in fouling of the engine.

Dealing with ring and liner materials, he was sorry to note that there were two important omissions, on which it would have been very useful to have had some comparisons: cylinder liners with chromed bores and piston rings of nodular cast iron. Mr. Taylor's company were getting satisfactory results from rings in spheroidal graphite iron, but he had not yet got any figures which he could quote. Similarly, with chromed bores, he had not got any definite figures; up to two or three years ago evidence suggested that there was no particular advantage, but he believed that some operators had had extremely good results. It was most interesting to note that the Va/Ti iron, which had been in use for the last forty years (as far as he knew) when used with a hardened top ring, had given the best results. He agreed that the use of molybdenum banded liners could not be justified on the score of cost and also from the point of view of production.

Reference was made to spun cast liners containing two per cent nickel/copper. Since the figures published a year or two ago(7) more information had become available, and over a period approaching 30 000 running hours, it appeared that this material gave better results than the standard vanadium iron. Its average wear rate was about 75 per cent of the normal iron; but again the wide variation from one cylinder to another should be stressed. These results were based on only three cylinder liners in a nine cylinder engine, so probably it was rather unwise to draw too definite conclusions. The other point about spun cast liners was that, from the production aspect, they had advantages because of the soundness of the castings. The scrap rate in centrifugally cast liners was extremely low.

Finally, he would make reference to the use of alkaline lubricating oils. This matter had been discussed at length from the platform on a number of occasions. He thought that the results presented by the authors that evening brought home only too well the tremendous difference which resulted from the use of these sophisticated cylinder oils. An oil with a TBN number of 70 was now normally used with very satisfactory results.

The authors did not comment on the effect of variation of the feed rate of lubricating oil given in Table XII, where the rate had been varied by as much as 4:1, with no significant effect on the wear rate. He was quite sure that if they were to do that, the results would be rather disastrous.

Mr. A. D. Ruscoe, M.I.Mar.E., said that in the low speed engines referred to in this paper, surveys had been carried out in the past with the object of arriving at causes of wear, but these had invariably ended up as a collection of data telling little more than what the average wear had been over a long period of time in a wide range of engines under varying and unspecified conditions.

The majority of wear might well occur during unsteady conditions, e.g. manoeuvring, or when over loaded in heavy seas, and it seemed that really useful service data could only be expected when techniques were available to enable the measurements to be taken over a very short period. That had been done with radio active rings in a 760 mm, Götaverken, as reported by Pinotti *et al.*(13). Such tests were, for safety and other reasons, very difficult to mount, and had still to be extended to liner wear. So the next best solution was to run closely controlled bench tests, and this was what the authors had done so successfully.

Combustion of H.F.O. required time and space, both of which were relatively small in the engine used for these tests. At first, this engine would hardly run at all on this fuel, but not only did the authors succeed in developing the engines to do so but to do so consistently, which was a great deal more difficult.

It had been said, in connexion with other investigations, such as fatigue tests where a large scatter could be expected, that if you wanted only one answer you did only one test. The authors had done better than this, and had not been afraid to carry out careful checks. Excellent consistency for this kind of test had been obtained, as was borne out by a comparison of the results given in the original report for the separate 100-hours runs.

Another example was the sandwich tests at 70° and 30°C (Fig. 6). The consistent results obtained in such short tests, where the amount of wear was tiny, must be attributed to two things—know-how in running the engine and a well developed method of measuring the wear.

In this connexion, the device shown in Fig. 2 was noteworthy in that it was easy to set up, read directly from one gauge, and measured radial wear. This last feature largely eliminated readings confused by diametral distortion, which must often be responsible for anomalous results obtained in service; the latter were invariably based on only two diametral measurements. It seemed unlikely that axial distortion of the liner took place sufficiently to confuse the issue and, in any case, the most important measurement at the top of the liner was near the points of support on the unworn part. It did seem that, by having these two feet at the outer end of the liner and one at the top end, a further small theoretical improvement could have been made. If the gauge could not be traversed down to the unworn part of the liner to give a second datum from which wear all down the liner could be deduced, then it appeared that putting the fixed feet on the top side in Fig. 3 and the sprung feet on the lower side would have again given a small advantage in that the effect of diametral distortion at the outer end of the bore would have been largely eliminated. Certainly this method was subject to less error and difficulty than, for instance, the diamond impression as a means of eliminating the effects of distortion.

The split liner jacket tests had been very instructive. It might be thought that reversing the direction of the coolant flow usually found in large engines i.e. from bottom to top, might help matters in service, but the rise in coolant temperature through the engine must usually have been so small that this would not have been worthwhile. As stated in the paper, Cotti and Simonetti could take no account of the sweeping action up the liner. Schultze (14) had measured the electrical potential between the ring and liner in a Bolnes engine, and this broadly followed the wear profile. It might be asked why acid should not be swept down as well as up, and why it should not evaporate in the higher temperature zone. Muller (15) had shown that if the wall temperature were above the dewpoint, then acid of high concentration would be formed, but also pointed out that such high concentrations would be less aggressive.

On filtration, the last speaker had mentioned filters being used instead of centrifuges, for fuel preparation. In one land installation where this had been done, large settling tanks were used in case the sinter filters could not be relied on to do this.

It was interesting to see a reference to McConnell and Nathan's paper which, he believed, compared heavy fuel oil with gas oil having a sulphur content artificially increased to about the same level as that in heavy fuel oil. The latter gave less wear, and their hypothesis was supported by the authors' work in that, even with lubricants of high basicity, increasing the coolant temperature had still reduced wear, which suggested that very much the greater part had been caused by corrosion. To fit McConnell's results, this would have meant that asphaltenes had caused wear largely through the medium of sulphur, in other words, the first of the authors' formulae on page 400 would be scientifically more justified.

On page 404 it was stated that 30 hours of run in on a straight oil had been carried out before runs on the Alexia 40. It could take some 36 hours for the rate of wear to stabilize after changing oils, as was shown some years ago by Caltex in a Bolnes engine (16). The authors had taken the precaution of dismantling the engine and cleaning it. This appeared to have effectively eliminated the carry-over effect.

In comparing the rates of ring wear, total ring wear had been used. In service it was the ring with maximum wear, i.e. invariably the top one, which dictated piston pulling. Should not this have been quoted rather than wear for the whole pack? This might not be very significant here, but one did have to work through the table to check this. It did alter the percentage changes quoted, and put a different complexion on paragraph (iii) about the hardened top ring in a plain liner. It was generally the custom to change all rings in service rather than moving them up the piston and discarding the top one. The authors had quoted the maximum wear for the cylinder liner rather than the average taken down its length, and this was right.

Had not the high friction reported for the Colmonoy 5 banded liner been due to the hard particles being left slightly proud in grinding, and acting as an abrasive, as mentioned by the authors in their comment on the cobalt/tungsten banded liner on page 406 ?

The choice of viscosity grade for the cylinder lubricant of crosshead engines had always seemed a little arbitrary. At one time an SAE 30 grade had been used in certain engines for no other reason than that the lubricating pump, when worn, would not pass sufficient oil of heavier grades than this. One wondered if, all other things being equal, lighter grades would have spread better, possibly at the expense of a thinner film. Could, for instance, the improved wear reported at higher liner temperatures have been partly attributed to better spreading, bearing in mind that the test engine had only one quill? Did the authors' wear measurements reveal more even wear at high temperatures in the circumferential direction? Would a change in viscosity characteristics have been a means of improving the ratio ring/liner wear which they felt was desirable? If oil were fed to the top ring groove, what would happen if the ring broke? The dwell time would be very great. Would it not be better to introduce oil at the outside diameter of the land?

If the so-called gas-tight rings did their job, they tended to take too great a share of the load, and gave rapid wear. The complicated butts tended to be more vulnerable.

Regarding grooves, Mr. Ruscoe echoed the authors' comments on the effect, right from new, of chroming on ring/liner wear, due to the lowered coefficient of friction and the lack of adherence of carbonaceous deposits. Some years ago they had gone to considerable trouble in collecting groove wear data from service and evaluating some figures of typical wear. It was gratifying to see those confirmed in the authors' Table I.

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Mr. N. Fletcher said that it was not often that engine designers were successful in over-cooling thermally loaded components, but he noted from Mr. Taylor's contribution that Doxford's development engineers had now been able to exploit this potential by an increase in engine rating.

The questions arise as to whether large reductions in wear rate would have occurred in changing from mineral oil to high alkalinity oil, if the upper liner temperature had been more representative of those found in other engines, and also if wear would have been reduced by raising the lower part of the liner temperature if the upper liner temperature had the more typical value of 200°C.

With regard to the latter point, his experience on a number of industrial applications where latent-heat cooling was employed in which the jacket water temperature was 120°C instead of the usual 75°C was that a significant reduction in liner bore wear did occur, thus supporting the authors' work.

Another parallel problem was that of corrosive damage in the combustion chamber, in the form of cold corrosion of the fuel nozzle tip, particularly when operating on high sulphur fuels. A recent investigation carried out in conjunction with Mr. Fletcher's company's fuel injection equipment manufacturer had shown that at light load the nozzle tip temperature had been approximately 120°C. Nozzles which had suffered cold corrosion under these conditions had been examined using x-ray fluorescent techniques and had been shown to have significant deposits of sulphur which had again confirmed the authors' conclusions that corrosive damage could occur at this temperature. Raising the nozzle temperature or applying a noble metal protective plating both eliminated the damage, further confirming that it had been corrosive and not erosive.

In changing from mineral to high alkalinity oil, the paper recorded that there had been a change of viscosity grade and presumably also of viscosity index. Could the authors advise on the actual viscosity of the two lubricants at the ring/liner temperature as this could have a significant effect on the oil film thickness generated?

With regard to Fig. 6, the oil feed to the cylinder calculated out at about two-thirds per cent of the engine fuel consumption which was high by modern standards. Did the test engine show any signs of distress at the valve seat due to deposits of ash arising from such a high consumption of high alkalinity oil?

In attempting to reduce liner wear by raising the engine jacket water temperature, it was important to bear in mind that if a significant temperature difference was established between the cylinder block and the bedplate then the engine frame would hog. It had been his experience on latent heat cooled engines that crankweb deflexion readings between cold and hot conditions could change significantly and special aligning techniques must be used to counteract this effect.

Mr. A. J. S. Baker, A.M.I.Mar.E., congratulated the authors on having compiled a very useful range of data in directions which were all pertinent to the problems which affected engines burning heavy fuel. These data were more than usually useful in that they could be directly related between themselves, whereas in most cases it was necessary to attempt transpositions between engines types, if you wanted to use the data.

He believed that they were to be particularly commended in having stuck to their guns concerning the engine type used for this work, and he could well imagine that they had received plenty of criticism concerning the dissimilarities between their test engines and current marine practice. Nevertheless, he believed that they had demonstrated in convincing fashion that it was not so much the design of test equipment but the design of the experiments being conducted which was important. While the results might not be too directly comparable with those in other engines, the trends could be very readily perceived and one could apply them to other engine types.

Regarding the concept of wear comparisons by iron recovery, he could confirm that this worked quite well in other engines, as had been stated in Mr. Baker's paper to the Institute of Petroleum in 1964. They had found that it was possible to compare iron recovery in specific terms (g/bhp/g) and had done this between two engines of fairly large scale difference. They had assumed that each gram of oil, fed to the cylinder, had collected iron at the same proportion as that found in the drainings, although the draining recovery—or sludge—as reported in the paper had varied quite widely.

He had looked at some of the authors' results to see whether the comparison held good, and found that the specific iron recovery calculated in the same fashion appeared rather low, especially when account was taken of the number of shut downs involved by only running the engine for a portion of each day. Mr. Baker had always noted a fairly sharp temporary increase in wear rate each time a shut down had occurred, when they had monitored for iron in the drainings. This might have meant that the horizontal cylinder of the Crossley made better use of the lubricating oil fed to it than vertical cylinder test engines. Perhaps the authors had some thoughts on this? If, for instance, the cylinder oil draining rate loss to exhaust, for the Crossley, was lower, the same weights of iron would be distributed through a larger quantity of drainings and sludge.

This led him to page 409, in which future approaches for cylinder lubrication were mentioned. As the authors knew, he had advocated the admission of oil via the ring grooves for many different reasons. Principally, the changes of cylinder pressure were probably responsible for much of the fresh oil which was lost to the combustion zone simply because there was nothing to stop it being ejected from open ended liner quills by expanding gas in the extremities of the quill passages. On the other hand, oil entering the back of the ring grooves would have to pass the ring and crown land before it could be lost, and it seemed inevitable to him that a very high proportion of the oil would be deposited as a thin film on the working faces. Perhaps, in the written reply, the authors could go into the method of feeding oil on to the backs of the rings in some greater detail.

Regarding their comments on the possible reason for four stroke trunk piston engines returning lower wear rates than crosshead two strokes, he could not altogether agree that this was principally due to the absence of ports, although undoubtedly port losses of oil could be high in some cases. He believed that if care was taken to ensure sweeping or scraping of the oil to points outside the port belt, losses could be reasonably controlled. Moreover, it was not many years ago that he had had experience of a crosshead four stroke marine engine which had had very high wear rates and needed at least 1·0 g/bhp/h of oil for reasonably satisfactory operation. Where the four stroke trunk piston engine did score rather heavily in terms of wear was in the large amount of oil held around the working surfaces of the rings and liner. In addition, one must not lose sight of the fact that trunk piston engines tended to consume more oil than crossheads, and that virtually all oil lost departed by way of the exhaust, whereas the drainings collected from the crossheads could not be discounted from consumption because one could not use them again. The actual oil lost through the exhaust area was considerably less in the crosshead type.

MR. D. ROYLE, A.M.I.Mar.E., said that the authors, in a paper of this type covering a very complex subject, had stimulated those who had worked in similar fields to look very closely at the data presented that evening. Before making some detailed comments concerning the section of the paper dealing with the influence of the composition of the fuel on wear, there were two general observations concerning lubricating oil quality and liner wear rates which he would like to make.

The crosshead type engine had been found to operate with reasonable liner and ring wear performance with the alkaline cylinder oils of high basicity which came on the market during the 1960's. The medium speed trunk piston engine, either with or without cylinder lubrication, had been found to give the best results, not when using an oil containing only alkalinity but when alkalinity was combined with detergency. In other words, many of the lubricating oils used in these engines were at first nothing more than 30/40 TBN crosshead engine cylinder oils. However, more and more lubricating oil suppliers were formulating oils of 20/30 TBN. These oils were not cheaper than the 30/40 TBN oils because additional additives to give detergency and not necessarily basicity were being added. This concept of using essentially detergent type additives in crosshead type engine cylinder oils had never been completely satisfactory.

When discussing present wear rates in both crosshead and trunk piston engines, it should not be forgotten that engine powers had increased significantly over the past ten years. The fact that wear rates had not increased but were often at a lower level was due not only to improvements in liner and ring materials and lubricating oil quality, but also because of a very realistic approach made by the engine builders in reducing the thermal stresses within the engine. It might be possible to achieve conditions so that liners could be expected to last the life of the ship, but the economic factors could not be overlooked, and Mr. J. Schmidt-Sorensen (17) in the reply to his paper read at the Institute in 1971 had mentioned these other factors which should be considered. The correct decision might vary with each shipowner, depending on the trade of his vessel.

Turning now to the influence of the composition of the fuel on wear, the authors had used their data in a variety of ways to find some reasonable correlation.

There seemed no doubt that sulphur had a strong influence on wear, and the authors finally concluded that because of the spread of data the most practical formula was one which combined the sulphur and Conradson carbon.

Fig. 17 reproduced a figure contained in a paper read before the Institute in 1954 on the subject of "Fuel Features Related to Operating Experiences in Motor Ships Using Low Cost Fuels". The permanent liner wear rates were plotted against the average sulphur content of the fuels used and the figures in parenthesis indicated the average fuel ash contents. From these data it was concluded that liner wear rates increased with increasing amounts of sulphur and ash in the fuel. It would appear that the effect of the quantity of sulphur present was more pronounced than the ash, within the limits experienced.

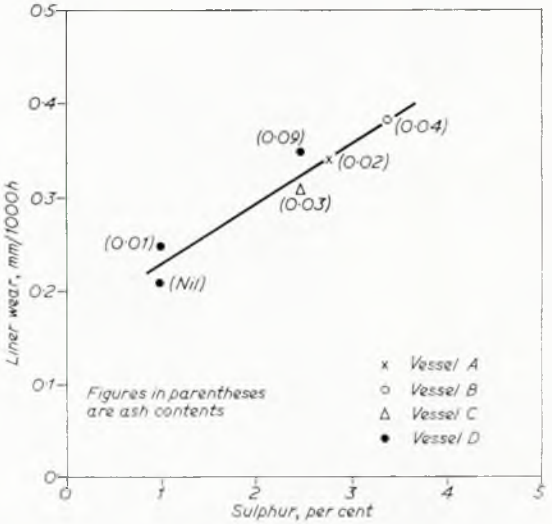

FIG. 17—*Effect of fuel sulphur and ash contents on liner wear rates*

At about the same time, Mr. P. Jackson of Doxfords had been postulating the belief that the combination of sulphur and Conradson carbon had been a critical factor and that a combined total of 14 should not be exceeded.

The authors' findings were very similar to these earlier predictions. However, there was some thought that asphaltenes were more important than Conradson carbon and, therefore, the authors' paper had been an excellent opportunity to study additional data.

The authors, in their graphs, when considering ash had used the uncentrifuged values, whereas there would seem to be a strong case for using the ash of the treated fuel, since this was the actual fuel used in the engine. Ash levels on treated fuel were not reported on all the fuels. It had been felt that the change in ash level would not be very significant on fuels with ash levels below 0·05 per cent, and these fuels could be retained in the study. However, it had been necessary to discard fuels 3, 4, 6 and 9, as the ash content was above 0·05 per cent, and they could not be sure what would be the effect of centrifuging.

Two fuels which never appeared to fit any of the authors' graphs were fuels 12 and 14. Looking at the source and pick-up points of these two fuels and with some other knowledge of the suppliers, it was a fairly reasonable assumption that these two fuels came from the same refinery and were from the same crude. The liberty had therefore been taken of averaging all the fuel inspection and engine wear data on these two fuels and assuming that it had all come from one fuel.

By means of a computer, Mr. Royle obtained the index of determination for a linear function using various formulae as shown in Table XVII. The index of determination was an indicator that determined how well the regression line fitted the observed data. An index of determination of 1·0 was a perfect fit.

TABLE XVII

Formula	*No. of points*	*Index of determination linear function*
$\text{Sulphur}\left[1+5\left(\text{ash}+\frac{\text{CC)}}{100}\right)\right]$	15	0·62
Use centrifuged ash data—exclude fuels 3, 4, 6 and 9 fuels 12 and 14 data averaged		
$\text{Sulphur}\left[1+5\left(\text{ash}+\frac{\text{CC}}{100}\right)\right]$	10	0·55
$\text{Sulphur}\left[1+5\left(\text{ash}+\frac{\text{asphalt}}{100}\right)\right]$	10	0·58
$\text{Sulphur}\left[1+5\left(\text{ash}+\frac{\text{asphalt}}{50}\right)\right]$	10	0·64

The first formula was exactly the same as used by the authors, using 15 fuels and giving an index of determination of 0·62. So this was the same as Fig. 13.

Taking the two aspects already mentioned of ash after centrifuging and the similarity between fuels 12 and 14 into account, they were reduced to 10 fuels.

Still using the authors' formula, the index dropped to 0·55. This indicated a larger spread in the points, although the number of points had been reduced from 15 to 10.

By substituting the asphaltenes instead of Conradson carbon, they had found an improvement in the index from 0·55 to 0·58. However, it was felt that the asphaltenes justified more contribution in the formula related to wear, so instead of being divided by 100 this had been reduced to 50. The substantial increase in the index of determination to 0·64 suggested that this had been a correct assumption, and now even with only 10 points the index of determination rose above the level obtained by the authors in Fig. 13.

REFERENCE

(17) Schmidt-Sorensen, J. 1971 "Development of B and W KGF Engines". *Trans. I. Mar. E.* Vol. 83, Part 13.

Dr. P. G. Casale was amazed at the number of variables particularly relevant to large bore marine engines that the authors had managed to study in detail using a fairly small engine, and no doubt the authors' conclusions and thoughts for the future were well worth careful consideration.

He agreed in principle with their conclusion that higher coolant temperature should result in less acid condensate, but did not believe that such higher coolant temperatures would, by themselves, produce the marked improvement in liner wear at the top ring travel that one might expect from the authors' suggestion, in the opening paragraph of page 7, that it was indeed acid, deposited on the lower (hence cooler) parts of the liner, that caused wear concentrated near the top of the ring travel. He was inclined to agree with another school of thought which suggested that mechanical wear was just as important in the upper part of the ring travel. A reduction in the amount of acid condensate would thus contribute only partially to reduction of wear in that upper area; whilst, on the other hand, it might be quite beneficial to the rest of the liner. Furthermore, increasing gas forces with high pressure engines would inevitably result in increased importance of mechanical wear as opposed to corrosion wear.

Field data obtained and shown in summary form in Table XVIII would confirm this.

Table XVIII

Cylinder oil	A	B	Ref
Base oil	a	b	c
Overbasing type	— same —		d
TBN	— same —		70
Liner wear	(70)		
● Over 85 per cent ring travel above BDC	— same —		same
● Over remaining 15 per cent (liner top)	"A" is 50 per cent higher than "B"		same as "B"
Test hours	8900	6000	14 900
Number of cylinders	4	4	4

It seemed reasonable to assume that it had been a matter of mechanical wear (e.g. through lubricating film breakdown) rather than corrosive wear that resulted in oil A being that much worse than oil B, both oils having in fact the same amount and quality of neutralizing material.

Also, as the authors said on page 409, one should not lose sight of the abrasive aspect. Their theory that detached fragments of cylinder deposits were the most likely cause of abrasion was, he thought, very sound, and liner scoring, at times rather heavy, caused by piston deposits was well known.

He would not, however, have discarded the contribution of abrasive material from the fuel, as the authors did, as well as increased wear due to poor combustion associated with dirty fuel injectors. Particulate contamination of the fuel would increase the number of discrete areas of lube oil film breakdown, hence the ring/liner contact.

The authors' evidence against these particulates contributing to wear was based on the results of their sandwich tests on centrifuged and untreated fuel. Since differences between untreated and cleaned fuel were in effect made up by a small percentage of foreign material, he would suggest that much longer tests than the fairly short sandwich tests adopted would be needed to show the advantage of clean over untreated fuel in terms of measurable wear.

The results discussed on pages 396 and 397 would not, therefore, be sufficient in his opinion to conclude with confidence, as it was done on page 397, that complete abolition of all centrifuging would result in deleterious effects on liner and ring wear *only* in exceptional circumstances. Such circumstances arising from use of fuels possibly similar to fuel 15 (of Tables V and VI) tested by the authors, would most probably lead to unacceptable wear as opposed to just somewhat higher wear.

Would the authors give an indication of the repeatability and reproducibility of their experiments?

The sandwich 100 hour test procedure adopted had consisted of fitting a new ring in the lowest groove and moving up one groove all the other partly worn rings before the next test. In view of the importance of groove/ring clearances and condition, on rate of both ring and groove wear, were the authors satisfied that the procedure that they had adopted had not affected the accuracy of the results obtained?

Mr. G. W. van der Horst said that on the test procedure, for the proper implementation of the results of a test programme, one was always interested in the repeatability. Could he have an indication of this? Although Fig. 6 did contain results of a repeat test, had the authors' statistical data on repeatability for both the 24 hour and 100 hour tests?

From the data in Fig. 6 he concluded that the wear rate during the run-in was rather more constant and lower than during the normal test and would assume that milder conditions had been used. Was this correct?

With regard to Fig. 5, where justification of the iron recovery method was given, he would support this as being fully justified. In the laboratory of Mr. van der Horst's company they had operated different Bolnes engines and were currently operating a turbocharged one. They had also found that the drip oil iron content was not affected by the recovery rate, although generally they had fewer variations in recovery than the authors had. Mr. van der Horst's company had used tapered face rings and felt that this reduced fluctuations in the recovery rate and in this connexion he would be interested in the type of rings used by the authors.

Mr. van der Horst's company had also seen the effect of coolant temperature, and the effect of low feed rate on wear more clearly than the authors.

The curves in Fig. 7 invited a comparison between the full scale engine and the laboratory engine. Although the authors had wisely not done so, he would caution against such comparison. The rate of corrosion was dictated by the quantity of acid formed and the area of the liner exposed to acid attack. The mechanism of the corrosive wear was very complex and controlled by many parameters such as air temperatures, fuel oil ratio etc., and here he would refer to articles by Mr. Müller (18) and a paper by Mr. Simonetti (19).

In engine wear tests as described in the paper, any abrasives would affect the results and should therefore be minimized. What kind of air treatment had the authors been using? Had they filtered the air fed to the engine?

With respect to the fuel test, he wondered whether they had made a study of the particle size in the fuel after centrifuging. Mr. van der Horst's company had found that, after centrifuging the fuel to the test engine, particulate matter was still in the fuel and about 20 per cent was above 6 microns; they had therefore installed extra filters.

What would the correlation have been if the Conradson carbon had also been included.

With respect to the liner/ring material test, he wondered whether the engine could run for such a long time without ring sticking on straight mineral oil, and if the authors had experienced ring sticking in their 100 hour test. His company's engine could not run that long on a straight mineral oil without having ring sticking.

The authors had taken great pains to ensure that the microstructure of the materials were similar to the structure in the full scale engine. He took it that the surface condition of liners and rings was the same throughout the test. Could the authors give some information on this point?

REFERENCES

(18) Muller, Dr. Ing. P., "Kraftstoffschwefel und Naszkorrosion Im Dieselmotor", *MTZ*, Heft 7, July 1962.

(19) Simonetti, Dr. Ing. G., "Diesel Engines Operating on Residual Fuel—Cylinder Liners—Wear Through Corrosion and Means to Eliminate it". *Fiat Technical Bulletin*, January-March 1960.

Mr. E. F. Barton, M.I.Mar.E., said that whilst some of the work was of ten years ago, much of the paper was relevant. One thing which should be relevant was the need to make another reduction in cylinder liner wear. He hoped that current work by designers and development engineers would result in engines in which the failure of liners, due to mechanical and thermal damage, before they had run full term was prevented. He hoped that there was a need for a wear rate for a liner which promised to last the life of the ship.

Fig. 1 was also timely showing the effect of fuel temperature on fuel viscosity and performance. There were now engines where the fuel arrangements made it safe to operate with 140°C and operators were beginning to be willing to do so, although some heating arrangements did not allow one to go above 120°C. The authors had shown a good straight line fit whereas of course this was the law of diminishing returns. With that type of curve there was an even better fit to the authors' data points, for fuel consumption, and extrapolation did not indicate a better specific consumption than that for gas oil if temperature was sufficiently increased.

There had been some discussion on the effect of fuel properties on the wear rate. He was disappointed that the authors had not given some specific information on the water content of the fuels. Perhaps the authors would confirm that in Fig. 9 there were three points up at the top indicating a much higher wear rate, which did not fall into the pattern and two of these had had appreciable water content. From one of their references, it would seem that all the fuels containing measurable water, plotted above the correlation line. One has read that free water in the fuel did act to increase the acid dewpoint in the combustion process. With this, one would expect that under given conditions, for a liner surface of varying temperature, one would get a greater area suffering acid deposition and hence more acid wear. If the authors had seriously considered this question—as he would think they had done—would they expand on this point in their reply?

He wholeheartedly agreed on the remarks on centrifuging as long as one read them properly. This was that in service, from their results they would expect no gain in wear rate to be obtained by centrifuging and clarifying as against just centrifuging. His company had a class of ten similar ships with ten similar engines, and a most conscientious examination of wear rates and running conditions had been carried out. Two ships entered service with the centrifuging/clarifying stage. The remaining eight had centrifuging only. After the first 10 000 hours the first two ships changed to centrifuging only for about 10 000 hours. No effect on wear rate could be found, and no effect on injection equipment due to omission of the clarifying stage. With regard to water content, if ships were on a particular trade, or because of certain aspects of deterioration on board were plagued with persistent water content, there might be value in double centrifuging instead of centrifuging and clarifying, if the equipment was there to do it.

In regard to the authors' comment on the variation in service of cylinder liner wear rate, he thought that they had stated the case rather conservatively. From examination of a number of engine types over many years, he believed that one should not be surprised to find in any engine a wear rate variation of about three between liners; between engines of the same type operating under supposedly similar conditions, a variation of three was also possible for wear rate, but for individual liners in the same type of engine in one operator's fleet of ships a tolerable wear rate variation between individual liners was five between the best and the worst. If it was greater than that, one investigated what was wrong with the bad liner and tried to correct it, but really one would like to find out why the good liners were so good.

Eng. Lt. P. A. Knowles, R.N., A.M.I.Mar.E., said that his particular interest in the paper was the relationship between the cleanliness or the dirtiness of the residual fuel and the amount of wear. The figures given on the solids content would be most valuable to those designing equipment for its removal.

One might get the impression from the results of the tests that it was hardly worth fitting fuel treatment at all, except that one must ensure against the odd batch of really dirty stuff. The authors' conclusions were given in the context of piston and ring wear only. However the wear on the injection equipment particularly, could be catastrophic if fuel treatment was abandoned.

Could the authors say whether they had experienced any difficulties with fuel injection during their tests when operating without centrifuging, particularly with the Doxford fuel?

Also of interest was the method of iron recovery in the used piston lubricating oil. For the medium speed Diesel, at least, any iron wear material generated would enter the lubricating oil system and would have to be removed to protect the bearings. Did the authors, besides obtaining the weight of iron, also examine for particle size?

Correspondence

MR. F. HARDESTY wrote that the wide range of residual fuels tested and the detailed results of their application were of particular importance. This indicated the diversity of oils which the engineer must handle and the obvious difficulty in attempting to draw hard and fast conclusions. However, the curves attempting to relate wear to the variables ash, Conradson carbon and sulphur content were very interesting. The deduction that sulphur and Conradson carbon were fairly decisive was probably reliable and had been postulated by many investigators.

The sulphur burned to SO_2 and some of this under the prevailing conditions of temperature and pressure undoubtedly formed some sulphuric acid, a portion of which dissolved in the oil and sludge whilst most passed out in the exhaust. Both sulphuric acid and aqueous SO_2 solutions were highly corrosive.

The Conradson carbon was a measure of the carbonaceous matter formed by thermal decomposition in the virtual absence of air and this material was frequently very hard and abrasive, to the extent of being able to scratch a glass surface. Such thermal decomposition was likely to occur on hot surfaces and the particles falling into the cylinder would exert an abrasive influence, aided by acidic products formed from the sulphur. But many investigators had found that high Conradson values need not give high wear using low sulphur oils.

A factor which seemed to be overlooked was the action of the sulphuric acid on any unburnt or partially decomposed oil to form carbonaceous material. This could also be hard and abrasive, adding to the deleterious conditions in the system. In his experience this might account for about 0·1 lb/ton of fuel i.e. 0·05 per cent as measured by the recovered sludges and contain up to 10 per cent sulphuric acid. It was rather unfortunate that the physical condition of the sludges had not been noted and a fuller analysis carried out to ascertain the extent of abrasiveness of the deposits.

When dealing with additive oils the anti-corrosive agent was frequently an alkaline earth or other metallic compound, which was decomposable by acids giving salts such as calcium sulphate. The feasibility of these acting as hard particles, binders for carbonaceous matter etc. should not be overlooked, as salts formed from the ash in the fuel.

The influence of ash per se in regard to particle size and grittyness in Diesel engines was possibly a minor source of wear as opposed to spark ignition engines where clearances were much smaller, however there were other factors to be considered and these included the alkali salt content and the vanadium. The latter during combustion most likely formed V_2O_5 which would assist in the catalytic oxidation of SO_2 to SO_3 and thence to sulphuric acid. However, as he had pointed out in a research on use of heavy fuel oils in Doxford engines twenty years ago, the absence of vanadium would not greatly alter the formation of acidic products of sulphur. It would be most harmful in combination with alkali salts when it exerted a fluxing action on very hot surfaces where the skin temperature might momentarily exceed 600°C e.g. piston crowns, parts of the exhaust system etc.

The authors had stated that they had tried many ways of plotting their results and considered that the best method was wear α sulphur + Conradson Carbon/4 per cent. This gave a mean deviation of 0·0364 g/h. However, he suggested that the plot of wear α sulphur + asphaltenes per cent which gave a slightly higher deviation of 0·040 g/h was worthy of consideration. It introduced no arbitrary numerical factor and the asphaltenes were more readily decomposed under the engine conditions by thermal and chemical means than many of the other constituents in the oils. This was only a surmise and it would require a detailed constitutional analysis of the fuels to validate this contention.

The alteration of the thermal gradient of the cylinder wall and use of a baffle and the data related to wear decrease with higher liner temperatures was useful supporting evidence for the vital role of sulphur product corrosion in the wear process. As pointed out, this had been suggested many times before, however this was additional evidence. It was a well established fact that air heaters in land based steam boilers must be maintained at at least 150°C to prevent sulphuric acid deposition from flue gases, or serious corrosion results. Obviously this created a serious loss in thermal efficiency by allowing so much heat to escape. For efficient lubrication in Diesel engines it was unlikely that a temperature near to 100°C could be maintained over the whole surface of the liner, neglecting other problems, and more exotic coolants to raise the temperature above this level could be discounted. There was however, a further source of condensation which occured and its extent was difficult to assess, that was when cold air entered the cylinder and chilled any residual products of combustion.

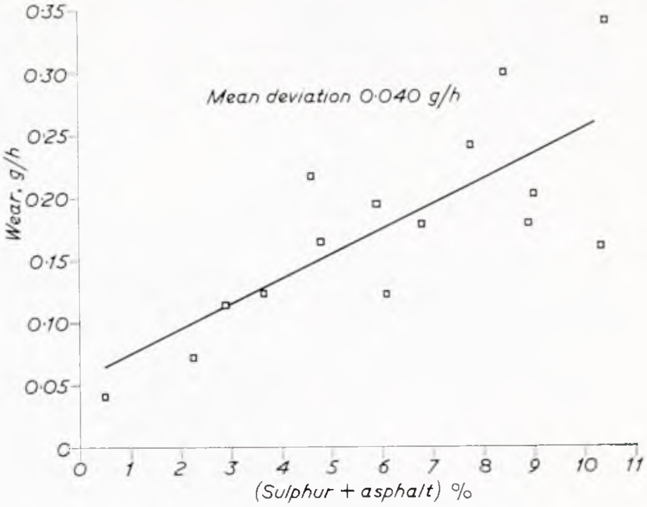

FIG. 18

Clearly any attempts to lower wear must include trials with new materials of either greater abrasion resistance and/or corrosion resistance. Where the beneficial effect was by a surface coating, adhesion and cohesion were vital otherwise failure was certain from the commencement and could even result in worse behaviour. A porous coating allowed sub-surface corrosion which ate away the underlying metal and thus destroyed adhesion, and the detachment of the coating. If normally an abrasive material, then it would act as such to the detriment of liner and rings; some of the tests showed this simple fact only too clearly.

It would be interesting to know what the lubricating behaviour of some of these materials was, bearing in mind that chromium and high chromium alloys, aluminium alloys etc. were difficult to lubricate without special surface preparation. Possibly this was the cause of the disappointing results with Colmonoy 5.

The use of an austenitic liner of the type mentioned would possibly give greater wear reduction with a suitable additive lubricating oil. Such an alloy had about four times the resistance to attack by dilute sulphuric acid as the standard cast iron used and its resistance to aqueous solutions of sulphur dioxide was about 13 000 times as great. Further, its lower thermal conductance would assist in raising the liner temperature and reducing the condensation problem.

Table V indicating the minor differences in wear results for the majority of oils in the treated and untreated condition was interesting but the authors' note of caution in the text was necessary. It was true that many projects by Sulzer Brothers Ltd. and others from 1912 onwards used untreated oils, but they had possibly been lucky in drawing from more restricted supplies. Today not only were these more numerous but there was the additional factor of the type of refinement that had produced the oils, which could affect the constitutional content and the resulting behaviour. Emulsification could occur readily in the presence of water and cause blockage, combustion problems, as well as carrying water soluble substances such as salt into the combustion chamber.

Mr. G. McConnell commented on the authors' concluding remarks about abrasive wear, in which they said that the abrasives which caused the wear were most likely detached fragments of cylinder (carbon) deposit. The possibility of this being correct could not be dismissed, but at the same time, the evidence which the authors had quoted to support their hypothesis was not, in his opinion, very convincing. They had cited the occurrence of severe scuffing and subsequent ring-blowing which had been caused by pieces of carbon which had become detached from the piston crown land. This, he suggested, was not really the same phenomenon as the abrasion process under discussion. The process under discussion was a general one, not a local one and furthermore it was caused by a vast quantity of small particles and not by one or two fragments.

The authors had quoted the work of Cotti and Simonetti and the work of Cook, but he was not sure whether the quotations were intended to support the authors' case. These investigators had demonstrated that with relatively low-sulphur fuels the use of a too highly-alkaline oil might promote engine wear, which was an entirely different case from the one which the authors were dealing with i.e. the wear process which operated when using a zero TBN oil and a high-sulphur fuel.

He believed that there was no better hypothesis for the occurrence of abrasive wear in heavy-fuel engines than the one put forward by his late colleague Dr. Nathan. He had suggested that the surfaces of cast iron rings and liners had been weakened by a sulphuric acid attack and that the resulting ferrous debris had been heated in the combustion flame to form ferric oxide; this oxide was the abrasive which had subsequently produced heavy scoring on ring and liner surfaces. His hypothesis had been backed by reasonable evidence. Laboratory tests had demonstrated the feasibility of the weakening of the surface of a cast iron specimen by sulphuric acid attack, and "laboratory weakened" specimens had borne a marked resemblance, in structure, to piston ring specimens as examined after an engine test. Samples of lubricant, extracted during running from an engine cylinder, at the top ring/top dead centre position, had contained iron at a concentration nine times greater than that of the next major inorganic constituent. X-ray analysis had shown that the iron had been present as $\propto \mathrm{Fe_2O_3}$ and $\gamma\ \mathrm{Fe_2O_3}$; this analysis had also shown that no carbon had been present in a crystalline form, i.e. in the form in which carbon was most likely to be abrasive. Tests on the lubricant sample had shown that it contained abrasive particles which could scratch a metal surface having a hardness of 900 Vickers Pyramid Number (VPN). Iron oxide, prepared in the laboratory both from ferrous sulphate and from iron, had also been capable of scratching a 900 VPN surface, whereas "coke" prepared from residual fuel would not have marked any surface which had been harder than 200 VPN.

Dr. Nathan had realized that this had been mainly circumstantial evidence in support of his case, but he had had a philosophy regarding his (and any other) hypothesis which Mr. McConnell intended to follow. That was that if all the assembled facts fitted the hypothesis then one must stick to that hypothesis; when some piece of evidence came to light which did not fit, then, and only then, was it time to modify ones ideas. Mr. McConnell intended to stick!

Mr. A. Oolbekkink wrote that many of the results and conclusions in the paper tied in with the results which his company had found aboard ships and in their Bolnes test engine over a period of some twenty years.

They were, however, surprised and shocked to find that they did not know that such exhaustive and fundamental research in their own specialized field had been in progress, under the auspices of the BSRA from 1959 to 1968.

Porous hard chrome plating of the liner bore was the historic and standard solution not only to problems of liner wear, but also to assist in the control of lubricating oil consumption in trunk piston engines.

Mr. Oolbekkink's company had their own test engine and research and development programme, and also a considerable volume of data from the performance of their liners at sea. They had also, through a subsidiary company, considerable experience in the hard chrome plating of piston ring grooves, and of the effect of this process on liner, ring groove and ring wear.

The following figures, results from two sisterships after 7000 hours running time, showed a comparison between wear on cast iron and wear on chrome plated liners.

Cast iron liners		**Chrome plated liners**	
cyl.		*cyl.*	
1	6·00 mm	1	1·90 mm
2	2·40 mm	2	1·90 mm
3	4·00 mm	3	1·75 mm
4	5·35 mm	4	1·90 mm
5	2·00 mm	5	1·66 mm
6	3·80 mm	6	1·40 mm

In later years they had found that chrome plating of both sides of ring grooves was very beneficial to decreased wear of grooves, rings and liner surface. They had found that the period between overhaul could often be doubled if the combination of chrome plated ring grooves and chrome plated liner was used. For instance, much material had been collected by the director of his company's German office in Hamburg on M.A.N. direct driven main engines.

They had also discovered that grooves cut in the liner surface radiating from the oil quills helped very well in spreading the oil.

It was their standard procedure in liners over 500 mm bore to have oil grooves interconnecting the oil quills and being cut under an angle with the horizontal. In some cases they had found that oil quills and oil grooves decreased the wear of the liner a lot even in trunk engines being splash lubricated. He fully agreed that lifting of the rings off the bottom side of the oil grooves during reversal in four stroke engines helped with the lubrication and not only the underside of the rings and also helped in transporting oil.

He noted the authors' use of sprayed application of hard facing materials in liners, and that they appeared to have got away with it on a small bore engine under test conditions. Mr. Oolbekkink's company's experience was that the adhesion of such sprayed coatings in large bore engines did not stand up to the mechanical and thermal stresses.

They had found the porosity in the chromium a great help in transporting and spreading the oil, apart from the fact that the lower friction co-efficient and high wear resistance of their porous chrome had given a great increase in liner life.

Could the authors include a chrome plated liner in their test programme?

Mr. P. E. Wiene wrote that the beneficial effect that the authors mentioned in connexion with Fig. 8 of keeping the top of the cylinder liner cooler than the lower part had been confirmed several times in practice. For instance, it was the standard execution for B and W's K-type engines and would be for the future K90GF.

As a curiosity it could be mentioned that, when in 1944 an attempt had been made to obtain a patent on this execution, a British patent from 1933 (412.432) had prevented it.

Authors' Reply

The authors wrote that Mr. Taylor had commented in a very helpful and complete way on all the findings given in the paper and they would reply to these where necessary.

They thought that the halved wear rate of the top ring in the upper exhaust piston of Doxford engines, as compared with the lower scavenge piston, might not only have been a matter of the one third lower piston speed. Might it not have been that the liner surface temperature swept by the exhaust piston top ring was higher? Figures given in the 1969 paper by Mr. Taylor* on the 'J' engine suggested that the top ring of the upper piston as it moved down traversed the exhaust ports at around 150°C. Below the exhaust ports the surface temperature dropped to just under 100°C for only about 1/5 the stroke or 100 mm rising to 160°C at the inner limit. However the lower piston top ring in moving up from BDC had to traverse ¾ of the stroke or 1200 mm at a temperature slightly below 100°C, and the surface temperature only rose above 100°C in the upper ¼ of the stroke to 180°C at the inner limit. Thus there could have been some ten times more condensate to be swept up by the top ring in the lower piston than the upper since there was some ten times the length of liner traversed by the top ring at a temperature slightly below 100°C.

It was encouraging that the measures taken in the 'J' engine to reduce the jacketted length of liner, and so increase liner temperature lower down in the scavenge cylinder, had been successful; and this had paid off by a significant improvement in liner wear.

The authors were conscious of the omission of trial of a chrome plated liner. This was because at the time it had not been felt that chrome plating was sufficiently resistant to corrosive attack by sulphuric acid products. This was not true when anti-corrosive cylinder oils were used. They also would have liked to have tried nodular iron piston rings.

It was interesting that the three centrifugally cast liners of 2 per cent nickel/copper material were showing after a longer period of running of 30 000 hours in the 'J' engine an average wear rate 75 per cent of the normal vanadium sand-cast liners in line with the authors' findings, whereas at 17 000 hours the gain had not been obvious. This should encourage the trial of further liners in this material to obtain more certain evidence, as Mr. French had remarked as being desirable in the discussion.

It was encouraging to find that quite a number of companies had omitted the fuel clarifying stage for a number of years successfully. However, the authors noted the warning that some filtration was essential. Also the warning that larger amounts of sludge appearing at the single purifying stage had in Mr. Taylor's experience usually coincided with fouling of the engine.

The fact that they could reduce the rate of oil supply to the cylinder of the Crossley engine without any increase in the wear rate, was probably due to the fact that the original level had been high, and that the reduced level on the basis of g/m^2 of surface swept on the expansion stroke had been about the same as the normal rate occurring in the full size engine. The supply could not in fact be reduced further without getting piston ring blow-by.

The authors agreed with Mr. Ruscoe that it would have been interesting to have been able to measure more instantaneous rates of wear, and so be able to see how transient conditions such as starting from cold, and then increasing load affect wear; as in fact Pinotti, Jones and Svenson in their 1962 CIMAC paper had described. They had used an irratiated top ring in a Götaverken 760 mm bore engine. However, in the Crossley engine, wear had been measured mainly under steady state conditions, though the wear included the period of starting up from cold each day and putting on load, since all the iron recovery tests had been carried out by daily running periods of eight hours' duration.

In connexion with his remarks on liner temperature, as the authors understood it, corrosion hardly occurred above the dewpoint, since condensation was prevented. Maximum corrosion and condensation was believed to occur some 30°C below the dewpoint. In a small high duty engine corrosion at the upper limit of top ring travel had been stopped by ensuring that the liner temperature was above 130°C here. The quantity of sulphur in the fuel was however low, 0·8 to 1·0 per cent, and the fuel a distillate gas oil (see "Life tests on a Small High Duty Engine with Particular Reference to Chrome Bores", by B. W. Millington, D.E.U.A., ref. 240).

However, when running on a residual fuel, if the sulphuric acid products were conveyed to the cylinder wall partly by absorption by carbon particles, then one might perhaps have expected some corrosive action to occur above the dewpoint.

Filter systems for residual fuel effectively separated water. This might be partly separated in the service fuel tank and partly at the filters.

The authors agreed with Mr. Ruscoe that in comparing ring wear rates, it was that of the top ring which mattered rather than the total wear of the ring pack. However, both had been given in the wear tables of the paper, because in some builds used the wear of the lower rings had been high.

As Mr. French had stated at the meeting, the high friction reported in the Colmonoy 5 banded liner had not been due to any particles being left slightly high after honing. The surface after running had appeared smooth and polished in contrast to the cobalt/tungsten carbide lands in which hard particles of tungsten carbide had been protruding from the cobalt matrix.

The authors thought that the spreadability of oil films probably had not been studied sufficiently carefully. If in fact reduction of viscosity improved this, then trial of lower viscosity oils might be worthwhile. However, it was generally well known that the higher 30 and 40 grade oils gave improved scuff resistance during run-in and in later life, and this was probably the reason for their choice in the larger engines.

The authors agreed that if cylinder oil was fed through the top ring groove, then ring breakage followed by the loss of a piece of ring through a port would have serious consequences. Admission through the second groove might be sufficiently safe, or alternatively, as Mr. Ruscoe suggested, admission could be via an additional oil groove in the top land between the top and second rings.

The authors felt that the pursuit of any measures which would stop the blast of gas through a gap of some 12 to 25 mm of the top ring might result eventually in reduction of top ring wear, since this blast must be a contributory cause of wear.

They had noted that such rings had butts which tended to break, and that in Mr. Ruscoe's experience these rings wore rapidly as a result of taking too great a share of the load. However, they had hoped that with better ring materials or the sharing of load to the lower rings by drilled gas passages, better results than obtained with plain ring gaps would eventually be obtained.

Mr. Fletcher had commented on the low liner temperature of 120°C at the upper limit of the top ring travel occurring in the Crossley engine with a jacket temperature of 70°C, and asked whether wear would still be reduced if this figure were raised to 200°C when the lower liner temperature had been raised from 30°C to 90°C. The authors believed it would, because they believed that the condensate was swept upwards by the piston rings. Possibly the wear contour would be different and maximum wear occur lower down below the top ring travel limit as Cotti and Simonetti had shown.

Mr. Fletcher's remarks on the condensate on a nozzle tip at 120°C were very interesting.

The authors did not have viscosity curves of the oils used but assuming they had had conventional viscosity indices the straight 30 grade oil would have had a viscosity of approximately 11 cS and the Alexia 40 a viscosity of approximately 14·5 cS at 100°C.

Mr. Fletcher pointed out that the lubricating oil consumption shown in Fig. 6 was high, but it was not as he stated 2/3 of the engine fuel consumption, but less than 1/20, as Table XI showed. For the 500 hour tests the authors had reduced this to less than 1/50, but such reduction had had no effect on the wear rate.

They did have trouble with the exhaust valve on 100 hour runs in the early stages but this had been cured by Stellite facing. However, for the 500 hour runs, they had fitted a valve rotator as well.

Mr. Barton had commented on the beneficial effect of increase of fuel temperature at the injector on fuel consumption, as shown in Fig. 1. The authors thought it would be unsafe to assume that the same gain would be obtained in the full size engine, although they would have expected the same trend. The

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* Taylor, B., 1969, "Development of the Doxford J-Type Engine", *Proc. IMAS '69* p. 4c/26

authors agreed that one could not expect to do better than the gas oil consumption after taking into account any differences in calorific value, and that strictly speaking their straight line should curve and flatten towards the gas oil figure.

The authors did not really think that the high water content of the two fuels shown in Fig. 9 with high wear rates, namely fuels No. 13 and 14, had had much connexion with their high wear rates. For instance, the untreated No. 14 Las Palmas fuel, the fuel with the highest water content in Table II, had had 3·8 per cent by volume of water. After treating either by double centrifuging or in the ship's Gravitrol centrifuge there had been no significant reduction in wear rate.

It was true that the water content of the fuels after double centrifuging had not been measured, but the Las Palmas fuel would have lost 0·85 per cent of its water judging from the water extraction figures given on page 396. Combustion roughly produced a volume of water equal to the volume of fuel, hence the total water vapour present after combustion would have only increased by some 3 per cent compared with a fuel with almost nil water content.

The authors were aware that in marine service water must be kept down to figures of 0·01 to 0·05 per cent on account of the injection equipment since with fuel temperatures above 100°C the water was likely to flash to steam in the near atmospheric conditions at the lower end of the fuel pump plunger barrel and to cause corrosion. Such corrosion could also occur on the needle valve guide of the nozzle.

Mr. Barton's evidence of the successful use of a single stage centrifuging of fuel was interesting confirmation of the results given in the paper.

Mr. Barton's remarks did show up the economic gain that would be possible from an investigation which would result in reducing the large cylinder liner wear rate variations of the order of 5:1 that he mentioned were normal in a fleet of ships using the same engine type, and of 3:1 between the liners of the same engine.

Mr. Oolbekkink had written in and said that in their experience the chrome plating of liners plus the chrome plating of piston ring grooves gave the lowest wear figures.

The authors were very sorry that their tests did not include a chrome-plated liner. They thoroughly believed in the benefit of chrome plating either one or both sides of the piston ring grooves. They considered, however, that the reduced wear obtainable by chrome plating the liners must be weighed against the extra expense.

It was important to realize that chromium was also attacked by sulphuric acid condensate and hence anti-corrosive cylinder oils were as essential with it as with unplated cylinders.

In reply to Mr. van der Horst, for the wear tests using the iron recovery method, as stated in the authors' answer to Dr. Casale, the repeatability of four consecutive sandwich tests of some 100 hours each had been minus eight per cent, plus ten per cent on the mean wear rate figure.

For the 100 hour tests with various liner and ring materials in which liner wear had been measured directly and ring wear by weighing, repeatability of the radial wear step mean wear over some four consecutive runs did lie within −4 per cent, +6 per cent of the mean figure at best when the radial wear step had been about one thousandth, but it could rise to −23 per cent, +38 per cent at worst when the wear step had been about 0·5 thousandths of an inch.

The wear figures quoted in the tables were in many cases the mean figures from three or four or five runs.

Occasional rogue results had appeared but generally not without explanation.

The 500 hour runs had been single tests because of the length of time involved. Wear with the standard No. 1 build had been less over such a 500 hour run without any strips than over 5 separate 100 hour runs, as shown in Table X. This was in line with expectation.

In the data given in Fig. 6 the iron wear rates were the uncorrected rates. The corrected rates were given in the text above Fig. 6. The engine had been running at its normal rating.

Air filters had not been used. The Shoreham laboratory was in the country, about two miles from the seacoast.

They did carry out a particle count of the sludge removed by the centrifuges at one point in the tests measuring down to a 2 micron size. They had found the majority of particles to be small. They did not extend such a count to the centrifuged fuel, but they would not have expected to have found many large particles, but perhaps they were in error here.

However, they did not experience any injection pump troubles although no filter after the centrifuges had been used.

They had never experienced any ring sticking when running on the straight lubricating oil, and so clearly not on the additive oil.

They did not check the surface finish of each liner but in fact all the liners had been supplied and finished by the same manufacturer. The surface finish had been 20/40 µ in C.L.A. The standard rings had come from one source, but the special rings from another source.

The authors thanked Mr. Hardesty for his informative contribution and noted with interest his points regarding fuel composition, particularly with reference to the formation of particles hard enough to scratch glass attributable to the fuel Conradson carbon content. As stated at the Newcastle meeting, no analysis of the cylinder sludge other than the measurement of the iron content had been made. Being wise after the event, it was now apparent that a check of the particulate content of these drainings as regards the existence, hardness, size and composition of any such particles would almost certainly have been illuminating as regards the presence of hard carbonaceous material resulting from reactions between sulphuric acid and oil products, as regards any hard material attributable to the lubricant sulphated ash, and also as regards any iron present as hard particles of iron oxide.

As indicated previously in the discussion, asphaltenes had been considered by the authors in their own original work but the results had offered slightly less favourable co-relation than did those factors quoted, as had been shown by Mr. Hardesty. It had, of course, been appreciated that this margin was small and the authors had therefore selected those factors which had appeared to them to have the most practical significance in view of the possible side effects which could have been encountered in a fuel in which any lack of compatibility between the asphaltene contents was present. As stated in the text of the paper, however, oil companies of course took pains to ensure compatibility of the asphaltene contents of all components present in a particular residual fuel.

Mr. Hardesty's remarks on the dangers of using porous liner and ring coatings were noted, though in some cases such as plasma gun sprayed chrome, and Van der Horst porous chrome, sub surface corrosion did not appear to occur provided the condensed acid was neutralized.

The authors did think that the Colmonoy 5 bands would have shown an unusually high coefficient of friction against cast iron for reasons not clear. This might have been resistance to wetting by an oil film. However, Table XIV showed low liner wear but excessive ring wear.

The authors did agree with him that austenitic liners were one of the materials worthy of trial in direct drive engines, provided the lowered conductivity did not raise surface temperature too much at the top of the liner, and provided that allowance was made at the location outside diameters for the increased coefficient of expansion.

The authors thanked Dr. Casale for his kindly comments regarding the scope of the investigation that they had had the opportunity to conduct. With regard to the influence of coolant temperature on acid condensation and subsequent acid attack, they suggested that since they were considering only small quantities of acid present in an oil film on a metallic surface, then the rate of corrosion would be partly a function of the quantity of acid present in this film and partly of the residence time of that acid on the metallic surface. The major part of the liner surface would be subject to a high frequency sweeping by the piston rings and the consequent fortification of the oil film by relatively acid-free lubricant. At the top of the top ring travel, however, this sweeping action would concentrate acid deposits which unless evaporated by a sufficiently high surface temperature of the liner, would be permitted to make an uninterrupted attack of the metal surface. Acid attack would thus be preferential in this area irrespective of the source of its condensation. The authors suggested therefore, that acid condensation should be avoided as far as is practicable on any part of the liner and that the lower sections where lubrication and heat flow presented problems less arduous than at the top of the liner, offered a potentially useful zone for such attention.

This did not in any way mean that they did not appreciate the problem of abrasive wear, and indeed their theory that detached fragments of cylinder deposits were likely causes, might well account for the differences in wear Dr. Casale had reported between oils A and B; formulation A might well have had an unfavourable influence on the physical characteristics of such deposits. By the same token they would anticipate that poor combustion due to faulty injectors could also be likely to have an adverse effect on wear.

Dr. Casale's point regarding the duration of tests necessary to determine the influence of fuel centrifuging on wear was taken with interest. However, as practical considerations would require a single centrifuging stage or the equivalent, as indeed they had recommended, they would suggest that as far as service conditions were concerned their conclusions were valid as they stood.

In reply to Dr. Casale's question regarding test repeatability and reproduceability, they had taken as representative the results of four consecutive sandwich tests, and extracted the corrected iron recovery figures (wear rates), for the test periods at the beginning and end of each sandwich, which had been carried out under standard conditions using the standard fuel, with the following results:

Test number:	1	2	3	4
Initial wear rate:	0·170	0·191	0·197	0·204
Final wear rate:	0·176	0·183	0·175	0·187

These values gave a mean iron recovery of 0·185 with a minimum value eight per cent below the mean and a maximum ten per cent above. This showed good repeatability; reproducibility, as indicated by a comparison of the results obtained using two different engines, yielded results of a similar order of magnitude.

The technique of fitting a new ring in the lowest groove and moving all the other partly worn rings up by one groove, discarding the ring previously used in the top groove, had been adopted in order to maintain as consistent a ring pack as possible and avoiding the necessity of starting a test with a completely new and unbedded set of rings. This procedure had led to no problems, and in view of the test repeatability they would regard this as having been sound practice.

The authors appreciated Mr. Baker's support concerning the engine type and size used for this work; they had indeed received comments on the dissimilarity between the Crossley and modern direct drive engines.

The authors were also interested in Esso's successful use of a corrected iron recovery wear measurement technique in other engines. They had complete faith in this method themselves.

They had no immediate thoughts as to why there should be differences in the specific iron recovery rates that they had obtained and those obtained by Esso unless this was a function of lubricating oil feed rate on the datum wear rate. The loss of cylinder oil drainings to the exhaust was, of course, taken into account by the use of the corrected iron recovery technique.

They were indeed aware of Mr. Baker's advocacy of the injection of the cylinder oil via the ring grooves and appreciated his support of their own proposal to do so. Their reasoning in favour of such a course of action was that this could provide a vastly improved distribution of lubricant and also, assuming the theory of abrasive wear being induced by detached fragments of cylinder deposits to be true, would provide the rings with uncontaminated oil, washing such contaminants clear of the rings instead of offering them what might well be a mild form of grinding paste as a lubricant. Furthermore, since the piston would be lubricated rather than the liners this would tend to minimize the adverse effect of ports on oil film distribution, and if in addition it were found possible to introduce the lubricant between the sealing face of the ring and its groove this would minimize the effect of uni-directional loading of the rings leading to increased lateral wear due to poor lubrication between the sealing faces of ring and groove.

They would certainly agree that lower wear rates on four-stroke trunk piston engines might well be a function of the greater quantity of oil present on their pistons resulting in improved lubricant distribution as opposed to cross-head engines. Some increase in oil consumption as far as the cross-head engines were concerned would also, they believed, be to their advantage in this respect.

Further to Mr. Knowles' comments regarding the effect of fuel centrifuging on injection equipment wear, the authors did in fact make some attempt to investigate this subject by the use of a single cylinder Harland and Wolff direct drive engine fuel injection pump. A suitable contaminant carrier had been prepared from a blend of straight mineral oil and gas oil having the same viscosity at 40°C as did the 1500 second residual fuel used as a reference for the Crossley tests at 100°C (the temperature at which the fuel had been maintained in the "day tank"). This clean carrier had then been contaminated with silica powders of controlled particle size ranges. The contaminated liquid had been maintained in an agitated condition by means of an electric stirrer. Sulphated ash determinations made on the uncontaminated liquid (to prove the initial freedom from contamination), and on the contaminated carrier after approximately 24 hours residence time in the rig, had indicated that the silica had refused to remain in suspension. From this it had therefore been concluded that particles large enough to cause damage to the fuel injection pump were unlikely to remain in suspension in a fuel in a ship's heated "day tanks" in service. (For relationship between contaminant particle size and wear see "Wear ofFuel Injection Equipment and Filtration of Fuel for Compression-Ignition Engines" by A. E. W. Austin and B. E. Goodridge, I.Mech.E., Auto.Div.Proc. Part III (1950–51), p. 85.)

The authors had encountered no difficulties and had observed no wear problem with fuel injection equipment during their tests when operating with or without fuel centrifuging, including tests on the Doxford fuel.

The cylinder sludge obtained during this test had not been examined for its contaminant other than the weight of iron recovered i.e. no particle size determinations had been made. Being wise after the event the authors now wished that this had been done (see contribution from Mr. F. Hardesty). They would, however, have expected the ferrous contaminant of the used oil to be present only in very small particle sizes. In the case of the medium speed Diesel, therefore, as long as these particles were smaller in diameter than the oil film thickness in the bearings then they would anticipate that no wear would be likely to result from their presence.

The authors thanked Mr. McConnell for his interesting contribution. However, while they did not seek to dispute Dr. Nathan's theory that abrasive wear was caused by oxides of iron generated as a result of sulphuric acid attack, they did not think that this was the only cause and therefore made the following observations:

1) Mr. McConnell had stated that "coke" prepared from residual fuel would not have marked any surface harder than 200 VPN. The authors had introduced the point that detached piston crown deposits had caused scuffing purely in order to establish as fact that actual engine deposits were indeed sufficiently malignant physically to cause damage as severe as scuffing when trapped between piston rings and a cylinder bore.
2) Following on from this they had proposed that material possessing such hostile physical properties would also have been capable of causing abrasive wear when present as a quantity of much smaller particles instead of as one or two large fragments.
3) Cotti and Simonetti had obtained a lower rate of wear as a result of reducing the alkalinity of the lubricant with

low sulphur fuels. This most certainly would not have reduced acid attack, either directly by reducing corrosive wear, or indirectly by reducing the ferrous wear debris resulting from the corrosive attack, as postulated by Dr. Nathan, and it was therefore a reasonable hypothesis to presume this reduction in wear to have been a reduction in abrasive wear due to some other agency. Since the only change effected by Cotti and Simonetti had been to reduce the alkalinity of the lubricant it was logical to suspect that the reduction of the alkaline contributing material had resulted in this lower rate of wear.

4) This hypothesis received further support from the work of Cook, who had also demonstrated that from the wear aspect there was a somewhat precise optimum as regards lubricant Total Base Number for a fuel of given sulphur content burning in a given engine under a given set of conditions.
5) The foregoing led the authors to the conclusion that the wear mechanism, while embracing the corrosive attack of sulphuric acid and the probable associated abrasive wear attributable to the corrosion debris, also included an abrasive element associated with the cylinder deposits. The authors would suggest that such deposits could, in fact, not merely consist of soft carbon but might be modified due to the combustion process, and laced with ash derived from the lubricating oil.
6) What seemed to be needed was further work on the character of cylinder oils drained from the bottom of cylinders using residual fuels of as wide a range as was met in service, and using cylinder oils with various formulation approaches.

Further to Mr. Royle's comments on the relative TBN values for cross-head engine cylinder oils and those used for trunk piston engines, they suggested that, as considerably more oil had been present on the pistons of the latter engines than was the case where cross-heads were used, then for a given lubricant more additive would be present also. The authors would have therefore expected a lower TBN to satisfy the anti-corrosion requirements of a trunk piston engine than was the case for a cross-head unit. As had been stated elsewhere in the paper and discussion, superfluous alkalinity would appear to have an adverse effect on wear, so the lower TBN oils mentioned by Mr. Royle could be expected to behave as he had stated on this account, quite apart from a detergency aspect. They of course agreed with Mr. Royle in that there was indeed an economic boundary to the degree to which anti-wear measures might be pursued beyond which it was unreasonable to venture.

The authors were gratified at the general agreement between the figures collected by Mr. Royle regarding the effect of fuel composition on wear and their own findings.

They were grateful to Mr. Royle for his interesting extrapolation of the asphaltene aspect of this work but felt somewhat reluctant to discount any of the fuels actually used on the grounds that, in principle, the results from all experiments might be endeavouring to teach something if the language could be understood.

In their original work the influence of asphaltene had of course been considered, but when including all the fuels actually used the results had appeared to offer slightly less acceptable co-relation than did those factors they had quoted.

The influence of the ash content of centrifuged fuels had also been considered at that time when a mean deviation of 0·0629 had been obtained as compared with 0·0603 for the untreated fuel as reported in this paper. There had therefore appeared to be no justification for using the centrifuged values, particularly as, from the point of view of vessel operators, untreated fuel figures would be the ones to which they had access.

Related Abstracts

Calculation of heat release in Diesel engines based on fuel injection rate

Heat release data have been obtained by analysis of cylinder-pressure diagrams from a variety of two-stroke and four-stroke internal combustion engines, ranging in bore from 86·4 mm to 304·8 mm with variation of power, speed, and air-supply conditions. These data have been used to develop a method of calculating heat-release rates suitable for performance calculations using a digital computer. Relatively simple equations are used, based on a single-zone model for conditions in the cylinder. The correlation is primarily empirical, based on a simple model for the rate of mixing between fuel and air, but the chemical kinetics of the burning process are also involved in the prediction of the initial burning rate. Some limitations of the simplified model are made apparent by the experimental data, but these may be overcome to some extent by the use of a two-zone model in which temperature and gas composition in the region of the fuel spray can be calculated, rather than relying on cylinder average values.—*Whitehouse, N. D., and Way, R. J. B., SAE Paper presented at Automotive Engineering Congress, Detroit, 11–15 January 1971; Paper No. 70134; Journal of Abstracts, The British Ship Research Association, November 1971, Vol. 26, Abstract No. 31 638.*

Experimental and analytical scavenging studies on a two-cycle opposed piston Diesel engine

This paper describes a theoretical and experimental study of the scavenging process in an opposed piston engine, with the object of obtaining efficiency data and more detailed information on the effect of boost and delivery ratios, and engine speed.

The introduction to scavenging theory discusses two idealized models, the one based on constant pressure and volume, and the other allowing for variation of pressure, volume and temperature during scavenging. Energy equations are derived, assuming perfect mixing and scavenging.

In the experimental work, which was carried out on a Rootes TS-3, three-cylinder opposed piston engine, tracer gas (carbon monoxide) injection coupled with infra-red spectroscopy was used as an analytical technique.

Comparison of the theoretical models with the experimental results shows that although the postulated two-zone model can be used to simulate any engine cylinder where ordered swirl is the predominant air motion, the tracer gas method is limited by incomplete combustion of carbon monoxide in the cylinder.—*Wallace, F. J., and Cave, P. R., SAE Paper No. 710175 presented at Automotive Engineering Congress, Detroit, 11–15 January 1971; Journal of Abstracts, The British Ship Research Association, November 1971, Vol. 26, Abstract No. 31 639.*

Engine cleaning system

International Red Hand Marine Coatings has established an engineering department to market a motor cleaning system known as MCS/R-MC for ships' Diesel engines whilst they are in use. Developed by the Norwegian engineering company of Ivar Rivenaes of Bergen, the motor cleaning system has already been tried with success on a number of Scandinavian vessels.

It removes continuously—in fine powder form and not flakes—carbon, sulphur, and other deposits from all parts of the engine including: turbocharger, inter-coolers, scavenging air channels, combustion chambers, exhaust channels, and exhaust turbines. Additional advantages claimed are that fire risk in the scavenging air channels is eliminated as also is carbonization of piston rings. Long-term advantages are reduced cylinder wear and longer intervals between routine piston cleaning. Operation is effected without any reduction in engine speed.

The R-MC cleaning fluid used is completely non-flammable and does not contain nitrates, magnesium, or any material that could lead to an explosion. Corrosion inhibitors are incorporated in the formulation, which is chemically neutral (*p*H of 7·3), has a freezing point of −5°C and an indefinite shelf-life.

Consisting of one or more pressure tanks, special nozzles, hygrometer and a set of special flexible hoses complete with couplings, the MCS (motor cleaning system) has no moving parts and can be fitted in 30 minutes by any competent ships' engineer using a small welding kit. The stainless steel nozzles have bores down to 0·2 mm and it is therefore impossible to flood the system. The nozzles are installed within the air filter, the scavenging air channel or in the bore for water-washing in the blower house. The R-MC cleaning fluid follows the air stream in atomized form, simultaneously loosening and transforming all deposits into a very fine and dry powder.

The system is operated for only one hour at a time, and it is emphasized that this entails no loss of speed.—*Shipbuilding International. February 1972, Vol. 14, pp. 42–43.*

Unsteady heat transfer in a motored i.c. engine cylinder

After a brief review of the existing formulae for the unsteady heat transfer in i.c. engine cylinders, a new approach is described.

It is shown that the existing empirical heat transfer data of forced convective case for the flat plates or pipes can be used to predict the heat transfer. Experimental results obtained on a motored engine are presented which include the measurement of gas velocity, temperature, pressure and metal surface temperature to obtain the convective unsteady heat transfer through the engine cycle. The experimental results are compared with the empirical data on a flat plate and it is concluded that the agreement is within 20 per cent.—*Paper by Hassan, H., submitted to The Institution of Mechanical Engineers for written discussion; Proceedings 1970–71, Vol. 185 80/71.*

The surging phenomena in the air charging system of supercharged Diesel engines

The surging phenomena as frequently observed in the air charging system of the supercharged Diesel engines are considerably different from those experienced with the ordinary blower systems.

The periodic disturbance caused by intermittent opening of the scavenging ports has an important effect upon the fluid flow in the air charging system.

In this study, the authors analysed through calculation the surging phenomena occurring in the air charging system to determine the effects of each element on the phenomena, and carried out the experiments using the test apparatus. A good agreement was observed between the calculation and the experimental results, and it was confirmed that the method of calculation could have practical application.

Further, the study turned up some other findings about the surging phenomena in the air charging system which were of interest to note when compared with the ordinary blower system. —*Yano T., and Nagata, B., Mitsubishi Technical Bulletin No. 72, July 1971, pp. 1–15.*

The interaction of air motion, fuel spray and combustion in the Diesel combustion process

This paper is pertinent mainly to combustion in open-chamber Diesel engines employing air swirl. It is shown how an increase in air swirl rate can cause a marked loss of combustion efficiency unless fuel spray penetration is increased. High swirl reduces radial fuel spray penetration with central injection and the resulting excess fuel in the central area may be trapped by buoyancy forces following ignition, becoming isolated for as much as a tenth of a second in a chamber of 101·6 mm diameter. A brief explanation of fuel injection in terms of the mechanics of fluid jets is given and circumstances described in which buoyancy forces assist fuel-air mixing following ignition.—*Melton Jr., R. B., and Rogowski, A. R., Transactions of the ASME, Journal of Engineering for Power, January 1972, Vol. 94, pp. 11–16.*

Observations on the lubrication of medium-speed Diesel engines burning residual fuel

The author points out the necessity for lubricants to fulfil the dual function of both crankcase and cylinder oil in trunk piston engines. The necessary properties of oils are outlined, in relation to piston cleanliness, where they must be capable of reducing piston ring groove deposits to maintain freedom of the rings, and to alkalinity, where they must be able to neutralize the sulphuric acid formed during combustion, which will otherwise attack the cylinder walls and piston rings. Neutralization results in the formation of insolubles from the additive in the oil, and the lowering of jacket temperatures thus affects the oil adversely, both by reducing its reserve of alkalinity and by increasing its insolubles burden. The relation between the corrosive properties of the acidic condensate and wall temperature, and its implications, are discussed, together with the effects of a reduction of sulphur content.

The necessity for keeping in suspension the insoluble contaminants, which are prevented by the detergency of the oil from forming piston deposits, is dealt with, and also the effect of these insolubles on oil viscosity. It is concluded that, providing the resistance on starting can be overcome, and the oil can be fed to bearings and cylinders, its effective viscosity under running conditions will be influenced only marginally by even large amounts of insolubles, provided that these are dispersed. The use of centrifugal cleaning to keep the level of insolubles under control is considered, in conjunction with the question of water tolerance in oils.—*Belcher, P. R., The Motor Ship, December 1971, Vol. 52, No. 617, pp. 396–398.*

Lubricants for medium speed trunk piston Diesel engines operating on distillate and residual fuels

The paper first describes the essential differences in the lubrication of trunk piston and crosshead type engines, brought about by the differences of design. Examples of modern highly rated trunk piston engines are given, of both two-stroke and four-stroke designs, with leading particulars tabulated. The main characteristics and classifications of distillate and residual fuels are discussed, also their influence on engine performance and on the quality requirements of lubricating oils. Starting from basic principles of lubricating oil formulation, the paper describes the development of lubricants designed to meet the requirements of trunk piston engines operating on a wide variety of fuels, from distillates to commercial grades of residual fuels with viscosities up to 4000 sec Redwood 1 at 100°F. Details of tests carried out with two lubricating oils in several different designs of engine are described, with tabulated particulars and illustrations. Finally, brief observations are made on the reasons for the analysis of used oils and the inferences which may be drawn from the results.—*Seth, B. N., and Clark, G. H., Diesel Engineers and Users Association, Publication No. 322, February 1969, pp. 1–16.*

Investigations into the effect of fuel on temperatures and heat flux in a slow running Diesel engine

This report describes the continuation of the work reported in *European Shipbuilding* No. 4–1969, which dealt with investigations on the thermal load of a uniflow scavenged large bore Diesel engine.

In previous investigations, certain thermal instability phenomena were described, which might result in overheating of combustion space components. The mechanism of thermal instabilities, briefly, comprises three main factors.

Combustion: under certain conditions, combustion may produce carbon in larger quantities than usual and with large particles as an intermediate product. This results in increased heat transmission in the periphery, due to the centrifugal field of the swirl motion of the charge. A secondary effect of this may be accumulation of carbon particles in the piston ring zone, giving rise to gas leakage. Gas leakage: when considerable, there may be a displacement of the combustion zone towards the periphery. Gas leakage also disturbs the piston ring action. It may arise from mechanical defects in the ring zone, excessive or uneven liner wear, or as a consequence of the above-mentioned effect. Friction: if the lubrication of liner and piston rings is disturbed or ceases, the piston ring friction may increase drastically, particularly if there is scuffing. The friction heat which is developed contributes further to the overheating of the piston. There are strong indications that combustion anomalies are the primary initiating factor in the chain of events leading to a fully developed thermal instability, and that these anomalies may be due to certain fuel characteristics.

The conclusions reached on the combustion process and instability phenomena are largely based upon observations of secondary phenomena and metal temperatures with a time delay of uncertain length in relation to the actual process. A need was felt for more direct methods for studying combustion and heat transfer. The investigations were based upon a more advanced instrumentation of the experimental piston and liner.

The main object of the investigations described, was to compare the effects of two different fuel oils, and to evaluate the effects of different fuels and fuel treatment on the combustion, heat transfer and thermal load. For this purpose, a specially designed fuel system was installed, which could supply the test cylinder independently of the other cylinders. One of the test fuels was a large sample collected from a ship which had had problems with this fuel. The other test fuel was the ship's normal bunker, which had an analysis generally recognized as good.

The findings largely confirmed the conclusions in previous investigations in this project. Based to a large extent on statistical data, it was then found that water in the fuel had a significant effect on thermal load and thermal instability.

With this background it is suggested that the main characteristic of a "bad" fuel is its ability to keep water in a stable emulsion and precipitate sludge. Some experience seems to indicate that these properties are connected to the acidity of the fuel, but no stringent proof has yet been found for this.

Assuming that nozzle carbonizing is the most likely effect of water in the fuel and that this carbonizing impairs the combustion, it is pointed out that other factors may also have the same effect; nozzle carbonizing has been observed with high-quality fuels, and even with distillate fuels. In connexion with these observations thermal damage and signs of extensive afterburning have been noted. There may be various reasons for this such as the design and maintenance of the fuel injection system. Generally, a need is noted for fuel and combustion system designs which are less sensitive to fuel properties and which maintain a stable and clean combustion.—*Langballe, M., European Shipbuilding, 1971, Vol. XX, No. 4, pp. 3–15.*

Paper read at the Institute on Tuesday, 22nd February 1972

NEW DEVELOPMENTS IN MARINE FUELS AND LUBRICANTS—THE INFLUENCE OF THE CHANGING SCENE IN SHIPPING

D. W. Golothan*

The growth in world trade and energy requirements, intense competition and the mounting costs of manpower and maintenance are resulting in profound changes in the shipping industry. Container ships, combination carriers and tankers are likely to be the dominant ship types of the future, and the traditional types of propulsion unit, i.e. the slow speed Diesel and the steam turbine, will be increasingly challenged by the medium speed Diesel and the gas turbine. Automation, already well established, will become almost universal in the future and will demand the utmost in reliability in all components, including all products supplied by the petroleum industry.

This paper reviews the problems involved in the lubrication of marine propulsion units and describes the properties required of the various types of oils involved, both now and in the future. Developments in fuels are also discussed, since these can have an important influence on lubrication also. Finally, some comments are made on the role that the oil industry can play in shipping activities of the future.

Mr. Golothan

INTRODUCTION

Far reaching changes are taking place in the shipping world to satisfy the rapidly growing demands for transportation. It is generally accepted that, to meet these demands, shipping can no longer be considered as a separate entity, but as an integral part of an overall international transport system embracing land, sea and air modes. Shipping companies are, therefore, acting accordingly, and are increasingly merging with one another and with other companies having related interests, so forming large associations which amalgamate all the various facilities and knowledge of the individual members.

Integration on such a large scale is already transforming the pattern of trading—the growth of the container business is an outstanding example—and is also radically changing the means of transport for both freight and passengers. There will, therefore, be a continuing need for improvement in all spheres of ship design, construction and operation, and a similar need will extend to all other forms of transport within the overall scheme.

The oil industry has an important contribution to make in supplying the energy which will make these developments possible, but it is equally true to say that the developments themselves will in turn place new demands on the petroleum products required, especially fuels and lubricants. To appreciate these demands, however, and the manner in which they can be met, it is first necessary to review briefly the changes in shipping activities and ship types that will have most influence on fuels and lubricants in the future. These predictions are based on statistics supplied by various authorities(1, 2, 3).

DEVELOPMENTS IN SHIPPING

The Trading Pattern

The seaborne trade in oil has risen by around 10 per cent per year in the last ten years, while in the corresponding period dry cargo (bulk and general cargo) shipments have risen by 6·5 per cent per year. Most forecasters agree that this rate of growth will continue through the next ten years, i.e., total world trade will approximately double during this period. This trade will be very largely transported in bulk carriers, container ships and tankers, and the use of the dry cargo tramp ship will decline to an extent that it will be limited to routes where trade is insufficient to justify a liner service.

Because of intense competition, the use of container ships has not so far brought to their owners the economic benefits that were at one time expected. Nevertheless, there seems little doubt that further expansion of the container business will continue to dominate world markets in the future.

The world tanker trade, now in the order of 1300 million tons/year, is expected to grow at its present rate at least until 1985. After that time, nuclear power will probably become more widespread, with a consequent reduction in the demand for energy from petroleum fuels and a decline in the growth of trade for tankers.

The carriage of passengers by sea will greatly diminish, but because of increased leisure time and higher standards of living the numbers of cruise liners will probably at least double in the next 15 years. For the same reason a corresponding increase may also be expected in car ferries.

Ship Types

The general trend for all the main cargo carrying ships in the future will be towards increased size and speed to provide more economic operation. Towards this end, there will be rapid advances in ship design, especially for container ships, which will make maximum use of unconventional hulls, propulsion systems, handling methods and storage arrangements. The present lift-on/lift-off type of ship will continue in popularity, but barge or lighter-carrying ships (LASH ships) will become increasingly used, together with various other forms of container vessel, such as the segmented ship, where the containers form part of the ship's hull, and the warehouse ship, consisting basically of a large container box carried by a ship type displacement vessel. There will be a growing demand for combination carriers, such as oil-

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bulk-ore (OBO) carriers, and many of these will be very large in size.

Tankers will become even larger than they are today and most of the new tonnage will be for mammoth tankers of 200 000 dwt and above. Megaton tankers are technically feasible, but there may not be adequate docking facilities for such ships for many years to come. Fears of pollution are also likely to retard the introduction of vessels of this size. Very large nuclear powered submarine tankers may be coming into operation on certain routes within the next 15 years, however, and there are already proposals for five such tankers to move Alaskan oil to an ice free North Atlantic port.

Large numbers of specialized ships to carry selected bulk cargoes will increasingly enter service in the future. These cargoes will include sulphur, ammonia and natural gas in liquid form.

Rapid progress is being made with hovercraft and many such ships, capable of a wide variety of commercial applications, will be in operation by 1985. Another high speed ship, the hydrofoil, is also likely to increase in popularity for carrying passengers and freight over relatively short distances where air or road transport cannot compete.

Automation

The mounting costs of manpower and the difficulties of obtaining highly trained crews make the adoption of some form of automatic control almost mandatory nowadays. The principle has now been taken to the extent that a ship has been tested with no engineers on board, computers and data loggers performing the duties of the entire engineering staff. Even completely unmanned ships may not be out of the question for the future and certain shipbuilders are known to be already working with this end in view.

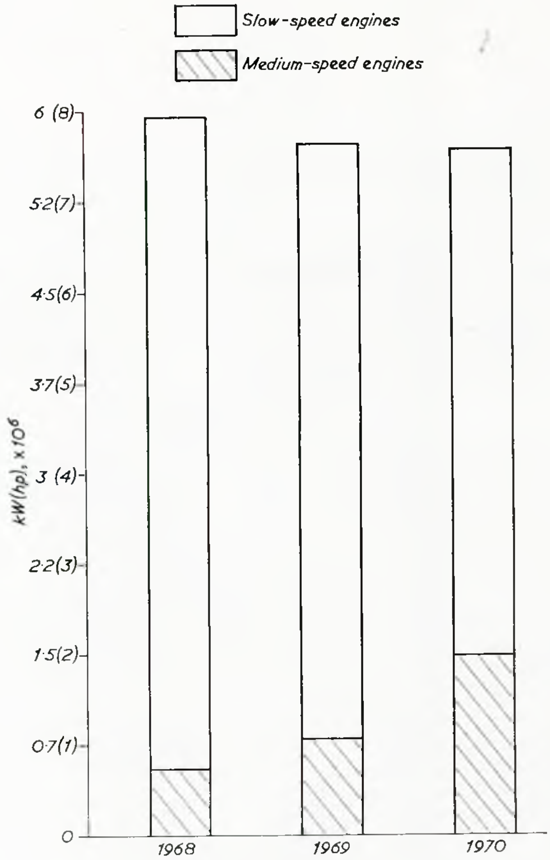
The extensive use of automation has had a profound effect on ship operation, and will have an even greater impact in the future. To compensate for the reduction or disappearance of engineering staff on board ship, shipyard engineering skills will have to become very highly developed and deployed. Shore based engineers will probably be flown to the ship and even cleaning operations will be carried out by land based mobile squads. The crew on board ship will be kept to an absolute minimum.

The key to all these far reaching changes in absolute reliability of engines and instrumentation and that stage has not yet been fully reached. In the pursuit of this object, however, the initial cost of any items which will improve reliability is likely to be of secondary importance to the shipowner. These items will include all the various products supplied by the oil industry.

Propulsion Units

In the same way that the ship will be only part of an integrated transport system, so must the propulsion system be considered as a unit in which there is a close relation between the characteristics of the main machinery and its ancillary equipment and the needs for auxiliary power. Economic and manpower criteria will be increasingly important and the propulsion systems will, therefore, be chosen on a basis not only of first cost and performance, but also from the standpoint of overall running costs and maintenance throughout the life of the ship.

In the foreseeable future, most ships will continue to use the same propulsion systems that are currently in use. The very large Diesel engines now entering service may be expected to continue in operation for at least 25 years, but it is most unlikely that their size will be any greater than that of the "cathedral" engines of today. The slow speed Diesel will meet increasing competition from other forms of propulsion, including the medium speed Diesel (see Fig. 1), which by 1985 is likely to be by far the most popular form of propulsion for the smaller ships up to about 20 000 tons. Maintenance problems with the multi-cylinder medium speed engine will undoubtedly be largely overcome during the next 15 years and this type of engine will have obvious advantages over the slow speed engine, not only in weight, space saving and first cost, but also in improved propulsive efficiency arising from the use of large slow running propellers in conjunction with geared installations.



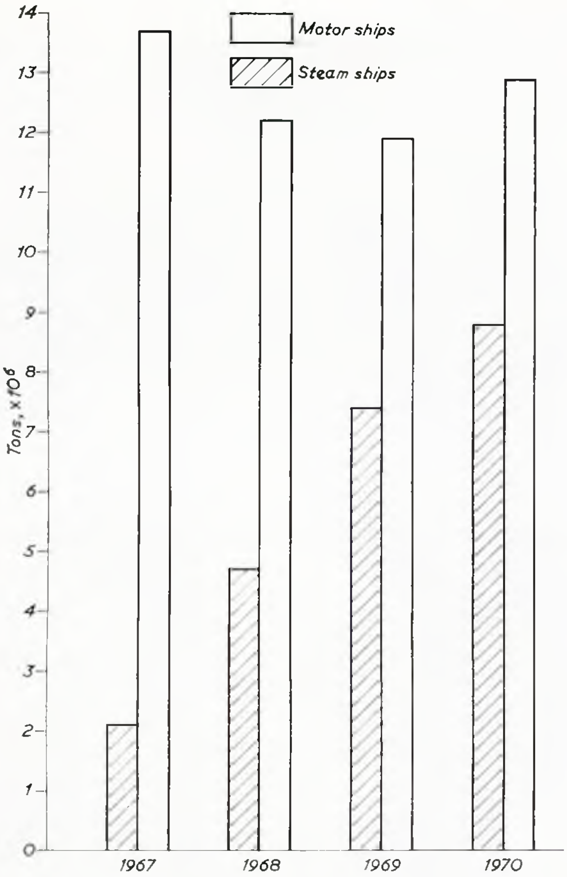
By courtesy of The Motor Ship

FIG. 1—*Annually installed kW (hp) motor ships*

The use of the steam turbine has shown a pronounced revival recently (Fig. 2), largely due to the increase in size and speed of vessels such as tankers and container ships, and to significant improvements in such features as boiler design. The gap in fuel consumption between steam and Diesel is also narrowing, especially if the turbine uses reheat. Very high power outputs are now available; the recently announced General Electric MST-19 range for example, will deliver up to 89 480 kW (120 000 shp). The steam turbine in the short term, up to the next ten years or so, will, therefore, continue to be used for most of the largest ships, but after that time it is itself likely to be increasingly challenged by the gas turbine.

The marine gas turbine is now gaining serious consideration from shipowners. It is already in widespread use for naval combat vessels, but for merchant ships it is only just beginning to compete with the established forms of main machinery. The gas turbine manufacturers are naturally making strenuous efforts to overcome the current disadvantages of high fuel consumption and the necessity to burn relatively expensive distillate fuel, and within the next decade it is likely that these problems will have been overcome. If the economics of its operation can be improved, the gas turbine is likely to provide some competition for all other forms of prime mover, especially in the higher power ranges, by virtue of the advantages of simplicity of design, reduced machinery weight and space, and the ability to replace a complete unit quickly and easily if a breakdown occurs.

Nuclear propulsion is receiving much attention nowadays and its application for submarines has already made revolutionary changes in naval task forces. For merchant shipping, however, there are still grave doubts about its economic justification, although demonstration ships, such as *Otto Hahn*, are claimed to be giving promising results. It is unlikely that nuclear propulsion



By courtesy of Lloyd's Register of Shipping

Note: *1 ton* = *1·016 tonne*

FIG. 2—*Annual tonnage of ships launched world-wide (excluding U.S.S.R.)—Motor v. steam*

will make any spectacular advances for merchant ships within the next 15 years or so, but by the year 2000 it is probable that the widespread use of commercial nuclear power will in turn make nuclear propulsion economically attractive for marine applications.

DEVELOPMENTS IN FUELS

There is unlikely to be any major change in the future in the present pattern of demand for fuels for Diesel engines and steam turbines, which for some time to come will meet most marine propulsion requirements. The large slow speed Diesels and the steam turbines will continue to use heavy fuel of 365–852 cSt (1500–3500 sec) viscosity almost exclusively, but fuel of this type will not be much used for medium speed Diesels because of the possibility of engine operating troubles, especially reduced valve life caused by ash deposits. The faster running Diesels will more likely burn thin fuel oils (TFO) with a viscosity between 49–146 cSt (200–600 sec). In view of the rapidly increasing numbers of such engines it may be expected that there will be a considerable increase in the demand for TFO in future.

To meet anti-pollution regulations the quality of heavy fuel for inland use has now to be more strictly controlled, especially in sulphur contents. These regulations do not apply to marine use—although there may be some restrictions on fuel burnt in harbour—and specifications for marine fuel are therefore unlikely to change in the future. However, since low sulphur components will be increasingly used for inland consumption, it may be that in the coming years the average values for sulphur content and other properties will increase in those fuels intended for the marine market.

A development which has attracted some attention recently has been the possibility of engines burning crude oil instead of the normal heavy fuel. The first of two Spanish built motor tankers, specifically designed to burn crude oil, entered service in 1971. It is understood that low sulphur Libyan crude will be burnt, and no doubt special precautions have proved necessary to permit this type of fuel to be used, especially in view of its higher flammability compared with normal fuel. It is unlikely that there will ever be a widespread use of crude as a fuel, however, because its financial value is higher than that of the heavy fuel produced from it; nevertheless the ability to burn crude would be useful if at times refinery output were unable to keep pace with the demand for heavy fuel.

As a result of the growing need for absolute reliability of operation, shipowners in the future will probably be prepared to pay more for a fuel of better quality which helps to improve such reliability. As general shipping costs rise, the fuel costs form a smaller proportion of the total and a point will eventually be reached where the extra cost of a higher quality fuel would be outweighed by the savings resulting from reduced maintenance and trouble-free operation. Thus, the user of 852 cSt (3500 sec) fuel might change to 365 cSt (1500 sec), and similar changes might take place in the TFO range. The ultimate is for a user of TFO to change to a distillate fuel and there are already indications that a number of shipowners have been considering such a step. In view of the present price differential between TFO and distillate it is unlikely that a switch will take place in the immediate future, but there is a distinct possibility that it could occur within the next five to ten years.

To determine the economics of the change, the increased cost of the fuel has to be balanced against the likely savings, which might possibly include a reduction in manpower resulting from more reliable engine operation, cleaner engine rooms, reduced annual overhaul costs etc. With manpower costs continually rising, this saving could be the most important of all. From these assumed savings the "break-even" differential in price between the two qualities of fuel can readily be calculated.

One of the important benefits of changing to a distillate fuel is the improved crew morale derived from the absence of the unpleasant cleaning jobs associated with the use of heavy fuel. It is difficult to express this advantage in economic terms, but it is nevertheless worth taking into account as crews become increasingly difficult to obtain and to keep.

Gas Turbine Fuels

The growth of the marine gas turbine is also likely to have an important effect on the pattern of fuel supply in the future. Aviation gas turbines are at present the predominant types for use in ships, both for naval and commercial applications, and these turbines are required to burn a distillate fuel having strict limits on ash content, particularly vanadium. Special fuels are supplied for naval use—for example, the U.S. Navy uses a "multi-purpose" distillate which is intended to be burnt in all their propulsion machinery, including gas turbines, steam turbines and Diesels.

In commercial applications it seems that in certain countries marine Diesel fuel as currently marketed would be suitable for gas turbines, though special precautions may have to be taken to avoid contamination during transport and storage. In some parts of the world, however, marine Diesel fuel contains a proportion of residual material, and would not therefore be suitable for aviation type marine gas turbines. The only appropriate fuel thus available at present which is 100 per cent distillate world wide is marine gas oil, but the price of this fuel is higher than that of marine Diesel fuel.

The fuel supply situation would be eased considerably if the industrial type gas turbine, rather than the aviation turbine, became the main type for marine use in the future. The industrial turbine has the advantage that it can burn heavy fuel, but mainly because of the large amount of space required for the regenerator it seems to be less popular at present than the aviation type gas turbine for marine purposes. However, General Electric have recently agreed an $8 million contract with the U.S. Maritime Administration to develop the industrial gas turbine for marine use, and as a result of this and other investigations it may be that the industrial turbine could in time rival or even perhaps supersede the aviation gas turbine for ship propulsion purposes.

A particular type of fuel which has recently been proposed for use in gas turbine ships is a heavy waxy distillate, which some suppliers claim could be marketed at a price lower than that for conventional marine Diesel fuel. This type of fuel is produced at the refinery by vacuum distillation of the residue from the primary distillation column; it is normally used as a feedstock for the production of lubricating oil and gasoline. The presence of wax in the fuel means that heating equipment is necessary to keep the fuel liquid, but the wax itself has valuable combustion properties in the gas turbines.

The availability of such a fuel at selected ports could make the use of the marine gas turbine more attractive economically, since the relatively low price of the fuel would help to offset the high fuel consumption that is its main disadvantage at present. No doubt a fuel of this type would also be in demand for Diesel engines, provided it could be marketed within a suitable price range. However, it should be emphasized that the availability of this special distillate fuel is strictly limited at present and future supplies will depend on many factors, including the growth in numbers of gas turbine ships and the consequent fuel demands for these vessels.

DEVELOPMENTS IN LUBRICANTS

High maintenance costs and the need for unmanned engine rooms mean that the lubricants used for ship machinery must be of the highest quality, and technological advances in propulsion units must be met where necessary by corresponding improvements in lubricating oil performance. Changes in the pattern of machinery, such as a swing from slow speed to medium speed Diesels, mean that the type of lubricant most in demand will also change, and the oil supplier must be prepared for such changes so that lubricant of the right quality will be available when required.

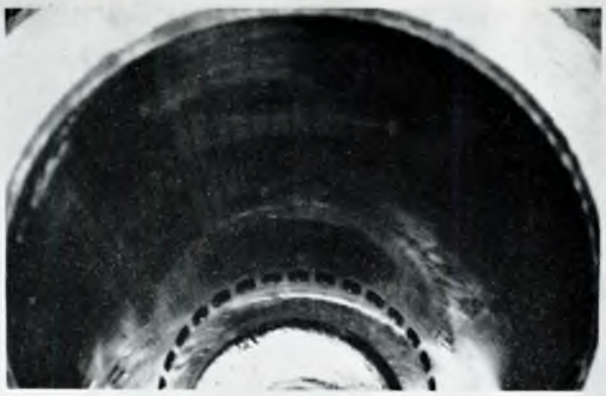
Another factor influencing the selection of lubricants is the need for rationalization of oil grades, so that the number of grades carried on board ship can be kept to a minimum. By doing this, the shipowner can considerably ease his problems of ordering and of storage, and is also likely to reap financial benefits by ordering in bulk. The growing need for rationalization has an important effect on oil properties, in that one oil may be required to lubricate several different items of machinery instead of only one. This requirement will be apparent for a number of the different types of oils that are used in marine service, as discussed under separate headings.

Cylinder Oils

For many years, highly alkaline oils, having a Total Base Number (TBN) of around 70, have given invaluable service as cylinder lubricants for slow speed Diesel engines burning heavy fuel. The demand for such oils has increased steadily in the past in proportion to the growth of the slow speed engine, but it is expected that in future, as other types of propulsion unit compete with the large Diesel, the growth in demand for cylinder oils will slacken off somewhat. Nevertheless, the requirement will continue to be large for many years to come and the properties of cylinder oils must continue to be studied, and modified if necessary, in relation to any changes in demand of the engine itself.

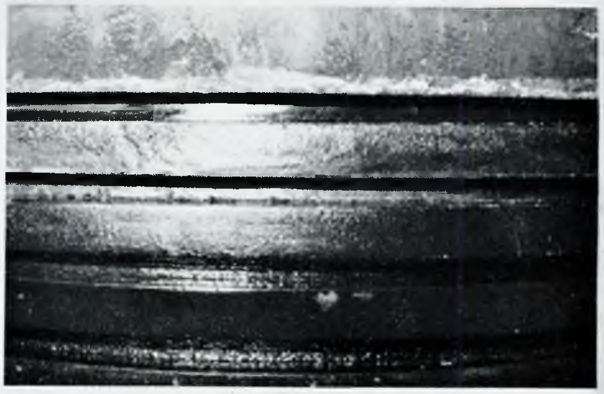
For the present, the performance of cylinder oils in general appears to be very satisfactory and cylinder wear rates as low as 0·02 mm/1000 h (0·001 in/1000 h) are sometimes recorded. At this level, new cylinder liners would not be required within the life of the ship and a piston overhaul time of up to 10 000 hours may be achieved.

The latest slow speed engines, notably the "super large bore" engines, do not appear to be any more severe in their lubrication requirements than earlier types. This is indicated by the cylinder and piston temperatures that have been quoted by the various manufacturers of these engines. For example, the temperatures at the back of the top piston ring groove of the leading makes of engine lie within the range 90°–150°C (194°–302°F) at full load.



No. 6 cylinder liner

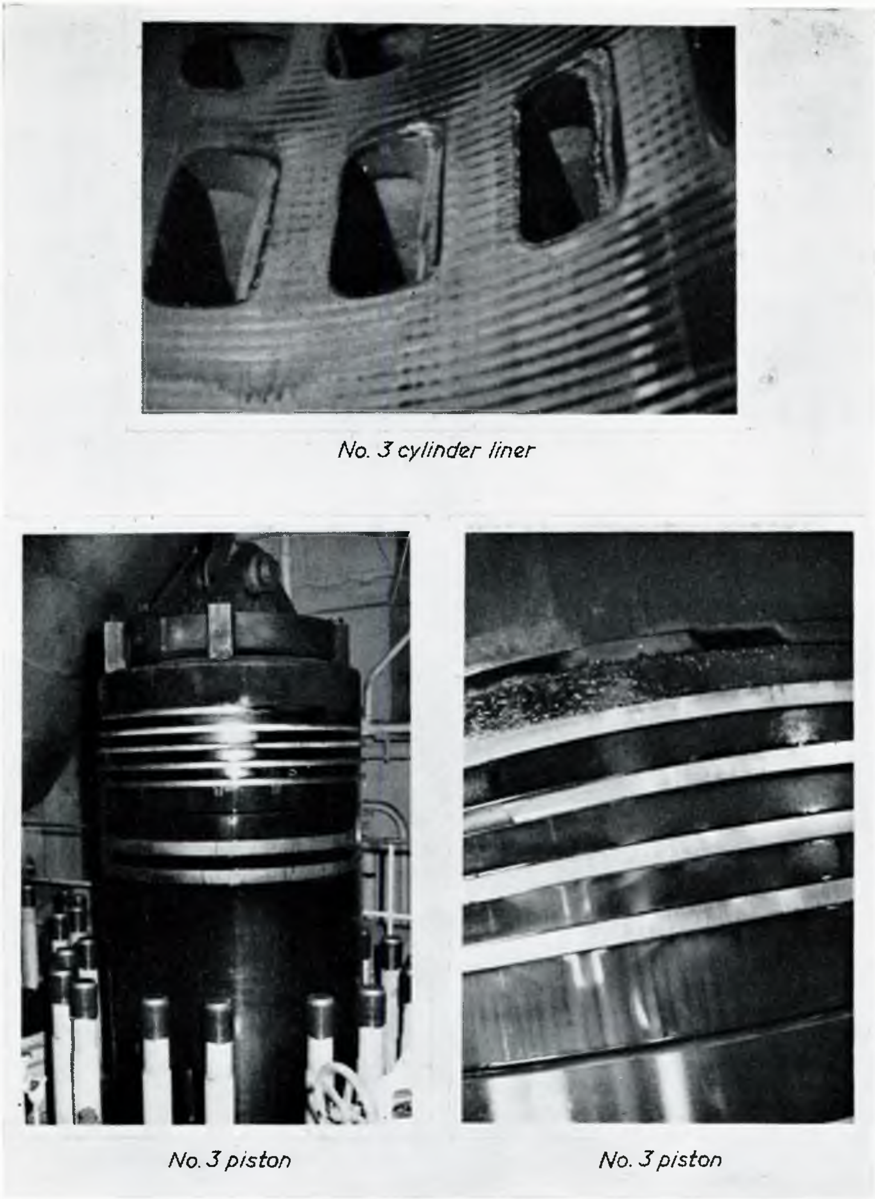
No. 6 piston



No. 6 piston

FIG. 3—*Burmeister and Wain K98FF engine after approximately 10 000 service hours*

Experience with "super large bore" engines in service has confirmed that their lubrication requirements are fully satisfied by current cylinder oils. As proof of this, Figs. 3 and 4 show the condition of Burmeister and Wain K98FF and Sulzer RND105 engines after approximately 10 000 hours and 7000 hours



No. 3 cylinder liner

No. 3 piston

No. 3 piston

FIG. 4—*Sulzer RND 105 engine after approximately 7000 service hours*

respectively, both engines lubricated by a commercially available cylinder oil of 70 TBN. Maximum cylinder wear was approximately 0·08 mm/1000 h (0·004 in/1000 h) in each engine.

Although the latest engines are more highly rated than their predecessors, therefore, improvements in design have been such that current cylinder oils are still quite adequate to meet the demands placed on the lubricant. It seems that in future, changes in lubricating oil quality are more likely to be dictated by changes in the fuel than in the engine itself. Of special importance here is the possible trend towards higher sulphur contents in the fuel: at present, maximum sulphur contents are in the order of 3·5 per cent, but if this level rises to 4 per cent or above, then a corresponding increase in oil alkalinity might be called for, especially if oil feed rates are relatively low. Some cylinder oils of 100 TBN have been made available on an experimental basis and oils approaching this level of alkalinity might be more generally required in the future. Alkalinity is not the sole property that is of importance in a cylinder oil and other properties, such as oxidation stability and load carrying capacity, must also receive close attention in the development of a new oil.

Whilst engines burning heavy fuel might impose more severe lubrication conditions owing to increased levels of fuel sulphur, any trend towards greater use of distillate fuel would considerably reduce the need for a high level of alkalinity in the cylinder oil. There might therefore be an increased demand in the future for cylinder oils designed for use with fuel sulphur levels not exceeding 1·5 per cent.

The "Low Sulphur" Problem

Apart from distillate fuels, certain residual fuels, especially from Eastern Europe and the Far East, are already available having very low sulphur contents, perhaps 0·5 per cent or less. The use of such fuels in conjunction with cylinder oils of high alkalinity has given rise to what has become known as the "low sulphur" problem, which is associated with high wear and/or scuffing of cylinders and pistons. The magnitude of this problem appears to have been much exaggerated, since many engines of all types are known to be operating quite satisfactorily with low sulphur fuels and with the normal highly alkaline cylinder oils. Such oils are of course not strictly necessary under these conditions, but the problems of using an oil of reduced alkalinity are firstly that the shipowner usually does not know the sulphur level of the fuel supplied to him and secondly there can be no guarantee that the fuel sulphur level will consistently be low at all bunker stations. It is therefore advisable to use a highly alkaline cylinder oil to ensure good lubrication even if a low sulphur fuel is sometimes taken on board.

There undoubtedly seems to be a genuine low sulphur problem, but the instances are rare and dependent on a number of other factors in addition to the fuel and oil. The main feature seems to be high piston and cylinder temperatures, which above a certain critical level can give rise to piston ring groove deposits, ring sticking and subsequent gas blow-by and destruction of the oil film on the cylinder walls. Such high temperatures may be inherent in the design of the engine, or, more likely, are derived from faulty fuel combustion or maloperation of the engine. Temperatures may be equally high whatever the sulphur content of the fuel, but with heavy fuels of relatively high sulphur content the production of sulphuric acid in the piston ring zone is of course greater than with fuels of low sulphur content. Similarly, more acid will be present if the lubricating oil is of low alkalinity. It is believed that the acid may be beneficial in one respect, in that it acts as a catalyst in the decomposition of intermediate oil oxidation products and, at high acid levels, there is, therefore, less oxidation and thickening of the oil around the piston rings.

The evidence from laboratory tests and service experience points to the fact that a genuine low sulphur problem can exist only if exceptionally high cylinder temperatures are involved as well. The combination of these three factors, low fuel sulphur, high oil alkalinity and high cylinder temperatures, appears to be sufficiently uncommon to be discounted as a serious problem. High cylinder temperatures on their own, however, can lead to trouble regardless of the oil or fuel used and sometimes an alleged low sulphur problem is in fact the result of high temperatures arising from some abnormal feature of engine operation. An example of this is a failure to match fuel viscosity to injector characteristics, since low sulphur fuels are often of lower viscosity than those of higher sulphur content.

Running-in

Faulty running-in of an engine can often lead to many subsequent operating troubles, because an effective seal between piston rings and cylinder has never been allowed to develop. The result is that there is excessive gas blow-by past the rings, leading to overheating of the piston and destruction of the oil film on the cylinder walls. Breakage of the rings may then follow, with consequent further deterioration of the lubrication conditions.

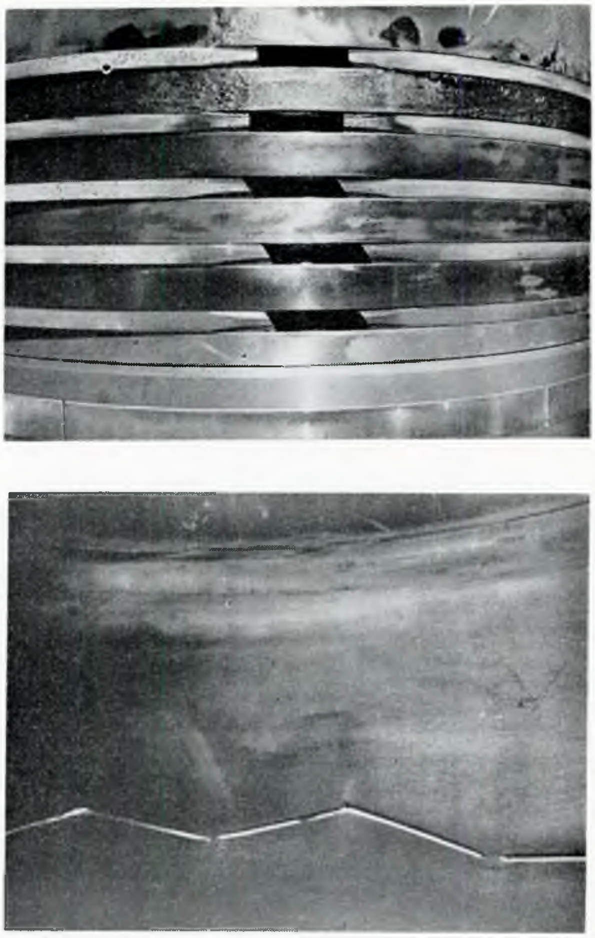
Usually an engine is run-in in the factory before installation in the ship, but sometimes a new engine has to be run-in in the ship itself. Similarly, when a new cylinder liner is fitted in service, it is necessary to run it in at sea. Running-in is a time consuming process, during which the ship's speed has to be reduced and the resulting loss of time is often a disadvantage under the tight sailing schedules of modern shipping.

Any means of accelerating running-in would, therefore, be of benefit to the shipowner and certain running-in aids are now available for use in either the fuel or the lubricant. The action of these materials is to produce a finely divided abrasive compound in the combustion chamber when the fuel or oil is burnt, which helps to lap in the rings against the cylinder. For smaller high speed trunk-piston engines, or for larger engines lubricated by splash, the running-in additive may be applied by means of the fuel, but in large slow speed engines, or in trunk-piston engines fitted with a separate cylinder lubrication system, it is more convenient to apply the additive via the cylinder oil.

Fig. 5 illustrates the condition of the cylinder and piston ring from a slow speed engine after a special running-in oil was used.

System Oils

In earlier engine designs, the main function of the system oil in a crosshead type engine was to lubricate the bearings and the demands placed upon the oil were not particularly severe. Good quality straight mineral oils without additives were generally quite adequate and the oil could often be used in the engine for several years without any need for renewal. In modern engines, however, the system oil is exposed to more severe conditions and a straight mineral oil is generally no longer adequate. The following conditions, in particular, demand remedial action by the use of additives in the oil:



Note: Exhaust side above oil grooves

FIG. 5—*Piston rings and cylinder of a large-bore engine run in with a special running-in oil*

a) contamination by cylinder oil drainings, which increases the burden of insolubles, allows an accumulation of pro-oxidant materials and may introduce strong acids into the oil;
b) exposure to high temperatures; this condition applies particularly to those engine types which use oil for cooling the piston;
c) contamination by water, either salt or fresh; leakage from coolers often causes the introduction of fresh water into the oil.

Some of the latest engines have improved designs of gland for the piston rod with consequently a much reduced risk of cylinder oil drainings contaminating the system oil. The need for additives in the system oil to combat the effects of contamination is, therefore, lessened, but nevertheless the majority of manufacturers of slow speed engines still have a preference for an additive type system oil.

Since the system oil is continuously centrifuged in service, most of the dirt and water is removed before it can cause any damage. Furthermore, when straight mineral oils were commonly used, they were normally water washed and this treatment helped further to clean the oil. Strong acid is also removed by water washing, but even so it is possible for corrosion to occur in the engine before all the acid can be eliminated.

A more effective way to deal with strong acid is to combat it by means of an alkaline additive in the system oil; any acid reaching the oil via contamination from cylinder oil drainings is then neutralized immediately, before it can attack metal surfaces such as crankshaft journals. With an alkaline additive in the oil, however, water washing is not recommended because the additive is likely to be removed by the water.

Although much of the dirt in the oil can be centrifuged out, it is still possible with a straight mineral oil for a sludgy layer to form on various parts of the crankcase. This sludge is not only unsightly, but might also be harmful if it is allowed to be baked on to hot parts such as piston undercrowns. A certain amount of "dispersancy" is therefore desirable in a system oil, so that insolubles are maintained in the oil as very small particles and do not settle out on engine parts. The crankcase is therefore kept clean. On the other hand, the degree of dispersancy must not be too high because the insolubles are then so finely divided that they cannot readily be removed by centrifuges or filters; furthermore, any water present will be similarly dispersed, and will give rise to an emulsion which is very difficult to break. Any additive used in the oil to confer dispersancy must, therefore, strike the right balance between a clean engine and adequate removal of insolubles and water from the oil by the cleaning treatment.

The requirement for the system oil to resist oxidation at high temperatures can be met by incorporating an oxidation inhibiting additive in the oil. In modern highly-rated engines the oil used to cool the piston may reach temperatures as high as 250°C (482°F) and, under these conditions, uninhibited oils would tend to break down and form coke-like deposits in the cooling spaces. In engines with water cooled pistons the system oil is not subjected so such high temperatures.

FIG. 6—*Piston cooling space of oil cooled piston of a slow speed crosshead engine—One year's operation with an additive type system oil*

Fig. 6 shows the absence of deposits that can be achieved in a piston cooling space after a suitably inhibited system oil has been used (one year's operation in this instance). The similarly clean condition of the crankcase is illustrated in Fig. 7.

Finally, the system oil must be tolerant of accidental contamination by water. As already indicated, additives used to provide alkaline and dispersant properties often also act as emulsion stabilizers, and it may be difficult to centrifuge the water out of the oil. There may also be a tendency for the water to remove some of the additive, particularly the alkaline component. Additives must therefore be selected which are not too sensitive to water, and it might also be desirable to include an emulsion-breaking additive in the system oil as an aid to separating out the water.

FIG. 7—*Crankcase from same engine as Fig. 4*

Since properties such as alkalinity, dispersancy and oxidation stability have to be built into the system oil to make it suitable for modern engines, the possibility then arises of using the oil in applications, other than in the main engine itself, where these properties would be of advantage. This extension in use of the system oil would allow the number of oil grades carried on board ship to be reduced, with resulting advantages mentioned earlier. An obvious additional use for the system oil is as a crankcase lubricant for the trunk-piston auxiliary engines and, if the oil can be fortified to meet this requirement, a further wide range of applications is immediately opened up, e.g. compressors, turbochargers, stern tubes etc.

The requirements for trunk-piston engines are discussed in more detail below, but it should be emphasized here that the system oil can be expected to lubricate only moderately rated auxiliary engines burning distillate fuel. In fact, the majority of auxiliary engines come within this category. Highly rated auxiliary engines having b.m.e.p. of around 17·7 bars (256 lbf/in^2) usually require a lubricating oil of correspondingly high performance, such as an oil meeting the Series 3 specification and, in the interests of economy, it is not practical to formulate a multi-purpose oil of this performance level. The system oil needed for the main engine is often carried on board ship in very large quantities—maybe 25 tons or more—and to make the oil much more expensive for the sake of relatively minor usage in other applications would be unacceptable to the shipowner. A compromise is therefore essential to achieve the required performance level at a reasonable cost.

Trunk Piston Engine Oils

The growing importance of the medium speed trunk-piston engine as a main propulsion unit, apart from its use for developing auxiliary power, has meant that in recent years much attention has been paid to the lubrication requirements of this type of engine. Where such engines burn distillate fuel, the lubrication requirements are much the same as with high speed Diesels and the oil used may be similar for both types of engine. Generally, however, trunk-piston engines used for main propulsion are now designed to operate with heavy fuel and, in this application, oils intended for use with distillate fuel are no longer satisfactory. It has therefore proved necessary for the oil industry to introduce special lubricants for medium speed engines burning heavy fuel.

Two different types of medium speed engine may be distinguished: those having cylinders lubricated by splash and those fitted with separate cylinder lubricators. The lubrication problems are basically similar for both types of engine, but in theory engines having separate cylinder lubricators could be lubricated by different types of oil for the cylinders and for the crankcase. There is generally an interchange of the two oils, however, some of the crankcase oil reaching the cylinders by splash and some of the cylinder oil draining down into the crankcase. In practice, the same oil type is often used successfully for both cylinders and the crankcase, although some engine manufacturers recommend a higher viscosity for the cylinder oil than for the oil used in the crankcase.

Since in a trunk-piston engine the oil is directly exposed to fuel combustion products, one of the main functions of the oil is to deal with the products of combustion and make them harmless to the engine. Sulphuric acid is always formed with either distillate or residual fuel and must be neutralized before it can result in corrosive wear of cylinders or other engine parts. An alkaline additive is therefore essential in the oil and it has been found in practise that a TBN of around 8–10 is adequate with a distillate fuel having a maximum sulphur content of around 1·5 per cent, whereas with residual fuel having a sulphur content in the order of 3·5 per cent maximum a TBN of around 25 is necessary. With these levels of alkalinity in the oil, depending on the fuel used, wear rates can be very low, even with residual fuel. For example, maximum cylinder wear rates of 0·02 mm/1000 h (0·001 in/1000 h) or less are frequently recorded.

The normal addition of make-up is sufficient to maintain the TBN of the oil at an acceptable level throughout its life. Provided the oil is given an appropriate cleaning treatment, its life may be very long—perhaps up to several years for the system of a large engine used for main propulsion. If depletion of the alkaline additive does proceed beyond a certain stage, however, changing the oil is recommended. As a guide, in an engine burning distillate fuel the TBN should not be allowed to fall to a level which is numerically below that of the sulphur content of the fuel. With residual fuel, it has been found that the minimum TBN is in the order numerically of twice the fuel sulphur content, e.g. with a sulphur content of 3 per cent, the TBN of the oil should not fall below 6. This recommendation is based not so much on control of corrosive wear, but rather on control of piston deposits, since it has been found that deposits begin to build up rapidly after the oil alkalinity has fallen below a certain critical level (Fig. 8).

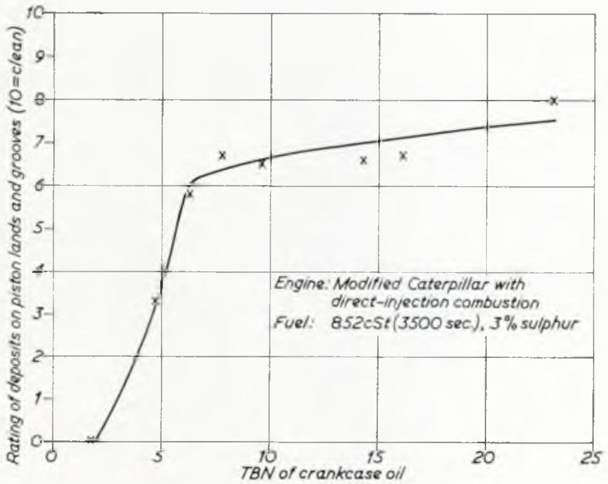


FIG. 8—*Influence of crankcase oil alkalinity on piston deposits*

It should be emphasized that these remarks apply to oils containing additives for which TBN is an indication of general performance level, not only of protection against corrosive wear. In other oils the alkalinity level might not necessarily be associated with other properties, and it is therefore important to seek the advice of the oil company concerned on the criteria to be used for assessing the useful oil life.

The property of oil dispersancy is very important in trunk-piston engines, whatever the fuel used. In the system of a slow speed crosshead engine, dispersant properties in the oil are required to keep the crankcase clean and the same requirement applies to a trunk-piston engine. However, the trunk-piston engine oil also has to lubricate the piston and it is essential that the oil should not allow the formation of any excessive deposits in this region, especially on the undercrown, where they might impair heat transfer, or around the piston rings, where they might result in ring-sticking.

Generally, the level of insolubles in the oil would be expected to be higher when residual fuel is burnt, since combustion tends to be less complete than it is with distillate fuel. As with system oils, it is not advisable to have too high a degree of dispersancy in the crankcase oil, because the insolubles may then be too finely divided to be readily removed by the cleaning treatment. Centrifuges of adequate capacity are, therefore, essential to maintain the insoluble matter in the oil at an acceptable level. Up to about 3 per cent may be considered tolerable with modern additive type oils; above that level, the oil will thicken and might not flow so readily to bearings and other engine parts. Furthermore, there is a possibility that soot and other insoluble material in the oil will tend to settle out in the engine if at any time the oil additive loses its effectiveness.

Water in the oil is a problem that often occurs in trunk-piston engines, with results that have already been described for system oils. Again, the additive combination in the oil must be selected so that the additive is resistant to removal by water and does not encourage the formation of a stable emulsion which cannot be broken in a centrifuge. As with additive type system oils, water washing of the crankcase oil in a trunk-piston engine is neither desirable nor necessary.

A third essential property in the crankcase oil is resistance to oxidation. If excessive oxidation is allowed to occur, the performance of the oil deteriorates: the products of oxidation cause the oil to thicken and are deposited on hotter parts of the engine, especially the piston, in the form of a lacquer and sludge. Organic acids may also be formed in the oil and these are liable to corrode bearings, especially the copper-lead type.

If oil and engine temperatures are relatively low there is little likelihood of oil oxidation, but in modern engines having b.m.e.p. of 17·7 bars (256 lbf/in^2) or more the conditions for the oil are much more arduous. The pistons in such engines are generally very effectively cooled—for example, a piston top ring groove temperature of about 120°C (248°F) maximum has been reported for a typical new design of medium speed engine operating at full load, but the oil as well as the cylinder coolant must remove large amounts of heat for such low temperatures to be achieved. The oil must, therefore, be fortified with additives to enable it to resist severe oxidizing conditions and a high quality base oil is also essential.

Another problem which may be mentioned here is that of scuffing of pistons and cylinders. A number of instances of this particular type of failure have been reported in recent years in medium speed engines, but the causes often remain obscure. There are many reasons for scuffing and the operating conditions and engine design obviously play a large part. Sometimes inadequate running-in of new parts is responsible, but scuffing is also sensitive to such factors as surface finish of cylinders and piston rings, clearances between piston and cylinder, and distribution of the oil on the cylinder walls. Distortion of the piston or cylinder is also sometimes suspected as a cause of the problem and pistons have to be designed to take account of such distortion, particularly under severe operating conditions.

Changes in the cylinder lubricant itself, apart from viscosity, generally have little effect on the incidence of scuffing. The use of friction reducing additives, which are effective in other applications such as gear lubrication, do not appear to prevent cylinder scuffing unless perhaps they are used at very high concentrations. However, it may be undesirable to use large amounts of these additives because of a consequent increased tendency to deposit formation.

To satisfy the various requirements of the medium speed engine, using either residual or distillate fuel, it is evident that an additive "package" is needed, which may be either a blend of different additives, each giving the required property, or perhaps a multi-functional additive in which several such properties may be combined. The balance of the additives must be correct, to avoid such undesirable effects as a stabilizing action on emulsions, and it is equally important to guard against over-treatment, particularly with metallic additives. An excess of these might give rise to heavy ash deposits on components such as valves and turbochargers.

Finally, as an aid to rationalizing the numbers of oil grades on the ship, it would be desirable where possible to bear in mind the use of the engine oil for other applications, particularly gearboxes. It is possible to formulate an engine oil which will also give excellent protection against wear of gears; hence, for oils intended to be used in engines burning distillate fuel, the oil price may be sufficiently low to bring the use of the oil within the economic range for gear operation as well. Oils intended for lubrication of engines burning residual fuel, however, are of necessity more expensive, because of their higher additive content and it is probable that the cost of using such oils in gearboxes would be unacceptably high, even allowing for the advantages of rationalization.

Turbine Oils

No less important than engine oils are the oils used to lubricate steam turbines, which as already noted are more than holding their own at present against competition from the Diesel and are now being designed to produce the highest power outputs likely to be required for the next few years. The lubrication of these turbines and their associated reduction gears demands a high level of performance of the oil, which even under prolonged operation must continue to meet all the requirements placed upon it.

Among these requirements are high resistance to oxidation, to give long service life; good demulsibility, so that any water contamination can be readily removed; adequate load carrying capacity for gear lubrication; good resistance to rusting of steel components; and a low level of corrosivity to copper and copper alloys, which are widely used in the oil system. To these properties may be added freedom from foaming and easy release of air from the system, although this may be difficult to achieve if the turbine oil has been contaminated by another type of oil, e.g. any preservative oil remaining in the system of a new or overhauled turbine.

As turbines increase in power, the thermal stress on the oil increases and further advances in oxidation stability are likely to be required in the future. Additional demands will be made on the ability of the oil to give protection against rusting and corrosion, and improved anti-wear properties will be needed to give effective lubrication at the higher gear tooth loadings expected in the future. There will of course continue to be a requirement for a long oil life, perhaps in the order of ten years or more.

For gas turbines there is already a wealth of experience from the development of suitable lubricating oils for the aviation industry. One of the main requirements of such oils is a high resistance to oxidation and thermal breakdown, since temperatures in conventional gas turbines generally rise to very high levels. Temperatures in the bearings rise to a peak during the initial period after the turbine has been shut down; during that time there is an extensive "heat soak" into the bearings from the turbine region and temperatures in the bearings may reach 300°C (572°F) or more. Mineral oils are not capable of standing up to such high temperatures and synthetic oils have proved to be necessary. Similar oils, perhaps modified to some extent to take account of the marine environment, are likely to be needed for the aircraft derived gas turbines now entering service for ship propulsion.

These oils will be required particularly to lubricate the bearings of the gas generator; the power turbine and associated reduction gearing may be lubricated by a conventional gear oil. In view of the advantages of rationalization, however, the synthetic oil should ideally incorporate load carrying capacities that will enable it to lubricate the gearbox as well as the gas generator and power turbine.

Industrial type gas turbines run at lower temperatures than aviation turbines and in this application mineral oils, such as those used to lubricate steam turbines, have given good service. Conventional steam turbine oils may therefore be expected to be satisfactory lubricants for marinized industrial type gas turbines.

THE FUTURE ROLE OF THE OIL INDUSTRY

This paper has so far been confined to developments in fuel and lubricants for marine engines and turbines only. There are of course similar developments taking place in the lubrication of all other items of machinery on board ship, such as transmission and hydraulic systems, but lack of space precludes any consideration of these activities here.

Sufficient has been said, however, to indicate that the oil industry must be continuously alert to the changes that are occurring in shipping and in its associated machinery. The essential requirement in all operations is reliability so that manpower and maintenance costs can be reduced to a minimum. Breakdowns in equipment will become increasingly intolerable in view of the ever mounting costs of repairs and delays and, although the equipment manufacturer has perhaps the primary responsibility here, it is no less imperative that the oil industry should play its part in maintaining smooth and trouble free operation of all items of ships' machinery. This means that technical advances in shipping must at all times be matched by corresponding improvements in the performance of the petroleum products used, especially lubricants.

Mostly, the developments of the equipment and oil industries occur in harmony and it is rare for technical advances in machinery to be held up because of inadequate performance of the petroleum products required. Sometimes advances made by the oil industry have a profound influence on developments in machinery. A notable example of this was the introduction in the mid-1950s of highly alkaline cylinder oils, which permitted relatively inexpensive heavy fuels to be successfully burnt in Diesel engines. The economics of Diesel engine operation were thereby transformed and there is no doubt that the widespread use of the Diesel engine, which continues to the present day, could be traced back very largely to that innovation by the oil industry.

There must therefore be frequent contacts between the oil industry, equipment manufacturers, shipbuilders and owners so that their activities and thinking may be co-ordinated and the problems of each side may be fully appreciated by the others. In this way, difficulties will be resolved, not in isolation, but in a much more efficient manner by the co-operation of all the parties involved. In the automotive industry, this sharing of information and pooling of resources is achieved by societies such as the Society of Automotive Engineers and the Co-ordinating Research Council in the U.S.A., but similar activities seem to be somewhat lacking in the shipping world. There are of course classification societies, associations of shipowners, and technical institutes, but there still seems to be scope for better integration of the activities of the oil industry and those of the equipment manufacturers and the customer.

The major oil companies are also large shipping operators in their own right and much of their acquaintance of marine problems may be drawn from their own experiences. Even with such resources, however, the knowledge gained can represent only a part of the total shipping scene and the various developments in fuels and lubricants described in this paper could not have taken place on the basis of information from tanker fleets only. The need for the closest co-operation between the oil and shipping industries generally still remains if the interests of all concerned are best to be served in the future.

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Discussion

Mr. R. E. Penfold said that he had found the paper extremely interesting and had felt reassured that in those areas where the Royal Navy had to decide the most appropriate practices when using fuels and lubricants to their own specifications they had reached decisions which were very much in harmony with those advocated by Mr. Golothan.

The statement in the paper that the U.S. Navy used a multipurpose distillate which was intended to be burnt in all their propulsion machinery, including gas turbines, steam turbines and Diesels, could give a somewhat over simplified picture. The situation as it had last been reported to Mr. Penfold was that a product called Navy Distillate had been introduced into the U S. Navy with the intention that by 1973 it should be in use in all their conventional steam boilers. This had involved a very considerable programme of conversion and maintenance to make sure that auxiliary equipment such as pumps were capable of handling the fuel. As far as its use in Diesel engines and gas turbines for marine propulsion was concerned, engine tests were taking place to see if this fuel, either to its present specification or a somewhat revised one, could embrace these uses. At the present time if a gas/oil type of fuel was not available to the U.S. Navy for Diesel engines, high flash point kerosene used for shipboard aircraft would be used. In fact, what was stated in the paper as being the case for the U.S.A. was more correctly applicable to the U.K., where in certain classes of ships it was present policy for Diesel fuel with rather close specification limits to be used in a multi-purpose role. This included fuelling boilers, gas turbines used in marine applications, Diesel engines and, in some cases, shipboard helicopter engines.

Under the heading "System Oils" reference was made to trying to ensure the right balance between the desirability of incorporating certain additives to give a degree of dispersancy with the desire for the oil to separate rapidly from water without producing any appreciable hydrolosis of the additives. He had been surprised when he had discussed this subject with members of the oil companies that there seemed to be a general absence of tests to assess the suitability of oil for use and storage in the presence of water. The Royal Navy had tried to introduce a requirement into their Diesel engine specification for OMD 113. At present this was based on either a demonstration that almost complete separation of the water took place on centrifusion or, if this was not so, a very small amount of additive breakdown took place. The additive breakdown achieved on hydrolosis they had assessed by filtering the oil and water mixture and determining the quantity of additive metals retained by the filter.

The author's reference to Total Base Number suggested that the Royal Navy's policy of setting a limit of 9 when using 1 per cent sulphur fuel in medium speed engines was adequate. He thought the comments also lent support to the Royal Navy's willingness to accept a somewhat lower TBN if an extra engine test at low temperature in a caterpillar L1 gave adequate performance. However, it might well be that even with an adequate L1 test some absolute limit of TBN should be set, and a figure which bore in mind the sulphur limit of the fuel would seem appropriate. The 3 per cent insolubles limit which was suggested as the maximum that should be tolerated in a used engine oil was in line with the guidance figure used by the Royal Navy, and he was glad to see quoted in the paper the suggestion that this figure was only allowable with modern additive type oils. He had always seen the raising of the insolubles limit to 3 per cent as being associated with the change of oil quality from OMD 112 to OMD 113 standard.

Under the section entitled "Turbine Oils" two points emerged. Firstly, with regard to mineral oils it was appreciated that with higher gear tooth loadings improved anti-wear properties would be required. How did the author hope to achieve this? By increased E.P. agents, or by improving the base stock? Secondly, the author stated that for gas turbines there was already a wealth of experience in the development of suitable lubricating oils in the aviation industry. He went on to say that due to the higher temperatures involved in the bearings of gas turbines, mineral oils were replaced by synthetic oils. In the Royal Navy they were using 7·5 cSt synthetic oils, and knew that there were oils of improved oxidation stability at the 5 cSt viscosity range.

The author had repeated the phrase used by many, that similar oils, perhaps modified to some extent to take account of the marine environment, were likely to be needed for the aircraft derived gas turbines now entering service for ship propulsion. Could the author enlarge on this statement with experience from fleet trials or laboratory work, and indicate what detailed changes might be needed?

He noticed, with sadness, that the author under "The Future Role of the Oil Industry" when referring to co-ordinating bodies and associations had made no reference to the Co-ordinating European Council. This body certainly took an interest in engines used in a marine role, and the major oil companies were represented on its panels and working groups. Perhaps this was just one more reflection on the U.K.'s tendency to look at what was going on in the U.S.A. and perhaps forget about what was going on in the U.K. and the rest of Europe.

Dr. P. G. Casale said the author had compressed very neatly in the paper several important facets of the changing marine world, and it was to his credit that a rather complex subject had been transformed into a very absorbing paper.

With regard to cylinder lubrication, could the author supplement the information given on liner wear of large and super large bore engines with an indication of ring wear as well, in both types of engines?

Concerning the liner wear figures, he said he would confirm the very good liner wear rates that the author showed were achieved by present 70 TBN oils, both with large and super large bore engines. With regard to the latter type of engine, much of the credit for this achievement went certainly, as the author had stated, to the engine builders, who managed to keep piston and upper cylinder temperatures low in spite of increased rating.

Higher sulphur content of the fuel would certainly increase corrosive wear, and the author had forecast a requirement for higher levels of TBN approaching 100. Such levels of alkalinity, which represented an increase of up to 50 per cent over the present level of overbasing, would certainly have to be carefully checked against equally important properties of thermal and oxidative stability and load carrying capacity, as the author had said.But perhaps it would not be necessary to go to such TBN levels. Rather than by quantity of overbasing, it might just be possible to tackle the new situation with a concerted action on several other parameters. For instance, to mention a few:

1) quality of overbasing, say faster rate of neutralization;
2) timing of lubrication, a fair proportion of alkalinity was,

in fact, discarded unused with the cylinder drainings because the oil did not always reach the liner when it was most needed;

3) improved spreading of the oil in the cylinder.

In any case, special attention should be paid to keeping piston rings well lubricated. Ring wear rates, already that much greater than liner wear rates, could increase remarkably with high sulphur fuel. Some field data of Mr. Casale's company's seemed to indicate that ring wear was possibly more responsive to increasingly corrosive environment than liner wear. Had the author any comment to offer on this, or experience to contribute?

Still dealing with sulphur content of fuel but at the other end of the spectrum, i.e. the low sulphur problem, he welcomed the remarks the author had made in this respect. When the problem had first been discussed in some detail at IMAS 69,* he had felt that it had been enunciated in a somewhat spurious manner, being based on considerations which were not giving enough weight to those several instances of normality of operation with low sulphur/high TBN combination in a number of installations. He therefore felt grateful to the author for restating the problem in a different way, redefining it and expressing its limits. This approach might well point the way to a solution. The author felt that altogether the problem was not serious because it needed a combination, which was claimed to be uncommon, of three factors, low sulphur fuel, high TBN and high cylinder temperature. He differed to some extent with the author, and suggested that perhaps the problem might be somewhat more serious. In fact, it was likely that large bore engines would be increasingly run at maximum output to compete with greater output of super large bore engines. Possibilities of very high cylinder temperatures would thus increase. Also, high sulphur content, i.e. 4 per cent and above, would require greater neutralizing capacity of the cylinder oil. This meant that a fuel of, say, 0·8–1·0 per cent sulphur might have practically all its sulphur neutralized just as effectively as it was now at the 0·5 per cent (maximum) level. Further, fuels of 0·8—1·0 per cent sulphur were not so uncommon, and therefore the spectrum of fuels qualifying for low sulphur definition would be considerably broadened. Altogether, the combination of the three factors, high cylinder temperature, low sulphur fuel and high TBN, would then become less uncommon than it was today.

Dealing more specifically with the mechanism of the low sulphur problem put forward by the author, could the author expand on the subject and possibly give some details, for instance, of the laboratory tests that had led him to his theory? Also, perhaps the author could give an indication of how long an engine could run at exceptionally high cylinder temperature before trouble set in.

He understood from the paper that the low sulphur fuels referred to were residual fuels only. Could the author confirm this and say whether this meant in fact that satisfactory operation should be expected from the use of low sulphur distillate fuels in conjunction with high TBN? In this case, could the author explain the reason?

MR. N. SWINDELLS, M.I.Mar.E., said that Mr. Golothan, as usual, had given a thought provoking paper and on this occasion a wide ranging one. In fact, many of the subjects in the paper really merited a paper of their own.

He said he was going to devote himself to only one or two sections, and dealt first with the section on running-in. It had been common practice, and was common practice on the industrial side with small bore high speed engines to use either additives or running-in compounds, and it was natural that most of the oil companies when studying the running-in of the much larger bore marine engines would also consider the possibility of using additives. His own opinion was that it was marginal whether one used straight mineral oil or a running-in additive when running-in a large bore marine engine. What was more important was the procedure of running-in—the number of hours one ran on the running-in oil, the type of fuel used, the feed rate of the running-in oil, and the loading whilst running-in. His experience was that provided the engine manufacturers' procedure was followed there should not be any problems with running-in. One very relevant point on the question of running-in was that it was equally important to run-in a replacement cylinder liner as it was to run in a whole engine. This was all too often forgotten.

He then turned to system oils and concentrated on the large bore crosshead engine system oils. Some years ago his company had decided that the existing straight mineral oils would not be suitable for future engines, and about eight or nine years ago they had introduced an oil that incorporated rust and oxidation inhibitors. Using this same oil as a base they then commenced a research programme during which they experimented with varying amounts of other additives such as dispersant, detergent, alkalis and improved oxidation inhibitors. Their basic ideas, however, had been somewhat different from Mr. Golothan's in that they had thought that most of the modern engines would have had efficient piston rod glands. They had not really visualized that a lot of the piston drainings would reach the crankcase and had also thought that as they were neutralizing the majority of the acids in the cylinders by virtue of the high TBN cylinder oils, that the majority of those drainings that did reach the crankcase should have been neutralized. They had therefore worked not on the basis of a high TBN oil in the crankcase, but on a fairly low TBN oil, one which they had thought would give sufficient insurance so that if there was any strong acid entering the crankcase, more by accident than normal running, the alkali would take care of them. All during their research programme they had had in mind that they must at all costs keep the amount of additive to a minimum. The reason for this (as Mr. Golothan had brought out in the paper) was that the higher amount of additive, particularly the dispersancy additive, that one had in an oil, the more likely one was to hold in suspension fine carbon particles and, more important, water.

He believed that the oil referred to in the paper had a TBN of around 11 or 12, and he asked Mr. Golothan if he had had any trouble with emulsification of this oil. The oil his company had developed had a much lower TBN (around 4·5) and some four or five years ago when carrying out trials of a new ship they had had approximately 25 per cent water contamination in the crankcase. Fortunately, there had been no damage to the engine itself and when the ship had come back into port they had pumped the system oil into the settling tank and had successfully separated the oil and water. There had been a small loss of TBN, but in general the oil had been satisfactory for further use. He felt, although he was not sure, that if this had been their normal detergent type auxiliary engine oil of around 11 TBN, they might not have been so fortunate. He wondered if the author would care to comment on this point.

Finally, he said that with a title such as "New Developments in Marine Fuels and Lubricants" he would have thought that there might have been a section on hydraulic oils which, to his mind, was one of the most rapidly expanding areas in the marine lubricating oil field. He thought that this was the area on board ship, when one was trying to rationalize on the number of oils, where a real reduction in the number of grades carried could be made. There were already in service a number of oils with very high viscosities 49 cSt (200 sRed) and low pour points (−40°C) and a small number of oils of this type would cover all the hydraulic applications on board ship, which these days ranged from telemotors to hydraulic winches. Oils like these allowed the equipment to operate successfully regardless of the climatic conditions the ship might be going into, this being particularly true of deck equipment which was expected to work efficiently whether the vessel was in Norway or the Persian Gulf. He asked the author if he would give his thoughts on hydraulic oils.

MR. ADOLPH, A.M.I.Mar.E., said he assumed that the piston rings in the top photograph of Fig. 5 had been arranged specially for the photograph. He could not help feeling that if all the butts were in line as in the photograph it would severely impair the running-in of this particular cylinder.

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* Cotti, E. and Simonetti, G., 1969 "Combating Wear in Large and Medium Diesel Engines Operating on Residual Fuels". *Proc. IMAS 69* pp. 4b/15–4b/33.

In the section on the developments in fuels, the author had stated that in the future there was the possibility that shipowners might be prepared to pay more for fuels of better quality. This, he thought, was a very interesting statement. Certainly up to the present shipowners had been most reluctant to pay anything other than the very minimum for their fuel oils, but with the development, for instance, of container ships running to an extremely tight schedule, and where maintenance was now very much at a premium, he thought they might be arriving at the situation where, if an improved quality fuel could definitely be proved to bring about a reduction of maintenance, then it might be that a case could be made to the shipowner for paying a premium for this fuel. However, he thought this was something that would have to be gone into very carefully and quite a lot of proof put forward before this situation would arise. At the moment they still saw examples of precisely the reverse trend. For instance, in North West Europe with medium speed engines for short sea traders using 49 cSt (200 sRed) fuel oil, many shipowners were tending to move up to 146 cSt (600 sRed) fuel oil in order to realize a slight saving in this direction. With slow speed two stroke Diesel engines one did not see much change in the fuel pattern over the years, as the author had indicated. However, one had seen odd cases where, for instance, a ship burning 852 cSt (3500 sRed) fuel oil had decided to go down to 365 cSt (1500 sRed) fuel oil, but he thought this had been done to reduce the amount of heating required.

He agreed with the author that it was a most unpleasant job to clean heavy oil purifiers, but with the development of self-cleaning centrifuges (and by and large these centrifuges on present day ships were housed in their own room with extremely good exhaust ventilation) he thought this problem had been largely removed. It would, of course, remain on a lot of older ships for a considerable time to come.

On the question of high and low sulphur content, he said that they were already in some parts of the world seeing fuel oils with around 4 per cent sulphur content. These did occasionally crop up on motor ships. It rather depended on the particular crude slate available in the area. He thought the indications were that 70 TBN level cylinder oil was capable of coping certainly with this level of sulphur, and he tended to think even somewhat above this level, providing they had the other parameters as they wanted them with particular reference to spreadability and the speed of acid neutralization.

He said that he had for many years hoped to see some developments with regard to the timing of cylinder oil injection and was rather beginning to wonder if he would ever see any major development in this direction. It certainly seemed a little doubtful that it was going to come in the near future, so he thought they must continue to pay attention to the question of spreadability and the rate of acid neutralization in order to deal with the higher sulphur fuels. Most of the major oil companies were doing, or had done, work on higher TBN levels. 80 to 100 was generally the sort of area of this work. Whether these oils would ever see the light of day was another matter, but he thought the shipping industry could be assured that if the requirement for these oils did become evident they undoubtedly could be produced. However, there were a number of safeguards that would have to be looked into very carefully before these oils were generally introduced because anything which increased the ash content of these oils was in many respects undesirable.

A number of people were looking into the problem of compatibility of the higher alkaline oils with low sulphur fuels. It was inevitable that by virtue of the nature of the shipping business, a number of vessels would from time to time pick up one day a low sulphur heavy fuel, and a few weeks later a high sulphur fuel. It was totally unrealistic, as had been said, to change the cylinder oil to cope with these fuels, also, as the author had pointed out, chief engineers of vessels were not even aware of the sulphur content of the fuel they were lifting and therefore it was essential that the cylinder oil must be capable of dealing with wide variations of sulphur content. So they had two cases that they had to be able to deal with. In the first case they must have sufficient alkalinity to deal with the high sulphur fuel oil and the acid neutralization, and at the same time they must have an additive type that when it was operating in conjunction with a very low sulphur fuel oil would not produce any tendency towards scuffing. Additives were available which would, under these circumstances when operating with low sulphur fuel, decompose in such a way that they were harmless and would not promote scuffing. He thought that this was the way that these cylinder oils must go in the future.

Turning to crankcase oils, he said that the author had made a statement regarding the preference of manufacturers for an additive type system oil. If by an additive type the author meant an actual alkaline oil, he said he would dispute this statement. In Europe there was not at the moment a demand from the engine builders for these types of oils. They accepted them, and in some cases when the shipowners preferred them the manufacturer was naturally only too pleased to co-operate with this requirement. However, at the present time he did not think they could actually state that there was a preference for this type of oil. He thought the preference overall was still for a rust and oxidation inhibited mineral oil rather than an alkaline oil.

Ever since the introduction of heavy fuel oil they had seen vast amounts of time and money spent on developing alkaline cylinder oils to cope with these fuels. These cylinder oils had now reached a very high stage of their art, and he felt that future developments of cylinder oils were going to be won only at great expense both of money and time, and it might be that the time had now come when they should possibly look at the quality of the fuel oil.

Mr. R. M. Hosie said that fuels and lubricants from whatever origin were selected or specified because they performed certain functions or possessed certain properties. Some of these properties were well defined and therefore easily appreciated. For example, the physical state which could be solid, liquid, or gas, would obviously affect the way in which a material, fuel or lubricant, was applied in order to perform its intended function. Some of the other properties, however, were more or less obscure, since their influence was due largely to chemical changes in the material while performing this function. A clear understanding by engineers of these latter properties was essential since they played an important role in the long term economy of machinery operation.

The use of petroleum fuels and lubricants in marine service had been universal and virtually exclusive for many years. It might be surprising to realize, therefore, that even at the present time practically all the expertise in the optimum usage of these products remained vested with the oil suppliers. Certainly, a little research would have revealed that the principles and practice of the application of these essential materials did not appear to be formally taught in many, if indeed any, of the engineering schools up and down the country. Consequently, engineers, whether serving at sea or, and just as important, employed ashore in the design and manufacture of marine machinery, must acquire this vital knowledge how and where they could.

This situation might well explain the continued recurrence year after year of so many of the same types of operating problems which involved the use of these products. While it was not unreasonable to expect some residues from combustion and some wear in lubricated contacts (no process was quite perfect) there would seem little doubt, as exemplified in the paper, that the incidence of severe corrosion, deposition, sludging, wear, etc. could be avoided. This, however, could only follow if first the effects of the interrelationships between equipment design, petroleum products and service conditions upon economic performance were clearly understood, and then suitable operating practices adopted.

It was obvious that the oil industry had unique experience of the effects of these interrelationships, yet this situation could give some cause for concern. For such was the now apparently expected familiarity among users with the correct application of petroleum products to obtain maximum economy and efficiency, that there had been in recent years some discernible reduction in the ready availability of technical assistance in the solving of operational problems which had been at one time so freely given by the oil suppliers. This appeared particularly to be the case in the handling of fuel oil quality complaints resulting from combustion difficulties or deposit problems. Nowadays these were simply met with an analysis report which invariably showed that the fuel delivered was "within specification". This information, however factual, was of little real assistance to the shipowners' technical management who, while able to engineer the replacement of the damaged parts, could still be faced with a return of the trouble since the unrecognized root cause might lie in one of the other interrelated factors.

In his conclusion the author had made an appeal for greater co-operation between the interested parties—the oil suppliers, the equipment manufacturers and the shipowners—possibly on the lines adopted in the automotive field in the U.S.A. No doubt some useful results would be forthcoming which could be used in future development work. But this would surely be long term in effect, and would not meet the immediate needs of shipowners, viz: a substantial reduction of operating difficulties in their very considerable existing tonnage.

From his own experience Mr. Hosie felt that this requirement could more likely be achieved by the further education of those engaged in operating marine machinery. For, if the author's analogy of automotive practice was further examined, it would be found that the greatest influence upon satisfactory vehicle performance in terms of overhaul life was in fact the driver and his habits. This had been shown to completely outweigh all the other factors affecting operating costs, such as equipment design features and petroleum product quality.

Reverting to marine practice, he said that it should be remembered that the actual firing of combustion appliances and the oiling and greasing of machinery was normally carried out by personnel other than engineers, though of course under their supervision. It was then all the more important that the education of shipboard supervisory staffs in the properties and practice of application of fuels and lubricants be effectively achieved. It would be interesting to learn the author's views on how the oil industry could contribute to meeting this requirement.

Mr. E. R. Lysakowsky, A.I.Mar.E., complimented the author on the way in which he had tackled an extremely complex problem which was of interest to everyone concerned with ship operation.

In discussing the system oil requirements for crosshead Diesel engines, the author had referred to "straight mineral oils without additives" as being the primary choice for the operator, and then followed on to develop the case for a multi-purpose detergent-dispersant type system oil. Although straight mineral type system oils were still available on the market, the premium quality grades currently offered to the shipowner by a majority of oil companies in fact contained rust and oxidation inhibitors. In his experience, this type of oil was still capable of offering extremely good service to the operator prepared to maintain high standards of oil hygiene in the vessel. Continuous centrifuging allowed elimination of water and solid contaminants. Water-washing did not affect the additives and could be carried out on regular routine basis, thus removing the possibility of corrosion by strong acids. In engines equipped with oil-cooled pistons, oils of this type offered satisfactory deposit control and there was every reason to believe that this would continue in current designs because, as the writer pointed out elsewhere in the article, of the fact that the piston temperatures were maintained at a low level.

He agreed with the author about the advantages of a system oil containing alkaline additives, particularly if these were coupled with rust and oxidation inhibitors. In practice alkaline additives possessed a certain amount of detergency, and this in his experience allowed the attainment of excellent cleanliness of piston underside areas as well as the crankcase while using system oils with TBN as low as perhaps 4. The water-shedding characteristics of an alkaline system oil would in most cases be comparable with those of straight mineral oil. Water-washing was not necessary, but on the other hand it did no harm other than reducing the concentration of alkaline additives in the oil; thus there would be no serious problem with reclaiming the oil inadvertently contaminated with water. In case of severe depletion of alkaline additives, one would return to square one, i.e. a straight mineral oil with rust and oxidation inhibitors.

The dispersancy requirement seemed to be questionable. The higher additive treat inevitably increased the cost of the product, while in most cases the presence of a dispersant adversely affected the water-shedding and demulsibility characteristics of the oil. One apparent advantage was the capability of this oil to lubricate auxiliary Diesel engines. However, as the author had pointed out, the detergent-dispersant system oil could only be expected to lubricate moderately rated auxiliary engines, or otherwise it would be priced out of the market. It seemed that most of the auxiliary Diesels being installed in new construction fell into the category which required oils with detergency levels not far below Series 3 requirements and alkalinity of about 12–15 for satisfactory lubrication, and these were not feasible targets for a detergent-dispersant type system oil. The author's company had recognized this fact by recently introducing a new product on the market to meet the requirements of auxiliary Diesels of this type. One would therefore question the concept of there being a market requirement for a detergent-dispersant multi-purpose type system oil.

He suggested that the following products were likely to be required in the future;

1) the premium quality straight mineral oil with rust and oxidation inhibitors as the primary recommendation;
2) the alkaline system oil for more critical applications and/or for the operator who required additional "safety margin" in his operations and was prepared to pay a slight premium for it;
3) the detergent-dispersant type oil for some cases where the lubricant of this type would suffice for auxiliary engines and when the operator would be prepared to pay the higher price differential for the benefit of reducing his storage tank requirements. This need could in most cases be met by a suitable conventional heavy duty lubricant with a TBN of about 8–10. He said he would like to hear the author's comments on these suggestions.

The author had quoted some guidelines as to the acceptable level of insolubles in trunk piston engine lubricants. By which method had the insoluble content been measured? In his experience the generally used D893A method gave somewhat misleading results with dispersant type oils, i.e. the actual level of insolubles in the oil might be higher than indicated by the test. This anomaly increased with increasing levels of dispersancy. He had found that to obtain a realistic figure on insolubles in the lubricants developed for modern trunk piston engines burning residual fuels it was necessary to use a D893B "with coagulant" version of the method, which neutralized the action of the dispersant. The "with coagulant" figure might be several times higher than the conventional one, and therefore the use of this method necessitated the adoption of new standards for acceptable levels of insolubles. He asked the author whether he had any data regarding the correlation of the A and B versions of this method.

With reference to developments in marine fuels, there were two clear trends which were developing at present, both of which had largely been generated by the forthcoming anti-pollution legislations. One of them was, as pointed out by the author, the probable increase in sulphur and metal levels for heavy fuels intended for marine use. This might be coupled with a reduction in their availability. The other point which was not mentioned in the paper was that the probable changes in refining techniques—mainly the use of vacuum gas oil refining and de-sulphurization plans—were likely to produce increasing quantities of low sulphur heavy distillate fuels which might be marketed at economically attractive prices. This would be of interest to the Diesel engine operator wishing to combine greater reliability of operation provided by distillate fuels with lowest possible operating cost. The operator might be presented with a wider choice than at present. It was difficult to predict which trend would prevail, but he suggested that not all trends in fuel quality were likely to be for the worse. He said he would welcome the author's comments on this point.

Correspondence

Mr. A. Oolbekkink, in a written contribution said a cylinder wear rate of sometimes as low as 0·02 mm/1000 h was mentioned in the paper with reference to a large slow speed Diesel engine. He thought this must have been a very rare case indeed and that wear-rate of between 0·10 and 0·20 mm/1000 h in those engines having cast-iron liners was nearer the normal figure.

A temperature at the back of the top piston groove of 90°–150°C was also mentioned while a temperature at top dead centre on the liner surface of 150°–200°C was not abnormal and it was this temperature the oil had to withstand. These seemed also to be the temperatures found in much smaller engines but highly supercharged.

In his experience, also, there seemed to exist a "low sulphur problem". One theory was that the high wear and scuffing were caused by a too clean surface. Normally the sulphuric acid condensing on the liner surface caused some metal sulphates to be formed, even while using an alkaline lubricating oil. Metal sulphates were known to have a very good lubricating action, especially when the normal oil film was destroyed.

The lack of sulphates was far less detrimental to chrome plated liners than to cast-iron ones, so that apart from normally having a lower wear and a cleaner liner whilst using chrome plating, the "low sulphur problem" was much less than on cast-iron whilst using a low sulphur fuel.

The author had said that instances of low sulphur problems were rare but Mr. Oolbekkink wondered if this was true, especially with the very large bore engines. They seemed much more to be apt to run into a higher wear rate than engines under 800 mm bore and not very highly supercharged.

Chrome plating the liner would also take care of the problems of running-in the liners, since a chrome plated liner did not have to be run-in. A new liner, chrome plated, could be fitted and immediately the engine could be used at full load. This even helped the rings to get a better fit in a shorter time.

Chrome plating of the ring grooves would take care of the ring sticking to a great extent. This problem was mentioned several times in the paper and was often quite a problem. By using a combination of chrome plated liners and chrome plated ring grooves sticking hardly occurred at all, while ring breakage was also diminished. This gave one the opportunity to extend the period between overhauls to often double or more the normal time.

Author's Reply

Mr. Golothan, in reply, thanked all the contributors for their comments, which he had found most interesting and helpful.

With regard to the point made by Mr. Penfold concerning the multi-purpose distillate fuel for the U.S. Navy, he agreed that it was premature to imply that it was already being extensively used in all types of propulsion units, although he understood that its use in steam plants had by now become firmly established. If the current test work on this fuel gave satisfactory results, it might be expected that its use by the U.S. Navy would eventually be on a much wider scale.

With respect to system oils, he said his company had used various laboratory tests to study water separation in additive type oils. As Mr. Penfold commented, there was, with the exception of the OMD–113 test, a general shortage of standard procedures to evaluate water compatibility, and each laboratory tended to have its own preferred procedure. In his company, the procedure most often used was a modification of ASTM D–665, which was strictly a rusting test, but laid down a method for producing an emulsion of water in the oil. Since contamination of the oil by water was a common problem in service, a study of the effect of this water, both in terms of separation and of breakdown of the additives, must clearly play a large part in the development of additive-type system oils.

He agreed that with 1 per cent sulphur fuel in medium-speed engines a Total Base Number (TBN) of 9 was about right, while if the sulphur content were consistently 0·5 per cent or less, even lower TBN would be acceptable. However, he pointed out that TBN indicated only one aspect of oil performance. With certain additives, it told one only about the alkalinity, i.e. the ability to neutralize strong acids, whereas with some other types of additives it was also an indication of other properties which were associated with the alkalinity value. The type of additive used was thus very important in this respect.

He was glad that the Royal Navy agreed with the suggested limit of 3 per cent insolubles, and agreed with Mr. Penfold's comment that this limit should be applied only to modern additive-type oils. In changing the oil, other properties had to be taken into consideration, apart from the insolubles, and if the oil was otherwise in good condition it might be possible to accept even high levels of insolubles without harmful effects. Every case had to be judged on its merits, taking into account the equipment, the type of oil used, and the operating conditions.

With regard to the point about the necessity for improved anti-wear properties in turbine oils, he said that his company had carried out investigations on oils containing extreme pressure (E.P.) additives, and had reported the results in a paper presented some time ago.* The use of E.P. additives appeared to be a promising means of achieving the results required.

He said that they had not carried out fleet trials on marine gas turbine oils, work so far having been confined to the laboratory. More work would be required in the future, but service trials were difficult to arrange at present since so few merchant ships powered by gas turbines were so far in service. The properties mentioned in the paper, as well as resistance to water, would obviously have to be studied under service conditions as well as in laboratory tests.

He was sorry that he had not referred specifically to the Co-ordinating European Council (CEC), and fully recognized the valuable work that this organization was doing, including activities in the marine field. He knew that the CEC were attempting to standardize an engine test procedure for the evaluation of marine oils, and this, he thought, was part of the co-operative effort he was referring to. However, he felt that there was still room for some further activity, such as other committees or councils, on which shipowners could be better represented to supplement the work that the CEC was already doing.

Dr. Casale had enquired about the piston ring wear of large bore engines. Ring wear was as critical as cylinder wear in its effect on engine performance, and while the two were not necessarily related, both cylinder and ring wear were acceptably low in the examples quoted in the paper. Maximum wear of the top piston ring in the super large bore engines averaged about 0·6 mm/1000 h; this seemed to be a fairly representative figure for smaller engines also. It did seem on occasions that ring wear was more sensitive than cylinder wear to corrosive conditions, but it was difficult to draw consistent conclusions on this point. Much seemed to depend on the engine type, the component material and the operating conditions.

With regard to the point about oils of higher TBN than 70, it would seem that additives used in the current 70 TBN oils might not necessarily be the best type to use for oils of higher

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* Fowle, T. I., and Hughes, A., 1970 "Experience with E.P. Turbine Oil". *Proc. of the I.Mech.E.*, Vol. 184–3 (0), pp. 122–30.

alkalinity. One would have to take into account not only alkalinity; oxidation stability and load-carrying capacity were very important properties to consider also There were, of course, other ways of tackling the problems for engines in the future. Dr. Casale's suggestions concerning a faster rate of neutralization and improved spreading of the oil in the cylinder had been considered and were still being looked at. Timing of lubrication had been investigated from time to time in the past, but had never been widely adopted. If the timing were perfect, and remained as it was originally set, then it should certainly offer advantages. However, much depended on the position of the non-return valve in the system, and whether gas could blow back into the quills. If this occurred, the timing could be altered, and the original beneficial effects would be lost.

A low sulphur content in the fuel was still a very controversial subject, but his own company's investigations strongly suggested that low sulphur in the fuel and high TBN in the oil did not, on their own, lead to problems There was some other abnormality which was necessary to introduce the difficulties of high wear and scuffing, and if this abnormality could be removed then the problem would be overcome. The evidence that high cylinder temperatures might be involved was provided by laboratory work in a small crosshead engine, which showed that oxidation and thickening of the oil in the ring zone, and possibly ring sticking, were necessary preliminaries to excessive wear or scuffing of the rings when a low-sulphur fuel was used. This problem did not arise to the same extent with fuels of high sulphur content, even under the same severe operating conditions.

He suggested that in service high cylinder temperatures were largely associated with poor combustion. It had been shown that if deposits formed on injectors the cylinder temperatures could rise considerably, and it was reasonable to assume that if one or two injectors became subject to fouling it was the cylinders in which these injectors were fitted that were likely to give trouble. In reply to Dr. Casale's question about the length of time the engine could run at high temperatures before the onset of trouble, it was likely that this time was quite brief, probably only a few hours, but there was not yet enough evidence from service to confirm this supposition.

The comments in the paper related largely to residual low-sulphur fuels, but some engines, mainly older types, were known to be running on distillate fuels in conjunction with high TBN cylinder oils. So far as was known, these engines did not give trouble in service. Also, distillate fuels were often used for manoeuvring, but it did not appear that this practice led to difficulties if a high TBN oil was in use. However, until more evidence was available, he would not care to conclude that a distillate fuel would necessarily always be trouble-free if a high TBN oil was used.

Mr. Swindells had questioned whether the use of a running-in oil was any better than the use of a straight mineral oil, and had said that the running-in procedure was more important. The author agreed that the procedure was indeed very important, but it had been shown that certain oil additives could be used to advantage. Not only could the running-in procedure be accelerated but the piston ring surface was generally in a better condition than it was with a straight mineral oil.

The running-in oil developed by his company also had dispersant porperties, and kept the piston and rings clean during the running-in period. This was not always possible with a straight mineral oil, with which there could be a danger of piston ring sticking, even during the first few hours of running-in.

Certainly many system oils were giving a satisfactory performance with only oxidation inhibitors in the oil, but his company considered that an alkaline additive was desirable as well, as a safeguard against the risk of acid cylinder oil drainings entering the system. He agreed that with modern engines there was less risk of such contamination, but in older engines this contamination could sometimes occur. Even with cylinder oils of high TBN the cylinder drainings were not always alkaline. His company had analysed some samples of these, and had found that many had a very low TBN level, and some were even acid.

The system oil he was referring to in the paper did not in fact have such a high TBN as Mr. Swindells implied. Mr. Swindells had thought it was 11 or 12; in fact, his company considered a level of about 8 was satisfactory. As pointed out in the paper, it had been necessary to select additives which were not too sensitive to water, and there had not been any serious problems with emulsification of this oil in service.

His company had built multi-functional properties into the system oil because they considered there was a need for a multi-purpose oil which could be used in the auxiliary engines as well as for other applications on board ship. However, the oil was intended primarily for the system of the main engine, and there was therefore a price restriction. The oil could not therefore be expected to meet the requirements of certain highly rated auxiliary engines which needed an oil approaching Series 3 level, and which was therefore relatively expensive.

He had not referred to hydraulic oils in the paper, since he had restricted the subject of the paper essentially to oils for propulsion units. He said that a number of excellent papers had been written on hydraulic oils, and he gave two examples.*

Mr. Adolph had referred to the illustration of the piston after the running-in trials. The author confirmed that the ring gaps had been manipulated so as to be all in line, thus allowing the photograph to reveal the condition of the ring grooves as well. Certainly if all the gaps had been in that condition in service, serious trouble could have been expected because of the torching effect of the blow-by gases.

He agreed that shipowners so far were not showing many signs of changing to fuels of better quality, because they were not at present prepared to pay the higher price. However, if better and more expensive fuels could be proved to reduce manpower and maintenance costs, he thought that in time the situation would change. A number of shipowners had already expressed interest in this subject, even to the extent of considering a change from redisual to distillate fuel, but at present the price differentials generally were too high.

He had already referred to the possibility of cylinder oil drainings being acid, even with 70 TBN oils. Much depended here on oil feed rates also. If the feed rate were sufficiently high the drainings would probably remain alkaline, but there was a tendency in the interests of economy to cut down on oil feed rates. Where this happened, all the alkalinity might be depleted on the areas remote from the oil quills, and there might be the effect known as "clover-leafing", where there was high wear in between the oil holes. Reducing oil feed rates too far was thus a false economy because if the owner cut down on oil costs he might then introduce additional costs because of the need to replace cylinder liners more frequently.

The low sulphur problem was difficult to resolve in service because sulphur contents varied so much in different bunker supplies. Few ships were bunkering low sulphur fuel all the time, and the chief engineer rarely knew the sulphur content of the fuel. Even if he had this information, he did not know the sulphur content of the mixture in the tank, so the oil, therefore, must cater for all levels of fuel sulphur. In the interests of safety it would seem to be preferable to choose a high TBN oil, since with such an oil he believed there was less risk of a problem than with a low TBN oil used in association with a high sulphur fuel.

With regard to engine manufacturers' recommendations for system oils, he agreed that although the makers of the main crosshead engines accepted alkaline oils, and realized why they were necessary, they also approved many oils which contained only rust and oxidation inhibitors.

Whether the quality of the fuel oil for marine bunkers would change in the future was rather doubtful at present. He suggested that if any improvements were made, especially in terms of reduced sulphur contents, most of this low sulphur fuel would be allotted to inland customers, that is, the people who had to comply with anti-pollution regulations. Certainly it was possible to produce de-sulphurized fuel oil, but so far as he knew most of this fuel was destined for inland markets.

He agreed entirely with Mr. Hosie's comments on the

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* Jackson, T. L., 1969 "Hydraulic Fluid for Hydrostatic Systems". *Engineering Materials and Design*, Supplement to August issue. Jackson, T. L., 1965 "An Introduction to Industrial Hydraulic Oils". *Fluid Power International*, January and February.

desirability of improved education in fuel and lubricant technology. Presumably technical colleges and training centres would have to take the lead in this matter, supported by material and information supplied as necessary by the oil industry.

The author questioned whether the oil industry did not give enough technical assistance in fuel oil problems. He thought that whenever possible they tried to help, but in many cases so little was known about what had happened on the ship. Often all that was told to the fuel supplier was that the ship had been in trouble, and it was believed to be something to do with the fuel. Without the necessary technical details, the fuel supplier could give only limited help to supplement the routine analysis of the fuel.

In connexion with the point about associations of shipowners working in conjunction with engine manufacturers and oil companies, he mentioned the recent activities of the Large Bore Project in Norway. The findings of this Project had been the subject of a most valuable paper which had been presented at the International Marine and Shipping Conference (IMAS) in 1969.* Investigations of this sort must be of considerable benefit to all those involved, and indeed to the shipping industry generally, but this particular Project was probably unique in the scale of its operations.

Mr. Lysakowsky had referred to the desirable properties for system oils, and had said that water washing, while not strictly necessary, was not harmful with additive-type oils. The author confirmed that his company advised against water washing of additive-type oils, since apart from the possibility of removal of additive by the water, a stable emulsion might be formed if water washing were carried out on a regular basis. His opinion was that an oil containing an alkaline additive gave a better safety factor than water washing. Water washing would remove strong acid from straight mineral oil, but it was possible that these acids could already have caused damage before the washing removed them, whereas the alkaline additive would neutralize the acids immediately.

It was also true that dispersant additives dispersed water as well as insolubles. Therefore one had to be careful to keep this type of additive to the minimum, and not to choose an additive which was too highly dispersant. In the automotive field, certain very highly dispersant additives were extremely effective in keeping the engine clean, but this type of material could not be used in marine system oils.

As auxiliary engines became more highly rated and required oils of higher performance, the application of the multi-functional type of system oil could well become less. However, there were large numbers of ships in existence which had auxiliary engines which were currently quite satisfactorily lubricated by a multi-functional system oil, and this situation was likely to continue for some years yet.

He did not think that there was really a need at present for three types of system oils with differing levels of performance. He thought it more convenient to make available a premium type multi-functional oil, which offered the attraction to the shipowner that the number of oil grades carried on board ship could be reduced.

With regard to the question of determination of insolubles, he said that his company normally used their own procedure based on Sterimat filtration Their laboratories had tried the ASTM method with the coagulant some time ago, and had found difficulty in getting a good correlation. They had therefore proceeded no further with this particular method. Although alternative methods could be used, his company considered that overall the filtration method gave the most reliable and consistent results.

The heavy distillate type of fuel produced by vacuum distillation was mentioned in the paper in the section devoted to marine gas turbines. This fuel would certainly be of interest to the users of Diesel engines as well as of gas turbines, but at this stage it was difficult to forecast the price at which a fuel of this type would be sold. It was also uncertain at present how widely this fuel might be made available in future.

The author thanked Mr. Oolbekkink for his interesting written contribution, pointing out the merits of chrome plating. It was known that sulphides acted as lubricants and would prevent or retard the development of scuffing if the oil film broke down—this was in fact the basis of the action of extreme pressure additives in certain oils—but the author had not previously seen reference to sulphates acting in this capacity. It was an interesting new theory to explain the low sulphur problem, and a possibility that should be taken into account in future experimental work.

There was at one time a belief that engines of very large bore gave higher wear rates than engines with smaller bore diameters, but to the author's knowledge there was insufficient evidence to associate these problems with the sulphur content of the fuel. The Norwegian Large Bore Project, already referred to, confirmed that large bore engines, correctly operated, need not give rise to problems, and in fact the present "super large bore" engines seemed to be giving very satisfactory cylinder wear rates in service.

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* Sarsten, A., Hansen, A., Langballe, M., and Martens, O., 1969 "Thermal Loading and Operating Conditions for Large Marine Diesel Engines". *Proc. IMAS* 69, pp. 4c/64–4c/80.