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OBSERVATIONS ON THE LUBRICATION OF LARGE BORE DIESEL ENGINES AT SEA

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Careful investigations of typical large bore engines at sea, of which some results were first reported by the authors at Europort '73 Conference[1], showed that commonplace measurements of operating conditions, like coolant temperature and rotational speed of turbochargers, could be related to wear. The level of accuracy and frequency of the measurements, required to predict wear trends, was within the scope of routine engine logging equipment and practice. However, a reasonably long period of operation was required before reliance could be placed upon the predictions thus derived.

Detailed analysis of liner temperature and accurate spot wear checks were also obtained, which confirmed the existence of a general relationship of wear to temperature, the Dimple Wear Method being used for wear measurements as particularly suited to the requirements of the observations carried out.

Finally, evidence was found for supposing that clover-leafing wear patterns in large bore cylinders may be characteristic of the spot cylinder oil feed system and thus related to the mechanism of circumferential oil transport, rather than a function of lubricant quality within a range of lubricants of uniformly high total basicity.

INTRODUCTION

This paper deals with some aspects of design and operation which have a direct bearing on the wear processes of cylinder liner and piston rings of large bore diesel engines. The observations discussed were obtained from a relatively older generation of engines, which, however, still power a large number of vessels in service. In the author's opinion, the conclusions drawn from their experiences are of a general nature and quite pertinent to lubrication and design of current and future engines. The authors also hope that their observations can make a contribution to the debate about desirable engine maintenance schemes. In this regard the authors will not delve into the question of what constitutes an acceptable cylinder liner and piston ring wear rate or an optimum lubricating oil consumption[2], rather they propose to discuss some operating conditions which are more likely to result in less satisfactory lubrication and greater mechanical and thermal loadings with consequent increased maintenance need and costs.

Most of the research and test work described in this paper were carried out in the motor vessels *Esso Castellon* and *Strathardle*, though some reference will occasionally be made to a third ship, *Pontos*. In fact, some results from the systematic investigation of the cylinder lubrication and wear in *Pontos* and *Strathardle* have already been reported at Europort '73 Conference[1]. As remarked on that occasion, the outstanding co-operation of the respective shipowners and operators of *Pontos* and *Strathardle* was of paramount importance to the success of the authors' work. Equally, the assistance of both the *Esso Castellon* operator and the respective engine builder was essential to gather information which the authors regard as quite relevant to a better understanding of certain features of cylinder liner lubrication of large bore diesel engines.

Primary considerations in the choice of the test ships were their operational condition, standard of maintenance, voyage patterns, and willing availability for test purposes rather than make or type of their main engines. In make, their engines represent, nevertheless, three of the foremost large bore machines which, although exhibiting small individual characteristic performance differences, all show similar patterns of wear behaviour. Thus it is not the purpose of this paper to single out "better" or "worse" engine makes or types.

PARTICULARS OF TEST VESSELS

The motor tanker *Esso Castellon* is a 76 000 dwt, 16·5 kn service speed, company-owned tanker which ran mostly between the Persian Gulf and Europe during the test period. Test work in this vessel was concentrated in one highly instrumented cylinder liner.

The motor vessel *Pontos* is a 7150 dwt, 22 kn service speed, refrigerated cargo carrier operated by F. Laeisz (Hamburg), mostly trading across the Atlantic between Central America and Europe.

The motor vessel *Stathardle* is a 12 550 dwt, 22 kn service speed, specialized fast cargo liner of the Peninsular and Oriental Steam Navigation Company (London). This vessel had a fixed voyage pattern of three months' duration taking the ship regularly around the world from Northern Europe to Japan (*via* Cape of Good Hope) and back (*via* Panama).

Principal particulars of the main engine installation and operational parameters of the vessels are given in Table I.

METHODS OF WEAR MEASUREMENT

Cylinder liner wear was measured by the Dimple Wear Method, which was first reported at C.I.M.A.C. 1971[3].

The principle of this method is to assess liner wear through the reduction in diameter of the edge of a conical hole drilled into the wearing surface. This method will not be described here in any detail, as in the context of this paper it will suffice to remember that its basic characteristic is an accurate assessment—at 95 per cent confidence level—of wear both in specific surface areas (standard

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TABLE I—SOME PARTICULARS OF ENGINE INSTALLATIONS AND OPERATIONAL PARAMETERS

Vessel	*Esso Castellon*	*Pontos*	*Strathardle*
Engine make	Sulzer (Winterthur)	ACEC—M.A.N.	Mitsui—B and W
Engine type	9 RD 90	K9Z 70/120E	984–VT2BF–180
Commissioned	May 1968	January 1969	January 1967
Rated (100 per cent)	15 440 kW (20 700 hp) 119 rev/min	9400 kW (12 600 hp) 150 rev/min	14 100 kW (18 900 hp) 110 rev/min
Operating	14 170 kW (19 000 hp) 118 rev/min	8200 kW (11 000 hp) 140 rev/min	13 420 kW (18 000 hp) 108 rev/min
Turbocharging	Impulse	Constant pressure	Impulse
Cylinder oil feed rate	0·80 g/kW h (0·60 g/hp h)	1·07 g/kW h (0·80 g/hp h)	0·48 g/kW h (0·36 g/hp h)
Fuel—Viscosity Redwood No. 1 at 38°C	1500 s (mostly) 3500 s (max)	1500 s (max)	1500 s (max)

deviation 0·0093 mm) and diametrally (standard deviation 0·013 mm) over short operation periods, i.e. 1000 to 1500 h.

The ability to assess wear in specific liner areas is a particularly important feature because it becomes possible to study specific liner wear patterns and the underlying causes. Since first introduced in 1969, the Dimple Wear Method has thus been consistently used in the authors' company's controlled field tests of marine diesel cylinder lubricants. More recently, several engine builders have also become familiar with the method, using it mostly in connexion with their research and development work in test-bed engines and occasionally in seagoing installations.

Piston ring wear was measured by standard micrometer technique because, firstly, this can be relied upon when determining ring thickness, and, secondly, the dimple wear technique is practical only in connexion with liner wear measurement.

Determination of iron content (by x-ray fluorescence) of cylinder oil drainings was the technique used to monitor overall wear—liner and rings—as it developed. This technique was used in one vessel only, i.e. m.v. *Strathardle*, where drainings were collected in suitable catch-trays fitted to the bottom part of the liner.

OUTLINE OF TEST WORK IN M.V. "STRATHARDLE"

Research work in m.v. *Strathardle*, discussed in this paper, is essentially confined to the relationship of wear to engine operational parameters and it covers the period July 1969 to July 1972, during which the vessel completed twelve voyages of which eleven (July 1969 to April 1972) had practically the same pattern as that shown in Fig. 1. The last voyage (April 1972 to July 1972) was, on the other hand, different as the ship did not return to Europe through the Panama Canal and the operational conditions had also somewhat changed.

During coasting, such as approaching or leaving a port, distillate gas oil fuel was used and this represented about 5 to 7 per cent of the operation hours of each voyage. The average duration of each voyage was about 1350 hours.

Each voyage consisted essentially of three approximately 25 day long periods, two of which being at steady operating conditions (taking the ship outward from London to Hong Kong and homeward from Kobe to Rotterdam) while the third, between Hong Kong and Kobe, was made up of short or basically coastal runs between Far Eastern ports and fairly variable stay periods in the same ports. Two short runs, from Rotterdam to Hamburg, and then to London, completed the voyage. For ease of reference, periods of variable operating conditions in the Far East and Europe are referred to as coastal in later sections of this paper.

For each voyage, an average value and relative standard deviation were obtained for 38 individual entries in the ship log books for the three periods (outward, homeward and coastal) as defined above. This constituted a fairly detailed examination of operational parameters as it meant screening about 20 000 log figures related to the period July 1969 to July 1972. Additionally, considerable information was obtained on compression and maximum pressures (using a Farnboro indicator), cylinder oil feed

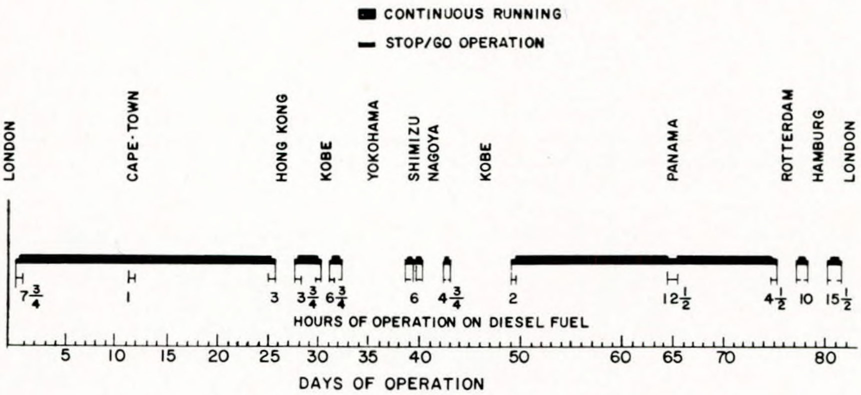

FIG. 1 — *M.V.* Strathardle — *Typical ship voyage pattern over period July 1969–April 1972*

rates and fuel consumption. This was, in fact, one of the tasks carried out by a company technician who travelled on the ship from July 1969 to April 1971. During the same period, cylinder oil drainings were recovered, as previously mentioned, from all liners by way of two catch-trays, each covering approximately 120° of the liner bottom part in starboard and port positions. A total recovery system was effected over periods of 24 hours each so that the total amount and rate of drainings recovered and iron content could be monitored over the entire duration of each voyage. Whenever possible, sampling periods were shorter than 24 hours during periods of variable operation so that wear phenomena occurring during such generally short periods could be more easily differentiated from those related to steady operation.

Besides iron content, other changes of oil properties like TBN, TAN, insolubles content and viscosity, were also followed as equally revealing of operational conditions requiring special attention.

With regard to lubrication, five cylinder oils, some experimental and others of established service performance, all at 70 TBN level, were used throughout the test period. These oils will be referred to as A, B, C, D and R.

Finally, throughout the period July 1969 to July 1972, fuel was routinely bunkered from the same supply points and monitored by frequent sample analysis which did not uncover any significant change in fuel quality.

INTERPRETATION OF RESULTS AND OBSERVATIONS IN M.V. "STRATHARDLE"

Information obtained on liner and ring wear rates, and their dependence on cylinder and turbochargers layout as well as metallurgy, has already been reported by the authors at the Europort '73 Conference[1].

Conclusions and observations from the analysis of cylinder oil drainings are meant to supplement the above information, whilst at the same time being possibly of greater interest to research and development of lubricants and engines than to operation of machinery.

Relationship of Wear to Engine Operational Parameters

Linear regression analysis (see Appendix) of wear, mostly liner's, versus operational parameters was carried out using mean and maximum wear rates and average values of operational parameters for the period to which the wear rates were related. Some regression lines were also calculated for mean ring wear rates but data from two different oils (oils D and R) had to be combined to obtain a sufficient number of points for analysis. This procedure was considered acceptable because these two oils (D and R) showed comparable ring wear performance. The most significant findings of that analysis are given below.

1) There appears to be a relationship between liner wear rates and both exhaust gas temperatures and turbocharger rotational speed. The regression lines of Fig. 2, with a statistical significance of up to 99 per cent, would indicate that higher wear rates can be expected from running conditions giving higher operational temperatures; and conversely, any reduction of such temperatures would lower the wear rates. In fact, higher turbocharger speeds can be expected to give higher total air/fuel ratio, under most circumstances resulting in lower exhaust temperatures and lower heat fluxes in the engine components[4].

Most engines of the generation described were designed to have adequate total air-to-fuel ratios and thus operate at or near rated conditions with sufficient blowdown to maintain reasonable heat flux levels in the liner,

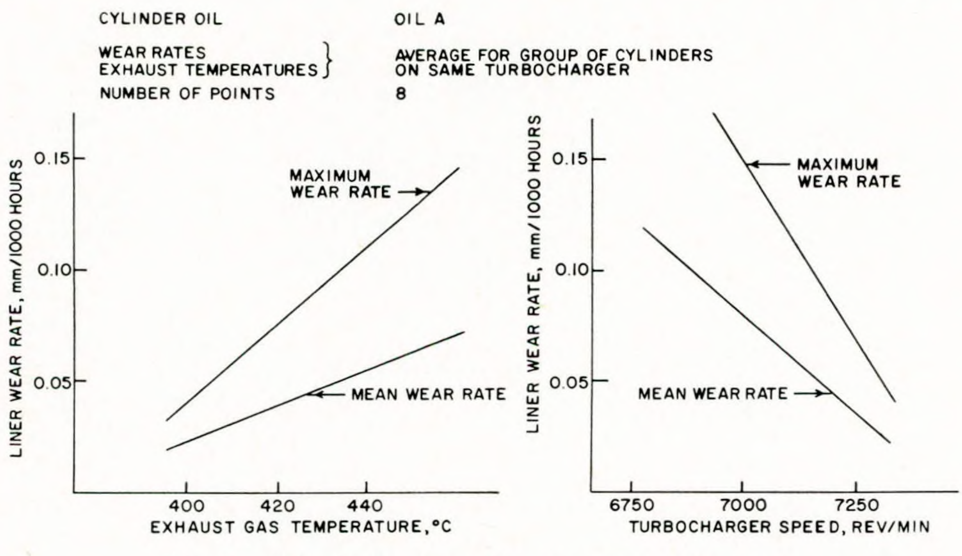

FIG. 2 — *M.V.* Strathardle — *Liner wear rate vs exhaust gas temperature and turbocharger speed*

What the authors propose reviewing now is the correlation between wear and engine operational parameters as obtained from analysis of data logged from normal ship's instruments during ship's engineer's routine checks. This should thus clearly indicate that much useful information of relevance to good operation is available within the vast array of operationally logged figures routinely obtained from ships at sea. Frequently, however, such data are not sufficiently analysed to the level necessary to detect trends of significance, despite the data having been carefully obtained by ship engineering staffs.

piston and cylinder cover. However, Ref.[4] shows how quickly heat fluxes may start to increase as the total air-to-fuel ratio falls below values of around 30:1. Such conditions may easily occur, even with engines and auxiliaries designed for adequate margins of charge air, should charge air coolers become partially blocked or turbochargers lose speed due to such things as turbocharger nozzle ring fouling. As is well known, those conditions may originate from low fuel quality or poor combustion due to bad atomization.

2) Liner wear rates and liner coolant outlet tempera-

tures seem related, the regression lines of Fig. 3 showing that conditions in the middle cylinders (Numbers 2, 5 and 8) may be more severe than in the wing cylinders (Numbers 1, 3, 4, 6, 7 and 9). Fig. 3 should be considered in the wider context of temperature/wear relationship, which is discussed later on in this paper. In fact, the regression lines of Fig. 3 do not necessarily imply a cause/effect relationship between coolant temperature and liner wear, since it is not known to the authors whether the higher coolant temperatures were the direct cause or merely symptomatic of higher liner heat fluxes produced, for instance, by reduced total air-to-fuel ratios.

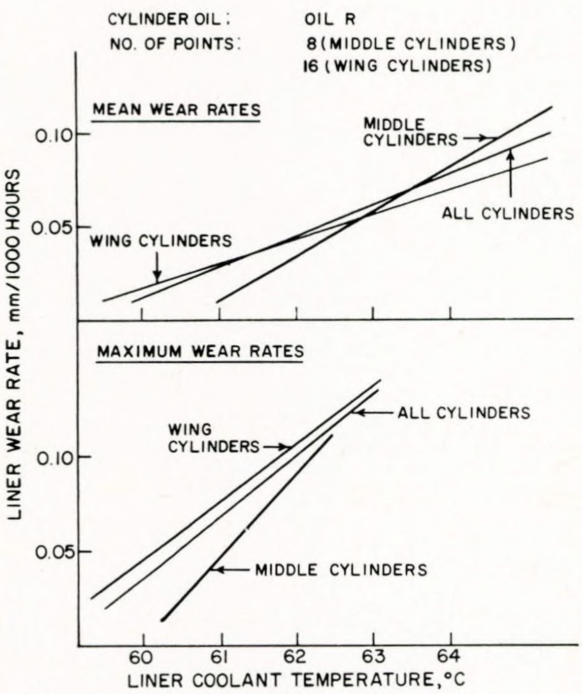

FIG. 3 — *M.V.* Strathardle — *Liner wear rate vs liner coolant temperature*

3) Higher ring wear may result from higher thermal loadings, of which cylinder temperatures—both piston and exhaust gases, (Fig. 4)—can be an indication. This should not be surprising, though the striking feature of these correlations is that they can be established through simple analysis of routine log entries. As it is conceivable that also cylinder liner wear would result from higher thermal loadings, it should not be concluded that a reduction of wear rates can be obtained simply by lowering coolant, hence cylinder liner, temperature. In fact, as is well known, overcooling of the cylinder liner may actually promote greater corrosive wear, particularly in the lower portion of the liner.

4) Equally interesting is that liner wear rates—as assessed by the accurate Dimple Wear Method—so clearly suggest a relationship to power output and brake mean effective pressure, even if the near constancy of these two operational parameters over most of the voyages effectively restricted the field of data to a few readings on oil A in three cylinders (Table II).

5) Finally, stop-go operation results in increased overall wear. This can be argued from Table III, where the iron content—and specific iron recovery—of the cylinder oil drainings are shown to be greater during the crossing of the Panama Canal compared with either steady or coastal operation. On the other hand, the same Table would indicate that running conditions may well be the least severe during coastal operation.

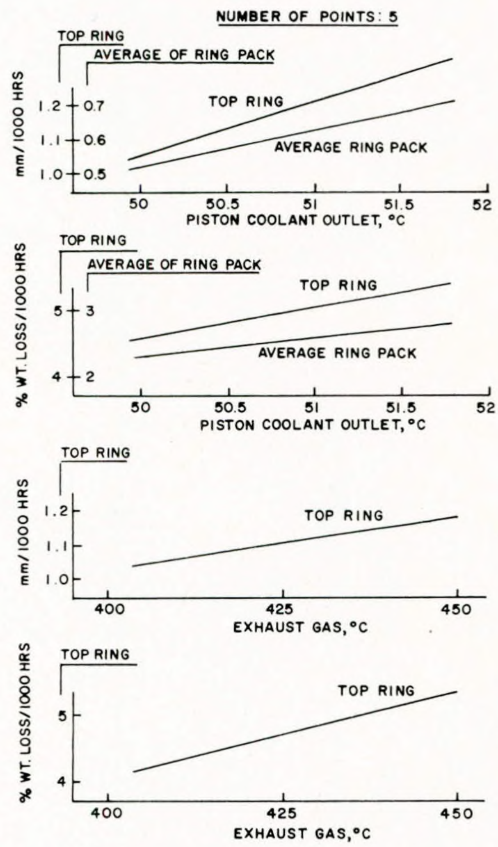

FIG. 4 — *M.V.* Strathardle — *Mean ring wear rate vs piston coolant outlet temperature and vs exhaust gas temperature*

TABLE II—M.V. "STRATHARDLE" LINER WEAR RATES VERSUS POWER OUTPUT AND BRAKE MEAN EFFECTIVE PRESSURE

Number of Readings	3	9
Cylinder Oil	<——— Oil A ———>	
Cylinders	<— Numbers 7, 8 and 9 —>	
Power Output, kW (hp)	12 774 (17 130)	13 475 (18 070)
BMEP, bar (kg/cm^2)	7·87 (8·03)	8·14 (8·30)
Liner Wear Rates, mm/1000 h (average for reading indicated)		
—Maximum	0·047	0·068
—Mean	0·020	0·035

As reported in Ref.[5], rates of iron recovery clearly reflect cylinder wear rates provided the iron recovery is expressed as g/kW h and calculated as follows:

$$\text{Specific Iron Recovery} = \text{per cent iron in cylinder drainings} \times \text{feed rate}/100$$

In fact, the figure of 0·128 g/kW h, given in Table III for stop-go operation, was calculated assuming that the feed rate was the same as that accurately recorded throughout both steady and coastal operation. The reason for that approach was that the average power output was not available for the stop-go period, though Table IV would suggest that such weighed average may well fall short of 50 per cent of a steady power output. On the other hand, the total quantity of cylinder oil injected during the entire period of the navigation through the Canal was generally about 50 per cent the quantity normally used for a steady operation. Altogether, the 0·128 g/kW h is therefore a rather conservative estimate of the actual increase of severity experienced by the engine during a stop-go operation.

TABLE III—M.V. "STRATHARDLE"
IRON RECOVERY FOR STEADY AND VARIABLE ENGINE OPERATION

Average Per Cent Iron Content of Cylinder Oil Drainings over Five Voyages	Steady		Coastal		Stop-Go	
Cylinder No.	Outward	Homeward	Far East	Europe	Panama Canal	Weighed Average of Voyage
1	0·254	0·296	0·192	0·226	0·312	0·261
2	0·224	0·230	0·178	0·206	0·258	0·219
3	0·208	0·236	0·260	0·193	0·414	0·226
4	0·251	0·235	0·262	0·250	0·256	0·246
5	0·171	0·195	0·173	0·193	0·196	0·184
6	0·190	0·234	0·160	0·203	0·258	0·206
7	0·139	0·156	0·154	0·160	0·170	0·150
8	0·295	0·196	0·225	0·194	0·286	0·236
9	0·139	0·169	0·181	0·173	0·252	0·162
Overall Average of Engine	0·208	0·216	0·198	0·200	0·267	0·210
Specific Iron Recovery g/kW h($\times 10^2$)	0·100	0·104	0·095	0·096	0·128	

Assessment of Engine Conditions and Operation Through Cylinder Oil Drainings

The evaluation of the effects of different lubricating oils and operating conditions on cylinder liner and piston rings wear by analysis of cylinder drainings for iron by x-ray is a well-established technique. Moreover, if combined with suitable chemical analysis, more information is obtainable on lubrication condition inside the engine without recourse to opening up of cylinders.

Several examples of fairly successful application of the drainings analysis technique are reported in the technical literature in association with a variety of types of engines, situations and requirements[5, 6, 7, 8, 9]. It is the authors' experience, however, that there are certain limitations in the response of this technique to wear situations in the case of large bore engines in seagoing installations. In particular, drainings inspection for iron are not easily related to engine operational conditions on a day-to-day basis unless changes are as drastic as those apparently occuring during the traversing of the Panama Canal discussed earlier.

TABLE IV—M.V. "STRATHARDLE" TYPICAL ENGINE OPERATION DURING NAVIGATION OF PANAMA CANAL

Total Duration	10 h 53 min	
Engine Operation	Total Number	Time as Percentage Total Duration
Stops	42	40 per cent
Dead Slow	29	13 per cent
Slow	18	5 per cent
Half Speed	19	7 per cent
Full Speed	5	35 per cent

Also there are some difficulties in detecting differences between cylinder oils when these differences are relatively small. Moreover, certain analyses, like pentane and benzene insolubles, cannot provide an indication of oil changes because drainings from large bore engines are not sufficiently homogeneous for such determinations. Finally, effort and cost involved in operating such technique in seagoing installations are quite considerable.

Notwithstanding the above limitations of accuracy and overall reservations, the authors were able to draw several fairly reliable conclusions from the numerous samples inspected, the most significant of which being:

a) There are significant variations of iron content of drainings from cylinders on the same turbocharger for a given cylinder oil. Such observations, pointing to different wear conditions, were generally confirmed by subsequent actual wear measurements.

b) There is no relationship between iron content and recovery rate of drainings, the same being true for TBN versus recovery. Recovery would thus seem to depend more on parameters like geometry of catch-trays, movements of scavenge air and fouling of catch-trays than, for instance, on differences in volatility between cylinder oils.

c) There is possibly a slight tendency to greater iron recovery rate in conjunction with greater amount of unused TBN in the drainings. This observation is quite interesting in so far as it may point to quite different phenomena possibly operating together, i.e. poor oil distribution and relatively slow rate of acid neutralization by the lubricant. On the other hand, another and more mundane explanation is that greater alkalinity of the drainings is symptomatic of somewhat higher residual dispersancy properties of the used oil, with consequent easier task for the drainings to keep in suspension larger quantities of iron.

d) There is no significant relationship between strong acid content of the drainings and either iron recovery rate or unused basicity. It should be noted, however, that all samples analysed showed some residual TBN and therefore the authors do not intend to exclude the possibility of a relationship of strong acidity to iron content once the oil basicity has been completely used up.

e) Iron content, TAN and TBN of cylinder oil drainings vary widely, and may depend on the type of operation of the ship, any relationship being, however, essentially qualitative. This is quite evident, for instance, for residual TBN which tends to be higher during coastal or stop-go operation compared to steady running (Fig. 5).

OUTLINE OF TEST WORK IN M.T. "ESSO CASTELLON"

A better understanding of the effects of cylinder oil quantity, quality, distribution and delivery timing, as well as liner temperature, on liner/ring wear pattern was the objective of some test work initiated in m.t. *Esso Castellon* in mid-1970. This investigation was concentrated in a comprehensively instrumented liner which was fitted in one cylinder of the engine. Its main features were:

i) 32 thermocouples;
ii) 80 dimples cut in the liner surface;
iii) additional instrumentation on main engine for continuous monitoring of some specific operational parameters (like fuel temperature at the nozzle) directly related to the test work envisaged;
iv) special ring pack in the piston, consisting of Sulzer KOC (gas tight) rings in grooves 1, 2 and 3; Sulzer K1 ring in groove 4 and an oil spreader ring in groove 5;
v) timed lubrication;
vi) new design of lubricator quill and quill orifice, without oil distribution groove.

The thermocouples' layout, illustrated in Figs. 6 and

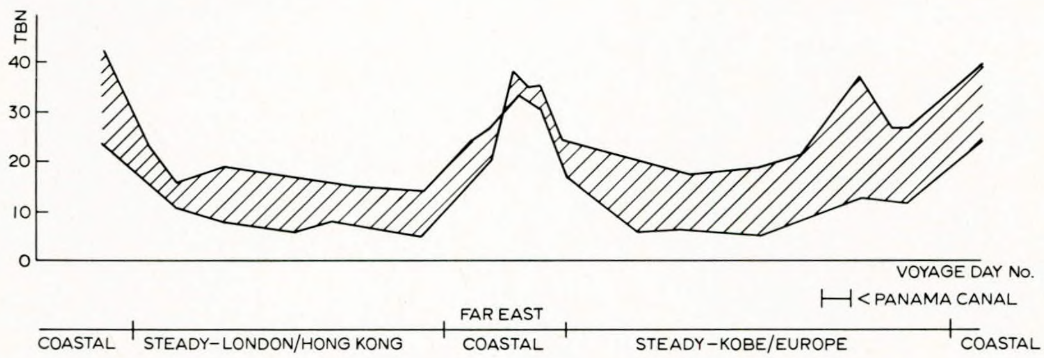

FIG. 5 — *M.V. Strathardle — Typical residual TBN pattern of cylinder oil drainings*

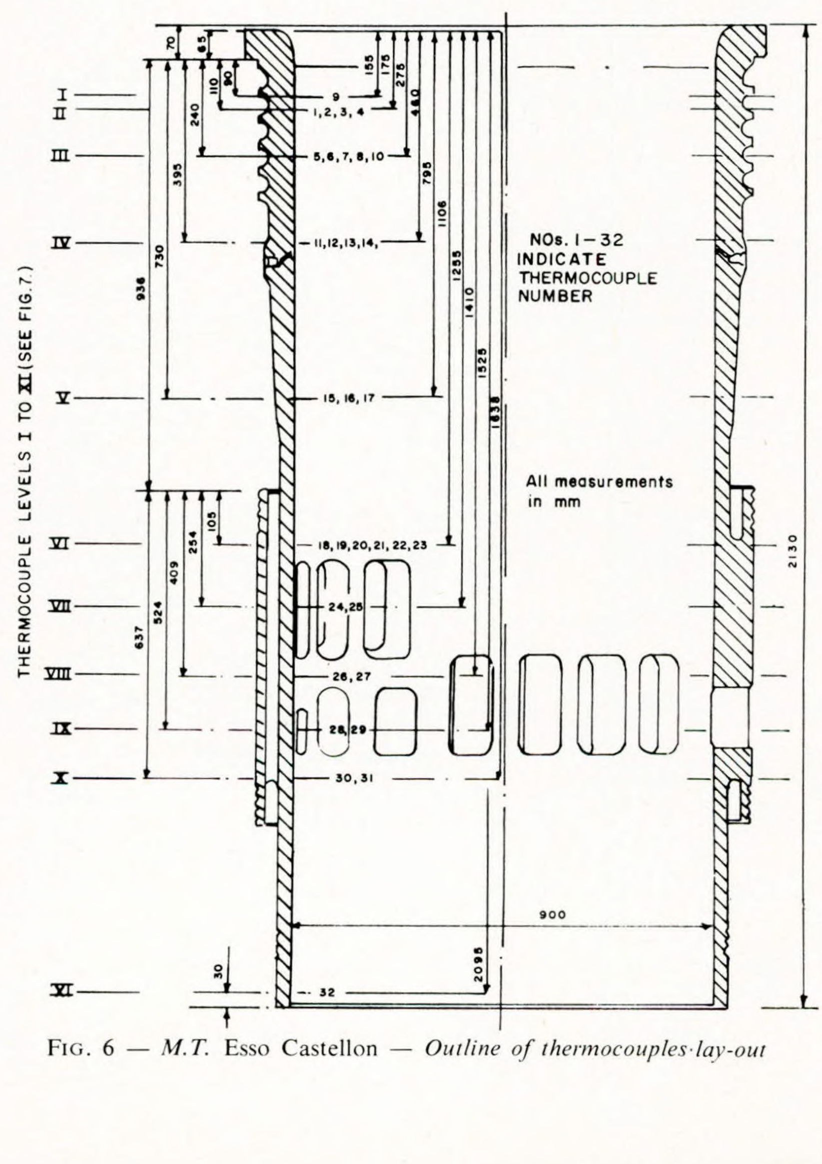

FIG. 6 — *M.T.* Esso Castellon — *Outline of thermocouples lay-out*

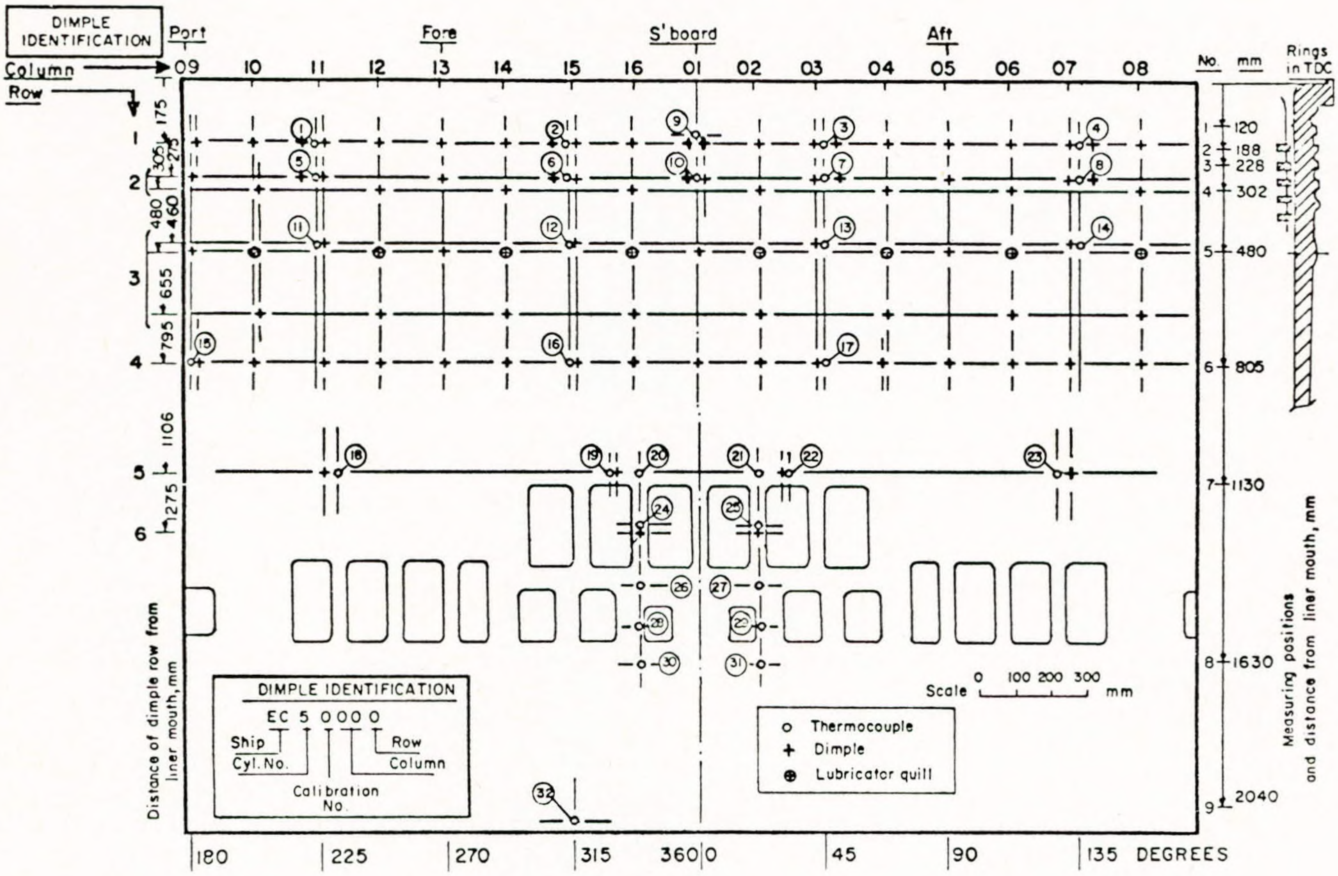

FIG. 7 — *M.T.* Esso Castellon — *Details of thermocouples and dimples lay-out*

7, was meant to offer the best chance of mapping out the liner thermal conditions comprehensively with a relatively low number of points and help to investigate specifically:

1) liner temperature over ring travel;
2) liner temperature pattern across port zone;
3) liner temperature at oil lubricator outlets;
4) ring sealing *versus* liner temperature.

The thermocouples were of chromel/alumel type and protected by an approximately 3 mm o.d. metal microtube, were Sulzer made and both liner drillings and thermocouple installation were carried out by Sulzer. The holes were drilled up to 5 mm from the liner working surface (Fig. 8). Twenty thermocouples, i.e. practically all those located in the upper zone of the liner, were connected to a magnetic tape, 20-channel data logger, with reading time intervals adjustable between 1 and 30 minutes depending on the specific need of the test envisaged. The remaining 12 thermocouples were connected to a chart recorder. The information stored on the magnetic tape was then processed by way of a computer programme designed to show maximum and mean temperature, standard deviation, as well as give a measure of intensity and density of sudden changes of temperature.

The dimple layout, also represented in Fig. 7, was designed to give a measure of liner wear related to:

a) liner temperature (average of maximum and mean readings for specific areas over a period of time);
b) cylinder oil transport;
c) port area environment;
d) some of most relevant diametral measurements in both F/A and P/S directions.

Dimples close to the thermocouples were generally cut at the level of the thermocouples, about 10–12 mm (about 1° 30′) away from the thermocouples. Two dimples were cut at either side of those thermocouples located in the

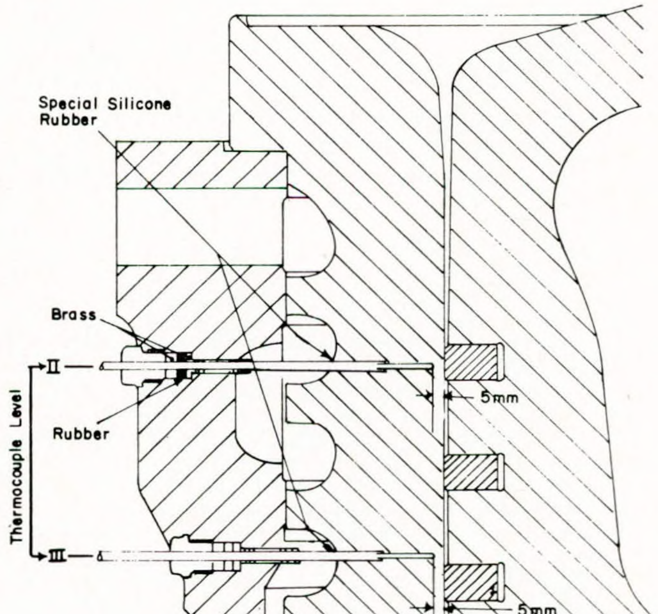

FIG. 8 — *M.T.* Esso Castellon — *Details of thermocouples in upper half of liner*

top 30 mm of ring travel. This arrangement aimed at obtaining accurate wear readings in a liner region as close as possible to a point of known temperature history without affecting that temperature in any way.

The overall arrangement of levels was such that there were 21 dimples opposite the top ring in TDC; 13 practically at the level of the third ring, 24 around the lubricator quills at the same distance from the quill orifice and either in line or in the middle of the quills, 16 half-way between port belt and quill level, and finally six in the ports area itself, of which two were just above the ports and two in the port bars.

Regarding timed lubrication, i.e. features (v) and (vi), this was of specific interest to the engine builder who has reported in some detail on this development at C.I.M.A.C. 1973[10].

Four cylinder oils were used during the two years of test work (July 1970 to June 1972), these being in fact oils B, C, D and R already mentioned in connexion with m.v. *Strathardle*. Dimple wear readings were obtained at the intervals illustrated in Fig. 9, the test being discontinued at 13 873 hours.

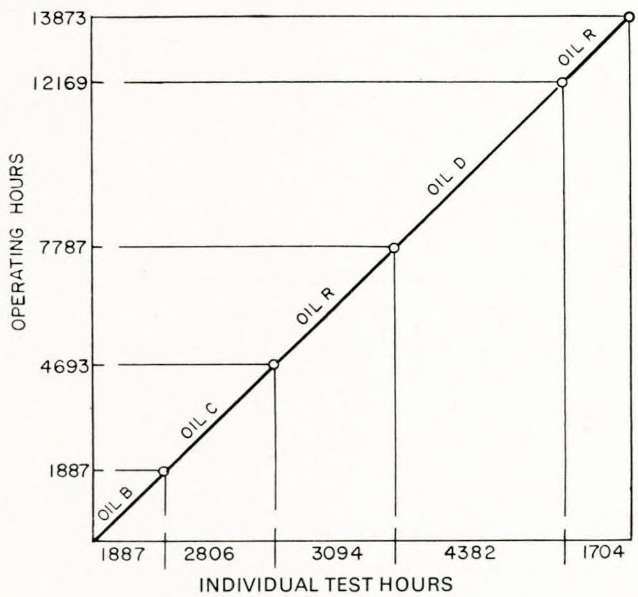

FIG. 9 — *M.T. Esso Castellon* — Tests sequence in instrumented liner

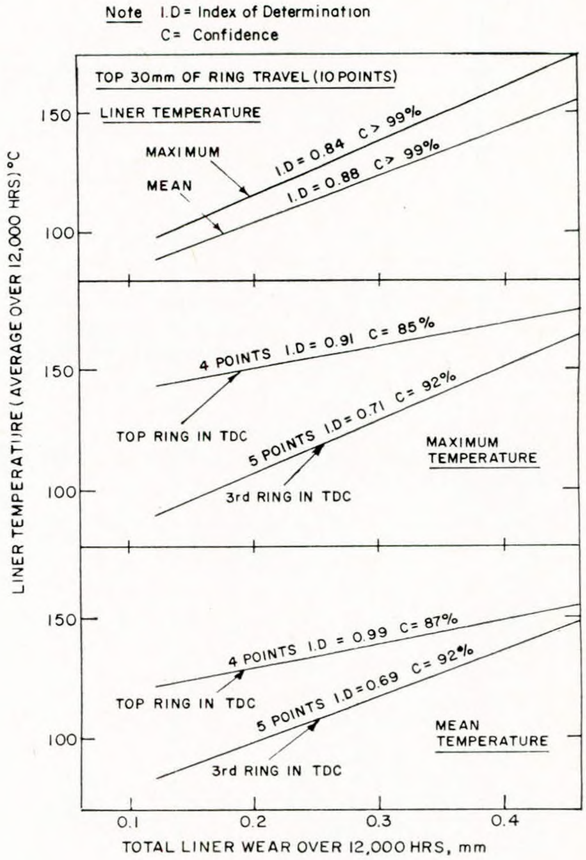

FIG. 10 — *M.T.* Esso Castellon — *Relationship of liner temperature to wear*

INTERPRETATION OF RESULTS AND OBSERVATIONS IN M.T. "ESSO CASTELLON"

All the observations recorded during the approximately 14 000 hours of test work point to the complexity of the relationship of wear to engine design, operational condition and lubrication parameters. The authors' comments will be confined though to the relevance of liner temperature to wear in general and to some observations concerning that well-known liner wear pattern commonly referred to as "clover-leafing".

Relationship of Liner Temperature and Wear

Temperature is an important factor controlling wear, though establishing the true nature of the temperature/wear relationship is a difficult task[11]. Various physical and chemical parameters, in fact, determine wear mechanisms and such parameters are generally affected by changes of temperature which make experiments difficult even under laboratory conditions. Field data, like those obtained by the authors, can only therefore establish a broad relationship between metal temperature changes and wear, which becomes better defined with increasing length of the observation period.

The wear data used in Fig. 10 cover a period of 12 000 hours and clearly indicate that higher wear should be expected if the liner temperature increases. This relationship is well-defined whether peak or mean temperatures are considered. The slope of the regression lines vary, however, quite markedly depending on the liner area. Thus, the wear/temperature relationship is more pronounced, though with slightly more dispersed data points, for positions at the third ring in TDC than for those opposite the top ring in TDC. This is most probably a reflection of the greater mechanical wear to which positions at third ring in TDC are subjected. In fact, higher liner temperatures, by lowering the lubricant film viscosity may well increase the frequency and severity of asperity contacts between ring and liner. Moreover, at the third-ring-in-TDC level the chances of asperity contact are 5 to 1 greater than those of the top-ring-in-TDC position because both top and second rings would be passing over that position twice, in addition of course to the third ring. This is also borne out by theoretical analysis of oil film thickness derived by the methods set out in Ref.[12].

The wear/temperature influence and the importance of mechanical wear are further illustrated in Figs. 11 and 12, which show the liner "clover-leafing" phenomenon as it developed from new until approximately 14 000 hours' operation at top and third ring in TDC levels. High temperatures, as well as a considerable increase of intensity of the temperature fluctuations, were apparent during the very last part of the test period envisaged for that liner (Table V). These abnormal thermal stresses, eventually detected in malfunction of the cooling system of this unit, must have resulted in the collapse of the lubricating oil film even where such film is at its thickest, i.e. in line with the lubricator quills. A metal-to-metal contact ensued with abnormally higher wear rates being recorded particularly in those areas which, through previous abundance of lubricating oils, had until that time shown lower wear and consequently were the peak of the gentle waviness of the clover-leafing of the liner surface.

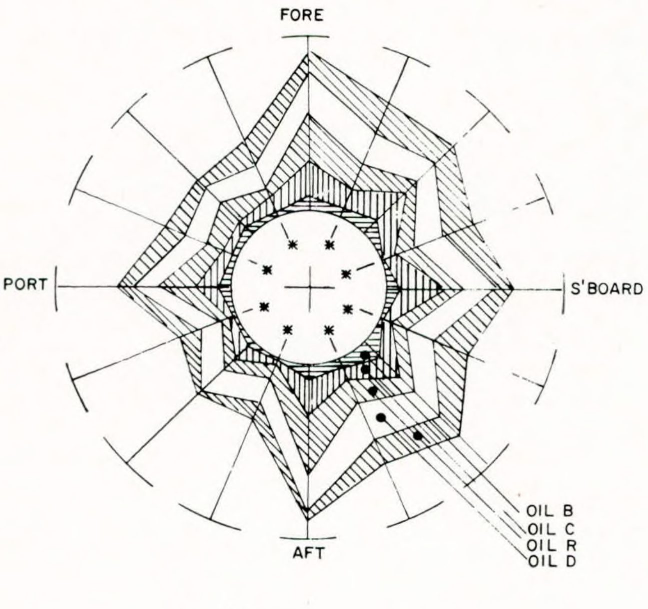

FIG. 11 — *M.T.* Esso Castellon — *Liner wear configuration opposite top ring in TDC*

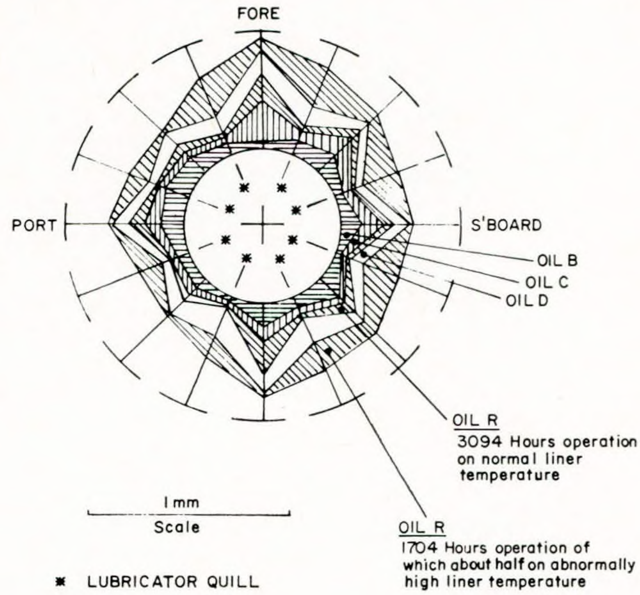

FIG. 12 — *M.T.* Esso Castellon — *Liner wear configuration opposite third ring in TDC*

Liner "Clover-Leafing" Wear Pattern

Turning now to clover-leafing phenomena in particular, both Figs. 11 and 12 are a clear illustration of the problems related to oil distribution inside the liner. The progression of liner wear during the period of normal operation, i.e. from new liner up to over 12 000 hours' liner life, which was followed through several premium oils all at 70 TBN level, would indicate that clover-leafing can be considered a complex function of both oil transport as well as oil spreadability. The former is mainly a design/operational feature (ring type, quills position, feed rate) whilst the latter is essentially a physico-chemical characteristic of the lubricant, fairly hard to identify and assess.

It is the authors' opinion, however, that by far the most important role in oil distribution is played by the design of the lubrication system. They would thus suggest that, for instance, the apparent uniform wear around the liner circumference of oil D (as shown in Fig. 11) is not so much an indication of superior spreadability of that oil compared to all other oils, rather the consequence of an equilibrium situation of pressure between ring and liner. If, in fact, the ring is considered, in first approximation, as a beam supported by the liner areas in line with the quills, as schematically illustrated in Fig. 13, a condition can be postulated where such beam is subjected to forces which will increase in direct proportion to the increase of $W_{bq}-W_{lq}$, i.e. the difference of wear of areas between quills (W_{bq}) and areas in line with quills (W_{lq}). Greater forces will exercise greater pressures on the beam supports and greater (mechanical) wear will follow through occasional collapse of the lubricating film adjacent to the quills which would now be subjected to such excessive pressures. A temporarily greater wear in such areas would result in a reduction of $W_{bq}-W_{lq}$ and consequently the net forces on the ring would be reduced. At the same time, the oil film adjacent to the quills is rapidly renewed and because it would now be subjected to lesser pressure, it would again be able to prevent asperity contacts between the running surfaces of ring and liner.

With regard to liner wear between quills, this would be, on the other hand, an on-going process of variable intensity, related to the slower replacement of oil loss,

TABLE V—M.T. "ESSO CASTELLON". TYPICAL LINER TEMPERATURES OF INSTRUMENTED UNIT UNDER NORMAL AND ABNORMAL THERMAL CONDITIONS

	Normal	Abnormal
Temperatures, °C		
(Data Logger at 6 Scans/Hour)		
Above Top Ring in TDC		
(S Board Position Only)		
—Maximum	190–200	270+
—Mean	170–180	215+
At Top Ring in TDC		
(Over Entire Circumference)		
—Maximum	150–195	230–255
—Mean	140–175	150–205
—Temperature Changes at		
10 Minutes Scanning Intervals		
(Frequency Over 100 Hours Operation)		
Increases, by 10–14°C	3	15
by ≥ 15°C	3	21
Decreases, by 10–14°C	3	16
by ≥ 15°C	2	30

NOTE : Abnormal Temperature Conditions shown cover operation from 13 040 to 13 440 hours, at which time an electrical fault developed in the data logger.

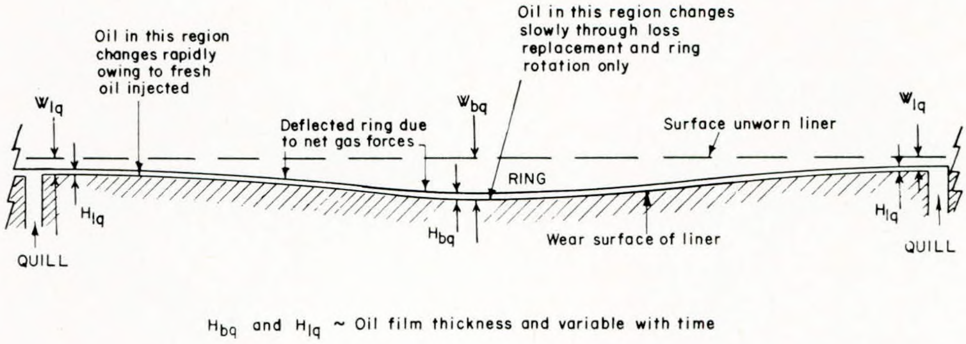

FIG. 13 — *Schematic diagram showing probable ring condition in clover-leafed liner*

with ensuing greater probability of asperity contacts, gas blow-by and generally hotter surface conditions.

On the whole, it would appear that the circumferential wear pattern is essentially the outcome of an equilibrium situation, established in some point in time in the liner life, which would prevent the difference W_{bq}—W_{lq} from increasing beyond a certain level which presumably is typical for certain design, operational and lubrication conditions of the engine considered. Fig. 14 seems to support this hypothesis.

The average difference of wear W_{bq}—W_{lq} after about 5000 hours of operation of the special *Esso Castellon* liner is comparable to that measured for the remaining eight liners (of standard design with oil distribution grooves) of the same engine after about 30 000 hours. Moreover, the maximum difference between consecutive wear data points at the same level is also practically constant (Table VI). The inclusion of different makes of engines (all with oil distribution grooves) appears to strengthen the authors' point and if the ratio $W_{bq}:W_{lq}$ (which is less dependent of actual wear levels) is plotted against the operation hours, then all points seem to fit the same asymptote. Also, as shown in Table VI, the ratio of $W_{bq}:W_{lq}$ is similar at different levels of the top part of the ring travel for a certain type of engine.

The wear difference W_{bq}—W_{lq} is certainly greater for *Strathardle* than for either *Esso Castellon* or *Pontos*. However, the authors feel this difference is not a reliable measure of the relative merit of locating quill outlets higher up (*Esso Castellon* and *Pontos*) rather than lower down (*Strathardle*) in the liner, the design of the relative engines being so fundamentally different.

Finally, the clover-leafing wear pattern described in this paper is that noticed in the very top part of the liner. Overall conditions in this region are, in fact, fairly comparable, at least in the first approximation, for different designs of engine. If regions lower down the liner were considered, then it is the authors' experience that wear between quills (W_{bq}) is still greater than wear in line with quills (W_{lq}). In these liner regions, two major phenomena, not present in the top liner zone, can, however, play an important role and affect considerably the ratio $W_{bq}:W_{lb}$.

These are:

i) localized thermal deformations of the liner in proximity of the exhaust port area (cross- or loop-scavenged configuration);
ii) occasional formation, under certain operational conditions, of lacquer in areas between quills in cooler liner zones (uniflow-scavenged type).

The condition outlined in ii) above, which is relatable to oil transport in general, can actually result in reduced wear rates for the lacquered areas, at least until such time as the lacquer film is removed. This comment is based on the observation of extremely low wear rates for those dimples which, during the authors' test work, were occasionally found covered by a tough lacquer film. This observation does not, of course, imply that, under certain circumstances, lacquer and carbon may not be capable of absorbing corrosive media and thus promoting wear. This possibility was discussed by McConnell and Nathan as early at 1962[13].

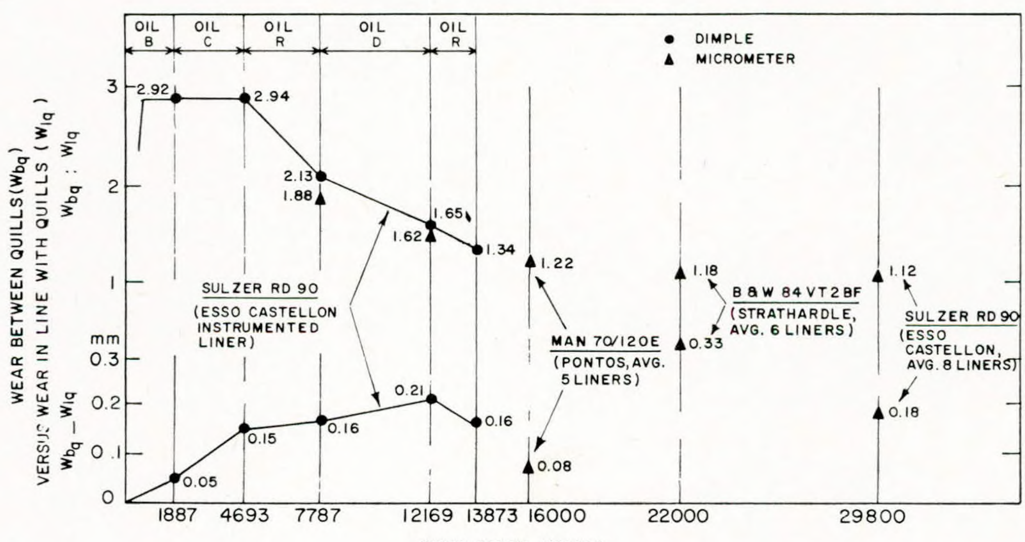

FIG. 14 — *Liner wear at top ring in the TDC position areas between quills compared to in line with quills*

TABLE VI—LINER WEAR W_{bq} (BETWEEN QUILLS) COMPARED TO W_{lq} (IN LINE WITH QUILLS)

Vessel	*Esso Castellon*						*Strathardle*	*Pontos*
Engine Type	Sulzer RD 90						B and W 84VT2BF	MAN 70/120E
Hours	1887	4693	7787	12 169	13 873	29 800	22 000	16 000
No. of Liners	<— Instrumented Liner —>					8	6	5
$W_{bq} : W_{lq}$ (Avg.)								
—Position at TDC								
Top ring	2·92	2·94	2·13	1·65	1·34	1·12	1·18	1·22
2nd ring	—	—	—	—	—	1·13	1·15	1·20
3rd ring	1·71	2·14	2·50	1·74	1·07	1·14	1·13	1·20
$W_{bq} - W_{lq}$ mm								
—Average	0·05	0·15	0·16	0·21	0·16	0·18	0·33	0·08
—Maximum between Consecutive Points at Top Ring in TDC	0·12	0·25	0·46	0·51	0·46	—	—	—
Maximum Bore (Avg.), mm (Above Nominal)	0·17	0·53	1·09	1·50	1·64	2·26	2·35	0·56

Some Comments on the Importance of Circumferential Oil Distribution

It is widely recognized that less fresh oil is carried into the areas between the quills as opposed to areas in line with the quills[14, 15]. This would appear to be essentially a design problem, with physico-chemical properties of the lubricating oil playing little part, and the authors feel that a viable theoretical argument can be developed to back such hypothesis.

Thus far, analysis of piston ring induced oil motion in cylinder liners has been confined to vertical transport[12]. This shows that rings retain a given quantity of oil in the liner and unless some special arrangement is made to change some of the oil in a given liner circumferential segment, only small additions are needed to make good losses from each segment. Normally the losses are made good from the bands of excess oil scraped by each ring to the extremities of ring travel on the liner.

In the large bore engine with spot cylinder oil feeds, the majority of oil being changed on the liner tends to be that circumferentially closest to the lubricator quills. Moreover, apart from small additions of oil to make good losses occurring mid-way between the quills, little change of oil occurs in those regions of the liner. Thus, although sufficient oil exists on the liner between quills for the characteristic hydrodynamic lubrication of the rings to continue unimpeded, the proportional dosages of acidic combustion products received by the oil in the regions between quills may vastly exceed those accorded the oil in positions vertically adjacent to the quills. In addition, the very existence of this equilibrium quantity of oil per unit of liner circumference is an impediment to a desirable exchange for fresher oil which has lately issued from the quills.

From this mechanism of circumferential distribution, it will be realized that the chance of available alkalinity in the lubricant remaining uniformly distributed on the liner all round its circumference is extremely remote. For this reason, corrosive wear may predominate at points mid-way between quills, mitigated only by the reduced level of ring loading encountered in the beam analogy referred to above. Even if very high levels of alkalinity were administered as additive in the oil reaching the quills, only a marginal improvement could be expected in combating corrosive wear under these conditions of slow oil replacement.

The above explanation appears to go some way to indicate the reasons for frequently finding residual alkalinity in cylinder drainings at the same time as manifestations of corrosive wear between quills.

Clearly, currently there exists little which might be added or altered in an oil to make it capable of forcing an exchange with other oil which has become depleted in alkalinity between the quills.

Obviously a degree of circumferential oil migration can be expected from piston rings which rotate as the engine runs. Observations of ring rotation made during the Norwegian Large Bore Engine Investigation of 1965, headed by Professor A. Sarsten, indicated that some rings did rotate at rates between 15 minutes and several hours per revolution. However, some rings rotated in one direction while others on the same piston might rotate in the opposite. So far, however, the authors are not aware of any work in large bore engines to develop rotating rings or rotating pistons, although the latter have enjoyed certain advantages in medium speed engine practice in late years.

GENERAL COMMENTS ON RESULTS

Despite apparent correlations which, throughout this paper, have been shown to exist between cylinder temperatures and wear, it must be reiterated that these correlations do not represent a cause-effect relationship. Similarly, this observation applies to turbocharger speed. The true variables influencing wear are numerous and have frequently been defined by engine builders. Nevertheless, the results show that by treating long term records of cylinder temperature and turbocharger speed as indicators, an association with wear may be observed. Obviously this does not mean that wear can be reduced or increased purely by changing the above indicators, which were chosen simply because of their ease of observation.

CONCLUSIONS

Improvements and refinements of previous generation designs are important features of the development of large bore diesel engines of ever increasing output. At the same time, a greater awareness is required about the effects of changes of operational parameters on the performance of machinery so that greatest advantage can be taken of their increased potentialities, whilst at the same time minimizing operating costs, such as off-hire and maintenance. With this in mind, the authors hope that their experience on previous generation of engines and their operation, described in this paper, can make some contribution, however modest, to the present-day efforts in developing new machinery and optimizing its performance.

Two main conclusions appear to be particularly relevant.

1) The complex physico-chemical relationship of metal wear to metal temperature, which keeps exercising the mind and skills of dedicated experimenters, manifests itself in large bore engines in the form of highly significant regression lines, whereby higher liner and ring wear are seen to be related to higher engine temperatures. Moreover, such wear trends are generally detectable by reference to normal shipboard equipment, provided the log records of conventional type are analysed to a similar extent to that referred to in this paper. Such analysis is essentially of a simple low level type and therefore does not require either particularly sophisticated techniques or equipment.

The authors recognize, however, that relatively long operational periods and a consistent vigilance may be required to detect trends of significance, since day-to-day changes in the conditions of machinery can be quite small and easily overlooked, even though their trend would quite clearly point to serious consequences unless acted upon in good time. It is, therefore, also recognized that there is considerable merit in establishing some sort of automatic data logging of some selected parameters (be it turbochargers' speed or temperature of engine components), capable of providing an early warning of significant deviations of such parameters from their normal value. The ever increasing role played by engine builders and specialized instrument manufacturers in developing deviation warning systems will undoubtedly result in improved reliability and maintenance of machinery, thus contributing to control of off-hire and operating costs of modern ships.

2) The irregular circumferential wear pattern, commonly referred to as "clover-leafing", does not appear to be influenced by changes in lubricant formulae of similar total basicity. Observations carried out through accurate assessment of spot wear rates by Dimple Wear Method, over an approximately 14 000 hour long period, would, on the other hand, suggest that clover-leafing is a complex wear phenomenon which is characteristic to the pattern of oil transport in large bore engine cylinders lubricated with spot feed quills. This lubrication arrangement does not possess, in fact, any specific mechanism to provide a uniform distribution of fresh oil (alkalinity). The current mechanism does not go beyond the natural migration afforded from oil loss and replenishment within the liner segments remote from the quill outlets, which is helped to some extent by the adventitious rotation of the piston rings in the piston grooves. It is known, however, that this aspect of development is presently under consideration and experiment at certain engine builders' works.

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A special mention must be made of the assistance provided by Sulzer Brothers Limited in connexion with the instrumenting of one of their cylinder liners and the open and friendly relationship provided by their personnel.

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Appendix

LINEAR REGRESSION ANALYSIS

As is well known, regression analysis is the method used to determine statistical relationships between two or more variables, the most common type of relation being the linear function. As the theory of the regression analysis is most effectively set out in any text dealing with statistical theory, this Appendix will only illustrate in outline the approach followed to determine the value of the coefficients a and b of the linear regression equation

$$Y = a + bX$$

where X and Y represent paired observations on two variables (for instance, temperature and wear).

Calculations were carried out with an *ad hoc* time-sharing computer programme (in BASIC language), the output of which was:

1) least squares estimates of the linear regression coefficients;
2) 95 per cent confidence limits for the regression coefficients;
3) an analysis of variance table which contained the sum of squares, degrees of freedom, and mean squares for:
   a) total variation;
   b) reduction due to the regression;
   c) error;

4) A listing of:
   i) the observed values of the independent variable and the dependent variable·
   ii) the estimated value and 95 per cent prediction limits for the dependent variable.

To complete the analysis, two more quantities, derived from the analysis of variance, were also shown, i.e. the index of determination ρ^2 and the F-ratio test statistic.

Through the quantity ρ^2, it was possible to determine how well the regression line fitted the observed data. Expressed in mathematical terms, the index of determination has, in fact, the following property:

$$0 \leqslant \rho^2 \leqslant 1$$

where $\rho^2 = 1$ means that observed *Y's* and estimated *Y's* are the same, hence a perfect fit of the estimated regression line to reality.
$\rho^2 = 0$ means that there is no linear functional relationship.

Clearly, the closer ρ^2 approaches the value of 1, the better the fit.

The F-ratio test statistics was the way of determining the significance of the estimated regression relationship for the given set of observed data. A degree of confidence could thus be associated to each line, such statistical quantity being obtained from F-distribution tables (included in most statistical tests) in conjunction with the degrees of freedom for regression and error as shown in the analysis of variance table.

Discussion

MR. A. R. MURRISON, F.I.Mar.E., said that the primary motivation for the work described in the authors' paper had indubitably been a need for a field trial research project to confirm laboratory tests of various oils designed with specialist cylinder application for use in large bore marine diesel engines. Nevertheless, in view of the meticulous measurement procedures applied, together with collation of data from three vessels over an overall period of three years, the results obtained must be recognized as a major contribution to the field of wear control of engine cylinders and pistons.

Having been personally involved with the organization of facilities aboard *Strathardle,* he congratulated the authors and their team of technicians for the attention to measurement detail, thoroughness of the trial application, and data collection; requirements which admittedly had sometimes conflicted with the maintenance programmes but at no time were they responsible for delay to the vessel's operational duties throughout the period of evaluation.

Whilst engine speed, exhaust temperature, mean effective pressure and air/fuel relationships were known parameters for wear, some explanatory thoughts would be most welcome to substantiate the authors' views that liner wear rates should bear relation to middle and wing cylinder positions serving impulse gas to each of *Strathardle's* three turbochargers. Perhaps the liner coolant temperatures recorded gave rise to a pattern of random chance, as represented by Fig. 3, or, on the other hand, a related conclusion of differential scavenge air received to exhaust work done in producing scavenge air per cylinder might have dictated the situation.

Referring to thermal loadings, he said it would be interesting to have the authors' views on the analysis of cylinder oil drainage relating to the cause of identifiable inclusions. It was envisaged that drainage collection analysis might well present a future monitoring medium for the recognizable ills of corrosive wear, material overheat, breakdown of lubrication effect, fuel injection and combustion problems, especially if geared to a recording meter for watchkeeping surveillance at sea. This could be of specific use, especially if one accepted the authors' view that good machinery operation was not assured solely by careful data collection unless computerized for evaluation as presented at all machinery running times.

The authors' remarks regarding circumferential cloverleafing effects of wear between cylinder lubricating points as measured gave ample support to the theory that piston ring breakage might often result from such wear patterns which allowed gas pressure to create a wedge action between ring and cylinder wall. He wondered if one might therefore deduce that carbon build up, sticking rings or excess groove clearances were the popular contributory factors without notice of clover-leaf pattern being also present.

The authors' suggestion that spot cylinder oil feed systems should be re-designed by manufacturers was supported in principle. Could it be that a staggered position injection into a scroll annulus would promote the desired distribution spread of cylinder lubricant to reduce the effects of cloverleaf wear and thus minimize the problem?

Much had been reported on the pros and cons of timed lubrication of engine cylinders. However, in the light of probable importance to the selective effects of various grades of lubricating oil, he asked for updated preference for:

1) steady flow;
2) injection timed applications — bearing in mind that the latter if not maintained in correct sequence might be far less effective than the former conventional system.

With regard to the Dimple Wear Measurement Method of gauging liners, he said that apart from its obvious accuracy to establish data for the authors' trials, the most revealing fact to be highlighted was that all cylinders of most engines apparently had unrelated cylinder wear which took place in all directions, i.e. port, starboard, forward and aft and other combinations without definite relation to comparable cylinders in other similar engines. This might not be of great dimension, but doubtless the original vertical alignments of cylinders in one engine must deviate as the wear proceeded. If, as might be expected, this gave rise to custom wear in crossheads and guides, the lay of these units might be sadly upset when the worn liner was eventually renewed and thus contribute to operational defects in these areas, about which the shipping company maintainer was well aware. Perhaps the old micrometer method of liner gauging should give way to the Dimple System for both measurement and direction control of gaugings for corrective attention where necessary.

The authors' earlier paper had referred to metallurgical compatibility of liner, piston and ring material. Experience in *Strathardle* and sister vessels had shown that they were all prone to rapid piston groove wear, broken piston rings and excess liner wear rates during the first year of operation after building, irrespective of which proprietary lubrication was used. Subsequently, and well before the trials mentioned in the paper, all piston heads had been reconditioned with standard size grooves having the lower lands chrome faced, the previous chrome inclusion rings had been changed for ordinary cast iron material and all difficulties had been removed ever since except that, as might be expected, a few more piston rings were used because minimum wear did take place in these, but without breakage excesses to date.

The specific fuel consumption stated in the paper's *Strathardle* data, he suggested, should correctly read 221 g/kW h (164 g/bhp/h). Whilst agreeing to this figure at the time of the trials it was necessary to add that consumption now averaged 211 g/kW h (156 g/bhp/h) using average quality fuel and with all conditions normal. This improvement had been made by the installation of a chemical injection to ensure turbocharger intercooler cleanliness and the substitution of original fuel valves for the maker's recommended four hole mitre seat type for longer life, better fuel spread in the combustion area and atomization improvement.

MR. D. W. GOLOTHAN, M.I.Mar.E., said that the authors had given a paper illustrating the relationship existing between wear and various features of engine operation, and had obviously carried out a lengthy programme of detailed and painstaking work to enable them to arrive at their conclusions. His company knew from its own experience that such information was very difficult to obtain in the normal course of a ship's operation, and so the continued presence of a research technician on the ship was really essential to collect the very comprehensive data which the authors had analysed in their investigations.

Most of his company's work in the lubrication of large bore engines had been carried out in their laboratory at Amsterdam, and his colleagues there had not in general observed the trends reported in the paper relating wear to various engine temperatures. However, although they had used a full scale crosshead engine for their work, a two cylinder Sulzer RF68, the normal test duration did not exceed 400 hours. The authors' observations were based on very much longer operational periods which were clearly necessary to observe any significant trends such as those they had reported.

The relationship shown for exhaust gas temperature and turbocharger speed were perhaps not unexpected, but the wear seemed surprisingly sensitive to cylinder liner coolant temperature. Over a fairly narrow range of temperature between 60 and 64°C the liner wear, according to Fig. 3, had practically trebled. He wondered whether such a relationship was typical or might apply only to this particular engine.

His company had also found in service that corrosive wear increased appreciably if the coolant temperature was allowed to fall below about 60°C, so probably over a wider range of temperature a minimum wear rate could be shown at a critical temperature, with the wear increasing with either an upward or downward change from that particular temperature.

The use of recovery trays to collect cylinder oil drainings was a valuable method for studying lubrication conditions within the cylinder, but he agreed that careful supervision was necessary to ensure that the technique was used properly. His company could not envisage it being used as a routine method.

Iron content of these drainings did, in his company's experience, give a fairly good guide to wear within the cylinder over a short period of operation. The authors showed some interesting observations on the effect of type of service on iron recovery in the drainings, the highest iron content being shown during the stop-go operation in the Panama Canal. The tendency towards higher cylinder wear in that part of the world supported his own company's experience. The authors implied that the type of operation was the main cause of the higher wear, but he tended to believe that the main cause of the problem was in fact the high air humidity

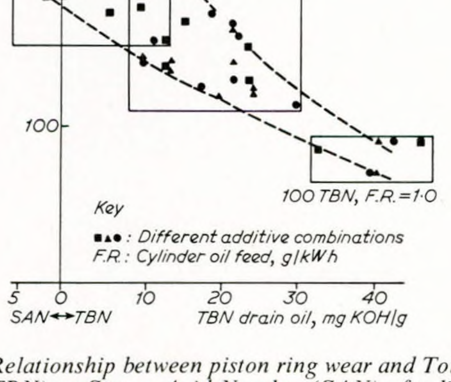

FIG. 15—*Relationship between piston ring wear and Total Base Number (TBN) or Strong Acid Number (SAN) of cylinder oil drainings (Sulzer 2RF68 engine)*

which had led to excessive quantities of condensed water being carried into the cylinder with the scavenge air. This water would obviously tend to wash away the oil film on the cylinder walls. Some engine manufacturers were nowadays paying particular attention to this aspect. He asked whether the authors had any experience of this problem.

Some of his company's results, both from service and the laboratory, seemed to differ from those of the authors; in particular, the relationship between strong acid content and iron content in the cylinder drainings. The presence of strong acid was invariably associated with a high iron content, which one would expect in view of the likely increase in corrosive wear.

They also found from the large bore Sulzer laboratory engine that there was quite a good correlation between piston ring wear and the total base number (TBN) of the cylinder oil drainings as illustrated in Fig. 15. This figure also showed the importance of cylinder oil feed rate in controlling wear. On the horizontal axis was plotted the TBN of the cylinder oil drainings, developing into the strong acid number (SAN) on the left hand side. On the vertical axis was plotted the total piston ring wear for the three upper piston rings in grammes over a 400 hour test. Each point represented the result from a 400 hour test. The various symbols represented different additive formulations which had been used.

Clearly there was a reasonably good correlation between the TBN and wear. As the TBN of the drainings increased there was a pronounced tendency for the wear to be less.

These results had been divided into three separate blocks. The upper block referred to a conventional 70 TBN oil, with the normal cylinder oil feed rate for that particular engine of 1 g/kW h (0·75 g/bhp h). The second block, showing a group of lower wear figures, represented results obtained at the same oil feed rate with a 100 TBN oil. The greater alkalinity had clearly tended to reduce the wear. The same block also applied to the 70 TBN oil with a higher feed rate, i.e., 1·35 g/kW h (1 g/bhp h). It would appear, therefore, from these results, that the same wear rate could be obtained either by increasing alkalinity in the oil at the normal feed rate or by increasing the feed rate with the 70 TBN oil.

The best results of all had been obtained with a 100 TBN oil at the high feed rate of 1·35 g/kW h (1 g/bhp h). Such a high feed rate, however, was unlikely to be used in practice.

In tests of this time duration, his company had only been able to show significant differences in piston ring wear. It was not possible to establish differences in cylinder liner wear, which was negligible in most tests owing to the relatively short duration.

Fig. 16 illustrated the effect of cylinder oil feed rate on piston ring weight loss in another laboratory engine. This was a smaller engine, a single cylinder Sulzer T48 which had a bore of 480 mm and was a fully ported two stroke engine of rather old design. It had been used for much of his company's work in the past. Fig. 16 showed that as feed rate was increased it had a very significant influence on the weight loss of the piston rings. The two curves illustrated the maximum wear and the minimum wear that were obtained in repeat tests. Clearly there was a tendency for the wear to go down as the feed rate was increased, but beyond the level of about 2 g/kW h (1·5 g/bhp h) there was little further tendency for wear to be reduced.

One conclusion to be drawn from these results was that at low feed rates there was a very much greater scatter in results in the engine. There was much better repeatability as the feed rate was increased. In other words, at a low feed rate the ring wear appeared to be more sensitive to minor changes in the engine, perhaps in piston or ring materials or to small differences in operating conditions.

Turning to the results from *Esso Castellon,* he said there appeared to be some discrepancy between Figs. 11 and 12, and the authors' statement that the greatest cylinder wear occurred opposite the third ring at top dead centre. Both the figures were on the same scale and it seemed in fact that the greatest total wear had occurred opposite the top ring at the top dead centre position. Had he misinterpreted these results?

He also asked if the authors would consider whether there was any significant difference in performance between any of the four oils that were tested. All these oils were of 70 TBN, and it seemed to be suggested later in the paper that from the anti-wear point of view there was little improvement that could be made to cylinder oils of equal alkalinity.

The clover-leafing type of wear seemed to be particularly troublesome in certain engines, and the authors' investigations threw new light on this problem. His company had, however, some doubts whether the spreadability of the oil itself was of much significance, since they knew from experience that an oil of relatively poor spreadability could give quite a good result in an engine. They tended to believe that the distribution of the oil on the cylinder surface was influenced far more by the swirling movement of the hot gases in the cylinder and perhaps to a lesser extent by mechanical distribution methods, such as oil grooves.

The effect of ring rotation, which was mentioned in the paper seemed not to be proven at present.

His company also firmly believed that cylinder oil feed rate was of major importance in influencing wear in between the oil quills. The effect of the oil feed rate on overall ring wear had been shown in Fig. 16, and if the feed rate was reduced below a certain critical level, then wear increased sharply, particularly in between the quills.

It was also interesting to compare loop scavenge and uniflow scavenge engines in respect of their oil feed requirements. The loop scavenge engine usually needed a higher specific feed rate than the uniflow scavenge engine if comparable wear rates were to be obtained. This might be due to the more complex gas movement within the loop scavenge engine resulting in greater disturbance of the oil film. It would be interesting to have the authors' comments on this particular aspect.

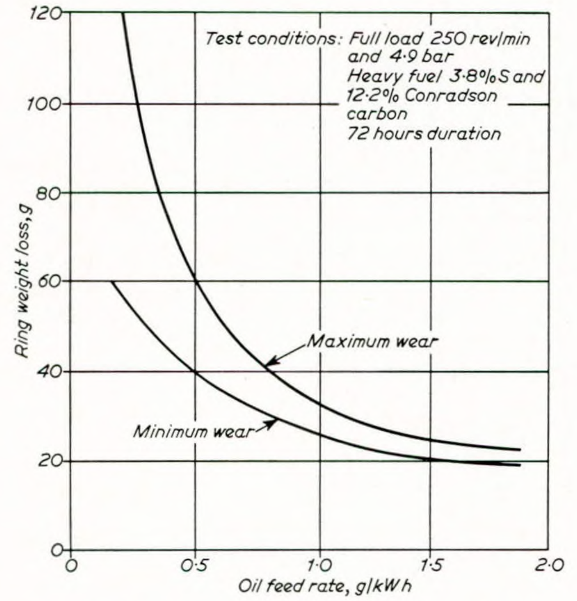

FIG. 16 —*Influence of cylinder oil feed rate on piston ring wear (Sulzer T48 engine)*

His company thought that clover-leafing was usually caused not so much by inadequate lubricant between the oil quills but by the fact that most or all of the alkaline additive had become used up by the time the fresh oil supply could reach this area. This was especially true when conditions were favourable to acid formation, as when a fuel of high sulphur content was used.

Fig. 17 illustrated what he believed to be a convincing picture of clover-leafing caused by corrosion. This was a chromium plated bore from an older type of uniflow scavenge engine which showed clearly the corrosive wear which had occurred on the cylinder. The white areas were chromium sulphate which showed up as a very distinct pattern on the bore, and these areas were convincing evidence of corrosion by sulphuric acid. The patches occurred both above and below the oil distribution grooves. Quite clearly they were in line with the axes in between the oil holes, so the areas in line with the oil holes were evidently receiving sufficient oil and alkaline additive to neutralize the acid. Elsewhere the alkaline additive had presumably been used up and corrosion of the chromium surface had occurred.

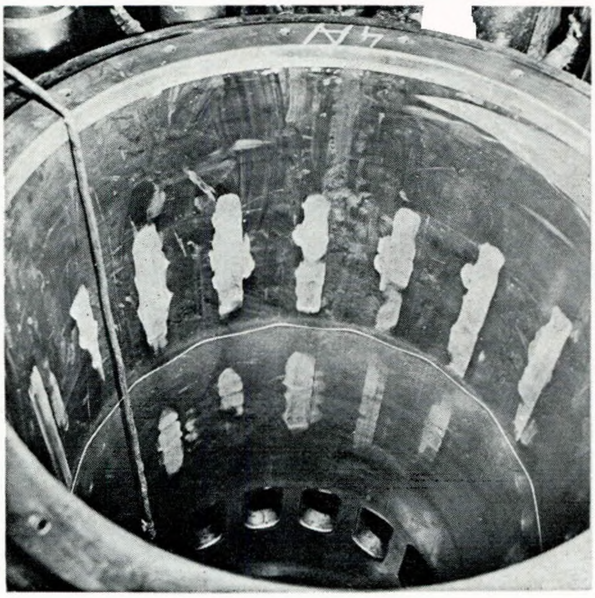

FIG. 17—*Clover-leafing (corrosive) wear on chromium-plated cylinder liner*

On a cast iron bore it was noticed that sometimes there was a corresponding lacquer deposit, and when the lacquer was scraped away it was often observed there was a pitting type of corrosion underneath the lacquer.

In his company's experience this type of clover-leafing wear could be much reduced by resorting to cylinder oils of alkalinity highter than 70 TBN, in fact up to 100 TBN, and in this respect it would appear his company's observations were at some variance with those of the authors. Again, however, they had found that the oil feed rate was critical, since if it was reduced much below the normal level then the benefits of the higher alkalinity were largely lost.

MR. G. AUE (whose contribution was presented by MR. D. ROYLE) stated that the authors findings as to the cause of clover-leafing present in all three investigated engine types confirmed the old basic fact that in order to prevent wear there must be at all times:

a) a sufficient quantity of oil between the rubbing surfaces in order to prevent metallic contact and thus mechanical wear;
b) this oil must have an adequate chemical activity in order to prevent corrosive wear.

This latter fact could be clearly seen in chromium plated cylinders running under poor conditions, where "milky patches" indicating corrosive attack sometimes developed between the oil quills.

He was very glad that analyses of some recent results, as yet unpublished, which had been obtained with similar methods confirmed the authors' theories.

MR. L. R. C. LILLY said the results shown in the paper were interesting because they showed the wear rate increasing as both the load and liner temperatures over the ring pack at top dead centre increased.

A few years back the contributor's company had carried out an extensive programme of wear tests on behalf of the British Ship Research Association on a horizontal Crossley engine of 241 mm (9·5 in) bore and 406 mm (16 in) stroke converted to run on residual fuel. This work was in 1972 the subject of a paper to I.Mar.E. entitled "Towards Wear Reduction in Engines Using Residual Fuel". Wear was measured by means of an iron-recovery method, and also by

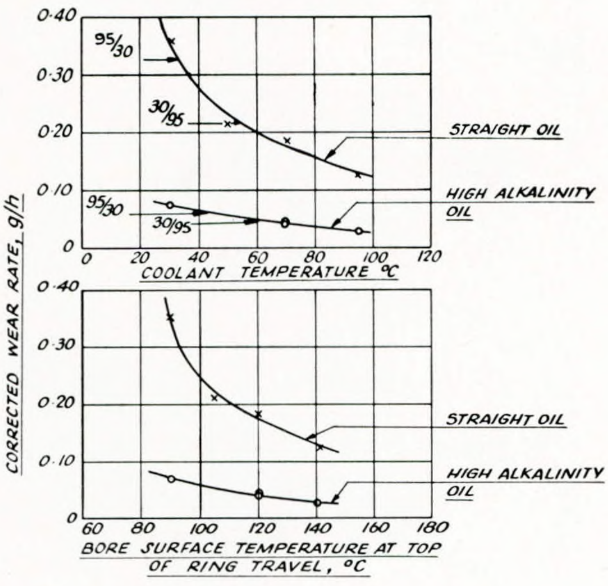

FIG.18—*Effect of jacket temperature and lubricant on wear*

direct liner measurement. These results had shown a decrease of wear as the jacket temperature was increased, more obviously when using a straight lubricating oil, but the same trend had been present with a TBN 70 oil. Tests had also been made with the cylinder jacket divided, so that the top 76 mm (3 in) had been separated from the outer portion. These tests showed that both with the straight lubricating oil and with the TBN 70 oil a cold portion was more damaging than a cold top portion. Fig. 18 illustrated these effects.

Because of these results, his company had formed the view that condensation of the sulphuric acid products of combustion could occur in the lower half of the liner and be swept up by the rings to the top to give corrosive wear. Hence it appeared desirable to keep the lower half of the liner as hot as possible since the dew point at the end of the expansion stroke would be around 130°C.

It might be thought that these results directly contradicted the curves shown in Fig. 3, in which the liner wear rate doubled when the jacket temperature rose from 60°C to 64°C. Clearly, of course, this small rise of jacket temperature could not be responsible for such a large increase in the wear rate, and was probably caused by the increased cycle temperatures resulting from the reduction of airflow when the turbocharger speed fell presumably from fouling as shown in Fig. 2. The increase in wear observed must also be the result of these changed, less favourable, operating conditions.

He finally asked what was the general sulphur level of the residual fuel used in the authors' tests.

MR. W. J. PACKHAM, M.I.Mar.E., said the paper had dealt with cylinder wear related to engine temperatures, and a fellow contributor had spoken of TBN levels related to high sulphur content fuels. It might not be generally known that one of the largest Sulzer engine licensee manufacturers had recently withdrawn all approvals for cylinder lubricants because of excessive cylinder liner wear when running on fuels with a low sulphur content, mainly of Chinese or Russian origin. These were East European ships. He would like to have the authors' views on this problem.

MR. B. C. C. ROUT, F.I.Mar.E., referred to Fig. 5, where the total base number of the drainings from the cylinder under coastal operations was much higher than elsewhere. He asked if the authors thought it was possible that under coastal operations with a high percentage of manoeuvrings the cylinder oil feed rates were perhaps disproportional to lower power outputs.

MR. S. CROSBY, F.I.Mar.E., referred to Mr. Golothan's remarks on 100 TBN oil and said he would like to have the authors' impressions on the increased feed rates up to 1 g with particular respect to deposits on ring belts, such as calcium, etc.

Correspondence

MR. A. A. MCGLASHON, F.I.Mar.E., said in his written contribution that the paper contained a wealth of information on cylinder liner wear which was based on fact, backed up by careful in-service investigations. Too often theories had been put forward on this subject which were based only on opinions.

In the conclusions of the paper the problems of cylinder liner wear had been clearly and concisely set out. Trend recording, whether it be carried out manually, or by data logging, which was another argument entirely, would certainly give early warning of impending troubles ahead. The major area to begin looking for problems was in the air and exhaust paths. This did not require sophisticated instrumentation and the most useful tool was the "U" tube manometer to measure pressure drops across turbocharger air filters and air coolers. These readings coupled with cylinder exhaust temperatures, turbocharger inlet temperature and rev/min were the main readings required in order to get a meaningful picture of the condition of the air tract. If these were plotted in graphical form the trends would be apparent very quickly. As the build-up of pressure drops usually occurred at a relatively slow rate only daily recording of these results was necessary. Where a waste heat recovery unit was in the circuit the pressure drop across this should also be regularly logged.

If air flow measurements through the turbocharger could be measured, even as a percentage, this would be an even better guide for the engine operator. Perhaps the pressure drop across the entrance volute into the impeller would suffice to give this reading.

Mr. McGlashon's own company's attention was first drawn to the air flow/cylinder liner wear relationship a number of years ago. One class of vessel, with uniflow scavenging main engines was giving excellent wear rates with regard to cylinder liners. The next class delivered some three years later with main engines of the same type, bore, stroke power and speed, also manufacturer, had extremely bad liner wear rates. On investigation it was found that while the scavenge ports were identical in number and width, in the latter the port heights had been lowered by 39 mm. The engine builder had made this modification to reduce the fuel consumption, which it did do in the latter class, but cylinder liner consumption went up dramatically.

Having the experience with the earlier class, cylinder liners were modified in the later engines by machining the scavenge ports and re-timing the exhaust valve. Wear rates dropped to that of the earlier engines.

In the above investigation it was found that the earlier class had a ratio of weight of air to fuel of 59·6 to 1 whereas the original ratio in the later class was 51·5 to 1. It would therefore seem that an air fuel ration of 30:1 quoted on the paper was rather too low. Perhaps the authors would give their views on this?

Authors' Replies

Referring to Mr. Murrison's contribution, the authors said that the graphs of Fig. 3 should not be seen as necessarily indicating that wear rates bore a relationship to middle and wing cylinders' position in the same fashion as wear could be said to be related to operational parameters like mean effective pressure. The authors simply reported observations, which consistently showed an association of liner wear rate to coolant temperature such as it could imply a somewhat greater response of wear to changes of liner coolant temperature for the middle cylinders compared to the wing cylinders. The authors wanted to re-iterate their warning that the regression lines of Fig. 3 did not necessarily imply a cause/effect relationship between coolant temperature and liner wear. Nevertheless, other correlations between observed values of other operational parameters, like exhaust gas temperature and turbocharger speed had also resulted in a somewhat steeper regression line for the middle cylinders compared to the wing cylinders.

The authors said also that, from their own past published work on thermal loading and air distribution or air consumption on single cylinder engines, they thought it was quite likely that the air distribution in some parts of a multi-cylinder engine with several turbochargers feeding more than one cylinder, could result in different air through-put between cylinders. Changes of operating parameters for each single unit of a multi-cylinder engine could thus be anticipated. Of course, this was only one factor and they thought that there were quite probably a number of other factors, including alignment of the individual cylinders, which could influence wear. Summing up, the authors were thus inclined to postulate that wear could be related to cylinder position but in a randomized fashion.

The idea of a recording meter to analyse drainings' samples continuously during the ship's operation, was undoubtedly very attractive. There was, however, a major difficulty in implementing it because they did not know of any such meter being available. So far no viable alternative to x-ray fluorescence or chemical analysis of the drainings to obtain a reliable indication of iron content had been found. The use of these standard techniques was unsuitable for the purpose envisaged by Mr. Murrison. However, the authors wondered whether his comments were prompted by his knowledge of the existence of any such meter, in which case the authors would welcome the opportunity of doing some field testing with it.

With regard to clover-leafing, the authors were pleased Mr. Murrison agreed with them that some pattern of overall design must emerge before the clover-leafing phenomenon was resolved. Perhaps some of the work being done on oil transport patterns gave already some indication of the direction research and development should take. Though such work was largely concerned with vertical rather than circumferential transport, the authors felt that the work already done suggested that, unless some exchange of fresh oil or part used oil was taking place all round the circumference of the liner in a continuous and uniform fashion, then the oil between the quills was not going to be renewed as frequently as that immediately in line with the quills. So the theory was not at variance with facts, though it was not yet sufficiently advanced to take into account the circumferential features which were involved in the multi-point distribution.

Mr. Murrison was quite right in enquiring about the possibility that clover-leafing might lead to ring breakage. The authors had explored this situation very closely and, with the assistance of the engine builder of *Esso Castellon*, had monitored, at regular intervals, the conditions at which the ring might be subjected through a wedge action between ring face and cylinder wall. Such wedging could in fact be originated by gas pressure and would increase with the widening of wear differential between adjacent "peaks" and "valleys" of the clover-leafing pattern. In fact, they were satisfied that, even at the very maximum value of 0·5 mm difference observed between such adjacent positions, the rings were still well within the tensile strength limits which were characteristic of their geometry and material. Moreover, wear differentials between consecutive "peaks" and "valleys" did not appear to increase indefinitely — in the authors' experience — and therefore they concluded that ring breakage should not directly result from the geometry of the clover-leafing.

With regard to the best selection of lubricants for timed or normal spot feed, they felt that it did not make much difference whether the feed was timed or not as to the sort of characteristics which should be sought in the cylinder lubricant. The whole idea of timed feeding was to get as much value for money as possible out of the highly expensive highly alkaline lubricants, and they did not believe that it was possible at this stage in the understanding of the matter to produce a special lubricant specifically for timed lubrication.

The authors did not quite know whether Mr. Murrison was proposing that dimples should be put into ships for surface measurements. If he was, then the Dimple Method, like most fairly powerful tools, had its strengths and its weaknesses. Its strength was that one could obtain accurate dimensional data on changes of the cylinder surface. The weakness was that the dimples needed some special care and attention to exploit their full potential and justify the additional effort required. As an experimental method, the authors' company had found the Dimple Method extremely valuable, and several of the major engine manufacturers had picked up the technique from them and were using it to this day with great success for experimental work. Clearly if a ship operator had a vessel which he regarded as a key to some of his future operations and wished to examine its characteristic performance closely, then the Dimple Method could very well be the method that he would choose, but the authors did not believe that in these days of mean manning the use of dimples as a routine measuring technique could really be recommended because of the labour involved to get accurate results.

With regard to Mr. Murrison's comments on the material compatibility question, the authors had seen vast changes in performance made by change of piston ring material, particularly in the days when ring inserts were used. This could be a very decisive factor not only in piston ring wear but also in cylinder liner wear and piston groove wear. The change to the chromed lower grooves, or lately the grooves which were chromed on both the lower and the upper sides, were a considerable improvement. In fact, chrome-plating of the groove had, firstly, reduced the overall wear in the groove and the piston rings and, secondly, it had enabled changes of piston ring iron to be made far more readily than would ever have been the case with the wearing band, which had a much more severe compatibility requirement than the hard chrome of the groove. It should be recognized in fact that the groove wear was mostly due to a fretting rather than a sliding regime, because the movements taking place between rings and grooves were extremely small. The authors thought that most people now would acknowledge that chrome was a very satisfactory ingredient for one side of a junction operating in a fretting regime.

With regard to Mr. Golothan's and Mr. Lilly's point that the liner wear seemed particularly sensitive to cylinder liner coolant temperature (as shown in Fig. 3), the authors said that they could not but stress again that the regression lines were only an association and not a cause/effect relationship. In other words, they had simply analysed the wear rates associated with certain values of the coolant temperature over relatively long operation periods and come up with a statistically sound correlation. Indeed it was most probable that at the same time that the coolant temperature changed, other features of the operation of the engine also changed. Altogether it was a whole set of operational conditions to bring about a significant variation in wear rate, not just a change of coolant temperature which in fact could be regarded merely as one of several indications of engine operation.

On a more general level, the authors agreed that there was probably a critical temperature for liner surfaces *per se*, though this should be considered in the context of two principal modes of wear taking place, i.e., abrasive and corrosive. The abrasive wear could be related to the instantaneous oil film thickness which was generated between the rings and liners, and there were reasonably well established methods of calculating such thickness. The principal feature related to this oil film, which was in fact controllable, was the oil film temperature, and this was reflected in a critical liner temperature. At the same time, the corrosive aspect of wear was almost always present and this was also a function of temperature. In practice, therefore, there was a balance to be achieved between the maximum oil film thickness and the minimum corrosive reactivity to ensure proper lubrication. It was likely that this balance would occur for a given set of operating conditions at one specific temperature, but tied to that, the authors felt that one should not overlook the likelihood of other operational or design conditions which would also be critically optimal. So the authors agreed in principal with what Mr. Golothan observed, but thought it necessary to highlight the complexity of the matter.

On the question of air humidity, they were naturally aware of the increasing interest in it, especially in the Far East. However, whilst agreeing that the very high humidities likely to occur in certain vessels in the Far East, were extremely important in terms of lubrication, they did not see much evidence of its effect on iron recovery with *Strathardle*, whilst she was operating (either at full or reduced speed) in the Far East under normal rated conditions. The authors, therefore, concluded that it was the type of operation, typical of the traversing of the Panama Canal, that was the main cause of higher wear in case of *Strathardle* when in that part of the world.

With regard to the relationship of the strong acid to iron recover, the authors did not think that their results were at variance with those of Mr. Golothan. In fact, as pointed out in the paper, all samples analysed which showed some SAN, also had some residual TBN. The authors had at no time intended to exclude the possibility of a relationship of SAN to iron recovery once the oil basicity was completely used up.

Mr. Golothan's figures, showing the relationship of ring wear to oil basicity and feed rate and the clover-leafing in chrome-plated liners, were very interesting illustrations of a number of experimental observations that the authors' company had also had the opportunity of carrying out with their engine test facilities or of witnessing in the field. The authors felt, however, that some of the comments made using such graphs were introducing arguments which were quite extraneous to the nature of the paper, albeit such topics as merits of TBN levels, effects of oil feed rates and characteristic differences between major large bore diesel engine designs were certainly worth a long discussion in their own right. The authors were, therefore, reluctant to comment on some specific points like relative merit of TBN or engine design as they did not wish to see their paper polarized towards any form of suggestion or cajolery that one form of lubricant or one method of using a lubricant was any better than anything else.

The authors agreed that air movement was extremely important in oil distribution, especially where thick films of oil occurred. They were thinking particularly of the oil grooves which were cut in great numbers of the large bore liners. These grooves would not, in fact, operate unless such air swirling was not present, particularly when a piston ring in a position opposite the grooves, was effectively ensuring the funnelling of high speed, high energy gas into the grooves themselves. However, such air swirling could not have all that relevance to clover-leafing which seemed to be conferred to it by Mr. Golothan. If, in fact, greater air swirl, as postulated by Mr. Golothan for one type of engine compared to the other one, was the primary cause of spreadability, then such type of engine should show a decisive advantage in terms of less clover-leafing compared to the other type. Clearly this was not the case as observed by the authors over a long period of engine operation and measurements.

With regard to the effect of cylinder oil feed rate, the authors concurred that this had appreciable merit in reducing clover-leafing but really wondered whether this use of high, possibly excessive feed rates was not only impractical financially and operationally but also resembled the case of the drug that deadens the pain without curing the illness.

The authors denied that there was inconsistency between Figs. 11 and 12. In fact Fig 12 clearly indicated that liner wear at the third ring in TDC position was exceptionally high just in line with the quill during the last 1704 hours of operation. This wear had increased enormously in comparison with wear normally occurring at that level and was also somewhat greater than wear occurring at the top-ring-in-TDC position during the same period. The authors' interpretation was that during those last 1704 hours, the lubricating regime had gradually worsened under the effect of abnormally high liner temperature. The situation could thus be broadly described as one of boundary lubrication deteriorating steadily until, in fact, the test had to be discontinued. Under these conditions, mechanical and abrasive wear would predominate and it came as no surprise to the authors that liner wear was so much greater in areas where there was a greater likelihood of metal-to-metal contact.

With regard to Mr. Packham's comments about low sulphur content in fuels, some of their work in their experimental Abingdon B-1 two-cycle engine had led them to conclude that the combustion characteristics of the particular fuel which was involved, was of primary importance whilst the question of the overbased additive content of the lubrication oil was of secondary order. The authors were not aware of the incidence of an engine builder's position *vis-a-vis* the question of low sulphur fuel/high TBN oil, mentioned by Mr. Packham, though they hoped that enough information could be made available to substantiate such attitude so that they would compare it with the results of their experimental work in the Abingdon B-1 engine, which were reported in fact in a paper presented to I.Mar.E., Trans. 1974, Vol. 86, Part 7 by A. J. S. Baker and J. D. Kimber, "Research Engines for Low and Medium Speed Applications".

So far the problem with nearly all the low sulphur outcries was that these were nearly always something which happened in a ship somewhere with some fuel. Specifics of the cases, preferably with sufficiently large quantities of the fuel in question, as far as they knew, had never been made available. The authors thought that there was enough justification to collate all the observed or reported incidents and investigate them, preferably with an experimental engine. The authors had entertained some high hopes of the Norwegian shipping groups tackling this problem but perhaps they had been too hopeful. On the other hand, the authors were sure that their company would be very pleased to participate in some of these observations, and perhaps some of the contributors might consider offering their comments on any observations on the same topic which might have been carried out by their respective companies.

In reply to Mr. Crosby, their company had naturally experimented with 100 TBN lubricants and they had not found anything particularly worrying about the deposits. The most important thing about 100 TBN lubricants was that such oils were meant to cover situations representing extensions of the range of applicability of the current 70 TBN premium quality products. Of course, the additional product cost would most probably play a considerable part in the customer's decision to use it.

With regard to the observations of high TBN content of the cylinder drainings during coastal operation, a slight increase of feed rate had indeed been noticed but, in answer to Mr. Rout, this had been generally around 10 per cent or less, not enough therefore to account for the significant increase in the unused TBN content of the drainings.

No correlation could also be established with sulphur content of the fuel that had been between 2·5 and 4 per cent throughout all the tests. This was an up and down average change as the vessels were bunkered over a very large period and at different locations.

The authors thanked Mr. Aue for his interesting contribution and said they were looking forward to learning about his results as to the cause of clover-leafing, when in fact these were published.

Finally, in answer to Mr. McGlashon, the authors acknowledged the soundness of his observations concerning charge air throughput effects upon wear and specific fuel consumption. His recommendations for comparing air throughputs by simple pressure drop measurements over the charge air coolers and other parts of the scavenge tract were also entirely practical and very useful. However, since most of the suggested sites for pressure drop measurements were themselves liable to constriction, because of fouling in service, the authors would suggest that observations of at least two different sites should be maintained during comparisons of significant duration. The reason for this stipulation was to enable pressure drop changes due to constrictions, to be isolated from pressure drop changes due to mass flow changes.

Regarding the observations in the two ship classes with similar engine type mentioned by Mr. McGlashon, it would appear that the scavenge port modification he had described for the second class, as delivered, had been designed to increase the trapped charge density of air in the cylinder. This would have the effect of increasing the air standard efficiency of the thermal cycle at the expense of increasing the maximum cycle pressure and level of heat fluxes in the cylinder walls due to the attendant decrease in blow down mass. Because air standard efficiency was increased, specific fuel consumption was decreased. However, the increased maximum cylinder pressure would tend to decrease the minimum oil film thickness between the rings and liner, while at the same time the increased heat flux would produce higher surface temperatures at the liner wall, thus further reducing oil film thickness as the lubricant viscosity fell in step with surface temperatures.

The authors were slightly surprised at the values of total air to fuel ratios quoted by Mr. McGlashon as most engines of this generic type tended to operate with air flows somewhat lower than his figures. However, this was not of so much significance as the relative difference of about 15 per cent of air throughput between the two scavenge porting arrangements. The authors had published a relationship between liner temperature, close to the surface, against total air to fuel ratios, in a paper at IMAS '69 (Ref.[4]). This showed how sharply liner temperature might increase, albeit at lower air to fuel ratios than those quoted by Mr. McGlashon. Nevertheless the relationship seemed to be confirmed against large bore engine data, by comparisons from a paper also at IMAS '69 by the late Dr. Hugo Scobel, the authors' comparison being published in the discussion of Dr. Scobel's paper, (Scobel H., 1969, "New Developments in the Field of Low Speed Two-Stroke Diesel Engines" Proceedings IMAS '69 Section 4(c) p.42–51).