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A REVIEW OF THE CAUSES OF CYLINDER WEAR IN MARINE DIESEL ENGINES

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In this paper, wear of the cylinder is taken to mean not only wear of the liner but of the piston ring assembly also, since usually, though not always, the wear of the one is closely related to that of the other. The wear process may be corrosive, abrasive or frictional, and it is likely that all three processes occur together to varying extents, depending on such factors as engine design and operating conditions.

Occasionally, very high wear can occur, resulting in premature renewal of the liners and piston rings, and possibly an expensive overhaul. There are many possible causes for this high wear, and this paper reviews some of them, with special emphasis on fuel and lubricant aspects.

Various engine sensors, together with data logging equipment, are now available to the operator to give an early warning of abnormal conditions which might result in high cylinder wear or other damage. By this means, the appropriate preventive maintenance may avert more serious damage later in the life of the engine.

INTRODUCTION

In low-speed marine diesel engines, wear of cylinder liners of up to 0.1 mm/1,000 hours is normally considered acceptable, giving a liner life of about 7 years. This means that the liners have to be changed twice if the life of the ship is about 20 years. In a medium-speed trunk-piston engine, cylinder wear is generally much lower than in a low-speed engine (around 0.015 mm/1000 hours), so that the liners often do not need changing throughout the life of the ship.

Although such satisfactory wear rates apply to the majority of engines, there are sometimes incidents of much higher wear, resulting in the need for an expensive overhaul and premature renewal of liners and pistons. There are many possible explanations for this exceptionally high wear, and some of the causes and remedies are reviewed here. Particular emphasis is given to those aspects relating to lubrication or to fuel, but other factors will also be considered.

MECHANISM OF CYLINDER WEAR

Three types of wear may be distinguished: corrosive; abrasive (caused by hard foreign particles between sliding surfaces); and frictional (caused by temporary breakdown of the oil and resulting metal-to-metal contact). In a normally running engine, all three types of wear probably occur together, although which type predominates at any particular time depends on a number of factors, especially the operating conditions.

Corrosive wear is caused by the formation of sulphuric acid within the cylinder, the sulphur in the fuel having first burned to SO_2 which then combines with excess oxygen to form SO_3. In the presence of water vapour the SO_3 is converted to sulphuric acid, which forms on the cylinder surfaces if temperatures are below the dew point for condensation of the acid. Fortunately, only a relatively small proportion (about 0.1%) of the sulphur in the fuel is normally converted in this way to sulphuric acid, the remainder of the sulphur oxides passing out of the cylinder with the exhaust gases. The tendency to form sulphuric acid obviously increases with increasing sulphur content of the fuel, and the most effective means of preventing corrosive wear caused by this acid is to use an alkaline additive in the lubricating oil. With residual

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fuels containing high contents of sulphur (up to 4%), the concentration of alkaline additives in the oil must be correspondingly greater.

Abrasive wear is caused by hard particles in the inlet air, or by the products of wear which are themselves abrasive, or by hard carbon (caused by poor combustion) and other material which breaks away from the piston or cylinder surfaces. Effective air filtration is of course important, although abrasive material in the inlet air is rare in a marine environment. In a trunk-piston engine it is equally important to ensure adequate filtration or centrifuging of the circulating oil, to remove all foreign matter which scores not only the cylinders but the bearings as well.

A mild form of frictional wear, sometimes known as "micro-seizure", appears to be a normal process in the cylinder. If for any reason there is a breakdown of the oil film between the asperities on two surfaces in sliding contact, the asperities will touch one another and the tips will be torn away. This type of wear is especially liable to occur during the running-in period, before the asperities have been worn down. Even in a run-in engine, light wear of this type can take place at times on various parts of the cylinder, and after subsequent running it will be observed that the wear marks have healed. The formation and reformation of this frictional type of wear need not give rise to concern if the overall wear is within normal limits, but in more severe cases it may on occasions lead to serious damage of the cylinder and piston rings.

The familiar pattern of wear in the cylinder is that the maximum wear occurs at or just below the top of ring travel, the lowest wear being round the middle of the cylinder, and a small increase in wear again occurring at the bottom of the ring travel, or, in a two-stroke engine, just above the cylinder ports. The high wear at the top of the cylinder may be due to a combination of factors; at this point, the gas load behind the top piston ring is at its maximum, and the cylinder is also hottest in this region. The viscosity of the oil film will therefore be correspondingly low, and more liable to break down with high loading. Corrosive wear may also occur, because although cylinder temperatures are high they might still be below the dew point for condensation of acid; the dew point is raised by a combination of high cylinder pressures and high sulphur content in the fuel, an aspect which is discussed in more detail later in this paper. In addition, corrosive acid formed on the cooler regions lower down the cylinder may be swept to the upper and lower extremities of ring travel by the scraping action of the rings.

The increase in wear at the top and bottom of the ring travel may also be caused partly by the abrupt change in direction of the rings, the oil film having been scraped upward or downwards, so that metal-to-metal contact could briefly take place before the oil film has time to become re-established. The lower wear at the bottom of the ring travel, compared with the upper limit of travel, may be explained by the relatively low gas pressure behind the rings at this point, and, in a four-stroke engine, by the greater quantities of oil flung up from the crankcase.

In a two-stroke engine, the increased wear above the ports may be due to a variety of reasons, one of which is that there is no idling stroke, as in a four-stroke engine, so that oil cannot spread so easily to renew the interruption in the film caused by the ports. In addition, there is usually some leakage of combustion gases past the top ring into the scavenge ports at the bottom of the stroke (distortion of the cylinder in this region may accentuate the leakage), and the hot gases would tend to burn off the oil film.

CAUSES OF EXCESSIVE WEAR

When excessive wear of piston rings and cylinders occurs, the cause is usually one or more of the following factors:

1) Improper running-in.
2) Misalignment of the pistons, or distortion of cylinders, preventing bedding-in of pistons and cylinders.
3) Inadequate oil supply, or unsatisfactory arrangements for lubrication.
4) Lubricating oil too low in viscosity, or too low in alkalinity (Total Base Number - TBN).
5) Piston ring clearances incorrect.
6) Unsuitable cylinder liner material.
7) Contamination of lubricating oil by extraneous abrasive material.
8) Cylinder wall temperatures too high or too low.
9) Overloading the engine.
10) Scavenge air temperature too low, especially in humid climates, resulting in excessive quantities of condensed water entering the cylinder.
11) Inefficient combustion, promoting deposit formation and degradation of the lubricating oil.
12) Use of a low-sulphur fuel (containing less than say 1% sulphur) in conjunction with a highly alkaline cylinder oil - this particular fuel/lubricant combination is not necessarily harmful, but has sometimes been blamed for instances of high cylinder wear or scuffing.

These factors are discussed in turn below.

Running-In

Probably the most critical period in the life of a cylinder is the first few hours of operation. During this time, the piston rings have to form an effective seal against the passage of destructive blow-by gases, the most important requirement in this process being the smoothing of the surface roughness on both cylinders and rings so that the two surfaces slide freely against one another without the asperities welding together when the engine is under load. It is also important to attain geometric conformity between the two surfaces, since it is unlikely that the cylinder will be perfectly round over the whole are of ring travel. Satisfactory conformity may require several hundred running hours to attain, whereas the smoothing of surface asperities should take place in a much shorter period, perhaps 10-20 hours, depending on the engine type.

In addition, metallurgical changes take place on the metal surfaces during the initial running, in that a relatively thick work-hardened layer is formed, which has good anti-wear properties in subsequent operation. High temperatures during the running-in might impede the development of such a layer, and lead to certain undesirable constituents which have poor frictional properties and could promote scuffing.

Careful operation of the engine during running-in is therefore essential to ensure good bedding-in of the piston rings and a satisfactory low wear afterwards. Engines are usually run-in on the manufacturer's test bed, at gradually increasing speeds and loads, but a further running-in period is desirable after the engine has been installed in the ship. This means that the ship should steam at reduced speed for the first few hours before full service load is applied.

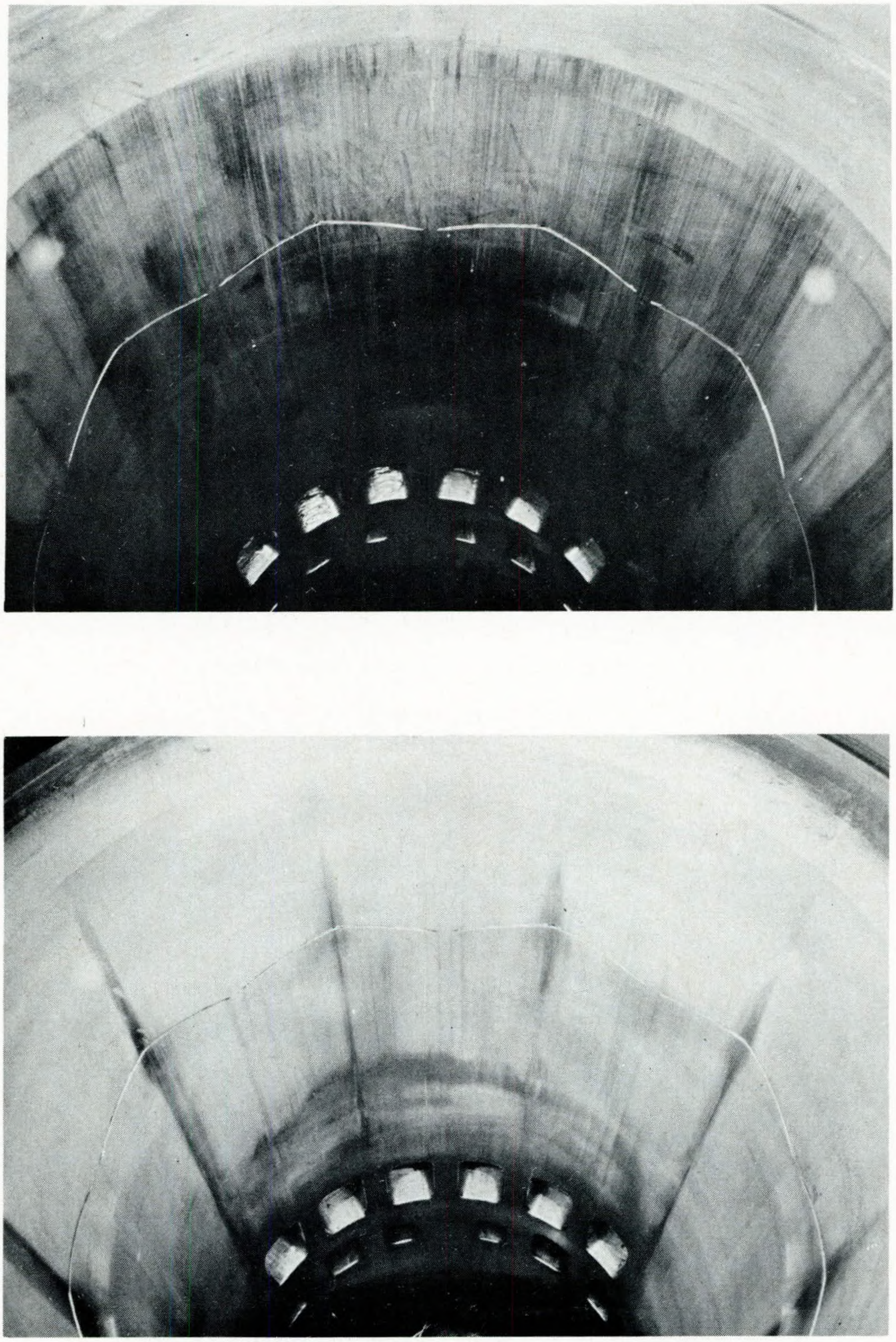

Fig.1 – Sulzer 2RF68 laboratory engine: cylinder liner of cylinder 2 (exhaust side) before and after applying special running-in oil

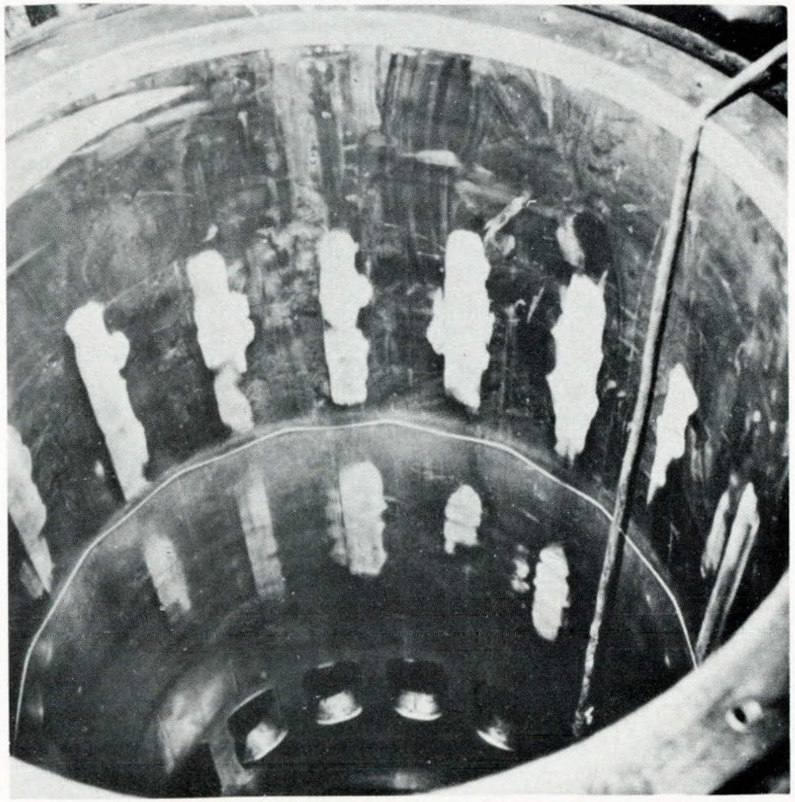

Fig. 2 — Clover-leafing (corrosive) wear on chromium plated cylinder liner

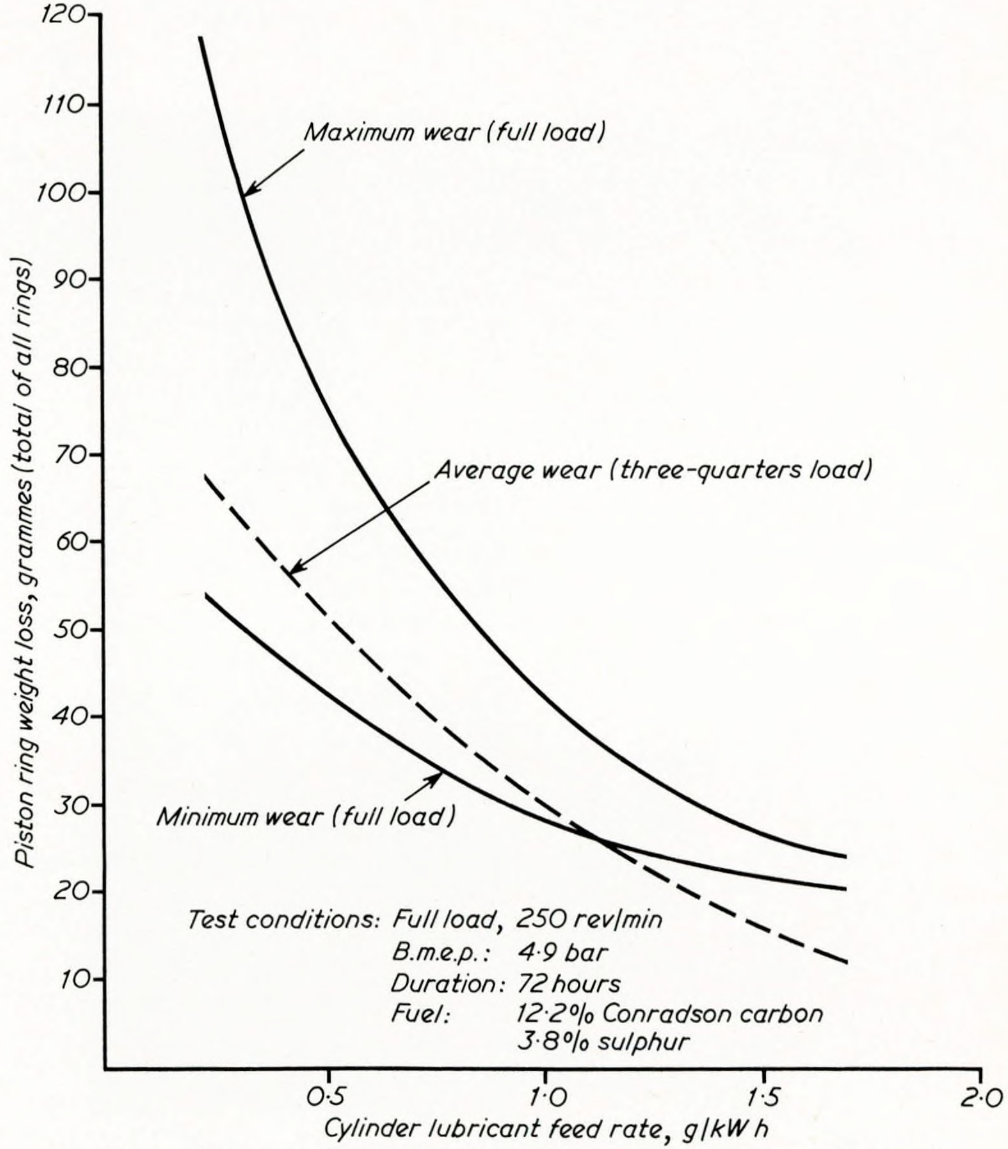

Fig.3 — Effect of cylinder oil feed rate on piston ring wear (Sulzer T48 laboratory engine)

On the test bed it is normal to use distillate fuel, and fuel of this type is also sometimes used for the initial running in the ship. In low-speed engines it is preferable to use an oil of low alkalinity while distillate fuel is burnt, because the sulphur content is generally lower than that of a residual fuel. Since running-in is essentially a wear process, it seems to be beneficial to encourage a certain amount of corrosive wear during the first period of running, and the use of a highly alkaline oil during this time is therfore inadvisable, especially if a low-sulphur fuel is used. However, in trunk-piston engines it is not feasible on board ship to change the crankcase oil after the run-in because of the large volume in circulation, and it is normal to use the same oil for running-in as for subsequent operation.

Sometimes, a straight mineral oil without additives is used for running-in low-speed engines. With modern highly rated engines, however, there is a risk of piston deposits and perhaps ring-sticking at the higher engine loads if the oil contains no additives to prevent deposit formation. If the piston rings are stuck or partially stuck, the piston starts its life in poor condition, and blow-by gases past the rings will probably cause scuffing and increased cylinder wear subsequently.

Special lubricating oils are available to assist running-in of both low- and medium - speed engines. In low-speed engines, an oil of this type accelerates running-in by means of an additive which, when burnt in the combustion chamber, produces a very finely divided abrasive which helps to lap in the rings against the cylinder. The use of an oil of this type for a limited period may also help to smooth off surface damage and remove lacquer formation which has occurred in earlier running with a conventional lubricant (see Figure 1).

For medium-speed trunk-piston engines, a different approach is used, and a running-in oil has been developed for such engines which contains a high concentration of an anti-scuff additive which protects against scuffing of cylinders and cams/tappets. This latter type of oil, however, has so far been used mainly for running-in engines in the factory rather than on board ship.

Misalignment and Distortion

Cylinder wear and scuffing in low-speed engines has occasionally been found to be due to misalignment of the piston in the cylinder. This of course results in much heavier loading on one side of the cylinder, and a consequent tendency for the oil film to be "squeezed" from the cylinder surfaces by the pressure exerted by the piston and piston rings. Only one or two pistons in a multi-cylinder engine might be out of alignment, so that wear and scuffing occur only in these cylinders, the other cylinders being in normal condition.

Similarly, distortion of the cylinder can lead to local areas of high loading and perhaps of high wear and surface damge. Thermal stresses in the cylinder can cause distortion, and mechanical distortion might be caused, for example, by uneven tightening of the cylinder head holding-down bolts. With modern hydraulic assembly equipment, however, this cause of distortion is now rare.

Oil Supply

An adequate supply of lubricant to all parts of the cylinder swept by the piston rings is one of the most important requirements for preventing wear and maintaining the cylinder in good condition. In a trunk-piston engine there is not usually any problem in this respect, since the copious quantities of oil flung up from the crankcase, and afterwards scraped down again by the piston rings, are sufficient to maintain satisfactory lubrication over the whole cylinder surface. In some of the larger medium-speed engines, the lubricant from the crankcase is supplemented by separate cylinder lubricators, although these lubricators are not fitted by all engine manufacturers.

The oil consumption in a trunk-piston engine can be a critical factor. A normal consumption is in the order of 1.07 - 1.6 g/kWh, but if this is reduced appreciably by means of more severe scraper rings, increased wear might result, thus nullifying the economy of using less oil. There does not appear to be sufficient evidence to establish a critical lower limit, which would in any case vary according to engine type and operating conditions, but in trunk-piston engines a consumption of around 0.94g/kWh (i.e. about 0.45% of the fuel consumption) is probably the minimum desirable level. Fuel sulphur content is one of the most important operating factors to consider, and it is probable that with sulphur levels below about 1% (i.e. in most cases, with a distillate fuel) an oil consumption even lower than 0.94 g/kWh would give satisfactory wear rates and an acceptable oil life.

In a low-speed engine, where the lubricant is supplied solely from lubricators distributed around the cylinder, the situation is different in that the supply of lubricant to the cylinder can be more precisely controlled, but uniform distribution over the surface is more difficult to achieve. It should also be emphasised that the cylinder oil not only has to act as a lubricant, but also has to transport the alkaline additive over the whole cylinder surface so as to neutralise any sulphuric acid which may condense on the surface. Hence, while a reduction in the oil feed rate may still be sufficient to maintain an adequate oil film over the whole surface area, the alkaline oil additive may become totally depleted on the areas most remote from the oil quills. This will allow corrosive wear to occur on those areas, giving the uneven cylinder wear pattern known as "clover-leafing".

An example of clover-leafing is shown in Figure 2, the cylinder in this instance being chrome-plated. Acid corrosion on the areas in between the oil quills has resulted in the formation of the conspicious areas of milky-white chromium sulphate. A similar effect can sometimes be seen on cast iron liners, but in these instances the corrosion or pitting of the metal may be disguised by a layer of dark brown surface lacquer.

Maintenance of an adequate oil feed rate is therefore essential to prevent this type of wear. If in the interests of economy the feed rate is reduced to the critical minimum, there is likely to be a considerable difference in wear from one cylinder to another, since the wear is then much more sensitive to minor variations in operating conditions between the cylinders. This was established in a single-cylinder two-stroke laboratory engine fitted with separate cylinder lubricators, a series of tests having been run with various oil feed rates at both three quarters load and full load. The results are illustrated in Figure 3, which shows not only that piston ring wear was somewhat less at the lower load, but also that at full load with the lowest oil feed rates the scatter of results in repeat tests was much greater than at the higher feed rates. Above about 1.74 g/kWh there was little further improvement in wear, although in practice an engine of this type

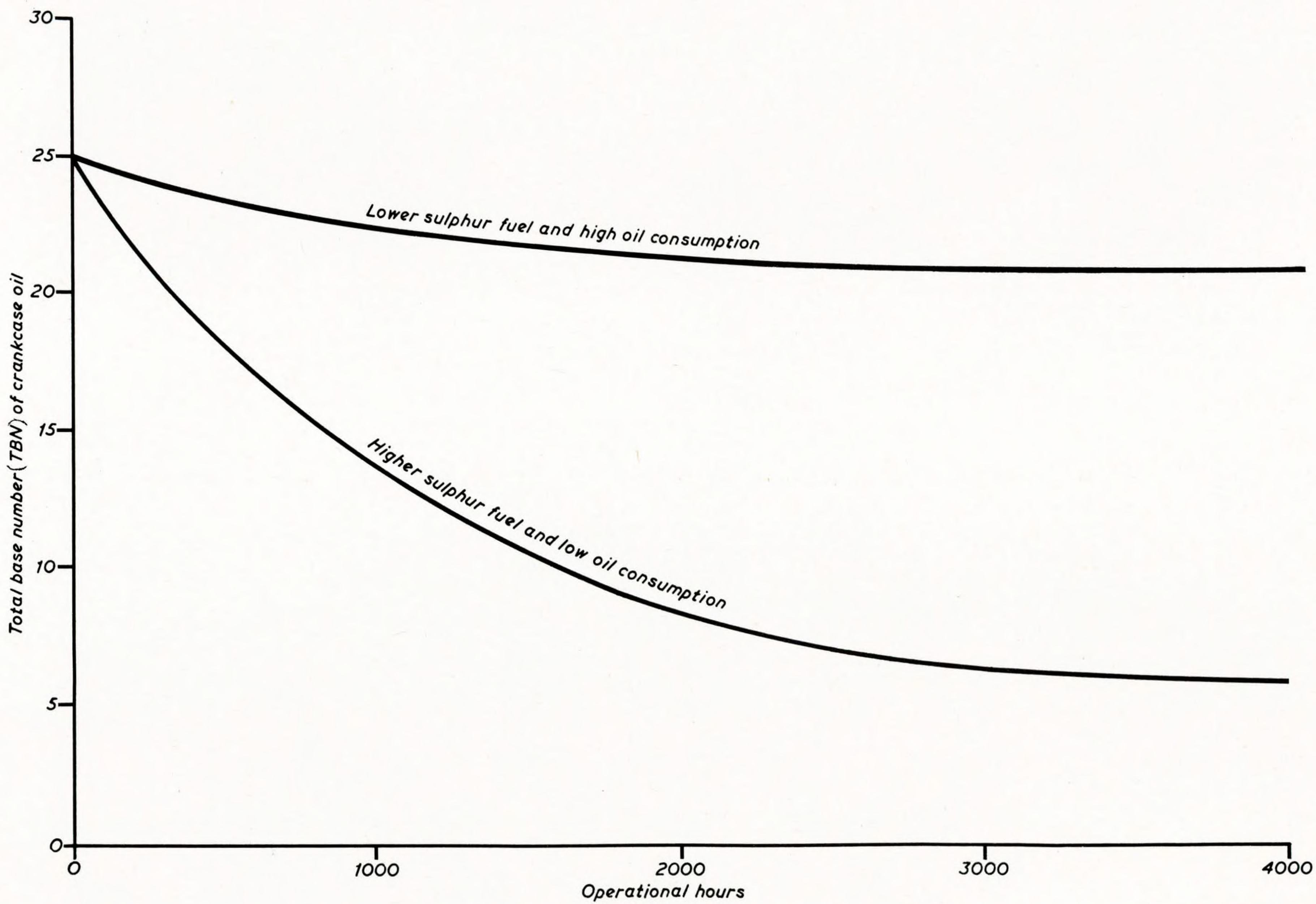

Fig.4—Change of oil TBN with service time under differing conditions

would have a feed rate appreciably lower than this - around 0.94 g/kWh.

At three quarters load there was a similar relationship of wear/feed rate as at full load, but the repeatability of results was much better. This suggests that with low feed rates at lower loads the wear is not so sensitive to conditions within the cylinder, so that in a ship running at reduced speed the oil feed rate appears to be rather less critical than it is at the maximum speed and load.

In general, oil feed rates of around 0.54 g/kWh have been considered normal for uniflow-scavenged engines, and around 0.8 - 0.9 g/kWh for loop- or cross-scavenged engines. It seems that in the latter type of engine, compared with the uniflow-scavenged engine, the complex gas movement has more influence on the distribution of oil on the cylinder surface, requiring a higher oil feed rate in compensation. However, there seems now to be general recognition that oil feed rates above these recommended values may be beneficial on occasions to reduce the scatter of wear results. It has also been found that a generous oil supply improves the sealing of the piston rings and helps to reduce blow-by, which might perhaps be caused by local scuffing or temporary collapse of the piston rings.

Oil Properties

In either a low-or medium speed engine, one of the most important characteristics of the oil is its viscosity, since on this property depends the ability of the oil to support load and to separate the surfaces in sliding contact. Most oils are a blend of light and heavy components, and the final viscosity of the oil is not the only factor to consider; the proportion of heavy ends or "Bright Stock" has a considerable influence on the capacity of the oil to carry load. Too high a concentration of Bright Stock, however, might result in excessive combustion deposits, and oils have to be blended to give adequate load-carrying capacity with the minimum tendency to produce deposits. For the crankcase oils of trunk-piston engines, an oil of SAE 30 viscosity is usually sufficient, whereas for the cylinder oils of low-speed engines a higher viscosity, either SAE 40 or 50, has been found to be necessary to give sufficient protection against wear and breakdown of the oil film. The correct viscosity of the oil to be used is recommended by the engine manufacturer, and it is unusual in practice for the cause of high wear to be traced to the use of an oil of too low a viscosity.

Other properties of the oil are regulated by the oil supplier, according to the additive formulation, and where heavy fuels of relatively high sulphur content are used a very important property of the oil is its alkalinity, as measured by Total Base Number (TBN). As with viscosity, manufacturers usually issue recommendations for the oil TBN appropriate to their engines, sometimes relating the TBN to the fuel sulphur content or the type of fuel being used. In low-speed engines, experience has shown that the TBN of the cylinder oil should be in the order of 60-70 to ensure the minimum of corrosive wear over a wide range of conditions, but nowadays oils of even higher alkalinity, with TBNs of between 85-100, are available to deal with very high fuel sulphur levels and the most severe operating conditions. As with the considerations for the most suitable oil feed rate, it has to be remembered that the oil must have a sufficient reserve of alkalinity over the whole of the cylinder surface, the most critical areas being those between the oil quills, so that the TBN of the fresh oil has to be high enough to neutralise corrosive acid even on these areas. Both the oil feed rate and the TBN of the incoming oil are therefore of equal importance in meeting this requirement. The use of a cylinder oil of too low a TBN could result in a clover-leafing type of wear, which might not be eliminated even if the oil feed rate is increased.

The condition of the oil draining from the cylinder, particularly the TBN and iron content, provides a useful indication of the adequacy of the supply of alkalinity tothe cylinder. In a laboratory engine it is possible to fit a special trough to collect these cylinder drainings for analysis, but this ideal arrangement may not be practical in service and it is then necessary to rely on samples collected from the under-cylinder space. This oil may not always be representative of that actually draining from the cylinder, but nevertheless collection of samples in this way has provided useful information in service trials where it was necessary to determine the most suitable TBN for a cylinder oil to be used with a particular type of fuel.

It has been found from experience that where heavy fuel having a sulphur content of 2% or more is used, the cylinder and piston ring wear tends to increase rather sharply if the TBN of the cylinder oil drainings is allowed to fall below about 10. This means that with normal oil feed rates the cylinder oil has to have a TBN of around 70, or even higher under some conditions.

In a trunk-piston engine, the copious quantities of oil splashed up from the crankcase mean that the supply of lubricant to the cylinder is more generous than in the cylinder of a low-speed engine, and consequently the high levels of oil alkalinity required for a low-speed engine are not necessary in a trunk-piston engine. With heavy fuels, the TBN of the crankcase oil is normally about 25-30, whereas with distillate fuels, having a low sulphur content, the TBN of the crankcase oil can be correspondingly lower, usually around 10-15. With both types of fuel a critical factor is the oil consumption, since too low a consumption - perhaps due to the use of piston scraper rings which are too severe in their action - could result in the TBN of the crankcase oil stabilising at too low a level, as shown in Figure 4. Experience has shown that the TBN of the oil should not fall below a level numerically at least three times that of the sulphur content of the fuel, e.g. with fuel containing 3% sulphur, the minimum TBN of the crankcase oil should be 9. If the TBN falls below this, wear and deposits in the cylinder are liable to increase.

In practice, it has been found that the addition of make-up oil is usually sufficient to maintain the TBN well above the critical minimum. The oil might have to be changed for other reasons, such as a build-up of soot and other insoluble material, but if, as is customary, such engines are fitted with continuously operated centifuges, then the oil change life can often be extended to many years.

Piston Ring Side Clearances

The clearance between the piston rings and grooves should ideally always be such that the gap is wide enough to ensure that the ring is free to move and so conform to any variations in the cylinder liner diameter, and yet not be so wide that excessive quantities of blow-by gases or lubricating oil can flow round the rings. On a

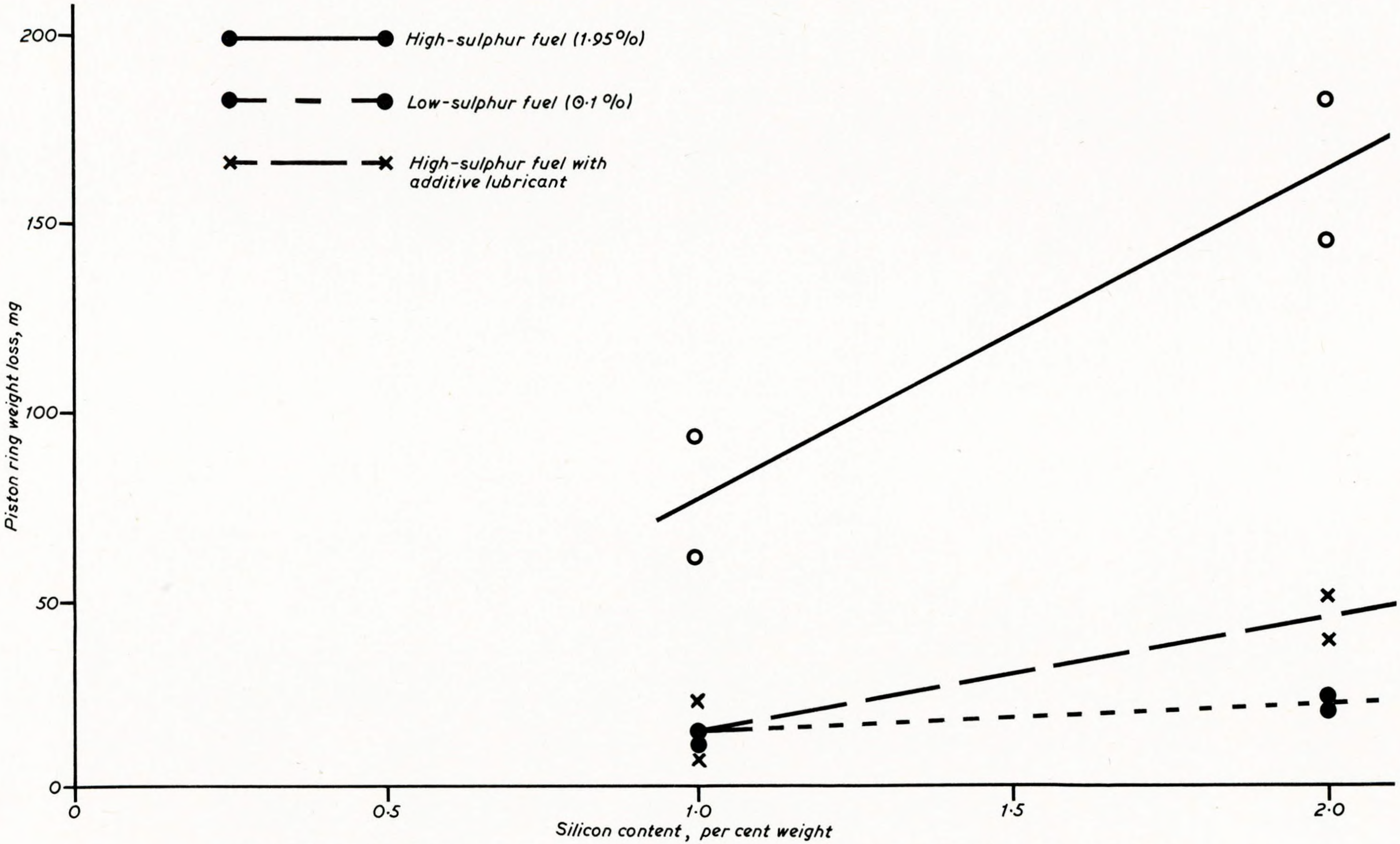

Fig. 5 — Piston ring weight losses for piston rings with high and low silicon contents run under various conditions

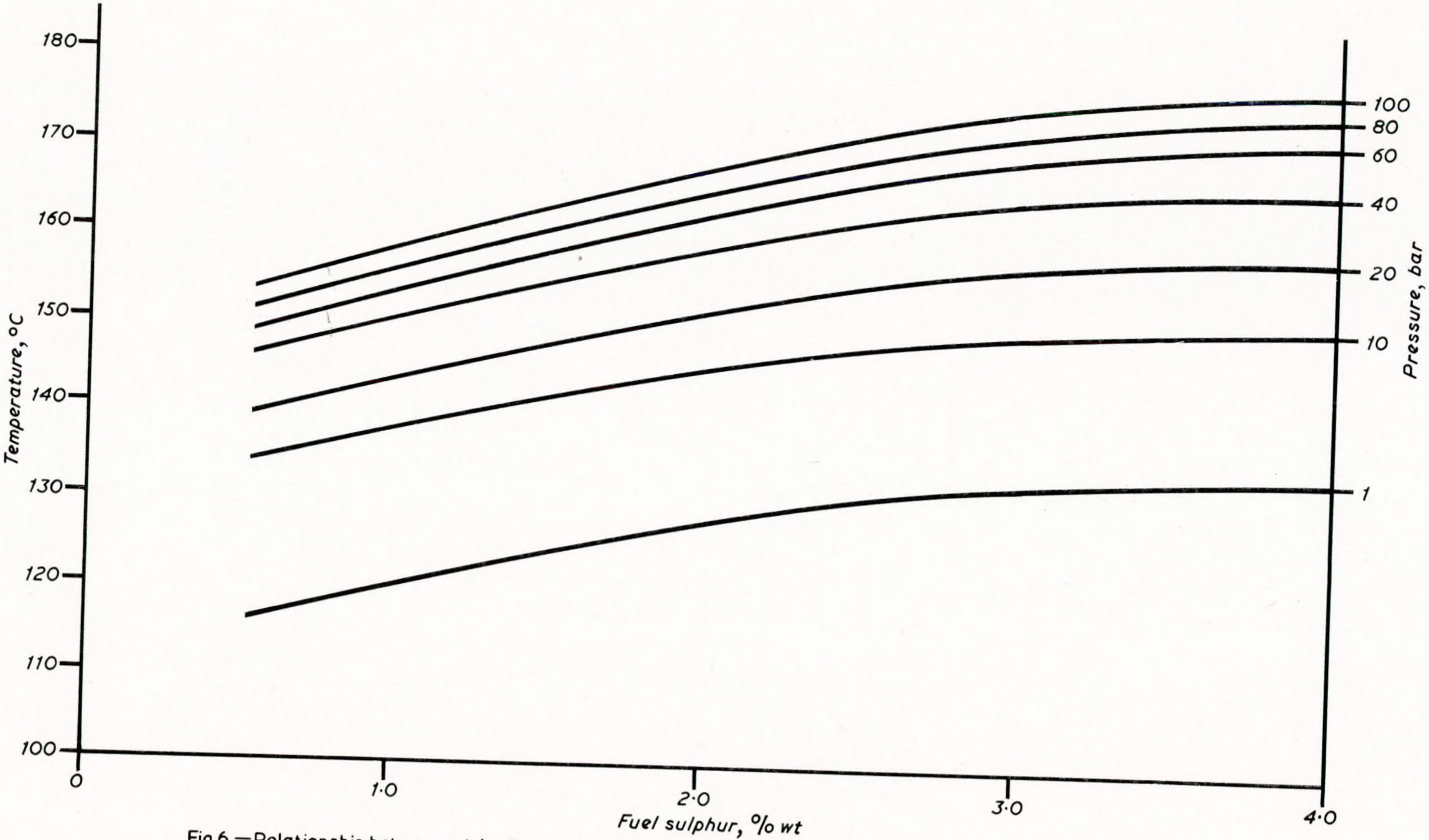

Fig.6 — Relationship between sulphuric acid dew point temperature and fuel sulphur content, at different pressures

new piston, the ring clearance is of course closely controlled by the manufacturer, but after service in an engine the rings and grooves become worn and may distort, thus disturbing the optimum relationship between them.

Wear of the rings and grooves may be either abrasive or corrosive, and is likely in turn to lead to corresponding wear of the cylinder liner, mainly because of the increased passage of hot blow-by gases past the rings, and the tendency to burn off the lubricating oil film. There may also be a greater flow of oil round the back of the rings and eventually up to the combustion chamber, resulting in heavy carbon and ash deposits on the top of the piston and in the combustion chamber. These deposits, especially on the crown land of the piston, are sometimes very hard, and may contribute to wear of the cylinder liner by an abrasive effect.

Too tight a clearance of the ring in its groove can lead to ring sticking, which is very harmful because the ring can no longer provide an effective seal in the cylinder, and blow-by gases then rapidly destroy the oil film. Sometimes, ring sticking is caused by an excessive build-up of deposit in the ring groove, but it has also been known to occur because of manufacturing faults resulting perhaps in the clearance being too tight initially or because of waviness in the ring groove causing tightening of the ring at certain points round the groove. Waviness or closing of the gap between the groove and the ring, can also occur during operation in which fluctuations of temperature within the cylinder give rise to distortion of the piston.

Ring breakage is sometimes a problem, especially in low-speed engines. When the ring breaks, of course, the seal between the ring and cylinder is no longer effective, and blow-by gases can burn off the oil and so increase wear of the liner. There are various causes of ring breakage, one of them being uneven wear around the cylinder, and perhaps around the ring grooves as well, resulting in the ring being supported at only a few points instead of uniformly around the cylinder. The ring breaks because of the high specific loading at these points.

Cylinder Liner Material

A detailed consideration of the metallurgical factors influencing wear is outside the scope of this paper, but obviously the composition and microstructure of the materials in sliding contact has a profound influence on the rate at which they wear. Many papers have been written on this subject, and only one or two aspects can be briefly discussed here.

In recent years, there has been increased use of nodular cast iron, or spheroidal graphitic (SG) iron. In conventional cast iron, the carbon is present as graphite flakes, which, although they provide good resistance against wear, also make the metal brittle because of the interruption to the continuity of the microstructure. By modifying the manufacturing process, it is possible to produce the graphite in the form of spheres or nodules, and the material is then less brittle than conventional cast iron and has better mechanical strength. SG iron has therefore proved particularly popular for piston rings as a means of preventing breakage, and it has also been used for components such as crankshafts which undergo shock loading. There is, however a penalty in using SG iron, since its resistance to mechanical wear is not so good as that of conventional cast iron containing graphite flakes.

Corrosive wear is influenced strongly by the composition of the cast iron, and two components in particular may be mentioned here: phosphorus and silicon. Phosphorus in the iron is present in the structure as relatively hard iron phosphide, and this provides good resistance to wear. However, it is also brittle, and for this reason its concentration has to be limited. It has been found that wear is reduced as the phosphorus is increased up to about 0.25%, but above this concentration there is little further benefit and there may be the disadvantage of increased brittleness.

Silicon in the cast iron has been found to permit an increased tendency to corrosive wear if the concentration is allowed to exceed about 1%. This was demonstrated in a small four-stroke laboratory engine operated at low temperatures to promote corrosive wear. Tests were run with two fuels, of high and low sulphur content respectively, and with a straight oil and an oil containing an alkaline additive. Two kinds of piston rings were used, one with a relatively low silicon content (1%) and the other with a high silicon content (2%). The results are illustrated in Figure 5, which shows that under corrosive conditions (high sulphur fuel, straight mineral oil) wear was appreciably higher with the piston rings containing 2% silicon. As might be expected, the use of the alkaline lubricating oil reduced wear considerably with both types of ring, but there was still an advantage for the rings of low silicon content.

Service experience has supported these laboratory observations, for example, in one fleet where significantly higher wear was found in cylinder liners of 1.6% silicon content than in liners of the same ships having a silicon content of 0.6%. However, there does not yet appear to be any satisfactory explanation why silicon should have this tendency to lower the resistance of the iron to corrosive wear.

Cylinder Temperatures

The temperature of the cylinder is of critical importance because, on the one hand, corrosive wear may be experienced because temperatures are too low, and on the other hand, piston ring sticking and breakdown of the oil film may occur if temperatures are too high. Ideally, the whole surface of the cylinder should be at a temperature above the dew point at which sulphuric acid can condense, in which case no corrosion should take place. However, the dew point is influenced by two important variables, i.e. the pressure within the cylinder, and to a lesser extent the sulphur content of the fuel. The relationship is illustrated in Figure 6.

Modern highly rated four-stroke engines have combustion pressures in the order of 140 bar, so that the dew point would, momentarily at least, be above the upper end of the group of curves illustrated, and the situation would be further aggravated by the use of a high-sulphur fuel. The dew point at the top of the cylinder could perhaps be as high as 180°C, and it is likely that parts of the cylinder in this critical region would be below this temperature.

It is therefore most important to control the cooling water at a sufficiently high temperature to avoid acid corrosion within the cylinder, but at the same time not high enough to cause over-heating. The most suitable coolant outlet temperature is generally in the range 65-70°C. Experience has shown that if this temperature is allowed to fall below about 55°C severe corrosive wear can result, even with a cylinder oil of the highest alkalinity. The effect of lowering temperatures is of course more pronounced with a fuel of high sulphur content.

The recent trend towards slow steaming in the

Fig. 7 — View of top of cylinder liner showing unusual staining in the vicinity of the top ring reversal position

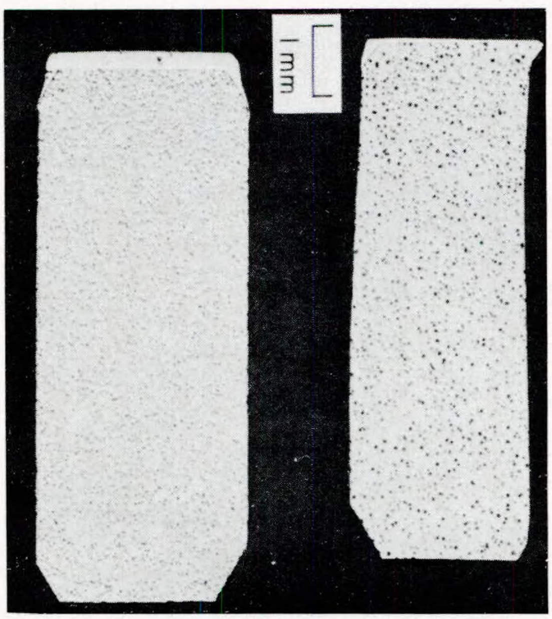

Fig. 8 — Comparison of worn and new compression rings, showing extent of top face wear, wear ridge on top edge and removal of chromium plate from the sealing face

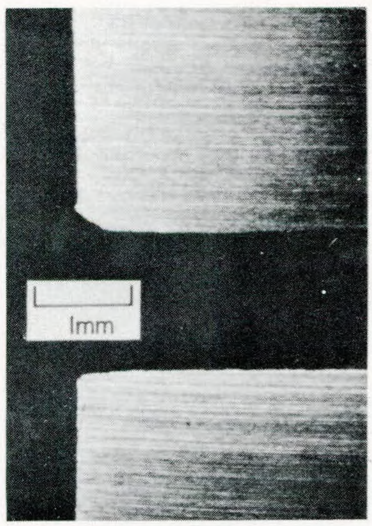

Fig. 9 — Sections through the top and bottom edges of the top ring groove, showing wear and rounding of the top edge

interests of fuel economy could accentuate the problem of corrosive wear because there is less heat to dissipate from the cylinder, and unless temperatures are carefully controlled they may fall into the region where excessive quantities of acid may condense in the cylinder. Although operating conditions are therefore less arduous in some respects as a consequence of the reduced loads, they may be in fact even be more severe from the point of view of acid formation. A highly alkaline oil is therefore still required to provide the necessary protection against acid corrosion.

An example of corrosive wear in service is illustrated in Figures 7 to 9. These are views of a cylinder liner and piston from a medium-speed engine which had been burning distillate fuel having a sulphur content of 0.5% maximum. Despite the relatively low sulphur content, high wear had occurred on both the cylinder and piston rings, and it was suspected that this wear was corrosive because of low engine loads and probable over-cooling.

The general view of the cylinder in Figure 7 illustrates the unusual staining in the vicinity of the top ring reversal position. A replica of this area showed a matt surface extending for 2-3 mm below the wear step, with no evidence of the original honing marks. There were no indications of abrasion, and the generally matt appearance of the bore strongly suggested corrosion as the principal wear mechanism.

Corrosion also appeared to be the main cause of wear of the top ring and groove, sections of which are shown in Figures 8 and 9 respectively. High magnification of the top face of the ring clearly demonstrated the pitting on the surface. The wear of the upper face of the ring, resulting in a wear "ridge" on the sealing face, supported the conclusion that the wear was corrosive rather than abrasive, since experience has shown that if the wear were abrasive it would generally occur on the bottom face.

In this particular instance, it appeared that a re-design of the cylinder liners had resulted in low cylinder temperatures and hence a greater tendency to corrosive wear. Although a thick-walled liner had replaced the original thin-walled type, the change in heat transfer characteristics meant that for the same water-side temperature the gas-side temperatures were lower on the thick-walled liner. It was concluded that higher cooling water temperatures were required to overcome this problem.

It is important, however, that cylinder wall temperatures should not exceed about 180-200°C, since above this temperature lubrication may suffer and thermal stresses and distortion may be induced in the cylinder and piston. Excessively high temperatures are mostly caused by overloading of the engine or faulty combustion, and these aspects are discussed under separate headings below.

Engine Loading

Deliberate overloading of an engine rarely occurs, and many engines today, especially if slow steaming, tend to run well below the maximum acceptable output for most of the time. If the engine is overloaded for some reason, the most harmful effect on cylinder lubrication, and hence the promotion of wear, is probably caused by an associated overheating and distortion of the piston and cylinder.

On the manufacturer's test bed, where the engine is run under ideal conditions, measured cylinder and piston temperatures are satisfactorily low even during continuous running at maximum load, and these low temperatures are achieved by close attention to design and operation, guided by an extensive background of experience. For example, the maximum temperature at the back of the top piston ring groove, which may be taken as an indication of the general temperature conditions prevailing within the cylinder, is often no more than about 150°C at full load. In service, however, measurements have shown that these temperatures may be up to 40°C higher than those recorded on the test bed, since the engine, for short periods at least, may have to run under overload conditions for reasons such as excessive hull fouling and operation in heavy seas.

Scavenge Air Temperature

In humid climates there is a risk of excessive quantities of condensed water entering the cylinder with the scavenge air. This problem is likely to be more acute in modern highly rated engines having rather high scavenge air pressures. If the temperature of the air cooler tubes is low enough, moisture condenses on them, and the droplets then break away and are carried over into the cylinder with the scavenge air.

This water may be very harmful because it tends to wash the oil film from the cylinder walls, and furthermore could contribute to corrosion or rusting by combining with the sulphuric acid derived from combustion of the fuel sulphur. Heavy wear or scuffing can thus occur on the cylinder and piston rings during the period when the ship is passing through the appropriate humidity and temperature conditions.

In some instances, the quantity of condensed water passing over into the cylinder can be very large - up to several tonnes per day have been recorded on occasions. Much work has been done by some engine manufacturers to design separators for removing the water, but this equipment, although very effective, is expensive and cumbersome to install and has so far been used to only a limited extent.

To avoid water condensation as far as possible, the cooling water inlet temperature to the air coolers should be controlled according to the humidity and temperature of the inlet air. One engine manufacturer has recommended that for the best results the air-cooler water should be maintained at a temperature 5°C below the dew point temperature of the air after the cooler. It has been found that to control the air temperature only does not necessarily prevent water entering the cylinder, since if the air cooler tubes are too cold, relatively large drops of water can condense and subsequently reach the cylinder walls before they have time to evaporate.

Fuel Combustion

The way in which the fuel burns in the combustion chamber is one of the most important factors affecting engine temperatures, and hence the efficiency of lubrication and consequent wear of the cylinder. Many variables influence combustion, such as air delivery, fuel injection characteristics and fuel quality, and although some of these variables are a function of design the majority of them are within the control of the engine user in that they depend on the general condition and operation of the equipment.

Apart from the effect on cylinder temperatures, poor combustion influences lubrication and wear by the production of partly burnt products, some of which reach the oil on the cylinder walls, and, in a trunk-piston engine, are eventually circulated

6.

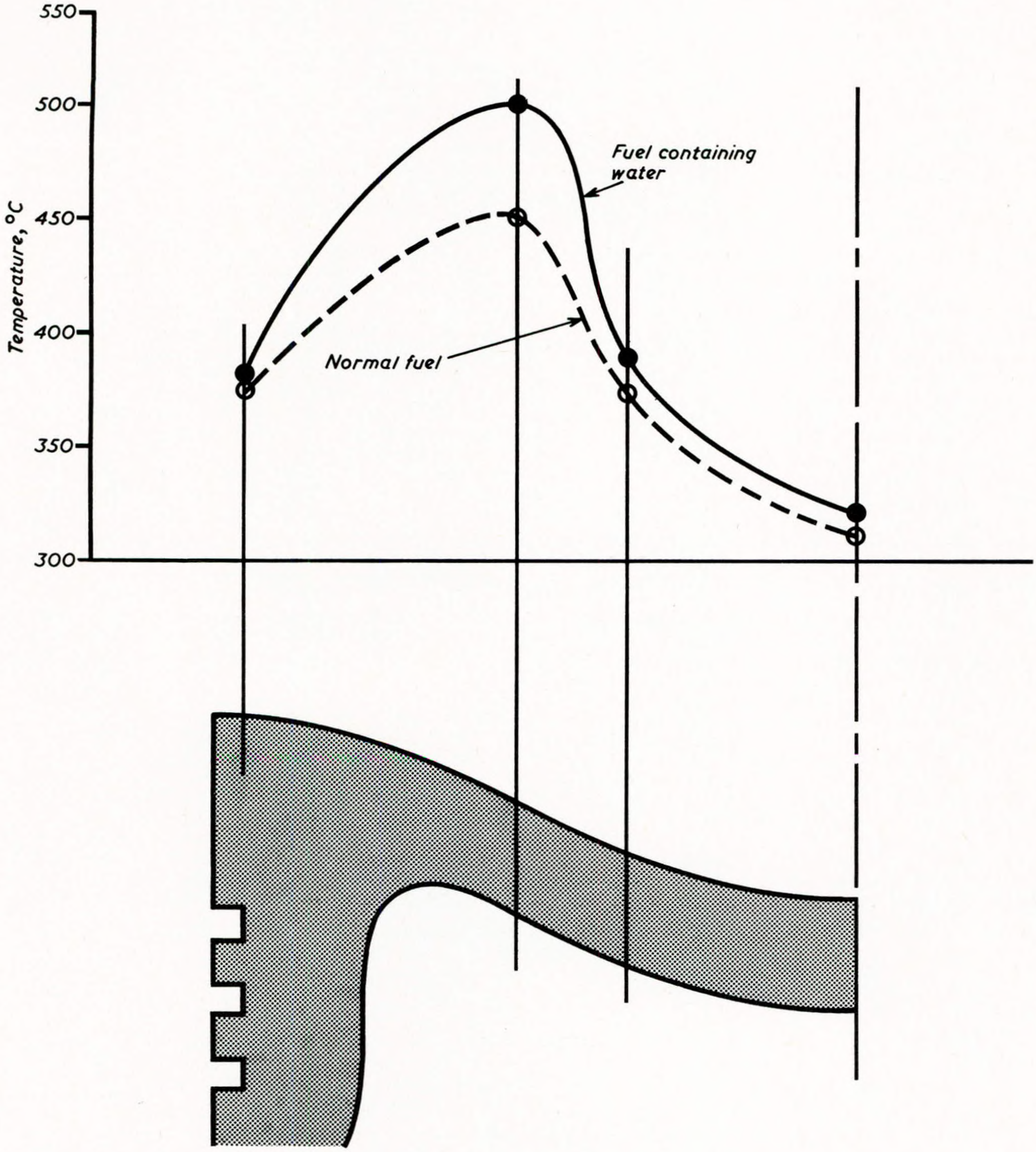

Fig.10 —Effect of water in fuel on piston crown temperatures

with the crankcase oil. These combustion products build up, for example in piston ring grooves, where they pack the back of the groove and may restrict the movement of the ring, and they may accumulate on turbocharger blades, or in the cylinder ports of two-stroke engines. Such deposits reduce the power output and may impair combustion even further.

Fuel properties of course have an appreciable effect on combustion. Heavy fuels are more difficult to burn than distillate fuels because of the presence of asphaltenes which are slow-burning and require the correct conditions to ensure complete combustion and to avoid the formation of deposits. Low-speed and medium-speed engines are in general designed to burn the most viscous heavy fuels commercially available, although the concentration of ash-forming material, especially vanadium and sodium, may be a limiting factor in some faster running four-stroke engines where valve deposits are troublesome.

The viscosity of the fuel at the injector must be carefully controlled within the manufacturer's recommended limits, otherwise the fuel might "dribble" from the injectors if the viscosity is too low, or the spray might impinge on the piston crown or cylinder surfaces if the viscosity is too high. In either event, combustion of the fuel is inefficient and conditions within the cylinder are made less favourable for the lubricating oil. Because of variations in different batches of fuel oil of nominally the same viscosity, it is not sufficient to heat the fuel at a fixed temperature, and it is preferable to control the viscosity by means of a heating device which automatically regulates the temperature to give the required viscosity at the injector.

It is very important to maintain the injectors in good condition so as to ensure a good spray pattern and correct combustion. In particular, deposits which build up on the nozzle must be cleaned off at regular intervals, otherwise the fuel supply might be restricted from some of the holes, or the spray might be directed into the chamber at the wrong angle. Burning fuel might therefore strike the piston crown or cylinder walls and raise temperatures to an undesirably high level.

A laboratory experiment in a single-cylinder trunk-piston engine of 400 mm bore, run at a b.m.e.p. of 8 bar, confirmed the harmful effects of using a fouled injector. Some of the injector holes were deliberately partly blocked to simulate the effect of deposits, and temperature measurements were taken on various parts of the piston and cylinder for comparison with similar temperatures taken when the injectors were in good condition. The results are shown in Table 1.

Temperatures on both piston crown and cylinder liner were very much higher when the artifically fouled injectors were used, and these differences were consistently observed in repeat tests. The exhaust gas temperature, however, showed less change than the other temperatures, so it appears from this observation that in service the temperature of the exhaust gases would not necessarily provide a reliable indication of conditions within the cylinder.

Of the various contaminants which may enter the fuel, water has probably the greatest effect on combustion. In low concentrations the water may do little harm, but at higher concentration the water may slow down combustion to such an extent that the fuel droplets may be still burning when they strike the cylinder or piston crown. The temperature of these surfaces is therefore raised significantly. This effect was demonstrated in work conducted by Norske Veritas, using fuel containing 7% water, a very high concentration in service but not beyond the bounds of possibility if say the centrifuges were inoperative for some reason.

The increase in temperature when fuel contaminated by water was used is illustrated in Figure 10. The overheating caused by the presence of water in the fuel might be sufficient to impair lubrication and hence result in wear or scuffing on the cylinder surfaces.

The correct treatment of the fuel is thus obviously of extreme importance to avoid the troubles associated with contamination, especially by water. Centrifuges are very effective in ensuring that the fuel arrives at the engine in the required condition, but problems have been known to occur if the centrifuge is not well maintained, or is perhaps not suitably matched to the engine consumption.

Filtration and homogenisation are other methods for treating the fuel, and both of these methods have their advocates. Coalascers are often used together with filters in order to remove the water, but with homogenisers any water present is delivered with the fuel in such a finely divided form that it is claimed that combustion is not in any way made less efficient.

Use of Low-Sulphur Fuel

There have occasionally been instances where high cylinder wear and severe scuffing have occurred when certain fuels of low sulphur content have been used in conjunction with highly alkaline cylinder oils. This problem has received much publicity in recent years, but the attention paid to it has probably been out of proportion to its true magnitude. The problem has proved particularly difficult to investigate, firstly because usually

TABLE I - INFLUENCE OF FUEL INJECTOR FOULING ON ENGINE TEMPERATURES (°C)

		Normal injector (average)	Fouled injector
Exhaust gases		330	350
Piston crown	(Combustion side	430	615
	(Cooling oil side	225	330
Cylinder liner	(Above swept surface	230	280
	(At level of first ring	180	215

only one or two cylinders in a multi-cylinder engine have been involved, and secondly it has been known that many ships using the same low-sulphur fuel have been operating together with highly alkaline cylinder oils without any trouble at all being experienced.

A number of different theories have been advanced to explain the high wear that can occur in these circumstances. One suggestion is that the piston deposits are different in composition and physical characteristics when low-sulphur fuel is used, and can be so hard, particularly on the piston crown land, that they can abrade the cylinder. Alternatively, they are sometimes considered to act as a "sponge" so that by their porosity they remove the oil film from the cylinder walls. Another suggestion is that a small amount of controlled wear is necessary continuously to keep the cylinder and piston rings in a well run-in condition, and if nearly all corrosive wear stops, as it would in the circumstances in question, scuffing is generated because the rings cease to conform fully with the cylinder, and the oil film is not retained so well on the cylinder surfaces.

A chemical explanation has also been proposed, in that small amounts of sulphuric acid in the hot parts of the cylinder may to some extent be advantageous because the acid acts as a catalyst for decomposing the intermediate oxidation products of the oil. If little or no acid is present, which would be the case under conditions of very low fuel sulphur and high oil alkalinity, the oxidation of the oil can proceed unchecked and eventually lead to oxidation products which could thicken the oil and result in sticking of the piston rings. There have been some observations from laboratory experiments which support this theory.

All these theories are based on the low sulphur content of the fuel, but to complicate the picture still further there is now some evidence to show that with certain low-sulphur fuels, at least, the sulphur contents may be largely irrelevant, the problem being derived from the unusual combustion characteristics of these fuels. It has been suggested that under certain operating conditions these characteristics could cause cylinder temperatures to rise momentarily to excessively high levels, with consequent destruction or degradation of the lubricating oil film.

Possibly all these theories are true to some extent, the explanation which may have most validity at any one time depending on the particular operating conditions then prevailing. It seems clear, however, that a combination of low fuel sulphur and high oil alkalinity are not on their own necessarily harmful, and some other condition has to be introduced to initiate the trouble. Probably this condition is an unusually high cylinder temperature for one reason or another, which in itself may be harmful of course, but which together with a critical combination of fuel and oil may impair lubrication to such an extent that high wear or scuffing will result.

It is perhaps significant that in the last year or so much less has been heard of ships suffering from a "low-sulphur problem". Perhaps the fact that many ships have been operating under slow-steaming conditions to conserve fuel has resulted in less severe conditions within the engine, especially from the point of view of cylinder temperature, and this has made the engine less sensitive to any peculiarities in the characteristics of the fuel used.

CONCLUDING REMARKS

The various circumstances which could result in increased wear comprise a formidable list, and it might seem that an engine would have little chance of avoiding all these circumstances throughout its life and so running satisfactorily with a low wear rate. The fact that so many engines do achieve this desirable condition can be considered a tribute to the engine designer, the operator and the oil industry. There are obviously many pitfalls to be avoided, and if the engine is allowed to run, even if only for a short time, under one or more of the conditions described here, then the wear can be very high or even catastrophic. These instances are often well publicised, but to keep any such problem in perspective the great majority of trouble-free ships should be borne in mind.

The investigation of a problem of high wear in service often presents difficulties, because the conditions causing wear may arise for only short periods of time, and may not be present when the investigation takes place. Furthermore, it is often found that the wear has occurred in perhaps only one or two cylinders, and the problem then is to discover how conditions within those cylinders have differed from those in the other cylinders, which are giving acceptable wear rates. This has been one of the puzzling aspects of the "low-sulphur" problem, for example, since the fuel and oil are common to all the cylinders, in which case they are clearly not necessarily harmful on their own. The third critical factor, as described above, is probably an unusually high temperature in some regions of the cylinder, and some of the reasons why temperatures could vary from one cylinder to another have already been discussed here.

When the causes of wear are obscure, as they often are, it is necessary to make a long and detailed examination of the various operating parameters which might be important. If all the relevant information is available, it might then be possible to detect a trend or some abnormal condition which is of significance, and which, if corrected, removes the problem amd may therefore be considered to have been its main cause. More often than not, however, a number of variables are changed at the same time in an attempt to make every effort to overcome the trouble, so that even if these efforts are successful it is not subsequently possible to establish with certainty which parameter was of most importance.

Prevention of the problem in the first place is of course preferable to curing it subsequently, and there is now available a range of sensors and data-logging equipment which can help the operator to detect any potential trouble at an early stage, before it can develop too far. This instrumentation permits a constant check on the running conditions within each cylinder, and by means of associated alarm systems which react to abnormal variations in the cylinder, the operator is alerted to conditions which might cause cylinder wear, scuffing or other troubles, and can take the necessary corrective action as soon as possible. By this means, the optimum performance of the engine is ensured, and any preventive maintenance work which proves to be necessary would probably be far less costly than the extensive repairs which might be needed at a later stage if there had been no means of bringing the early warning signs to the operator's attention.

ACKNOWLEDGEMENTS

Grateful acknowledgement is made to colleagues in Shell Research Ltd. (Thornton Research Centre and Koninklijke/Shell - Laboratorium, Amsterdam) who carried out much of the work on which this paper is based.

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DISCUSSION

MR G H CLARK FIMarE said that the author had made a wide-ranging summary of the main causes of cylinder liner and piston ring wear, in both two-stroke crosshead and four-stroke medium-speed marine diesel engines, particularly when burning residual fuel. Especially at the present time, with the depressed state world-wide of the shipping industry, any contribution, which would enable shipowners to reduce out-of-service time and high costs of engine maintenance and replacement components, was most welcome.

It was, perhaps, a pity that wear problems in crosshead engines and in trunk-piston engines were treated together. For easy reference and in order to avoid confusion, as it was considered that there were several important differences between the causes in each type, it might have been preferable to review them separately.

One somewhat surprising omission, particularly relating to the influence of suitable lubricants in the wear problem, was that no reference was made to the importance of good detergency/ dispersancy properties in cylinder lubricants in minimizing the adverse effects of sticking or sluggish piston rings, particularly with fuels having poor combustion properties and high ash and asphaltene contents. Whereas, in trunk-piston dual-purpose lubricants, good detergent/dispersant properties, with adequate alkaline properties (of about 11 to 15 TBN for distillate fuels and 22 to 30 TBN for high sulphur content residual fuels) were highly desirable, it was equally important that high TBN cylinder lubricants used in crosshead engines shuuld also possess similar properties, in order to ensure free movement of the piston rings, even under adverse combustion conditions. The author's views on this matter would be appreciated.

With regard to initial running-in of new liners and rings, perhaps it might be better to group frictional and abrasive wear together as, in practice, it was impossible to separate them. Micro-seizure could certainly be increased by the presence of abrasive foreign matter in the cylinder. High temperature micro-welding of the tiny surface asperities, as they slid over each other, was probably most likely to cause minute surface damage as the welds were torn apart. It was agreed that this form of initial wear was inevitable, probably even desirable, in new engines, provided that this was confined to micro-seizures or wear and did not proceed further to cause macro-wear or welding leading to scuffing.

It was agreed that the first few hours operation were critical in the life of a diesel engine cylinder and the careful control of engine loading and good combustion with a suitable fuel, preferably an all-distillate and not a blended marine diesel fuel, was most important. However, it was thought that it might take a much longer period, possibly up to about 2,000 hours, to form a work-hardened or Beilby layer on the liner surface. This could well be damaged, or even destroyed, by corrosive wear during the running-in period. Unfortunately, the shipowner usually insisted upon full-power trials, often on high-sulphur residual fuel, before acceptance of the ship. Perhaps, after acceptance, it might be stressed that, for the first 2,000 hours, it would be wise to restrict engine power to about 85% of MCR, preferably with a cylinder oil feed rate appreciably in excess of the usual accepted rate when fully run-in. Especially for cross-scavenged, oil feed rates of 1.1 to 1.3 g/bhph should be considered quite normal during this period.

Many authorities did not favour the use of fine abrasive compounds to accelerate initial running-in, on the grounds that, under operating conditions, it was difficult to control the degree of wear produced and, under unfavourable conditions, they could initiate undesirable surface scuffing. Furthermore, after running-in was completed, it was difficult entirely to remove all traces of the special abrasive oil, even when normal cylinder oil was used.

Special EP compounds or load-carrying agents in the oil were thought by many to be the best approach to this problem, although it might take longer to achieve the required surface finish of rings and liners.

During recent years, particularly in some cross-scavenged highly pressure-charged two-stroke engines, excessive local piston ring wear had occurred in way of the exhaust ports. In some cases, after only a few hundred hours, the rings had worn well below their safe limit, leading to ring breakage and even seizure. Additionally, excessive liner wear had been experienced some 75 to 100 mm above the exhaust ports, again promoting gas blow-by eventually leading to seizure. The author's views on the causes of this serious problem would be appreciated.

The author's view that, in crosshead engines, oil feed rates appreciably above those recommended by some engine builders, particularly in cross-scavenged engines, could be beneficial, was strongly supported. It was thought that the main reason why cross-scavenged engines gave better results with higher oil feed rates than was normal in uniflow-scavenged engines was that, in the former type, some degree of liner distortion, due to both thermal and mechanical causes, occurred and more oil was required to ensure a gas-tight seal between liner and rings.

The figure of 0.54g/kWh for uniflow-scavenged engines might well be increased to about 0.75g/kWh for the best rssults, wiile for loop-scavenged engines 1.0 to 1.1g/kWh, or even higher in some designs or operating conditions, would be beneficial.

The comments about the reserve alkalinity remaining in cylinder oil drainings were interesting, but the necessary tests to determine the TBN could only be carried out in a specialist laboratory and were, therefore, to a degree only of academic value to the vessel's engineers, unless a special test programme was in hand. Furthermore, to a large degree, the remaining TBN was dependent upon the cylinder oil feed rate.

The comments relating cylinder wall temperature, acid dew-point and corrosive wear were of particular interest. It appeared, however, that these related mainly to highly pressure-charged four-stroke engines and it was agreed generally that wear in crosshead-type two-stroke engines presented the biggest problem. Had the author any further data available on this subject, relating to the larger slow-speed engine.

Combustion pressures in crosshead engines were usually in the order of 70 to 84 bar, which, from Figure 6, would give an acid dew-point, with a 3.0% sulphur fuel, of about 170 to 174°C. Liner skin temperatures at the upper end were usually appreciably higher than this, figures of 210 to 230°C being not uncommon; therefore, it would seem that acid formation and attack upon the liner could take place only well below TDC.

It would be of interest to know how this data was obtained and whether the catalytic effect of fuel vanadium content upon formation of SO_3, also the effect of even small concentrations of SO_3 in raising the acid dew-point, had been taken into consideration.

Particularly with advent of highly pressure-charged two-stroke engines, the formation of water droplets, which entered the cylinder at high velocity as the scavenge ports opened, had become a major problem which was not always appreciated. It was quite common practice to open up fully the cooling water supply to the charge air cooler prior to starting up the main engine and to shut off the cooling water at "finished with engines". Under such conditions, particularly with high humidity, as the author pointed out, several tonnes of water might pass through an engine in a day. Some authorities believed that extensive liner pitting could occur opposite the scavenge ports, due to high velocity water droplets picking up SO_3 gas to form corrosive sulphuric acid which impinged on the liner.

It was essential, especially when manoeuvring and initial running, that all scavenge belt drains were fully open, to drain off condensed water. Prevention was undoubtedly better than cure and it was suggested that a simple thermostat-controlled re-circulation system should be fitted in the water supply to the charge air coolers and set to maintain the scavenge air at least 5°C above its dew-point.

Efficient water separators were now available, although initial installation cost was rather high. Perhaps it would be well worth while installing efficient water separators, as installed in gas turbine propelled warships, in a special deck house through which all air to the engine room, for ventilation and for combustion air for main engines and auxiliary diesels, would be supplied.

The section on fuel combustion was most interesting. Perhaps more details about the effects of residual fuels with good and bad inherent combustion properties would have been of value, also the adverse effects of high vanadium content fuels could well be enlarged upon.

Information about the adverse effect of water in the fuel entering the cylinder, with regard to delayed combustion, surface burning of impinged fuel on the piston crown and increased piston and upper liner temperatures, was most important. What, in Mr Golothan's opinion, was the safe permissible amount of water that was acceptable in the treated fuel. Recent cases had been reported, in high-speed, fine-line reefer and container ships, when, under light load conditions, double bottom fuel tanks had to be filled with salt water ballast as soon as they were emptied, in order to preserve ship stability. In order to achieve a rapid turn-round, when bunkering, it was difficult completely to pump out all salt water. As a result, appreciable amounts of water remained in the new bunkers. This salt water had not been removed completely by the fuel treatment system. As a result, fuel entering the engine had contained a relatively high water content.

In addition to causing corrosion of fuel pumps and injectors, this had contributed to port blockage and turbo-charger nozzle and blade fouling, adversely affecting running speed, with subsequent drastic fall-off in turbo-charger efficiency and reduced air supply to the cylinders, resulting in poor combustion.

It might well be that, in view of Mr Golothan's comments, piston crown and liner temperatures might have been excessive, leading to high ring and liner wear. His views would be welcomed.

When very low sulphur content residual fuels had been used (believed to have been mainly from Chinese crudes) in conjunction with high TBN oils, as discussed by Mr Golothan, in isolated cases, excessive liner and ring wear had been reported.

There did not appear to be any recognisable pattern to these problem engines. Several engine builders and others had carried out extensive tests with such fuels, but had been unable to repeat the results.

In addition to the suggestions made, it was possible that in, say, a 4.0% sulphur fuel, the combustion of the sulphur slowed down the combustion of the remaining carbon and hydrogen in the fuel. With fuels being virtually sulphur-free, it was possible that, especially with an increased hydrogen content, combustion was more rapid and the flame temperature higher. The larger flame produced could well impinge upon the liner walls, impairing the oil film resulting in high ring temperatures and excessive wear. Similarly, higher combustion chamber temperatures could cause distortion, again resulting in piston ring problems.

A further factor was that some of these fuels were believed to have high nitrogen contents. It was known from work in other fields that, during combustion, "nitrogen fixation" had caused very high combustion chamber temperatures. Again, Mr Golothan's comments would be appreciated.

DR T S EYRE said that all mechanical forms of wear (abrasion, scuffing and adhesion) were initiated by friction and this suggested, therefore, that the term "frictional wear" was not sufficiently precise. It was also misleading to talk about asperity welding (adhesion) of grey cast irons and it was likely that run-in wear was caused by abrasion between the ring and liner or by loose abrasive particles carried in the lubricant.

The problem in attributing increased corrosive wear to the presence of a higher silicon content was that it ignored other effects. As silicon increased there was a greater tendency for graphitization of the iron and an increased volume of graphite in the flake form would contribute to a reduction in mechanical strength, and this could cause an increase in mechanical wear. Clearly this was an area where further work was required to elucidate this reported effect.

The different forms of wear referred to by Mr Golothan, see Figure 11, were taken from liners from low speed marine engines. Scuffing (a) was caused by metallic contact between the ring and liner and, if the load should exceed the mild/severe transition load, plastic deformation occurred with the production of a plate like metallic debris. This was the main contributor to very high wear rates. Abrasion (b) was the more usual wear mechanism and this was characterised by fairly regularly spaced grooves running in the rubbing direction. These were usually more obvious near the top dead centre. Corrosive wear which was attributed to the sulphur content of the fuel revealed the structure of the iron by a direct selective etching process (c) to show the pearlite and steadite (phosphide). Different mechanisms might operate together in the same position on the liner or separately at different positions on the same liner. These photographs were taken directly from liners taken out of service. The use of plastic replicas enabled liners in service to be periodically examined. This non-destructive technique was very easy to apply and enabled a systematic study of the wear in different positions in the same liner, in different liners in the same engine and, periodically, with time through the life cycle. The replica (Figure 11d) showed the graphite structure, hard phases in the matrix and the pressence of abrasion and corrosion. This technique complimented the use of sensors referred to by Mr Golothan. Wear mechanisms must be understood if wear rates were to be controlled and reduced in any systematic way and these observations helped us to understand the basic problem and indicated areas of investigation from which solutions might arise.

Liners from different manufacturers had significant differences in chemical composition and in microstructure in an attempt to combat one or more of the wear mechanism referred to, and it was not always clear why one was superior to another. Wear was the result of the total systems environment in the cylinder including the ring and the liner, the lubricant, the products of combination and also the by-product of wear debris.

These observations had arisen out of collaborative work between Daros of Goteborg, Esso Petroleum Limited, and Brunel University.

MR A J WHARTON FIMarE commented that Mr Golothan's remarks on corrosion dealt mainly with the formation of sulphuric acid at temperatures below the corresponding dew point, did he not consider that some corrosion might also be caused at high temperatures by catalysis with vanadium and iron compounds present within the combustion gases ? Mr Wharton realised that this was more a problem for exhaust systems but wondered whether it might also contribute to increased wear adjacent to the combustion space, top piston groove and exhaust ports, all of which were in contact with high temperature gases.

Was it possible that time might be a function of these reactions ? He suggested this because of the higher wear rates in slow running engines compared with medium speed engines although the latter might have both higher peak pressures and mean piston speeds.

He was not clear on the recommendations regarding samples taken of cylinder drainings. Were they to be checked for neutrality so that the rate of lubricant injection might be adjusted if necessary ? From experience it would seem that the delay before receiving an accurate analysis from an oil company - probably via head office - made further information impracticable. Some engine manufacturers appeared to quote ambitiously low figures for cylinder oil consumption rates compared with those recommended by the author.

The copious splash of crankcase oil in the lower ends of trunk piston engine liners was fortunate when equilibrium valves as low as 8 TBN were considered.

The dangers from water in fuel were rightly stressed and it seemed that too little attention was placed on adequate settling and draining of tanks and the correct setting of centrifuge dams and throughput rates. Water washing of turbo-charger compressors and charge air coolers might add to the problems, particularly in cases where these were carried to excess. Insufficient use of cooler drains with or without moisture eliminators and under-cooling of air at reduced power all seemed to be too common.

Mr Wharton was a little depressed by the remarks on the low sulphur problem. From previous papers he had become confident that the reasons for and remedies to this had been found.

MR D ARIS said that the author had stated that effective air filtration was important, although abrasive material in the inlet air was rare in a marine environment. Number 7 in the Causes of Excessive Wear was described as extraneous abrasive material but this factor was not discussed later in the paper except as a short reference to contamination by soot. Anyone who had seen 60,000 tonnes of coal or iron ore cargo loaded into a bulker in 15 hours would appreciate that the environment was anything but clean, and although the main engines were not of course operating at this time, the diesel generators certainly were. Mr Aris recently had to fit effective air filters to the suction trunking of engine room vent fans on what were otherwise, two well equipped bulk carriers, these being extra to the specification.

CORRESPONDENCE

MR A OOLBEKKINK congratulated Mr Golothan on covering such an extensive field in such a concise and very clear way. Many users and manufacturers and people concerned with wear would profit from this paper.

In remarking on several points in the paper, Mr Oolbekkink began with the mechanism of wear, not only would all three types occur together most of the time, but they were more or less the same and certainly interacted to a great extent.

Corrosion would lead to small particles becoming isolated on the surface. They would break off and as they mostly consist of either carbon or carbides, the latter would form the hard and not necessarily foreign particles. Metal to metal contact could lead to the same breaking out of particles from the running surface. Depending on the size of the particles and the number entrapped between the two surfaces concerned, the wear could be mild or severe.

Breaking off of particles due to local welding of asperities could easily lead to scuffing; a large number of small particles led to a high wear rate but left a rather smooth surface; a lower number of smaller particles would give a "normal" wear rate.

Wear would be greatly influenced by the amount of oil being transported over the surfaces of rings and liner, and not only because it separated the two surfaces but, of equal importance, because of its cleaning effect in washing away wear debris.

Obviously a hard, tough surface with low friction to prevent cold welding and the breaking off of particles as much as possible, was a help in improving the wear rate. Hence the frequent use of a chrome layer on one of the two surfaces, preferably the larger one.

The greater wear at the top and bottom of the ring travel was not only affected by the amount of lubricant available and the change in direction of the rings, but often to the very abrupt changes in gas pressure behind the rings. Quite often, impressions of the rings could be found in the surface of a liner at the top, obviously caused by the ring(s) collapsing and being pressed on to the surface - again at a great speed: a hammering action caused by fluctuations in the gas pressure around the ring(s).

From time to time we were surprised by the very smooth wear that could occur when a piston was misaligned. The wear rate could be exceptionally high, obviously the lubricant was more or less completely squeezed out from between rings and liner surface; wear rates of 1 mm and more per 1000 hours could be found without sign of scuffing or seizure.

In the company's experience, corrosion was not only often disguised by a dark brown surface layer in cast iron. Both in cast iron and chrome plated liners big patches of such a deposit were found and in their opinion corrosion mainly took place under these patches. They seemed to collect the sulphuric acid and keep away the lubricant thus preventing neutralisation of the sulphuric acid underneath the deposit. The heaviest corrosion was often found after removing such deposits in areas covered by it.

They had advocated a higher feed rate than that often advised for years by the manufacturers. The result had nearly always been beneficial to the wear rate, as well as decreasing the corrosion, provided that the right type of lubricant and the right temperatures of cooling water were used. It was not thought that the savings in lubricant were worth the increase in wear and corrosion caused by using a low feed rate.

Especially on chrome plated liners, where corrosion showed up quite clearly, the adjustment of the feed rate to just about the right one was quite easy.

It would seem that a smooth, flat surface of the bottom side of the ring groove was, within limits, more important than the actual clearance. This would better assure a sealing against blow-by than a small clearance which could more easily lead to ring sticking. Ring breakage and wear could be very much affected by the condition of the liner and liner surface. In a series of tests in MAN KZ70 engines it was proved that by improving the wear rate, and decreasing local wear by chrome plating the liners, the ring life was more than doubled and ring groove wear went down by a minimum 50%, thereby reducing ring breakage due to uneven wear of the grooves.

Although there was no full explanation of why silicon would lower the corrosion resistance of cast iron, it had also been proved in other applications that with a lower silicon content cast iron was more corrosion resistant. A part explanation could be that silicon promoted the graphitization of cast iron, giving more and bigger graphite flakes. This promoted the forming of stronger local cells in the liner surface and could therefore result in stronger corrosive attack.

Although lower temperatures would lead to more acid condensation, it seemed quite certain that most engines showed a rather dramatic drop in wear rate while sailing at 75 - 80% of full power. This might be caused by an overruling effect of the mechanical wear but that would leave corrosive wear as rather insignificant, which it certainly was not. These results seemed to be a bit contradictory unless the drop in liner wall temperature at lower loads was less than expected.

The company's opinion on the problems sometimes caused by the use of low sulphur fuel together with a highly alkaline lubricant was that somehow more deposits were formed by the lubricant on the sides of and behind the piston rings, leading to sticking. The scraping action of the rings was then increased and much more metal-to-metal contact would occur under these circumstances, giving higher wear and even scuffing under conditions that, with a higher sulphur content of the fuel, would give quite normal wear.

Reducing the wear in cylinder liners, especially in large bore engines, was still a big challenge and still more knowledge on its causes was necessary to be able to decrease it. Ring materials, lubricant composition, liner material, surface treatments of both rings and liners were still areas which could be improved and then result in better wear rates.

MR JØRGEN CHRISTENSEN and MR P E WIENE wrote that Mr Golothan's paper had been read with great interest; they would like to add a few comments: It was mentioned in the paper that "Abrasive wear is caused by hard particles in the inlet air ..." but not that they could originate from the fuel, which in their opinion might be the most important source. Traces of such particles could be seen on the suction valve of the fuel pumps (see, for instance, paper A17 of the CIMAC-Congress 1977).

Abrasive wear of ring grooves often took place in the upper side of the groove (the main advantage of chromium plating the grooves was that the ceiling was also plated, where previously the rings rubbed against steel with inferior wear properties).

They did not remember that distortion of cylinders had been verified as a cause of wear in the company's engine types, possibly due to the symmetric design of the liners; distortion of piston rings, however, was very often harmful, the rings being mounted without the use of an adequate tool.

In the paper it was claimed that a certain amount of corrosive wear during the first period of running should be beneficial. In our opinion, however, the mechanical wear was more useful as it attacked the high points and thus produced the necessary smooth surface of rings and liner, obtaining an optimal radius of the ring surface; it was not necessary to add grinding particles by a special running-in-oil or by procuring corrosive wear; the problem was more to prevent this necessary running-in-wear from developing into scuffing, and for that reason they recommended increasing the load slowly and cooling by the ample addition of cylinder oil in this period.

Also, when after a long running-time on low load the load was decreased, the ring shape had to be changed by wear, and if during such periods the cylinder oil feed rate was increased essentially, it could be reduced during most of the running time by which a considerable saving could be obtained. This was far more economic than the way of preventing excessive wear by a "generous oil supply" during the whole running time (see also the contribution to paper B11 at CIMAC 1977, especially Figure 3).

As to scavenge air box drippings, in their opinion, what could be concluded was very questionable. It was possible to analyse the TBN and iron content of oil which was scraped downwards, but the really interesting thing was to know what happened to the oil which was scraped upwards where most of the wear occurred; and very little was known about the connection between these two quite different parties of the oil, depending as they did on the detailed and varying shape of piston rings, ring grooves etc.

They fully agreed with the author's concluding remarks concerning the difficulties involved in investigating cases of high wear and the importance of preventing them, or at least detecting them at an early stage. They much appreciated the contributions from the oil companies in clearing up some of the numerous aspects of this matter.

AUTHOR's REPLY

Mr Clark had mentioned the need for detergent/dispersant properties in the lubricant in order to keep the pistons clean and to prevent ring-sticking. This was certainly a very important property, but the means for achieving it were not necessarily the same in trunk-piston engines and in low-speed engines having separate cylinder lubrication. For the trunk-piston engines there was a wide range of dispersant additives available, both of the metallic and non-metallic type, and these additivies were very effective in maintaining soot and other contamination in suspension in the oil, and thus preventing it from settling out in the engine in the form of deposits. In the cylinder oil for a low-speed engine, these additives did not generally work so well in his company's experience, unless perhaps they were present in very high concentrations, and the most important properties seemed to be alkalinity and thermal stability. High alkalinity, in addition to preventing corrosive wear, seemed to help in keeping the pistons clean, perhaps because it neutralised acidic products which were precursors to deposits on the pistons and in the cylinders.

Likewise, the use of extreme pressure additives, which Mr Clark had mentioned later in his contribution, seemed to give far better results in the crankcase oil of a trunk-piston engine than they did in the cylinder oil for a total-loss lubrication system.

Mr Clark's comments on running-in were fully supported by the author, but it had to be accepted that for various reasons it was not always practical for the shipowner to operate the engine under the best conditions to ensure well run-in surfaces. Special running-in oils offered a means to accelerate the running-in process, and seemed to work well if used under proper supervision. The carry-over effect when changing to a normal cylinder oil had not been found to cause any problems in practice.

Wear in line with the exhaust ports was perhaps due to high temperatures burning off the oil film in that region, eventually leading to scuffing and ring breakage. The problem might also be made worse if the oil feed rate were marginal, and Mr Clark himself had stressed the importance of an adequate oil supply to ensure a good gas-tight seal in regions where some cylinder distortion might have taken place. It was interesting to note that as a means of improving the critical lubrication conditions in the exhaust port region, one major engine manufacturer had designed a cylinder liner with additional lubrication points above the exhaust ports, supplementing the normal lubricant supply higher up in the cylinder.

The comments in the paper relating to cylinder wall temperatures and dew point could apply equally to four-stroke trunk-piston engines or to two-stroke crosshead engines. The combustion pressures mentioned by Mr Clark seemed to be somewhat low for modern engines with high turbocharging, at least if maximum firing pressures were considered, and some engine manufacturers stated that the maximum cylinder pressure was in the region of 90-100 bar. Admittedly, this maximum pressure occurred for only a very brief period of time, and it was debatable whether the time at this maximum pressure was long enough to have a significant influence on sulphuric acid formation.

The data linking dew point with pressure and fuel sulphur content were based on theoretical considerations, not from actual measurements. The original calculations were derived from an earlier reference [1], and were applied under the conditions of pressure and gas composition likely to occur in a diesel engine. Certain assumptions were made, based on previous experience, concerning air/fuel ratio, water vapour content of the exhaust gases, and the concentration of fuel sulphur likely to be converted to SO_3.

The effect of SO_3 on a dew point had indirectly been considered in drawing up these curves, since the SO_3 might be considered to be dependent on the fuel sulphur content. The curves showed the dew point related to fuel sulphur for a range of pressures.

The catalytic effect of fuel vanadium was not one of the factors taken into account in establishing these curves. It was certainly another variable which should be considered, but there was insufficient experimental data to include the effect of vanadium in the calculations.

With regard to Mr Clark's comments on water in the scavenge air, and the means for preventing it, it was very likely that thermostatic control of the cooling water system, together with the use of separators, would be an effective way of overcoming the problem. The main reasons why separators are not often used at present seemed to be their initial cost and their bulk, but they might become more popular in future when their benefits were more widely appreciated.

It was difficult to say what was a "safe" level of water in the treated fuel, since so much depended on other factors such as the combustion conditions within the engine. Probably up to 1% could be considered tolerable, but more experimental evidence was needed to support this assumption. Salt water was particularly undesirable, for the reasons given by Mr Clark, and correct fuel treatment to remove as much water as possible, either fresh or salt, was clearly of the utmost importance.

Mr Clark had produced a further interesting theory to explain the occasional problems with low-sulphur fuels, but combustion flame photography studies did not support his suggestion that combustion was more rapid with low-sulphur fuels. In fact, the duration of the combustion flame with at least one fuel (from the Far East) was more prolonged than with conventional high-sulphur fuels, and it was supposed that there was therefore a longer time for heat to be released to the cylinder and piston. Some recent studies by a research project in Norway had supported this suggestion. With regard to Mr Clark's query concerning the effect of nitrogen on combustion temperatures, there seemed to be no experimental data available on this subject, with low-sulphur fuels at least, but it could be a fruitful field for further study.

Dr Eyre's remarks on the effect of silicon in the cast iron in increasing the tendency to graphitization were supported by the comments from Mr Oolbekkink in a later contribution. However, Dr Eyre had suggested that the increased volume of flake graphite reduced the mechanical strength, whereas Mr Oolbekkink believed that corrosive attack would be more severe because of the formation of stronger local cells in the liner surface.

Further details of the effect of silicon on corrosive wear were given in a reference dated 1960 (2), which supplemented reference (8) in the paper. The 1960 paper reported that, from the examination of a number of worn cast iron liners from service, with differing structures, it appeared that the wear rate could only be connected with the silicon content of the iron concerned. Samples were sealed in glass containers with 70% sulphuric acid and heated to 130°C for a period, the subsequent weight losses being measured. These showed a very definite correlation between corrosive wear and silicon content.

In order to eliminate the effect of structure, a number of cast iron samples were cast in the laboratory with varying silicon contents but constant micro-structure. Corrosion tests confirmed the correlation of corrosive weight loss with silicon content, at least up to 2% silicon (see Figure 7 in this present paper). It thus appeared that independent of the micro-structure, silicon had an important influence on the vulnerability of cast iron to corrosive wear.

In reply to Mr Wharton, it seemed unlikely that vanadium compounds would contribute directly to corrosion within the cylinder, since the melting point of these compounds, either vanadium compounds only or compounds of both vanadium and sodium, was well above 500°C, and they were not therefore corrosive below this temperature. Their effect would be harmful mainly on exhaust valves and turbocharger blades. However, as mentioned in the contribution by Mr Clark, vanadium was well known as a catalyst in the conversion of SO_2 to SO_3, so in this respect it did contribute indirectly towards higher corrosive wear within the cylinder.

Time could quite possibly be one of the functions involved in the higher wear in low-speed engines, but probably the difference in the lubrication systems of the two types of engine was one of the most important factors to consider, together with the difference in the combustion process; with a two-stroke low-speed engine where was no intermediate induction stroke which allowed some cooling down of the cylinder.

Analysis of cylinder oil drainings had so far been applied mainly to tests in experimental laboratory engines, or in closely monitored ships' trials, especially where a special trough had been fitted below the cylinders to collect the drainings. It was not practical as a routine method in normal operation, but certain test kits were available which allowed the alkalinity of the oil to be determined quite rapidly on board ship, or would at least confirm whether the drainings were still alkaline. Even this limited information could be helpful to the ship's engineer, provided it was certain that the sample collected was indeed representative of the oil draining from the cylinder.

Mr Wharton was perhaps rather too pessimistic about the low-sulphur problem. In the last year or two, genuine instances of this problem seemed to have been very rare, and the reasons for the problem were now understood a little better than they were in the past. Nevertheless, there were many questions still to be answered, and it would certainly be premature to say that the problem had been completely solved.

Mr Aris had emphasised the importance of extraneous abrasive material as a cause of wear in the marine environment. This particular cause was perhaps given insufficient attention in the paper, but in certain circumstances, such as those described by Mr Aris, it could undoubtedly be a serious problem if air filtration was not effective. Even at sea the air was not always clean, as for example when a sandstorm was blowing off the land in some tropical areas.

Mr Oolbekkink had made some interesting observations on the mechanism of wear, amplifying the comments in the paper. With regard to oil feed rates, there were clearly advantages in increasing the feed rate to reduce wear and provide a greater safety margin under unfavourable operating conditions, but there was an economic maximum limit beyond which any further improvement in wear did not compensate for the increased cost of the oil. This limit would no doubt vary considerably from one ship to another according to circumstances, but various calculations have been made by engine manufacturers to provide guidance for the shipowner in this respect.

Uneven wear of the piston ring grooves was a major cause of ring breakage, and chromium plating the side faces of the grooves had proved beneficial in many instances in reducing this wear. It seems that with inadequate wear protection, the grooves could wear in a "clover leaf" pattern, allied to similar uneven wear in the cylinder. The importance of liner wear on ring life was apparent from Mr Oolbekkink's comments.

Cooling water temperatures at reduced power should still be controlled at the same level as for higher powers, so that cylinder wall temperatures should not presumably change much with different power outputs. However, the low cylinder pressures at low power ratings would result in lower dew point temperatures, and pressures behind the rings would also be lower. In addition, there was of course less fuel burnt, and a lower throughput of fuel sulphur in the cylinder. These were probably the main reasons for a reduction in corrosive wear when a vessel was steaming at reduced speeds and loads.

Mr Oolbekkink had suggested excessive piston and groove deposits as a possible cause of the low-sulphur problem. Certainly heavier deposits had been found when some low-sulphur fuels had been burnt, but this observation could still be in line with the opinion expressed in the paper that the problem was basically caused by high cylinder temperatures, perhaps arising from unusual combustion characteristics of the fuel itself.

To MR JØRGEN CHRISTENSEN and MR P E WIENE, Mr Golothan replied : wear caused by abrasives in the fuel was rarely encountered in the author's experience, but it was interesting to learn from the two contributors with their overall view of one particular make of engine, that they considered hard particles in the fuel to be perhaps the most important cause of abrasive wear. Their experience highlighted the vital importance of efficient centrifuging or filtration to remove any particles likely to result in damage within the engine.

They had stressed the importance of mechanical wear in producing well run-in surfaces, but corrosive wear probably played some part also. Evidence for this was provided by the difficulty of running-in an engine when a highly alkaline oil was used together with a fuel of low-sulphur content, a combination which would produce little or no corrosive wear. If some corrosion was allowed to occur, it might be, of course, that the wear particles themselves then caused the mechanical wear which had the beneficial effects referred to by Messrs Christensen and Wiene.

The author agreed that the oil feed rate of a low-speed engine should not be increased above the normal rate for longer than was necessary. It did seem, however, that during the running-in period, or for a limited time during critical periods of engine operation, an increased oil feed rate helped to stabilize lubrication conditions within the cylinder and reduced abnormal wear such as scuffing. This was perhaps because the increased quantities of oil within the cylinder helped to provide better sealing between the rings and cylinder liner, as well as additional lubrication to areas where the supply of oil might be marginal.

The analysis of cylinder oil drainings was certainly more meaningful if a special collecting device could be installed beneath the liner. In laboratory experiments with a low-speed engine fitted with this device, there had been reasonable correlation between measured wear of piston rings and the iron content and TBN of the cylinder oil drainings.

In a ship, where the drainings were collected from the scavenge air box, the sample collected might, quite possibly, not be truly representative of the oil actually draining from the cylinder, although in service trials analysis of the oil collected from the scavenge air box did, in fact, provide useful information. Nevertheless, the author agreed that analysis of scavenge air box samples could not be applied on a routine basis.

In conclusion, the author would like to thank all contributors for their interesting and helpful comments.

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