CAUSES AND PREVENTION OF
ENGINE WEAR

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CAUSES AND PREVENTION OF ENGINE WEAR

By

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CAUSES AND PREVENTION OF ENGINE WEAR

I. Introduction

The subject of engine wear is a timely one in view of the fact that present-day engines are being designed to operate at higher speeds and greater specific outputs than ever before. Such conditions are bound to increase the wear to which the engine is subjected, and make it imperative for the designer to consider all phases of the wear problem before attempting to bring about its reduction.

Viewed broadly, the various factors which contribute to cylinder wear are numerous and complex. Often the various contributors to engine wear are interrelated with one another. In addition, changes in design and operating conditions to reduce one type of wear may often result in increased wear in some other form.

During the past fifteen to twenty years, a considerable amount of original research has been done on the wear problem. All phases of the question have been dealt with, some in great detail. It will be the purpose of this thesis to review some of the results of this research with particular reference to recent literature on the subject. Also, since most original research on the problem usually deals with only one or several aspects or phases of the question, it might be well to correlate and combine the results of this work in such a way as to show its relation to the entire picture.

Before proceeding with the subject at hand, it might be advisable at this point to state that this discussion will be confined to the wear problem as it applies to the power assembly only-- consisting of the cylinders, pistons, and rings. The reason for this restriction is that most engine wear is normally experienced here.

II. Pattern of Cylinder Wear

Before taking up the wear problem and all its ramifications, it first might be well to discuss the various characteristic patterns in which cylinder wear is manifested.

Figure I* shows a typical wear pattern for a worn cylinder bore. It may be seen that maximum wear occurs at the top of the stroke-- opposite the top piston ring-- and tapers gradually through a distance of two to three inches, reaching a minimum at mid-stroke; after which it remains relatively constant until the end of the piston ring travel, where it again increases slightly. Below the ring travel the wear is almost negligible.

One of the foremost authorities on the wear problem, Alex Taub,[1] states that all cylinders of the same engine do not wear uniformly; the rate of wear varies from cylinder to cylinder. This variation in wear is shown in Figure II.** In some cases, however, greater bore wear is noted in the intermediate cylinders which serves to illustrate the complexity of the problem.

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*Lamarque, P. V., "Piston Ring and Cylinder Wear in Automobile Engines", Engineering, December 22, 1944: Figure 1, p. 498

**Taub, Alex, "Cylinder Bore Wear and Corrosion", Automotive and Aviation Industries, March 1, 1944: p. 36

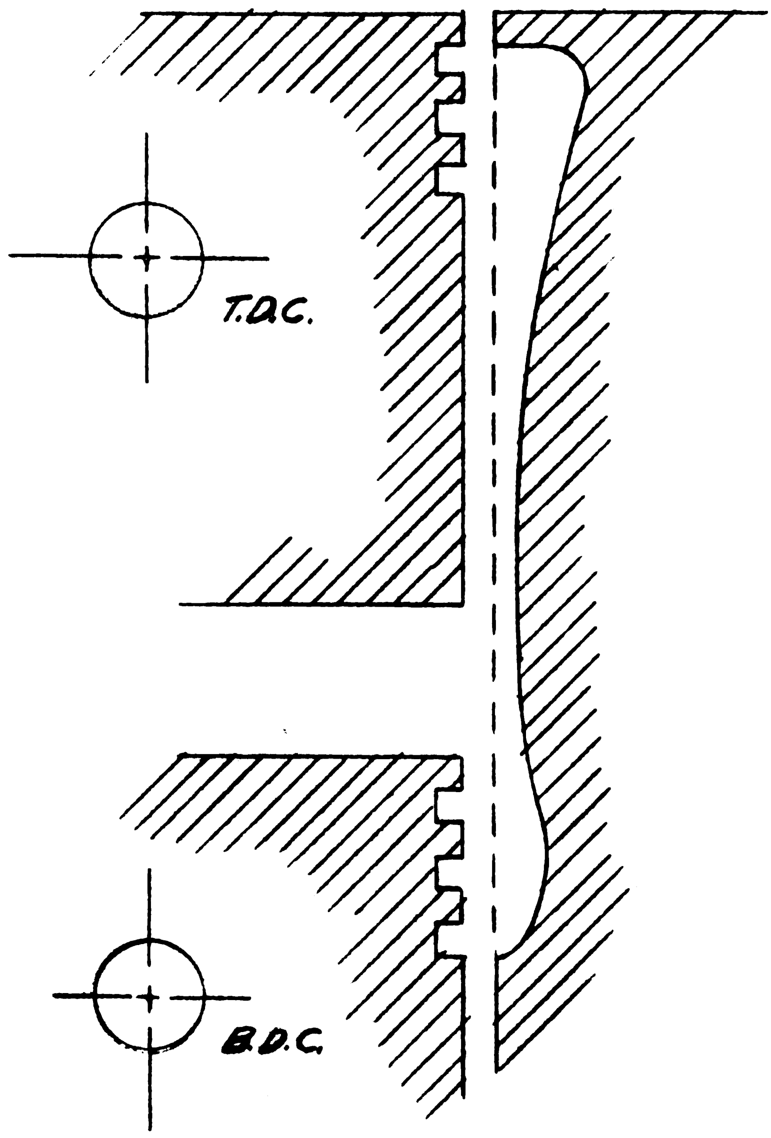

FIGURE I - CYLINDER BORE WEAR PATTERN

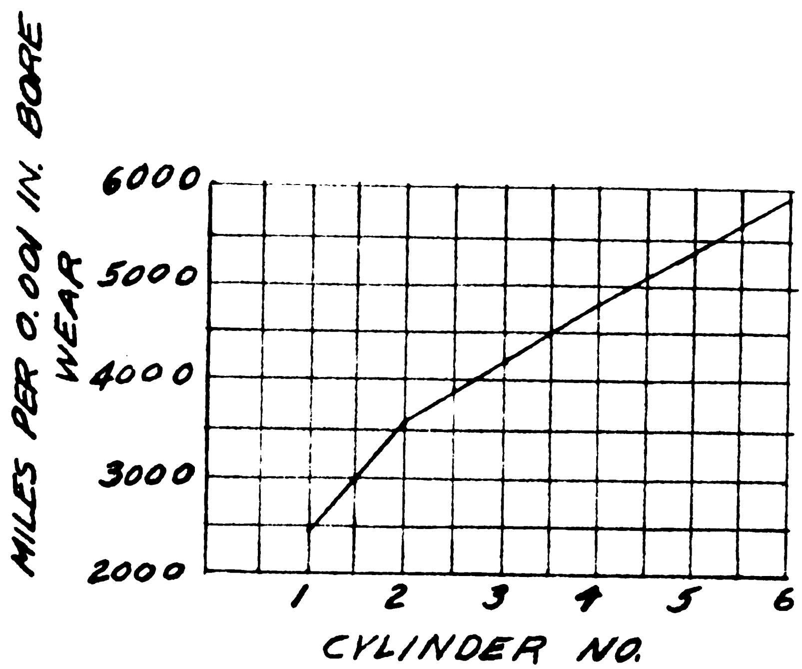

FIGURE II - VARIATION IN CYLINDER BORE WEAR

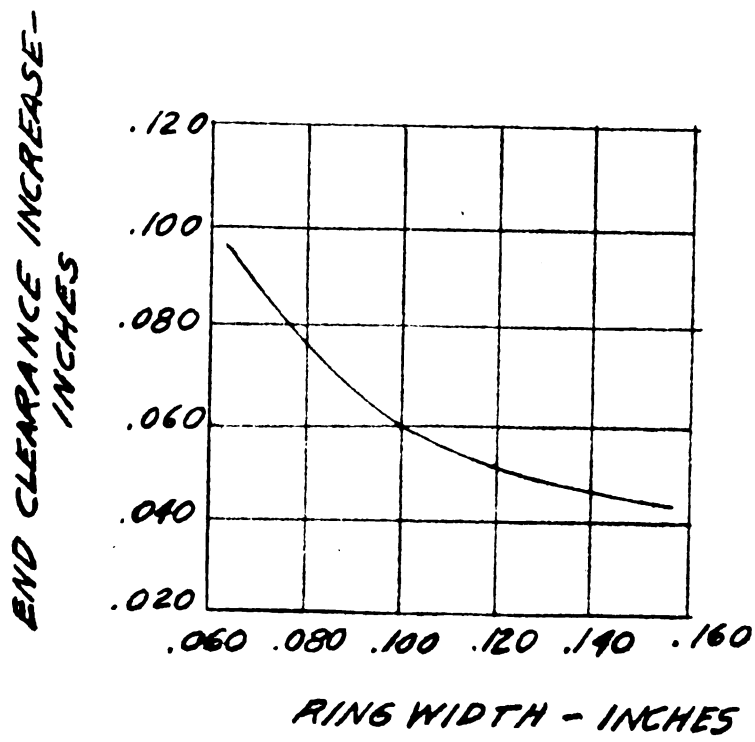

FIGURE III - EFFECT OF RING WIDTH ON ABRASIVE WEAR

Circumferential wear is not always uniform, either. Tests conducted at the National Bureau of Standards by C. S. Bruce and Jesse T. Duck[2] indicate that the point of minimum wear occurs, almost without exception, on the side of the cylinder opposite the one receiving the thrust of the piston. Maximum wear was found to usually occur on the sides of the cylinder in line with the engine, except in a few cases where the greatest wear was on the thrust face of the cylinder. Sparrow and Scherger,[3] of the Studebaker Corporation, are of the opinion that the piston rings, rather than the piston itself, are the major contributors to bore wear. The mechanics of the wear problem as related to the piston rings and cylinder bore will be discussed at length later on and will not be taken up in detail at this point.

III. Classes of Cylinder Wear

Among the authorities on the subject of cylinder wear, an almost complete agreement exists on the theory that three distinct classes of wear do occur. These types may be designated as follows:

1. Abrasion
2. Erosion or scuffing
3. Corrosion

As far as the relative importance of the classes is concerned, considerable controversy still exists. Max Roensch,[4] now of the Ethyl Corporation, is of the opinion that the factors as named in the order above are in their approximate positions of importance. It should be borne in mind, however, that variations in operating conditions, as well as changes in the design of the engine, air cleaner, piston and ring equipment, and type of lubricating oil used, may markedly affect the order of importance of these factors.

Having now established the prime factors to which engine wear may be attributed, it now becomes necessary to discuss in detail the mechanics involved in each of the three classifications and to show how the various causes of wear are related to these main classifications.

IV. Abrasion

Definition of Abrasion and Sources of Abrasive Wear

Abrasion may be defined as wear which is brought about by the scratching action of foreign particles in the oil film between the two rubbing surfaces.

Abrasion is probably the most common form of wear and can take place only under conditions of boundary lubrication. Usually this type of wear takes place in two distinct stages:

1. A wearing down or breaking off of the surface peaks to produce sufficient area to carry the load.
2. The scratching of at least one of the surfaces by hard particles.

The first stage may be taken as the cause of high initial wear, as when two new surfaces are run together. The second stage of wear usually results from abrasives embedded in the metal.

The mechanism of abrasive wear alters in degree with the hardness of the surfaces. In soft material, or hard materials with soft spots, the abrasive is embedded almost completely in the surfaces and a lapping action takes place. With hard materials the abrasive particles are embedded only sufficiently to hold them in position and the rubbing surfaces acquire a scored appearance.

Abrasives commonly encountered are metal particles, metal oxides, dust, carbon, and engine oil sludge.

The most common sources of entry of abrasive material, according to Roensch, are:

(1) Core sand, cast iron filings, chips and dirt which may be left in the engine and not taken out by the cleaning and washing process.

(2) Valve grinding compound or cylinder honing residue which may be left in the engine due to improper cleaning.

(3) Road dust which may enter the crankcase with the ventilating air.

(4) Road dust which enters the engine through the intake system.

While all the above sources of abrasive wear are important, the last mentioned deserves the greatest amount of attention, as it is the greatest single source of cylinder and ring wear.

In abrasion, as well as in all other forms of engine wear, cylinder and ring wear are interrelated; thus any attempt to reduce cylinder wear will result in a reduction of ring wear at the same time. Especially high rates of wear have been noted on the top piston ring under abrasive conditions. This is undoubtedly due to the fact that the top ring serves to pulverize the foreign material until the maximum particle thickness is less than the oil film; thus the abrasive action on the rings below is diminished.

Tests conducted by Sparrow and Scherger indicate that abrasive wear has the same general characteristics as encountered in normal operation (i.e., the greatest rate of wear is at the top of the bore) with the exception that the entire wear pattern has been multiplied or exaggerated under such conditions.

The question as to the quantity of dust entering an engine depends on the efficiency of the filtration system. Roensch states that the use of oil bath air cleaners may remove 95 per cent of the air-borne dust, but even the 5 per cent which remains may still cause appreciable wear. He also points out that with cars operated on paved roads without effective air cleaners the cylinder bore wear due to abrasion is increased (in summer driving) by 25 per cent. A. M. Brenneke,[5] of the Perfect Circle Corporation, states that abnormal wear rates may be expected if the amount of dirt admitted is in excess of 0.00025 grams per cubic foot of air. This applies to air after it leaves the filter and as it enters the engine, and refers to abrasive particles of 5 microns or less. Particles larger than this would have an even greater damaging effect.

Prevention of Abrasion. In discussing the ways and means of preventing abrasive wear it would be well to consider the following factors, since they have a direct bearing on the extent to which abrasion can occur:

1. The efficiency of the air cleaner in removing air-borne dust.
2. Piston ring materials and design.
3. Cylinder-block hardness and alloy content.
4. Amount of abrasive material in the engine oil.

The efficiency of the carburetor air-cleaner is of paramount importance, since if the dust-removal capacity of the air cleaner is high, a major source of abrasive wear has been eliminated. Considerable research is being currently conducted on the effect of air filters on engine wear by the Fram Corporation of Providence, Rhode Island. A progress report on these activities was submitted by W. S. James and B. G. Brown, both of the Fram Corporation, before the S.A.E. Summer Meeting in June, 1950. In this report dust tunnel tests are described in which the efficiency of oil-bath and oil-wetted air cleaners are determined by measurement of the engine parts before and after the test, the difference in these values being an index of the amount of wear which occurred during

operation. Those items which were measured included increase in piston ring gaps, change in radial thickness of the rings, changes in ring groove clearance, changes in cylinder bore diameter and changes in bearing clearances, thickness, and weight. A summary of their findings includes the following:

1) Some oil-wetted types of cleaners are of no value in removing air-borne dust.
2) Oil-bath air cleaners will, in some cases, reduce rings and bore wear to one-tenth of that occurring in oil-wetted types.
3) An increase in air-cleaner efficiency of from 98 to 99 per cent may reduce engine wear by one-half.

The effect of piston-ring design and material on abrasion is worthy of attention. It has been found that an increase in piston-ring width results in reduced abrasive ring wear. This is shown in Figure III,* the ring wear being measured by the increase in end clearance. From this relationship it would seem that if abrasive wear resistance were the only consideration, the widest possible rings would be the best. Unfortunately, however, there are other considerations to be taken into account which preclude this possibility.

As regards piston-ring materials, tests by James

*Brenneke, A. M., "How Diesels Wear and What to Do About It," S.A.E. Journal, April, 1950: Figure 4, p.36

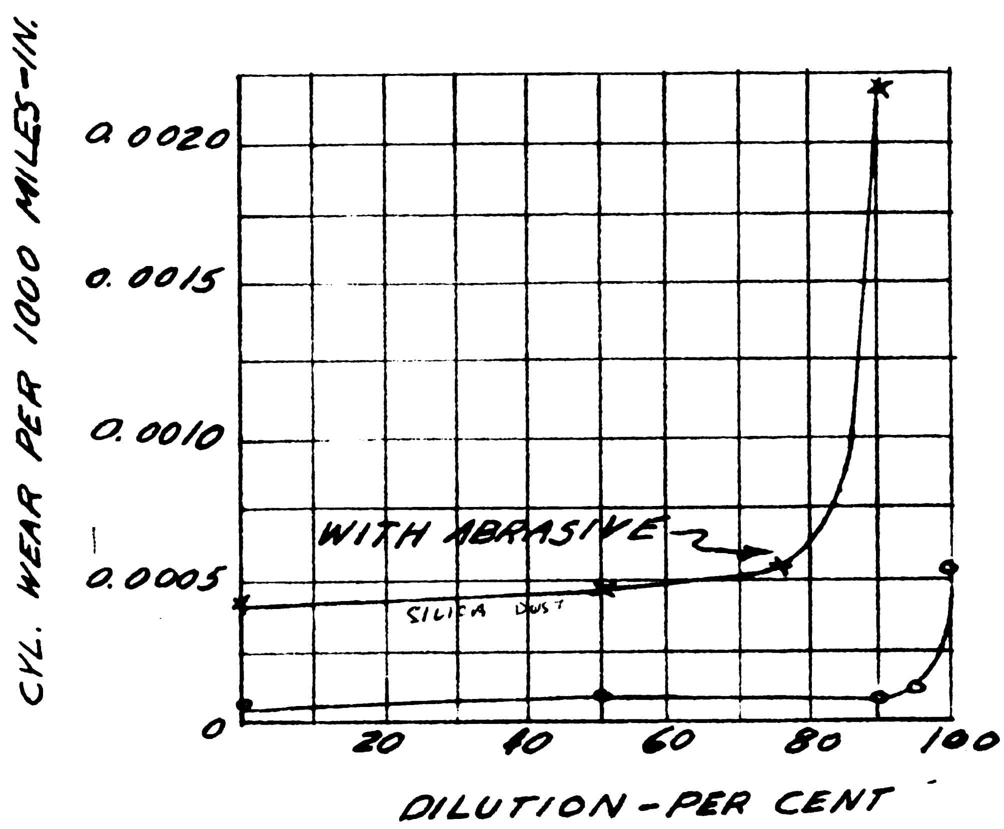

FIGURE IV - EFFECT OF CRANKCASE OIL DILUTION ON WEAR and Brown[6] show that the use of chrome-plated top rings will reduce the bore wear from abrasion by 75 per cent over that for grey iron rings of the same section thickness and unit pressure. In addition, an increase in thickness of the chrome plate on the top ring also contributes to increased ring life.

The use of chrome-plated cylinder liners in heavy-duty engines is sometimes employed as a means of minimizing abrasion. The subject of liners and also the effect of cylinder block hardness and metal structure on wear will be discussed at length later on, and will not be taken up at this time.

The effect of abrasive materials in the engine oil has been studied by C. G. Williams[7] in his extensive research on cylinder wear. Tests were conducted by him in which silica dust of 200-inch mesh size was introduced at the carburetor air horn at a rate of 8.5 grams per 100 hours. This rate is considerably greater than would actually occur, even under dusty road operation, so that the extremely large increase in wear indicated would not likely be realized in actual service. Figure IV* shows the results of this test-- cylinder wear being plotted as a function of oil dilution for both abrasive and non-abrasive conditions. Dilution of the oil in these

*Williams, C. G., "Cylinder Wear and What to Do About It", <u>Automobile Engineer</u>, July, 1933: p. 260

tests was accomplished by adding various percentages of kerosene to the engine lubricating oil. The interesting feature to note is that, even in the presence of excessive amounts of abrasive, rapid wear does not occur until dilution of the oil reached 80 per cent. Above this figure, however, a very rapid increase in wear occurs which would lead to the conclusion that abrasives in the oil are harmful at high amounts of oil dilution.

V. Erosion

<u>Definition of Erosion and Sources of Erosive Wear</u>. Assuming that clean air is supplied to the engine so that abrasive effects may be disregarded, we may then focus our attention on a second source of engine wear; namely, erosion or scuffing.

Erosion may be defined as wear produced by metal-to-metal contact between the piston or rings and the cylinder bore. The mechanics of erosion is discussed by P. V. Lamarque[8], who postulates that under such conditions of wear a frictional form of failure is induced due to the existence of boundary lubrication conditions between the rubbing surfaces. Local welding of the rubbing surfaces takes place, accompanied by a sharp rise in temperature of the welded areas, even when the surrounding metal mass is cold. This temperature rise takes place as a result of the liberation of energy following the shearing of the metallic bridges. It is worthy of note that only chemically clean surfaces are subject to erosion; thus the presence of surface films on the contacting surfaces will act as inhibitors toward this form of wear.

Lamarque also states that the scuffing tendencies of metals decrease with increases in surface temperature. Thus, in the case of cast iron, increasing the temperature from 300 to 450 degrees F. will reduce the scuffing resistance by one-half.

Since erosive wear is brought about by metal-to-metal contact of rubbing surfaces, the sources of erosion would be those factors which contribute to such a condition. These may be listed as follows:

1) Absence of lubricating oil films between the rubbing surfaces, due either to delay in establishing these films or dilution of the film with fuel as in cold starting or warm-up conditions.
2) Improper mixture ratios under both starting and fully warmed-up conditions.
3) Mechanical and thermal distortion of the cylinder walls.
4) Piston-ring design, material, and surface finish.
5) Piston design, material, and surface finish.
6) Undesirable metal structure of the cylinder bore iron.

All of the above mentioned factors, except the last one, contribute either directly or indirectly to the establishment or destruction of the lubricating oil film between the sliding surfaces of the piston rings, or piston, and the cylinder wall.

It might be well at this point to discuss each of these factors individually and in some detail, as the minimization of erosive wear depends primarily on the extent to which these conditions exist in engine design and operation.

Lubrication of the Rubbing Surfaces and Erosive Wear. The maintenance of an adequate lubricating oil film is one of the prime requisites in the minimization of scuffing. This depends chiefly on the following factors:

1) The quantity of the oil supplied
2) The viscosity of the oil
3) The time required, as in cold starting, before adequate lubrication is established
4) The degree to which the lubricating oil has been diluted by the fuel

Effect of Oil Quantity. The question as to the effect of the quantity of oil supplied on bore wear has been dealt with by C. G. Williams. As a result of tests conducted by him, he concludes that, with cylinder temperatures ranging from 250 to 500 degrees F. and under steady running conditions, a deficiency in the amount of lubricating oil supplied to the cylinder bores is unlikely to be a factor of practical importance in regard to cylinder wear. At temperatures below 194 degrees F., it is found that wear is influenced to a marked extent by the quantity of lubricating oil supplied to the cylinder walls. A discussion of the temperature effects on wear will be presented in the section on corrosion, and will not be taken up here.

The fact that the quantity of oil supplied has little effect on bore wear at normal operating temperatures does not mean that lubrication problems are non-existent under these conditions, however. W. A. Robotham[9] points out that the wide speed range of modern engines imposes severe problems in providing adequate lubrication of the cylinder walls. This is evident from referring to Figure V*, which shows the relationship between engine speed and oil consumption. This curve was obtained from dynamometer tests of a 1942 Chevrolet engine with 216.5 cubic inch displacement, and operating at road load conditions. The engine lubrication system was of the combined splash and pressure type; ring equipment consisted of two 1/8 inch S.A.E. taper face compression rings and one 3/16 inch drilled channel oil control ring. Pistons were of the cast-iron slipper type.

Although the shape of this curve may vary somewhat among engines other than that tested, depending on the lubrication system and ring equipment used,

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*<u>Piston Ring Manual</u>, Muskegon Piston Ring Company, p. 50

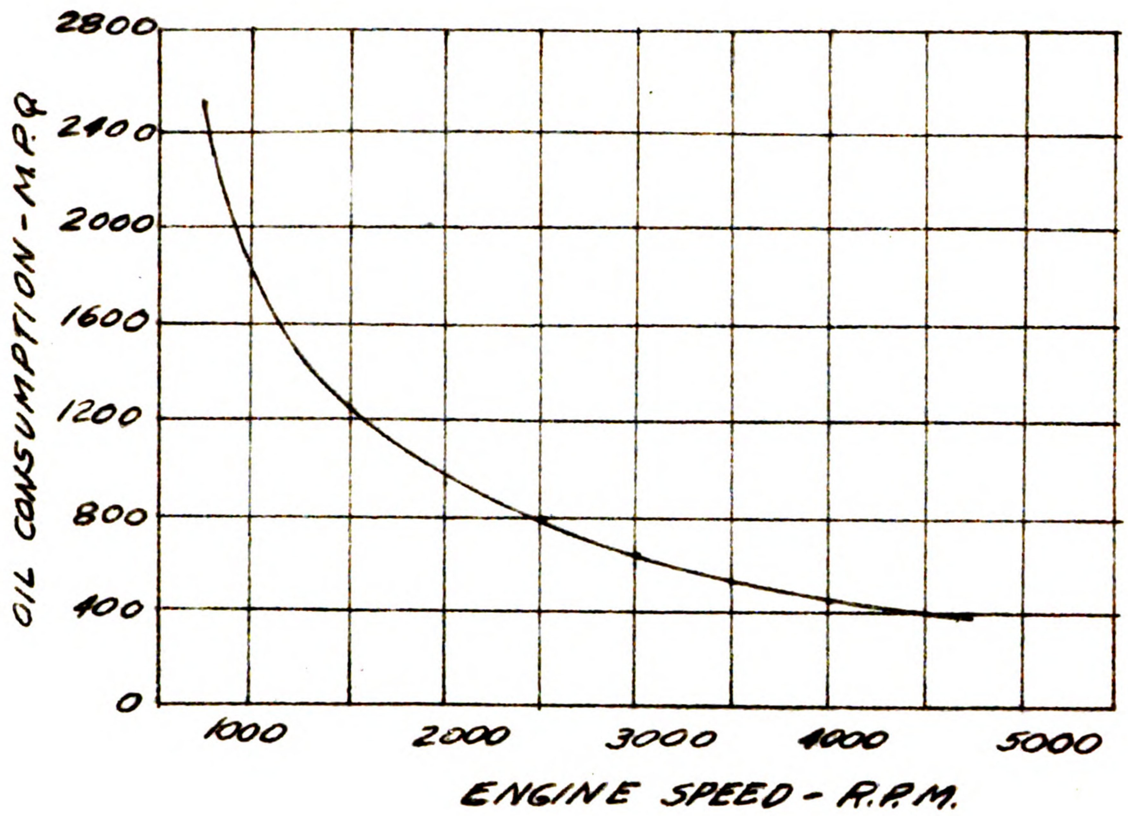

FIGURE II - EFFECT OF ENGINE SPEED ON OIL CONSUMPTION it is evident that if the speed range is increased the amount of oil passing the rings at maximum speed will be prohibitive unless the oil control maintained by the rings is increased correspondingly. If this is done, the oil consumption under low speed operation may become microscopic, resulting in boundary lubrication conditions and accelerated bore wear.

Effect of Oil Viscosity. The effect of oil viscosity on erosion is discussed by Robotham, in which he states that low-viscosity oil has been over-emphasized as a wear deterrent. Low-viscosity oils, he adds, have a lower film strength which may contribute to increased wear. He states that records taken from cars in customers' hands fail to show any definite wear reduction when the oil is changed from S.A.E. 30 to S.A.E. 20. In cases where thin oils are used, the degree of ring control must be increased proportionately to avoid excessive oil consumption at maximum speed, which might well counteract the advantages of improved lubrication when starting. Robotham also states that running-in experiments indicate that thin oils are not as good as heavier ones under boundary lubrication conditions.

Effect of Delay in Lubrication. The time required to establish an oil film on the cylinder walls is of paramount importance. Assuming that the engine is started from a cold condition, the lubricating oil may be too viscous to be thrown freely onto the cylinder walls during the first few minutes of operation. A certain amount of time must elapse before the oil reaches the proper viscosity to insure adequate lubrication of the cylinder walls. Obviously the time required for the oil to attain this condition depends on the initial viscosity of the oil, the lower viscosity oils showing to advantage in this respect. Often this time interval is not reckoned with in considering the lubrication requirements of the cylinder assembly. The actual time for establishing an oil film on the cylinder walls will depend to a large degree on the efficiency of the oil control rings.

P. V. Lamarque discusses results obtained in motoring tests on a 6-cylinder, 1½-litre engine which indicates to some degree the time element involved. The engine- the bore, piston and piston rings of which had been thoroughly cleaned and dried before the test- was motored at 1000 r.p.m. with the cylinder head removed and the time observed for an oil film to form on one of the cylinders. The results are shown in Figure VI* for three oils of S. A.E. grades 60, 50, and 10. In connection with these

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*Lamarque, P. V., "Piston Ring and Cylinder Wear in Automobile Engines," Engineering, December, 22, 1944: p. 499

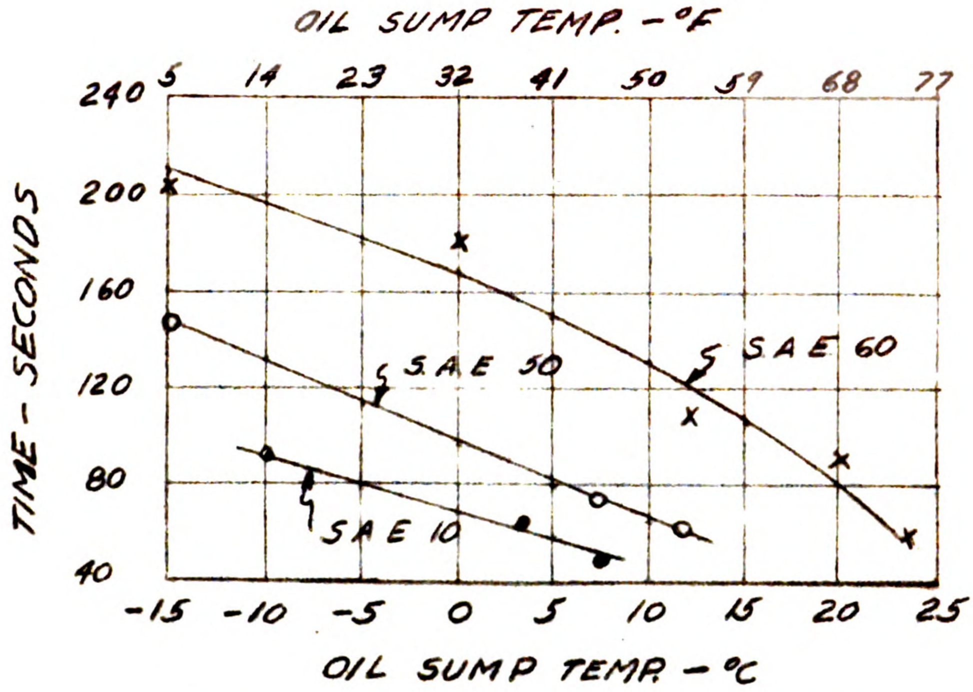

FIGURE VI - EFFECT OF OIL VISCOSITY AND TEMPERATURE ON TIME REQUIRED FOR LUBRICATION TO BE ESTABLISHED

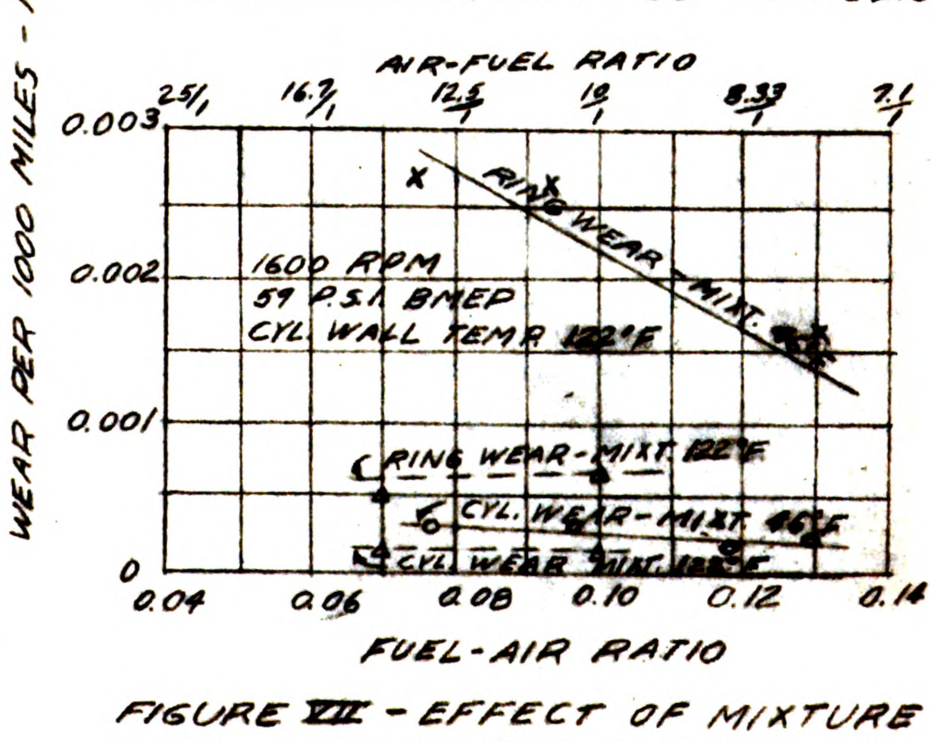

FIGURE VII - EFFECT OF MIXTURE RATIO ON CYLINDER AND RING WEAR tests, Lamarque states that in the case of the higher viscosity oils a large proportion of the time required to establish an oil film on the cylinder walls is due to delay in oil discharge from the big end of the connecting rod. Thus in the case of the S.A.E. 60 oil, for instance, of the 200 seconds required to form an oil film at 14° F., 120 seconds elapsed before any oil was thrown from the big end. Additional tests were also conducted in which the speed was reduced to 500 r.p.m., where it was found that the time required to establish an oil film was twice that required at 1,000 r.p.m. The delay in this case was attributed not to the time required for oil discharge at the big end bearing, but rather the increased time required to spread the oil on the cylinder walls.

Considerable variation in the time required for oil films to form on different cylinders of the same engine also occurs. Tests conducted on a 6-cylinder engine, motored at 700 r.p.m. with the head removed and bores wiped dry as before, showed that with an S.A.E. 50 oil the time required for excess oil to appear at the piston tops varies from 3 minutes to over 30 minutes. Such a condition might help to explain the reason for non-uniform wear rates in different cylinders of the same engine.

Effect of Oil Dilution. The question as to what effect dilution of the oil has on scuffing has been the subject of some investigation. C.G. Williams undertook some original research on the problem in which he conducted tests on a single-cylinder engine operating at a speed of 1,600 r.p.m. and a brake mean effective pressure of 59 lbs. per square inch. The oil in the crankcase was diluted with various percentages of kerosene, which resembles the lower end of the gasoline volatility range most responsible for crankcase dilution. The results are shown in Figure IV. This curve indicates that up to 90 per cent dilution of the oil, little increase in wear occurs provided normal operating temperatures are maintained. Tests were also run on kerosene alone, and even then excessive wear was not observed; although the viscosity of kerosene is 1/26th that of lubricating oil.

Air Fuel Mixtures -- Ratios and Cylinder Wear. Alex Taub[10] states that under cold starting conditions a 1/1 air fuel ratio is required to produce an inflammable mixture. Obviously under these conditions, when cylinder wall lubrication is just becoming established, scuffing may easily occur due to the washing of the lubricant off the cylinder walls when excessive use of the choke is employed.

Under warming-up conditions Taub indicates an 8/1 or 9/1 mixture ratio is needed, while for fully warmed-up, part-throttle operation any ratio up to 17.5 to 1 is desirable. During warm-up it has been found that both cylinder and ring wear decrease as the air-fuel ratio is decreased from 13/1 to 8/1. Figure VII* shows the results of tests conducted on the effect of mixture ratios on cylinder wear. The tests were carried out on a single-cylinder engine operating at 1,600 r.p.m. and a b.m.e.p. of 59 lbs. per square inch. Examination of Figure VII shows that as the mixture is progressively enrichened, the wear on the top piston ring is reduced for low-mixture temperatures. When the mixture temperature is increased to 122° F., enrichening of the mixture ratio has no effect on either ring or cylinder wear over a range of air-fuel ratios from 10/1 to 14/1.

Under high temperature operation increases in air-fuel ratio appear to produce the reverse effect. Taub cites the case of an engine under test in which the air-fuel ratio was increased from 12/1 to 14/1, which resulted in a three to seven fold reduction in cylinder bore wear. The fact that the engine was definitely under-oiled might account for this exceed-

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*Williams, C. G., "Cylinder Wear in Gasoline Engines," S.A.E. Journal (Transactions), May, 1936: p. 193

ingly large reduction; nevertheless, lean mixtures do appear to have a pronounced effect in reducing bore wear at high temperatures. Normally, it might be thought that lean mixtures would promote oxidizing conditions within the cylinder which would affect the bores adversely; thus it would seem that some other reason must be given to account for this behavior. Two theories have been advanced by Taub which might explain this phenomenon:

1) Increases in the air-fuel ratio at high temperatures will minimize dilution.
2) Leaner mixtures at high temperatures result in lower explosion pressures which tend to reduce the gas pressure behind the rings, and consequently the pressure exerted by the rings on the cylinder wall.

Of the two theories, the latter would seem to be the more plausible; since dilution takes place primarily under cold starting conditions.

In the case of warm-up operation a decrease in the air-fuel ratio is believed to bring about a reduction in the formation of corrosive agents, particularly CO_2, thereby reducing bore wear. A discussion of corrosion and its effects on wear will be withheld until later.

Since bore wear has been shown to be affected by mixture ratio, it might well be that this is one of the causes for non-uniform wear between different cylinders of the same engine; inasmuch as the various cylinders have different mixture ratios, depending on their particular location in the distribution system.

Effect of Cylinder Block Distortion on Bore Wear. Cylinder block distortion may be attributed to two factors; namely,

1) Thermal distortion

2) Mechanical distortion

Both of these factors are primarily due to the present practice of combining the cylinders in a monobloc casting. Distortion of the cylinder barrel, produced from either of these two causes, may give rise to high pressure areas which tend to break down the oil film between the piston rings and cylinder wall, resulting in scuffing of these rubbing surfaces.

Lamarque states that thermal distortion, more than any other factor, is responsible for abnormalities in the manner in which a cylinder wears. Improper cooling of the cylinder walls is one of the primary sources of thermal distortion. Care must be taken to arrange for proper distribution of the cooling water around each cylinder. The use of a water distributing tube and full-length water jackets will go a long way toward preventing bore distortion from uneven cooling and elimination of local hot spots.

The region near the top of the cylinder bore is probably the most critical, and it has been found that hot spots in this zone can rapidly reach a temperature at which breakdown of lubrication may occur. Recent research indicates that it is not unusual for the temperature of a hot spot in a cylinder barrel to increase from 330 to 500 degrees F. in 90 seconds, after increasing the engine speed from 2,000 r.p.m. to 3,500 r.p.m.- the temperature of the adjacent areas of the barrel remaining substantially constant. This non-uniform temperature condition would, of course, readily promote thermal distortion of the cylinder barrel.

Probably the chief source of mechanical distortion of the cylinder barrel is at the joint between the head and block, although thermal distortion plays a part here, too. Mechanical distortion at this point is due to the bolting of the head to the block, especially where inadequate support has been provided for the cylinder stud anchorages. Placement of these anchorages on the jacket wall, rather than the cylinder wall, so that the pull of the stud produces pure tensile stress on the material of the block may help to prevent this difficulty. Increasing the thickness of the cylinder wall in the section nearest the top may also reduce distortion.

Piston Ring Design and Cylinder Wear. Max Roensch states that proper design of the piston rings is of outstanding importance in the prevention of cylinder wear by erosion. An enormous amount of research has been and is being done by piston-ring manufacturere in an attempt to bring about further improvements in the design of piston rings which will contribute to longer engine life.

In discussing piston-ring design and its effect on cylinder wear it might be well to consider the following factors:

1. Ring sticking and blow-by
2. Radial pressure
3. Ring width
4. Oil control
5. Ring materials and surface finishes

Ring Sticking. While ring sticking is not actually tied up with piston-ring design, it is a factor which contributes to excessive scuffing of the rings and bore. Ring sticking is caused by the accumulation of sufficient cementitious material in the ring clearances to prevent movement of the ring in its groove. In the intermediate stages, the ring action becomes sluggish and results in increased oil consumption. Restriction in the free movement of the ring impairs its gas sealing properties and gives rise to an abnormal amount of blow-by passing from the engine breather.

The chief source of ring sticking is the oxidation and subsequent deposition of unstable products of the lubricating oil in the ring clearances, scraper ring oil holes, and rubbing surfaces of the piston. Two forms of ring sticking occur:

1) Low temperature ring sticking

2) High temperature ring sticking

Low temperature ring sticking, as its name implies, occurs in cold weather operation, where idling time constitutes a high proportion of total operating time. Under such conditions carbonaceous material derived from the products of combustion, together with condensed water formed during the burning of the fuel, acts to produce emulsification of the lubricating oil. The so-called sludge is then filtered out into the ring clearances and scraper ring oil holes where subsequent oxidation and decomposition occurs. The only solution of the low temperature ring sticking problem is to prevent the formation and accumulation of moisture by rapid warm-up of the engine and by providing adequate crankcase ventilation under light-load conditions.

High temperature ring sticking is caused chiefly by oxidation of the oil, mainly in the crankcase, followed by decomposition of the oxidation products at the high temperature points in the engine.

Ring sticking in compression-ignition engines is also believed to be caused to some degree by the fuel used. Aldehydes and unsaturated acids produced by hydroxylation during combustion may resinify easily; when they reach the ring grooves, they may result in ring sticking. Ring sticking in diesel engines is a much more common complaint that in gasoline engines.

Blow-by. Blow-by, or the leakage of combustion gases past the piston at high engine speeds, has become an increasingly important problem. Under conditions in which blow-by occurs, the piston rings reach such a stage in the engine speed range where their operation becomes unstable due to flutter or chatter. At this point a rapid increase in blow-by occurs (Figure VIII*) which results in rapid wear of the rings and bore and, in extreme cases, breakage of the rings. The point at which flutter of the rings occurs depends upon the ring tension, the radial pressure pattern, and the fit of the ring in the bore. Thus it will be seen that control of blow-by depends to a large degree on judicious ring design.

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*Taub, Alex, "Cylinder Bore Wear," Automobile Engineer, March, 1939: p. 85

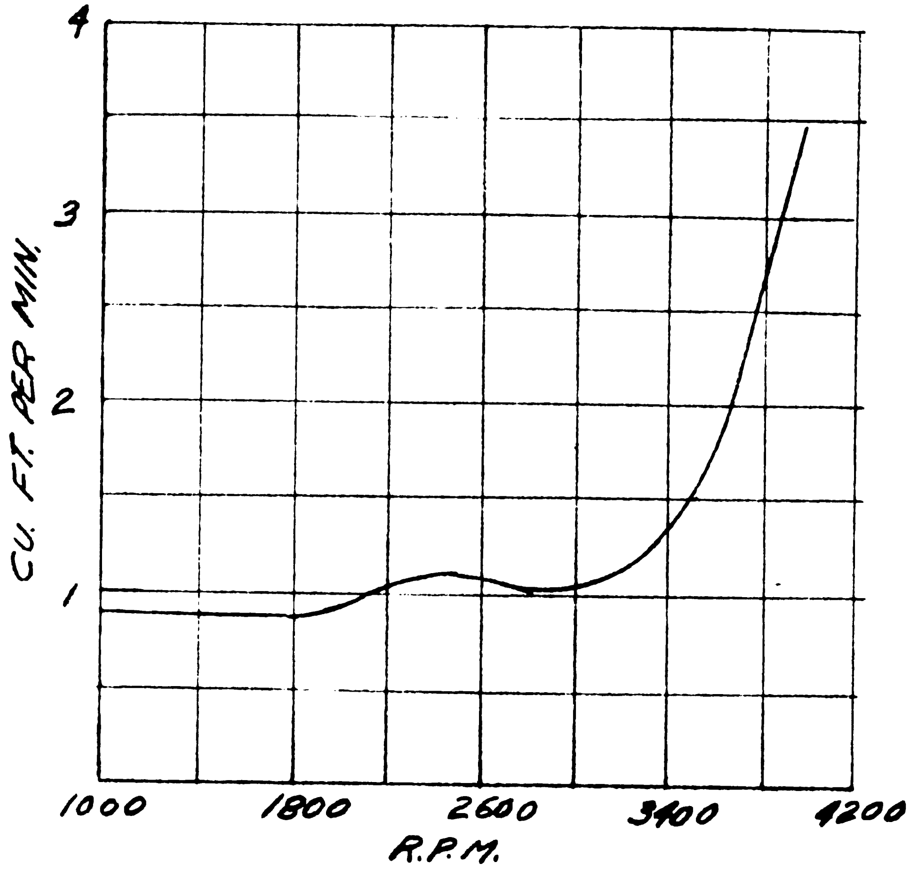

FIGURE VIII - CURVE SHOWING INCREASE IN BLOW-BY WITH ENGINE SPEED

One of the most common sources of blow-by is cylinder distortion, which was discussed in the preceeding section. In bores which have become distorted the piston ring is unable to conform to the contour of the cylinder barrel. At these points of nonconformity, hot blow-by gases pass the rings, which increases the temperature. A heavy oil film collects at this distorted area, as the rings cannot make contact with the cylinder walls with sufficient pressure to reduce the oil film thickness. This excess oil, in combination with the existing high temperatures, produces a layer of hard carbon on the cylinder walls. The formation of this layer of carbon prevents adequate lubrication of the cylinder wall and prohibits the proper sealing action of the rings. As a result, scuffing of the piston ring and cylinder walls occurs accompanied by further blow-by and excessive oil consumption.

Obviously, in new engines, or in engines which have new cylinders, blow-by may be somewhat of a problem during the running-in period. That this is true has become an established fact, and it has been observed that the main destructive agency during the running-in period has been the presence of blow-by with its accompanying evils. In new cylinders the piston rings must accommodate themselves to changes in the shape of the bores due to the release of casting and machining stresses. Such conditions promote bore distortion with resulting blow-by and ring scuffing. Taub advocates the use of pinned rings as a means of reducing scuffing caused by blow-by. Such rings would reduce the time of the running-in period and would promote better and faster bedding-in, since the rings would then be restricted as to rotational motion and would therefore conform to the contour of the bore more readily.

The question as to how much blow-by is permissible is answered by Taub with the statement that if blow-by is less than 1 cu. ft. per minute, no scuffing will occur. If the blow-by is above 6 cu. ft. per minute at 4,000 r.p.m. damage from scuffing will result in two hours' running time. Excessive amounts of blow-by also hasten the formation of sludge in oilways and scraper ring grooves, which may often lead to ring sticking and even piston seizure; however, a slight amount of blow-by in a new engine is to be preferred over one in which piston-ring wall pressures are so high that no blow-by exists.

Radial Pressure and Cylinder Wear. The present trend of modern engines toward high output and high speeds have dictated changes in the amount of radial pressure to be exerted by the rings, as well as the manner in which this pressure is to be applied. From 1920 to 1927 the common practice was to design rings for a uniform radial pressure with a diametral ring tension of from 7 to 9 pounds. From 1927 to 1932 the ring tension was increased to values ranging from 9 to 11 pounds, and from 1932 to 1937 the tension was increased to 16 to 18 pounds. At this point it was found that increased temperatures, pressures, and speeds made the control of blow-by a dominant factor, and that further advances in piston-ring design must be brought about by control of the pressure pattern, as well as increased radial pressure.

In Figure VIII it was seen that a break occurred in the blow-by curve at 3,400 r.p.m. Above this speed blow-by becomes excessive, and at 3,900 r.p.m. the blow-by is 4½ cu. ft. per minute. By proper design of the radial pressure pattern, the break in the blow-by curve may be shifted to occur at higher engine speeds.

The requirements of a proper pressure pattern for a compression ring have been set forth by R.R. Teetor and H. Bramberry in a booklet published by the Perfect Circle Piston Ring Company:

"Free piston ring shape is most important in obtaining good performance and long life. The most important portion of the rings to form is the 180-degree arc opposite the back half; that portion having the joint. The ring must be shaped so as to exert maximum pressure on the cylinder wall at the points and yet have such a shape on either side of the joint as to exert sufficient pressure immediately after installation to prevent blow-by. To accomplish this result has required considerable study of the proportions of radial wall thickness and free joint opening to the diameter. When these proportions are correct, the ring will conform at once to the curve of the cylinder wall with sufficient wall pressure at all points."

Teetor has also stated that the useful life of a ring having such a pressure pattern is governed by the point pressure; when the point pressure reaches zero, the ring is worn out. An ideal pressure pattern, advocated by Taub for rings of this type, is shown in Figure IX* The high point pressure typical of such a pattern is evident in this diagram.

Paul S. Lane, in a private communication, also supports the theory of high point pressure rings. He states that inasmuch as the points or ends of the ring are the weakest sections, sufficient rigidity must be provided to prevent point flutter. Also high point pressures should be provided to prevent wear and fatigue from making the points "negative" as to circularity. If the points are provided with sufficient "plus" circularity when new, the wear occurring in service should cause the shoulders

* Taub, Alex, "Cylinder Bore Wear", <u>Automobile Engineer</u>, March, 1939: p. 86

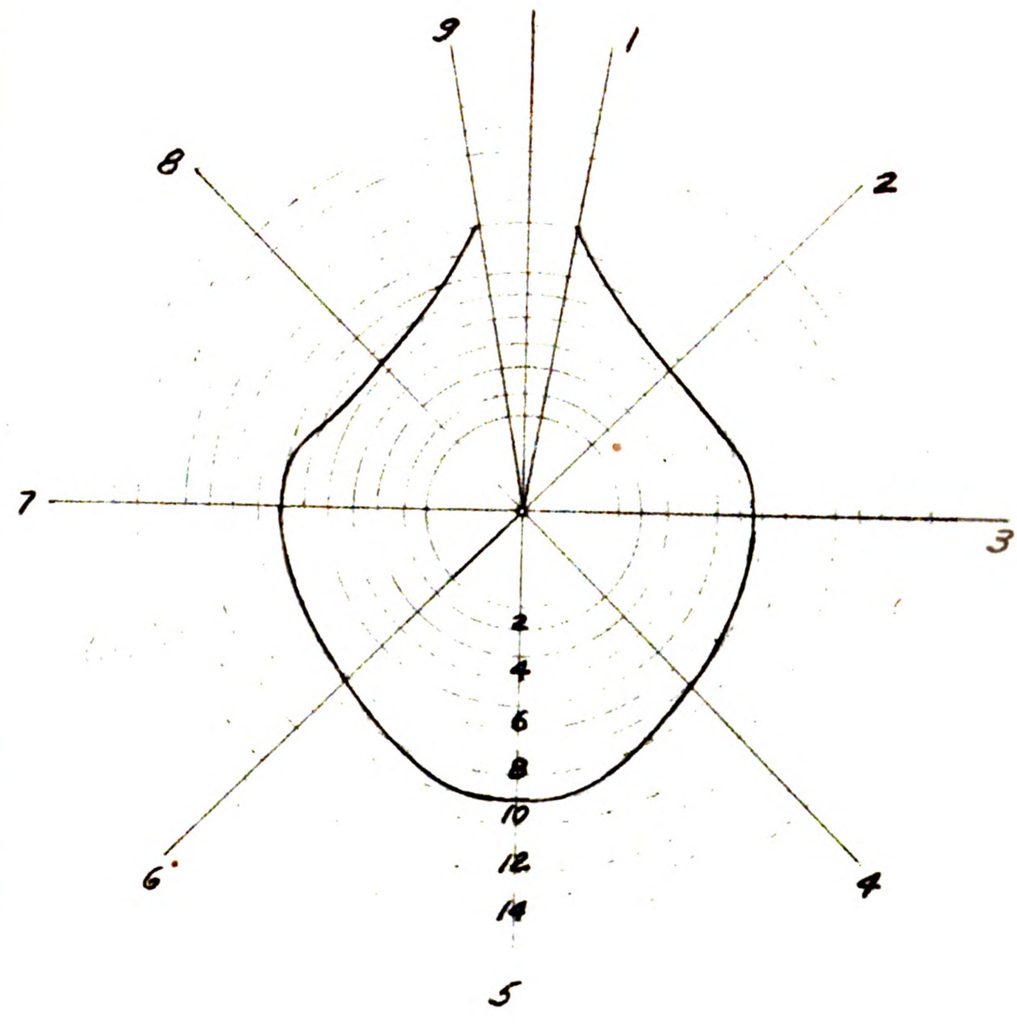

FIGURE IX - DIAGRAM OF AN IDEAL RADIAL PRESSURE PATTERN (the region adjacent to the points) to make good peripheral contact against the cylinder wall. It is Lane's belief also that uniform contact of the ring with the wall throughout the entire circumference, or "light-tightness", is essential for satisfactory ring performance. Examination of the radial pressure pattern (Figure IX) shows lower radial pressures at the shoulders, which might lead one to wonder whether such a condition would provide satisfactory light-tightness.

Ring Width and Cylinder Wear. Another factor which should be considered in connection with piston ring design is the effect of compression-ring width on ring and cylinder bore wear.

It has been found that a decrease in the width of the compression ring will result in a reduced amount of scuffing. It will be remembered that the reverse was true in the case of abrasive wear, where narrower rings were found to have an adverse effect. H. G. Braendel[11] of the Perfect Circle Company attributes this phenomenon partly to the fact that narrower rings operate at face pressures which are much less than would be the case for wide rings installed in cylinders of the same bore and subjected to the same combustion pressure. Calculations made by him show that face pressure ratios for two such rings, both with the same radial wall thickness, vary from 1.7 to 1 to 2.6 to 1 depending on whether the frictional force between the ring and the groove is acting with or against the back pressure of the ring. Obviously the effect of a lower face pressure would be to diminish the tendency for the ring to scuff. This would be especially true at the top portion of the stroke, since here the face pressures would be at a maximum due to the high gas pressures during combustion. Under such conditions the face pressures might reach such a magnitude in a wide ring that the lubricating oil film might be squeezed out at the relatively low sliding velocity during this portion of the stroke, resulting in heavy wear.

Braendel also points out another reason which might account for reduced wear on the part of narrow compression rings. He indicates that narrower rings may have a greater degree of axial conformability to the cylinder wall. This would mean that a narrower ring would conform to the bore at any particular time with a greater proportion of its area in contact with the wall than would a wider ring. In many cases, he believes, the actual contact area may be the same for both narrow and wide rings, with instances occurring where the narrower ring may have even a greater contact area.

The effect of ring width on blow-by is also important to note. Examination of Figure X* shows that as the ring width is decreased, the break in the blow-by curve is shifted farther to the right. This would indicate that the sealing capacity of narrower rings is superior to those of greater width.

Another advantage in the reduction of ring width is pointed out by Harold Myers,[12] of the Perfect Circle Company. He states that when narrow rings are used the inertia loads on the ring groove may be reduced, thus preventing the type of failure as shown in Figure XI**

Oil Control. The problem of oil control as it affects cylinder wear is extremely complex and implies a delicate balance between a number of design factors. If an oil control ring can be designed to exert a uniform pressure against the cylinder walls throughout the length of the stroke, regardless of the shape and changes of shape of the wall, a uniform oil film will be metered to the compression rings and the tendency toward scuffing will be virtually eliminated. With such a condition a corresponding decrease in oil consumption will then be ex-

*Lamarque, P. V., "Piston Ring and Cylinder Wear", Engineering, Dec. 22, 1944; Figure 8, p. 518
**Myers, Harold, "Engine Wear", S.A.E. Journal, August, 1951: p. 49

perienced, resulting in the paradoxical result that engines which run relatively dry will, upon disassembly, show exceptionally low wear. Fulfillment of such conditions also indicates that minimum uniform oil metering has been attained and that the compression rings have been provided with sufficient lubrication at all times.

Proper oil control implies considerably more than keeping oil out of the combustion chamber. Among the prime functions of a well designed oil ring is to provide a circulation of the oil supplied to the cylinder assembly. The capacity of the ring to pass or circulate oil is important; obviously, this is determined to some degree by the face width of the ring itself. Thus oil rings with wider face widths may have larger slots for oil drainage. For example, in a 3/16-inch oil ring the slots may be as wide as 0.093 inches; while in a 5/32-inch oil ring the slot width is usually only 0.062 inches-- a reduction of almost one-third in oil-handling capacity. In engines which are prone to sludging, varnish or carbon formations, adoption of greater width oil rings will provide increased ring life.

Adequate oil control is essential if a copious oil supply is to be maintained on the cylinder bores. Improper design of the piston and rings, or disinte-

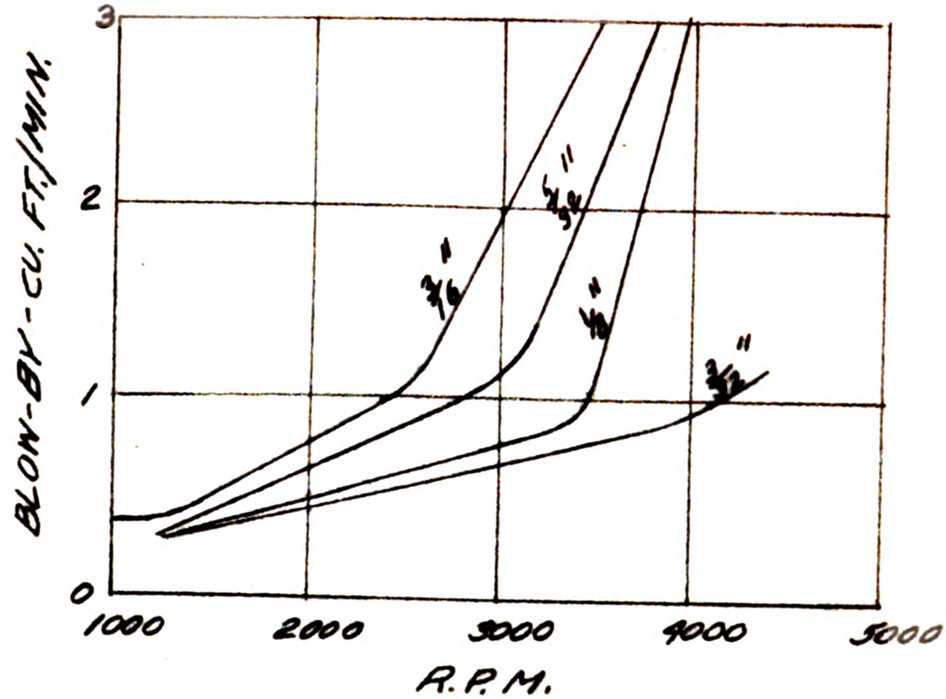

FIGURE X - EFFECT OF RING WIDTH ON BLOW-BY

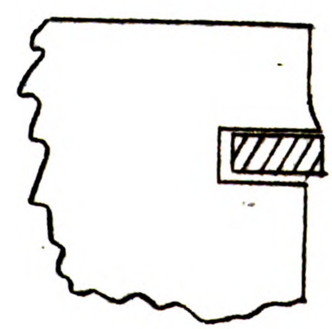

FIGURE XI - FAILURE OF PISTON DUE TO UPSETTING OF THE UPPER SIDE OF THE RING GROOVE BY RING POUNDING gration of the rings due to blow-by, may contribute to faulty oil control. Taub cites an example of such conditions in an engine where the oil supply is copious but an inadequate ring combination is used, such as two low-tension compression rings and two low-pressure oil rings. When the engine is new, the two oil rings will hold back a considerable share of oil and additional control will be maintained by the compression rings. Later on, when the compression rings become subjected to blow-by, they will soften and become covered with carbon, reducing their efficiency all the more. The blow-by gases then affect the upper oil ring, which causes it to lose tension and become covered with carbon. The oil control has now been reduced to a minimum with the oil supply still remaining a maximum, with the result of trouble, even though no serious wear may be indicated on the cylinder walls. Taub also points out that a difference between scraper rings of 9 pounds and 13 pounds diametral tension may mean a 50 per cent increase in oil consumption with the lower tension rings.

Another factor, besides ring tension, which influences oil control is the magnitude of the radius on the scraping edge of the compression and oil rings. It has been shown that a radius of 0.010

inches on the skirt ring will result in a marked increase in oil consumption. Obviously the sharpness of this edge would govern the amount of oil stripped from the cylinder walls by the ring. Changes in oil viscosity would alter the sharpness or radius to be maintained-- thinner oils requiring a smaller radius to maintain the same degree of oil control.

Ring Materials and Surface Finishes. The effect of the material used in piston-ring manufacture should not be underestimated. Even though attention to proper design and proportions of the ring are important, considerable thought must be given to the ring materials as well. Although grey iron is the universal material for compression rings in automotive use, some types of engines may require metallurgical characteristics beyond the scope of this material. It is obvious that, above all, the material must possess good wearing properties; however, some irons which posses this property do not necessarily make satisfactory rings. Lubrication conditions may often overshadow variations in material specifications. Perhaps one of the most important properties to be considered is that the ring should wear away with very little tendency to accumulate the wear products on the rubbing surfaces. A metal structure which, in abrading, will break down into extremely small particles that will cause little disturbance to the surfaces affected is essential. The "Piston Ring Manual", published by the Muskegon Piston Ring Company, gives the following chemical analysis for automotive type cast iron rings of 3/32 to 3/16 inch section:

Silicon	--	2.60 - 3.00 per cent
Sulphur	--	0.08 max.
Phosphorus	--	0.40 - 0.70
Manganese	--	0.55 - 0.70
Carbon	--	3.50 - 3.75
Rockwell "B"	--	98 - 105 B

The use of steel oil rings has been a rather recent innovation. These rings operate under relatively high unit pressures of 150 to 200 pounds per square inch. This increased pressure restricts greatly the amount of oil supplied to the upper ring belt and may sometimes contribute to greater wear of the cast iron compression rings. An advantage of this type of ring is that it can restore oil economy to engines having badly tapered bores without the expense of reboring the cylinders. The hardness of these steel rings ranges from 350 to 400 Brinnell, as compared with 240 to 260 Brinnell for cast iron rings. This increased hardness has been found to have no ill effects if the softer iron in the cylinder walls is provided with normal lubrication. In fact, the high hardness of the steel used in these rings reduces the tendency of the rings toward becoming loaded with abrasive material which may produce a lapping action on the cylinder walls, causing increased wear.

The importance of surface finishes on piston rings is receiving an increasing amount of attention. Surface finishes may contribute toward reduced scuffing during the running-in period only, or finishes may be used which result in reduction of ring and bore wear throughout the entire life of the ring.

Of the former class, the most common surface treatments used are metallic plating, oxide coating, phosphate coating, and acid etching. The material most commonly used in metallic plating is tin or cadmium, which is plated to a depth of 0.0001 to 0.0003 inches. The rings may be either plated all over, or on the outside diameter only. All-over plating has an advantage in that it affords additional protection from rusting. The oxide coating or Ferox treatment consists in producing a coating of iron oxide by treatment at 1,000 degrees F. in a gaseous oxidizing agent. The phosphate coating is produced by immersion of the ring in a water solution of phosphoric acid saturated with iron and manganese phosphate at 210 degrees F. Both of these coatings are 0.00025 - 0.00030 inches thick. The acid etching treatment (Graphitox) consists in impregnating the etched surface with colloidal graphite which provides the metal with excellent self-lubricating qualities.

A variation of the conventional Ferox treatment is sometimes practiced in the manufacture of piston rings for diesel engines. In order to facilitate the use of wide rings in these engines and still reduce ring scuffing to a minimum, grooves are cut in the ring faces to interrupt the continuity of the metallic surfaces. The grooves are then filled with a mixture of iron oxide (Ferox) bonded with sodium silicate. Figure XII* shows a cross section of this type of ring. Brenneke states that the scuff resistance of this type of ring in 1/4-inch width is comparable with that of 3/32-inch conventional rings.

In order to obtain a maximum degree of scuff resistance of both rings and bore throughout the entire life of the ring, it is becoming the practice to employ chrome-plated top rings. The use of these rings has been employed for some time in truck or diesel engines and is now being extended to the passenger car field. Present practice employs a plating of hard rather than porous chrome, ranging from 0.004 to 0.007 inches in thickness and up to 0.008 inches for heavy-duty equipment.

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*Brenneke, A.M., "How Diesels Wear and What To Do About It", S.A.E. Journal, April, 1950: p. 37

Offhand it might be thought that chrome-plated rings would contribute to increased wear of the cylinder walls due to the high hardness of the chrome, as compared with the relatively soft material in the cylinder bore. The reverse appears to be the case, however, and actually reduced wear of the cylinder wall occurs when such rings are used. Braendel believes that two reasons for this peculiar behavior exist. One is the lack of embedability of the surface of the chrome-plated rings. Abrasive particles are unable to become embedded in the ring surface and then act as cutting edges on the cylinder wall. Not only does this result in reduced cylinder wall wear, Braendel states, but also the life of the cast iron rings below the top chrome ring is increased for the same reason.

A second reason for the reduced cylinder wear experienced with chrome rings is the resistance of this type of ring to temperature effects. The fact that its melting point is higher than that of cast iron reduces the tendency toward localized welding of the rubbing surfaces when these are brought to the melting temperature by insufficient lubrication.

Figures on wear reduction with chrome-plated top rings are given by Brenneke[13] as 80 per cent over that experienced in the same installation using

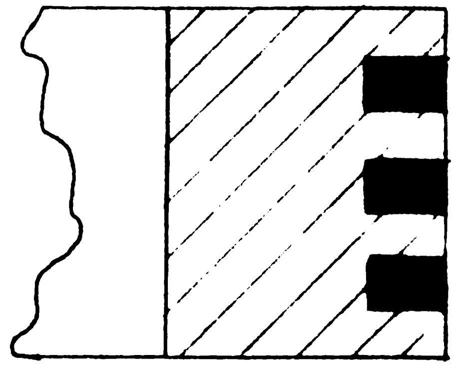

FIGURE XII - SCUFF RESISTANT RING HAVING GROOVES FILLED WITH IRON OXIDE

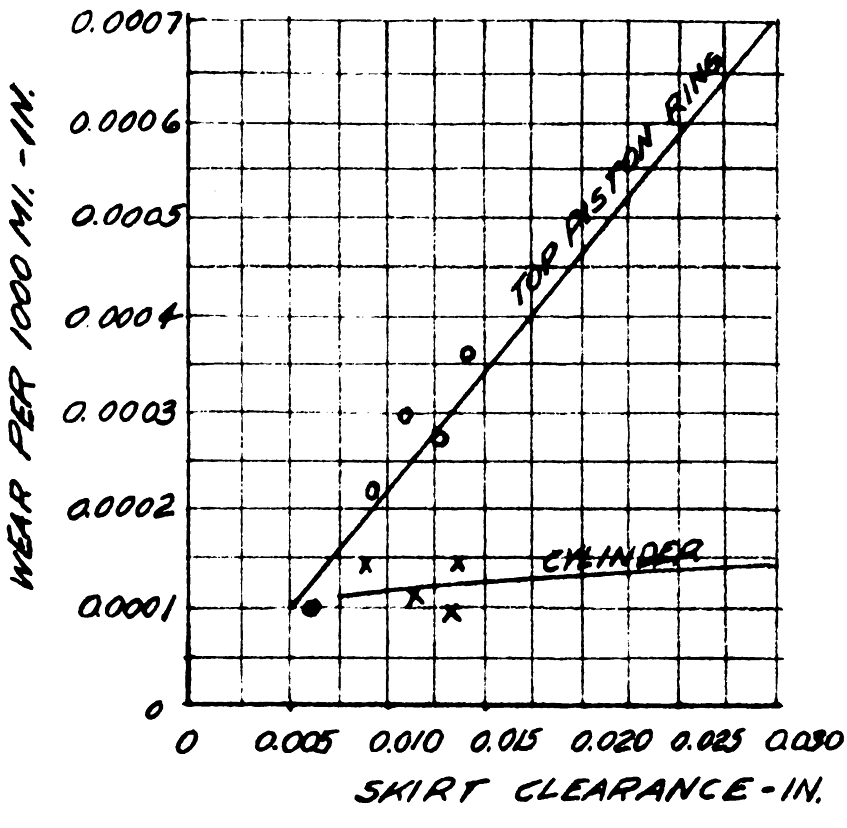

FIGURE XIII - EFFECT OF PISTON SKIRT CLEARANCE ON CYLINDER AND RING WEAR conventional ring equipment.

Piston Design and Cylinder Wear. Just in the case of the piston rings, proper design of the piston will do much to alleviate cylinder bore wear. Selection of the proper materials, combined with correct design procedure, is important. Also, since piston design influences to a great degree the amount of oil control maintained by the rings, it is necessary to consider this factor if a satisfactory end result is to be reached. Principles which should be considered in proper piston design procedure are the following:

1. Top land clearance
2. Skirt clearance
3. Ring side clearance
4. Location of the top ring groove
5. Size and position of the ring gaps
6. Degree of oil control to be maintained
7. Material and surface finish

Effect of Top Land Clearance. Lamarque cites results of tests in which the effect of top land clearance on blow-by was studied. Results show that the critical speed at which excessive blow-by occurred decreased as the top land clearance was reduced. Thus, in the case of a top land clearance of 0.020 inches, the critical speed is 5,400 r.p.m.; while with a clearance of 0.040 inches, the critical speed increases to 5,900 r.p.m. A possible explanation for this behavior might be due to the reduction in gas pressure acting on the top face of the ring when the top land clearance is reduced. This would allow the ring to break away from the lower side of the groove at a reduced engine speed, giving rise to a rapid increase in blow-by.

Effect of Skirt Clearance. The effect of skirt clearance on piston and ring wear is important. Even in the presence of ample lubrication, skirt clearance has a marked effect on top ring and cylinder wear; increased skirt clearances inducing higher wear rates as shown in Figure XIII*. Probably the reason for this increase in wear with increased skirt clearance is due to the destructive effect of piston slap. The use of controlled-expansion pistons such as the Auto-thermic and belted types, which maintain close clearances over a wide range of operation, would serve as an approach to this problem.

Effects of Ring Side Clearance. Increases in piston ring side clearance may be brought about by mutual wear of the piston ring groove and ring. Such wear is a common occurrence in the case of aluminum pistons. According to Myers, most of the wear under

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*Williams, C. G., "Cylinder Wear in Gasoline Engines", S.A.E. Journal, (Transactions), May, 1936: p. 194

such conditions occurs on the flat sides of the ring which may eventually cause it to assume a "T" shaped section as shown in Figure XIV*. It should be noted that the cross of the "T" is not in the zone of maximum wear, being at the outer periphery of the ring where it does not contact the ring grooves. If such wear continues until the side clearance becomes excessive, pounding of the ring in the groove will occur which may result in breakage of the ring.

In addition to causing groove pounding and ring breakage, side clearance has some effect on oil consumption. Tests, described by Lamarque, on a single-cylinder gasoline engine fitted with two compression rings and one oil ring indicate that at an engine speed of 1,500 r.p.m. an increase in the top ring side clearance from 0.004 to 0.012 inches results in a 60 per cent increase in oil consumption. When the engine speed was raised to 3,500 r.p.m. and the same increase in side clearance made, the oil consumption increased to 120 per cent. Increasing the side clearance of both the top and second compression ring to 0.012 inches brought a fourfold increase in oil consumption at 2,500 r.p.m.

<u>Effect of Location of the Top Ring Groove.</u>

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*Myers, Harold, "Engine Wear", <u>S.A.E. Journal</u>, August, 1950: p. 49

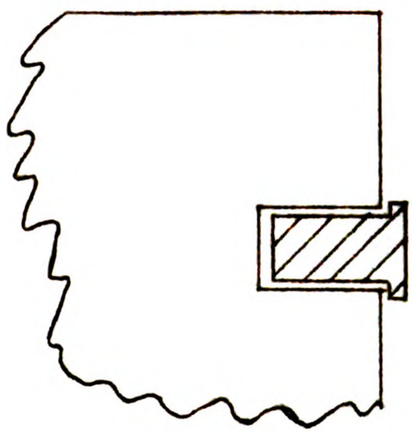

FIGURE XIV - WEAR ON SIDES OF RING CAUSES IT TO ASSUME A "T"-SHAPED SECTION

Proper location of the top ring groove on the piston has been found to minimize ring scuffing tendencies. Brenneke advocates locating the groove at such a point that when the piston is at the top of its stroke the top ring should not travel beyond the end of the water jacket. It is obvious that such a practice would avoid operation of the ring in excessively high temperature zones which are especially conducive to scuffing.

Provision of an adequate top land by locating the top ring well down on the piston also serves to protect the ring from the direct effects of combustion as well as reducing its operating temperature. Ring belts which operate at moderate temperatures have less tendency toward ring sticking and poor sealing ability, both sources of blow-by and accompanying rapid wear. The top ring must also be adequately supported by a strong second land if it is to have a low wear rate and good sealing ability. Brenneke advocates 0.20 inches per inch of cylinder diameter for top land width and 0.05 inches per inch of diameter for second land width.

<u>Effect of the Size and Position of the Ring Gaps</u>. It has been found that the size and relative position of the ring gaps on a piston have a marked effect on oil consumption. In tests using a ring having a radial

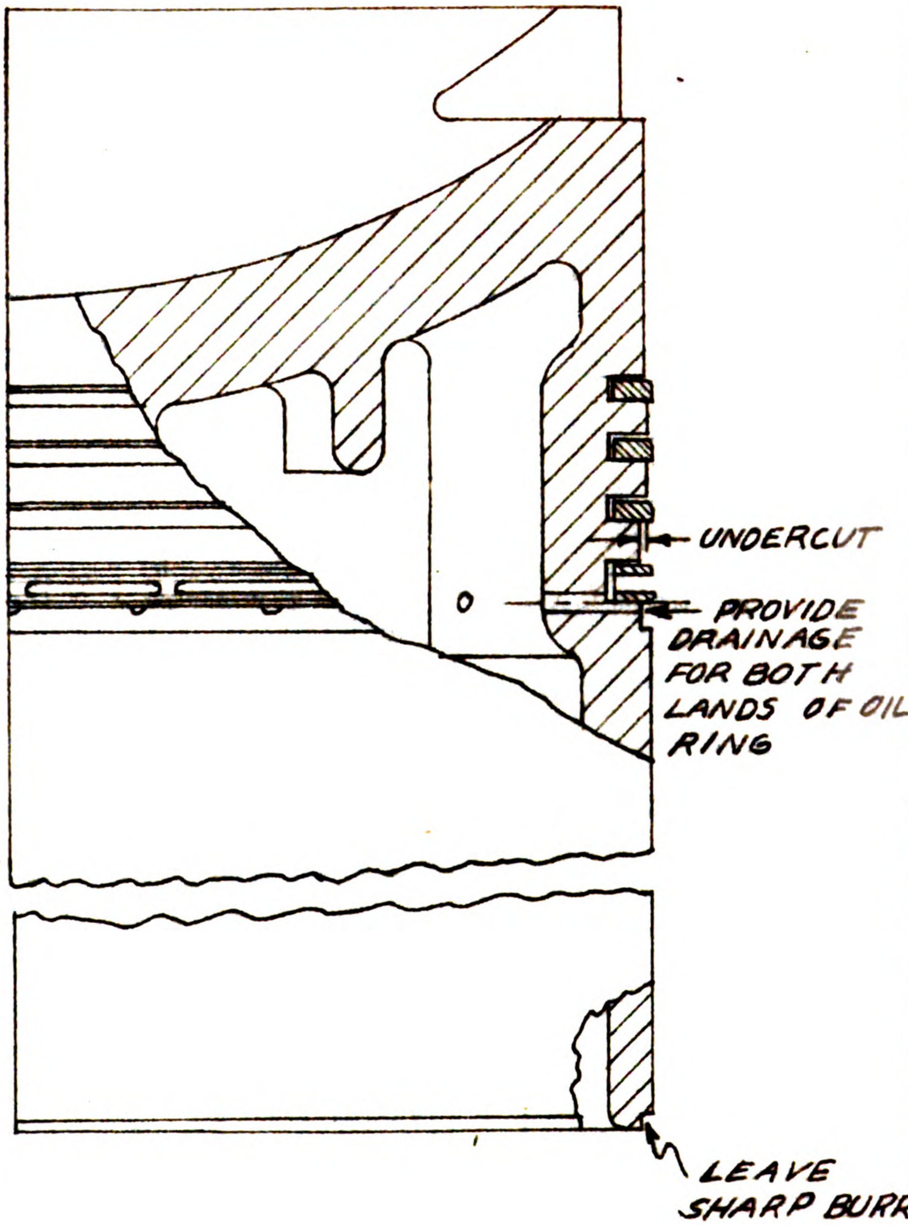

FIGURE IV - DIESEL ENGINE PISTON SHOWING DESIGN CHANGES ADOPTED TO FACILITATE OIL CONTROL pressure of 15 pounds per square inch, increasing the ring gap from 0.011 inches to 0.022 inches in an engine with a bore diameter of 3.375 inches gave a two-fold increase in oil consumption.

The effect of the position of the ring gaps on oil consumption was observed when two rings, each having 0.017-inch gaps, were installed on a piston, first with the ring gaps on opposite sides of the piston and next with both gaps on the same side of the piston. The oil consumption in the case of the former installation was slightly less than one-half of that experienced in the latter.

Effect of Piston Design on Oil Control. As was previously pointed out, piston design has a great effect on the amount of oil control to be furnished by the rings. A piston which is not structurally rigid may interfere with proper action of the rings, also its shape must be such that it will assist in metering the oil to the bores in order that a given combination of piston rings may not have to do more than was originally contemplated in their design. A properly designed piston should supply a new film of oil on the cylinder walls at each stroke, the function of the rings being to cut the oil film to the final smoothness.

Taub points out two factors in piston design which interfere with good oil control. These are:

1. Improper taper of the piston skirt
2. Improper amount of piston ovality

In many cases, due to manufacturing tolerances, a reverse taper is provided on the piston skirt. Normally, the taper of the skirt should be such that the clearance at the bottom is less than near the rings. Owing to these tolerances the skirt may either be 0.0005 inches smaller at the bottom than near the rings or it may be 0.001 inches larger at the bottom than at the ring belt. The oil consumption with a reverse taper has been found to be almost double that used with one which is correct.

In the case of ovality of the piston, tolerances are allowed for the difference in dimensions between the major and minor axes. According to Taub, the difference in oil consumption between an ovality of 0.004 inches and one of 0.008 inches on one particular piston was 40 per cent in favor of the small ovality.

Figure XV* shows the design of a four-cycle diesel engine piston advocated by H. G. Braendel. This piston is noteworthy in that it illustrates how modifications made in the present design can enhance oil control. Changes made to accomplish this in this case are:

1. The provision of a sharp edge at the bottom of the skirt. This feature is said to provide as

*Braendel, H. G., "Three Piston Design Tips for Improved Oil Control," S.A.E. Journal, April, 1950: p. 40

much oil control as an additional oil ring.

2. The oil control ring groove is provided with abundant drainage for both lands of the oil control ring. This is accomplished by providing an undercut and drilling the drain-back holes with their center lines coinciding with the lower plane of the oil ring groove.
3. The addition of an undercut of approximately 25 per cent of the radial thickness of the ring on the land between the oil control ring and the lowest compression ring. This undercut serves as a reservoir space for the oil scraped on the down stroke by the lowest compression ring. On each subsequent up-stroke this oil may then flow back to the inside of the piston through the side clearance of the oil ring.

Piston Material and Surface Finish. As far as the effect of piston material on cylinder wear is concerned, there appears to be no great difference in the amount of wear regardless of the material used. In the case of aluminum pistons severe ring groove wear has been found to occur, especially in heavy-duty, high-speed engines. One remedy for this difficulty is a bimetallic piston with a ferrous metal ring carrier which is either cast or mechanically attached to the aluminum piston. The increased hardness of ferrous materials is often offset by the poorer thermal properties of this material. As a result, ring belt temperatures may be much higher, causing a tendency toward sticking.

Among the most common surface treatments applied to pistons are tin plating and anodizing. Both treatments facilitate run-in and lessen scuffing, especially during the warm-up period.

Under cold starting conditions the cooling water surrounding the cylinder walls may prevent them from warming up as quickly as the piston. As a result the piston may become larger than the bore, causing "cold" scuffing of the rubbing surfaces, especially when lubrication is scanty. Anodizing prevents this by producing a hard surface, and at the same time, one which is porous enough to hold oil. Tin plating also prevents this condition, the tin acting as a metallic lubricant under the high shearing forces which accompany cold scuffing.

A rather new surface finish which has been applied to super-charged diesel engine pistons has been developed by the Zollner Corporation. It consists in knurling the rubbing surface of the piston to provide a series of tiny valleys or reservoirs for oil, which materially improves the lubrication of the piston, rings, and bore. Piston seizures, which previously had been reported, have been prevented with this type of finish.

Metal Structure and Surface Finish of the Cylinder Bore As Related to Wear Resistance. In the past, it has been the belief that bore hardness, rather than metal structure, has been the main factor in governing wear resistance in cylinder iron. Undoubtedly the reason for this belief has been based on the abrasive wear theory; for it is known that under purely abrasive conditions an increased hardness of the cylinder bore will reduce wear. Actually a cylinder iron of extremely high hardness, such as provided by nitrided cast iron, is a distinct disadvantage from the standpoint that such a material lacks the surface bearing qualities of the more normal irons; also, such an iron is more prone to scoring under conditions of limited lubrication, especially when in combination with equally hard surfaces.

The question of metal structure and its effect on wear and scuffing has been dealt with in some detail by Paul S. Lane[14]. It is his belief that the wear properties of cylinder iron are governed to a great degree by the speed of cooling of the casting which is, in turn, largely determined by the section thickness. Research work conducted by Lane and others indicates that cylinder wall thickness is a critical factor in controlling the cooling rate of the metal in zones at, or adjacent to, the bore. Failure to consider this relationship between wall thickness and cooling rate may result in the establishment of micro structures in the iron which may produce abnormally high wear rates and consequently reduced engine bore life.

From the point of view of obtaining a desirable metal structure a case exists for the use of cylinder liners, either wet or dry, because of the more uniform cross-section and the greater simplicity of the casting involved.

In regard to the surface finish of cylinder bores it has been found that, in addition to the actual smoothness of the surface, the metal structure left by the finishing process is of some importance.

Lamarque points out that cutting and abrasive methods of finishing cylinder bores result in a relatively fragile, crystalline surface structure which is not particularly conducive to the establishment of a stable oil film. During the running-in period this crystalline structure is transformed into an amorphous layer which greatly improves the load carrying capacity and reduces the rate of wear as long as adequate lubrication of the rubbing surfaces is maintained. In addition, running-in tends to remove any loose material remaining from the finishing process. A good deal of the uncertainty of the running-in process might be avoided if, in the first place, the cylinder bore could be finished to a state approaching the run-in condition.

One of the most important factors in cylinder surface finishes is that the finish produced must be of a sufficient degree of roughness to promote quick seating and wearing-in of the rubbing surfaces, as well as maintain sufficient oil retention properties. Braendel advocates a scratch-honed cylinder with a cross-hatched pattern having a roughness of 15-30 micro-inches as one which will give the best results.

Treatment of the cylinder-bore walls by a chemical sulphidizing process has been recently employed as a surface finish. Advantages claimed for this process include reduced scuffing during the running-in process as well as improved oil retention properties.

A new development in surface finishes for cylinder bores, which shows considerable promise, is the Bramberry Characterized Liner shown in Figure XVI.* A "characterized" pattern is cut into a previously machined, ground and honed liner sleeve. The pattern consists of two sets of 30-degree helical grooves, cut in opposite directions, with each groove having a "V" section and depth of 0.004 inches. This forms

*Ohly, C. W., "Progress Report on Bramberry Liner," Thompson Products Company, January 18, 1950

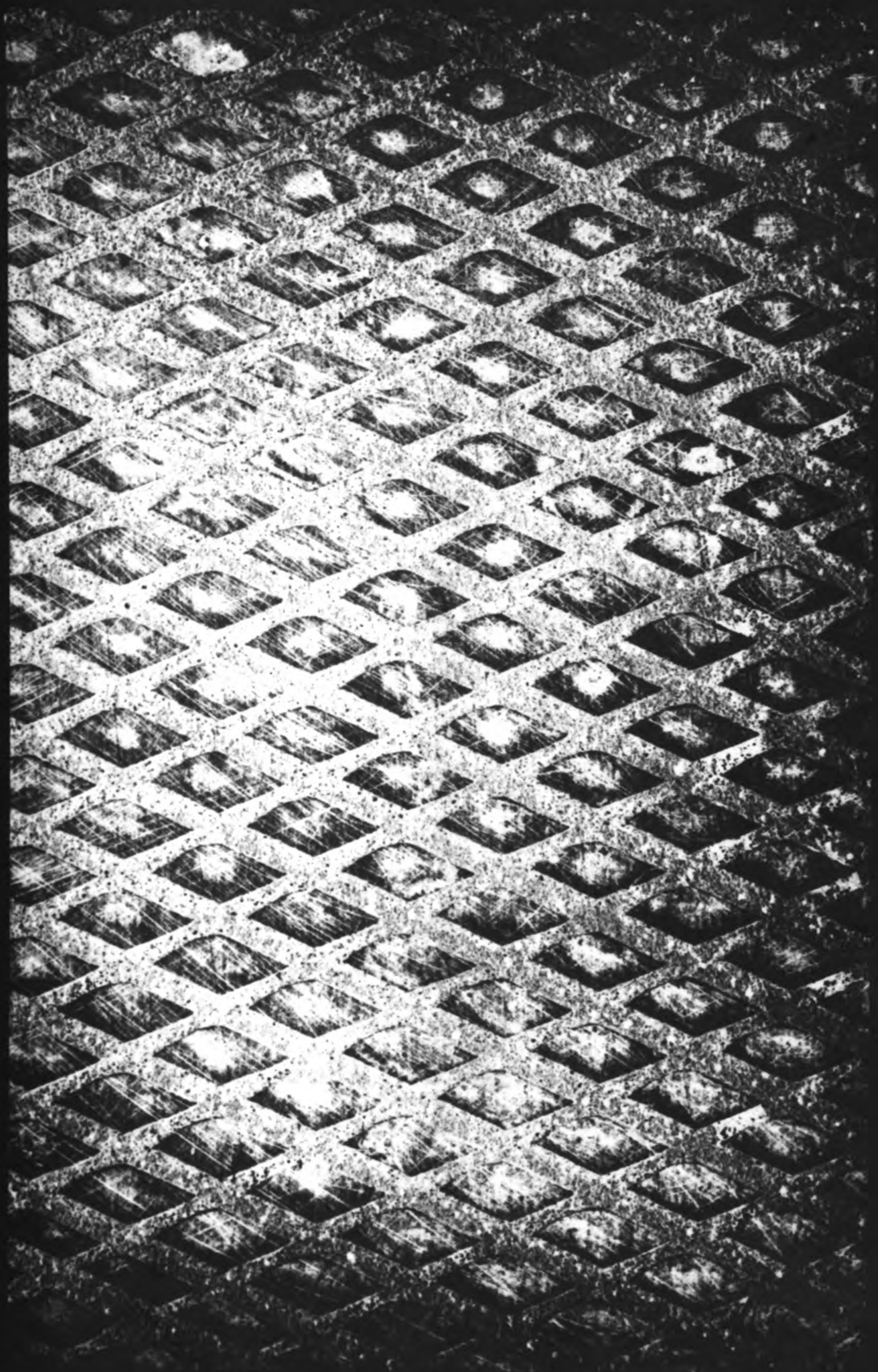

FIGURE XVII - BRAMBERRY CHARACTERIZED LINER a completely interconnected network of grooves and leaves an arrangement of diamond-shaped plateaus whose total area represents approximately 60 per cent of the bore surface. After a careful cleaning, the grooves are filled with a carbonaceous, plastic base compound. Following this, the entire bore surface is sprayed with a very fine graphitic solution which leaves a thin film of graphite on the wear surface.

Results of field and laboratory tests on such liners have been submitted by Mr. C. W. Ohly[15] of the Thompson Products Company. Tests show that these Bramberry sleeves have an average wear rate of between 0.0003-0.0005 inches per 10,000 miles in conventional cylinders of the same engine. One advantage of such liners lies in the fact that since the diamond heads are isolated from one another, a hot-spot developing in one location does not spread. In addition, the carbonaceous material has high oil retention properties which, when combined with the forces of capillary action and surface tension, spreads a thin film of oil over each diamond head. This enables continuous lubrication of the cylinder wall to be maintained, probably accounting for the extremely low wear rates with this type of liner.

Reduction in blow-by values of from 30-35 per cent have also been reported with these liners.

Chrome plating of the cylinder wall surfaces is being employed to some degree, although its use is more or less restricted to diesel engines and application outside the automotive field. The results obtained are similar to those experienced with chrome plated top rings. Chrome plating is especially effective under abrasive wear conditions and often excells nitrided liners in wear resistance. Abrasive wear with chrome plated cylinder wall surfaces is often reduced in the ratio of 15/1 to 40/1 over that of alloyed cast iron bores.

Present practice in the chrome plating of cylinder bores is to produce a porous, rather than hard, chrome surface in order to provide better oil retention properties. In some instances only the top third of the cylinder bore is subjected to the chrome plating treatment. Under such conditions the reduction in wear of the top portion by chrome plating also appears to reduce the rate of wear of the remainder of the bore. This is manifested by no sudden increase in diameter immediately below the chrome-plated portion, even after considerable mileage. The reason for such behavior might be explained by the fact that chrome plating the top portion of the bore reduces the amount of material worn off this portion, such material acting as an abrasive agent, which acts to increase the amount of wear during the lower portion of the stroke.

VI. Corrosion

<u>Definition of Corrosion and Sources of Corrosive Wear</u>. As its name implies, corrosion is the destruction of the metal surface of the cylinder walls by oxidation or chemical reaction with the products of combustion. It is difficult to differentiate between corrosion and erosion as the two phenomena often go hand-in-hand. Most authorities are inclined to agree that the greatest effects of corrosion are manifest during low temperature or low-speed, light-load operation. Under such conditions the condensation of water vapor on the cylinder walls may produce wear by either one of two ways: by washing off the oil film, thus giving rise to wear by abrasion or by corrosion. It is often difficult to determine just how much wear may be attributed to corrosion alone for this reason. Surfaces attacked by corrosion often present a pitted and pockmarked appearance, as shown in Zone "A", Figure XVII*. It would appear evident from this sketch that corrosion is taking place only in this zone. Actually, a closer examination would indicate that the entire area designated by "B" has also been affected, and that in Zone "C" the products of corrosion have been scrubbed off, leaving a bright surface.

*Taub, Alex, "Cylinder Bore Wear and Corrosion," <u>Automotive and Aviation Industries</u>, March 1, 1944: Figure 2, p. 37

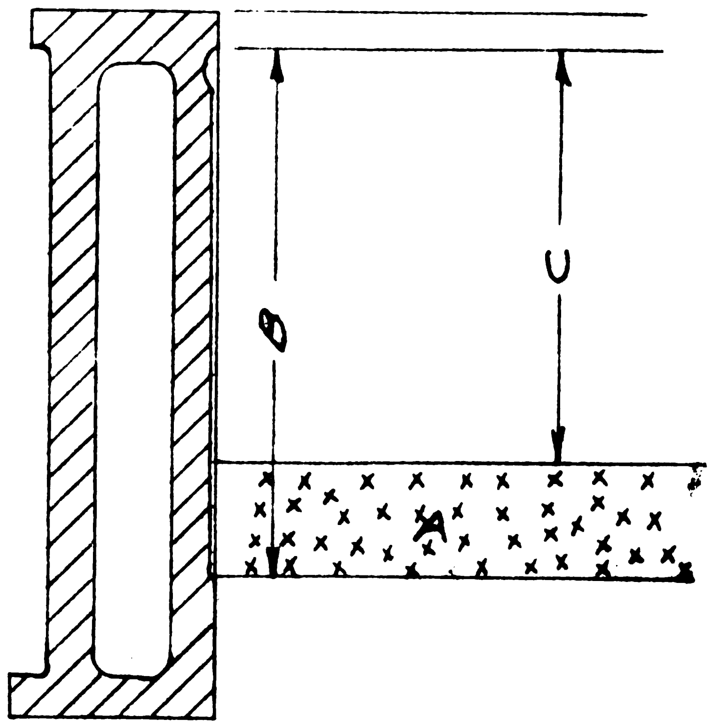

FIGURE XVII - PATTERN OF CORROSION

Knowing that corrosion is caused by acid attack on metal surfaces, it might be well to discuss those acids which are formed during the combustion process and their effects on cylinder wear. Williams, in his corrosion hypothesis, believes that the following acids are contributors to corrosion:

1. Organic acids, such as formic (CH_2O_2) and acetic ($C_2H_4O_2$) acid which are intermediate products in the combustion process. Williams states that formic acid, when added in proportions of 0.5 per cent to the water of combustion, will double the rate of corrosive wear.

2. Sulphuric acid formed from the sulphur in the fuel.

3. Nitric acid. At high temperatures some of the nitrogen and oxygen in the atmosphere combine to form nitric oxide (NO) which can be further oxidized to nitrogen peroxide; addition of water to the peroxide will subsequently form nitric acid. A condition necessary for the production of nitric oxide is rapid cooling. Such a condition usually exists within the combustion chamber during low temperature operation.

3. Carbon dioxide. Solutions of carbon dioxide

in water are slightly acidic and therefore possess corrosive properties.

Knowing that corrosive wear is favored both by the condensation of water vapor and by the acid-chemical reactions occurring during the combustion process, it would be well to examine those factors which might contribute to such conditions. These contributors might be listed as follows:

1) Low cylinder wall and operating temperatures.
2) Inadequate lubrication of the cylinder walls.
3) Chemical and physical characteristics of the fuel.
4) Piston ring and cylinder wall materials.

Effect of Low Cylinder Wall and Operating Temperatures on Corrosive Wear. In view of the fact that corrosive wear depends to a large degree on the amount of moisture condensed on the cylinder walls during the combustion process, it seems logical that reduced cylinder wall and operating temperatures would contribute to a marked increase in corrosion by allowing a greater amount of condensation to take place.

Research on the corrosion problem was undertaken by Williams in an attempt to determine the relation between cylinder wall temperatures and the rate of corrosive wear. As a result of a large number of tests carried out on several types of engines, he found that it was possible to construct a curve showing the relation between the rate of wear and cylinder temperatures under steady running conditions. Examination of Figure XVIII* indicates that between the range of 212 to 510 degrees F. the rate of wear is almost independent of the temperature; while below a temperature of 194 degrees F. there is a rapid increase in the rate of wear.

The reason for the increase in corrosive wear at temperatures below 194 degrees F. is associated with the condensation of moisture from the products of combustion. In the initial state this water is in the form of highly superheated steam within the main body of the combustion gases. Contact with a sufficiently cold surface, however, is capable of reducing the temperature locally to below the dew point, thus effecting condensation.

The effect of cylinder wall temperature on corrosion has also been pointed out by Taub. Tests are described by him in which engines operating under favorable conditions, including a minimum number of cold starts, with alcohol and water as cooling media and thermostats set to operate at 145° F., showed wear rates as 1 to 3 with alcohol and water, respectively. The cylinder wall temperature was found to be 30 degrees cooler with water than with alcohol.

*Williams, C. G., "Cylinder Wear in Gasoline Engines", S.A.E. Journal (Transactions), May, 1936: p. 192

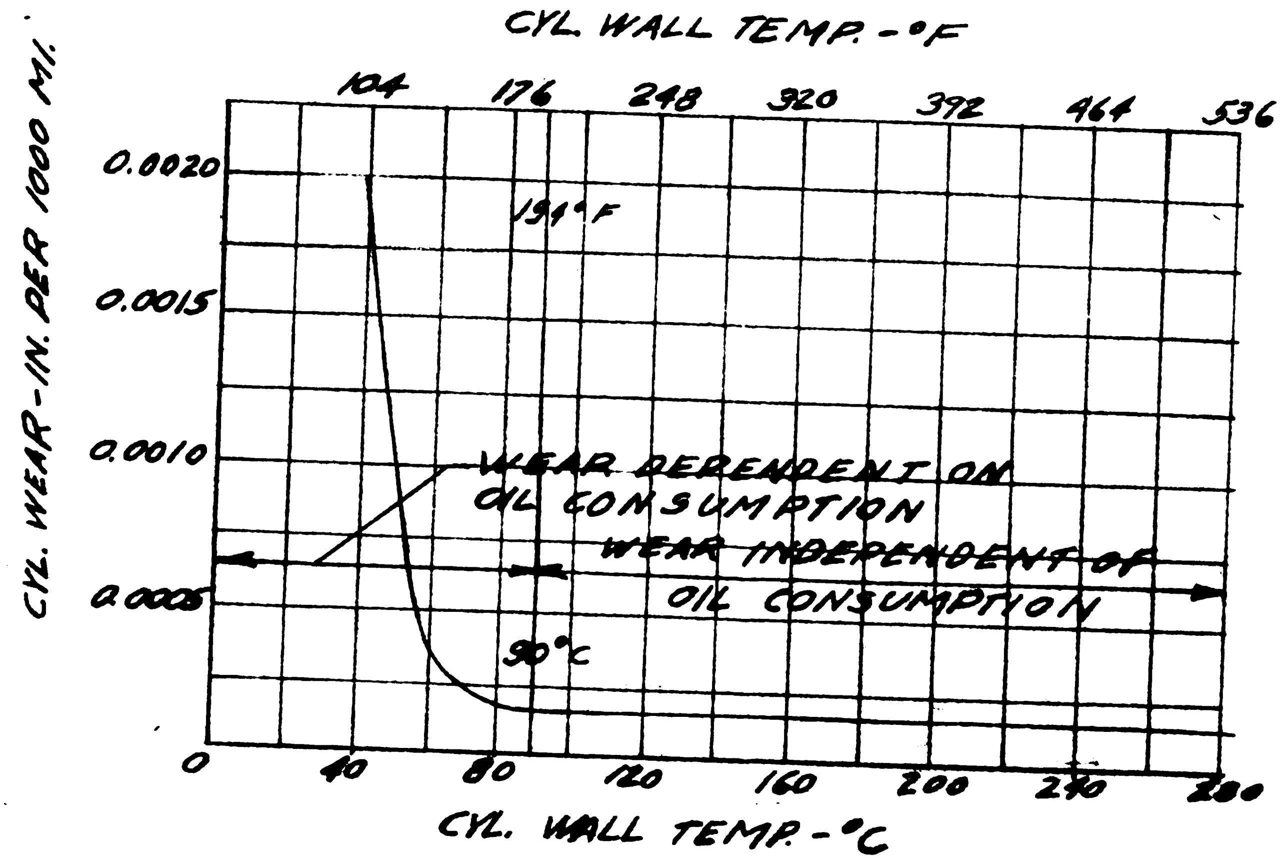

FIGURE XVIII - EFFECT OF CYLINDER WALL TEMPERATURE ON BORE WEAR

Brenneke is also in agreement on the effect of cylinder wall temperature on corrosion. It is his belief that a low coolant temperature is the most important contributor to corrosive wear. He maintains that jacket temperatures below 120° F. should be avoided if high rates of corrosive wear are to be prevented.

Since evidence leads to show that cylinder wall temperature plays an important part in the low-temperature corrosion problem, it would be well to consider this factor in its relation to cold-starting procedure. The common theory in the past has been to operate under very light load and low speed until the proper coolant temperature has been reached. From the standpoint of the corrosion theory, this procedure is the worst possible, as such operation does not contribute to high jacket water temperature. The present recommendation is that the engine should be brought up to speed and the load applied as quickly as possible.

Lubrication and Its Effect On Corrosion. It is obvious that lubrication of the cylinder walls plays an important part in the reduction of corrosion. Experience definitely indicates that if an oil film can be maintained on the cylinder walls the effect of the corrosive acids will be minimized. Conditions which tend to destroy this film, the most prominent of which is blow-by, need to be carefully controlled through proper design of the piston rings.

Even the establishment of an adequate oil film is not complete insurance against corrosion. Williams points out that measurable amounts of corrosion have taken place on oil-covered metal plates after ten minutes' exposure to an atmosphere of air and condensing steam.

The effect of the quantity of oil supplied on corrosive wear is also worthy of note. It will be remembered that under normal operating conditions, the rate of wear was very largely independent of oil consumption. Below temperatures of 194° F., however, the wear is influenced to a marked extent by the quantity of lubricating oil supplied to the cylinder walls. Tests conducted by Williams show that by an eight-fold increase in oil consumption it is possible to reduce cylinder wear at 113° F. from 0.0013 to 0.0005 inches per thousand miles.

The properties of the lubricating oil itself may also affect the amount to which corrosion may or may not take place. Experiments conducted on the effect of lubricating oil composition indicate that a high degree of oiliness is necessary to combat corrosive effects.

Fuel Characteristics and Corrosion. In the preceding pages, a discussion was presented on the various acids formed during the combustion process. The extent to which these acids are formed depends primarily on the chemical composition of the fuel used.

Sulfur is one of the most important contributors to corrosion. Just how sulfur causes wear is not definitely known, but it is believed that most of the sulfur in the fuel is converted to sulfur trioxide. This, in combination with the water formed during combustion, produces the highly corrosive sulfuric acid. Wear has been shown to be proportional to the sulfur content with amounts of sulfur in excess of one per cent causing marked increases in cylinder wear. An increase in sulfur content from 0.2 per cent to 1.0 per cent has been reported to give a two to six-fold increase in ring and cylinder wear. Since the sulfur content of diesel fuels is normally higher than for gasoline, more trouble from this source might be expected in diesel engines.

Sulfur content is not the only factor which may contribute to increased wear in diesel fuels. Volatility and viscosity of the fuel are also important in that they affect the combustion process; thus, fuels of low volatility and high viscosity may cause poor combustion resulting in a dirty engine with consequent increased wear. Tests show that improper combustion of fuels containing no sulfur may cause more wear than a fuel having two per cent sulfur and burned under favorable conditions.

Considerable research has been done in recent years on the effect of substitute fuels on corrosive wear in gasoline engines. Cyclic wear tests conducted by the National Bureau of Standards using a fuel composed of 95 per cent alcohol and 5 per cent water have been described by Bruce, Duck and Pierce. These tests were conducted on five 1942-model engines operating 24 hours a day on a test cycle which included a 20-minute operating time and a 10-minute shut-down time each half hour. During the 20-minute running time the engine was operated at conditions equivalent to a 40 m.p.h. road speed and also at an idling speed of 500 r.p.m. During the shut-down period cold water was forced through the cooling system and oil pan in order to simulate normal starting conditions at the beginning of the operating period. Wear measurements made during the test showed that the wear with alcohol fuels was approximately one-half that of gasoline in tests made under comparable conditions. The reason for this increase in wear is believed to be due to the difference in the corrosive characteristics of the two fuels under conditions of low temperature, intermittent operation.

Effect of Piston Ring and Cylinder Wall Materials on Corrosion. Obviously corrosive effects may be minimized by providing materials which are resistant to acid attack. The use of chrome-plated rings and cylinder liners is of value in this respect; although some reports indicate that high sulfur fuels even produce harmful effects on these materials. In cases where porous chrome plating is used, as on cylinder liners, absorption of corrosive materials into the pores may accelerate the rate of wear, thus reducing the life proportionately. Under conditions of high temperatures cracking has been observed on the surface layers of chrome plate. Such cracks might permit the penetration of corrosive fluids and thus introduce considerable corrosive wear.

Considerable attention has been given to the use of austenitic cylinder and ring materials in England. Cast iron having 14 to 15 per cent nickel, 6 to 7 per cent copper and 2 to 4 per cent chrome is austenitic and, as such, has increased resistance to corrosion. In fact, Williams points out, the resistance of this material to corrosion from certain dilute acids is several hundred times greater than that of ordinary cast iron. Austenitic iron, however, does not appear to have any advantage in the presence of dilute nitric acid. Williams also reports that tests on austenitic piston rings show that the top piston ring wear with such material is reduced in the ratio of 2 to 1 over that of conventional rings, and that a marked reduction in cylinder wear is also realized. In view of the fact that austenitic materials have a lower abrasion resistance than normal cast iron, this reduction in wear is undoubtedly due to the increased corrosion resistance of this material.

Several disadvantages in the use of austenitic materials are its high cost and poor machinability. One way of getting around these undesirable factors is the use of short austenitic sleeves about 1½ to 2 inches long which are shrunk into the top portion of a cast-iron bore, the zone of greatest corrosive attack. The cylinder is then bored to size throughout its entire length.

VII. Conclusions

From the discussion presented, it is evident that the wear problem, as a whole, is governed by two primary factors: operating conditions and design characteristics. The control of wear by providing favorable operating conditions alone is difficult, if not impossible. Only by taking into consideration the detailed design features discussed will it be possible to build a successful power assembly of piston, rings and cylinders which will not only provide extremely low wear rates but also provide good performance over a long period of operating life, even under heavy-duty operation.

Application of these design principles in a number of cases may be, at best, a compromise between the desired effects to be gained and the increased first cost. Present trends toward high specific output will eventually make the adoption of such design features as chrome plated piston rings, wear-resistant liners and other means of minimizing wear mandatory, if satisfactory service and long engine life is to be realized.

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