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LUBRICATION AND LUBRICANTS.

PART I.—LUBRICATION.

In unlubricated bearings the frictional force between the journal and the bearing is dependent mainly on the applied load and is nearly independent of the velocity of rubbing. It follows that the work converted into heat by friction varies with the product of the load and rubbing velocity. The heat that can be carried away for a given temperature of bearing will vary roughly with the area of surface in contact, so that the product of the bearing pressure and rubbing velocity (p.v.) will form a limitation to the design of such bearings. This limit is, of course, very low in entirely unlubricated bearings, but if a meagre supply of oil is introduced sufficient only to make the surfaces " greasy " it is found that the friction is much reduced and higher loads can be carried or greater rubbing velocity allowed. A figure much used in design of bearings of this type is p.v. not to be greater than 2,500 where pressure is measured in lbs./in.^{2} of diametral area of bearing and velocity in feet per minute.

It is of interest to note that the oil adheres very firmly to the metal surfaces and indeed once a journal is made " greasy " it will remain so until the original surface is worn away unless some special solvent is used to dissolve the oil.

If a copious supply of lubricant is introduced, the type of lubrication changes, with a very marked decrease in the frictional force and the new type of lubrication is called " film lubrication."

Roughly speaking, the introduction of small quantities of oil will reduce the friction of a bearing by about 10 to 1, and film lubrication will produce a further reduction of some 10 to 30 to 1 according to the particular conditions.

Film Lubrication.—In modern bearings for comparatively fast running machinery, such as Electric Motors, Turbines, etc., where a plentiful supply of oil is available, the lubrication assumes the type known as fluid or film lubrication. The journal runs eccentrically in the bearing, but the surfaces of the journal and bearing are separated by a film of lubricant ; due to the eccentricity, the surfaces of journal and bearing form a " wedge " into which oil is drawn by the rotation of the journal in a manner similar to the action of the Michell Thrust Block, *see* Fig. 1.

The theory of this form of lubrication was first investigated by Osborne Reynolds, following upon some experiments by Beauchamp Tower.

Without going into the somewhat lengthy mathematics of the investigation, the results may be given as follows :—

The permissible distance between the journal and the bearing at the point of nearest approach is limited by the roughness of the bearing surfaces.

With this limitation, for a bearing of given diameter, the permissible load per unit wetted area will vary with the viscosity of the lubricant, the rubbing velocity and inversely as the initial clearance provided.

The bearing loss, however, will vary with the viscosity of the lubricant, the square of the rubbing velocity and inversely with the initial clearance.

The requirements for a bearing to carry heavy loads, viz., a viscous lubricant, a high rubbing velocity and small clearance are therefore opposite to the requirements for low loss.

It should be noted that since the bearing " loss " consists of work converted into heat, it is necessary that this should be limited in order that the bearing may run cool.

The theory of lubrication set forth above presumed an oil film which was continuous round the bearing and a bearing of infinite length and therefore needs some modification for practical bearings, but experiments recently conducted by Professor Goodman and others have confirmed the general conclusions.

Fig. II shows the distribution of pressure in a journal bearing according to the Osborne Reynolds theory in the form of a polar graph. In practice, the high pressure is obtained in accordance with theory before the point of nearest approach, but the suction obtainable is limited by the Ultimate Tensile strength of the lubricant (about ½ ton/inch^2).

Journal Bearing Practice.—Since theory indicates that the requirements for high loading capacity and low loss are opposite, journal bearing practice resolves itself largely into a compromise between these two requirements.

In large turbine bearings, pressures up to 150 lbs./in.^{2} diametral area are often used, but 175 lbs./in.^{2} has seldom been exceeded.

Rubbing velocities usually found are about 150 ft./sec.

The supply of oil is many times that required for lubrication alone, the oil being used as a medium for carrying the heat away. There is no need to supply the oil under a definite pressure so long as the bearing is kept flooded ; to ensure the lowest loss the supply should be regulated by the temperature of the oil flowing from the bearing. Temperatures of 140° F. are quite safe in service practice, and bearings will usually be satisfactory with oil temperatures of 150° to 160° F. As the oil temperature increases its viscosity decreases, thus attaining lower losses at the expense of load carrying capacity, so that a temperature satisfactory for one bearing may be too high for another which is more heavily loaded.

It is found that the best results are achieved by bedding the journal on to the bearing over an arc of about 60 deg. and washing away the white metal at the horns of the bearing. If the bearing is bedded over a greater arc than this, disturbances are sometimes set up which are indistinguishable from those resulting from an out of balance condition of the rotor.

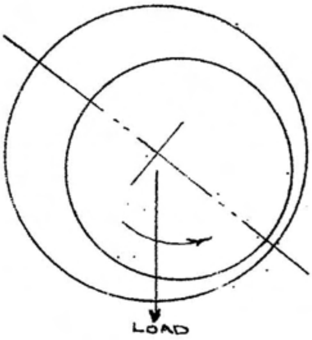

FIG: I

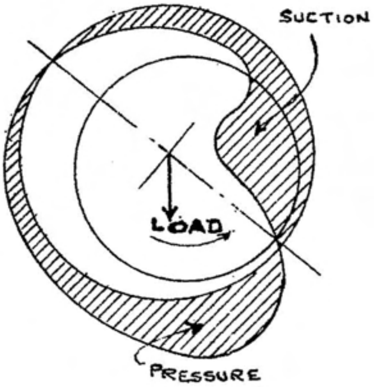

FIG II

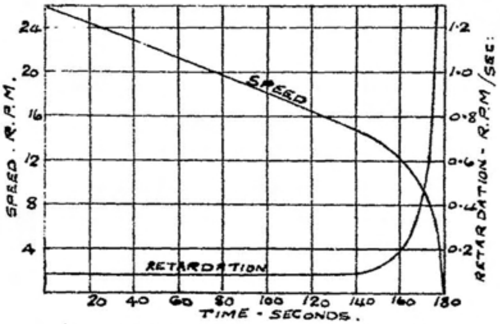

FIG III

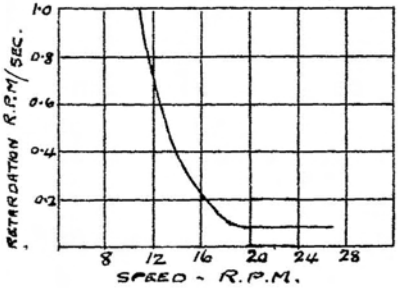

FIG. IV

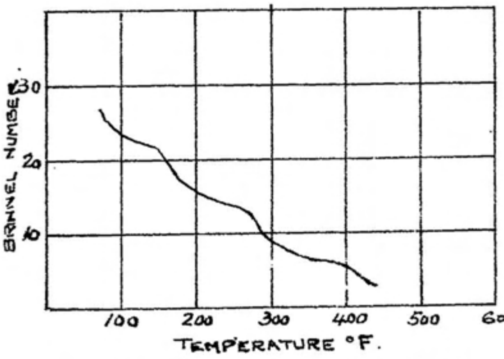

FIG. V

.HARDNESS OF TIN BASE WHITE METAL AT
VARIOUS TEMPS:

It was formerly common practice to make the bearing length not less than 1½ to 3 times the diameter, but modern bearings are often not so long as their diameter. Modern practice for turbine bearings, etc., where reversing loads are not imposed, tends to larger clearances, from 1½ to 3 thousandths of an inch per inch diameter being usual, the larger clearance ratios being used for smaller bearings.

At low rubbing speeds the oil film breaks down, and the lubrication reverts to the earlier type described. Tests on a large turbine were made by running the turbine up, then shutting off the steam supply and allowing it to come gradually to rest and plotting a graph of the speed and retardation on a time basis (Figs. III and IV).

At about 18 r.p.m. in this case the retardation became rapid, showing the very much greater resistance due to bearing friction on the breakdown of the oil film. This resistance would of course manifest itself in heating and wear of the bearings if the turbine were run for any length of time below the film breakdown speed. If the load on a bearing is greater than 200 lbs./in.^{2}, there is a liability that it will fail on starting up, as the oil may have been squeezed out during the period of rest and sufficient heat may be generated to cause failure before the oil film is established.

It is of interest to note that oil is not the only lubricant that may be used. Other fluids and even air may be used instead, but air has the disadvantage that its viscosity increases with temperature rise, whilst that of oil falls. Hence, if heating commences the rise in viscosity tends to increase the rate of heating and air is therefore only satisfactory for light loads.

In order to provide for the starting up conditions, however, before the film forms, it is in practice essential to use oil in the majority of cases.

Since the running clearance at the point of nearest approach is very small (of the order of ½ a thousandth of an inch in main turbine bearings) the cleanliness of the oil supply is very important, as particles of grit, etc., if larger than the clearance may cause wear of the bearing surfaces.

The rigidity of the bearing brass and housing is also of great importance, since the maximum film pressure may be of the order of a ton per square inch and if the bearing flexes appreciably under this load a great deal of the bearing surface will become non-effective.

In single-acting engines, the gudgeon pin bearings take longer to form an oil film owing to the intermittent motion and low rubbing velocity, and particular care is necessary in selecting the material of the pins and bearings. This specially applies to Diesel engines where the loads are high.

It is important in all engines to bar the engine round or turn it by turning gear and pump round oil before they are started, but it is particularly important in Diesel engines. When the engine has been stopped for a long time, it is a good plan to jack up the pistons and pump oil round before starting.

The action of the Michell thrust bearing is well known and need not be described here, but some particulars of the loading capabilities of this bearing may be of interest.

In normal practice the mean pressure on the total area of the thrust pads is limited to 250—300 lbs. per sq. in., but mean pressures as high as 600 lbs. per sq. in. have been carried satisfactorily and in one experiment a maximum pressure as high as 7,000 lbs. per sq. in. was recorded before failure occurred due to the excessive crushing stress on the whitemetal of the pads. So far as the oil film is concerned there is no sign of breakdown even at the highest loads, and where failure has occurred in this type of bearing it is probably attributable to particles of grit in the oil in all cases. Well filtered oil is of even greater importance for Michell thrust bearings than for journal bearings.

PART II.—LUBRICATING OILS.

Until the latter half of the last century, lubricating oils were derived almost entirely from the animal and vegetable kingdoms, but the vast strides made in the use of machinery have, apart from the question of their suitability, made these sources totally inadequate. The rise of the Petroleum industry fortunately coincided with the increasing demand, so that lubricating oils derived from the crudes were used as substitutes. Moreover, it is found that they are more suitable for modern requirements. In fact, animal and vegetable oils are now chiefly used "compounded" with mineral oils to augment, in some particular or other, the properties of the straight or refined mineral oil.

Vegetable Oils.—These are prepared by pressing, or "extraction" by solvents, of the oil from the seed pods. For many purposes subsequent purification is necessary; the quality of the oil depending on the extent to which this is carried out, *e.g.*, the medicinal castor oil is a very different finished product from the castor oil used in aircraft engines.

All vegetable oils oxidise and gum when in contact with oxygen; the ones least affected such as rape, olive and castor being used as lubricants. This, together with the fact that they do not separate out satisfactorily when mixed with water, entirely precludes their use for turbine forced lubrication.

Blown Oils.—Vegetable oils are sometimes artificially thickened by a process of partial oxidisation. This consists of blowing air through the oil, heated to a temperature of about 200° F. Oils thus treated increase both in density and viscosity, and are distinguishable by their characteristic nauseous smell. They are readily soluble in mineral oils and are chiefly used to thicken these oils.

Mineral Oils.—Crude Petroleums are very complex liquids—differing by reason of the different series of hydrocarbons present. Broadly speaking, crude oils may be divided into three classes. "Paraffin Base," "Asphaltic Base" and "Mixed Base" Oils. Paraffin Base crudes are those oils which yield an ultimate residue of paraffin wax. Pennsylvania is the only important source of supply of paraffin base oil. This oil after distillation of the "Motor Spirit," "Illuminating Oils" and "Diesel Oils" and a distilled lubricating oil leaves a residuum which is a thick lubricating oil, requiring only refinement with steam and Fullers Earth to make it fit for use as a lubricant. It is sometimes called "Bright Stock" and is used now chiefly as a thickener to blend with other mineral oils which are too thin after distillation.

The distilled lubricating oil is the best mineral oil from the Demulsification standpoint. Oils from paraffin base crudes are distinguished by a low specific gravity, usually in the region of 0·880.

Asphaltic base crudes are those oils which on distillation leave as a residue asphaltum or bitumen (California and Mexican oils). These oils are darker in colour, of greater density and more viscous than paraffin base oils.

Mixed base crudes, as the name implies, leave both paraffin wax and asphaltum as a residuum (Persian, Burma, Russian and some American oils). Both asphaltic and mixed base crudes are distilled, yielding lubricating oil. The less viscous are easily obtained, but the heavier fractions are smaller, and therefore it is very usual to blend some Pennsylvanian Bright Stock with these distillates to obtain oils suitable for use in Internal Combustion Engines. Lubricants obtained from both these crudes are usually referred to as Asphaltic Base oils.

It must be remembered that experience is the main factor that decides the type and quality of an oil suitable for any particular duty, and a specification is only necessary to ensure as far as possible that future supplies are of the same grade. The chief objects of a specification for oils used in forced lubrication systems are to obtain an oil that :—

(1) Will separate out from water.
(2) Will not oxidise and thicken after prolonged use or form sludge.
(3) Has acidity and sulphur content as small as possible.
(4) Has suitable viscosity at the probable working temperatures.

The difference in the anti-friction qualities of various mineral oils is so small that it is not worth measuring in practice and therefore does not enter as a criterion of the oil. It is important that the oil is used at its most economical temperature of course, depending chiefly on the speed and load of the bearing and the viscosity of the oil.

Lubricating oils may be divided into three broad classes, depending on the service for which they are required.

1. **Drip Fed Bearings.**—In drip fed bearings and other bearings where the oil film cannot be maintained, the bearing has in general to be content with "greasy" conditions, and the supply of an oil with good "oiliness" is indicated. Without doubt, vegetable oils are superior in this respect to mineral oils. They have, however, the disadvantage of drying and choking the worsteds, and also contain free fatty acids which in time are detrimental to the bearing surfaces. In practice, a blended oil meets the requirements most satisfactorily; such is "Admiralty Compound" oil, which is specified to be a refined mineral oil with not less than 10 per cent. of blown rape oil. It is required to be able to syphon through the ordinary worsted, and therefore its viscosity is limited to between 1,000 and 1,200 seconds in the Redwood viscometer No. 1 at 70° F.

2. **Turbine and Forced Fed Reciprocating Engines.**—The prime considerations in the selection of a suitable oil are that the oil should not thicken or sludge, and should separate out from the steam that must inevitably condense and mix to a certain extent with the oil. Paraffin base oils are more reliable in this respect than asphaltic base oils.

The Admiralty specification for this oil limits the specific gravity to 0·880, below which it is not possible to obtain asphaltic base oils. Further, the oil is required to be tested in a "Demulsification" machine, consisting of a gear wheel pump, pumping a mixture of two parts of oil and one of water from and back to a container for a total of one hour at 160° F., after which it must separate out under certain prescribed conditions.

Recently the "Edeleanu" treatment has been introduced for improving the demulsification properties of asphaltic base oils. This consists of passing liquid SO_2 for a period through the oil. This has the effect of extracting the heavier and less stable constituents of these oils. Some results, before and after treatment by this process, are given below. It remains yet to be proved if this treatment has any deleterious effects on the other properties of the oil.

	Asphaltic Base.	
	Before Treatment.	After Treatment.
Demulsification I.P.T. Test Seconds	250 (Approx. only)	60

Experience indicates that viscosities of not less than 105 seconds at 140° F. and of not less than 50 seconds at 200° F. are suitable figures for this type of machinery. To ensure that the pumping losses are small the viscosity is specified to be not more than 700 seconds at 70° F.

3. **Internal Combustion Engines.**—In the vast majority of Internal Combustion Engines the same oil is used for both the bearing and piston lubrication, although the temperatures at which they work must differ considerably. No comparative data are available from actual engines of the comparative wear of bearings using oil of different viscosities. In a special bearing testing machine definitely less wear has been shown to occur with lower viscosity oils. The bearings themselves run at a higher temperature with more viscous oils, other factors being equal; this would seem undesirable from the reduced hardness of the white metal alone. Fig. V gives the Brinell figure plotted against the temperature for a Tin Base White-Metal. The bearing temperature may easily be 30° to 40° F. higher than the return oil, and it may be that with high oil temperatures the white metal has lost nearly half its resistance to crushing.

The jacket temperatures may vary from 32° to 212° F. and throughout this range of temperature the oil, with its viscosity varying from several thousands to 50 to 60 Redwood seconds, continues to lubricate. Very little can be laid down in the way of figures as to the most suitable temperature and viscosity for piston lubrication. The latter may be assumed to range between 200 and 50 seconds. So as not to fall below this latter figure with engines running with high jacket temperatures, it is necessary to use a thick oil. This has the disadvantage that at low temperatures it is very much too viscous for efficient pumping or bearing lubrication. In order to obtain an increase of viscosity of 30 seconds at high temperatures it will be necessary to substitute an oil which at low temperatures may be four times as viscous as the one replaced.

In general, the viscosity of mineral oils decreases with temperature at a greater rate than that of vegetable oils. For this reason, compounded oils are sometimes used in an endeavour to secure suitable viscosity figures at high temperatures without the disadvantages of a pure vegetable oil. An example of such compounding is the well-known Castrol R., which contains 12 per cent. mineral oil.

The present trend of opinion is that no advantage is obtained either in efficiency or wearing qualities of an engine by the use of a compound oil; and, anyhow, if anything is gained it is more than offset by the additional carbon and sludge formed by these oils. Compound oils must not be used where there is any possibility of even small quantities of water finding their way into the oil.

Undoubtedly, the use of a thinner oil results in increased loss of oil past the rings, and this is only the disadvantage attendant on the use of oils thinner than those in general use commercially in these engines. In the Service, although extreme conditions are possibly not met with, Admiralty Special Mineral, because of its flat viscosity curve, together with its proved small sludging properties, appears from the evidence available to be as suitable an oil as any.

The changes in lubricating oils when in use may be grouped under two heads :—

(1) Formation of carbon deposits and sludge.
(2) Changes in the physical and chemical properties of the oil.

Formation of Carbon and Sludge.—There appears little doubt that the carbon found in the crank case and in the cylinders is mainly due to incomplete combustion of the lubricating oil carried past the piston. In Diesel engines this is possibly accentuated by the incomplete combustion of the fuel spray as well. Particles of oil in the process of combustion come into contact with the piston crown and cylinder walls and are cooled. Combustion then ceases, leaving a residue of carbon and gummy matter, which either gets caked into the hard carbon found on the piston tops, or gets carried down into the crank pit.

Owing to the longer periods of exposure to high temperature occurring in Diesel engines, these deposits contain more carbon and less gummy matter than is the case in petrol or paraffin engines ; and, in consequence, these particles adhere less readily to the piston tops, but are equally easily caught by the oily surface of the cylinder walls. This seems to account for the rapid fouling of Diesel oils, and the smaller carbon deposits on the piston crown.

Mineral oils vary considerably in the amount of carbon they deposit. A pure distilled mineral oil is much superior in this respect to a mineral oil containing " Bright Stock "—a cheaper oil. " Bright Stock " being a residuum, resists evaporation and therefore remains in droplet form, and, having been " cracked " by the intense heat, provides gummy carbon that will be deposited on the piston and cylinder walls. The results of 50-hour tests on a water cooled petrol engine, using various grades of mineral oils, are given below :—

——	Pure Distilled Oil.	Distillates, 80 per cent. ; Bright Stock, 20 per cent.	Distillates, 60 per cent. ; Bright Stock, 40 per cent.
Oil consumption in 50 hours (pints)	1·5	1·45	1·75
Carbon on piston crown (gms.)	0·43	0·90	1·43
Carbon on piston crown (gms.) per pint of oil consumed	0·37	0·62	0·82
Visc. (Unused Oil), Red :			
1 at 70° F.	2,470 secs.	1,980 secs.	1,922 secs.
1 at 140° F.	175 „	175 „	190 „
1 at 200° F.	58 „	60 „	66 „

The idea that the carbon found round the piston ring grooves is baked lubricating oil is probably fallacious. Laboratory tests of oil maintained at temperatures considerably in excess of any likely to occur near the piston rings fail to produce a solid " coke " in anything like the amount found in practice.

The sludge found in crank cases are by no means composed entirely of " carbon " carried down by the oil; they vary from almost hard carbons to soft slimes. Experiments carried out by Messrs. Ricardo have shown that even a small percentage of water (1 per cent. of the oil) greatly increases the amount of sludge produced. There is a complete lack of evidence regarding the sludge forming properties of the various mineral oils; all that can be said at the present time is that pure mineral oils are superior to compound oils in this respect.

Changes in the Physical and Chemical Characteristics of the Oil.—Although mineral oils are slightly acid and slightly oxidisable, these quantities are so faint as not to be comparable with those of vegetable oils. The acidity increases slightly in mineral oils after long use at high temperatures, but is most unlikely to become of practical importance. Further, the small amount of unsaturated compounds in a good distilled mineral oil should not affect, by their oxidisation, the properties of the lubricant to any appreciable extent. No chemical or physical change, beyond these, is known to occur which affects in any way the lubricating properties of a mineral oil itself however long it has been in use.

The criterion governing the period over which oils are retained in use is entirely a matter of the amount of foreign substances picked up by the oil during its circulation. In steam systems, dirt and water are the two important items. If the oil is allowed to stand preferably at a temperature of not less than 100° F., the water separates out and in so doing assists materially in carrying down the particles of dirt. The carbon and sludge formed in oil engines is not so easily removed, their specific gravities being near to that of the oil. For this reason centrifugal separators have been introduced. These have the effect of virtually increasing, by centrifugal force, the difference between the densities of the oil and various impurities. In effect, the centrifugal separator performs the service of a settling tank, but in a small fraction of the time required for settling the oil.