A STUDY OF OIL-FILM PERFORMANCE BETWEEN PISTON RINGS AND CYLINDER WALL BY THE ELECTRICAL MEASUREMENTS

by

YOUN-HUNG TING

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I. INTRODUCTION

The main purpose of lubricating oil is to maintain an oil film of satisfactory thickness in order to prevent two moving surfaces from scuffing; therefore, reducing friction and wear.

When two surfaces have oil supplied to them continuously and the load on them is not excessive, there is what is known as complete-film lubrication or hydrodynamic lubrication. The surfaces are separated by the lubricant. As long as a complete film is maintained, the friction loss is independent of the load on the surface and is dependent only upon the rubbing velocity and the viscosity of the oil. When the load is increased, or when the speed or the viscosity is decreased, the surfaces are separated only by a few molecular layers of oil. The chemical and physical properties of the metal surface and lubricant become important. This type of lubrication is termed "boundary lubrication." The general conditions which dictate "boundary lubrication" are relatively high load, high temperature, low speed and a low oil viscosity.

Whether the lubrication between the piston rings and cylinder wall in an internal combustion engine is of the hydrodynamic or of the boundary type is a question about which there are different opinions. However, reviewing experimental evidence, there seems to be no doubt that both types of lubrication exist. The local breakdown of the oil film not only consumes power due to friction but also causes serious abrasive wear on metals.

The combination of high temperature, high pressure and low speed at dead center positions of piston complicates the lubrication of piston rings. No satisfactory theoretical treatment, such as the journal bearing has received, has been brought forth for the problem of piston ring lubrication. Such knowledge, therefore, can be gained only by experimental work.

The electrical-resistance-measurement method has been used in the study of the oil properties between two working surfaces such as gears, disks etc.. Since oil is a kind of dielectric material, there is only a small limited range of voltage that can be applied across it. Beyond this range, the breakdown of the oil occurs because of ionization. It was found that the thickness of oil film was directly proportional to the applied voltage. Based on this knowledge this investigation was carried out.

II. REVIEW OF LITERATURE

The destruction of the oil film on cylinder surface was discussed by E.A.V. Horiak in 1933.(1) He stated that the destruction may take various forms. The film may be destroyed by the oil being forced away by too high a pressure. This high pressure may be attributed at times to (1) dirt, sand or metal which cause a high localized pressure that produces dry friction; (2) too high a specific pressure between the acting parts such as rings against the linear; (3) viscosity of the lubricant being reduced by dilution so that even small pressure will force the oil away; (4) high temperature reducing the viscosity which deteriorates the oil to a point where low pressure will break it down.

The temperature in the cylinder may become high enough actually to burn or carbonize the oil between the sliding surfaces. Horiak also claimed that the oil can be removed by external means such as being blown away by gas pressure, shaken off by the velocity of moving parts. Horiak pointed out, that for an engine having a compression ratio of 15:1 and a piston speed of 1500 ft/min, a temperature of approximately 5000°F at the point of ignition may be reached and falling rapidly to about 2550° F at a 60 degree crank angle. There are extremely high temperatures and could no doubt cause the actual vaporization of the extremely thin layers of lubricating oil. Of course, the rings do not operate at such peak temperature; however, they do operate at relatively high temperatures depending solely upon how well the rings are cooled. Mr. R. L. Boyer has stated that, for a well cooled two-cylinder engine, the section adjacent to the top ring has a maximum temperature of 164° F and that the third ring-land has a temperature of 161° F. Temperature of 500°F are not uncommon in the ring section of pistons which are not well cooled.(2)

Another important factor associated with piston ring lubrication is that zero velocity existed at dead center positions. It will be shown later that the oil-film thickness varies directly with speed at any given load. The breakdown of the oil film at top and bottom dead centers is therefore obvious. Also another complicated situation arises at the top ring where there is almost a complete lack of lubrication. The quantity of lubricant that may be fed to the top piston ring is extremely minute. However, a good portion of this minute quantity is burned off the cylinder wall before it gets a chance to lubricate the piston ring.

The piston rings are so constructed so that they are under tension which exert a pressure of 5 to 15 psi against the cylinder wall. When the gas pressure of combustion is applied above the piston, some of the gas leaks to the back of the ring, which causes the ring to be forced tightly against the cylinder wall. (17) (18) This phenomenon has been studied and discussed by several researchers.(3)(4) The measurements indicated that gas pressure behind the top ring follows closely the pressure in the combustion chamber. The gas pressure behind the second ring depends upon the sealing conditions of the first ring, but was found to average about half to one fourth of that in the combustion chamber. It was found from the experiments performed on an actual engine that the maximum gas pressure during the power stroke for first ring was 470 psi under full load operation conditions.

The electrical measurement method is one of the methods that has been used in the study of the thin film lubrication between two working surfaces.(5)(6)(8)(16) The differences in oil-film thickness might be indicated by the change in the measured resistance. Since the oil is a dielectric material, the characteristics of liquid dielectrics are a function of many factors which are uncommon in true conditions.

Early work by F.P. Bowden and D. Tabor (1939) has shown that considerable information concerning the area of contact between the stationary and moving surfaces may be gained by measuring the electrical conductance across these surfaces.(7) If two conductors make metallic contact over a circular junction of radius "a", the electrical conductance Λ of the junction can be written with sufficient accuracy as,

$$\Lambda = 2a\lambda$$

where λ is the specific conductivity of the metal.

If the conductor and the electrode are of different metals with conductivities of λ_1, and λ_2 respectively, the maximum conductance Λ_m corresponds to a single circular metallic junction of radius "a" was shown to be:

$$\Lambda_m = 4a \left(\frac{\lambda_1 \lambda_2}{\lambda_1 + \lambda_2} \right)$$

Their experiments were carried out on both stationary and moving surfaces. The results showed that regardless of whether the surfaces were lubricated under boundary conditions or not, the conductance and hence the area of contact was independent of the apparent area of the surfaces. For example, the conductance for two flat plates was found to be only twice that of two crossed cylinders even though the apparent area of contact was 40,000 times as great. This showed that only a small fraction of the surfaces was in intimate contact.

The experiments showed that the conductance depends on the load applied on these surfaces. Even if the surfaces are carefully polished, slight irregularities will still be present. The depths of the surface irregularities were found to be very large compared to the molecular dimensions of the oil. It was expected then, that under boundary lubrication conditions, the breakdown of the film would occur. The surfaces would be supported on the summits of the surface irregularities, and the real area of contact would be small---within molecular range. This means that, even with comparatively lightly loaded surfaces, the local pressure at the region of contact would be high and might easily exceed the yield point of material so that plastic flow and deformation occurred at the point of contact. If the sliding speed of the surfaces was sufficiently high, the process was assisted by a local high-temperature softening or melting, and finally caused the seizure and welding between the metals.

V. H. Brix in 1947, made his experimental study of the passage of an electric current through a thin oil film between working surfaces.(9) In the investigation, the thrust type of friction machine was employed. This machine consisted of a rotating element containing four flat circular pads. These rotating pads were pressed against a stationary disk within a heated oil bath. The results showed that at constant speed, the voltage across the film varied with pressure. An increase in thrust load would result in a decrease in voltage. It was therefore reasonable to ascribe the change in film voltage as evidence of changing the oil-film thickness between the pads and the disk.

When the voltage across the film was plotted against the current, the result curves are shown in Figure 1. The slope of the current-voltage curves increase rapidly with increase in voltage. Until a certain critical voltage across the oil film is reached, the current under this voltage increases to infinite value and the breakdown of the oil film occurs. To establish the relationship between the oil-film thickness and the oil-film voltage between two parallel plates, Mr. Brix made the static electrical tests on a machine consisting of two parallel disks both being finished with emery paper. The small distance between these two disks were recorded by means of the deflection of a light beam, the magnification so obtained was in the order of 1,025 times the distance between the two disks. The voltages across the film were obtained at a constant current setting of 2 amps. It appeared from the test that the relation between film thickness and film voltages was almost linear. The film thickness was found to increase with the voltage. Furthermore, it was found that the oil-film thickness at electrical breakdown lie roughly over a range from 10^{-4} to 10^{-3} inches. Brix also stated that the voltage-thickness characteristics was not greatly affected by the surface temperatures, but the moisture content of the oil was found to be a most important factor. The breakdown voltage dropped very rapidly with only a slight increase in moisture. The properties of "boundary" film depended upon the lubricant and upon the nature of metal surfaces between which the oil was enclosed. It was found by Mr. Brix that the voltage across the film increased as the load decreased but increased with speed of the surfaces.

A. Cameron and his co-workers (10) in 1958 made an electrical investigation on the study of thin oil-film characteristics. In their experiments, an one-inch steel ball was placed on an insulated steel plate. Both the ball and the plate were connected to an electrical current

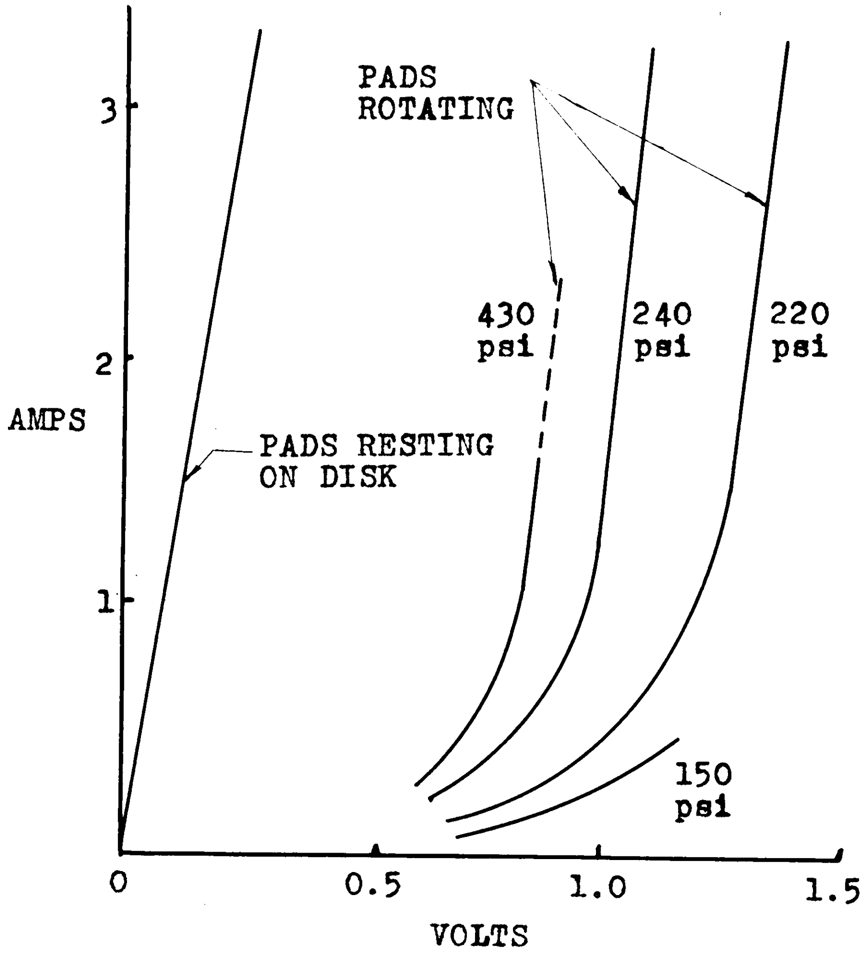

FIGURE 1: THE ELECTRICAL CHARACTERISTICS OF OIL FILM BETWEEN CHROMIUM AND STEEL AT SEVERAL LOADING PRESSURES.(9)

source. When the plate supporting the ball was flooded with oil, the ball separated from the plate by a small distance, the voltage-current curve changed greatly. At a current value above ½ amp, the curve was parallel to the ohmic line and the voltage was shown essentially constant from ½ amp up to 350 amps. The curves are shown in Fig. 2. The vertical distance between the ohmic line and the curve obtained with the presence of an oil film was defined as the "discharge voltage." Therefore, the discharge voltage is the "net" voltage change caused by the oil film. This voltage was found to be independent of the types of oil having different viscosities as long as those oils were taken from the same crude.

The relationship between current, voltage and resistance of oil film had been well explained by A. Cameron in his earlier work done on gear teeth in 1954.(11) Curves of resistance versus current were plotted and the following equation found:

$$RI^k = C$$

where, C = constant
R = resistance (ohms)
I = current (amps)
k = constant

The curves are shown in Figure 3. If $k = 0$, then R = constant. This is shown by the current-resistance curve being comparatively flat at lower values of current. The oil behaves more or less as an ohmic resistance. If $k = 1$, then RI = constant. This indicates that regardless of the value of current, the potential across the film is constant, and this constant is the breakdown voltage of the insulating oil film.

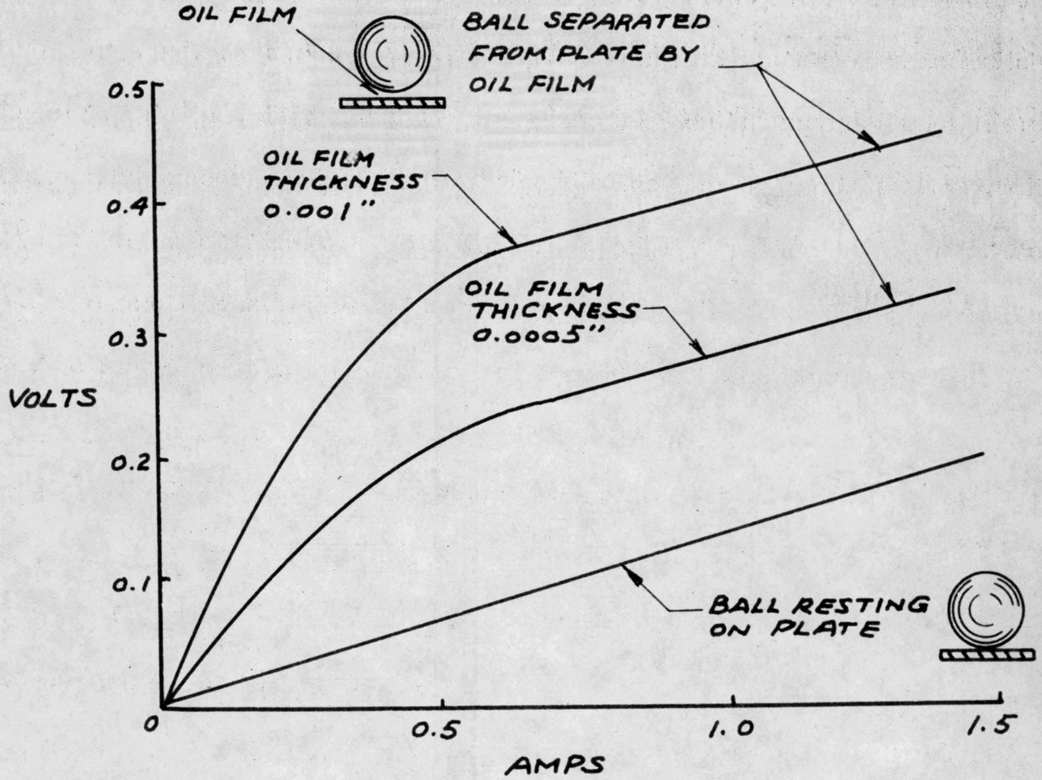

FIGURE 2: VOLTAGE/CURRENT CURVES OF THIN OIL FILM.(10)

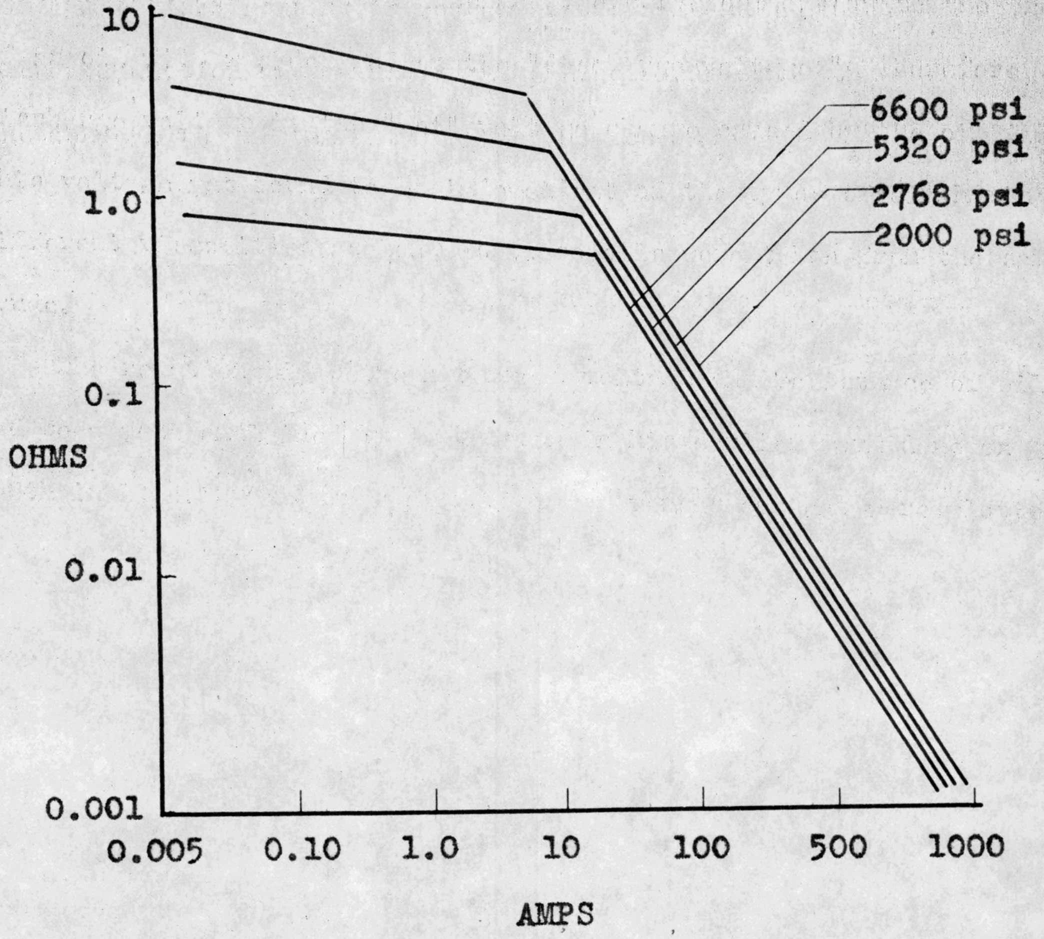

FIGURE 3: THE CURRENT-RESISTANCE CURVE OF THIN OIL FILM AT DIFFERENT PRESSURES.(11)

The electrical breakdown phenomenon was well explained by A.H. Sharbaugh and R.W. Crowe.(14) Consider a system composed of a liquid dielectric placed between two parallel-plate metal electrodes. If a voltage is applied to the electrodes, free electrons are accelerated toward the anode. The acceleration will continue until the rate at which electrons lose energy by collision with molecules just equal the rate at which they gain energy from the electric field. The electric current at this time will remain small. If, however, the applied voltage is sufficiently high, the free electrons gain enough energy to knock other electrons from the molecules of the liquid. Since each new electron produced by collision is also free to undergo the same process, the result is an electron avalanche. The liquid is said to be fully ionized. Under this condition, the electric current through the liquid will be high enough to lead to a runway process culminating in the spark. The liquid is converted rapidly from an insulator to a conductor and the breakdown of oil film occurs.

During their investigations, Cameron and his co-workers made the static and dynamic calibrations between film voltage and film thickness.(10) It was found from the static calibration that the film thickness and film voltage were proportional to each other. (This result was in agreement with the work done by Mr. Brix in 1947) The dynamic calibration apparatus consisted essentially of a rotating shaft against which was loaded very slightly by two ½ inch plates. There was an angle of inclination between these two plates. When the shaft was rotating, there would be a thin oil film building up between the shaft and the plates, which was then detected by a light beam. The results showed that: (1) the value of the variation of the film voltage with film thickness was slightly lower than which was gained from the static calibration, but were still proportional to each other, (2) the variation in speed had little or no effect, (3) no significant difference was found when brass plate was used instead of steel, (4) the film thickness to film voltage constant was found to be 4.0 volts per 0.001 inch.

In 1952, T.B. Lane and J.R. Hughes(12) in pursuit of information concerning the nature of lubrication in gears, measured the electrical resistance between meshing teeth of rotating gears by the use of a cathode-ray oscilloscope. Measurements showed by this approach that the resistance of an oil film of 10^{-5} cm thick (of the order of the height of the asperities on the gear teeth) was about 10^9 ohms. The experimental results showed that the resistance was inversely proportional to the load applied and the sliding speed. The resistance reached its maximum value in the neighborhood of pitch line where one pair of teeth carried the load. The value of applied voltage used during the experiments was 0.2 volts.

A. W. Crook(13) in 1957 described some experiments performed with disk machine in which the electrical resistance between the rotating disks was measured. It was found that when the machine was first started the resistance was less than one ohm, and increased steadily until at the end it reached 5×10^4 ohms. This showed that there was considerable metal to metal contact at the beginning and the fully hydrodynamic lubrication was developed when the speed was sufficiently high. Mr. Crook also stated that the resistivity decreased rapidly with an increase in temperature. When the surface temperature rose, not only the oil resistivity but also the oil viscosity would decrease. This in turn reduced the oil-film thickness and would cause surface damage due to metallic contact.

The electric breakdown of non-conducting lubricating oil is accelerated by the presence of foreign bodies, such as lint, sand, metal particles and water droplets. These foreign bodies will align themselves in the electrical field to form a bridge along which discharge can ultimately take place. C.M. Allen(15) found that an addition of a small amount of silica powder caused the reduction in the oil film between a shaft and bearing surface. It was believed that the dielectric breakdown was achieved through the silica powder or else initiated by it. It was also believed that the real affect of silica grit was to disturb the bearing surface. Silica grit embedded in the surface caused localized heating, thereby resulting in a reduction of the minimum oil-film thickness.

III. INVESTIGATION

Object of Investigation

The object of this thesis was to:

1. Investigate some of the factors that might affect the oil-film performance between the piston rings and the cylinder walls of internal combustion engines.

2. Construct an electrical-resistance-measurement apparatus which could be used to study of the oil-film characteristics between the moving piston rings and the cylinder walls of internal combustion engines.

Modification and Construction of Apparatus

The Engine Used

A single cylinder, air-cooled, four-cycle gasoline engine was selected. The engine was manufactured by Reo Motors Incorporated and gave an output of 1½ hp at 3000 rpm. The diameter of cylinder was 2 inches. The stroke was measured to be 1-3/4 inches.

The Insulation

Since an electric potential would be applied across the oil film between a piston ring and the cylinder wall, it was necessary to insulate the ring from the rest of the engine block. The piston ring-groove was found to be the best place to fit the insulator.

The following considerations were made concerning this special insulation problem:

1. The insulator must have high temperature resistance. The piston-temperature at the upper ring-groove is usually around 300°F to 500°F depending on how well the piston is cooled.

2. Due to the relative motion between the ring and the piston, the insulator must have high impact strength.

3. The insulator must be inert to gasoline and oil.

4. The insulator must have low coefficient of thermal expansion.

5. The insulator should be thin.

6. The insulator could be cemented on piston permanently.

Different kinds of thermosetting plastics were tested. Most of them decomposed at temperatures up to 300°F. However, Teflon* (tetrafluoroethylene) was found to meet the necessary requirements. The properties of Teflon are shown in Appendix I.

Teflon is supplied in various sizes and shapes: powder, tubes, sheets and tapes. The 0.010 inch etched Teflon tape was selected. The etched tape was chosen since the etched side would serve as a good cementing surface.

The cement, Silicone Resin was selected because it remains flexible at temperatures as low as minus 150°F and is stable at temperatures as high as 500°F. Furthermore, Silicone Resin also has good oxidation-resistant and good dielectric properties. The Silicone Resin used in this investigation existed as glue-like material. The setting time of this kind of adhesive was two hours at a temperature of 400°F.

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* Du Pont trademark

Preliminary testing was done to test the properties of the Teflon and the cement. A small piece of Teflon tape was cemented on an aluminum block. Before cementing, the surface of the aluminum block was polished by fine emery paper and cleaned by acetone. To test the temperature stability of the Teflon and the cement, the sample was heated at 500°F for one hour. No particular change in characteristics could be found. During this preliminary test, the cement coating had a thickness of 0.003" ± 0.0005".

The piston had two 3/32 inch wide compression rings and a 3/16 inch wide oil ring. It was decided to insulate the second ring-grove because the temperature in second groove was considerably lower than that of the first groove. The dimensions of the piston are shown in Figure 4. The total side clearance between ring and ring groove was only 0.002 inch. It was therefore necessary to enlarge the ring groove in order to maintain clearances built in the engine.

The width of the enlarged ring-groove was estimated by the summation of the following terms:

1. The original width of the ring-groove (0.0975").
2. The thickness of Teflon tape (0.010").
3. The thickness of cement (0.003").

The total width of ring-groove after the enlargement therefore should be:

Original width of the ring-groove + 2 X thickness of Teflon tape + 2 X thickness of cement, which was

0.0975" + 2 X 0.010" + 2 X 0.003" = 0.1217"

The back side of the ring-groove should be enlarged according to the thickness of Teflon tape and cement which was:

0.010" + 0.003" = 0.013"

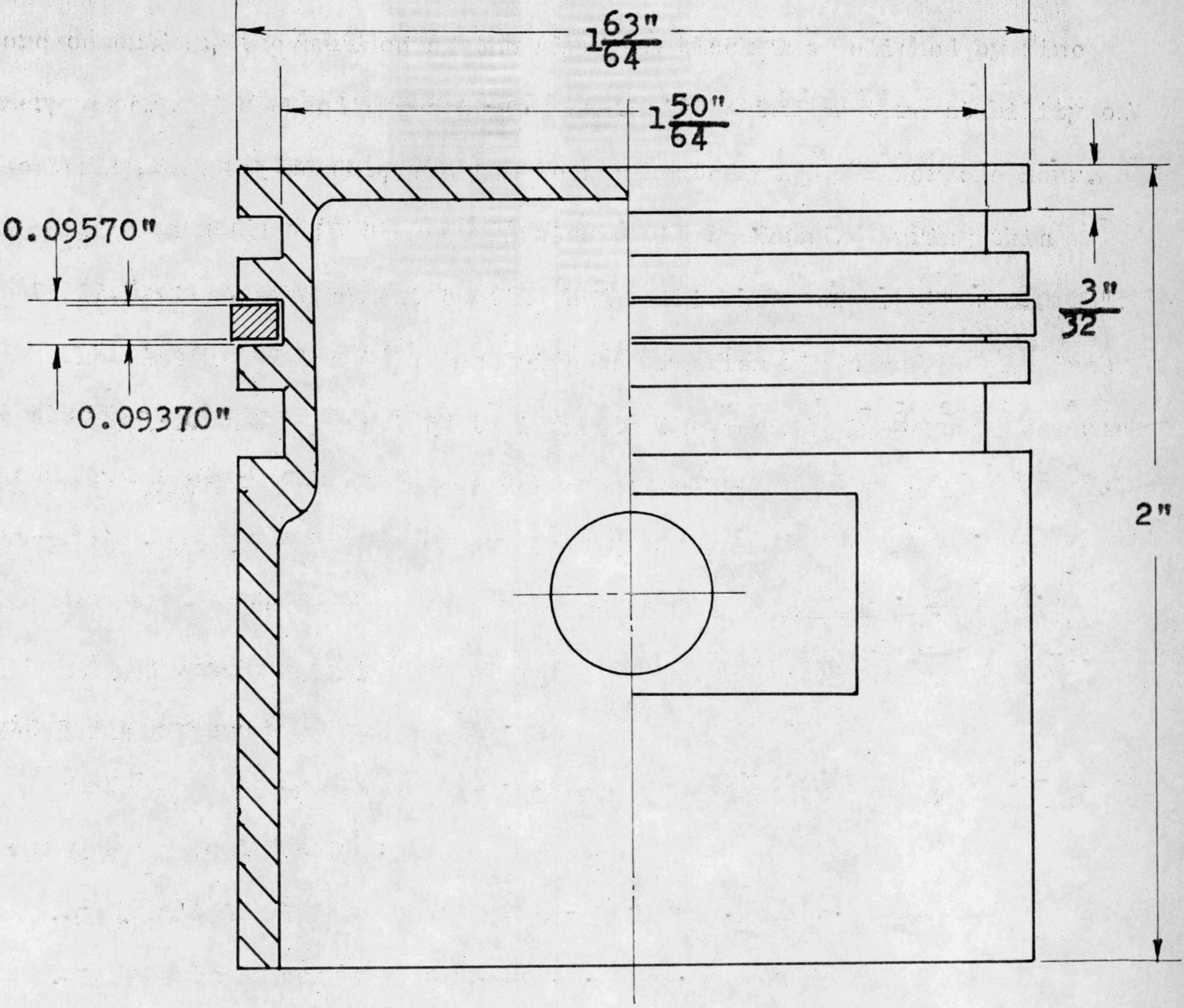


FIGURE 4: THE PISTON BEFORE INSULATION

For the purpose of the enlargement of the ring-groove, a special cutting tool was made. The width of this tool was exactly 0.1217"inch.

The second ring-groove was enlarged to the desired dimension on a lathe by using the special cutter. A hole of 3/64 inch was drilled through this groove. See Figure 7. The sectional view of the second ring-groove before and after the enlargement are shown in Figure 5(a) and Figure 5(b) respectively.

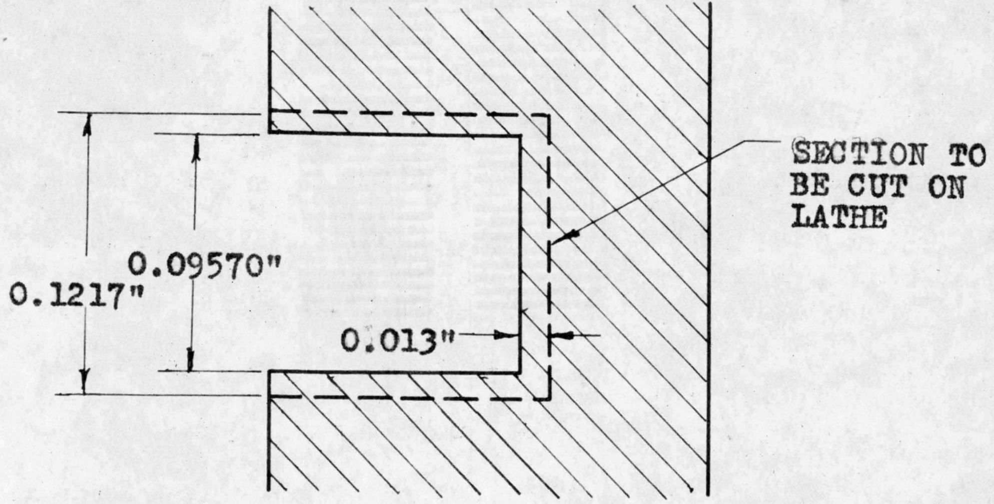
The surfaces of the enlarged ring-groove were then carefully polished by means of fine emery paper and degreased by acetone.

In order to have the ring completely insulated from the rest of the piston, both the side faces and the back face of the groove were covered by Teflon tape.

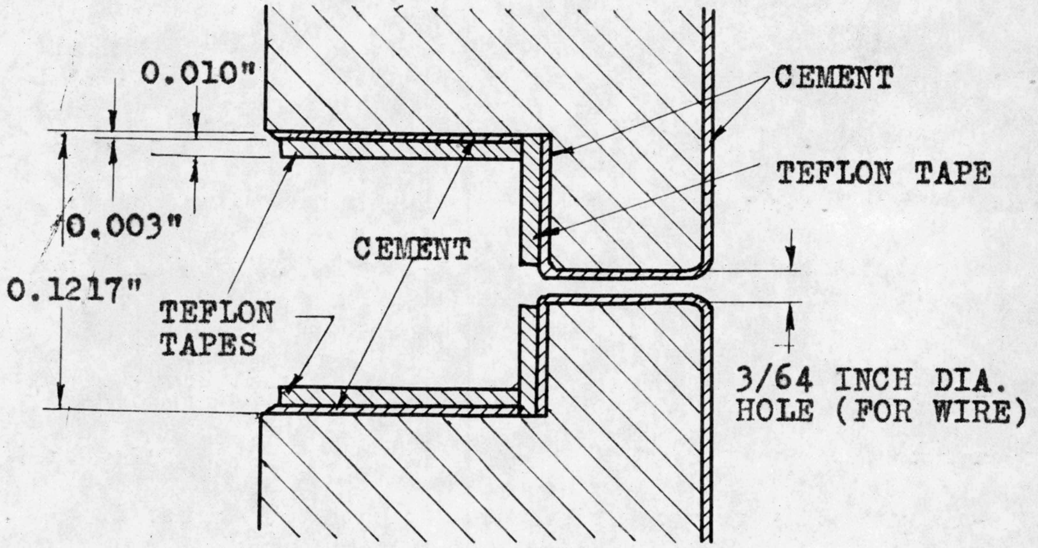
To insulate the upper and the bottom faces, two "Teflon rings" were cut off from a sheet of 1 mil Teflon tape. Each "ring" had an outside diameter of 1-31/32 inches and inside diameter of 1-25/32 inches. A Teflon strip, 5-3/4 inches long, 0.1217 inche wide and 0.010 inch thick was used to insulate the back face of the ring-groove. The Teflon ring is shown in Figure 6. The "V-shaped" cutting at point "P" was to make it easy to put into the piston ring-groove.

The Teflon insulators were then cemented to the inside of the enlarged ring-groove and heated in an oven for two hours at a temperature of 400°F. The piston thus insulated gave satisfactory results throughout the investigation.

The arrangement of Teflon tapes in the ring-groove is shown in Figure 5(b). The photographic view of the piston after insulation is shown in Figure 7. The area in the vicinity of the hole was not covered by Teflon strip but coated with silicone cement.



BEFORE THE ENLARGEMENT
(a)



AFTER THE ENLARGEMENT
(b)

FIGURE 5: THE SECOND RING GROOVE BEFORE AND AFTER THE ENLARGEMENT

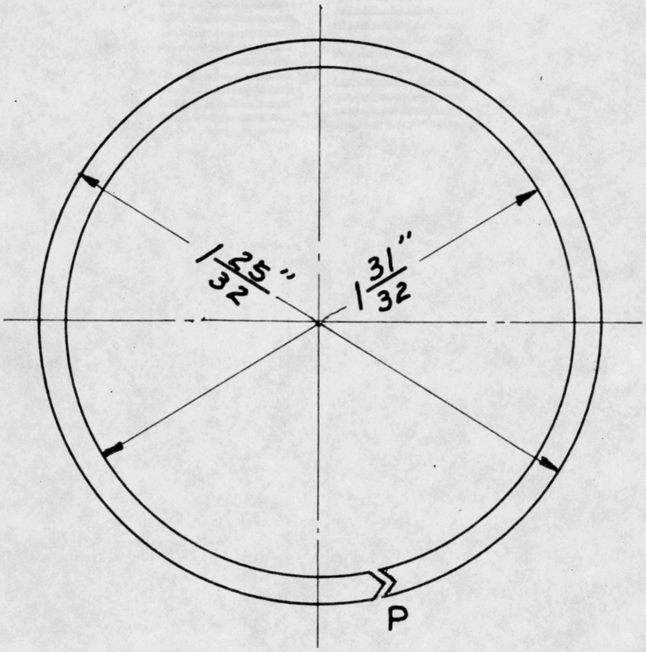


FIGURE 6: THE TEFLON INSULATING RING
(THICKNESS: 0.010")

The Piston Ring

A commercial gray cast iron, chromium-plated piston ring was used. A 7 mil diameter formvar coated copper wire was soldered in a slot on one end of the ring as shown in Figure 8. The soldered surface was then reduced to its original dimension by means of fire and sand paper. The length of the wire was two inches.

The Piston and the Method of Connecting the Leads

Figure 9 shows the position of the ring and the method of connecting the leads. The copper wire, which was soldered on one end of the ring, was led through the hole which had been drilled through the piston ring-groove wall. The spring made in the wire permitted enough flexure to absorb shock. The end of this wire was connected to a $\frac{1}{8}$ inch diameter test prod lead. The test lead was selected because of its flexibility . Both wires were then cemented on the piston skirt by using the epoxy adhesive as shown in position "A" of Figure 9.

The wire broke frequently during the early stage of testing. The wire broke mostly by tangling on the crankshaft and by being cut by the moving parts of the engine. To avoid these difficulties, the best way was to shorten the loose part of the wire within crankcase. To do so, however, the fatigue strength of the wire was considered. Figure 9 shows the arrangement of the wire. "B" is a metal clamp, which was fastened to the connecting rod by a screw. The variation in distance between point A and point B was less than one fourth of an inch during each revolution of crankshaft.

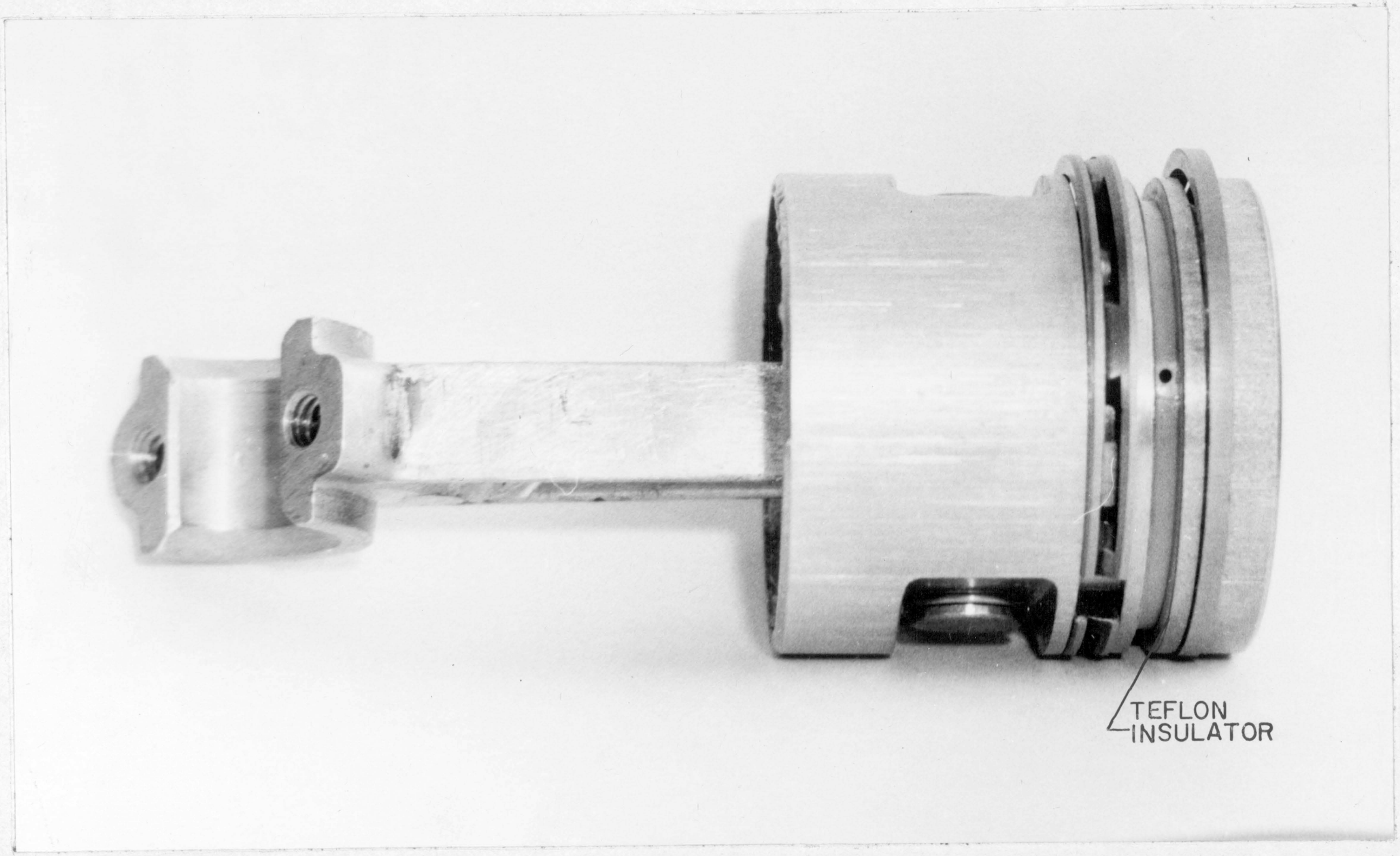


Figure 7. Photographic view of the piston after insulation.

Figure 8. The Ring and the Connection of the Wire.

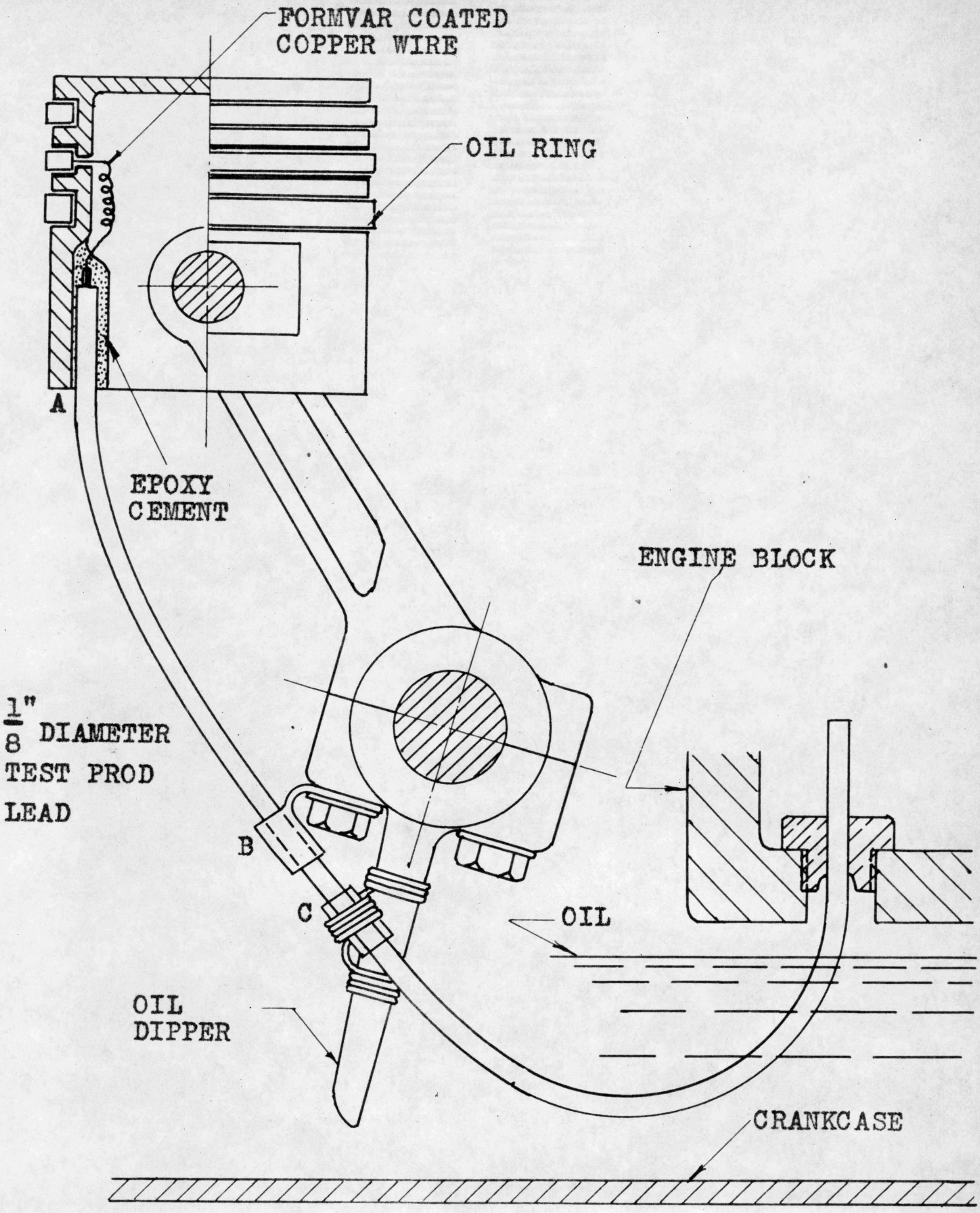


FIGURE 9: THE METHOD OF CONNECTING THE LEADS

The wire was then fastened in position by clamp B and led out through crankcase by fixing it on the oil dipper at point C. The plastic tube at point C was used to protect the wire.

Engine Motoring System

To facilitate accurate control of operating condition for "without combustion" studies, a $\frac{1}{2}$ kilowatt direct current generator, driven as a motor, was coupled to the engine by means of a "V" belt drive.

A rectifier was used to give a direct current supply. The lowest output from the rectifier was 24 volts and the generator was rated at 18 volts. The supply electromotive force was fifteen percent higher than the recommended limits. However, no difficulties were experienced with the generator.

For the purpose of controlling the speed of the motor, a special connection was made on both the armature and the field of the generator as shown in Figure 10. A resistance rack, used to control the armature current, was connected in series with the armature. Two adjustable resistors, R_1 and R_2, used to control the field current, were connected in series with field.

The resistance rack had twenty knife switches mounted on its slate top. The blade side of the switches were located on the longitudinal centerline with terminals extended through the slate top so that the electrical connections for the resistor elements were made from underneath. A row of twenty spring-clips, tapped through to bus bars underneath the slate top, were mounted on either side of the blades so that the resistors could be connected in parallel or series as desired.

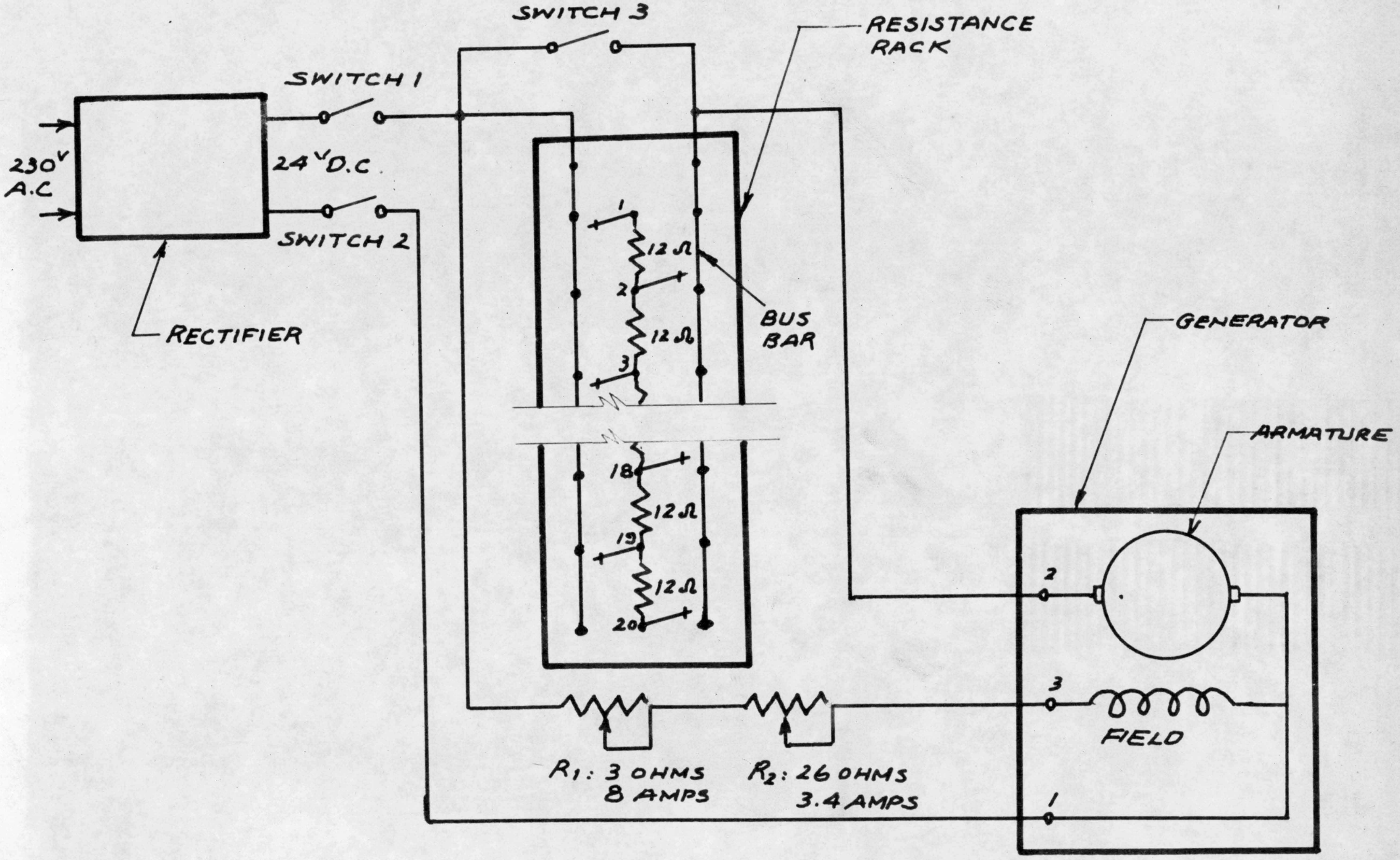


FIGURE 10: THE MOTOR CONTROL SYSTEM

Nineteen Glocoils, used as the resistor elements, were screwed into insulated ceramic sockets mounted on the vertical tin sides of the rack.

The maximum current of two adjustable resistors R_1 and R_2 were 8 amps and 3.4 amps, respectively. When an input voltage of 24 volts was applied to the generator, the field current measured 4.8 amps. This was little higher than the maximum capacity of R_2, but no overheating occurred.

Three single-blade switches were used in the circuit. Switch 1 and switch 2 controlled the output line from rectifier. Switch 3 short-circuit the resistance rack when speeds above 1000 rpm were desired. The speed of the generator could be lowered to 300 rpm by adjusting the resistance rack with R_1 and R_2 setting at zero ohm and switch 3 opened. A speed of up to 2500 rpm could be reached by adjusting R_1 and R_2 and with switch 3 closed.

The D.C. Bridge Circuit

A d-c potential was applied across the oil film through a bridge circuit shown in Figure 11. The d-c power source comprised of three 1.5-volt batteries connected in series. The output voltage was dropped to 0.20 volts by means of a 30 ohm adjustable resistor R. One arm of the bridge was formed by the oil film, while the other arm had a sensitive adjustable resistance box. The resistance box was adjustable from 0.1 ohm to 100 ohms by 0.1 ohm increments. The maximum capacity of the resistance box was 0.5 watt. The resistors R_1, R_2, each had a resistance of 70 ohms, made the other pair of balancing arms. A cathode-ray oscilloscope connected on terminals 1 and 2 in Figure 11, was used to detect the unbalanced voltage across the oil film. An ammeter was inserted in the arm formed by oil film to detect the current across the oil.

Layout of Experimental Apparatus

The layout of the experimental apparatus is shown in Figure 12. The detailed constructions of these items were mentioned in the previous sections. The synchronizing impulse, produced by the electric magnetic pickup, was fed to the External Synchronizing terminal on the oscilloscope. This synchronization triggered the oscilloscope sweep at the time when the piston was at its bottom dead center positions at the beginning of each cycle.

Figure 13 shows the apparatus and instruments. The functions of the apparatus and instruments will be listed in the next section.

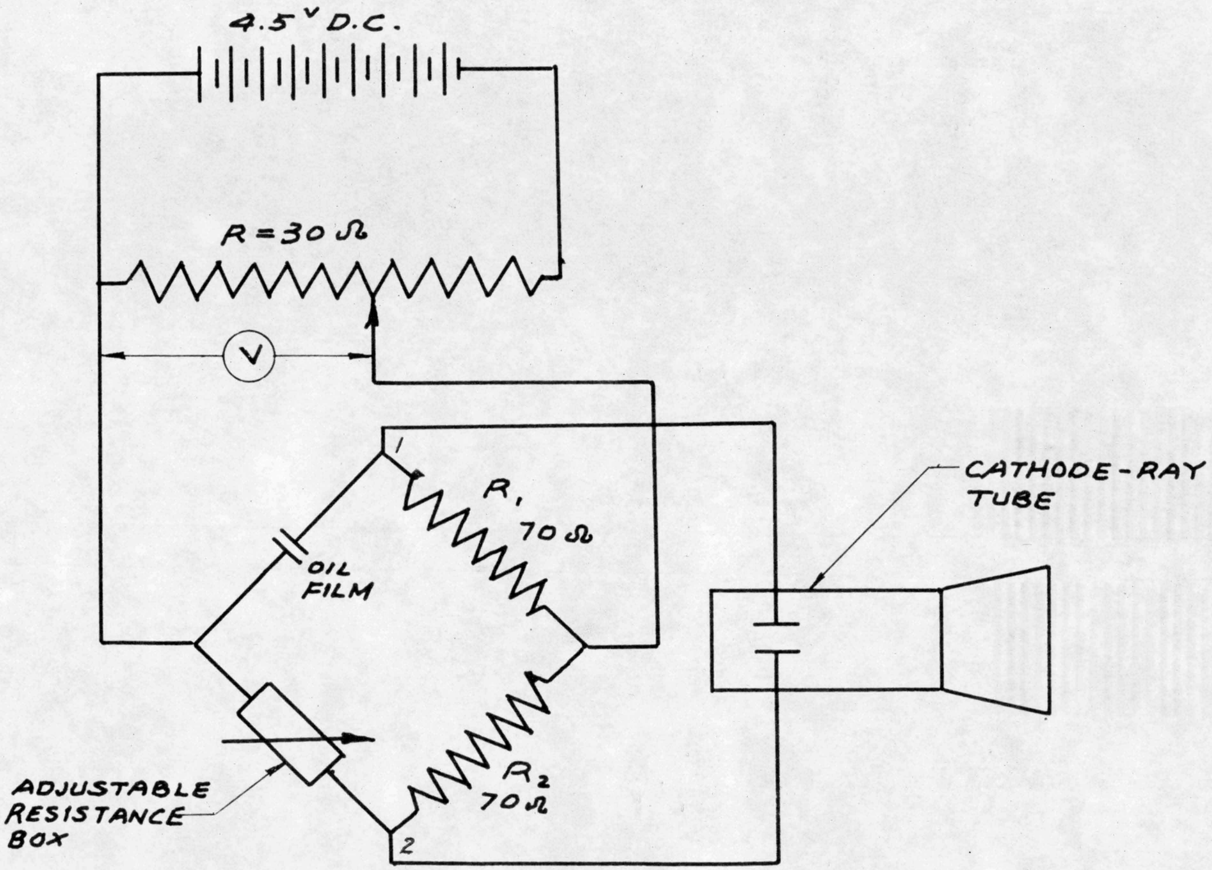


FIGURE 11: THE D. C. CIRCUIT

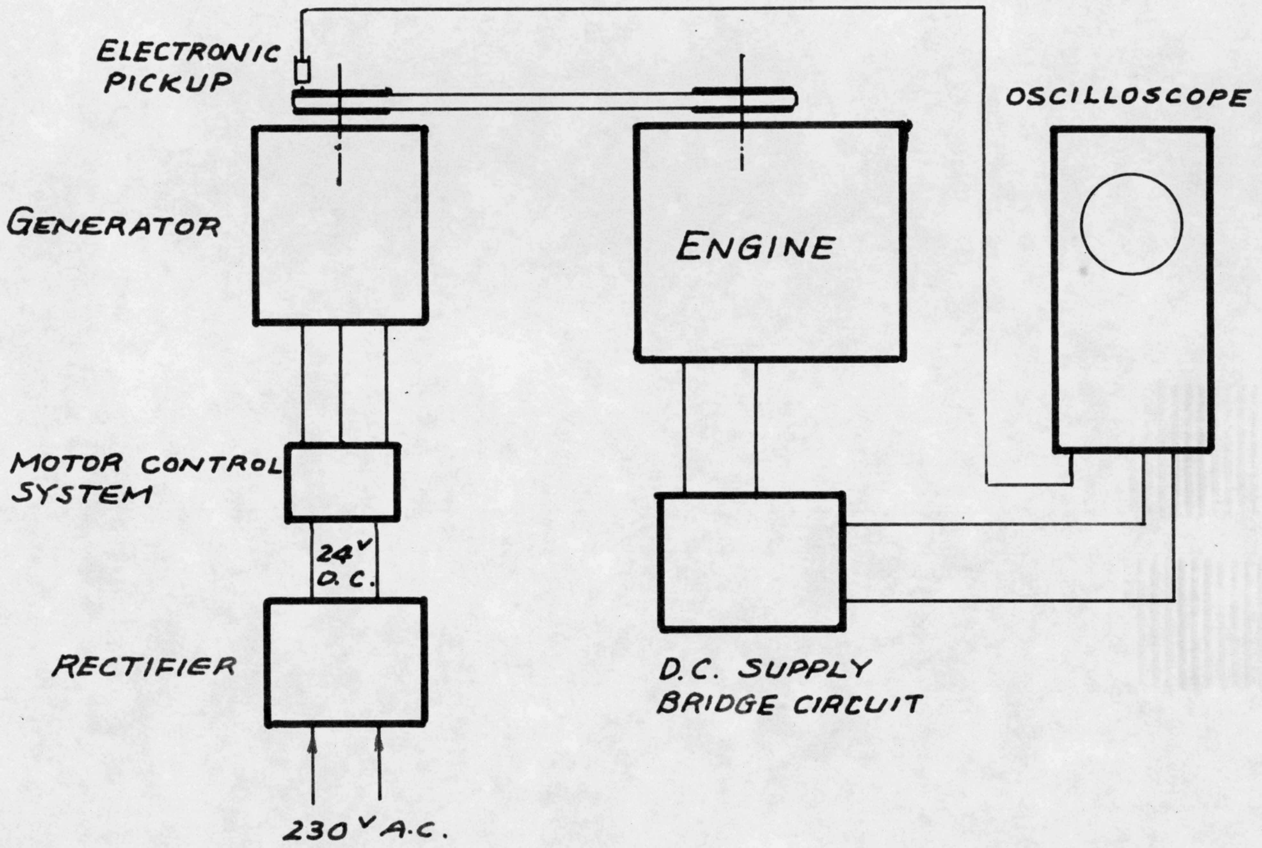


FIGURE 12: THE LAYOUT OF EXPERIMENTAL APPARATUS

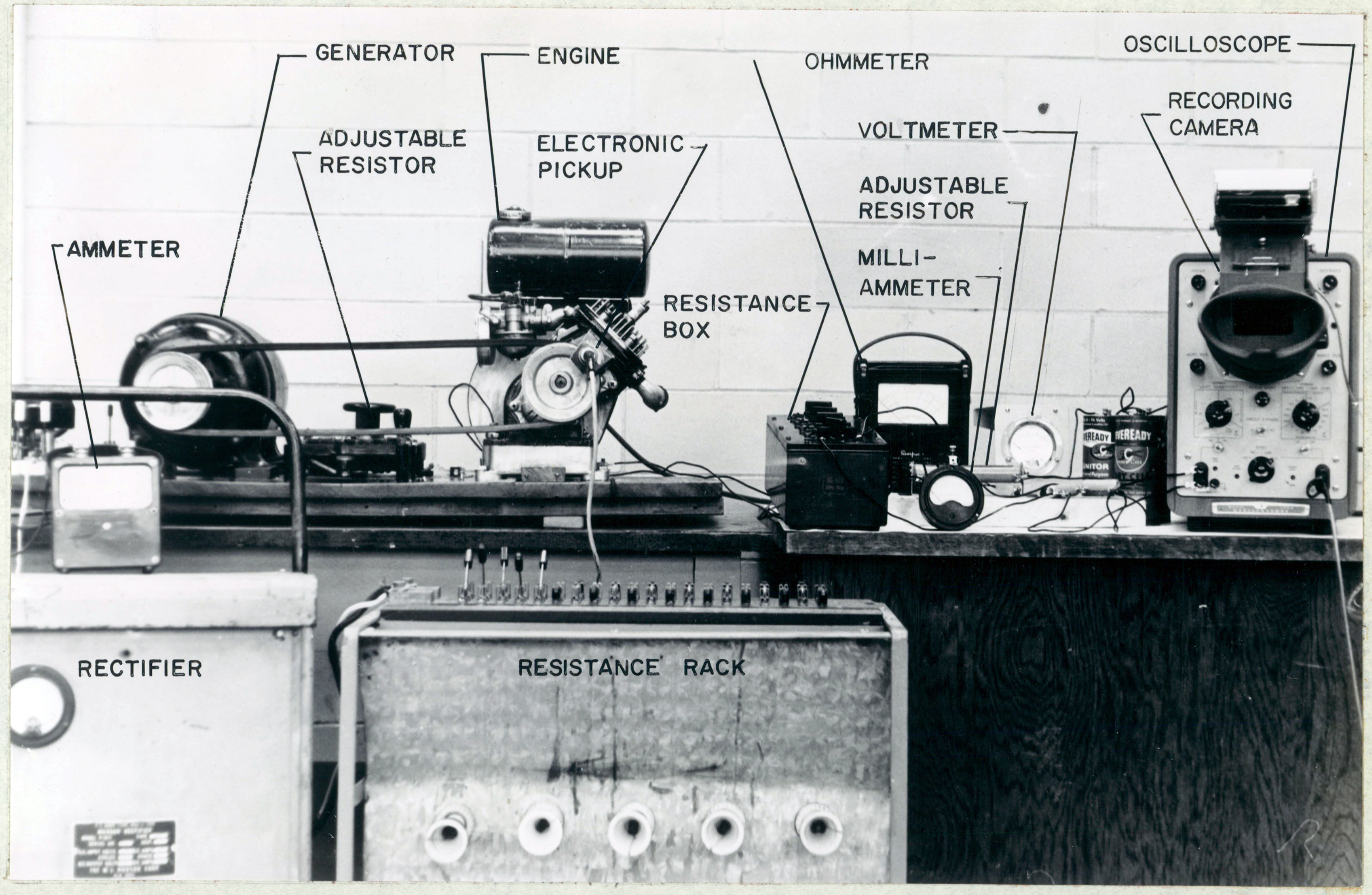


Figure 13. Experimental Apparatus and Instruments.

List of Equipment

The apparatus and instruments used in this investigation will be listed below:

D. C. Generator. Model 32646, Type SD, 0.5 kw, 18 volts, 27.8 amps, 1725 rpm. Manufactured by General Electric Company, Schenectady, N. Y.. Used as a D.C. motor to drive the gasoline engine. Shown in Figure 13.

Rectifier. Maxson Rectifier Model P-1011, Type A.P., Input: 230 volts A.C., 20 amps, 50/60 cycles, 3 phase. Output: 24 volts D.C. 130 amps. Manufactured by The W. L. Maxson Corp., New York, N.Y.. Used to supply D.C. current for motor. Shown in Figure 10 and Figure 13.

Resistance Rack. Composed of nineteen 1000 watt, 115 volts, cone Clocoils. Property of Mechanical Engineering Department, V.P.I.. Used to control the current in armature of the motor. Shown in Figure 10 and Figure 13.

Oscilloscope. Hewlett-Packard Model 120-A, serial 1750, 115/230 volts, 50/60 cycles. Manufactured by Hewlett-Packard Company, Palo Alto, California. Used to detect the unbalanced voltage across the oil film. Shown in Figure 13.

Oscillograph- Record Camera. Dumont Type 297, serial 5850, Polaroid-Land camera. Manufactured by Allen B. Dumont Laboratories, Inc., Clifton, New Jersey. Used to record the signals on oscilloscope. Shown in Figure 13.

Decade Resistance Box. Type 102K, serial No. 5714. Maximum Capacity 0.5 watt. Manufactured by General Radio Company, Cambridge, Massachusetts. Used to balance the bridge circuit.

D. C. Voltmeter. Model 1301, type KS-14509, 0-0.5 volt, 1000 ohms per volt. Internally shielded. Manufactured by Western Electrical Instrument Corp., Newark, N.J.. Used to measure the input voltage of the bridge circuit.

D. C. Ammeter. Model 430, No. 19994, 0-50 amps. Manufactured by Western Electrical Instrument Corp., Newark, N.J.. Used to measure the field current of motor.

D. C. Milliammeter. Model 431, 1-100 milliamperes. Manufactured by Burlington Instrument Co., Burlington, Iowa. Used to measure the line current in the bridge circuit.

Adjustable Resistor. Type CR 8003, 3 ohms, 6.7-8 amps. Manufactured by General Electric Company, Schenectady, N.Y.. Used to control the field current. Shown as R_1 in Figure 10.

Adjustable Resistor. 26 ohms, Maximum current 3.4 amps. Manufactured by Ward Leonard Electric Company, Mount Vernon, N.Y. Used to control the field current. Shown as R_2 in Figure 10.

Tachometer. No. K-08 123536, 300-4000 rpm. Manufactured by James G. Biddle Company, Switzerland. Used to measure the speed of motor.

Electronic Pickup. Electro Products Model 3010 A- series, 5/8", 2 threads. Manufactured by Electro Products Laboratories, Chicago, Illinois. Used to synchronizing the oscilloscope with the engine.

Ohmmeter. Model 260, 20,000 ohms per volt D. C., or 1000 ohms per volt A. C. Manufactured by Simpson Electric Company, Chicago, Illinois. Used to measure the line voltage.

Preliminary Investigations

Analysis of the D. C. Bridge Circuit

For the purpose of analyzing the d-c bridge circuit, Figure 11 is redrawn to the analytical form shown in Figure 14. X is the resistance of the oil film. R_3 is the total line resistance of the arm which is formed by oil. R_4 is an adjustable resistor. R_1 and R_2 are two equal resistors. V is a constant input voltage to the bridge circuit, and E is input voltage to the oscilloscope.

Since V is constant, then:

$$I_1 = \frac{V}{R_3 + X + R_1} \qquad \text{and} \quad I_2 = \frac{V}{R_4 + R_2}$$

$$\begin{aligned} E &= E_2 - E_1 \\ &= I_2 R_4 - I_1 (R_3 + X) \\ &= V \left(\frac{R_4}{R_4 + R_2} - \frac{R_3 + X}{R_3 + X + R_1} \right) \qquad \ldots\ldots\ldots\ldots\ldots(1) \end{aligned}$$

When the engine is stopped, there is a complete metal to metal contact between the piston ring and the cylinder wall. X, at this instant, approaches zero. R_3 was measured and then by setting $R_4 = R_3$, thus the bridge was balanced.

Once the engine is running, the oil film builds up causing X to increase, as a result, $R_3 + X$ is greater than R_4.

Hence:

$$E_2 \geqq E_1$$

Since $R_3 = R_4$, $R_1 = R_2$, according to Equation (1), when the engine is stopped ($X = 0$), E approaches its maximum value:

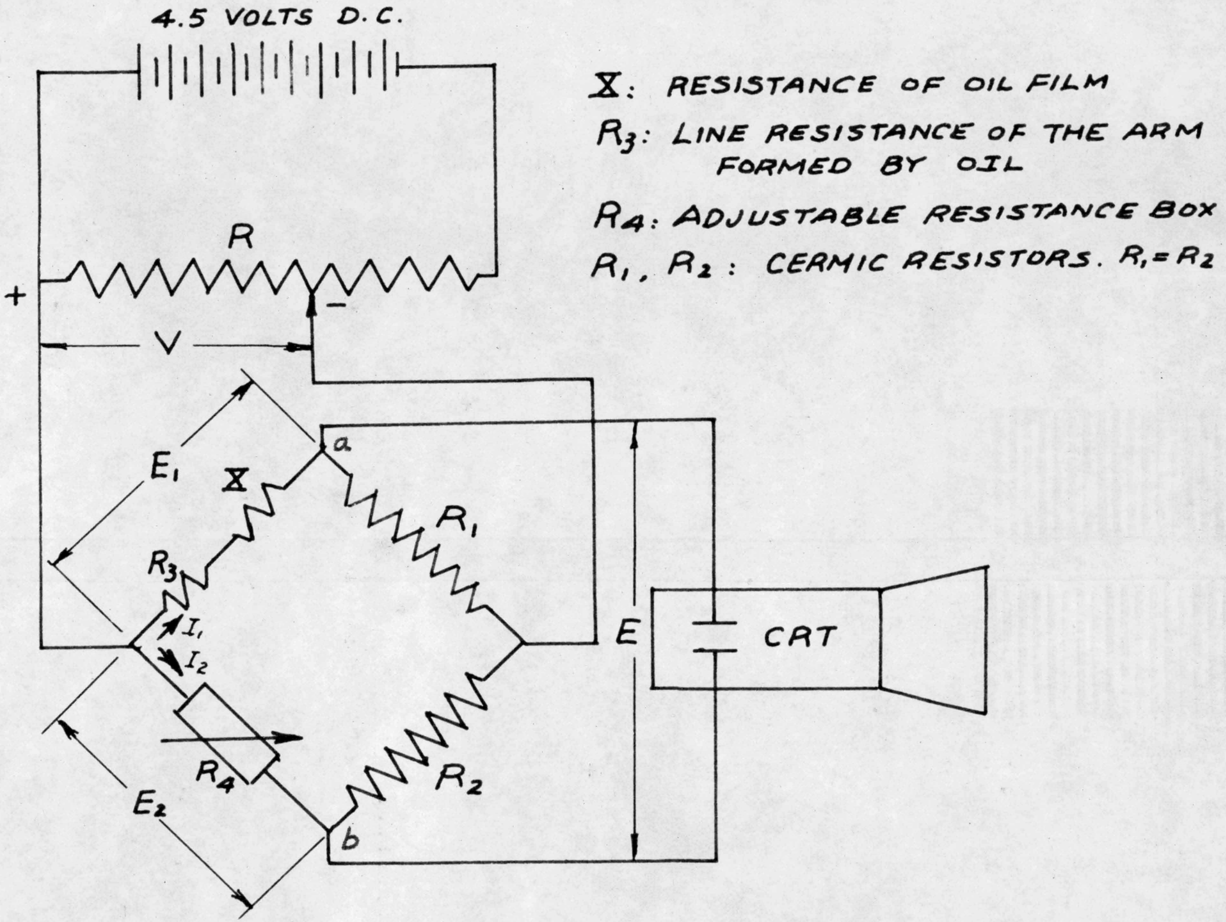


FIGURE 14: THE D.C. CIRCUIT

$$E_{max} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

When the engine is running, oil film builds up, i.e. $X \neq 0$. From Equation (1),

$$E = V \cdot \left(\frac{R_4}{R_4 + R_2} - \frac{R_3 + X}{R_3 + X + R_1}\right)$$

If the oil film is sufficiently thick, $X \to \infty$. E approaches its minimum value:

$$E_{min} = \lim_{X \to \infty} E$$

$$= -\frac{R_2}{R_4 + R_2} V \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Equations (2) and (3) indicate that the input voltage E of the oscilloscope varies between zero and $-\frac{R_2}{R_4 + R_2} V$.

In this investigation, $R_4 = R_3 = 4.1$ ohms and $R_1 = R_2 = 70$ ohms.

Thus,

$$E_{max} = 0$$

$$E_{min} = -\frac{R_2}{R_4 + R_2} V = -\frac{70}{70 + 4.1} V = -0.94V \quad (4)$$

Therefore,

$$-0.94V \leqq E \leqq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

The Determination of the Input Voltage V of the Bridge Circuit

From the literature review, it was learned that only a limited range of voltages that could be applied across the thin oil-film. Beyond this range, the electric breakdown of the oil occurred. Also it was found that within this range, the oil behaved more or less as an ohmic resistance. To study the variation in contact resistance from potential drop across the oil film,it was therefore necessary to work with voltages within the limits of breakdown voltage of the oil film.

For the purpose of determining the input voltage of the bridge circuit, a preliminary test was carried out. This preliminary test was based on the knowledge that as soon as the breakdown of the oil occurred, there would not be any voltage difference between terminals "a" and "b" in Figure 14. Therefore, no signals appeared on the oscilloscope.

A series of input voltages from V = 0.1 volt to V = 1.0 volt was applied to the balanced bridge circuit by adjusting the resistor R (Figure 14). The voltages were applied by each 0.1 volt increments. For each step, two types of oil, A and B, were tested. The engine speeds for each oil were 300 rpm and 1800 rpm, respectively. Signals appeared on the oscilloscope for all cases indicating that there were no breakdown of the oil within these working ranges.

The final selection of the input voltage V (0.2 volt) to the bridge circuit depended upon the scale of the oscilloscope and the size of the recording camera film.

From Equation (5) of the previous section, the input voltage to the oscilloscope E varies between zero and - 0.94V.

Therefore:

$$-0.94 \times 0.2 \text{ volt} \leqq E \leqq 0 \text{ volt}$$

i.e. $$-0.188 \text{ volt} \leqq E \leqq 0 \text{ volt}$$

By setting the scale of the oscilloscope at 0.1 volt per cm, five photographs were taken on each film.

Experimental Procedure

Before starting each test, the following two procedures were always done.

1. The bridge circuit was checked and balanced.
2. To avoid the interference of dirt, the moving parts of the engine were cleaned by means of acetone before new oil was poured into the crankcase.

Testing the Effect of Time on Oil Film Performance

1. The crankcase was filled with oil A - SAE 30.
2. The engine was driven by an external motor.
3. The resistors in the motor control system were adjusted to obtain a constant speed of 1400 rpm.
4. The time base of the oscilloscope was synchronized with the engine speed.
5. The engine was stopped.
6. The engine was started again and pictures were taken after one second, three seconds, six seconds, nine seconds, and fifteen seconds.
7. The engine was stopped and the temperature of oil in the crankcase was recorded.

Testing the Effect of Engine Speed

1. The crankcase was filled with oil A-SAE 30.

2. The engine was driven by an external motor.

3. The speed of the motor was adjusted to 250 rpm.

4. The time base of oscilloscope was synchronized with the engine speed.

5. Pictures were taken after 30 sec. from starting.

6. Follow the same procedure, pictures were taken at 400 rpm, 1200 rpm, 1800 rpm and 2400 rpm.

7. The temperatures of oil in crankcase were recorded after each picture was taken.

Testing the Effect of Oil Temperatures on Oil Film Performance

1. The crankcase was filled with Oil A-SAE 30.

2. The engine was driven by an external motor at the speed of 1200 rpm.

3. The time base of oscilloscope was synchronized with engine speed.

4. Pictures were taken after 30 sec.from starting.

5. The engine was stopped and the oil temperature in crankcase was recorded.

6. Oil A-SAE 30 was heated to 100°F and was filled into crankcase.

7. The engine was driven by an external motor at the speed of 1200 rpm.

8. Pictures were taken after 30 sec. from starting.

9. Repeated the same procedure for Oil A-SAE 30 at the temperatures of 120°F, 140°F and 160°F respectively.

Comparison Between the Effect of Oil Temperatures and the Effect of Oil Viscosities on Oil Film Performance

1. The room temperature was recorded.

2. The crankcase was filled with Oil A-SAE 10 at 80 F.

3. The engine was driven by an external motor at the speed of 1400 rpm and the time base of oscilloscope was synchronized with engine speed.

4. Pictures were taken after 30 sec. from starting and stopped the engine, the oil temperature in crankcase was recorded.

5. From the Viscosity-Temperature Curves (Appendix II), found the viscosity of SAE 10 oil at 80° F was 380 SUV. From the same chart, found the temperature for SAE 60 oil at 380 SUV was 152°F.

6. Oil A-SAE 60 was heated to 152°F and was filled into the crankcase.

7. The inside of cylinder was heated with electric heater to 152°F approximately.

8. The engine was driven by an external motor at the speed of 1400 rpm and the time base of oscilloscope was synchronized with engine speed.

9. Pictures were taken after 30 sec. from starting.

10. The engine was stopped and the temperature in the crankcase was recorded.

11. Followed the procedures 1-10, tested the Oil A-SAE 20 at 80°F and Oil A-SAE 60 at 142°F respectively.

12. Followed the procedures 1-10, tested the Oil A-SAE 30 at 80°F and Oil A-SAE 60 at 121°F respectively.

Testing the Effect of Combustion on Oil Film Performance

1. The crankcase was filled with Oil A-SAE 20.

2. The engine was driven by its own power at the speed of 410 rpm.

3. The time base of oscilloscope was synchronized with engine speed.

4. Pictures were taken and the engine was stopped to record the oil temperature in crankcase.

5. Followed the same procedures and pictures were taken at the speed of 1720 rpm.

6. The crankcase oil was changed to Oil A-SAE 40.

7. The engine was driven by its own power at the speed of 405 rpm.

8. The time base of oscilloscope was synchronized with the engine speed.

9. Pictures were taken and the engine was stopped to record the oil temperature in crankcase.

10. Followed the procedures 8-9 and pictures were taken at the speed of 1805 rpm.

11. Let the engine to cool to room temperature.

12. The crankcase was filled with Oil A-SAE 20.

13. The engine was driven by an external motor.

14. After pictures were taken, the engine was stopped to record the oil temperature in crankcase.

15. Followed the same procedure in the previous test and pictures were taken at the engine speed of 1720 rpm.

16. The oil in crankcase was changed to Oil A-SAE 40.

17. The engine was driven by an external motor.

18. Pictures were taken at the engine speeds of 405 rpm and 1805 rpm respectively.

19. Oil temperatures in crankcase were taken after the pictures were taken.

Testing the Effect of Oil Mixtures on Oil Film Performance

1. The crankcase was filled with Oil A- SAE 30.

2. The engine was driven by an external motor at a speed of 600 rpm and the time base of oscilloscope was synchronized with engine speed.

3. Pictures were taken after 30 sec. from starting.

4. The engine was stopped and the oil temperature in crankcase was recorded.

5. The crankcase was filled with an oil mixture of 80% Oil A-SAE 30 and 20% Oil B - SAE 30.

6. The engine was driven by an external motor at a speed of 600 rpm.

7. Pictures were taken after 30 sec. from starting.

8. Followed the procedures 5 - 7, tested an oil mixture of 50% Oil A - SAE 30 and 50% Oil B - SAE 30.

9. Followed the procedures 5 - 7, tested an oil mixture of 20% Oil A - SAE 30 and 80% Oil B - SAE 30.

10. Followed the procedures 5 - 7, tested 100% Oil B.

Testing the Effect of Heated Oil Mixtures on Oil Film Performance

1. The crankcase was filled with Oil A- SAE 30 at 300°F.

2. The engine was driven by an external motor at a speed of 1800 rpm.

3. The time base of oscilloscope was synchronized with the speed of the engine.

4. Pictures were taken after 30 sec. from starting.

5. The engine was stopped to change oil.

6. The crankcase was filled with a mixture of 60% Oil A - SAE 30, 20% Oil B - SAE 30 and 20% Oil C - SAE 30 at 300°F.

7. Pictures were taken by following the procedures 2-5.

8. Followed the procedures 2 - 5, tested an oil mixture of 20% Oil A - SAE 30, 40% Oil B - SAE 30 and 40% Oil C - SAE 30 at crankcase temperature of 300°F.

Testing the Effect of Foreign Particles on Oil Film Performance

1. The crankcase was filled with Oil A - SAE 30.

2. Added into the crankcase with 1 gram of fine particles of cast iron, small amount of carbon (taken from tne cylinder head of an old engine) and 2 grams of water droplets.

3. The engine was driven by an external motor at a speed of 200 rpm.

4. The time base of oscilloscope was synchronized with the engine speed. Pictures were taken after 30 sec. from starting.

5. By using the same oil (procedures 1 - 2), the speed of engine was increased to 1800 rpm by the external motor.

6. The time base of oscilloscope was synchronized with the engine speed.

7. Pictures were taken after 30 sec. from starting.

8. The engine was stopped and the oil temperature in crankcase was recorded.

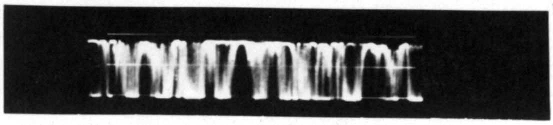
9. The oil in the crankcase was changed to clean Oil A - SAE 30 and followed the procedures 2 - 8 to take pictures at the engine speeds of 200 rpm and 1800 rpm, respectively.

Testing the Effect of Oil Viscosities on Oil Film Performance

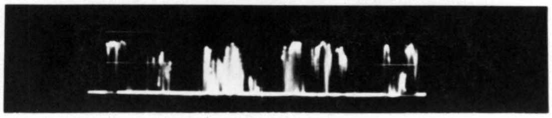
1. The crankcase was filled with Oil A-SAE 10.
2. The engine was driven by an external motor at the speed of 1200rpm.
3. The time base of oscilloscope was synchronized with engine speed.
4. Pictures were taken after 30 sec. from starting.
5. The oil temperature in crankcase were recorded immediately after stopping the engine.
6. Repeated the same procedures for Oil A-SAE 30, Oil A-SAE 40, Oil A-SAE 50 and Oil A-SAE 60 respectively.

IV. DATA AND RESULTS

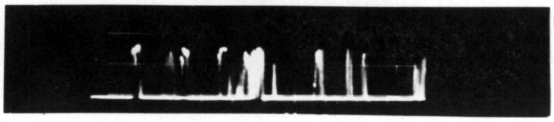
The data collected in this investigation are shown in Figures 15 - 23.



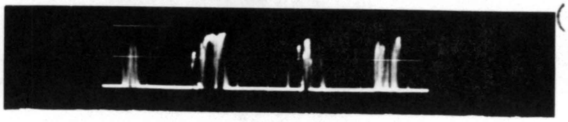
(a) 1 sec After Starting
Engine Speed: 900 rpm
Crankcase Temperature: 79 F



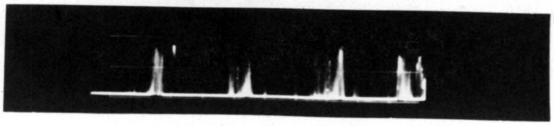
(b) 3 sec After Starting
Engine Speed: 1350 rpm



(c) 6 sec After Starting
Engine Speed: 1400 rpm



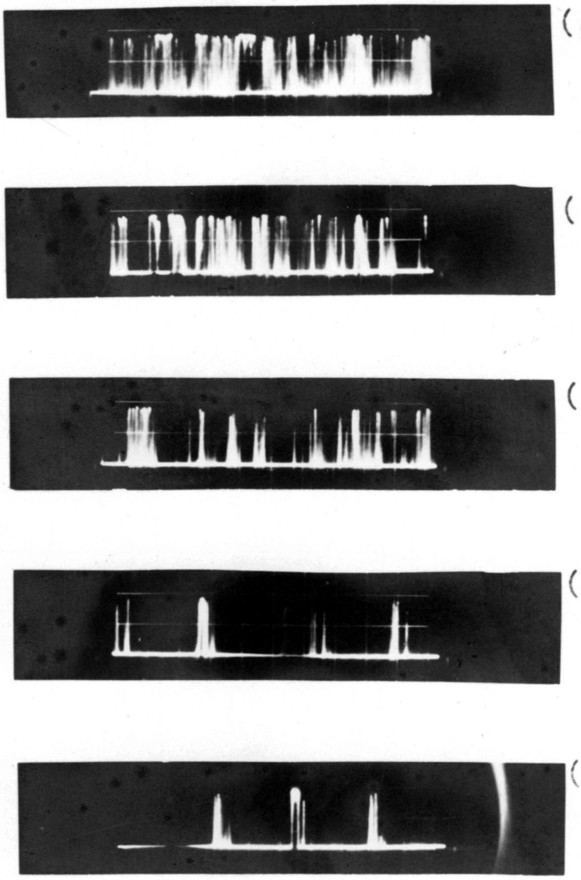
(d) 9 sec After Starting
Engine Speed: 1400 rpm



(e) 15 sec After Starting
Engine Speed: 1400 rpm
Crankcase Temperature: 79 F

Type of Oil: Oil A - SAE 30
Engine Condition: Driven by External Motor
Room Temperature: 79 F

Figure 15: The Effect of Time on Oil Film Performance



(a) Engine Speed: 250 rpm
Crankcase Temperature: 77 F

(b) Engine Speed: 400 rpm
Crankcase Temperature: 77 F

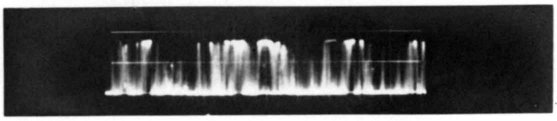
(c) Engine Speed: 1200 rpm
Crankcase Temperature: 77 F

(d) Engine Speed: 1800 rpm
Crankcase Temperature: 78 F

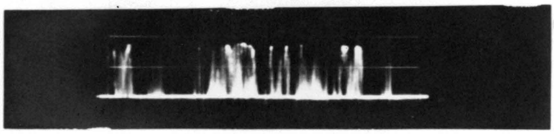
(e) Engine Speed: 2400 rpm
Crankcase Temperature: 78 F

Type of Oil: Oil A - SAE 30
Engine Condition: Driven by External Motor
Room Temperature: 77 F

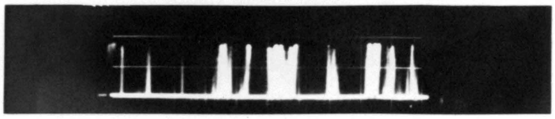
Figure 16: The Effect of Engine Speed on Oil Film Performance



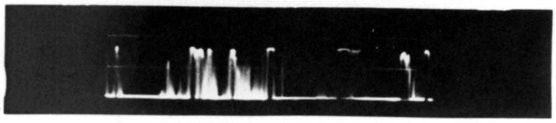
(a) Oil A - SAE 10
Crankcase Temperature: 78 F



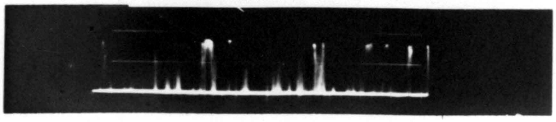
(b) Oil A - SAE 30
Crankcase Temperature: 78 F



(c) Oil A - SAE 40
Crankcase Temperature: 78 F



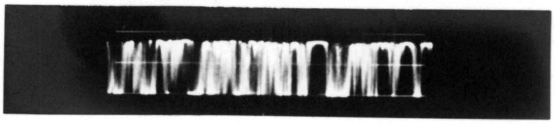
(d) Oil A - SAE 50
Crankcase Temperature: 78 F



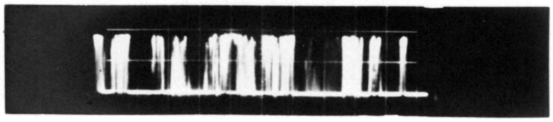
(e) Oil A - SAE 60
Crankcase Temperature: 78 F

Engine Condition: Driven by External Motor
Engine Speed: 1200 rpm

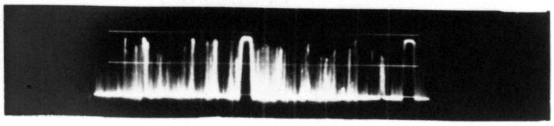
Figure 17: The Effect of Oil Viscosities
on Oil Film Performance



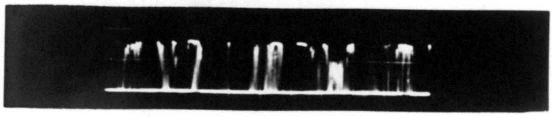
(a) Crankcase Temperature: 160 F



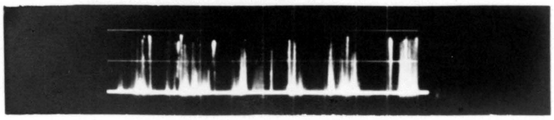
(b) Crankcase Temperature: 140 F



(c) Crankcase Temperature: 120 F



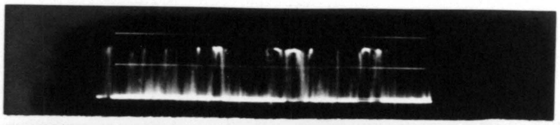
(d) Crankcase Temperature: 100 F



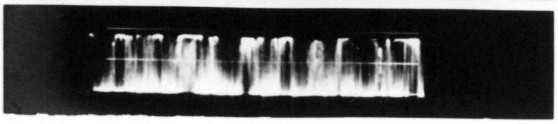
(e) Crankcase Temperature: 79 F

Type of Oil: Oil A - SAE 30
Engine Condition: Driven by External Motor
Engine Speed: 1200 rpm
Room Temperature: 79 F

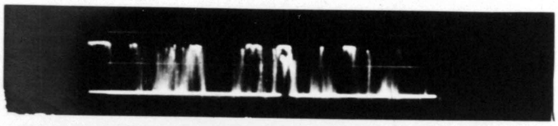
Figure 18: The Effect of Oil Temperatures on Oil Film Performance



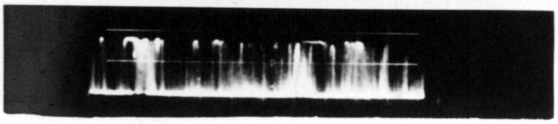
(a) Oil A - SAE 10
Oil Temperature: 80 F
Oil Viscosity: 374 Sec SUV



(b) Oil A - SAE 60
Oil Temperature: 152 F
Oil Viscosity: 383 Sec SUV

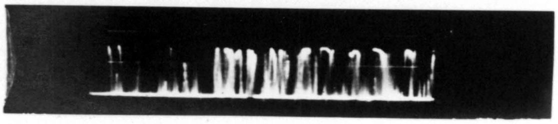


(c) Oil A - SAE 20
Oil Temperature: 80 F
Oil Viscosity: 504 Sec SUV



(d) Oil A - SAE 60
Oil Temperature: 142 F
Oil Viscosity: 491 Sec SUV

(e) Oil A - SAE 30
Oil Temperature: 80 F
Oil Viscosity: 896 Sec SUV



(f) Oil A - SAE 60
Oil Temperature: 121 F
Oil Viscosity: 878 Sec SUV

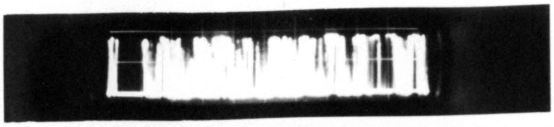
Engine Condition: Driven by External Motor

Engine Speed: 1400 rpm

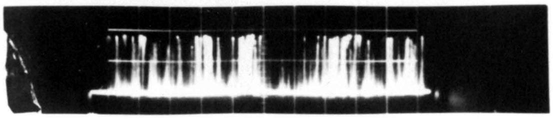
Room Temperature: 80 F

Figure 19: The Comparison Between the Effect of Oil Viscosities and the Effect of Oil Temperatures

(a) Oil A - SAE 20
Engine Speed: 410 rpm

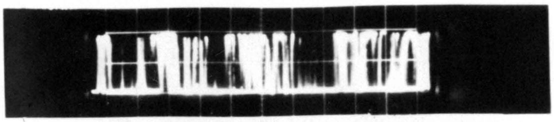


Engine Driven by Its Own
Power (Combustion)
Crankcase Temperature: 118 F

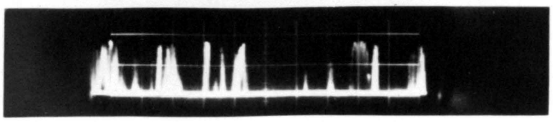


Engine Driven by External
Motor (Without Combustion)
Crankcase Temperature: 80 F

(b) Oil A - SAE 20
Engine Speed: 1720 rpm

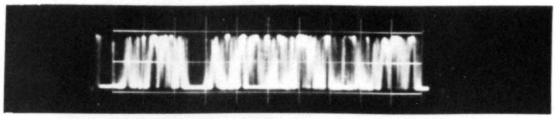


Engine Driven by Its Own
Power (Combustion)
Crankcase Temperature: 121 F

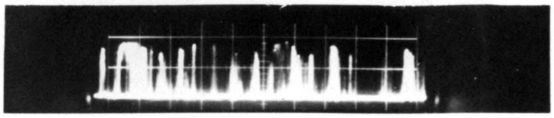


Engine Driven by External
Motor (Without Combustion)
Crankcase Temperature: 82 F

(c) Oil A - SAE 40
Engine Speed: 405 rpm

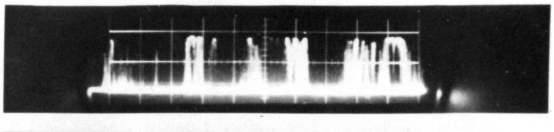


Engine Driven by Its Own
Power (Combustion)
Crankcase Temperature: 124 F

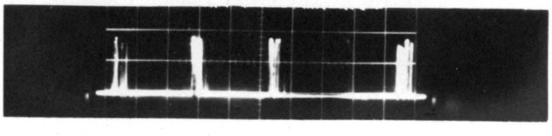


Engine Driven by External
Motor (Without Combustion)
Crankcase Temperature: 82 F

(d) Oil A - SAE 40
Engine Speed: 1805 rpm

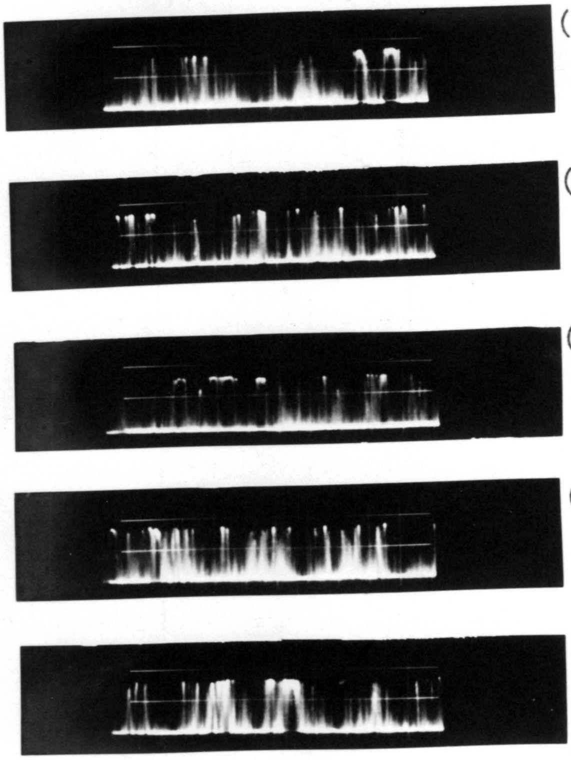


Engine Driven by Its Own
Power (Combustion)
Crankcase Temperature: 129 F



Engine Driven by External
Motor (Without Combustion)
Crankcase Temperature: 81 F

Figure 20: The Effect of Combustion on
Oil Film Performance



(a) 100% Oil A
Crankcase Temperature: 78 F

(b) 80% Oil A + 20% Oil B
Crankcase Temperature: 78 F

(c) 50% Oil A + 50% Oil B
Crankcase Temperature: 78 F

(d) 20% Oil A + 80% Oil B
Crankcase Temperature: 78 F

(e) 100% Oil B
Crankcase Temperature: 78 F

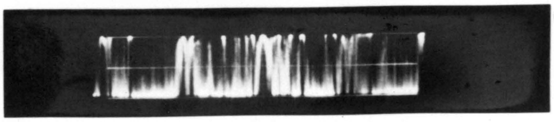
Types of Oil: Oil A - SAE 30
Oil B - SAE 30

Engine Condition: Driven by External Motor

Engine Speed: 600 rpm

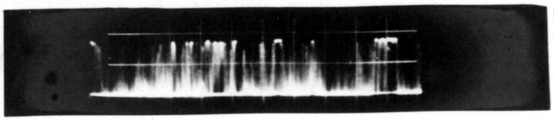
Room Temperature: 78 F

Figure 21: The Effect of Oil Mixtures on Oil Film Performance



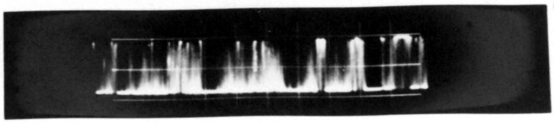
(a) 100% Oil A

Crankcase Temperature: 300 F



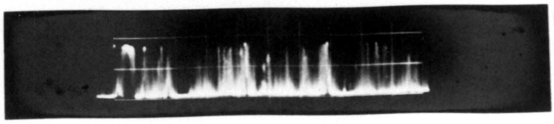
(b) 60% Oil A + 20% Oil B
+ 20% Oil C

Crankcase Temperature: 300 F



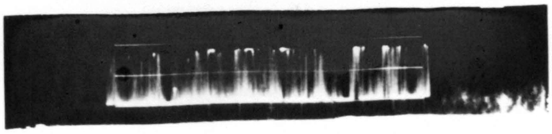
(c) 40% Oil A + 40% Oil B
+ 20% Oil C

Crankcase Temperature: 300 F



(d) 20% Oil A + 40% Oil B
+ 40% Oil C

Crankcase Temperature: 300 F



(e) 100% Oil C

Crankcase Temperature: 300 F

Types of Oil: Oil A - SAE 30
Oil B - SAE 30
Oil C - SAE 30

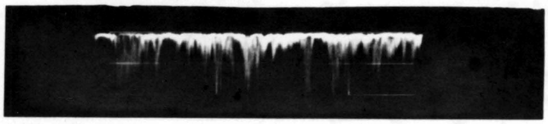
Engine Condition: Driven by External Motor

Engine Speed: 1800 rpm

Room Temperature: 79 F

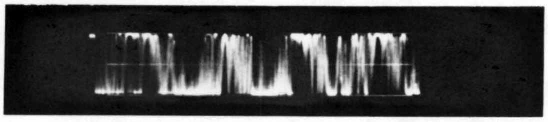
Figure 22: The Effect of Heated Oil Mixtures on Oil Film Performance

(a) Engine Speed: 200 rpm



Oil With Foreign Particles

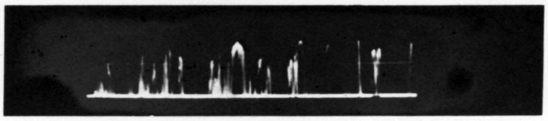
Crankcase Temperature: 79 F



Clean Oil

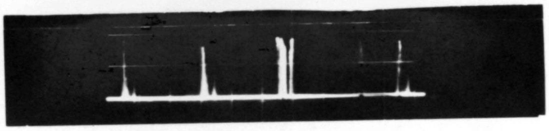
Crankcase Temperature: 79 F

(b) Engine Speed: 1800 rpm



Oil With Foreign Particles

Crankcase Temperature: 79 F



Clean Oil

Crankcase Temperature: 79 F

Types of Oil: Oil A - SAE 30
Oil A - SAE 30 Added With one gram of Cast Iron Particles, one gram of Dust Particles, Small Amount of Carbon and Two grams of Water Droplettes.
Engine Condition: Driven by External Motor
Room Temperature: 79 F

Figure 23: The Effect of Foreign Particles on Oil Film Performance

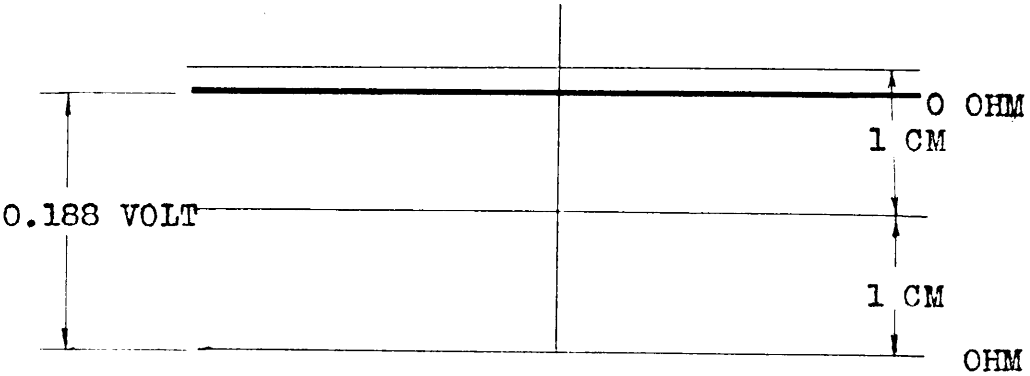
V. DISCUSSION

The Analysis of the Traces on Cathode-Ray Tube

The trace on cathoe-ray tube of the oscilloscope indicated the unbalanced voltage due to the changes in oil resistance. Two typical traces are shown in Figure 24. Before the engine was started, the piston ring tension caused metallic contact between the ring and the wall. This is illustrated by a straight line in Figure 24(a). After the piston began to move, the oil film thickness varied which caused the oil resistance to change. Figure 24(b) shows the trace on oscilloscope for each cycle when the speed of piston, or the viscosity of the oil, was sufficiently high. Four peaks in Figure 24(b) show that the metallic contact existed at two dead center positions.

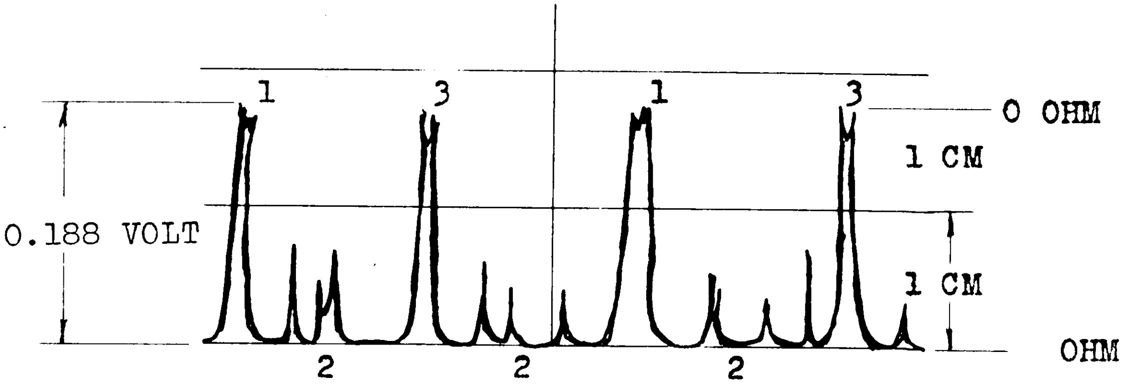
In this investigation, the input voltage of the oscilloscope varied between zero volt and -0.188 volt, while the oil resistance varied from zero to infinity (see the previous analysis). The vertical scale on the oscilloscope was set at 0.1 volt/cm, i.e., two centimeters on vertical scale represented 0.2 volt. The height of each peak in Figure 24(b) was measured to be 0.188 volt which was in agreement with the calculated value.

Points 1 and 3 in Figure 24(b) represent the dead centers. Point 2 represents the ring at center position of each stroke. The peaks which appear between points 1 and 3 represents instantaneous breakdown of the oil film between dead centers. Fewer peaks on oscilloscope means less metallic contact; thus, better lubrication. Theoretically, at least, four peaks should appear during each complete cycle.



ENGINE STOPPED

(a)



ENGINE RUNNING

(a)

FIGURE 24: THE TRACES ON OSCILLOSCOPE
(SCALE: 0.10 VOLT/CM)

The Effect of Time on Oil Film Performance

Figure 15 shows the effect of time on the oil film performances. The engine speed of the test was 1400 rpm. The pictures show that almost complete metallic contact existed at the beginning of the test. The oil film became stable after nine seconds. The results show that the proper amount of oil could not be supplied to the cylinder wall immediately after starting, resulting in a time delay.

Picture (a) in Figure 15 was taken after one second from starting. The engine speed at this time was measured to be approximately 900 rpm. The engine speed increased rapidly to 1350 rpm at the time when picture (b) was taken. The low starting speed caused an insufficient oil quantities.

Due to the size limit of the film in recording camera, only five pictures could be taken in the test. Based on the above results, the pictures in the latter tests were taken after 30 seconds from starting.

The Effect of Engine Speed on Oil Film Performance

The pictures in Figure 16 show the improvement in oil film thickness when the speed of the piston was increased. At low speeds the lubrication was much worse than at high speeds. The hydrodynamic lubrication theory when applied to journal bearings, states that among other factors the film thickness is proportinnal to speed. The experimental results of this work show that this theory can be applied to piston ring lubrication as well.

Picture (e) in Figure 16 shows that the piston ring and cylinder wall were almost completely separated by an oil film except at four points. One may conclude, that at dead center positions, the zero piston speeds caused the oil film break down completely. This is the reason that at least four peaks appeared in the pictures.

The Effect of Oil Viscosities on Oil Film Performance

The increase in oil viscosities improves lubrication. The higher the oil viscosities, the thicker the oil film developed. This result is shown in Figure 17.

By reviewing pictures (d) and (e) in Figure 17, even with the heaviest oil used, which are uncommon to automobile practice, there was an instantaneous breakdown of the oil film in the middle of piston stroke. This shows that from the point of view of automobile engine lubrication, an increase in viscosity does not give as good results as an increasing the speed of the engine.

A viscous oil increased power consumption due to frictional drag as was apparent in this investigation. When SAE 60 oil was tested, the input voltage of 24 volts was not sufficient to raise the speed of the motor to 1200 rpm. An input voltage of 28 volts was necessary. Therefore, the use of viscous oil in internal combustion engines introduces power losses.

The Effect of Oil Temperature on Oil Film Performance

The results in Figure 18 was gained by testing same type of oil at different temperatures. At high temperatures, the lubrication was much worse than for low temperatures. The decrease in the degree of lubrication at high temperatures was caused by the decrease in viscosity.

For the purpose of making further study on the effect of oil temperatures on the oil film characteristics, another series of tests was performed. The results are shown in Figure 19, In these tests, the oils with higher viscosities were heated so that they would have the same viscosities of light oils at room temperature. The viscosities of both light oils and heated heavy oils were checked by means of a Saybolt Universal Viscometer. The errors were found to be within ± 10 SUV. To make some comparisons, the engine speeds of each test were kept equal. The results show that although the viscosities of both oils were the same, the light oils provided better lubrication than did the heated heavy oils. This phenonmenon was probably due to the existance of a sulphur residue in the heated oils which caused the local breakdown of the oil film. Another possibility might be that the "chain", or "bond", between the oil molecules was broken, or damaged, by the elevated temperatures. Therefore, causing decrease in film strength of the heated oils.

From the standpoint of the lubrication only, it is desirable to keep the temperature as low as possible in cylinder. On the other hand, however, lower temperature reduces thermalefficiency.

The Effect of Combustion on Oil Film Performance

Figure 20 shows the effect of combustion on an oil film. The results indicate that when the engine was under its own power, the lubrication was much worse than when it was driven by an external motor.

The high combustion temperature might be one of the factors that caused the breakdown of the oil film. The high pressure gases in the cylinder might leak through the clearance between the ring and the ring-groove to the back of the ring. This gas pressure forced the ring against the wall disrupting the thin oil film. The lubricating oil in the vicinity of top dead center could be blown off by the high gas pressure in the cylinder. Furthermore, there was always an insufficient oil supply at the upper portion of the piston stroke. These factors could cause rapid cylinder wear at top dead center positions.

The Effect of Oil Mixtures on Oil Film Performance

Three kinds of commercial lubricating oils were blended together. Oil A was paraffin-based mineral oil. Oil B was straight mineral oil. Oil C was mineral oil plus corrosion and wear inhibitor. The results are shown in Figure 21 and Figure 22. No appreciable change in oil film characteristics could be found. The tests were performed using oil mixtures at room temperature as well as at elevated temperature.

Based on the testing results, these oils are considered to be "compatible" from the point of view of film strength only.

The Effect of Foreign Particles on Oil Film Performance

Foreign particles, such as metal, dust, carbon and water droplets were added to the oil. The results are compared with those gained by using clean oils. Figure 23 shows more metallic contact occurred between the ring and the wall, if the oil contained foreign particles. This was apparently caused by the existance of foreign particles between the ring and the wall. These particles were embedded in the metal surface thereby increasing the rate of wear.

VI. CONCLUSIONS

Based on the results of the investigation, the following conclusions are made:

1. It is possible to utilize the electrical-resistance-measurement method in the study of piston ring lubrication.

2. Considerable time delay is associated with engine lubrication during starting.

3. Lubrication can be improved in internal combustion engine by increasing the engine speed or decreasing the operating temperature. Any prolonged idling time will cause extensive damages to the engine.

4. An increase in oil viscosity can improve lubrication, but at the same time, increases power consumption.

5. High temperature and high pressure during combustion causes deterioration of the oil film.

6. No appreciable change in oil film characteristics could be found by mixing a few different types of commercial lubricating oils.

VII. RECOMMENDATIONS

1. It would be more desirable to use a water cooled engine instead of air cooled engine to facilitate accurate control of the cylinder temperatures.

2. The size and shape of piston ring are important factors in the piston ring lubrication. Rings with different widths could be tested in further investigations.

3. Similar test could be done on an engine with forced-feed oil system.

4. More accurate control on oil temperatures is recommended.

5. Teflon, used as an electrical insulator in this investigation, was found to give satisfactory results. However, Teflon is also a good heat insulator, it prevented the conduction of heat through the piston wall. This might give some errors in the study of the temperature effects. Further survey on insulating materials is recommended.

VIII. ACKNOWLEDGMENTS

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X. APPENDICES

APPENDIX I. PROPERTIES OF TEFLON*

Chemical Properties	Value
Chemical Resistance	Excellent, except to fluorine
Moisture Absorption	Less than 0.001%
Weatherability	Excellent
Gas Permeability	
Nitrogen	12 Gms/100 m^2 / hr./mil
Oxygen	30 "
Carbon Dioxide	40 "
Acetone	56 "
Acetic Acid	27 "

Physical Properties	Value
Ultimate Strength	3000 psi
Ultimate Elongation	300%
Impact Strength	4 Kg/cm/mil
Flex Life	4000 cys
Tear Strength	125 g/mil
Density	2.15 Gms/cc
Coefficient of Friction	0.09

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* Taken from "Du Pont TEFLON FEP-Fluorocarbon Film"-Technical Report.

APPENDIX I. PROPERTIES OF TEFLON

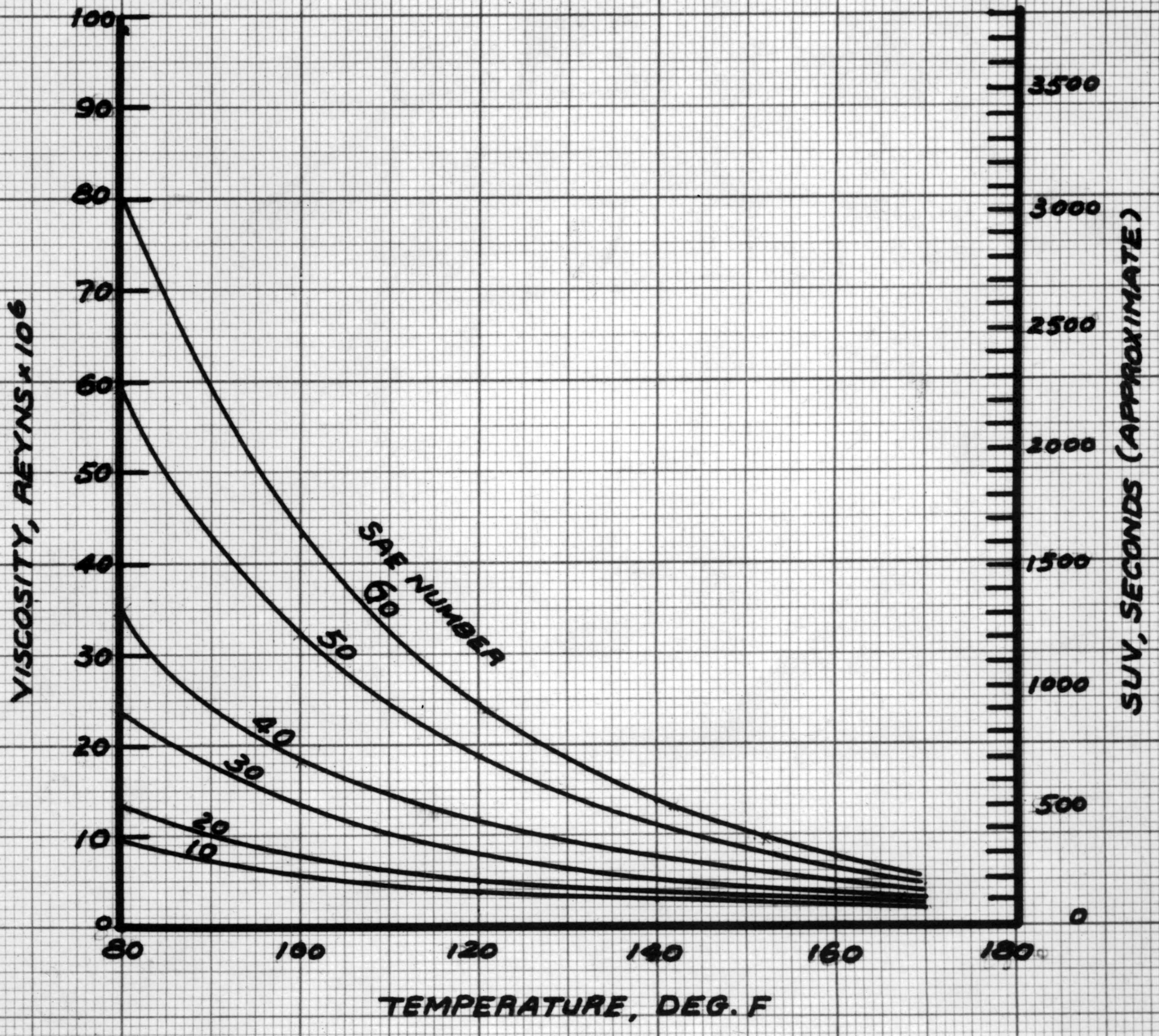
(continued)

Thermal Properties	Value
Temperature Range	
Continuous	-427° F to + 392° F
Intermittent	-427° F to + 527° F
Melting Point	545° F to 563° F
Coefficient of Thermal Expansion	
-100° F	4.61 10 in./in./ F
+160° F	5.85 10 in./in./ F
Flammability	Nonflammable
Thermal Conductivity	1.35 BTU/Hr/Ft^2/°F/in.
Heat Sealability	Good

Electrical Properties	Value
Dielectric Strength (85°F, 60cps)	400 volts/mil
Dielectric Constant (85°F, 100cps)	2.1 ± 0.1
Volume Resistivity (100°F to +490°F)	10^{17} ohm-cm
Surface Resistivity (-100°F to +490°F)	10^{16} ohm/sq.

APPENDIX II

THE VISCOSITY-TEMPERATURE CURVES OF REPRESENTATIVE SAE CLASSIFIED OILS



ABSTRACT

The object of this thesis was to investigate some of the factors that might affect the oil film performance between piston rings and cylinder walls.

An apparatus was constructed to measure the instantaneous changes in resistance across the oil film. A piston ring of an air-cooled single cylinder engine was insulated from the rest of the piston using Teflon. A bridge circuit was used to feed the unbalanced signals to an oscilloscope. The traces on the oscilloscope were recorded by means of an Polaroid-Land recording camera. An external motor having a speed control system was used to drive the engine.

It was found from this investigation that the lubrication could be improved by increasing the engine speed and oil viscosity. More metallic contact was found when the engine was under its own power. The results also showed that the breakdown of oil film occurred when the oil temperature was increased.

The experimental results indicated that the piston ring and the cylinder wall were never separated by lubricating oil at dead centers. The breakdown of oil film occurred at these positions in every case.