# DISCHARGE PHENOMENON AS A TOOL IN THE DYNAMIC MEASUREMENT OF THICKNESS OF THIN OIL FILMS BETWEEN HEAVILY LOADED MACHINE ELEMENTS

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The load-carrying capacity of machine elements, such as gears and roller bearings, depends on the lubricant film thickness that may be sustained between the loaded surfaees. This paper describes one of the methods of direct measurement of oil films called the discharge voltage method and presents a presumptive theory for the discharge phenomenon in oils. Some of the author's results using discharge voltage technique are presented together with his conclusions pertaining to the applicability of the method to running gears. With a better and more comprehensive calibration of discharge voltage, the quantitative interpretation of the results is expected to be reliable.

## Introduction

In order to evaluate the load-carrying capacity of gears and other rolling and sliding machine elements, a reliable quantitative method of measurement of lubricant film thickness (of the order of 20 micro-inch) borne by the surfaces is essential. While several methods of reasonable accuracy have been developed for the dynamic measurement of film thicknesses between large discs, [1-3] there is none so far available for direct application to more complicated configurations, such as gear teeth. A promising method is Cameron's voltage discharge method which depends on the discharge phenomenon in oils.

Cameron[4] working with a disc machine collected extensive data to study the effect of applied voltage on oil film resistance, By plotting the resistance against current (Fig. 1) he deduced a simple relationship,

$$C=RI^{k} \tag{A}$$

where C=constant, designated discharge voltage, R=resistance, I=current, k=constant$\simeq$1 for currents above 0.5 amp. Cameron's hypothesis for the mechanism underlying the relationship (A) was that the applied voltage causes a discharge to pass through the oil. The discharge will ensure that any amount of current can pass, as the oil is heavily ionized, such ionization occurring at large currents. At lower values of current, oil behaves as an ohmic resistance as seen from the flatter curves of Fig. 1 with $k \to 0$.

Cameron[4] next showed that discharge voltage is sensitive to load (Fig. 2) and to speed, (Fig. 3) and proposed that discharge voltage is in fact a function of the gap between the surfaces, that is, the oil film thickness. Siripongse et al[5] investigating the phenomenon found that when a steady D.C. voltage of about 6V is applied to two metallic surfaces separated by an oil film, discharge voltage-current characteristic was ohmic up to about 0.5 amp. current, but for larger currents, the discharge voltage was proportional to the thickness of oil film separating the surfaces (Fig. 4).

## Discharge Phenomenon in Oils

In order to understand the breakdown phenomenon of oils, a somewhat obscure field as yet,

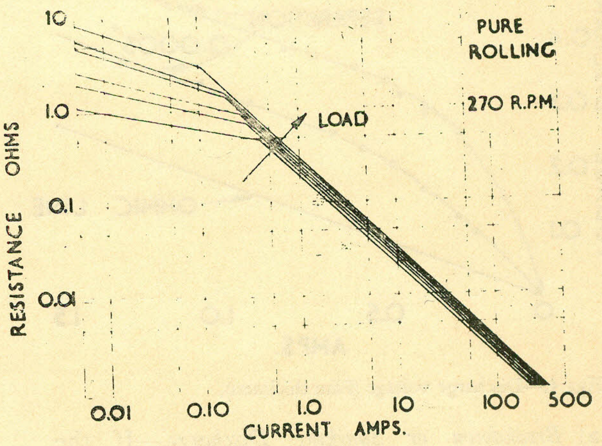



Fig. 1.—Oil resistence-current characteristics.

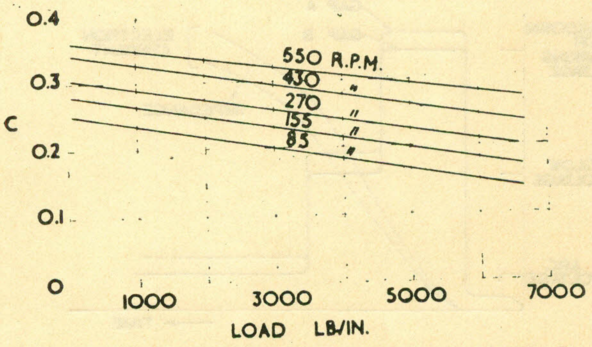



Fig. 2.—Discharge voltes-load characteristics.

*Now at N.E.D. Government Engineering College, Karachi breakdown of gases, a comprehensively investigated field, may be considered for analogy.[6,7] When an electrical potential is applied to two electrodes separated by a gaseous medium, the following time-dependent phenomena occur under the stipulated conditions (Fig. 5):—

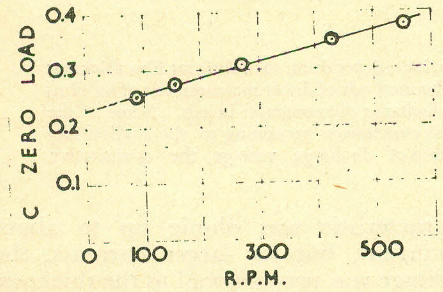
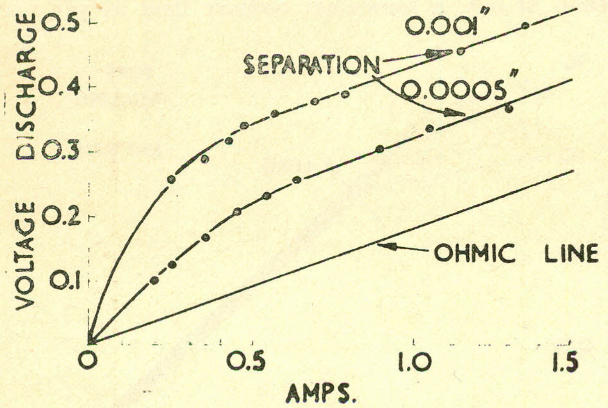



Fig. 3.—Discharge voltage-speed characteristic.




Figs 4.—Discharge voltage (Film thickness),

(a) *Breakdown or Sparking Discharge.*—If the applied potential is sufficiently large, the insulation of the gas breaks down. First a flash occurs and then a large electron current passes if the circuit impedance is low.

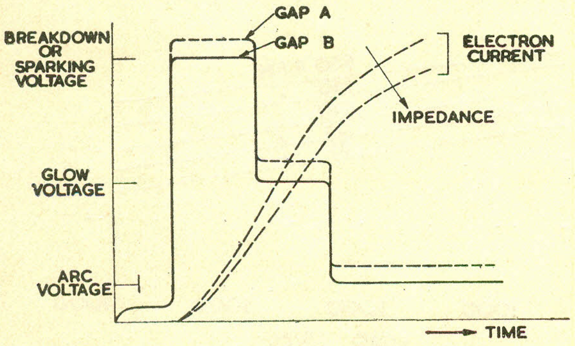



Fig. 5.—Discharge voltage-time characteristic.

(b) *Glow Discharge.*—In the initial phase of the breakdown the electron current is minute, because very few electrons are produced but later on more ions and electrons are produced in the gas and the current increases. If the applied voltage is approximately equal to the ionization voltage, the current will increase to a maximum. This discharge is known as the glow discharge. The voltage may be higher or lower than ionization voltage depending on the discharge conditions, geometry and the nature of the gas (Fig. 6).

(c) *Arc Discharge.*—If the nature of the two surfaces permits, electrons may be emitted from them under the force of the applied field, The phenomenon is known as "Field Emission" setting up an arc discharge. When the number of electrons produced is sufficiently large, a glow will grow into an arc and the applied voltage will fall below the glow voltage and become constant.

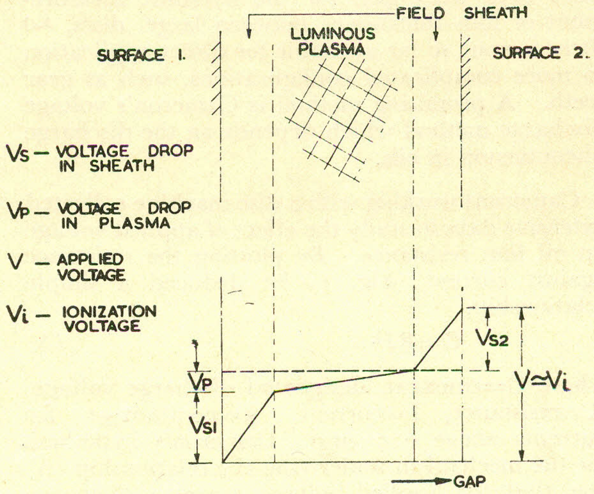



Fig. 6.—Glow discharge voltages.

For the several phenomena to be started in most gases, depending on the nature of the surfaces, the order of magnitude of applied voltage is:—

15—50 V for ionization,
50—200 V/cm. for breakdown per mm. Hg.
At $10^6$ V/cm. and above, field emission from metallic electrodes is to be expected.

An applied voltage-current characteristic for the breakdown in gases is shown in Fig. 7,

With oil dielectrics comparable phenomena will occur when dissociation takes place promoting ionization, The magnitude of applied voltage or the purpose may have to be larger because of the complex structure of oil molecules. Even so, discharge may become manifest at low applied voltages as has been the experience of Siripongse et al.[5] Crook and others[1] in their resistance measurement techniques used voltages of the order of 0.2V down to 0.015V, As an illustration, considering the least figure of 15 mV and assuming a generous hydrodynamic oil film of $10^{-4}$ in., the voltage across the gap works out to

$$15 \times 10^{-3}/2.5 \times 10^{-4} = 60 \text{ V/cm}.$$

At this applied voltage some dissociation of oil into gaseous substances may be expected and a discharge may well occur. The presence of air bubbles in the oil further increases the probability of a discharge becoming manifest.

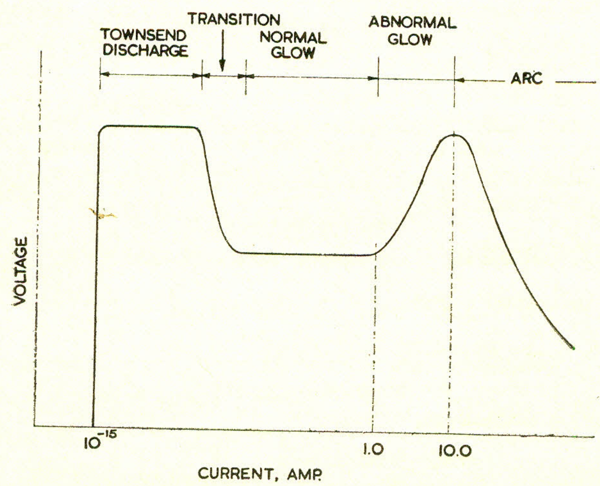



Fig. 7.—Breakdown characteristic for gases.

Again, when the oil becomes conductive, the passage of an electric current should always be associated with definite chemical changes. The substance of the conductor is decomposed at the surfaces of the electrodes where contact is made. Such decomposition must also be expected to be promoted by the presence of dirt particles, metallic and carbonaceous in nature Siripongse et al.[5] found that filtering out of foreign particles tended to increase the breakdown voltage, This is understandable as their presence promotes electrochemical action and hence dissociation of the oil.

The electrothermal effects introduced into the dielectric by virtue of the applied voltage are:—

(a) ionization and breakdown of oils accompanied by their chemical dissociation;

(b) discharge accompanied by high electron temperature 5000—30000° K;

(c) ion bombardment of surfaces at high velocity.

These aspects will contribute heat to the dielectric and hence to the bounding surfaces.

**Discharge Regime for Cameron's Technique**

Reviewing the techniques of Cameron[4] and of Siripongse et al.[5], it is worthwhile to find out the regime in which their work was done, whether it was glow discharge, arc discharge or a random combination of the two. The arc discharge phenomenon is characterised by:

(a) pulling out of electrons from the surfaces;
(b) severe ionic bombardment of the bounding surfaces at a velocity given by $6 \times 10^7 V$ cm./sec, where V=applied voltage.

As a consequence of this process (Fig. 8), the surfaces are worn out. The severity of wear may

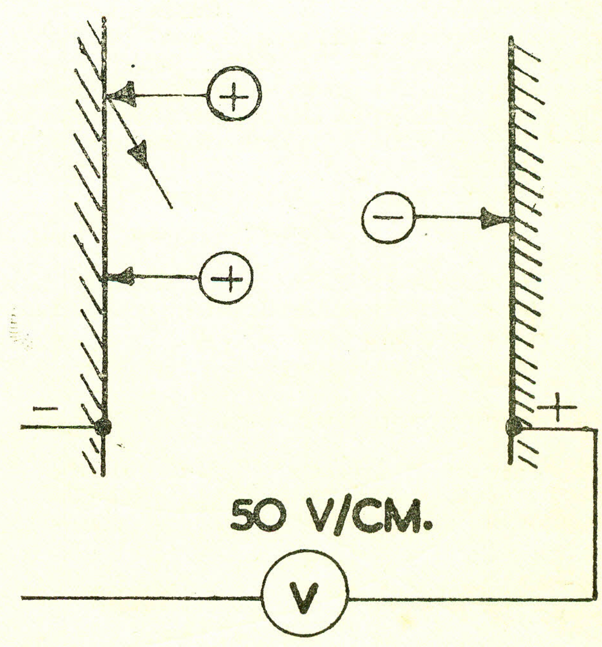



Fig. 8.—Arcing between metal surfaces.

be realised from the fact that A.E.I. have marketed an Ion Etching Apparatus working on Argon ions. Using wear as a criterion, it may be said that arcing could not be taking place in the region of energy levels employed by Siripongse et al.[5] This is also the experience of the author, who failed to detect any abnormal wear detritus to occur in gears.

Further arguments against the possibility of Siripongse et al.[5] having worked in the arc discharge regime are:—

(a) The discharge voltage ranges from $10^4$—$10^5$ V/cm. which is insufficient for field emission from the surfaces and for arc discharge to be established.

(b) The initial discharge characteristic (Fig. 4) resembles that of abnormal glow (Fig. 7).

(c) The large pressures in the contact, $10^5$ lb/in$^2$ which render the resistivity of the discharge to be large because of high pressure electron-neutral scattering and so inhibit the growth of an arc.

(d) The physical aspect of the voltage-current characteristic (Fig. 4), which is positive, would become negative as shown in Fig. 7 if arcing had set in the characteristic.

It may, therefore, be suggested that abnormal glow characteristic of Fig. 7 is applicable to the regime in which discharge voltage was investigated by Siriponges et al.[5] The current passing through the discharge is, however, larger than that indicated for gases in Fig. 6. This appears to be due to the presence of carbon particles which are highly conductive.

## Theory

The electron resistivity of the abnormal glow discharge between two surfaces may be considered as comprising two parts (Fig. 9).

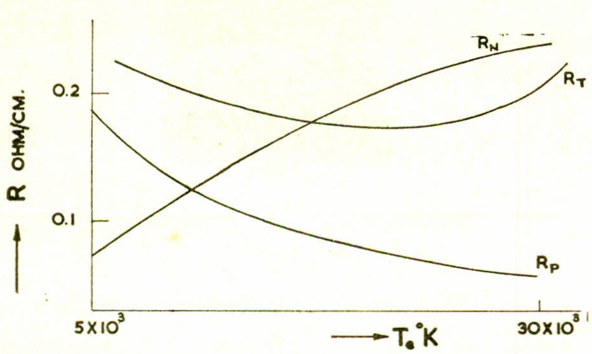



Fig. 9.—Glow discharge analysis.

(a) *Electron-ion Resistivity of Hydrocarbon Plasma.*—It is surmised that at a voltage 50 V/cm., dissociation of some oil would occur giving rise to a gaseous hydrocarbon plasma. The resistivity of this plasma[7] is given by

$$R_p = \left(\frac{T_e}{1000}\right)^{3/2} \text{ ohm/cm.},$$

where $R_p$ = Plasma resistance,
$T_e$ = Electron temperature, °K, which for abnormal glow may be assumed as 10,000 to 30,000 °K,

(b) *Electron-Neutral Resistivity.*—Due to the large pressures in the dielectric, the electron-neutral resistivity is an important factor in the phenomenon[8] and is given by

$$R_n = N\left(T_e\right)^{\frac{1}{2}}$$

$$\text{with } N = \left(\frac{8Km}{\pi e\ 4}\right)^{\frac{1}{2}} \left(\frac{\sigma c.n_o}{n_e}\right).$$

where $R_n$ = Electron-neutral resistivity, $T_e$ = Electron temperature, K = Boltzmann constant, e = Electronic charge, e/k = 11,600, an electron constant, m = electron mass, $10^{-30}$ kg., $\sigma c$ = Neutral cross-section for the electrons in hydrocarbon vapour, experimentally determined, $n_o$ = No. of atoms cm$^3$., ne = electron density $\simeq 10^{14}$/cm.$^3$.

The total resistivity, $R_T$ (Fig. 7) may then be written as

$$R_T = G(R_P + R_n)$$

where G = Geometric factor of electrodes, 1 to 1.5
= 1 for parallel plates.

The relationship determined by Cameron[4], equation (A) for parallel plates is then

$$V_D = (R_N + R_N)I = R_T.I$$
$$= RI^k \text{ with } k \simeq I$$

where $V_D$ = Discharge voltage.

## Dynamic Calibration of Discharge Voltage

Siripongse et al.[5] used an apparatus whose essential feature was a rotating steel shaft, 1″ diameter against which 1/4″ wide steel pads bear under variable load. The gap between the pads and the shaft due to the presence of an oil film was measured using a type of Lamb's Extensometer mounted on the loading arms carrying the pads. The bearing surfaces could be changed as required by adjusting the shaft axially and the pads vertically. For several unfiltered, straight mineral oils, different loads and speeds, the discharge voltage plotted against corresponding gap width determined by the extensometer gave a linear relationship (Fig. 10). The calibration constant was 4.5 V corresponding to $1 \times 10^{-3}$ inch oil film thickness.

## Possible Sources of Error in the Calibration Method

(a) The discharge voltage-speed characteristic of Cameron[4] (Fig. 3) did not pass through the origin. This was in all probability due to a static oil film which persisted between his stationary loaded surfaces and discharge through the film gave the zero error. Therefore the possibility of this phenomenon must be recognised and due allowance made for it by using it as a correction term.

(b) Decomposition of the oil occurs every time a discharge passes through it. Oil coming out of the mesh should be washed off and scavenged out.

(c) Inclusion of air bubbles in the oil is inevitable in the actual gear or disc running. To simulate this condition, it is desirable to introduce air with the oil jet.

(d) Measurement of film thickness by the independent method should precede the discharge voltage measurement. Simultaneous use of the two methods will measure the gap containing partially exploded oil.

(e) Care should be exercised to see that discharge is held in the abnormal glow regime using 1 to 3 amps. Arc discharge introduces significant heating, promotes field emission and has a negative voltage-current characteristic.

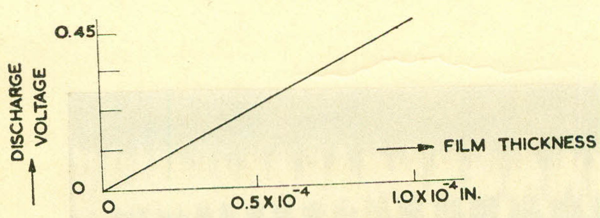



Fig. 10.—Calibration curve for discharge volts.

## Analysis of the Discharge Voltage Signal

The method of receiving discharge voltage signal on an oscilloscope screen and the procedure of recording the trace using a high speed camera are explained in literature.[9-10] These records have enabled the study of the oil film thickness from tooth to tooth of loaded spur gears over one or more revolutions with the help of a time base. The analysis of the variation in the film thickness from pitch line to root of any one tooth pair is then possible by suitably magnifying the trace. Figs. 11 and 12 show the traces for one pair of tooth going through one half of the meshing cycle at the same load, 2500 lbs/in., but different speeds, 1350 r.p.m. and 30 r.p.m. The oil in both cases is Oil E.

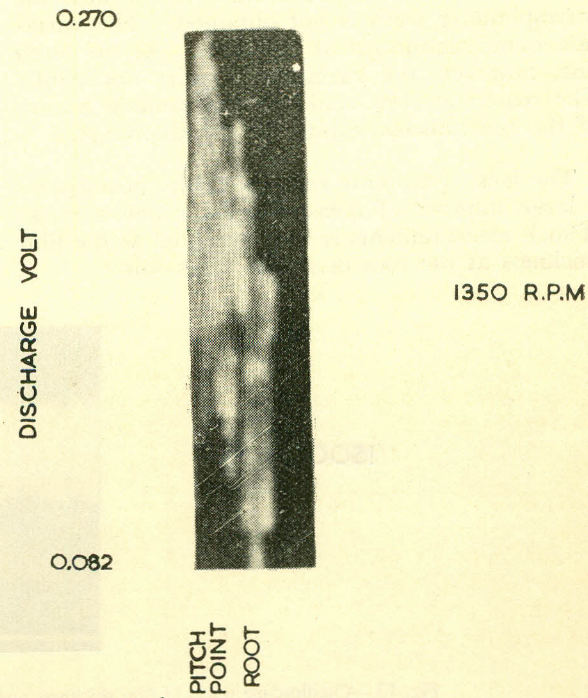



Fig. 11.—Oscilloscope trace of film thickness signal from pitch point to root at 1350 RPM.

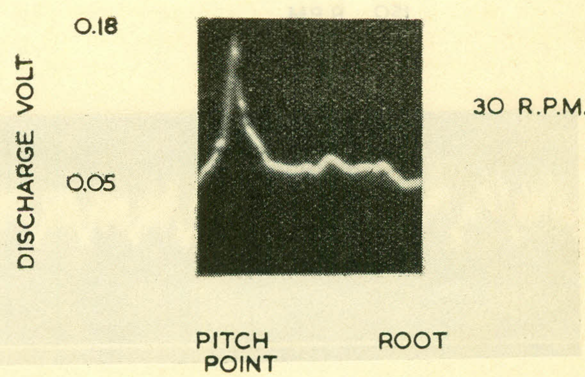



Fig. 12.—Oscilloscope traces of film thickness signal from pitch point to root at 30 RPM.

## Reproducibility of the Discharge Voltage Trace

Figs. 13 and 14 show representative traces of discharge voltage signal for two revolutions in each case at the same load, 1000 lbs/in. but at two different speeds, 1500 r.p.m. and 150 r.p.m.

(The unequal spacing of the trace of Fig. 14 is due to non-uniform speed of the recording camera device). The oil used in both cases is Oil B. The photographs show that exact reproducibility of the trace from one revolution to the next for corresponding teeth is not obtained. The variation is not significant at the roots. At the pitch line, however, the variation is quite noticeable. The reason for this could be the random nature of the phenomena setting off the discharge.

The lack of absolute reproducibility necessitates a large number of measurements. The average of such measurements is then accepted as the film thickness at the root or at the pitch line.

1500 R.P.M.

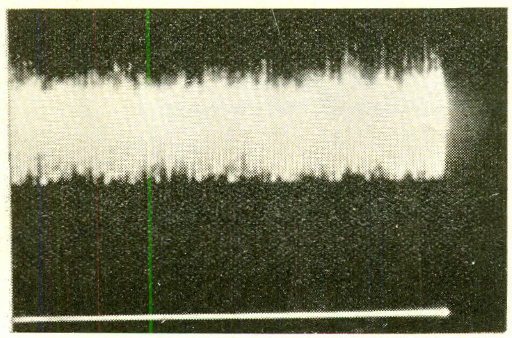


Fig. 13.—Oscilloscope traces of film thickness over two revolutions of loaded gears at 1500 RPM.

150 R.P.M.

DIRECTION OF ROTATION.

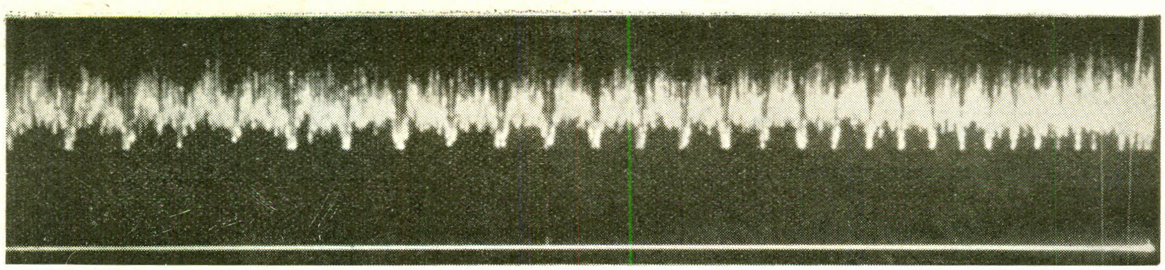


Fig. 14.—Oscilloscope traces of film thickness over two revolutions of loaded gears at 150 RPM.

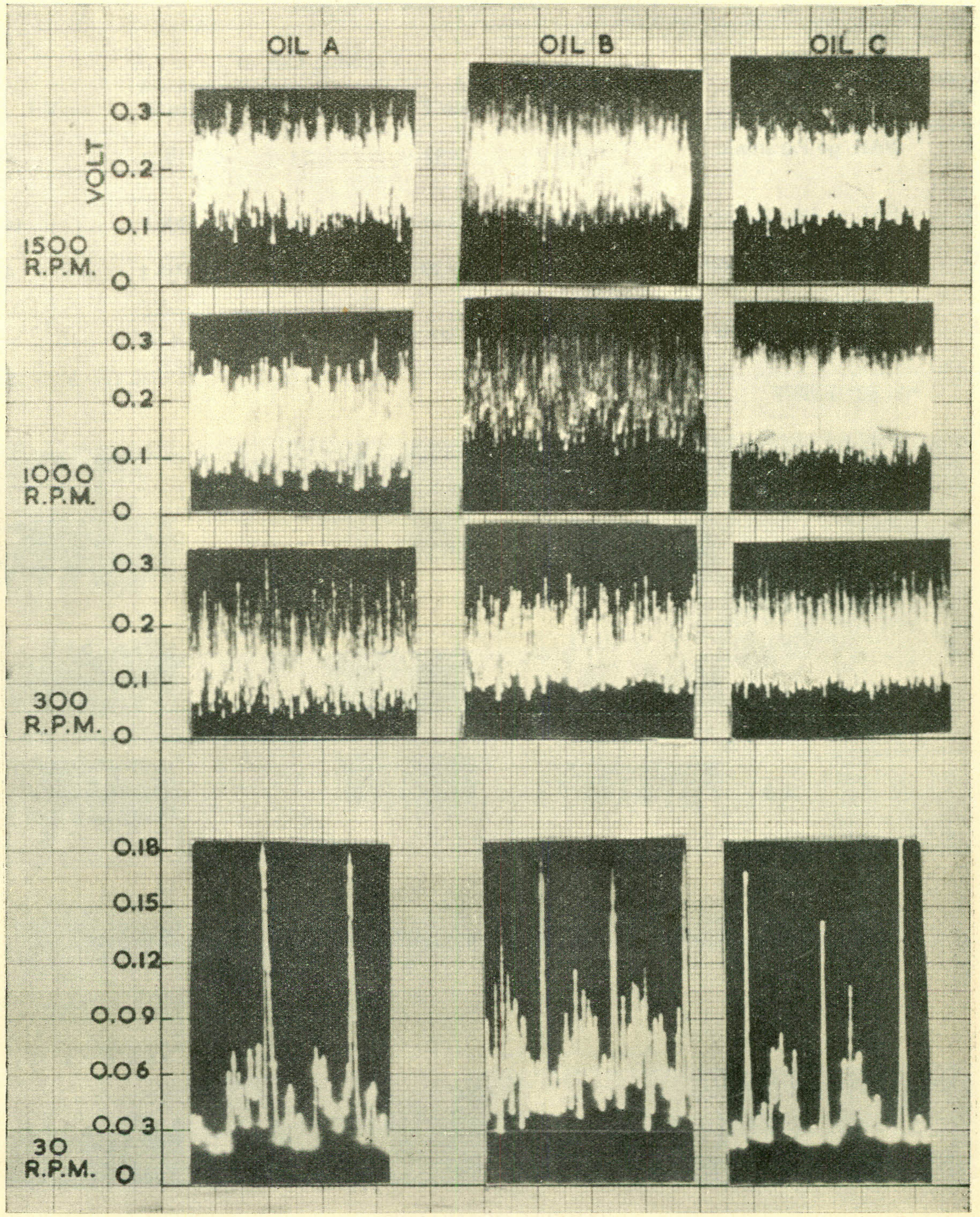
## Sensitivity of the Discharge Voltage Signal

It is well established that the oil film thickness between two contacting elements is a function of the oil viscosity, the speed of the elements and to a lesser extent the load impressed. Discharge voltage being sensitive to the gap between the electrodes, should be expected to vary when film thickness varies. Figs. 15 and 16 illustrate the discharge voltage traces for three oils, A, B and C, when worked at different speeds and loads. The traces confirm that discharge voltage is readily responsive and is sensitive to oil film variation due to changes in viscosity, speed and load.

## Conclusions

(a) The pioneering work of Cameron[4] has yielded a method of oil film measurement which is simple in instrumentation and possesses the unique advantage of direct application to running surfaces. The phenomenon underlying the method, although complex, has a reasonable theoretical proof.

(b) The calibration technique of Siripongse et al.[5] failed to take into account the various sources of error, and hence their calibration constant cannot be relied upon to give always correct quantitative results.




TOOTH CONTACTS
PITCH LINE LOAD: 1169 LBS./IN

Fig. 15.—Oscilloscope traces of of film thickness signal for different oils.

Table 1.—Test Oils—Specifications.

| Code No | Oil Grade | Specific Gravity At 60°F | Viscosity, C-S. at 100°F | 140°F | 210°F | V.I. |
|---|---|---|---|---|---|---|
| A | SAE 90 Paraffinic | 0.8960 | 237.0 | 74.0 | 18.0 | 91 |
| B | SAE 30 Paraffinic | 0.8845 | 110.6 | 39.4 | 11.6 | 100 |
| C | SAE 30 Naphthenic | 0.9075 | 139.8 | 41.6 | 10.4 | 44 |
| E | Paraffinic Distillate | 0.8607* | 21.5 | — | 4.1 | — |

*At 68° F/68°F

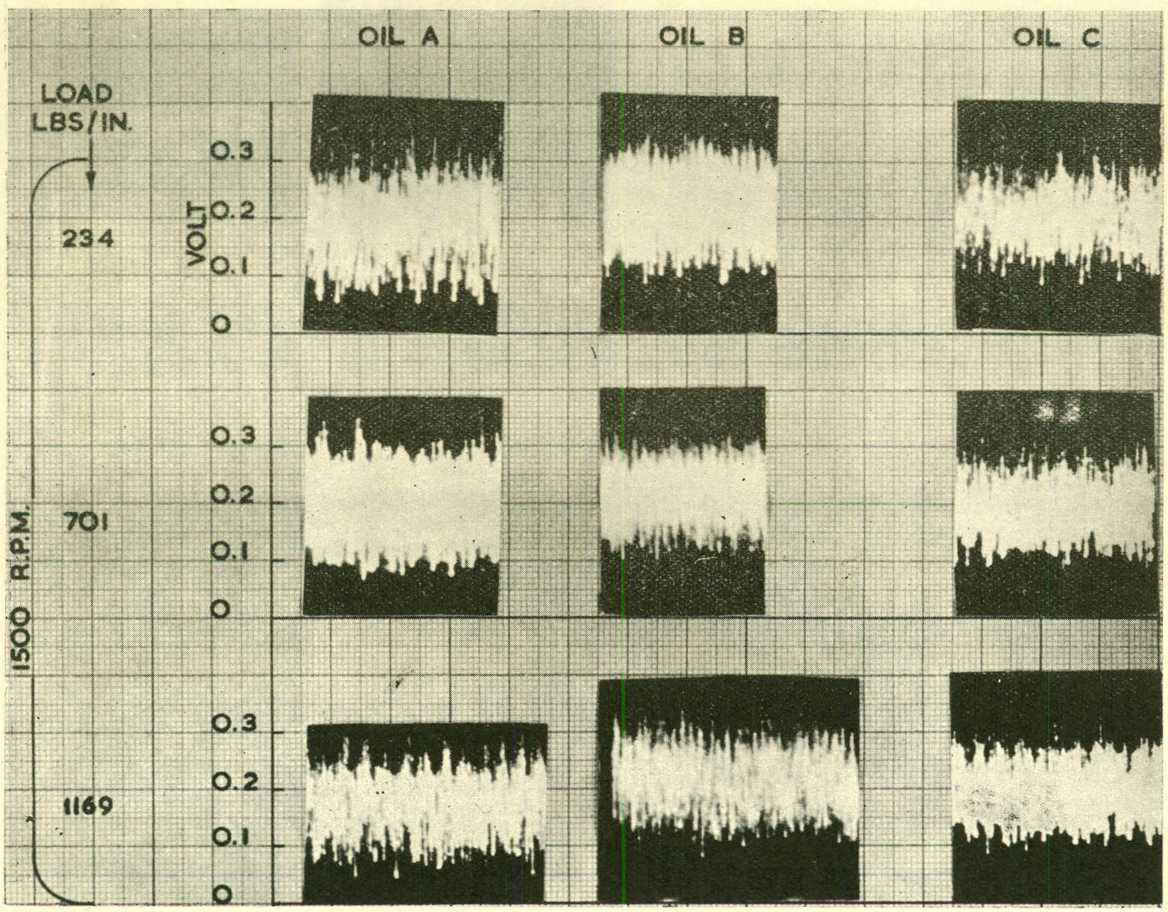



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Fig. 16 (a).—Oscilloscope traces of film thickness signal for different oils.

OIL A OIL B OIL C

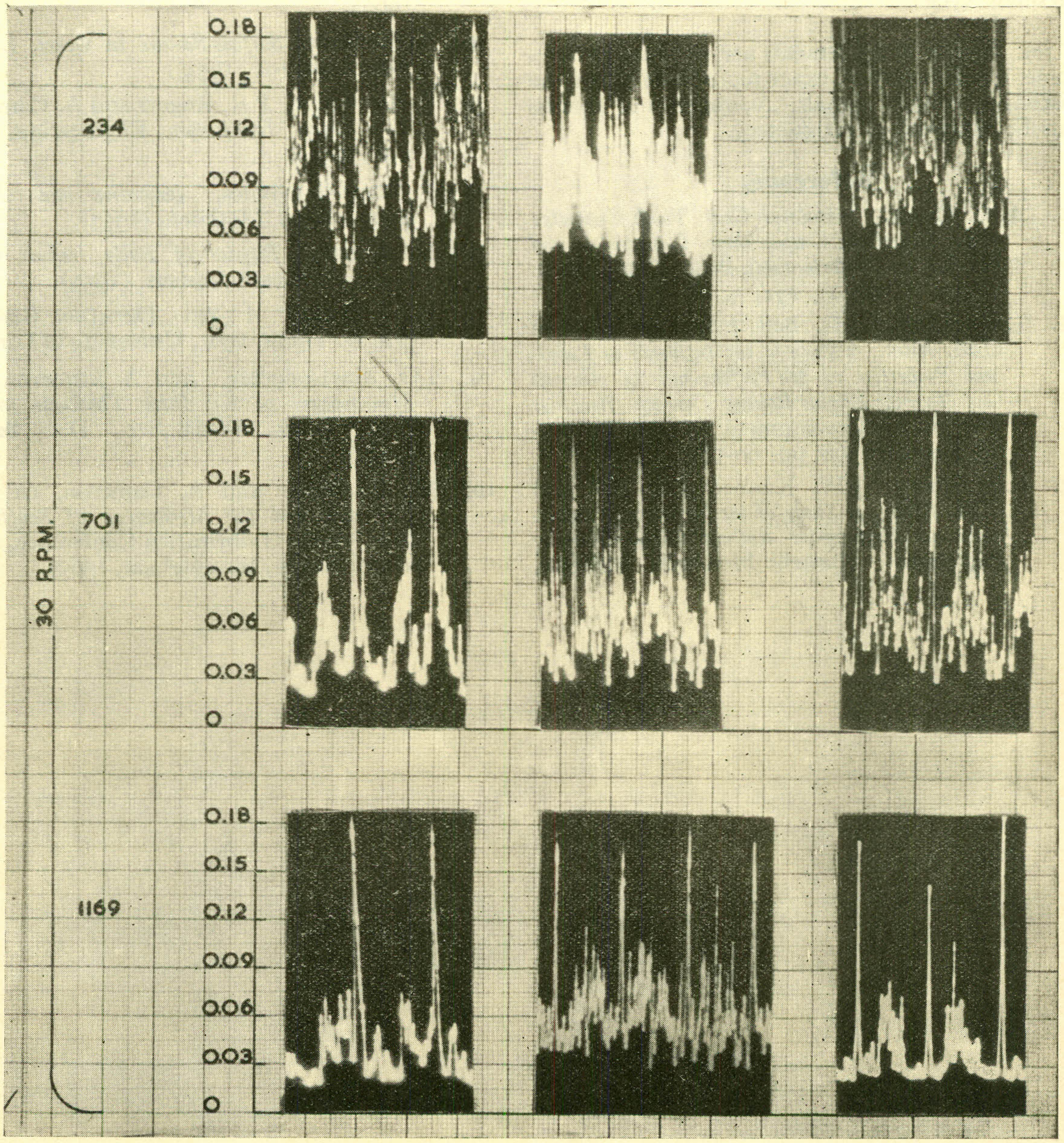


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Fig. 16 (b).—Oscilloscope traces of film thickness signal for different oils.

(c) Discharge always occurs through the least path, that is minimum film thickness. Even under normal glow condition, the dispersal of the discharge at the ends of the gap has been experimentally noted not to exceed 5% of the gap height. The suggestion sometimes heard that discharge is likely to pass through the ends rather than the gap is ill-founded. There is a possibility, however, of the discharge occurring close to the falling pressure, exit end of the gap where $dp/dx=0$ In this region any dissolved air will come out of the solution and discharge through the air bubbles will be facilitated. But the gap here is indistinguishable from the minimum. Therefore, this aspect is not a serious source of error.

(d) The discharge phenomenon is both readily responsive and sensitive to variation in oil film thickness. Discharge voltage measurement enables the determination of the oil film thickness at every point of contact of the teeth through their meshing cycle.

(e) Several measurements are essential to overcome the difficulty of exact reproducibility of the discharge voltage signals. Averaged out resuslts can be accepted as satisfactory.

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