THE ELECTRICAL CONDUCTIVITY OF THIN OIL FILMS.

Part I.—General Nature of the Phenomenon.[1]

By H. E. Watson and A. S. Menon.

It has long been a common practice to cover accumulator terminals with vaseline; Price and others in a discussion at the Physical Society (*Proc. Phys. Soc.*, 1903, **18**, 479) mentioned that potentiometer contacts were improved by immersion in kerosene oil; Manley (*Phil. Mag.*, 1917, **33**, 211) found that the resistance of the plugs in a resistance box was invariably more constant and very nearly always lower when they were lubricated with vaseline than when they were dry; Kraus (*Electrotechnik u. Maschinenbau*, 1920, **30**, 1) and Melsom and Booth (*J. Inst. Elec. Eng.*, 1922, **60**, 889) in investigations upon contact resistances, such as switches for electrical machinery, obtained similar results. Vaseline and heavy paraffin oil are now widely used for application to plugs and sliding contacts on measuring instruments.

In view of the fact that these substances are ordinarily regarded as excellent insulators, their use for the above purpose appears somewhat anomalous, and the object of the present investigation is a detailed examination of the region in which a transition from insulation to conduction appears to take place.

Branly (*Compt. rend.*, 1912, **155**, 933), in his experiments upon the coherer, found that films of guttapercha, collodion, mica, celluloid and paraffin wax from 5 to 25 μ in thickness conducted electricity when pressed between optically polished metal discs, and the resistance was reduced by an oscillatory discharge in the vicinity. He did not measure the actual thickness of the dielectrics. Wilson and Daniel (*Ind. Eng. Chem.*, 1922, **14**, 683) measured the contact resistance of two flat metallic surfaces pressed together and found that a dry resistance of 0·03 ohm increased on immersing the surfaces in mineral oil, continued to increase for about 6 hours and reached a final value of 4·4 ohms, pointing to the gradual building up of an adsorbed film. On application of a very small 1,000 cycle alternating E.M.F. the resistance fell rapidly to 0·4 ohm. These results do not appear to be in agreement with those of previous workers since the resistances

[1] Reprinted from the *Proceedings of the Royal Society*, 1929, A **123**, 185.

are much higher. The resistance of the plugs measured by Manley was of the order of 0·002 ohm. The difference may be due to the pressure, which in Wilson and Daniel's experiments was 311 gm./sq. cm., while in the other cases it was probably much greater.

The present paper deals more with the phenomena of breakdown than with the actual values of resistance when 'contact' has been established, and is largely an account of the experimental methods used for determining the nature and the thickness of films obtained in different ways. For most of the work a heavy paraffin oil $d30° = 0{\cdot}886$ and with very slight action on bromine has been used. The breakdown strength, kindly measured by Mr. Yoganandam in the Institute high tension testing laboratory, was found to be 92,000 volts r.m.s. per centimetre between 2·5 cm. discs 3·8 and 1·2 mm. apart at 60 cycles. Although suffering from the disadvantage of being a mixture of unknown composition, yet, for preliminary work, this is more than counterbalanced by the high insulating properties, large viscosity, low volatility and freedom from action upon metals of the oil, coupled with the fact that it is readily obtainable in large quantities while, since it is actually used for lubrication of contacts, an investigation of its electrical properties is desirable.

It is found that there is a critical thickness of the order 10μ at which the dielectric strength falls very suddenly and that breakdown takes place in two stages. Measurements have also been made upon the air film which is formed under certain conditions between two plane surfaces.

EXPERIMENTAL.

The experiments were started shortly after the publication of Hardy and Bircumshaw's Bakerian Lecture (*Proc. Roy. Soc.*, 1925, A **108**, 1) on boundary lubrication in which the coefficient of friction was shown to vary with the thickness of the oil film. It was thought that these results might be of value in correlating the thickness of the film with the conductivity, and consequently an apparatus somewhat similar to the one used by these authors was set up and friction measurements were made simultaneously with the others.

The determination of the capacity of the condenser formed by the two metal surfaces and the oil film suggested itself as a possible method of measuring the thickness of the latter and, consequently, arrangements were made to measure this quantity. The whole apparatus is shown diagrammatically in fig. 1.

The slider *A* weighed 30·3 gm. and consisted of a triangular 6 mm.

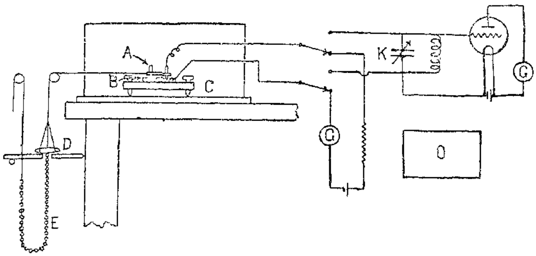

FIG. 1.

plate of 35 mm. side with three 6 mm. legs. These were turned down to 3 mm. at the ends, case-hardened and polished. They rested upon a polished steel plate B, half of which was silvered, supported upon a levelling platform C. The whole could be enclosed, if required, by a glass cover with ground edges under which was a dish of phosphorus pentoxide, but the presence of this drying agent had no marked effect, probably because experiments were not made with perfectly clean surfaces and the laboratory air was very pure and, at the time of the experiments, exceedingly dry. For determining the friction, a fine thread from *A* passed over a pulley and supported a scale pan D with an adjustable release which would only allow a drop of about 1 mm. Weights nearly sufficient to move *A* were placed in the pan and the final adjustment to the weight necessary to cause slip was made by means of a fine calibrated chain suspended below D, the principle being that of the chainometric balance. In this way the weight could be increased very smoothly and measurements could be rapidly repeated.

In order to determine if the film was conducting, the slider and plate could be connected in series with a battery, galvanometer and high resistance (about 100,000 ohms) to limit the amount of current passing, connection being made to the slider by a very fine wire to avoid strains. The capacity of the condenser when the film was non-conducting was measured by connecting it in parallel with a calibrated condenser K and an inductance. The circuit could be tuned to resonance with the oscillations from a separate oscillator O, the resonance point being determined by means of the simple valve circuit shown (*Cf.* Hobbs, *Wireless World*, 1924, **14**, 77). Wave-lengths varying from 100 to 300 m. were used. In order to avoid errors due to change in lead capacity, the circuit was first set to resonance with A resting on the oil film, the slider was then raised about 3 mm. by inserting a small ebonite strip between the top and the plate B and measuring the change in K necessary to restore resonance. This change was substantially equal to the capacity of the condensers formed by the three legs of the slider and the plate when separated by the oil film.

WIPED FILMS.

As soon as the experiments were started, it was found impossible to obtain a non-conducting film by placing oil, vaseline, or even a thin film of a solid, on the plate and standing the slider upon it, but if the substance was wiped off until almost invisible, a very stable film was obtained which would frequently withstand the application of 100 volts. The nature of this type of film will be discussed later.

Preliminary experiments were made with myristic acid. A small crystal was melted on the plate, previously thoroughly cleaned by boiling in alcohol and allowed to cool in a vacuum desiccator. The film so formed was wiped, and, when the slider was placed on it, was non-conducting. A number of measurements of the coefficient of friction were made, the slider being allowed to move about 1 mm. and then replaced in its original position.

TABLE I.

Coefficient of Friction, Steel-Silver, Myristic Acid, Non-conducting.

	a			*b*	
Weight:	30·3	80·7	130·8	30·3	130·8
Coefficient of friction	0·413	0·283	0·253	0·374	0·185
	0·390	0·279	0·252	0·354	0 184
	0·400	0·282	0·249	0·354	0·183
	0·403	0·284	0·237	0 337	0·187
		0·282	0·255	0·347	
		0·284	0·250		
Mean..............	0·401	0·282	0·249	0·353	0·185

The values (*a*) and (*b*) were obtained with different films, and it will be observed that, while sufficiently concordant results with a maximum variation of about 10 per cent. can be obtained in the same part of the same film, much larger variations are found with different films. In the case of a brass plate and the steel slider, a mean value of 0·355 was found for a load of 30·3 gm. The area of contact of each leg of the slider was 6·75 sq. mm., so that the actual loads in the three cases were approximately 150, 400 and 650 gm./sq. cm.

Measurements were next made of the thickness of the films by the dielectric constant method. It was at once found that the film thickness was by no means of molecular dimensions, but large even in comparison with the wave-length of light. Very exact optical polishing of the surfaces was consequently not necessary. The first slider used was slightly convex at the ends of the legs, the flatness over about one-third of the total area being within 1 μ. This was measured by placing a piece of optically worked glass over the legs and observing the positions of the Newton's rings. These were drawn on a larger scale on squared paper and the area corresponding with each thickness computed. The approximate thickness of the film was calculated by means of a curve showing the relation between minimum thickness and capacity.

Table II gives some results for this series of experiments with different films.

A number of experiments with myristic acid showed that widely divergent values could be obtained by placing the slider on different films or on different parts of the same film. The first two figures are the maximum and minimum capacities which were found in this way. The coefficients of friction varied between 0·37 and 0·44, but there appeared to be no relation between the coefficient of friction and the capacity. For determining the variation with pressure, the same part of the same film was used, and it may be seen that the coefficient of friction ρ decreases considerably with increase of pressure in agreement with Hardy's results (*loc. cit.*), but the capacity changes very slightly except in the case of paraffin wax. These results are shown in brackets. Where two sets are given for the same substance, the figures refer to different films or the same film after wiping. The various substances used were not specially purified for the preliminary experiments as the object was to ascertain the magnitude of the effect of the material of the film upon the thickness. Actually, the variations with one substance were so great that it was impossible to compare the results for different substances, although it is interesting to note that the thickest films were obtained with paraffin oil and

TABLE II.

Coefficient of Friction and Minimum Thickness of Non-conducting Wiped Films.

Film	Weight, gm.	ρ	Capacity, $\mu\mu$ F	Thickness, mm.$^{-9}$ ($\epsilon = 1$)
Myristic acid, silver steel	30·3	0·43	50 8	1·27
	30·3	0 40	34·2	2·42
	30 3	0·45	36 0	2·24
	80·3	0·31	37·0	2·15
	130·3	0·24	38·9	1 99
	230·3	0 25	39·5	1·93
Paraffin wax, silver-steel	30·3	0·36	29·4	3·10
	80·3	0·175	32·4	2·62
	130·3	0·175	38·0	2·07
	230·3	0·135	44·0	1 63
Paraffin oil, steel-steel	30·3	0·39	22·5	4·55
	80·3	0·19	23·5	4 30
	130·3	0·21	26 4	3·67
	30·3	0·39	45·7	1·52
	80·3	0·32	47·5	1·43
Stearic acid, steel-steel	30·3	0·33	52·0	1·20
	80·3	0·195	57·0	1·03
	130·3	0·155	60·8	0·91
Oleic acid, steel-steel	30·3	0·40	47·5	1·43
	80·3	0·26	48 0	1·41
	30·3	0·36	31·0	2 85
	80·3	0·27	31·0	2·85
Linolenic acid, steel-steel	30·3	0·44	51·5	1·25
	80·3	0·34	53·5	1 16

the thinnest with stearic acid. The thicknesses given are the minimum thicknesses, calculated in the manner already described, but, apart from the uncertainty introduced by the curvature of the slider legs, they involve the assumption that the film under each leg is of equal thickness and, consequently, cannot be considered as accurate values. Subsequent experiments after regrinding and polishing the legs until they were almost flat gave very similar results, so that the error is probably not large. In any case the figures for the variation in thickness on weighting are likely to be substantially correct.

The thickness has been calculated with the value 1 for the dielectric constant of the film, whereas the value for all the materials used was not far from 2. The original calculations were made with the latter figure leading to double the film thicknesses given. It was, however, quite obvious that these results were impossible as a film even 1 μ in thickness was quite opaque, while the wiped films were hardly visible. On discussing the matter with Sir William Hardy, he suggested that the films really consisted of air. This would account for the high insulating properties, since it has been shown by Broxon (*Phys. Rev.*, 1922, **20**, 476) that air films of the order of 0·5 μ in thickness will withstand a gradient of 640,000 volts per centimetre before breaking down.

Examination under the microscope revealed the rather unexpected fact that the films are not continuous, but consist of a number of minute globules which appear not to wet the surface. Fig. 2 is a microphotograph of a film of paraffin oil on stainless steel in the initial stages of wiping. Fig. 3 is an adjacent portion of the steel plate upon which a

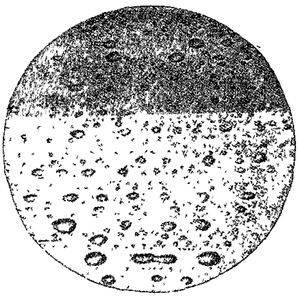

FIG. 2.

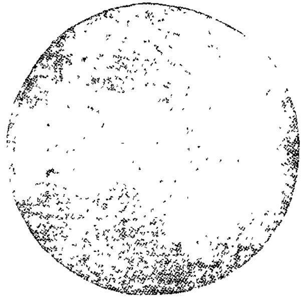

FIG. 3

× 80

steel cylinder had stood overnight in a pool of the oil. Both portions were wiped simultaneously and had stood for 24 hours before being photographed.

The appearance is quite different and it is evident that wetting of some kind has taken place. Melted myristic and oleic acids also formed globules, but nonyl alcohol spread in a continuous thin layer.

These facts suggest that non-conducting wiped films consist of a number of small oil globules between two adsorbed films of air or water vapour on the metallic surfaces, but their exact nature seems to be one of some complexity, and further discussion will be deferred until the experiments with flooded films have been described.

Flooded Films.

As already mentioned, it was not found possible to obtain a stable non-conducting film when the slider was placed in a pool of lubricant. This was also the case when a steel cylinder of diameter 10·9 mm. and weighing 11·2 gm. was substituted for the slider. It was subsequently found that discs of brass and case-hardened mild steel 18 mm. in diameter and weighing 8·6 and 7·9 gm., respectively, would not only float on the oil but would remain suspended above the plate when the oil was removed.

In order to obtain a film of varying thickness which changed slowly enough for observations to be made with some accuracy, the following device was adopted.

A piece of thick plate glass A, fig. 4, with a good optical surface, was silvered or platinised by splashing for half its width, as shown by the shaded area. The silvering was removed for 1 cm. at one end. The glass was placed on a stainless steel mirror or a similar piece of glass with the unsilvered end in contact and the other supported on a small piece of mica C, 32 μ thick, cut into two. The silvering thus formed a wedge with the mirror but was insulated from it. Electrical contact was made at the end of the plate and a drop of liquid was allowed to flow between the two pieces of mica. This gradually extended along the wedge and its progress could be watched through the clear side of the glass. At a certain point the film became conducting and the wedge was then opened and the farthest point to which the liquid had penetrated was observed. From this the thickness could be deduced. The thickness of the mica was measured as accurately as possible with a micrometer. Capacity measurements were not very satisfactory, possibly owing to irregularities in the silvering. The values obtained for the thickness were greater than by direct measurement.

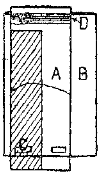

Fig. 4.

It was found that with very thin layers of oil between two slightly curved plates there was a considerable attraction which was sufficient to bend the plates. In the present series of experiments a few interference bands could be seen at the end of the plate at D, and these did not move appreciably on admitting oil, so that mechanical distortion was absent.

The surfaces were carefully cleaned in boiling ethyl alcohol or by washing with petrol followed by anhydrous methyl alcohol, and paraffin oil or triolein run into the wedge. Some of the individual results for the thickness at which the film became conducting were as follows :—

Paraffin oil—

Silver-steel	A.C., 8 μ, 15 μ.
Silver-silver	D.C., 6 v.–10 μ; 110 v.–11 μ.
*Platinum-steel	D.C., 2 v.–11 μ; 24 v.–11μ; 80 v.–13 μ.
Silver-steel	D.C., 2 v.–14 μ.

Triolein—

Silver-silver........	D.C., 6 v.–13, 16 μ; 110 v.–18 μ.
Silver-steel	D.C., 6 v.–13, 13 μ.

In all cases the point of breakdown was very sharply defined. The thicknesses are not very exact owing to the difficulty of determining the effective thickness of the mica, but the same mica was used throughout so that the values are comparable. In the experiment marked with a star, a quartz fibre 27 μ in diameter was used instead of the mica and the diameter of this could be measured with some accuracy. The silver films softened after a few experiments and had to be frequently renewed, but the platinum resisted the oil better.

The most striking feature of these results is that the breakdown thickness appears to be nearly independent of the applied voltage. Exact reproduction of the experimental conditions was a matter of some difficulty, but a good example is seen in the three experiments at 2, 24 and 80 volts with platinised glass. These were made as far as possible under comparable conditions and conduction occurred at very nearly the same thickness in all cases. The possibility of the result being due to a small projecting piece of metal was excluded by the fact that the oil ran rather unevenly, and although at the same distance from the end, it was in contact with different parts of the film when breakdown occurred. The figures for triolein appear to be slightly larger than those for paraffin oil. In most of these experiments only the first stage of conduction was obtained; that is to say, the film resistance fell to about 1 megohm.

Although the wedge method was of value for determining the approximate thickness at which conduction took place, its application was limited and it seemed desirable to supplement the results in other ways. For this purpose a more accurate method of measuring capacities was adopted similar to the one used by one of us (*Proc. Roy. Soc.*, 1927, A **117**, 43) for determining dielectric constants. The condenser under observation was placed in parallel with a precision condenser and the capacity determined by the method of beats at a frequency of about 600 k.c. Approximate measurements of the resistance of the condenser could be made simultaneously. With this arrangement a vertical displacement of 0·003 μ could be readily measured, and it was possible to determine if necessary much smaller shifts by means of a vernier condenser. The method possessed the advantage that even rapid movements could be qualitatively followed by ear.

Attempts were first made to determine the thickness at which conduction took place by placing the slider, or the steel cylinder already mentioned, in a pool of oil and noting the maximum capacity reached before oscillation stopped. With paraffin oil, conduction occurred within about 2 seconds and no reliable measurements were possible. With the cylinder, the thinnest film measured was 10 μ in thickness and with the slider and vaseline 8 μ, but these values are probably too large. The magnitude of the alternating E. M. F. applied could not be measured as it varied rapidly, but it was certainly less than 2 volts. The load per square centimetre in the two cases was 144 and 12 gm. When brass and steel discs corresponding to loads of 3·6 and 3·3 gm. per square centimetre were used, they floated in the oil and the films did not conduct. Another system was then tried. A condenser was made by standing the steel cylinder on two quartz or pyrex fibres stretched across a stainless steel mirror. For a very convenient method of drawing the glass fibres we are much indebted to Dr. E. P. Metcalfe, of the Central College, Bangalore. A small bead of glass is melted on an electrically heated platinum wire and the fibre drawn by touching the bead with a very fine platinum wire and pulling out by hand. By regulating the temperature and the rate of pulling, a fibre of approximately correct diameter can be drawn.

Numerous observations have been made with condensers of this type using the method of beats. The results are somewhat irregular, but certain features appear to be fairly definite. The thickness of the air film calculated from the capacity is always slightly greater than the measured thickness of the fibres except in one or two cases in which a fibre may have been displaced while putting down the cylinder. The difference is more noticeable for the thinner fibres. For film thickness of the order of 8 μ and under, it was frequently noticed that the cylinder at first assumed a metastable position and could be made to sink by gently tapping the plate or cylinder, but even prolonged tapping would not reduce the thickness to that of the fibres. At the same time attempts to remove a fibre only result in fracture, so that adhesion of some kind is present. The thicker films will stand a D.C. voltage of over 100 without breaking down, the insulation resistance being over

50 megohms and potential gradients of 100,000 v/cm. having been reached. The thinner films break down frequently on application of from 2 to 40 volts and become partially conducting, sometimes the resistance becomes very low. Usually, but not always, a film which has broken down subsequently conducts on application of a lower E.M.F., although it did not do so previously. Tapping restores the insulation. This might possibly be due to a thin bridge of metal, but a calculation of its diameter from the measured resistance in one or two cases assuming the ordinary resistance law to hold, gives a diameter of the order of 3×10^{-7} cm., a rather unlikely quantity. The alternating voltage applied to the film varied from 2·5 to 3 volts r.m.s., but it was not convenient to determine the breakdown point for alternating current with the more sensitive apparatus, as the power factor of the thinner films was appreciable and tended to stop the oscillations before actual conduction occurred. It is noteworthy that all films which would withstand 2 volts D.C. could be measured with the alternating E.M.F. mentioned, a result not to be anticipated from the work of other observers.

In making these measurements the cylinder was placed on the fibres and the capacity of the system measured. Any change on tapping was noted and oil was then run under the cylinder and the capacity remeasured. The values for the dielectric constant were very close to the correct value and afford a remarkable confirmation of Sir William Hardy and Miss Nottage's observations (*Proc. Roy. Soc.*, 1928, A **118**, 224), which reached India just after these experiments had been conducted, that a flat steel cylinder does not come into contact with a flat plate when stood upon it, but that a stable air film intervenes and the distance between plate and cylinder is not affected by introducing a lubricant between them. The examples in Table III show, however, that this is not true if the system is in the metastable state already mentioned, since in this case high values are obtained for the dielectric constant indicating that the lubricant pulls the cylinder down to the stable distance. It may be mentioned here that the capacity method has been criticised on the ground that the dielectric coefficient alters for very small thicknesses, but the recent work of Kollmann and Dorch (*Z. physikal. Chem.*, 1927, **126**, 305) who have been unable to detect any variation for several materials down to 1 μ, renders this unlikely, especially when taken in conjunction with the above results obtained by two independent methods.

Table III gives a few of the results obtained. The value for ϵ is the ratio of the capacities after and before filling with oil allowing for stray capacities. The thickness of the oil film is calculated on the assumption that $\epsilon = 2{\cdot}21$, the value obtained by measurement in a larger apparatus. The figures represent mean thicknesses, but the minimum thickness is nearly the same (within 0·5 μ) as the cylinder and plate were almost flat. Although the absolute values are subject to an error of this magnitude, the relative values are much more accurate.

TABLE III.

Thickness of Air and Oil Films.

Experiment No.	Fibre, μ	Air film, μ	Oil film, μ	ϵ	Remarks.
1	33 app.	30	30	2·21	Quartz fibre, R very high.
2	2·8	4·5	4·73	2·08	Initial thickness 8·2 μ, value 4·5 after tapping. Oil film 4·15 μ with 50 gm. weight on cylinder. Conduction irregular.
3	2·8	6·36	6·36	2·21	Initial thickness 15·0 μ, 6·36 after prolonged tapping. Conduction partial.
4	12	16·8	16·9	2·20	Oil film reduced to 13·7 μ with 50 gm. weight. No conduction 120 v.
5	9	—	9·9	—	Conducted partially.
6	3	11·0	10·9	2·22	Fibres slightly oily; conducted 6 v.
7	3	9·9	10·1	2·17	Thickness before tapping 13·8 μ. Conducted 6 v.
8	9	11·8	11·6	2·24	Partially conducted 24 v.
9	9	10·1	8·3	2·68	Same fibres, one very near edge possibly washed out by oil. Partly conducted 14 v.
10	2·5	4·95	4·9	2·22	Broke down at 66 v.
11	0	2·11	2·10	2·22	No fibres. Initial ϵ = 2·04. Partly conducted 2 v.

Experiments 2 and 3 clearly show the metastable floating effect, the thickness of the air film having been reduced to approximately one-half by tapping. Experiment 11 was the only one of many attempts to float the cylinder on the plate without fibres which was successful. It was accomplished by washing the surfaces with anhydrous methyl alcohol, wiping with a clean cloth and immediately placing the two together. Under these conditions it is highly probable that the surfaces were contaminated by an adsorbed layer of alcohol. The cylinder sank slowly (0·04 μ in 10 minutes) just as if it were floating on oil, and was fairly stable to tapping. On introducing oil it rose nearly 0·2 μ, and then sank, at first rapidly, then more slowly, to the original distance, at which point oscillation stopped owing to the high conductivity.

The actual thickness of the air films (4·0 μ) measured by Hardy and Nottage on a contaminated surface is of the same order as those recorded in Table III for very thin fibres. As it has not been possible to obtain a non-conducting layer even with a moderately clean surface, the observation that the film is thicker when the surfaces are clean could not be confirmed. In this connection it may be mentioned that through the courtesy of these authors, we were enabled, while their experiments were in progress, to examine the conductivity of one of their steel plates and cylinders after careful cleaning according to their standard method. The non-conducting state could not be obtained even with the application of only 1·4 volts, but on rubbing the plate with the finger and replacing the cylinder, a very stable non-conducting film, with a resistance of over 10 megohms, was formed and the cylinder could be shaken or moved about on the plate without producing any signs of conduction.

On p. 224 of the paper under reference it is stated: 'If more accurate methods should confirm the figures, the distance between the cylinder and plate would be the same for a gas as for a liquid and independent of the chemical constitution of the lubricant and of the enclosing solids.' If this is true, the constancy should hold good not only for any gas but for any gas at any pressure. The present experiments, although limited in scope, indicate that the agreement under suitable conditions may be as close as 1 per cent. for paraffin oil and air at 685 mm. pressure, and, consequently, it was considered of interest to examine the effect of reducing the pressure. The cylinder was floated on an almost invisible 'wiped' film of the oil and the whole covered with a bell jar which could be evacuated. The film thickness was 4·0 μ. On reducing the pressure to about 100 mm. a slow steady fall set in, but the distance moved was only 0·01 μ in 9 minutes. On readmitting air the cylinder rose 0·005 μ in 7 minutes and then remained fairly steady. The cylinder was then slightly repolished and floated on a fresh contamination giving a film 3·74 μ in thickness. A similar reduction of pressure caused a fall of 0·027 μ in 3 minutes, the subsequent rise to a steady value being 0·022 μ in 3 minutes. Paraffin oil was then run under the cylinder causing the resistance to fall below 300 ohms, but on vigorous tapping it increased to 50,000 ohms, and then to several megohms, and the film thickness was found to be 3·54 μ, a value sufficiently close to the one with air, considering the somewhat rough treatment the cylinder had received.

In another experiment with a larger gap of 12·5 μ, a fall of 0·67 μ, of which half was in the first half minute, was recorded, followed by a rise of 0·38 μ on readmitting air. In this case the cylinder was not fully stabilised by tapping. After three more evacuations to 2 mm. the fall was only 0·07 μ and the rise 0·035 μ. A change in capacity, probably due to the removal of air from the gap and its readmission, could be heard as it was quicker than the movement of the cylinder, but a similar effect would be produced if the cylinder were slightly raised by a release of the pressure on top of it, assuming that the air only issues slowly from the gap. It is not possible to distinguish between the two effects.

These experiments indicate that there is a critical distance between two surfaces at which unexpected phenomena occur. In the case of the cylinder this distance is about 4 μ and for the slider with 3 mm. legs something over 1 μ. The total film thickness depends on the amount of contaminant, as it decreases with wiping or with reduction in size of the glass fibre separators, which appear to act in a similar manner to the oil film, and it might perhaps be expressed as 'effective contaminant thickness + a constant.' The effect is the same as if each surface were covered with a rigid layer and the contamination forced the two apart, but the formation of these layers appears to be facilitated by the presence of the contamination, since it is very difficult to arrive at the non-conducting state with two clean surfaces. If the quantity of contaminant is excessive, as in the case shown in fig. 2, where the larger droplets are about 50 μ in diameter, when the upper body is placed on them, contact with the oil takes place long before the critical distance is reached, and the effect is the same as when the body is placed in a pool of oil, *i.e.*, conduction occurs if the pressure is sufficient. Non-conducting wiped films can only be obtained when the film is practically invisible.

The rigidity of the composite film is evident from the results in Table II and its stability is so remarkable that it is, on first experiencing it, almost impossible to remove the impression that it is due to dirt between the surfaces, but the reason for the formation of the film is obscure. An electrical repulsion, due to the polarisation of the molecules, appears to be excluded, since the distance remains unchanged when a liquid of different dielectric constant is introduced into the gap, and at present no further explanation is forthcoming. A method has been devised for measuring the thickness of conducting films, and it is intended to examine outgassed surfaces in the hope that further light may be thrown on the matter.

To return to the figures in Table III: with the exception of experiment 10, which appears to be abnormal, all the films of 11 μ and under in thickness conducted on the application of comparatively low E.M.Fs., but there is no obvious relation between the film thickness and the breakdown E.M.F. This is perhaps to be expected from the results of the wedge experiments. In nearly all cases the first stage of breakdown was to a partially conducting state in which the resistance varied from about 10,000 ohms to a few megohms. The conduction was frequently of an intermittent nature as the galvanometer needle tended to fluctuate some 20 per cent. from the mean, but, occasionally, particularly with heavier currents, it was steady. There appeared to be no polarisation of the electrodes as no current was obtained on shorting the source of E.M.F., whereas a film of octyl alcohol under similar conditions gave an appreciable reverse current for a few minutes changing in direction with a change in the polarity of the initial E.M.F. The resistance of the film invariably decreased with increase of current, and in several cases there appeared to be a tendency for the potential drop across the film, e, to remain constant, some of the results being shown in Table IV where c is in microamps and e in volts.

TABLE IV.

Conductivity of Partially Conducting Oil Films.

A		B		C		D		E		F		G	
c	*e*	*c*	*e*	*c*	*e*	*c*	*e*	*c*	*e*	*c*	*e*	*c*	*e*
1·5	0·44	0·2	1·8	2·1	6	0·5	9	10	9	16	8	75	13
3·2	0·66	1·1	2·9	2·9	7	4·4	10	69	14	46	19	225	18
4·9	1·0	2·5	3·4	9	11	10	10	125	17	108	19	420	18
7·0	1·0	4·2	3·8	16	14	20	10	220	18	208	19	640	17
		6·2	3·8	22	17					475	18	880	12
												1,100	12

Columns A and B refer to the film of experiment No. 3 of Table III with 1 megohm in series. After making the measurements "A," the plate was tapped and the resistance increased to over 100 megohms when tested by applying 4 volts. At 6 volts there was partial breakdown and readings "B" were taken by applying 2, 4, 6, 8 and 10 volts in succession. On tapping, the resistance again became very high, but the film broke down partially at 4 volts, and with 6 the resistance became very low indeed. This behaviour was typical of the thinner films. The remaining figures all refer to one film, No. 8, of Table III, 11·6 μ in thickness. This film initially broke down with 24 volts. In a preliminary series of readings the resistance fell from 28 to 9 megohms. On repetition it was found to be only 3 megohms and the readings "C" were obtained. After standing 24 hours the film became non-conducting with a resistance of over 1,000 megohms, but broke down with 62 volts, giving irregular readings. After tapping and allowing to stand for some hours, the fairly steady values "D" were found at a room temperature of 31°. After standing overnight, 14 volts were required to break down the insulation which had again become high and the values "E," "F" and "G" were obtained in succession at 30°.

With both films the E.M.F. increases with the current for small values of the latter, but Ohm's law is not obeyed; with larger currents the E.M.F. becomes nearly constant and on still further increase it decreases. The behaviour in the later stages resembles the discharge in a gas without a positive column in which the E.M.F. remains constant until the cathode is covered with the glow, followed by arcing under suitable conditions. The steady potential appears to depend upon the thickness of the film, but it may also vary considerably for the same film. Until further experiments have been completed, it is not possible to say whether the conductivity is due to impurities in the liquid, to the type of discharge usually associated with dielectric break-down or to some other effect.

Disc Experiments.

As mentioned above, it was found that discs of brass and steel would float on a layer of oil or of air. The latter effect appeared to be produced very readily if the discs were lightly polished with rouge and water on a pitch polisher and then cleaned with anhydrous methyl alcohol. After immersing in oil and cleaning several times, flotation was more difficult to secure. It seems possible that a trace of contamination from the polisher assists the formation of the film, although it was not sufficient to produce an insulating layer in the case of the slider and the cylinder.

The loads per square centimetre with these discs were 3·6 and 3·3 gm. Ormandy (*Proc. Inst. Mech. Eng.*, 1927, I, 307) has given some results for a larger disc in a pool of paraffin oil producing a load of 4·7 gm. per square centimetre. His thicknesses have been miscalculated and should be only one-fourth of those tabulated. The films became conducting after some minutes and a minimum thickness of 2 wave-lengths or 1·2 μ was measured, much less than that obtained in the present experiments. In the latter a brass disc placed in a pool of paraffin oil sank in 6 minutes at a temperature of 25° to a distance of 19 μ from the plate, but was still falling slowly. After pressing it sank to 17 μ and remained quite steady. By repeated pressing this distance was reduced to 12·7 μ, on releasing the pressure (about 500 g.) the disc rose immediately a distance of 0·03 to 0·05 μ.

The same disc floated at a distance of 9 μ from a contamination of myristic acid, while a steel disc initially rested at a distance of 12 μ from a clean plate, sinking very slowly. On tapping it fell to about 4 μ and remained steady. On admitting oil to these air systems in a stable state, values of 2·30, 2·24, 2·24 and 2·33 were obtained for the dielectric constant, showing that the disc was pulled down slightly. On one occasion oil was admitted before tapping and the value found was 2·70, showing a much larger movement. Values for the conductivity analogous to those with the cylinder were obtained, but it was difficult to polish the discs sufficiently flat and, consequently, the figures for the thickness are not very reliable. Further experiments will be made after repolishing.

In conclusion, attention may be drawn to a recent paper by Joffé, (*Trans. Faraday Soc.*, 1928, **24**, 65) in which he states that exceedingly thin films were found to have a very high dielectric strength. In the absence of experimental details it is difficult to compare these results with those recorded in the present communication.

SUMMARY.

Methods are described for determining non-conducting film thicknesses by means of capacity measurements; with suitable arrangements very minute changes in thickness can be measured.

There is a strong tendency for a film of air of the order 1 to 4 μ in thickness to form between two plane surfaces, particularly if one of them is slightly greasy. Hardy's measurements have been confirmed and his hypothesis that the film thickness is unchanged when the air is replaced by oil has been shown to hold good, with certain limitations, to an accuracy of at least 5 per cent. The thickness has also been shown to be nearly independent of the air pressure down to 2 mm.

The coefficient of friction for the air film between contaminated surfaces has been shown to decrease with increase of pressure, although the distance between the surfaces remains nearly constant and there is no relation between the coefficient of friction and the thickness.

Air films have a high insulation resistance and when they break down the resistance usually becomes very low. Flooded films of paraffin oil will stand a high potential gradient (over 100,000 v./cm.) as long as their thickness is more than about 15 μ. At 11 μ there is a

tendency to break down with a much smaller potential gradient and the breakdown thickness does not vary greatly with the voltage. The film becomes conducting in two stages; in the first, the resistance is of the order of 1 megohm, Ohm's law is not obeyed, but there is a tendency for the E.M.F. across the film to remain constant with variation of currents over a certain range. In the second stage the resistance is very low.

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[Accepted, 23-9-29.]

PRINTED AND PUBLISHED BY GEORGE KENNETH AT THE DIOCESAN PRESS, POST BOX 455, MADRAS—1929 C9255