ELECTRICAL DISCHARGES FROM POINTED CONDUCTORS.

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SYNOPSIS.

Surface Action in Electrical Discharges from Points.—The lag phenomena shown by the discharges from some points indicate a special surface action. Various possible surface actions are discussed and attention is centered upon an adhering layer of gas molecules. Further evidence is sought in discharges from points made of different materials.

Electrical Discharges from Water Points. Surface Electric Intensities and Stopping Voltages.—Discharges from water points begin impulsively. The surface intensity during positive discharges is independent of the current and a simple relation exists between values of this intensity, point radii and air pressures. Empirical relations are given connecting point radii and stopping voltages. The results are compared with those from similar metal points.

Electric Fields for Water Points in Air, Oxygen, Hydrogen and Carbonic Acid.—A table of these fields is given for two water points with different gas pressures ranging from 10 cm. to 87 cm. of mercury but no relation between these values and other constants was found.

Comparison of Electric Fields for Points of Water, Glycerine and Methyl Alcohol, and of Stopping Voltages for These Liquids and for a Brass Point.—The comparison was made in air at different pressures, and no differences between the different substances were observed with the exception that some of the results for methyl alcohol were smaller than those for the other substances.

Starting Voltages for a Brass Point Coated with Various Salts.—The surfaces were far from smooth but the positive discharge started at nearly the same potential from all of the different coatings, while the negative starting potentials varied greatly among themselves.

Dependence of Critical Fields upon the Curvature of Surfaces of Points.—An explanation is given of the fact that the critical field required for the production of a discharge is larger the smaller the radius of the point. The dependence of the field at the surface of a point during a discharge upon the divergence of the field is shown experimentally.

Discharge Currents for Points Made of Different Materials.—Testing for a possible ejection of ions from a surface by impact, similar points of platinum, brass, copper and water under the same conditions gave the same currents except that the negative current from water was slightly smaller than from the other substances.

POSSIBLE SURFACE FACTORS IN POINT DISCHARGES.

1. The theory of the flow of electrical currents from pointed conductors which is generally accepted assumes that the ions which carry the discharge current are produced solely by collision with molecules of the gas of the few ions normally created in the gas by radiations from radioactive substances. Many of the general characteristics of these dis-

charges may be explained qualitatively on this theory by the known properties of ions, without the need of assuming any action at the discharging surface such as ejection from it of ions by the impact of those colliding with it or such as would arise if the ions met with difficulty in discharging to the metal surface.

There are some features of these discharges, however, which indicate that at least under certain circumstances a special action does take place at the discharging surface.[1] Thus for example the discharges from some metallic points begin very impulsively as the voltage applied is gradually increased, as if some resistance had been suddenly overcome; and what is even more significant, on decreasing the voltage after a discharge has started in these cases the current breaks off abruptly. An explanation of this sensitivity of some points, as such behavior is often called, must be sought in some condition at the discharging surface because points to all appearances similar differ very markedly in this property; and a point not possessing the property may be made to acquire it by treatment which does not appreciably change the form of the point.

Edmunds[2] however ascribes the retardation in the commencement of discharges from points to the fact that the ions normally in the gas are few in number and that some time may elapse after a voltage is applied before ions may chance to assume a favorable distribution along that restricted region where the field is strongest and where accordingly ionization by collision can take place for the lowest permissible applied voltage.

It is difficult to see why this argument should apply to some points and not to others to all appearances of the same form which do not show the lag phenomenon. Moreover, the abrupt stopping of a current which accompanies the lag in starting cannot be explained in this way.

However, when a point is in a condition to show a lag in the commencement of a discharge, the discharge is often brought on by the sudden production within the field of force of an exceptionally large number of ions, a matter which will be considered more fully at a later time.

2. What possible actions may we suppose taking place at a discharging surface which surface conditions could aid or retard? We may suppose that electrons or ions are being pulled from the surface by the strong electric field; or that electrons or ions are being ejected from the surface by the impact of other ions against the surface; or that under some

[1] See J. Zeleny, Phys. Rev., N.S., 3, p. 69, 1914.

[2] P. J. Edmunds, Phil. Mag. (6), 28, p. 234, 1914.

circumstances ions coming from the gas may find it difficult to discharge themselves to the surface. The state of the surface might influence greatly any of these actions.

That the pulling of ions from the surface by the field plays any appreciable part in point discharges is made improbable by the results of Almy[1] who working at distances of the order of a wave-length of light found that no discharge passed between the electrodes for fields as high as 1.7×10^7 volts per cm., although a discharge did pass with still higher fields. The field at the surface of a discharging point is ordinarily very much smaller than the field named and the only possibility of any such action actually taking place lies in the fact that in Almy's experiments the conditions were not favorable for the multiplication by collision of any ions that might have come from the metal.

The ejection of electrons from metal surfaces by the impact of ions is postulated in the explanation of some phenomena connected with discharges at low pressures, and a similar activity at the surface of a discharging point is not excluded. Ionization of gas molecules adhering to a metal surface by the impact of ions coming to it would produce effects similar to those resulting from ejection of electrons from the surface, and moreover might take place with either a positively or a negatively charged point. Neither of these effects however could change appreciably the voltage at which a current is observed to begin from a *positively* charged point, since a positive ion coming from the surface would be unable to ionize molecules of the gas by collision if the negative ion which produced it had not been able to do so, and without further increase these added ions could not give an observable current unless the highly improbable supposition were made that each original ion that strikes the surface gives rise to nearly a million new ions at the surface. The production of ions at the surface should result rather in an increased current for voltages above the critical one over the current due to the ionization produced by collision of those ions which originated in the body of the gas. See section 21.

What seems to be the most probable part that the surface plays in the discharge phenomenon is that under certain conditions, owing to the presence of a non-conducting coating, ions from the gas find more or less difficulty in discharging themselves to the surface, and hence a larger voltage than usual is necessary for the commencement of the discharge.

The lag in the commencement of the current from points can scarcely be laid to the accumulation of non-conducting dust on the surface, for

[1] J. E. Almy, Phil. Mag. (6), 16, p. 456, 1908.

Edmunds (loc. cit.) took great care to free the air from dust in the discharge vessel used; and points may be sensitive when no dust can be seen on the surface with a low power microscope. Small dust particles doubtless influence the magnitude of the current from a point to which they are adhering, but they would have to cover a large part of the surface to produce the large lag in starting, which is observed at times.

The sensitivity in question cannot be due to contamination of the surface by volatile substances since it occurs with metal points which have been heated to incandescence.[1]

Gorton and Warburg (loc. cit.) have shown that with points made of copper or iron the sensitivity appears and disappears with the formation and reduction respectively of a layer of oxide. But sensitivity can scarcely be ascribed in general to the influence of non-conducting oxides, since it is known to occur with platinum points as well as with points made of other metals.

A possible cause of the lag phenomenon applicable to all materials, is to be found in the condensed layer, either of water molecules or of molecules of the surrounding gas, which is believed to cover the surfaces of solid and liquid substances, for if this layer is a poor electrical conductor it is probable that under certain conditions it exerts a marked effect upon these discharges by preventing or retarding the passage of electricity from the gas to the metal point.

That gaseous ions do not readily give up their charges to a metal surface is shown by the experiments of Gaede[2] who found that metal plates to which a discharge from a point had been allowed to flow exhibited a marked polarization when tested for the Volta effect. Gaede found that even 15 secs. after a measured quantity of electricity was allowed to flow from a point to such a plate, on immersing the plate in an electrolyte, over one half of this charge could be recovered from the plate. It is natural to suppose that it is the non-conducting layer of condensed gas that keeps the ions from discharging readily to the metal.

3. To account for the behavior of sensitive points by such a layer of gas or water molecules it is necessary to assume first, that this layer when solidly packed must be punctured and partially dissipated before a current of any considerable magnitude is able to flow to the surface, and second, that the layer is able to reform and thus interrupt the discharge when the current is below a certain value.

On these assumptions sensitive points should be those having smooth homogeneous surfaces on which closely packed layers of condensed gas

[1] F. R. Gorton and E. Warburg, Ann. d. Phys., (4) 18, p. 128, 1905.
[2] W. Gaede, Annalen der Physik (4), 14, p. 669, 1904.

can form. Normal or insensitive points on the other hand should be those that have either surface roughnesses not large compared to a molecule, thus preventing a close packing of the adhering molecules, or those where the adhering molecules have such a loose packing as to leave places in the gas layer through which the oncoming ions can pass, and in so doing eventually perhaps clear the neighboring surface of the molecules adhering to it.

It may be cited that, in agreement with this view, it is found that points with freshly ground or filed surfaces are in general not sensitive, whereas among points showing a large lag are those made smooth by fusion and zinc points made smooth by amalgamation (Gorton and Warburg, loc. cit.) and liquid points, whose surfaces are inherently smooth. Professor Kovarik informs the writer that when the usual method of making a steel point sensitive by fusion fails, a microscopic examination of the surface reveals the presence of a slightly raised scale of oxide formed by a crack in the otherwise glossy surface.

There are some ways of making points sensitive, however, which cannot easily be reconciled with the idea that a smooth surface is always a necessary condition. Thus Gorton and Warburg (loc. cit.) found that a platinum wire could be made sensitive by heating to incandescence by the passage of an electric current, in which case the surface was not hot enough to smooth down slight inequalities by fusion. They also found that the sensitivity was produced when the wire point was thus heated in moist air or moist oxygen whereas when sensitive the point was reduced to its normal condition by heating in these gases after they had been dried by passage through sulphuric acid.

A circumstance of significance is that on certain days it seems almost impossible to prepare a metal point showing sensitivity (when used in the open air), whereas at other times nearly every point shows more or less sensitivity. This behavior rather indicates that something gathers on the point surface which is more abundantly present in the atmosphere on some days than on others. Water vapor naturally comes to mind, but Edmunds (loc. cit.) observed lag in gases which had been well dried.

Unless a wrong interpretation has been put upon the experimental evidence cited, none of the views presented gives a satisfactory explanation by itself of the lag phenomenon under all of the circumstances that are known to affect it.

Some of the experiments to be described below give additional evidence on this problem, although others are also included in this paper which are of interest mainly from other considerations.

In seeking for a possible effect of a surface layer, no attempt was made to look for a very slight effect. The accuracy attainable in the measurements is usually not sufficient for distinguishing differences of less than one per cent. in the current or voltage which a change of conditions may produce. There are certain irregularities present in these discharges, especially noticeable with small negative currents, which often make it impossible to get exact repetitions of observations made with the same point. These very irregularities however point to some action at the surface. As the edge of the luminous area on a negative point is observed through a microscope, certain irregularities of outline are seen to be constantly changing as if something more is taking place at the surface than the mere delivery of charges by the ions coming from the gas. A similar effect is noticed in the glow areas on the electrodes of discharges at low pressures. A spark often shows a reluctance to move from one portion of a metal surface to another. These effects as well as the lag phenomena which appear with sparks and discharges in tubes at low pressures are probably of the same character as those observed with point discharges.

4. The amount of condensed gas upon a surface is generally supposed to depend upon the nature of the material of which the surface is composed, upon the pressure and the nature of the constituents of the gas itself, and upon the temperature; but Langmuir[1] has recently brought forward evidence favoring a mono-molecular layer which for different materials varies in closeness of packing.

Another factor which may possibly also enter into the problem is that the surface layer of gas on highly electrified points and even the density of the gas in the immediate neighborhood of such surfaces may be augmented by the attraction to which the gas molecules are subjected owing to their polarization by the strong field. A calculation shows that of itself this attraction is not sufficient to hold molecules against the surface; but when added to the forces already present which are capable of holding neutral molecules in position, it may for certain gases increase the number of molecules adhering to the surfaces of some materials, at least. This argument fails if, as postulated by Langmuir (loc. cit.) we are to look upon each adhering molecule as held by a definite bond which it completely satisfies in a classical sense.

Precht[2] found that coating a steel point with copper did not change either the voltage for which discharges commenced from the point or the magnitude of the currents at higher voltages, but Hovda[3] concludes

[1] I. Langmuir, Am. Chem. Soc. Jour., 38, p. 2221; 39, p. 1848.

[2] J. Precht Wied. Annalen 49, p. 150, 1893.

[3] O. Hovda, Gottingen Inaugural Dissertation, 1913.

from a long series of careful measurements that the voltages for which discharges begin do depend to a slight extent upon the nature of the metal. But doubt is thrown upon this conclusion by the fact that there were noticeable differences in the sharpness of the ends of the conical points which were used, differences whose effect could not be wholly eliminated and which may easily account for the small differences in the results obtained.

Liquid Points.

Some time ago the writer[1] did some work on electrical discharges from a new class of points, consisting of minute hemispherical drops of water protruding from the ends of fine tubes. A method of measuring the electric intensity at the surface of the drops was devised and a study was made of the value of this intensity in air at atmospheric pressure, for a number of points differing in size. It was noted that the surface of the water becomes agitated when the electric current starts to flow from the point. For positive discharges this agitation is confined to small values of the current, the surface being quiescent for larger currents. A careful study was made later[2] of these initial surface disturbances and it was shown that they arise from the surface becoming unstable when the electric intensity exceeds a certain limit. Under these conditions fine threads of liquid are rapidly pulled from the surface which break up into myriads of minute drops that act as carriers of the electric charge. When water, in air at atmospheric pressure, is used, the surface instability begins at a potential which is only a little below that at which the discharge would start from an undisturbed surface. For this reason the true cause of the surface disturbances was not discovered until some work was begun on discharges in other gases than air.

The values of the electric intensities given in the paper first mentioned and the relation found for the dependence of these intensities upon the curvature of the discharging surface apply to conditions for surface instability rather than to the initial stages of the electric discharge, although for the smaller points the intensities for the two phenomena are almost identical.

The electric forces at the surface of water points, when about to discharge positive electricity, which were indicated by those measurements, were considerably smaller than those found at the surface of platinum points by Chattock.[3] It seemed desirable therefore to repeat some of the measurements on the electric forces acting with discharges from liquid

[1] J. Zeleny, PHYSICAL REVIEW, 3, p. 69, 1914.

[2] J. Zeleny, Proc. Camb. Phil. Soc., 18, p. 71, 1915; PHYSICAL REVIEW, 10, p. 1, 1917.

[3] A. P. Chattock, Phil. Mag. (6), 20, p. 270, 1910.

points under conditions free from surface instability to ascertain whether these forces are actually different from those that obtain at the surfaces of similar metal points. The difficulty arising from surface instability may be avoided by working with air at reduced pressures, since in this way the discharge voltage is lowered while the voltage at which instability sets in is not affected.

Apparatus for Discharces from Liquid Points.

6. The apparatus used for work on discharges from liquid points was arranged as shown in Fig. 1. T is a brass cylindrical vessel 15 cm. high

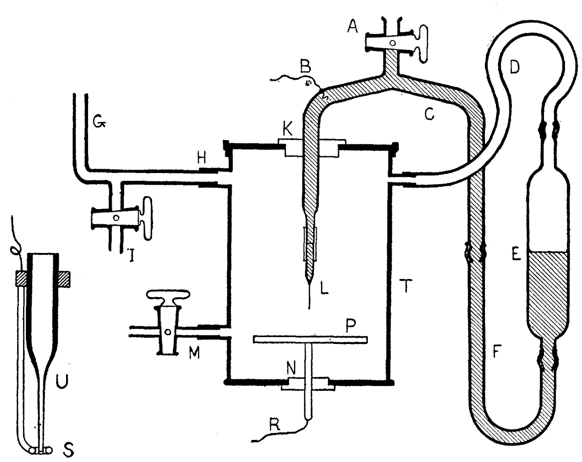

Fig. 1.

and 9 cm. in diameter. The outlets G, I and M at the left, lead to a pressure gauge, to the gas supply and to the pump respectively. A glass tube C passes through an insulating plug K in the upper end of the vessel and carries at its lower end the drawn out glass point L from which the hemispherical drop of liquid protrudes, the electrical discharge from which is under study. The brass disc P receives the discharge from the point and is connected to earth through a galvanometer. The glass tube C is connected, by the rubber tube F, to the bottom of the movable reservoir E, the top of which is in turn connected by a similar tube D to the vessel T. Liquid extends continuously from the reservoir E to the drop at the end of L, and the height that the liquid surface in E is above the end of the point L is a measure of the pressure in the drop. The platinum wire B makes connection with the liquid in the system and leads to a Braun voltmeter and a battery of Leyden jars charged by an electrostatic machine. Some calcium chloride was kept in the bottom of the vessel T so that water overflowing to the sides of the point, as often happened, would be removed by evaporation. The drop at the end of the point L was observed with a microscope through glass windows which are not shown in the figure.

The distance from the tip end of a point to the plate opposite, which was 5 cm. in diameter, was 1.5 cm. in each case. This distance affects the voltage values but not the values of the surface electric intensities. The average temperature of the room was about 16° C.

The fifteen points which were used in the experiments had radii ranging from 0.117 mm. to 0.988 mm., and were made from quill glass tubing which was drawn down to the proper diameter and broken squarely across from a fine scratch. The distilled water used was very slightly acidulated with hydrochloric acid to increase its conductivity, so that during a discharge there was no appreciable potential drop between the end of the liquid meniscus and the voltmeter.

General Behavior with Liquid Points.

7. The electric intensity f at the end of the drop is obtained from the distance p, that the liquid surface in E must be lowered to maintain the drop of the same form when charged as when uncharged, by means of the relation

$$f = \sqrt{8\pi pdg}, \tag{1}$$

d being the density of the liquid. When the surface is not discharging a current, the electric intensity is not the same over the whole surface, being greatest at the tip end. To maintain equilibrium the shape of the drop changes slightly from the hemispherical form. This does not apply to a surface discharging a *positive* current, for the current flows from the whole hemisphere (except for very small currents) and the intensity is found to be independent of the current density.

A noteworthy feature of the discharge from water points in air at reduced pressures is the retardation in the commencement of the current. As the voltage of the point is gradually increased the current does not begin gradually, but rises more or less suddenly to a value of the order of a microampere.

The retardation for any point is not constant in amount, but depends somewhat upon the age of the liquid surface and upon the time that has elapsed since a current last flowed from the point, and upon a chance element in the formation of ions in the gas as the applied voltage is raised.

As has been stated in section 1, a similar retardation in the current often occurs from metal points, which is larger and more frequently present with negative discharges than with positive discharges. But with many metal points the retardation is very small or not present, whereas with water points a retardation is the general rule. This retardation would in many cases be still larger than is observed were it not for the fact that a voltage is reached first at which the surface becomes unstable and the discharge starts owing to a disruption of the surface.

When the current does start the water meniscus jerks back to a more flat position, because for the same voltage the electric pull is smaller with than without a current.

After the current has started, the meniscus is quiescent with a positive discharge (but not with a negative discharge), and large changes in the magnitude of the current produce very little or no effect upon the electric pull upon the surface. (See end of section 12.)

As is the case with sensitive metal points in a lesser degree, the discharge current may be diminished below the value it suddenly assumed at commencement, and as the voltage is lowered to within about 50 volts of the value at which the current would disappear if it kept on diminishing at its previous rate of diminution, the meniscus as a rule suddenly elongates and the current stops. The increase in the electric pull with diminution of voltage is so rapid during this final stage that it is extremely difficult to regulate both the voltage from the static machine and the liquid pressure necessary for maintaining the drop hemispherical, without having the water overflow to the sides of the glass tube. The most successful readings taken in this region showed that as the current fell to zero value, the total increase in the electric intensity as measured by the increase in the electric pull, may be as much as ten per cent. of the whole value.

8. The retardation which has been discussed, occurs both with positive and negative discharges, and accordingly it is not possible to get any very definite voltages nor surface electric intensities for which currents begin to flow from these points.

It is possible however to obtain definite values for the electric intensities at the surface of points from which positive currents above a certain minimum are flowing, and to obtain the voltages for which these currents stop; and this has been done. Such measurements cannot be made with negative discharges because with them the surface of the liquid is agitated, owing to an intermittent element in the current and to the fact that the negative discharge is confined to a minor portion only of the surface. Often with some of the larger negative currents, however, the surface becomes almost quiescent.

As explained above, the electric intensity at the surface of a point changes but little with the current except just as the current is about to stop, where its value rises rather rapidly about 10 per cent. The values which will be recorded were taken in the region of small currents where the intensity begins to be constant in magnitude, but they apply equally well to larger currents.

The range of pressures that could be employed in the experiments was limited, on the lower side, by the pressure (about 10 cms. of mercury) at which the water commenced to vaporize in the upper portion of the glass tube; and on the upper side, by the value for which the discharge voltage was smaller than the voltage for which the surface became unstable. For the smallest points, observations could be made up to atmospheric pressure but this pressure could not be reached with the larger points. Owing to experimental difficulties the limits mentioned were not always attained.

Electric Intensity at Surface during Positive Discharge.

9. The electric intensity at the surface of a point discharging a small positive current was determined for each point for a number of air pressures by the method previously explained. The results for some of the points expressed in electrostatic units per cm. are plotted as broken line curves in Fig. 2 against pressures expressed in centimeters of mercury, the radius of the point in millimeters being indicated on each curve.

From the whole set of these curves, the full line curves in Fig. 2 were constructed, each giving the relation between the electric intensities and the radii of the points, for the air pressure affixed to the curve. It is seen that the intensity diminishes as the radius of the point increases, the rate of change being most rapid for the smallest points. An explanation of this fact is given in section 19.

Empirical Relations.

10. The relations shown by the whole set of curves in Fig. 2 is expressed very well by the equation

$$f = 0.955\, p + 5.60 \sqrt{\frac{p}{r}}, \tag{2}$$

f being given in electrostatic units per cm. when p is taken in centimeters of mercury and r in centimeters.

An approximate formula of this form was obtained by Edmunds[1] for the field at the surface of a point at the commencement of a discharge

[1] P. J. Edmunds, Phil. Mag. (6), 28, p. 234, 1914.

(positive and negative not distinguished) between a point and a plane, who adapted to this case Townsend's method for coaxial cylinders, in which use was made of the empirical relation found by Baille for the

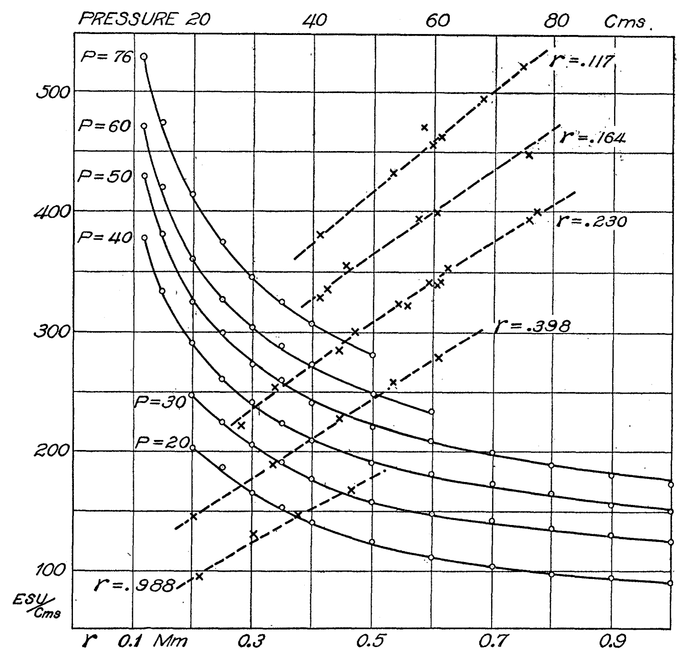

Fig. 2.

Electric intensities at surfaces of water points during positive discharge. Dotted line curves show the variation of the electric intensity with air pressure for individual points whose radii are given in millimeters. Full line curves show the variation of the electric intensity with size of points at constant air pressure expressed in centimeters of mercury.

dependence of the sparking potential between parallel plates upon the distance between them.

The constants in the formula as derived by Edmunds give values of f which are from 20 to 30 per cent. larger than those here determined with a current flowing.

11. Equation (2) may be written as

$$fr = 0.955\, pr + 5.60 \sqrt{pr}, \qquad (3)$$

showing that fr is a function of pr only. By taking different values of p and r whose products are constant, the products of the corresponding values of f and r are also constant. An illustration of this relationship is given in Table I., the data for which were taken from the curves in Fig. 2, a value of r being chosen from each pressure curve which gives the constant product of pr placed at the top of each set of numbers, and the value of f corresponding to this value of r being read from the curve. The last column indicates the degree of constancy of fr for each case considered.

TABLE I.

$pr = 0.912$.				$pr = 2.8$.			
r.	p.	f.	fr.	r.	p.	f.	fr.
.012	76	520	6.24	.0368	76	318	11.7
.0152	60	413	6.28	.0466	60	255	11.9
.0182	50	342	6.22	.0560	50	210	11.8
.0228	40	270	6.16	.0700	40	171	12.0
.0304	30	202	6.14	.0933	30	128	11.9
.0456	20	134	6.11				

Taking the average values of fr thus obtained and plotting them against the corresponding values of pr we get the experimental relation-

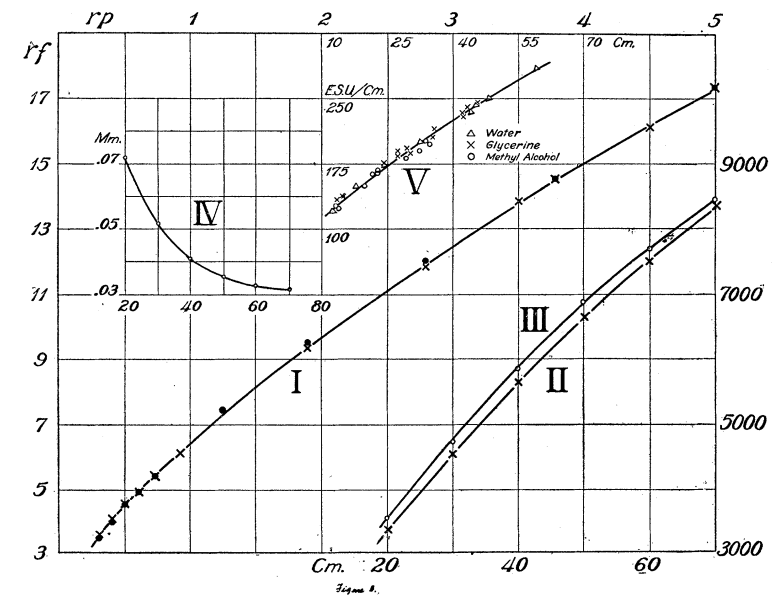

Fig. 3.

Curve I. represents the relation between rf and rp, r being in millimeters, p in centimeters of mercury and f in electrostatic units per cm. The crosses are experimental values and the circles values computed by equation (3).

Curves II. and III. show the variation with pressure expressed in centimeters of mercury of the constant a in equations (4) and (5) respectively, when v is in volts and r in millimeters

Curve IV. shows the variation with pressure of the constant b in equation (5), expressed in millimeters.

Curves V. gives the electric field in e.s.u. per cm., during positive discharge in air at different pressures expressed in centimeters of mercury, at the surfaces of the three liquids named for a point of 0.346 mm. radius.

ship shown by the crosses on curve I. in Fig. 3, which combines in one curve the data represented by all of the curves in Fig. 2. With the aid of curve I., it is possible to find the value of the intensity f which applies to a point of any radius in air at any pressure, within the limits used in the experiments. The points marked by circles on Curve I. represent values obtained from equation (3), and show the degree of exactness with which the equation respresent the experimental values.

12. Now Townsend[1] has already shown that it follows from the theory of ionization by collision that if the same number of ions is produced by collision in two similar systems the product fr must be constant for all conditions where pr is constant, it being presupposed that the current flowing is sufficiently small for the volume charges present not to affect the field appreciably; and that this relation holds for the critical fields required to start discharges from metal points has been shown by Edmunds[2] and by Tyndall.[3]

The work just reported proves that the product fr remains constant for constant values of pr not only for the case where the current is the same and small as is contemplated in Townsend's theorem, but irrespective of the magnitude of this current. This follows from the constancy of f for all currents above a certain minimum value. This constancy of the surface field f for all values of the current indicates that any increase of this field owing to an increase of applied voltage is compensated by a diminution arising from larger volume charges present in the gas with the larger currents.

The nicety of this compensation is hardly fortuitous and it is probable that when this limiting field exists at the surface the electric forces in the space where ionization takes place have reached a value such that a slight change in field results in a large increase in the number of ions produced and hence as the voltage of the point is raised nearly the whole of the change goes to strengthen the field beyond the main region of ionization, this being necessary for the removal of the increased number of ions produced. This process does not continue indefinitely for the glow discharge eventually changes into a brush or spark discharge.

Comparison of Fields with Metal and Liquid Points.

13. Only one result for the field strength at the surface of a metal point during positive discharge is available for direct comparison with values obtained at a water surface. This is found in a paper by Chattock[4]

[1] J. S. Townsend, The Electrician, 71, p. 348, 1913.

[2] P. J. Edmunds, Phil. Mag. (6), 28, p. 234, 1914.

[3] A. M. Tyndall, Phil. Mag. (6), 30, p. 640, 1915.

[4] A. P. Chattock, Phil. Mag. (6), 20, p. 273, 1910.

where a table is given from which the field at the surface of a platinum point of 0.18 mm. radius in air at atmospheric pressure (exact pressure not stated) with a positive discharge current of 0.79 microamperes is computed to be 413 e.s.u. per cm. as compared with 426 e.s.u. per cm. obtained for a water point of the same radius (as shown in Fig. 2).

A more extended indirect comparison may be made by making use of the critical fields determined at the surfaces of metal points when a current starts or stops. Such critical fields were obtained for a number of platinum points at atmospheric pressure by Chattock (loc. cit.) and the results embodied in an empirical equation, $fr^{0.45} = 85$ (f in e.s. units per cm. and r in cms.); and Tyndall's more recent paper (loc. cit.) shows the values of these fields at different pressures as well. The critical fields were computed from the square roots of the electric pulls on the ends of the points. A table in Chattock's paper (p. 273) shows that the square roots of these pulls is 7 per cent. greater as the current stops than it is with a current of the order of a microampere, and a curve in Tyndall's paper shows a difference of 11 per cent. for the same thing. The average of these values (9 per cent.) will be used for making the reduction.

There is an additional correction to be made. When a current flows from all parts of the hemispherical end of a cylindrical wire, which is the case for positive currents above a few microamperes, the electric intensity is the same over the whole surface and may be obtained directly from the electric pull on the surface. But when a current just ceases to flow, the electric intensity is greatest at the tip end of the wire, and to get the intensity at this place a correction of 8.5 per cent. must be added to the average value found from the electric pull, as was shown by Young.[1] This correction is included in the values of the critical fields represented by Chattock's empirical formula, and presumably also included in Tyndall's values. The critical fields for which a current stops may therefore be obtained approximately, by increasing by 17.5 per cent. the fields computed from the square roots of the electric pulls measured when a current above a certain minimum value is flowing.

Now the values of the critical fields computed by Chattock's formula are on the average about 15 per cent. larger than those shown by the curve for atmospheric pressure in Fig. 2, the difference being somewhat larger than 15 per cent. for the smallest points indicated on that curve and smaller than 15 per cent. for the largest points. On the other hand the values of the critical fields taken from Tyndall's curve are uniformly larger by about 13.5 per cent. than corresponding fields given on Curve I. of

[1] F. B. Young, Phil. Mag. (6), 13, p. 542, 1907.

Fig. 3 for liquid points with a current flowing. This indirect comparison shows therefore an average difference of over 3 per cent. between the results for metal points and those for liquid points, which is the same as that found above in the direct comparison made with the single result available for metal points. Considering all of the circumstances, great weight cannot be placed upon a difference of this magnitude, and it can only be said that if any difference exists between the fields during positive discharge, at the surface of a platinum point and a water point of the same radius, this difference is small.

Stopping Voltages for Positive Discharges.

14. The procedure followed in obtaining the stopping voltages was as follows. The current flowing from the point was measured for a number of decreasing voltages down to the one for which the water drop suddenly overflowed owing to the rapid increase of the electric pull. From these values the voltage was found graphically for which the current would have vanished if it had followed the previous rate of decrease. The voltage thus obtained was usually less than 100 volts below the last reading actually taken.

The experimental results on the voltages at which positive discharges ceased in air at different pressures are shown by the curves in Fig. 4. The two broken curves show the relation between the stopping

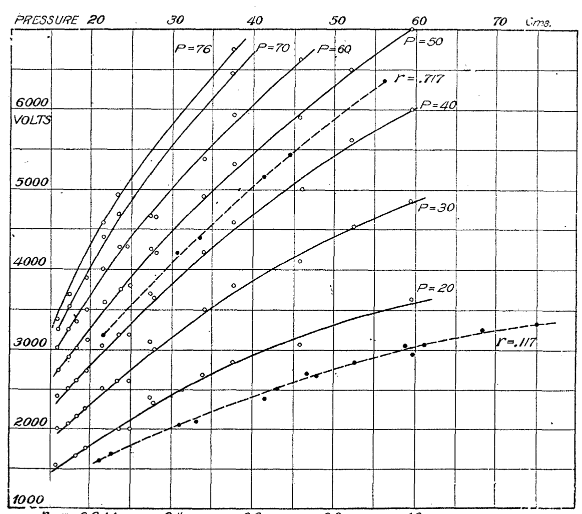

Fig. 4.

Stopping potentials in volts for positive discharges from water points of different radii expressed in millimeters, in air at different pressures given in centimeters of mercury. Distance to plate = 1.5 cm.

voltages and air pressures as obtained for two of the points whose radii are indicated on the curves.

It seemed preferable to plot all of the voltage-pressure results as radius-voltage curves and these are drawn in the figure as full line curves. Here each curve corresponds to a given pressure, whose value in centimeters of mercury is affixed, and represents the dependence of the stopping voltages upon the radii of the points used. The values for these curves were taken from the complete set of voltage-pressure curves similar to the two broken line curves shown in the figure.

The voltages at atmospheric pressure were obtained in the region bordering on the state of surface instability but they agree within experimental errors with results obtained previously[1] for positive discharges in air at the same pressure from the same sized points made of brass.

15. The radius-voltage curve for each pressure in Fig. 4 may be represented equally well by either of the two empirical relations,

$$v = a\sqrt{r} + b \qquad (4)$$

or

$$v = a\sqrt{r + b}, \qquad (5)$$

v being the stopping potential, r the radius of the point, and a and b constants.

The term b in equation (4) is small compared to the second term and hence its value is not obtained accurately. The numbers found for it from the different curves showed no regular tendency to vary with the pressure, and so the average value 340 volts,[2] was taken as common to all of the curves, and values of the constant "a" were found on this assumption. These values of a, for r expressed in millimeters, are plotted against the corresponding air pressures expressed in centimeters of mercury as curve II. in Fig. 3.

In equation (5), both of the constants a and b are dependent upon the pressure of the air. Values obtained for the constant a are shown by curve III. in Fig. 3 and are seen to follow in general the values of the corresponding constant in equation (4), represented by Curve II. The values of the constant[3] b vary from .072 to .032 mm., decreasing as the pressure increases, and are shown by Curve IV. in Fig. 3. Obviously a

[1] J. Zeleny, PHYS. REV., 25, p. 313, 1907.

[2] This constant may be interpreted to signify the lowest potential at which a discharge can occur; and its value is actually within a few volts of the minimum spark potential obtained for air by Strutt (341) and by Carr (350).

[3] A physical meaning which may attach to this constant b, is that the effective radius of the point in the discharge is greater by this value than the real radius, which would be the case if for example the region of the luminous glow (whose thickness increases as the pressure is reduced) were highly conducting.

combination of equations (4) and (5) would represent the experimental results equally well or better, and would involve quantities having the significance of both of the constants b in the two equations. It is to be noted that at the higher pressures the stopping voltages for the larger points become approximately proportional to the square roots of the radii of the points.

Fields in Different Gases.

16. The electric intensity during positive discharge at the surface of a water point was also measured at different pressures in the gases, carbonic acid, hydrogen and oxygen, as well as in air. The general behavior of the discharge in these gases was similar to that found for air. The electric intensity at the discharging surface was found to be very nearly independent of the magnitude of the current, but in oxygen the discharge was less steady than in the other gases, especially with small currents, the liquid surface becoming quiescent only after the current approached about two microamperes. The numerical results given in Table II. were taken from curves drawn through the experimental values obtained. The different upper limits of pressures used are imposed by surface instability. No simple relation is apparent between these values and other related quantities.

Table II.

Electric Intensities (in E.S.U. per cm.) at Water Surface during Positive Discharge in Different Gases.

	Radius of Point = 0.346 Mm.				Radius of Point = 0.162 Mm.	
Pressure of Gas in Cm. of Mercury.	CO_2.	Air.	H.	O.	CO_2.	Air.
10	157	117	97		250	189
20	205	155	128		330	238
30	248	191	155	183	387	281
40	286	225	180	212	436	325
50		255	203	239		367
60		283	225	270		397
70			246			
87			277			

Fields for Different Liquids.

17. Some experiments were made with a point of radius 0.346 mm. using the liquids water, glycerine and methyl alcohol in succession in air at different pressures, in order to determine whether the nature of the liquid has any effect upon the electric field at the surface during a positive discharge. The behavior of the discharge with glycerine and methyl alcohol was in general the same as has been described for water,

but both liquids were even more difficult to work with than water. The experimental errors in the measurements with these liquids were therefore greater than was the case with water.

The results of the measurements made are shown by Curve V. in Fig. 3, and it is seen that the three sets of points fit one curve within the experimental error with the possible exception that the values for methyl alcohol are somewhat low at the highest pressures used with this substance. Owing to the great difficulty of making measurements at all in this region, which is near the instability voltage for methyl alcohol, and owing to the fact that at lower pressures the results for this liquid are in agreement with those for the other liquids it is believed that there is no significance in the slightly lower values obtained with methyl alcohol for pressures above 30 cms.

A comparison was also made, over the same range of pressures as used above, of the voltages at which the positive discharge stopped from the three liquids and from a metal point made of brass wire with a rounded end of the same radius as that of the liquids. Here again no difference above the experimental error was found between the different substances with the same exception of the values for methyl alcohol above 30 cms. pressure which were again below those for the other substances.

Metal Point Coated with Various Substances.

18. In seeking evidence of the possible effect of the nature of the material of which a point is made, upon the potential at which a discharge starts from it, experiments were done in which a brass point (diameter = 0.5 mm.) was used when coated in succession with different substances, including cadmium sulphate, thorium oxide, potassium iodide, caustic potash, fluorescein, methyl violet and the chlorides of sodium, tin, copper, mercury, iron and cobalt. It was not possible in general to get a thin, uniform coat of the material on the point, either by evaporation from solution or by application in the form of a fine powder or by fusion, but notwithstanding this unevenness of the surfaces, the potential at which positive discharges started and stopped from the coated points was approximately the same throughout as from the uncoated point. The total variation among the results was about two per cent. which is somewhat greater than twice the experimental error of the voltage determinations. Within the limits named, therefore, the positive starting potential is independent of the nature of the material of which the point is made and equally independent of a considerable roughness of surface.

With negative discharges, however, the starting potentials showed a total variation of about 25 per cent., the values ranging on both sides of the value for the positive discharge.[1] Without more evidence, this behavior should be ascribed not to the influence of the material of the surface but rather to the effect of its inequalities, the greater localization of the negative discharges making such inequalities of moment for these discharges.

DISCUSSION OF FIELDS AT SURFACES HAVING DIFFERENT CURVATURES.

19. It is surprising at first sight that the surface field intensity required to start and maintain discharges should be the larger the smaller the radius of curvature of the point, but an explanation of the fact is found on the theory of ionization by collision by considering the nature of this process and the character of the field in the neighborhood of such surfaces.

The field intensity near the surface of points decreases very rapidly with distance from the surface, and the decrease is the more rapid the smaller the radius of curvature of the point. For illustration consider the nearly analogous case of two charged spheres, one of radius 0.01 cm. and the other of radius 0.1 cm. For the smaller sphere, the field at a distance of 0.01 cm. from the surface is only 25 per cent. of its value at the surface and at a distance of 0.04 cm. it is but 4 per cent. For the larger sphere, however, the fields at the same distances from the surface are 82 per cent. and 50 per cent. respectively of the value at the surface.

Now ionization by collision does not begin abruptly at a definite field strength, but owing to the chance elements entering, the process is a statistical one and hence if there is an appreciable rate of increase of ions by this process in the field at the surface of a point there must be an appreciable though smaller rate of increase at a distance from the surface where let us say the field is but half as strong.

Consider two points of different size so charged that the field intensities at their surfaces are the same, and imagine the same number of ions drawn toward each surface from the surrounding gas. Consider the multiplication of these ions in volume elements formed by equi-distant surfaces parallel to the surfaces of the points. In the two volume elements adjacent to the surfaces of the two points the rate of increase of the ions will be the same because the fields there are assumed to be equal but in all of the following volume elements the rate of increase will be larger for the point of larger radius of curvature because for this point the field strength falls off less rapidly with distance. Accordingly the total number of ions reaching the larger point per second will be greater than the number reaching the smaller point, and it follows that, in order to have

[1] For a point of this diameter the normal starting potential is the same for the two kinds of discharges. See J. Zeleny, PHYSICAL REVIEW, 25, p. 305, 1907.

ions reach the two point surfaces at the same rate, not so large a field intensity is necessary at the surface of the larger point as is required for the smaller point. It is thus made apparent why the field strength at the discharging surface is not the sole determining factor for the production of a discharge and that the manner in which the field changes with distance from the surface is of much importance; the field at the surface being least when the field is uniform and increasing more and more as the divergence of the field increases.

In discharges between a cylindrical wire and a concentric cylinder the field at the wire changes less rapidly than it does at the end of a wire of the same diameter, and accordingly the critical field required to start a discharge should be less in the former case than in the latter case. Watson[1] has computed the critical fields at different pressures at the surface of the inner of two concentric cylinders from the critical discharge voltages. The smallest wires he used correspond to the largest of those given in Fig. 2 and for these the values are almost identical with those of the figure named, showing when the correction discussed in section 12 is applied that the field at the cylindrical wires is about 17.5 per cent. smaller than for points of the same diameter.

Effect of Divergence of Field.

20. The effect of the divergence of the field at the surface upon the intensity of the field that obtains there during a discharge, is well illustrated by the following experiment in which the divergence of the field near a given point was artificially altered.

A small ring, S in Fig. 1, 4 mm. in external diameter, made of wire 1 mm. in diameter, was held by a vertical stem so that it surrounded the glass point U used (diameter = 0.53 mm.). The ring was adjustable vertically and was metallically connected to the liquid inside the point. The presence of this ring near the end of the point made the field at the point less divergent by an amount which depended upon its vertical position, the effect being greater the lower the ring. The electric intensities, f, at the surface of the point obtained when a positive discharge was passing in air at a pressure of half an atmosphere for different distances, d, that the tangent plane through the lower surface of the ring was above the end of the discharging point are given in Table III.

Table III.

	f.
2.0 mm.	249 e.s.u. per cm.
0.34	236
0.10	218
0.026	212
0.00	201

[1] E. A. Watson, The Electrician, Feb. 11, 1910.

The voltage required to maintain a current was increasingly larger as the ring was lowered, but the intensity at the surface became smaller and smaller as the field was made less and less divergent by changes in the position of the ring. The experiment was repeated at other air pressures with a like result and confirms the reasoning in the last section.

Comparison of Currents from Surfaces of Different Materials.

21. Since the velocity with which the ions impinge against the surface of a discharging point is large, it is possible that the impacts may liberate other ions from the surface which may appreciably increase the current due to the ions produced in the volume of the gas. If such is the case, it is probable that the number of ions so ejected by a given number of impacts should depend upon the material of which the point is made, and accordingly if similar points made of different materials are used the current obtained with the same voltage should not be the same from the different points. As already stated (Sec. 3) Precht found that after plating a steel point with copper the current obtained with a given voltage remained unchanged. Additional experiments were made on this subject by obtaining the voltage-current curves for both positive and negative discharges in air from points with rounded ends made of platinum, copper, brass and water. The points were used at a distance of 1.5 cm. from a plate and all had a common diameter of 0.41 mm. After a slight correction for differences in atmospheric pressure was applied, the results with positive discharges from the different materials were identical within experimental error. For negative discharges also, the metals gave identical results. The negative discharge from the water point produced an agitation on the surface. This became less violent as the current was increased until when the voltage was between 7,000 and 8,000 volts (starting voltage being 4,700) the surface was almost quiet and showed a hazy edge only under the microscope, owing to a small amplitude oscillation. Under these conditions the current from the water point was a little smaller than that obtained with the metal points, so that for example 7,600 volts was required on a water point to produce the same current as was obtained with 7,500 volts when the metal points were used. This small difference may be explained by any one of three causes. Either electrons are ejected in smaller number from a water surface than from a metal surface during the discharge, or the smaller currents with water are due to the changes in the shape of the point caused by the small oscillations present, or the reduction in current from water points arises from a diminution in the mobility of the negative ions owing to the presence of water evaporating from the point. On the whole, the results

indicate that if any ions are ejected at all from the surface by the impact of approaching ions, the number of such ions must be small compared with those producing them; unless indeed owing to the influence of volume electrification the currents from points in general are controlled almost entirely by the applied voltage and but slightly by the number of ions produced in the neighborhood of the point.

Discussion.

The ideal smoothness of liquid surfaces favors their use for the investigation of a possible surface action in point discharges, since with metal points the physical state of the surface and in most cases its chemical composition as well is a matter of constant concern, mainly because of the changes wrought by the discharges themselves.

Unfortunately the chemical composition of these liquid surfaces also was subject to change as evidenced by changes in surface tension. The action of a discharge appears to cleanse the surface, since the value obtained for the surface tension was always largest after a discharge and gradually diminished with time. It is possible that some of this surface ageing is to be attributed to the adsorption of gas molecules by the surface. While all of the liquids used showed a lag in starting for both positive and negative discharges, the amount of lag observed for any point may vary greatly on different trials, and it is probable that this fact is to be ascribed to the changes in surface composition, just noted.

The general presence of lag with liquid points lends support to the working hypothesis that the lag phenomenon is dependent upon a compact non-conducting layer of molecules upon the surface, since the smooth surfaces are favorable for the formation of such layers. The comparisons made of surface electric intensities during positive discharges show these to be virtually independent of the material of the surface, and hence it may be assumed that any non-conducting layers which may have been present at the start have under these conditions been removed.

Further discussion of the results given in this paper are reserved until some other experiments which have been made are reported in a second paper.

Summary.

Considerations are given for attributing the lag phenomenon in point discharges to the presence of a non-conducting coating on the discharging surfaces which may consist of adhering gas molecules.

Both positive and negative point discharges from surfaces made of water, glycerine or methyl alcohol show a lag in starting.

The electric intensity f at the surface during positive discharges is

practically independent of the current and of the material of the point. For water points f (e.s.u.) is related to the point radius r (cm.) and the air pressure p (cm. of mercury), by the relation $fr = 0.955\, pr + 5.60 \sqrt{pr}$.

The stopping voltages v for positive discharges from water points of radii r may be expressed by either $v = a\sqrt{r} + b$ or $v = a\sqrt{r + b}$ where a and b are constants for any pressure and have been obtained for a number of pressures.

The surface electric intensities during positive discharges in air, hydrogen, oxygen and carbonic acid at different pressures are given for two different points.

Coating a metal point with various substances was found to affect very little the potential at which positive discharges commenced whereas the effect upon the potential for the negative discharges was large, but this may be due to the unavoidable roughness of the surfaces used.

The influence upon the discharge of the divergence of the electric field at the discharging surface is shown to explain the fact that the field necessary for a small point is larger than for a large point.

Ejections of ions from a surface by the impact of other ions is made improbable in point discharges from a study of the voltage-current relation from surfaces of water, platinum, copper and brass.

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Yale University,
March 29, 1920.