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THE ELECTRICAL DISCHARGE FROM LIQUID POINTS, AND A HYDROSTATIC METHOD OF MEASURING THE ELECTRIC INTENSITY AT THEIR SURFACES.[1]

By John Zeleny.

1. The discharge of electricity from pointed conductors has been studied heretofore only from points made of metal. The assumption is generally made that all of the features of the discharge are independent of the kind of metal of which the point is made. In support of this view may be mentioned the results of Precht,[2] who found that, after a steel needle had been plated with a thin coating of copper, the potential at which the discharge ceased from the needle as well as the current obtained with any voltage, remained the same as before. In a study of the discharge from cylindrical points of different diameters, the writer[3] used platinum points for the two smallest diameters while the others were made of brass, and the results from both kinds of points could be expressed well by the same empirical formula, indicating that the nature of the metal is of no consequence.

2. There are a number of phenomena, however, attending the discharge from pointed conductors which can only be explained by attributing some importance to the surface from which the discharge is taking place. Thus Röntgen[4] found that the potential at which the discharge from a gilded needle began was dependent upon whether a current had been flowing from the point shortly before. Precht[5] gives an example where the beginning potential rose by 25 per cent. at the end of a number of successive determinations.

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[1] A preliminary paper on this subject was read before the American Physical Society on December 30, 1910.

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

[3] J. Zeleny, Phys. Rev., 25, p. 305, 1907.

[4] W. C. Röntgen, Göttingen Nachrichten, p. 390, 1878.

[5] Loc. cit.

Warburg and Gorton[1] found that the passage of a current from points made of various metals permanently increased the potential at which a discharge begins above that first required when the points were newly made. Subjecting such aged points to various radiations had the effect of temporarily reducing the beginning potentials to their original values. Similar effects were obtained by heating the points in a flame or by heating them to a glow by means of an electric current when they were immersed in oxygen or hydrogen. In some of the cases recorded, the potential increased by over fifty per cent.

Again, it is well known that some impulsive discharges of short duration and at considerable intervals of time may take place from a point at potentials much lower than are required for the first continuous discharge. Precht[2] cites the case of a point cut from a piece of aluminum leaf which gave the first impulsive discharges at + 1,871 and − 1,065 volts, while the continuous currents did not begin until the potentials were raised to + 4,173 and − 2,971 volts.

Such effects as these cannot be ascribed to changes in the circumambient gas, but must be attributed either to some chemical change at the metallic surface, to the accumulation there of some foreign material gathered from the gas, to the formation of or changes in an electric double layer, to changes in the amount of gas absorbed by the point or to changes in the layer of occluded gas. Some of the effects are most likely due to one cause and some to another. In any case, the changes mentioned involve the character of the discharging surface.

3. Although no systematic study has yet been made with points of different metals, it would seem that, for the investigation of influences arising from conditions at the surface of discharge, it would be well not to confine the experiments to metallic points, since metals in general may not differ greatly among themselves as regards some crucial property. In choosing between various materials it was decided to experiment first with liquids because of their radical difference from metals and because of some advantageous properties. A small hemispherical drop protruding from the end of a fine capillary tube may serve as the liquid point. The discharging surface may readily be renewed in this case by simply removing the drop. The chemical nature of the surface may be made quite different by a change of liquid; and this without changing the geometrical shape of the point. The surfaces of such liquid points are necessarily perfectly smooth,[3] but have the disadvantage of being liable to distortion.

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[1] E. Warburg and F. R. Gorton, Ann. der Physik, 18, p. 128, 1905.

[2] Loc. cit.

[3] The results of Precht (loc. cit.) and the writer (loc. cit.) indicate that the presence of

Apparatus Used.

4. The essential parts of the apparatus which was used in the experiments are shown in diagram in Fig. 1. The discharge took place in air at atmospheric pressure at the end of the point *A*, and the current passed to the brass disc *D* (6.3 cm. in diameter), situated 1.5 cm. below the end of the point, unless otherwise stated. From the disc the current passed first through a telephone receiver, used for detecting intermittence, and then to earth through a shunted D'Arsonval galvanometer whose greatest sensitivity was 3×10^{-9} amperes per scale division. The point *A* consisted of a cylindrical glass tube whose diameter was nearly constant for a length of 3 cm. and usually did not exceed one millimeter. The free end was broken off squarely across, and the upper end, with the piece of larger tubing from which the fine point had been drawn out, was connected at *B* by means of a piece of rubber tubing to the glass tube *T*. This mode of attachment made it easy to exchange points. Finally, the tube *T* was joined to the glass part *F* by the rubber tube *R*.

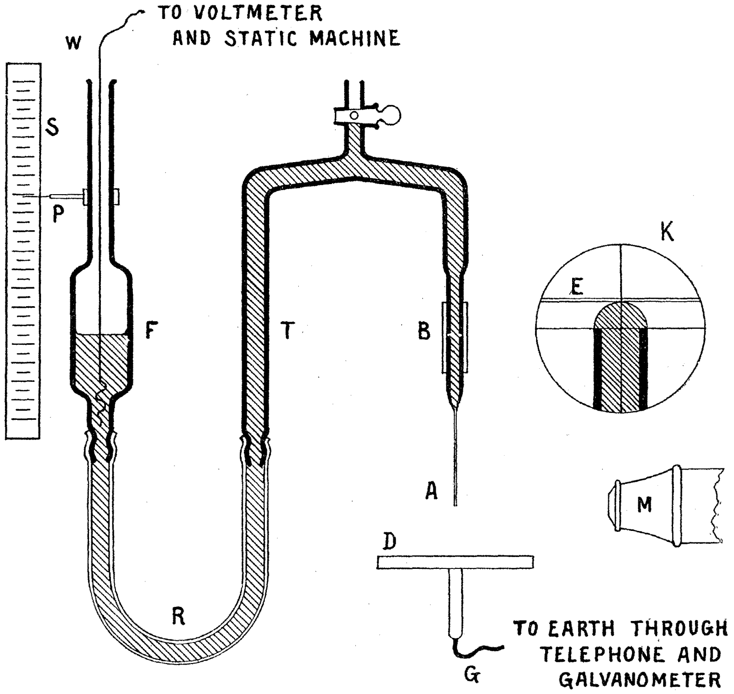

Fig. 1.
Diagram of apparatus.

minor irregularities on the surface is of no consequence and that the general geometrical shape is alone determinative for both the beginning potentials and the current obtained with any potential.

The liquid in the apparatus was connected by the wire *W* to a high capacity static machine and the voltmeter. The static machine was provided with 15 Leyden jars for steadying the potential, which could be regulated by shunting a part or all of the current to earth through a variable india-ink on paper resistance which was devised for such purposes in this laboratory.[1] A Braun voltmeter reading to 10,000 volts was usually used for measuring the potentials of the points. Its accuracy was tested by comparing its readings with other Braun voltmeters and Kelvin vertical electrostatic voltmeters of various ranges, some of which had been checked for the lower voltages by means of a high potential storage battery. The glass piece *F* could be raised or lowered by a rack and pinion motion on the stand to which it was clamped. Changes in the vertical position of the liquid surface at *F* were determined by a cathetometer or from readings of the pointer *P* on the fixed scale *S*.

The end of the discharge point was observed with a low power microscope which had an ocular micrometer and was itself carried on a micrometer slide. The latter permitted the measurement of the diameter of a point while in position. With the ocular micrometer a distance was measured from the end of the point equal to the height of meniscus it was proposed to use. The movable cross hairs were left in this position, shown at *E* in a picture of the field of view drawn at *K*, and the meniscus was simply raised to the point of tangency to ensure its being of the proper height.

5. The end of a point best suited to the purpose should have a sharp continuous edge, which moreover should lie in a plane which is perpendicular to the axis of the cylinder. Ground ends are not serviceable because the act of grinding breaks off minute chips from the edge and the meniscus on such a point can rarely be raised to a hemispherical form without the liquid crawling over the edge and running up the outside of the tube. The method adopted was to make a fine short scratch on the side of the tube and then break off the tube by a gentle pull. In a rather small fraction of cases the break was sufficiently straight across to permit of use. The roughened portion of the edge, due to the scratch, caused much trouble owing to the overflow of the drop at this point under certain conditions.

The choice of liquid to be used in the apparatus is confined to such liquids as do not leave a residue on evaporation, because the rapid evaporation at the surface of the point soon causes any salt solution to become saturated at this place and to form a deposit. In the experiments to be described in this paper, only one kind of liquid was used, and that

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[1] F. Aust, Physik. Zeitschrift, 12, p. 732, 1911.

was a very dilute solution of hydrochloric acid. The conductivity of this was large enough so that no account had to be taken of any fall of potential existing between the voltmeter and the end of the point. Some measurements of the various quantities with which this paper is concerned were made using distilled water and strong hydrochloric acid, and in each case the values obtained were essentially the same as those obtained with the very dilute acid.

PROCEDURE IN EXPERIMENTS.

6. When the liquid surface in *F*, Fig. 1, is on a level with the end of the tube *A*, the meniscus at the latter place is flat, it being presupposed that no electric charges are present. As *F* is raised gradually the meniscus at *A* bulges out more and more. The vertical height between the meniscus and the surface level in *F* is a measure of the hydrostatic pressure in the liquid drop. This pressure is a maximum when the radius of curvature of the meniscus is a minimum, which is the case when the meniscus becomes hemispherical.

Knowing *r*, the radius of the tube *A*, and *h*, the height of the liquid necessary to make the meniscus hemispherical, the surface tension *T* of the liquid can be found from the relation

$$T = \frac{rhdg}{2},$$

where *d* is the density of the liquid and *g* the gravity constant. This method of determining *T* is capable of giving fair results when a well-made point of small diameter is used.

7. If the liquid is gradually charged, the electric force acting at the surface of the meniscus tends to pull the drop outward. This tendency may be counteracted by lowering *F* until the meniscus is of the same height as it was before being charged. The distance *p* that the liquid surface was lowered is a measure of the electric pull per unit surface on the meniscus. Expressing this latter in terms of *f*, the electric intensity at the surface,

$$\frac{f^2}{8\pi} = pdg, \quad \text{or} \quad f = \sqrt{8\pi pdg}.$$

The electric intensity at the surface of the meniscus is thus determined by simply measuring the length of the liquid column whose hydrostatic pressure just counteracts the mechanical pull exerted by the electric field on the surface of the liquid. The electric intensity measured is evidently the largest value obtaining on any part of the liquid surface. If inequalities exist, equilibrium is attained by a distortion of the surface.

The method permits the measurement of the electric intensity in all cases where a definite meniscus can be maintained and has been used for determinations when no current is flowing, when a current is flowing, and under the conditions of the initial current from points.

No difficulty was experienced in getting the pressure reading when the point was charged to a considerable potential, but a great deal of difficulty was experienced with most of the points prepared in obtaining the pressure required to form an uncharged drop whose height approached that necessary to make it a hemisphere. This difficulty arose from the ease with which a drop of such a height overflows up the sides of the tube, the place at which this overflow starts being the scratch on the glass made for breaking off the tube as already mentioned in § 5.

8. The arrangement of a point opposite a plane does not permit of the calculation of the electric intensity at the surface of the point for any voltage. Determinations of the value of this quantity for various potentials below that necessary to start a current were made by the method described with a number of points with hemispherical menisci whose radii ranged from .021 cm. to .054 cm., and where in each case the distance between the end of the charged point and the earthed plane was 1.5 cm.

The results obtained may be stated in the following form: The electric intensity at the end of a point of the form used is sixty per cent. of the intensity that exists at the surface of the inner of two concentric spheres,[1] the smaller of which has a radius equal to the radius of the point in question and is charged to the same potential, while the larger has a radius equal to the distance between the point and plane (1.5 cm.) and is at zero potential.

Measurements of the electric intensity at the point for other distances than 1.5 cm. between the point and plane, made with one point only, gave for the above percentage, 57 per cent. for a distance of 3 cm., and 67.5 per cent. for a distance of 0.5 cm.

These results may be used for finding the electric intensity at the end of metal points of the same shape under the given conditions.

CHARACTERISTICS OF THE DISCHARGE.

9. Some of the phenomena which attend the starting of a current from the points deserve first consideration. Suppose the potential of a liquid point, which has not been used for some minutes, to be increased gradually while the meniscus is kept in a fixed position by proper adjustment of the liquid pressure. When the potential has reached a certain value,

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[1] Maxwell, Electricity and Magnetism, Vol. I., 3d ed., p. 189.

whose magnitude depends not only on the diameter of the point but also upon how long the surface of the liquid has stood unused, a momentary discharge takes place, a single click being heard in the telephone receiver and the galvanometer indicating a slight ballistic throw. A faint flash of light appears and the meniscus of the point jerks back into a more flat position, showing that some change has taken place which has resulted in an increase in the surface tension.

This solitary discharge is not repeated at the same voltage (not within some minutes at least) even after the meniscus has been brought to its initial position by added pressure. A second solitary discharge only occurs after the potential has been raised one or more hundred volts. This, too, is accompanied by a fall of the meniscus. Further discharges of the same kind are obtained on increasing the potential by constantly diminishing steps, except that this first stage changes after a few discharges into a second stage where, instead of one discharge following a rise in voltage, several take place at increasing intervals, finally stopping altogether. Going up in potential from this value, a third stage[1] is reached where discharges continue indefinitely, say, at the rate of about one a second. With further increases in voltage the discharges occur closer and closer together until the individual discharges cannot be distinguished either by the galvanometer which shows a steady deflection or by the telephone where a continuous sound is heard, or by the jerks of the meniscus whose upper surface simply appears very blurred through the microscope.

At a still higher potential, a fourth stage is reached with the positive discharge where the meniscus suddenly becomes perfectly motionless, the sound in the telephone ceases, and the galvanometer deflection assumes a smaller steady value. This last stage continues through increases of potential up to the limit used, which was 10,000 volts.

On lowering the potential of the point from its highest value, the steady state (stage four) passes back as suddenly into the intermittent one but this occurs at a somewhat lower voltage than at which it began.

The voltage at which the intermittent current stops is nearly the same as that at which the continuous intermittent stage (stage three above) begins, but is usually a little higher owing to the fact that this stage on the first trial begins at a lower potential than on succeeding trials. However, after a current of some magnitude has been allowed to flow from the point, the voltages at which the intermittent stage stops and then

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[1] A slightly different intermediate stage has also been noted where keeping the potential constant, a continuous series of discharges takes place, each consisting of a few discharges in rapid succession, the series being separated by an interval of rest of a second or two.

begins again are usually identical.[1] Potentials obtained under these conditions and the corresponding electric intensities determined at the same time have been taken as the values of these quantities which are necessary to start the discharge. This means that these quantities were measured for the surface conditions existing after the treatment noted.

After the current from a point has been stopped, the initial solitary discharges, mentioned under stage one above, may again come into evidence if the point is left standing for several minutes. The conditions have not been determined under which the first of these solitary discharges would occur at the lowest possible potential. Under the usual procedure of starting an experiment, the liquid surface is agitated during the manipulations and for such a surface the discharge usually begins with the continuous intermittence stage. The removal of one or more drops from the end of the point brings the initial discharge voltage nearly up to the value it has after a current has been flowing.

10. The following examples will give an idea of the range of voltages over which the various types of discharge extend. Thus a point with a hemispherical meniscus whose radius was 0.025 cm. gave the first momentary discharge at + 4,000 volts, the next came at 4,110, the next at 4,200, and so in turn others until at 4,700 volts the discharges came continuously. The intermittent stage changed to the steady stage at 5,125 volts. On lowering the voltage the intermittent stage was resumed at 5,000 volts and the current ceased at 4,750 volts. After raising the voltage to 8,500 and then lowering it, the steady stage repeatedly changed to the intermittent at 5,000 volts as at first, but the current now stopped at 4,800 volts. At the transition stage the steady current of 4.9×10^{-8} amperes changed to an intermittent current whose mean value was 5.8×10^{-8} amperes.

With another point having a radius of 0.034 cm. the first discharge was observed at + 4,100 volts, the next at 4,250, and so on until at 5,250 discharges passed continuously about one a second, and at 5,350 the rate had increased to several per second. At 5,750 volts the intermittent current of 9.8×10^{-8} amperes changed to the steady current of 6.2×10^{-8} amperes.

A still larger point of radius, 0.045 cm., gave the first momentary discharge at + 4,500 volts with others in turn as before. The intermittent current changed to the steady form at 6,050 volts. With decreasing potentials the steady current changed back to intermittent at 6,025 which ceased at 5,760.

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[1] If the current is diminished very rapidly to zero, it is apt to stop at a higher voltage than is otherwise the case.

In some cases the stopping potentials obtained on different days varied by as much as 3 or 4 per cent., but the condition accountable for this has not been ascertained.

Luminous Appearance.

11. The luminous effects which are seen in a dark room near the end of a liquid point at once decide that the positive discharge is of quite a different character when intermittent from what it is while a steady current is passing. In the latter case, for the larger currents the whole hemispherical surface is covered with a coating of steady purplish light of imperceptible thickness, and with the smallest current at which this form of discharge exists, usually less than half of the hemisphere is covered with the luminous coat.

When the current is intermittent, however, in place of the luminous coat, there is seen at each discharge a fibrous like brush of light which starts from a small area on the liquid surface and reaches out half way to the plane. Near the surface of the liquid, the light is confined to a narrow region and here it is much brighter than in the brush part proper. The general appearance is seen from the drawing *a* in Fig. 2. It appears to be a real positive brush discharge. Just before the intermittent form changes into the steady form the luminous effects of both kinds of discharges are seen at times. They either coexist or there is a rapid succession of changes of one kind into the other.

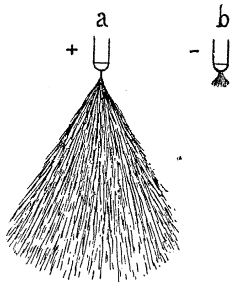

Fig. 2.
Appearance of intermittent positive discharge and of negative discharge.

12. The negative discharge is nearly always an intermittent one (occasionally no intermittence was observed) and in the dark the light from it has the appearance of a short stubby brush. The brush starts from a very small area of the surface and is especially bright at this initial point. Its appearance is shown at *b* in Fig. 2, and it is seen to be a typical negative brush discharge.

Oscillations of Meniscus.

13. The character of the oscillations of the meniscus during the intermittent stage of the discharge has been studied by making observations in light from the spark of a Leyden jar. Drawings of some of the instantaneous outlines, observed in this way during discharge from a point of 0.034 cm. diameter, are shown in Fig. 3.

For the smallest positive currents the oscillations usually are confined to the limits indicated in *a* and *b*, although now and then the form *c* was seen, the pointed top flying off in a drop having a diameter about one tenth of that of the tube. The outlines *d*, *e*, *f*, *g*, *h* and *i* show some of the forms seen with larger positive currents. When the current was about to change from intermittent to steady, the meniscus showed the agitated appearance indicated in *k*, the meniscus tossing about from side to side and drops of liquid flying off from its end. Without intermittent light this has the appearance *l*, as if the surface were breaking into spray. The contrast is very remarkable when the meniscus of so much commotion suddenly becomes a perfectly still and clear-cut hemisphere as the current changes to the steady form.

14. In the case of the negative discharge the appearance for small currents was much the same as with the positive, forms *a*, *b*, *d* and *e* being seen, but form *c* was not observed. With large currents (many times larger than the positive ones with which the form *k* was observed) using potentials above 8,000 volts, the meniscus was comparatively steady, although moving about as shown at *j*. Excessive pressure in a meniscus always results in large drops flying off, and it is difficult to know what external pressure should be applied which would make the meniscus hemispherical were it not in motion. Thus with the negative discharge just considered, where the applied pressure remained unchanged throughout, during the range of voltages from 6,000 to 8,000, large drops were thrown off from the meniscus, while this was not the case for lower or higher voltages than these. The conclusion is drawn that with this discharge, the electric intensity at the point, after the current has started to flow, first increases considerably with increase of potential and then falls again to the initial current value or still lower.

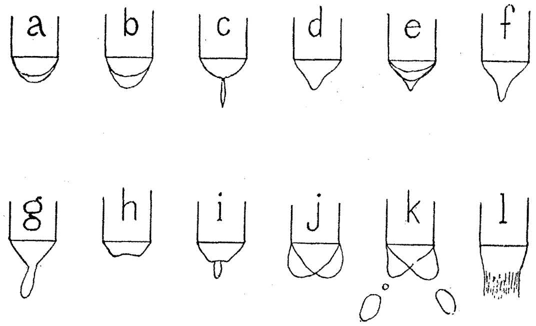

Fig. 3.

Oscillations of meniscus during intermittent discharge.

15. The oscillations of the meniscus are doubtless attributable to the intermittent character of the discharge, the electric force at the surface being smaller with the current flowing than without a current. The fact that during an intermittent discharge, this is of such a character that it is limited to a very small area on the surface, must produce differences of

surface tension over the surface which help to upset its equilibrium. Changes in surface tension actually occur after the first momentary discharges, as already described.

ELECTRIC INTENSITY AT A DISCHARGING SURFACE.

16. The principle of the method used for measuring the electric intensity has been described in § 7. The difference in level of the liquid surface in *F*, Fig. 1, when the point is at the potential under observation and when uncharged, must be measured, the meniscus at the end of the discharge point being of the same height in both instances.

For the steady positive currents, this pressure can easily be measured. The intermittent stage of the positive discharge is included in a rather short range of voltages and in the lower part of this range also, the pressure can be obtained quite accurately.

When the momentary discharges occur but slowly, it is noticed that just before each discharge the center of the meniscus rises slightly and forms a portion of greater curvature from which the discharge takes place, following which the whole meniscus flattens in the way already described in § 9. A little uncertainty arises from not knowing to just what height the meniscus should be forced in this case. The method adopted was to bring the meniscus to such a point that it rose to the adjusted cross hair (*E*, Fig. 1) at each discharge. However, a slight increase in pressure only was necessary to raise the meniscus from the position named to where it touched the cross hair before the sudden elevation preceding discharge, just noted, took place.

17. The measurement of the pressure within a high meniscus when at zero potential offered two difficulties. The first is the one already mentioned due to the ease with which the meniscus overflowed the sides of the tube. Running the discharge for a time helped matters considerably, unless the scratch on the side (§ 5) was too prominent.

The second difficulty arises from the way the surface tension of the meniscus changes on standing, while no discharge is passing. It was necessary to determine the pressure in the meniscus for zero potential immediately after the discharge was stopped in order that the surface tension might be as nearly as possible of the same value as during the discharge. The pressure thus obtained was usually a little larger than was found with a surface made fresh by the removal of one or more drops. It is possible that ordinarily some impurities collect on the outside of the glass tube and are able to pass gradually to the liquid, whereas the discharge dries this glass surface so thoroughly that it takes time before a layer of moisture, sufficient for permitting the passage of impurities to the meniscus, can form.

In finding the pressures necessary to overcome the mechanical pull on the surface of the meniscus for potentials below that required for a discharge, it was necessary in each case to start with a potential sufficient for a discharge current and after this had been flowing for a short time to reduce the potential to the one for which the pressure was desired. The results of such measurements have been stated already in § 8.

18. An example of the character of the results is shown in Fig. 4, where data are given which were obtained for the positive discharge from a point of 0.0281 cm. radius with a meniscus having a height *h* equal to two thirds of the radius of the tube. The ordinates of the curves starting at the left give diminutions in the water pressures[1] which were required to counteract the electric pull arising from the potentials expressed as abscissas. The curves at the right give the corresponding currents flowing from the points.

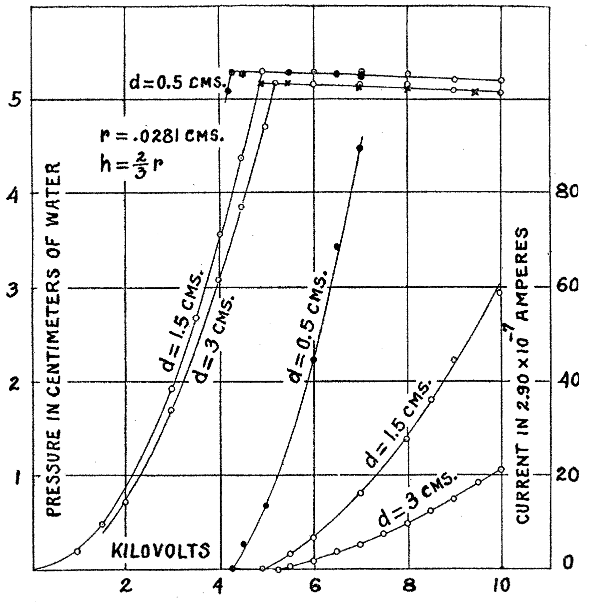

Fig. 4.

Positive discharge currents and liquid pressures required to counteract the mechanical pull of the electric field.

Starting at the origin of the right curve which is marked to indicate that the distance, *d*, between the point and the plane was 1.5 cm., it is seen how the pressure increases along a parabola as long as no discharge passes, but as soon as the starting potential of 4,900 volts is reached, the

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[1] For the sake of brevity, these diminutions of pressure will be spoken of simply as the pressures.

curve turns abruptly (follow open circles), and shows now a slight decrease in the water pressure with increase of voltage. This indicates that the electric intensity at the discharging surface for currents of all values is approximately the same as is required to start the discharge. A similar result for platinum points was obtained by Chattock.[1]

19. With a negative discharge, it was not possible to get the water pressures with any accuracy when the current was flowing, owing to the disturbed condition of the meniscus.

As indicated in § 14, however, the electric intensity appears to increase with voltage for a certain range after the discharge begins, and then to decrease again, finally reaching a lower value than was necessary to start the current. Measurements with the negative discharge were confined to the determination of the potentials at which the current started and ceased, and of the electric intensities at the surface which corresponded to these potentials.

The noteworthy result was obtained with all of the points used that the starting and stopping potentials and the surface electric intensities under these conditions were the same for the negative discharge as for the positive. When any differences were observed they were as often in one direction as in the other.

The result is contrary to the prevailing notion of the behavior of the two discharges from metallic points, which is that the negative discharge begins at a considerably lower potential than the positive. This is true for points of a very small diameter but some of the writer's previous results[2] with brass points show that the difference between the starting potentials for the positive and negative discharges becomes less and less as the radius of the discharge point is made larger and larger, until the two become the same when the radius is as large as 0.02 or 0.025 cm. The smallest point used in the present experiments had a radius of 0.0146 cm.

20. Some results obtained with the same point with distances of 0.5 cm. and 3 cm. between the point and plane are also given in Fig. 4. Those for $d = 0.5$ cm. are represented by black circles, the observations having been taken on the same day as those just given for $d = 1.5$ cm. It is seen that although the current begins at a much lower potential in this case (4,200 volts), the pressure in question after the current has started is nevertheless the same for each voltage as when d was 1.5 cm. The currents for corresponding voltages, as shown by the lower curves, are much larger with the shorter distance between point and plane.

The results given in the curves marked $d = 3$ cm. were obtained on a

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[1] A. P. Chattock, Phil. Mag., 20, p. 266, 1910.

[2] J. Zeleny, Phys. Rev., 25, 1907. Curves on pages 313 and 324.

different day from the preceding, the atmospheric pressure being less and the temperature higher. Some results obtained on that day with a distance of 1.5 cm. are represented by crosses on the horizontal part of the pressure curve for $d = 3$ cm., and it is seen that the pressures are again identical during the discharge.

These results show that the increase in the volume charge in the gas between the point and the plane almost exactly neutralizes all effect of increase of voltage of the point upon the electric intensity at the discharging surface. Since more ions are produced with the higher voltages this limiting electric intensity must extend farther into the gas, the larger the current. Hovda[1] has shown that in the space between the point and plane the electric force is very nearly proportional to the square root of the current. This proportion evidently does not hold at the discharging surface.

21. The relation between the currents i and the applied voltages V is not expressed well for these points by Warburg's formula,[2]

$$i = aV(V - M),$$

where M is the minimum potential at which a current flows. In most of the cases, M must be given a value larger than the observed minimum potential to make the equation applicable.

To illustrate the effect of changes in the height of the meniscus upon the current flowing from a point, some results are given in Table I. which were obtained with a point of radius 0.0281 cm. The heights of the menisci are expressed as before in terms of the radius of the tube. The numbers show that the shape of the meniscus does not influence greatly the current flowing from the point, for voltages removed considerably from the starting potential, which itself is changed considerably by a change of meniscus.

TABLE I.

Variation of Current with Voltage for Menisci of Different Height.

Height of Meniscus.	Starting Potential.	Currents in 2.9×10^{-7} Amperes.		
		6,000 Volts.	8,000 Volts.	10,000 Volts.
1/3 radius.	4,900 volts.	7.8	29.0	59.9
2/3 "	4,900 "	6.8	27.7	59.0
1 "	4,750 "	7.2	29.3	58.2
2 " [3]	4,200 "	8.0	27.2	56.5

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[1] O. Hovda, PHYS. REV., 24, p. 25, 1912.

[2] E. Warburg, Wied. Annalen, 67, p. 69, 1899.

[3] When the current is flowing from its surface, a drop may be drawn out in cylindrical form to an astonishing length.

22. The counteracting pressure during discharge was not found in all cases to be so nearly the same for all values of the current as in the example given in Fig. 4. The observed pressure was found in some cases to increase with voltage and in other cases to decrease, depending upon the height of the meniscus and upon the diameter of the point used. Some variations of this kind are shown in Fig. 5, by the curves giving results obtained with points of three different radii, whose values are indicated on the right side. Two or more heights of meniscus are represented in each case, the height *h* being given with each curve in term of the radius of the glass tube from which the meniscus protrudes. At *A* are drawn three menisci of the heights indicated, to picture more clearly the differences. The first reading at the left end of each curve is that corresponding to the voltage required to start the current, except that with the middle point some values are given on the downward slope of the pressure curve preceding the beginning of the current.

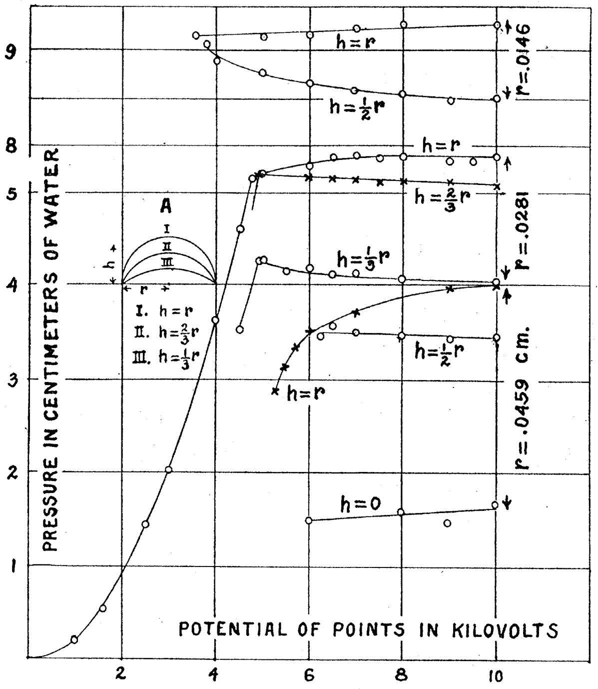

Fig. 5.

Effect of height of meniscus and size of point upon the electric force at the surface.

Considering first the smallest point, $r = 0.0146$ cm., it is seen that the pressure for the initial current is nearly the same in the two cases given, but while for $h = r$ the pressure increases slightly with increase of voltage, for $h = \frac{1}{2}r$ on the other hand the pressure diminishes considerably, more especially during the first part of the range.

With the second point, $r = 0.0281$ cm., the initial pressures are alike for $h = r$ and $h = \frac{2}{3}$, and for increasing voltages the values remain nearly alike, increasing somewhat with voltage in the first case and diminishing in the second case. When the meniscus is lowered to $h = \frac{1}{3}r$, the pressures for all of the voltages are smaller by twenty per cent.

In the case of the largest point, $r = 0.0459$, it is to be noted particularly, that with $h = r$ the pressure increases quite rapidly at first with increase of voltage. The curve for $h = \frac{1}{2}r$ starts higher and is nearly horizontal. A curve for a flat meniscus, $h = 0$, is also added, but this is not directly comparable to the others since the discharge here took place from the sharp edge of the tube.

The facts to be noted are that with increasing diameter of point the pressure which overcomes the electric pull diminishes, and that with the smaller points, the pressure where the current starts is almost the same for menisci differing considerably from the hemispherical shape. Since the electric intensities vary as the square roots of the pressures which have been plotted, the ratio differences between the intensities at various voltages or under different conditions are only about half as large as exist between the pressures.

23. In Fig. 6 are plotted pressure-voltage curves for positive discharge from some of the points of different sizes which were used, the height of the meniscus being in each case equal to the radius of the tube. The whole range of sizes used is included, the radius corresponding to each curve being given in centimeters at its right end. The first observation recorded at the left end of each curve represents the voltage at which the discharge stopped and began again. It will be noted that these plots are nearly straight lines for the smaller points, and that they become more curved and show a greater rise in pressure with voltage as their size increases.

Mention should be made of a peculiarity observed at times with some of the smaller points but not shown by any of the curves given. In these cases, as the voltage was increased above the minimum potential, the pressure at first fell rather rapidly by a small amount to the nearly constant value which obtained over a wide range of higher voltages.

The different character of the pressure curves for points of different sizes needs explanation. The difference may arise simply from the fact that with the larger points the meniscus differed considerably from the hemispherical shape at the starting potential and while small currents only were flowing, although with the larger currents the shape was as nearly hemispherical as the eye could judge. At *A*, near the bottom of Fig. 6, a curve drawn inside of a semi-circle shows approximately the appearance of the meniscus at the starting potential with large points. This distortion does not exist when the meniscus is not charged and hence acts to give too low a value to the pressures which have been plotted, since the increased curvature of the surface partly counteracts the electric pull on the surface. The pressure for zero potential with the distorted meniscus might be calculated from the known surface tension by measuring the curvature at the end of the meniscus and from this the true value of the electric pull might be determined. Again it might be assumed, from analogy with the small points, that the pressure at the high voltages where the meniscus is hemispherical is nearly what it would be at the starting potential for a meniscus of the same shape.

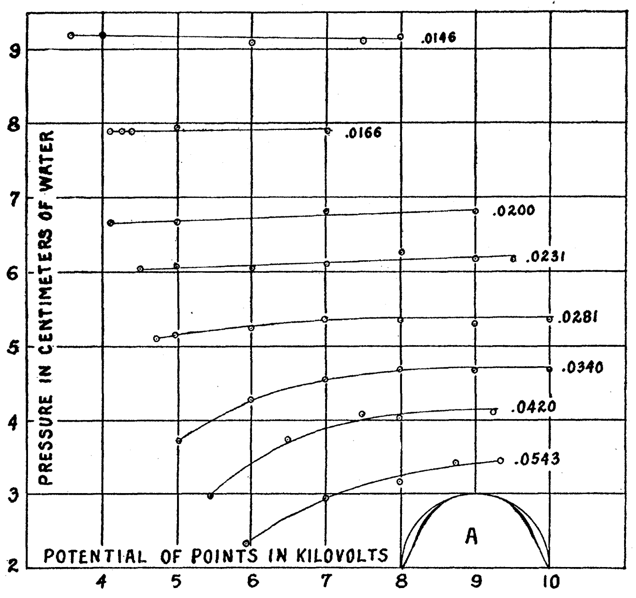

Fig. 6.

Electric intensities at the surfaces of various sized points, during discharge.

With these large points the currents, as indicated by the coating of light on the surface, only spread very gradually to the whole area of the hemisphere, and it is possible that this is the chief reason for the different shapes in these cases of the pressure curves under consideration.

24. An experiment was tried to see if any effect upon the electric intensity at the starting potential could be observed owing to the different

distribution of the electric field when in one case the point is charged and the plane is to earth, which was the usual arrangement, and in the other case where the plane was charged and the point was to the earth. The intensities in the two cases were found identical, notwithstanding the fact that to start the discharge when the plane was charged, the potential required was 1,000 volts higher (r = 0.0146 cm.) than in the other case.

25. In another experiment using a point of radius 0.02 cm., the plane was replaced by a hemispherical cup of 1.5 cm. radius, the end of the point being situated at the center of curvature. The value found for the intensity at initial current was not essentially different from the value obtained with a plane at 1.5 cm. distance, being about 2 per cent. smaller. The hemispherical cup might be used to advantage with large points as the field would tend to keep the menisci more hemispherical.

26. If the glass of which the tube is made were to act as a perfect insulator, the conducting portion of the point would consist of the liquid cylinder, expanding at the end into a hemisphere of considerably greater radius. The distribution of the field at the end of such a conductor would naturally be different from that obtaining where the material of the tube is conducting. Two tubes, having radii 0.045 cm. and 0.0185 cm. were therefore silvered on the outside and the value of the electric intensity determined at the surface of the liquid hemisphere for each, at the starting potential. The values found were identical with those obtained before the points were silvered, indicating that the clean glass surface either by conduction or from ions in the gas, gets the same surface charge a conductor would have.

27. The method used for measuring the electric intensity presupposes that the surface tension of the liquid has the same value when the two measurements of pressure are being made, *i. e.*, while the current is flowing from the surface and when the surface is uncharged. In the former case, it is possible that the current heats the surface sufficiently to change its surface tension by an amount that should be taken into consideration. To test this point a thermal couple made of very thin wires was introduced into the liquid of the meniscus by running the wires into the inside of the tube at the rubber connection, shown at B, Fig. 1. The apparatus was now used with the plate charged and the point to earth, and it was found that even with the largest currents which had been employed in these experiments, the temperature of the drop of liquid was changed by only about 2° C. Moreover, the temperature was diminished by the current, owing, no doubt, to an increase in the rate of evaporation. When the meniscus was lowered so that the wires

of the thermal couple protruded from the liquid and the discharge started from them, an increase of temperature of about the same magnitude was observed. This last is in agreement with some of the writer's former experiments.[1]

That some slight differences in surface tension over the surface of the meniscus exist during discharge is indicated by the circulation inside of the liquid of any small specks of solid matter that may happen to be there.

28. The effect of the gamma and beta rays from radium upon the starting potentials of several points was tested by bringing up a glass tube containing a little over 3 mg. of radium to within 4 cm. of the points. In a few cases this produced a change which amounted to a lowering of the starting potential by about 25 volts, this being the smallest change detectable with the voltmeter used. In such cases if the potential was reduced very slightly below the stopping potential while the radium was not in place, bringing up the radium caused a very small current to start which disappeared again on removal of the radium.

With metal points, the surface conditions cause a retardation of the starting potential so that when the current does start, it jumps at once to a value which is considerably larger than the smallest currents detectible in these experiments. The effect of radiations on such points is to reduce this retardation of the starting potential and make this latter coincide with the stopping potential, as Warburg and Gorton (loc. cit.) have shown. For these liquid points the current while beginning with an intermittent stage nevertheless starts very much more gradually than it does with the metal points, so that the same conditions are not present to be influenced by the radiation. The effect of more powerful ionizing agents which have been studied in some detail, is very pronounced but this will be considered in another paper.

29. The value of the electric intensity at the surface of the liquid when a positive current just ceases to flow from it was determined about ninety times all told with more than a dozen points ranging in radius from 0.0146 cm. to 0.0543 cm. Many of these determinations were made incidentally while other matters were under investigation, hence they are very unevenly distributed among the points used.

A summary of the results is given in Table II.

Column 1 gives the radii in centimeters, and column 2, the number of the determinations of the electric intensity f, the average of which is given in column 3 expressed in electrostatic units per centimeter. The individual results for f obtained with any point differ in but one or two

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[1] Proc. Royal Soc. London, 82, 1909. Note to paper by Barnes and Shaw.

TABLE II.

Electric Intensity at Discharging Surface.

1	2	3	4	5	6	
r	n	f (water)	$f\sqrt{r}$	T	f (brass)	
					+	−
0.0146 cm.	21	471	56.8	73.8	508	482
.0166	3	436	56.2	68.5	474	....
.0178	3	416	55.5	69.0	443	430
.0185	3	414	56.3	70.7	435	....
.0200	18	405	57.2	70.5	415	409
.0229	13	382	57.8	72.8	390	....
.0250	6	353	55.8	66.2	374	376
.0281	1	356	59.7	....	351	....
.0340	10	309	57.0	72.6	318	....
.0370	1	294	56.6	71.2	304	....
.0419	4	270	55.3	76.0	285	....
.0451	4	276	58.6	73.7	275	....
.0543	3	241	56.2	79.0	250	....
Average....	....	....	56.9	72.0	....	....

cases by more than two per cent. from the mean value given. The barometric pressure was usually close to 74 cm. of mercury with a maximum variation from this of about 5 mm. The temperature during most of the observations was about 22° C., although the extremes were 20° and 26°.

It is seen that the value of f for the smallest point is about twice that for the largest point. The results can be represented very well by the empirical relation $f\sqrt{r}$ = a constant. The values of this product are given in column 4, the average being 56.9.[1] There are no systematic variations in column 4 from this value, and the larger deviations which exist may be attributed to the lack of perfection in the ends of the points.

It must be remembered however that the considerations given in § 23 raise the question whether the values obtained for the electric intensity with the larger points are not really too low.

30. Column 5 in Table II. gives the values obtained by the method described in § 6 for the surface tension T of the liquid used (water very slightly acidulated with hydrochloric acid). The average of the values given for all of the points is 72.0. By the capillary tube method, the surface tension of the same solution was found to be 71.3.

The larger deviations from the true value are an indication of the

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[1] Combining this relation with the equations in §§ 6 and 7 it can be shown that $p = 9/10\,h$ nearly. This means that at the potential for which a current starts the liquid surface in F (Fig. 1) is always situated a small distance only above the level of the discharge point.

difficulty experienced in some cases of getting the true pressure owing to the readiness with which the liquid overflowed the sides when not charged, but in some cases they arise from the meniscus being somewhat distorted because of the unevenness of the edge of the glass tube. A distortion of the kind just mentioned, while it would result in giving an incorrect value of the surface tension, would not affect the determination of the electric intensity if it did not change its character with the charging of the liquid.

31. Chattock[1] found the relation $f.r^{0.45} = 85$ to represent his determinations of the electric intensity at the surfaces of platinum points when a positive current just ceased to flow. The size of the points used is not stated, but his formula when applied to the extreme limits of size used in the present experiments gives values over 20 and 30 per cent. larger respectively for the smallest and largest points. Whether this difference between the results with water and platinum surfaces is a real one arising from some inherent difference in the two kinds of surfaces or whether it is to be ascribed to some inaccuracy in one or the other of the methods used in making the measurements, remains to be determined.

Some of the results obtained by the writer[2] for the minimum potentials of brass points of various sizes were gotten under like conditions to those obtaining in the present experiments, except that the point was situated in a metal vessel. The method explained in § 8 should therefore be applicable to those results and the electric intensity at the surface of the cylindrical brass points with hemispherical ends may be calculated from the minimum potentials. Values of f thus computed from the results taken from Figs. 2 and 5 of the paper cited, are given in column 6 of Table II. The values for the brass points are on the whole several per cent. larger than for the water points, the divergence being largest for the smallest points.

Preferable to computing the electric intensities for the brass points, a more direct method of comparing the behavior of the two kinds of points would have been to compare the values of the minimum potentials. This is not done because the determinations of the minimum potentials with the liquid points show some peculiarities not fully understood. Thus the value obtained might be different by over a hundred volts on some occasions without any similar change in the electric intensity. This much may be said of the potentials obtained, and this should be contrasted with the relative values of the electric intensities given above, that for the lower half of the range of sizes used the minimum potentials

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[1] A. P. Chattock, Phil. Mag., 20, p. 266, 1910.

[2] J. Zeleny, Phys. Rev., 25, p. 305, 1907.

for the liquid points are almost the same as for the brass points, being a little higher in a few cases, but for the largest points used the minimum potentials are about six to seven per cent. lower.

32. Any discussion of the results which have been presented in this paper will be postponed until the results of some other experiments which have been completed are published. These further experiments deal with the discharge from various kinds of liquid surfaces; with the discharge in different gases at various pressures; and with the effect of intense X-rays and alpha rays upon the discharge from both liquid and metal points.

SUMMARY.

33. The electrical discharge from points whose discharging surfaces consist of slightly acidulated water when placed opposite a metal plate have been studied. The positive discharge was found to begin with a momentary current, which was repeated only by an increase in the potential of the point. At higher potentials the discharge current is intermittent and this is followed by a steady current at still higher potentials. In the last case the liquid meniscus is quiescent and the luminosity covers the surface and is confined to its immediate neighborhood.

With the intermittent form of positive discharge the liquid meniscus is agitated and the light starts from a small area on the surface and extends half way to the plate in the arrangement used.

The negative discharge is always in the form of a brush discharge and the current is almost always intermittent and the meniscus in motion. The light in this case, however, while starting from a small area of the surface also, extends out into the gas a distance which is only about equal to the diameter of the point.

The momentary discharges, which first take place from the liquid surface, produce some effects there which result in an increase in the surface tension. This arises, most likely, from the surface being cleansed of some material collected there. It is probable that some such effect is likewise produced when metal surfaces are used.

A hydrostatic method is given for measuring the electric intensity at the surface of liquid points both before and during discharge. The surface tension of the liquid may also be obtained with the same apparatus. The product of the electric intensity at the discharging surface when a current just ceases to flow by the square root of the radius of the point, was found to be a constant equal to 56.9. The radii of the points used range from 0.0146 to 0.0543 cm.

The electric force under these conditions, as well as the potentials at which the currents cease to flow, were found to be the same for the negative and for the positive discharges.

For the small points of the range given the electric intensity at the surface of a hemispherical meniscus, when a current of any magnitude is flowing, is nearly the same as at the minimum potential, but for the larger points the value increases with current, becoming nearly constant at higher values of the latter.

The electric force at the surface of the smaller points used was influenced to a small extent only by changing the height of the liquid meniscus considerably from the hemispherical form. This intensity was not affected by such changes in the distribution of the electric field as are brought about by changing the distance between the point and plane or by using a hemispherical electrode in place of the plane, or by charging the plane instead of the point itself.

With potentials considerably above the minimum value, the current flowing from a given point was found to vary but slightly when the height of the meniscus was changed greatly.

The temperature of the liquid of the meniscus during the discharge was measured and found to be slightly lower than it was while no discharge was passing.

Results were obtained which permit the calculation of the electric force under certain conditions at the surface of a point while no discharge current is passing.

The action of the beta and gamma rays from three milligrams of radium was found to lower slightly the starting potential.

The values obtained for the electric intensity at the minimum potential with liquid points are considerably smaller than those obtained by Chattock with platinum points and somewhat smaller than those calculated by the writer from some of his measurements on brass points.

Physical Laboratory,
University of Minnesota,
December 19, 1913.