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Corona from a Water Drop*

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Studies with a water drop point in a point-to-plane gap have yielded important results. Such a point has a very low secondary electron emission coefficient, and for the first time a large difference in positive and negative intermittent onset potentials in air, due to this, has been observed. The luminosity obtained with a negative drop point and the complex oscillograph pulses on both polarities have been accounted for by considering positive corona from charged droplets leaving the water point and assuming that true negative corona from a water surface is impossible. The space charge weakening of the field about a positive point, long assumed to explain the disappearance of the pre-onset streamers, is here confirmed by the reappearance of a stable drop point well above the initial potential required for disruption of the water surface.

A REVIEW of the beautiful experiments of W. A. Macky[1] on the disruption and sparking of water drops in an electric field had indicated certain peculiar effects which did not appear to be consistent with the generally accepted theory of the corona mechanism. Macky observed that water drops falling in a uniform field in excess of some 8000 volts per cm (depending slightly on the size of drop) became distorted. The induced positive end was drawn out into a fine point which emitted a spray and characteristic streamer-like corona processes. The induced negative end of the drop showed some pointing, but was mostly clearly defined and had a faint glow superficially resembling the negative point corona.

In view of the fact that the water surface should be a notoriously poor secondary emitter under positive ion bombardment, since it is a polar substance with no free electrons, it was felt that further study with stationary positive and negative water points, where the various techniques used with metal points could be applied, might throw important light on fundamental corona processes. Many years ago J. Zeleny[2] made a careful study of the effects obtained with positive and negative drop points, especially the former. He used liquids of different surface tension and a number of gases. This work was done before cathode-ray oscilloscopes and other modern instruments were available so that at that time the mechanism of the corona was little understood. Thus these excellent observations could not answer the questions at hand.

APPARATUS AND TECHNIQUE

In these experiments, as in all corona onset studies, the field strength at the electrode surface and outward is the important parameter. This field depends critically on the radius of curvature of the drop. The problem of using such a variable point was not easily solved. Difficulty was encountered in obtaining uniformity and stability of the drop without field at atmospheric pressure and below, and application of the field produced immediate distortion of the drop ending in its eventual rupture at the point where surface tension was overcome. In consequence, the available range of drop sizes was small, and the constant change of drop shape with potential made it impossible to determine more than an approximate average value of drop curvature and field.

Figure 1 shows the disposition of capillary tube and reservoir to give a liquid "point." The remainder of the apparatus has been described in a previous paper.[3] For reduced pressures both bell jar and reservoir were pumped. In arrangement b of Fig. 1 the capillary was tried with and without a coating of paraffin wax. At low

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[1] W. A. Macky, Proc. Roy. Soc. **133**, 565 (1931).
[2] J. Zeleny, Proc. Camb. Phil. Soc. **71**, 18 (1914) and Phys. Rev. **16**, 102 (1920).
[3] W. N. English, Phys. Rev. **73**, 170 (1948).

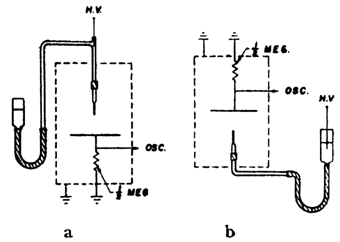

FIG. 1. Arrangement of apparatus for water drop corona studies.

pressures particularly Fig. 1b gave a less stable drop than Fig. 1a. The latter arrangement is essentially that used by Zeleny. Results obtained were the same with both. Resistance of the water column in Fig. 1a was three megohms for tap water, 30 megohms for distilled water. Adjustment of the reservoir height to give satisfactory results over the whole voltage range was critical. Generally, the hydrostatic pressure was varied until a nearly hemispherical drop was obtained just below corona onset. The reservoir level would then be about a centimeter above the capillary tip.

Although boiled distilled water was used, bubbles would often block the capillary at pressures below 300-mm Hg. At lower pressures also, the fields for corona onset were lower, so that the drop was not pulled out beyond the capillary, and negative corona sometimes took place from the glass corner. Adjustment of the reservoir under such conditions usually caused the drop to become unstable and fall off. These effects set the lower limit of observation at about 200-mm Hg pressure.

The following methods of observation were used:

(i) Corona gap: visual with 70X telemicroscope
- (a) Dark
- (b) Steady illumination at 135 degrees

(ii) Corona gap: photographic with Leica at f2, using Kodak Super XX film
- (a) Dark
  - (i) Time exposure
  - (ii) Moving film record obtained by winding film slowly by hand
- (b) Illumination at 90° from Edgerton flash lamp (50 μf at 1800 volts) with condensing lens. Flash time was about 300 microseconds (Fig. 2)

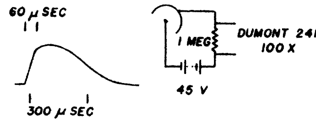

FIG. 2. Flash time for Edgerton lamp.

(iii) Dumont 241 oscilloscope
- (a) Visual
- (b) Photographic

(iv) Current-voltage characteristics

EXPERIMENTAL RESULTS

The drop on the end of the capillary will be referred to as the "main drop" or as the "point," the water spray emitted in discharge as "droplets."

It should be noted that the lack of exact control of drop curvature results in variation of the values of the potential for onset and other transitions. The values given are a typical run. A difference of several hundred volts might be observed under slightly different conditions. The important item in these studies was the *relative* values of the potential for the occurrence of the various phenomena. With care not to alter external conditions, these could be obtained to an accuracy not far short of that reached with a metal point.

One effect noted was that described by Zeleny[2] where the spray onset voltage increases steadily at first, then reaches a constant value several hundred volts above the initial onset. This he ascribed to the removal of surface impurities which lower the surface tension. Hydrostatic pressure had a large effect on the spray onset. Lowering the reservoir $\frac{1}{2}$ cm changed it from 6900 volts to 7500 volts in one instance. Vibration too played a significant part, and there was also apparently a variation in the way in which the main drop "sat" on the end of the capillary which sometimes caused a difference from one run to the next. Contamination of the water by electrolysis may also have entered. All these factors resulted in a variation of as much as 200 to 300 volts from one run to another, although if the point were not unduly disturbed a consistency of plus or minus 50 volts could often be obtained during a run of several hours.

Results with a Large Point

A capillary of 0.13-cm outer diameter, giving a point of about the same diameter of curvature, was used in the arrangement of Fig. 1b, with a 3.2-cm gap and atmospheric pressure.

Positive Point

When the potential was raised to 6800 volts, groups of positive pulses were observed on the oscilloscope. These were all of about 1000-microseconds duration and took one of three forms: increasing amplitude with almost no "streamer pulses" superposed; constant amplitude with a few "streamer pulses;" and decreasing amplitude with many "streamer pulses" (Fig. 3a). At the same time, under illumination, very fine spray droplets could be seen shooting from the tip of the main drop, causing an almost imperceptible wetting of the plane. In the dark, corona streamers were visible extending a few millimeters from the point. They were evidently associated with the spray, for the luminosity was "coarser" and more intermittent than for a metal point and was confined to the region out from the point where the spray appeared.

An increase in voltage above the onset gave an increase in spray, luminosity, and pulses up to 7100 volts. The spray pulses had been changing shape gradually since onset, the amplitude of the main pulse becoming less while that of the superposed streamer pulses increased, until at this voltage individual streamer pulses occurred separately. At 7500 volts the transition was complete, nothing but streamer pulses were to be seen on the oscilloscope, and the usual bright streamer "fan" was visible from the darkened point, with a steady burst pulse corona glow on the tip of the main drop. With illumination the main drop was seen to be rounded and stable, the ejection of water having ceased. This stable regime was noted by Zeleny,[2] but could not at that time be interpreted in terms of corona processes.

As the voltage was raised further, the point remained stable. The streamer pulses decreased in amplitude as the steady corona glow on the point increased until at 9000 volts only an occasional small streamer pulse occurred. The glow on the main drop could now be seen even with illumination, and it spread and got brighter as the voltage was further increased, as for a metal point.

The next transition occurred abruptly at 10,500 volts. The main drop was suddenly and violently disrupted. Large chunks of water were torn from its surface and drawn to the plane as drops, forming a puddle several centimeters across in a few minutes. Viewed in the dark, a bright ragged luminosity followed the broken water surface and at times shot out into the gap. On the oscilloscope large changes in potential were observed, while streamer pulses appeared intermittently. Further increase in voltage merely resulted in more and more water being drawn out of the capillary. Observations were made up to 16,000 volts.

The three voltage regions described above will be referred to as the "spray," "stable," and "drop" regimes.

Figures 3 and 4 show the oscilloscope pulses. The sequence of events for a positive drop with increasing voltage is summarized in Fig. 5. Figure 6 shows dark photographs of the gap and Fig. 7 flash photographs of the gap. A current voltage

iii ii i

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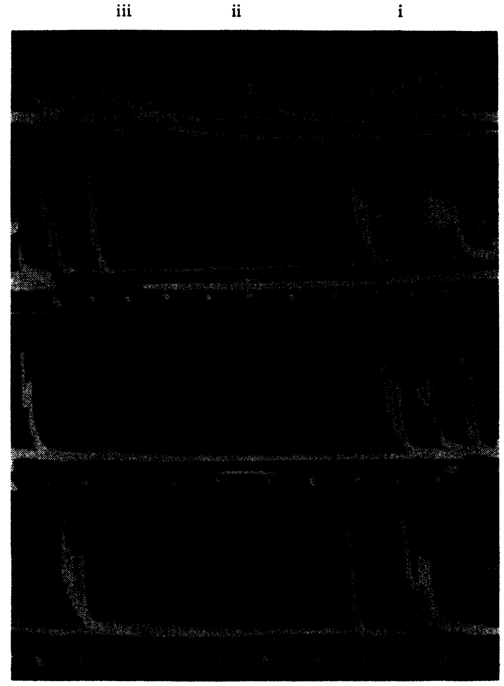


FIG. 3. Positive point spray pulses. 6800 volts. Timing interval in b, c, d is 0.001 second.

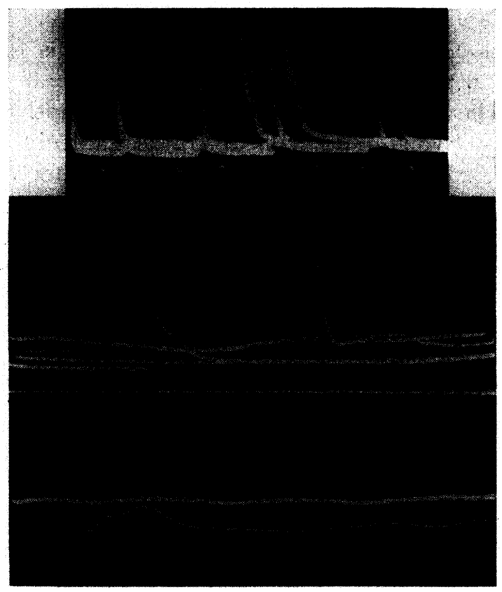


FIG. 4. (Top) Spray pulses and streamer pulses. Timing interval: 0.001 second. 6900 volts. (Center) Spray pulse, streamer pulses, and steady burst corona. Timing interval: 0.0002 second. 8000 volts. (Bottom) Electrostatic pulse due to large droplet leaving point, in "drop regime." Amplification very much less than in "spray" oscillograms. 16000 volts.

curve plotted from three different runs is given in Fig. 8.

Negative Point

Under the same conditions as above, spray onset for negative point was 6700 volts. Two types of pulses occurred on the oscilloscope as shown in Fig. 9, both of about 1000-microseconds duration, the many-peaked kind being

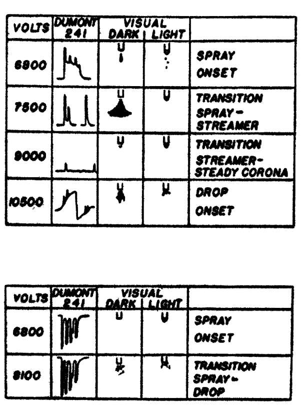


FIG. 5. (Top) Sequence for positive drop point. (Bottom) Sequence for negative drop point.

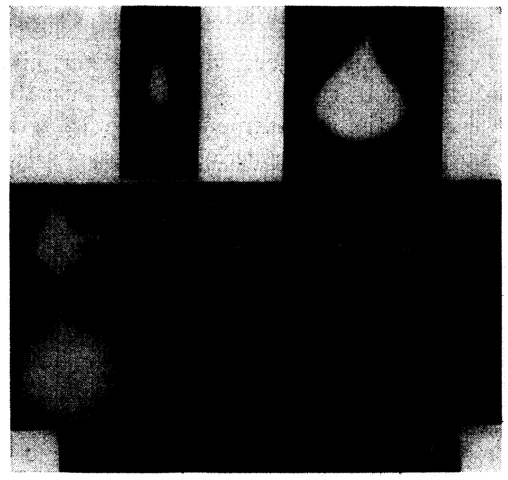


FIG. 6. (Reading from top to bottom) Dark photograph of spraying positive point. 3 min., 7300 volts. Dark photograph of stable positive point with streamers. 5 min., 8400 volts. Dark photographs of positive point in "drop regime," with moving film record obtained by winding film. 1 min. and 4 min., 13900 volts. Moving film record of 1-mm diameter positive platinum point showing steady corona. 8750 volts.

more frequent. Visually, with steady illumination, fine droplets of spray could be seen shooting into the gap, as for positive point. However, in the dark, no luminosity could be seen although it could be photographed in a ten-second exposure. An increase in voltage produced more frequent pulses of both kinds and more spray. At about 7100 volts a ragged fluctuating glow became visible in the dark. It differed markedly from that observed with positive water point in that it occurred intermittently all over the main drop, instead of being concentrated outward from its tip. Also it extended a much shorter distance into the gap and did *not* show the very characteristic structure of the negative corona from a metal point.

Further increase in voltage caused the spray emission and glow to spread still more over the point, while the pulses increased in numbers and amplitude. At 8000 volts spray emission and ragged glow covered the whole end of the capillary. About this voltage the "spraying" gave way to larger drops, which quickly wet the plane, as in the positive "drop" regime. Visually, the transition was fairly marked, and at times the discharge would fluctuate between "spray" and "drops." No noticeable change in current or oscilloscope pulses accompanied the shift, but this is not surprising as the current fluctuated considerably over the whole range and the oscilloscope screen at this voltage was pretty well filled with pulses. Observations were carried up to 9200 volts, the increased voltage causing increased ejection of water.

A summary of the effects described above is given in Fig. 5. Oscillograms for several voltages appear in Fig. 9. Dark photographs of the corona appear in Fig. 10 and flash photographs in Fig. 11. A current-voltage curve plotted from two runs on successive days is given in Fig. 12, with the positive curve for comparison. The current fluctuations were at least twice as great with negative point.

Results with Small Point

A capillary of outer diameter 0.041 cm was used, giving a point of about that diameter of curvature. Observations were at atmospheric pressure with 3.2-cm gap.

Positive Point

No streamers occurred at any voltage. Spray onset (after initial increase) was at 4000 volts. "Spray" consisted of single, almost invisible droplets which snapped off the main drop at a frequency depending on the voltage. Somewhat above onset the pulses could be synchronized almost perfectly on the oscilloscope; Fig. 13 gives a *tracing* of the pattern. No luminosity could be seen up to 4450 volts, after which a steady corona glow appeared on the tip of the main drop and the pulses ceased. The drop was stable up to 9000 volts where it was drawn out to twice the capillary diameter. Above this voltage large droplets would "snap off" the tip of the main drop at a deliberate rate, increasing with voltage. Pulses produced here were similar to those for the large point in the drop regime.

Figure 13 also shows, for comparison, pulses obtained when small drops are forced from the large positive point by raising the reservoir, at a voltage below spray or corona onset. The ratio of positive to negative pulses is 10 to 1 or greater. These negative pulses are probably due to a drop shattering process and may be disregarded.

With a small point the fields producing disruption of the drop will be obtained at lower potentials, since the curvature of the drop is greater. Further, the high field region will be smaller. In addition, the drop point appeared unusually stable, ripples and other irregularities

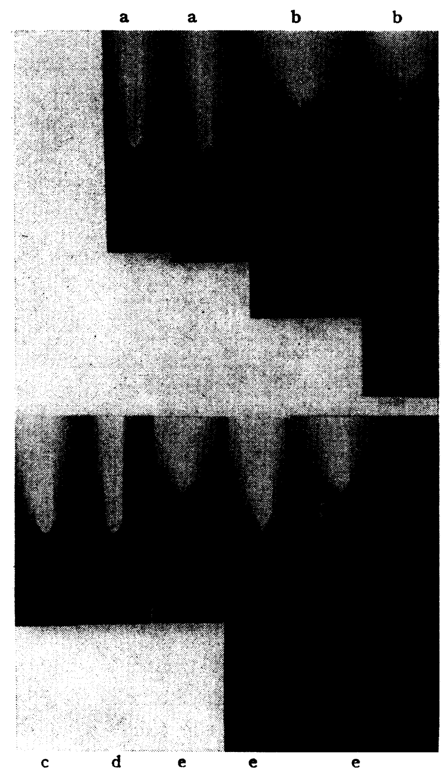


FIG. 7. Flash photographs of positive drop point. a. Distortion of spraying point. 6700 volts. b. Spray droplets from spraying point. 6800, 7600 volts. c. Stable drop: streamers. 8600 volts. d. Stable drop: steady corona. 9300 volts. e. Droplets ejected in "drop regime." 12500 volts. (Formation of droplets may be seen.)

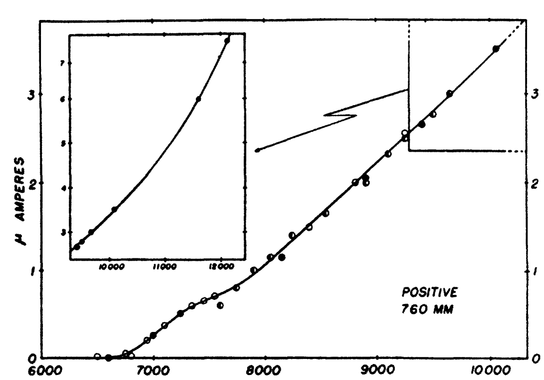


FIG. 8. Current-voltage characteristic for large positive water point. Three separate runs.

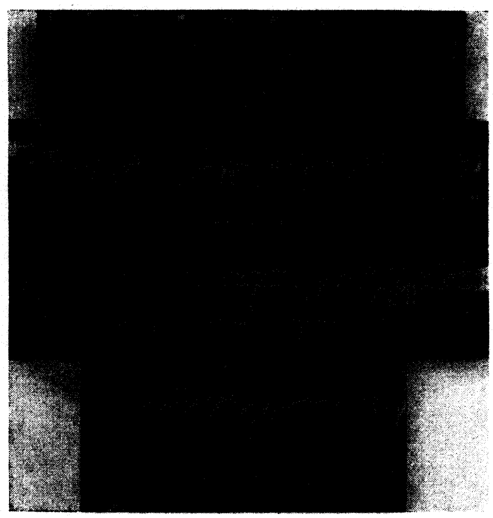


FIG. 9. (Reading from top to bottom.) Negative point spray pulses at 7350, 8100, 8100, 9000 volts. Note two types of pulse. Timing interval: 0.001 second.

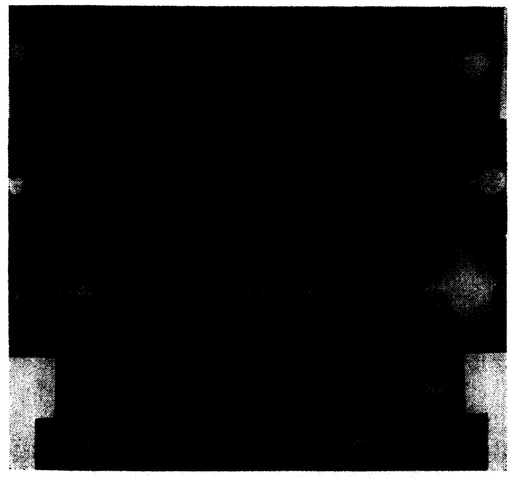


FIG. 10. (Reading from top to bottom.) Time exposure and moving film record of negative drop corona. 8100, 9100, 9100 volts. Time exposure and moving film record of corona on 1-mm diameter negative platinum point. 8750, 11900 volts.

being altogether absent. Apparently the droplets from such a point do not succeed in producing streamer breakdown in the fields available and the pulses observed are those due to the passage of charged droplets across the gap. This is confirmed by the similarity to the pulses obtained by forcing drops from the large point by raising the reservoir, at a voltage below corona onset. At 4450 volts the normal steady burst pulse corona appeared on the tip of the main drop, the space charge accumulation stabilized the point surface and, as for the larger positive point, a stable region was observed which here extended up to 9000 volts. Above this the fields are again able to disrupt the drop point. With the small drop point, however, the violent breaking observed with the large point in the drop regime was replaced by remarkable elongation of the point to almost twice its diameter and a regular snapping of small drops from its tip. In the absence of streamers and of the charging and discharging of droplets encountered with the large point, the phenomena at the small point were influenced primarily by surface tension conditions which were particularly uniform.

Negative Point

Here onset was at 4000 volts, and the behavior of the point the same as for positive. Pulses were very similar to those for positive point (Fig. 13) and became regular shortly above onset. Their frequency was not quite constant, giving a slight jitter on the synchronized trace. A faint glow, which flickered violently, was first visible at 4500 volts. It was close to the point at this and higher voltages, but ragged and intermittent.

Current-Voltage Characteristics

Current-voltage curves are given in Fig. 14 for positive and negative point. No rapid current fluctuations were evident on either polarity,

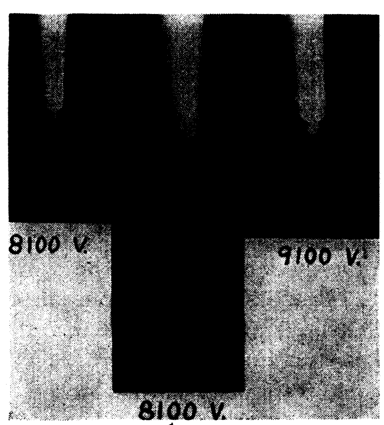


FIG. 11. a and c. Flash photographs of negative point showing corona luminosity in relation to point. Time exposure: about 10 seconds. Note the dark space. b. Spray droplets from a negative point.

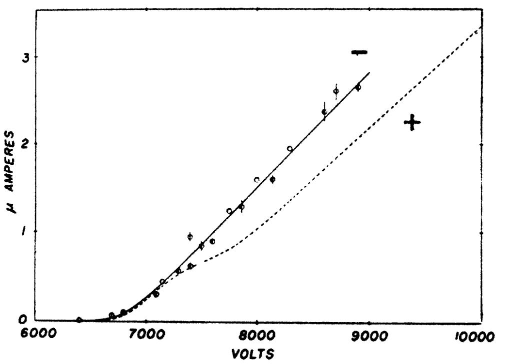


FIG. 12. Current-voltage characteristic for large negative drop point from two separate runs with positive characteristic for comparison. Vertical lines through points show *observed* variation in the current.

but there was considerable variation between readings taken some minutes apart.

There is no significant difference between these curves and those observed with the large point. In the absence of streamers and the strong drop charging and discharging mechanisms just above onset, the negative currents always lie above the positive for a given voltage because of the greater mobility of the negative space charge. The less conspicuous Ohm's law region may be ascribed to the normally narrow Ohm's law range for a smaller point, and also to the fact that space charges are less effective since a considerable part of the current is carried by charged droplets.

Intermittent Regime Onsets at Reduced Pressure

Comparison of Positive and Negative Onsets

The arrangement of Fig. 1a was used, with a capillary of 0.13-cm o.d. and a 4.2-cm gap.

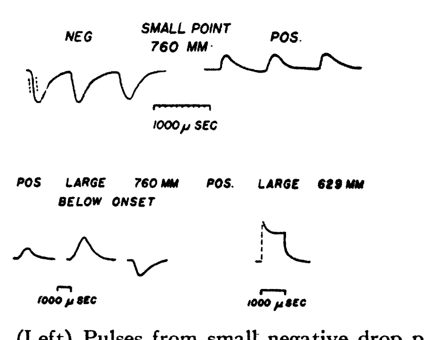


FIG. 13. (Left) Pulses from small negative drop point. Electrostatic pulses from large positive drop point below corona onset. (Right) Pulses from small positive drop point. Pulses from large positive drop point at slightly below atmospheric pressure.

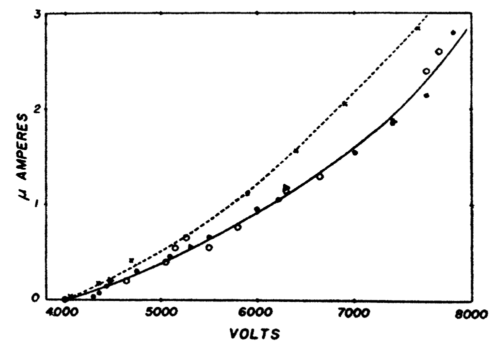


FIG. 14. Current-voltage characteristics for small drop point at atmospheric pressure. Dotted curve, negative; full curve, positive.

From the first observations it was now fairly clear that the negative water point corona mechanism must differ from that for a metal point. The crucial test lay in experiments at reduced pressure. The extent of this reduction was limited by difficulties already mentioned in obtaining a protruding stable drop. After some unsuccessful attempts measurements on onset potential were obtained at pressures of 756, 629, 505, 385, 310, and 206-mm Hg, other conditions being essentially constant. Positive and negative onsets were measured alternately, an interval of three minutes required to change polarity intervening. At 385 mm four consecutive determinations, alternately positive and negative, were made so as to detect any effect due to changed point conditions. In each determination the final steady value of spray onset was recorded after the initial rise due to surface impurities. Results are given in Table I. These results furnish a confirmation of the more elegant "onset *versus* pressure" curves to follow, from which the possibility of spurious results caused by change in drop characteristics has been practically eliminated. Since both sets of observations lead to the same conclusions, the discussion of the intermittent onset potential against pressure characteristics applies equally to Table I.

Curves of intermittent onset voltage, V_g, against pressure were obtained, first for a positive and then for a negative point, by increasing the pressure slowly from 236-mm Hg, and determining onset at frequent intervals. These are given in Fig. 15. The observations for negative

TABLE I.

Pressure	Onset voltage	Nature of onset
756-mm Hg atmospheric	pos. 6450	spray
	neg. 6250	spray
629	pos. 6450	spray
	neg. 6350	spray
505	pos. 5800	corona bursts
	neg. 6100	spray
385	pos. 5400	corona bursts and streamers
	neg. 6500	spray
	pos. 5400	corona bursts and streamers
	neg. 6700	spray
310	pos. 4700	corona bursts
	neg. 6400	spray
206	pos. 3400	corona bursts
	neg. over 6000	spray

point could not be taken below 420 mm without changing the reservoir level, owing to corona from the glass corner of the capillary. The amplitude of the corona burst pulses at onset, for a positive point, increased by a factor of about four as the pressure increased from 206 mm and 505 mm. The amplitude of the streamer pulses above onset also increased. The pulses observed at spray onset were very similar to those previously described for the large point at atmospheric pressure, except for positive spray onset at 629 mm. Here no streamers appeared on the pulses (Fig. 13). It will be noted at once that at the higher pressures the disruption of the water surface by the electrostatic forces occurs at a potential *below* the normal corona onset V_0. The breakup of the surface then initiates corona, which complicates interpretation. On reduction of pressure it is seen that below 629-mm Hg positive corona onset can occur without disruption of the water point.

Below this pressure the positive drop exhibits the normal corona onset phenomena observed with a metal point, beginning at a voltage which varies linearly with pressure. On examining Fig. 15 one might at first suppose that even though a positive corona at reduced pressure started at, say, 4000 volts, the drop would become unstable when the potential increased to the dotted line at 7250 volts. This does not occur, however, because the space charge from the corona has so reduced the field that the drop remains stable well above this voltage. As the potential is raised further the point will finally be reached where the field at the water surface is sufficient despite space charge, to break it up, and then the so-called "drop regime" will occur.

The negative drop point behaves very differently as the pressure is reduced. Onset is in all cases due to breakup of the drop, and occurs at the same potential regardless of the pressure. It is clear then, that the negative water drop cannot give the negative corona associated with a metal point, for the negative metal point corona onset shows a linear dependence on pressure very similar to that for a positive metal point (or a positive water point below 629 mm). This suggests strongly, as already indicated, that a water point with very low secondary electron emission cannot give normal negative corona.

DISCUSSION

It now remains to explain the peculiar luminosity, noted by Macky and in the present experiments, at a negative drop point. L. B. Loeb suggested the mechanism which appears to give the correct interpretation. It is that the light emission from the negative drop point is due to positive corona from the induced positively charged tips of receding droplets in the high electrostatic field near the point. In fact, when this suggestion was made it at once drew attention to the probability that, with both positive and negative drop points, the droplets would give the type of corona discharge observed by Macky in the high field region near the point. This materially aided in the interpretation of the oscilloscope pulses and other effects observed. The correctness of this point of view is borne out by considerations which follow. An appreciation of the nature and mechanism of the normal metal point corona will be necessary for the discussion. This has been indicated briefly in a previous paper,[3] and a full and authoritative treatment will be found in a forthcoming article by Loeb.[4]

Calculations made by Macky and Zeleny as well as by the writer indicate that with increasing field intensity the point becomes unstable with regard to conflict between the electrostatic and

[4] L. B. Loeb, J. App. Phys. (to be published).

surface tension forces at about the potential observed for onset.

The onset of discharge at atmospheric pressure must then be ascribed to a disruption of the water surface resulting in the fine spray observed. This potential is the same for positive and negative points and is not directly connected with any corona threshold for a point of this size. However, once the point begins to break up the intense electrostatic field, in conformity with Macky's observations, will result in electrical discharge from the spray droplets.

Let us regard the system of the large positive water drop point being drawn out by the field and emitting a succession of minute, positively charged droplets. The potential is sufficient to give streamers from the electrostatically deformed and breaking point. The droplet finds itself in a field in excess of 8000 volts per centimeter in the neighborhood of the positive point. In consequence, the droplet will be strongly polarized as shown by Macky, its own positive end will be drawn out to a point, and may give streamers if the field is sufficiently high.

We can envisage droplets leaving the corona point and experiencing one of several histories, depending on droplet size and field conditions. As the droplet leaves a positive streamer from the point gives it a high positive charge. In receding from the point with a velocity slow compared to the positive ions, it will from these receive an increase in positive charge. Macky has remarked on the ease with which a falling drop could receive a large charge in passing through the corona from a previous drop which had collected on one of the electrodes. If the charge which it receives and the field in which it finds itself are not adequate to discharge the drop, i.e., to give secondary streamers from its lower positive tip, a pulse will be observed as in Fig. 3a(i) in which the spike is produced by the primary streamer charging the droplet and the subsequent rise is caused by collection of positive ions. The exponential tail is instrumental. In cases where the drop is of such a size and shape and in such a field as to give a few secondary streamers from its lower positive end, one will observe the kind of pulse shown in Fig. 3a(ii). Where the droplet finds itself in a high field and is large enough and has enough charge to produce a powerful streamer tip at its lower positive end, it may materially discharge—giving pulses of the type shown in Fig. 3a(iii).

As the potential on the point is increased (at 7500 volts in our representative case) we reach the stable regime which appears when positive streamers and burst pulse corona are generating a substantial positive space charge. With metal points this region is characterized by the suppression of streamers by space charge and the appearance of the burst pulse corona as the sole manifestation at the point. In fact, it was this disappearance of pre-onset streamers which called forth an assumption of the building out of a positive space charge which lowered the field about the point to a value where streamers could no longer form. It is to be expected that the appearance of such a space charge would reduce the field at the surface of the drop below the value for disruption. The reappearance of the stable surface thus beautifully substantiates this hypothesis of space charge distortion. It may be noted that Zeleny, without knowledge of the space charge formations, correctly ascribed the reappearance of the stable drop to an increased *IR* drop in the gap.

With the disappearance of streamers the ordinary burst pulse corona with characteristic surface glow occurs, increasing in area over the

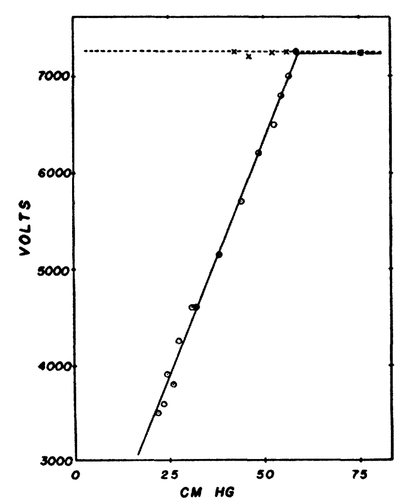


FIG. 15. Onset potential, V_g, *vs.* pressure curves. Full line: positive drop point; dotted line: negative drop point. ⊙ positive corona onset, point stable. + positive corona onset, point disrupted. × negative corona onset, point disrupted.

point surface. In this region, as with a metal point, space charge limitation of the current leads to a linear increase of I with V, the Ohm's law regime of Kip.[5] The symmetry and smoothness of a water point lead to an exceptional development of this region (Fig. 8).

On further increasing the potential (at 10,500 volts in our example) the field distortion from space charge is sufficiently compensated by the increased potential, and the water surface is again disrupted with intermittent streamers and strong burst pulse corona. This regime is characterized by a transition from the linear Ohm's law relationship to an up-curving $I-V$ plot and by considerable fluctuation in the current (as would be expected from the violent disruption of the point).

With the large *negative* drop point the pulses observed were of two types (Fig. 9). The first closely resembled the Trichel pulses from a metal point, but the second implied a steady negative corona for about a thousand microseconds, something which has never been observed with a metal point. This second type of pulse is nicely explained by assuming that it represents positive burst pulse corona from the positive end of a droplet, while the many-peaked type of pulse would correspond to a series of streamers from the same positive droplet tip to the negative point, under slightly different field conditions. The pulses are different from those produced by a positive point under comparable conditions of spraying, because the negative point droplet is incapable of discharging from its lower end.

The pulses from a small water point where no streamers occur are almost identical for positive and negative polarity. This would be expected if the primary mechanism were the result of droplet formation with rather feeble burst pulse corona.

The luminosity observed with the large negative point would occur wherever the water surface was disrupted, and would be separated from the point by the distance necessary for droplet formation and development of the streamer or glow. Such a mechanism, dependent almost entirely on the surface tension forces governing drop break-up, would produce a dark space and luminosity very different from the typical glow-discharge-like negative metal point corona, and whose shape and extent was not materially affected by pressure change. A dark space can be seen on photographs of the negative drop point discharge at atmospheric pressure, but it was not observed to increase with decreasing pressure, an effect which is very marked with a metal point, either visually or photographically. (This evidence is not conclusive, as the writer had not at that time seen the effect with a metal point, and it was not specifically looked for with the water point; but careful visual observations were made at all pressures used and it should certainly have been noticed if present.) Further, there is no sign of the very characteristic "shaving brush" shaped positive column, and Faraday dark space of the negative metal point corona.

A moving film photograph of the negative drop point shows that the luminosity is intermittent, while for a positive point under the same conditions of spraying it is continuous. A comparison with photographs of a positive and negative platinum point of comparable radius suggests that this effect is not merely due to the normal fluctuations of a negative point corona. Figures 6 and 10 show typical observations.

The positive and negative current-voltage characteristics (Fig. 12) coincide in the initial stages where the mechanisms are similar. The positive current falls below the negative at the voltage where streamer pulses are starting to predominate over spray pulses, as is the case with the normal corona for metal points.

In metal point corona in most gases, especially at reduced pressures where positive streamer formation is less efficient while the production of secondary electrons by positive ion bombardment is effective, we observe a threshold for negative corona materially lower than for positive. In air, probably owing to the effect of O_2 on the work function of the point electrode, the two onsets are almost the same. For a water point in air, negative onset is at least 3000 volts *higher* than positive onset. This indicates that the secondary electron emission coefficient from a water point must be exceedingly low, and suggests that any corona from such a surface

[5] A. F. Kip, Phys. Rev. **54**, 139 (1938).

must be carefully scrutinized before being attributed to a normal negative corona process.

Corona from Non-Metallic Points

The peculiar characteristics of the negative water point have suggested a review of the effects obtained with materials of different secondary emitting properties, so as to establish a connection between secondary emission and the character of the negative corona obtained. Previous perfunctory work by Kip and others in this laboratory had shown no noticeable difference for any of the common metals or carbon in air, but a more careful study is needed. The need for such study was further indicated by a rather surprising effect which occurred with negative drop points and which hampered work at low pressures where the effect can occur at fields insufficient to pull the drop out beyond the end of the glass capillary. The phenomenon consisted of a bright brush-like corona, rather coarse and streaked, which was apparently a negative corona occurring at high fields from the glass corner of the capillary and which produced on the oscilloscope myriads of Trichel-like pulses of moderate amplitude which looked like "grass" on the screen. Some work has already been done on non-metallic points, using CuO and FeS, which has given a negative corona threshold from 700 to 900 volts below the positive. This is in conformity with the recent considerations of Loeb[4] as to the mechanisms of the two coronas. This subject is undergoing further investigation.

ACKNOWLEDGMENT

The writer wishes to express his appreciation to Professor L. B. Loeb, for suggesting the problem and particularly for his assistance in the interpretation of results.

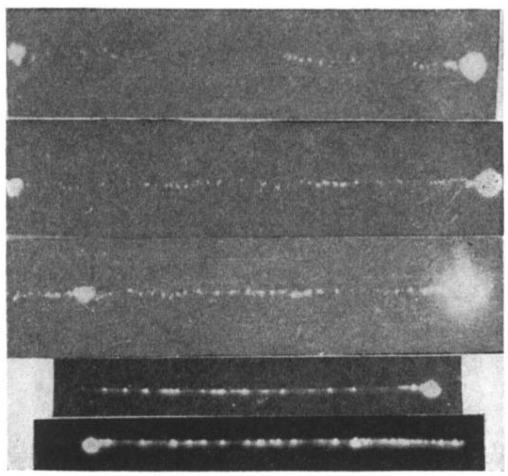
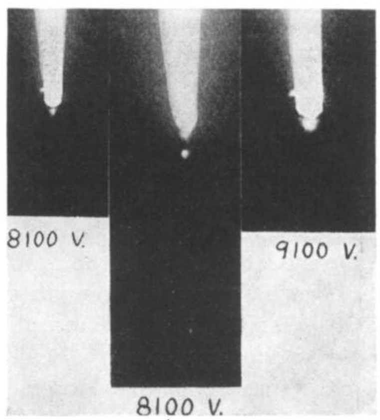


FIG. 10. (Reading from top to bottom.) Time exposure and moving film record of negative drop corona. 8100, 9100, 9100 volts. Time exposure and moving film record of corona on 1-mm diameter negative platinum point. 8750, 11900 volts.



a b c

FIG. 11. a and c. Flash photographs of negative point showing corona luminosity in relation to point. Time exposure: about 10 seconds. Note the dark space. b. Spray droplets from a negative point.

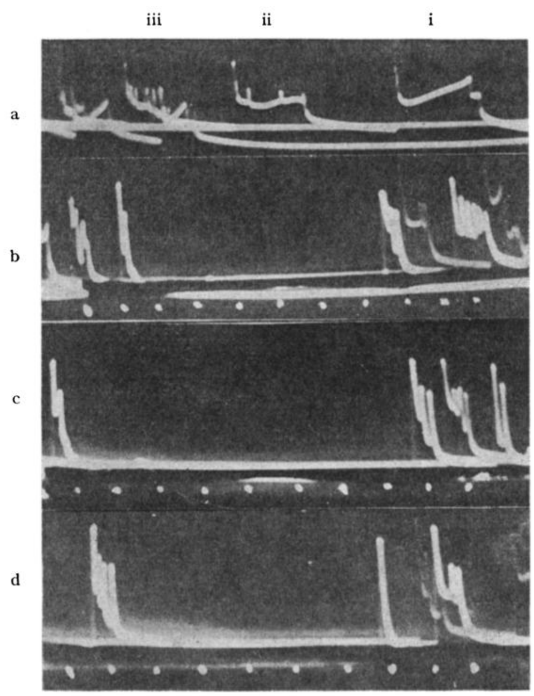


FIG. 3. Positive point spray pulses. 6800 volts. Timing interval in b, c, d is 0.001 second.

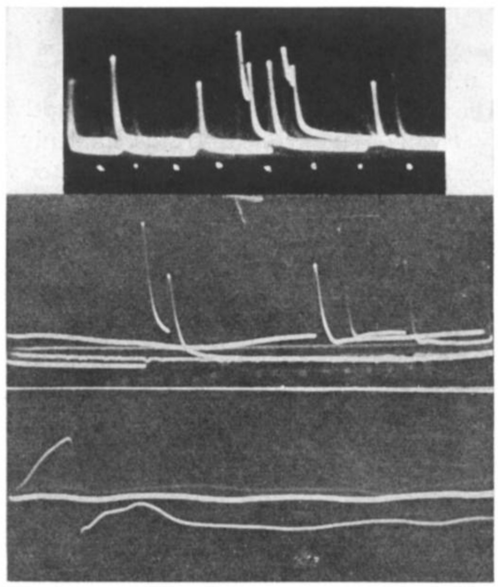


FIG. 4. (Top) Spray pulses and streamer pulses. Timing interval: 0.001 second. 6900 volts. (Center) Spray pulse, streamer pulses, and steady burst corona. Timing interval: 0.0002 second. 8000 volts. (Bottom) Electrostatic pulse due to large droplet leaving point, in "drop regime." Amplification very much less than in "spray" oscillograms. 16000 volts.

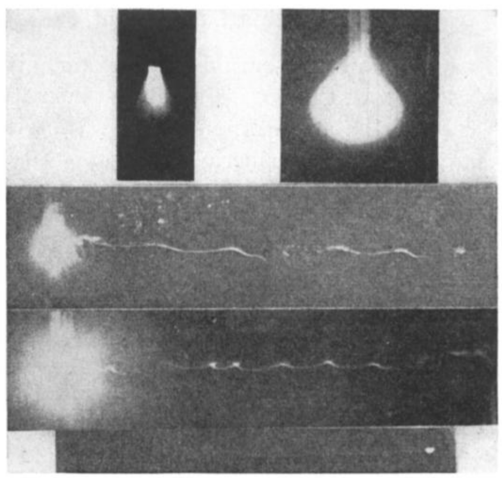


FIG. 6. (Reading from top to bottom) Dark photograph of spraying positive point. 3 min., 7300 volts. Dark photograph of stable positive point with streamers. 5 min., 8400 volts. Dark photographs of positive point in "drop regime," with moving film record obtained by winding film. 1 min. and 4 min., 13900 volts. Moving film record of 1-mm diameter positive platinum point showing steady corona. 8750 volts.

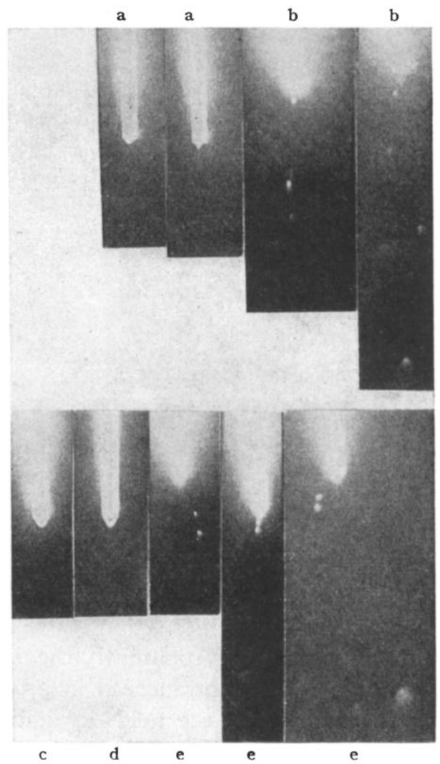


FIG. 7. Flash photographs of positive drop point. a. Distortion of spraying point. 6700 volts. b. Spray droplets from spraying point. 6800, 7600 volts. c. Stable drop: streamers. 8600 volts. d. Stable drop: steady corona. 9300 volts. e. Droplets ejected in "drop regime." 12500 volts. (Formation of droplets may be seen.)

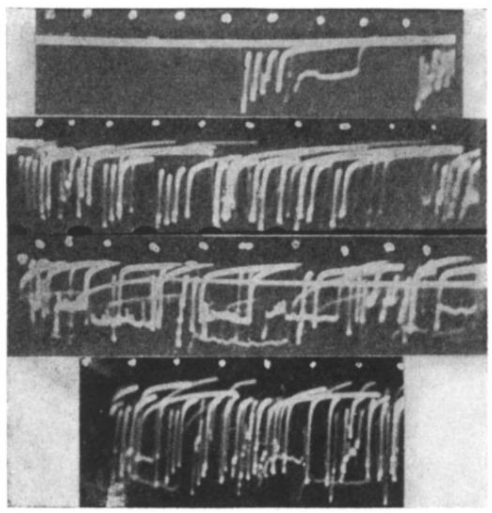


FIG. 9. (Reading from top to bottom.) Negative point spray pulses at 7350, 8100, 8100, 9000 volts. Note two types of pulse. Timing interval: 0.001 second.