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The Potential Field in and around a Gas Discharge, and Its Influence on the Discharge Mechanism

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In the first part of the paper, results on the spatial extension of cathode and anode fall regions in carbon arcs are reported. Potential-probe measurements reveal that the potential drop in front of either electrode is confined to less than one tenth of a millimeter. In the second part of the paper, the distortion of the potential field in and around any discharge, as caused by the non-uniform space charge distribution in the discharge, is discussed for the cases of a low current carbon arc and a negative point corona; for the latter case use was made of data by Loeb. The potential field distortions result in radial electric fields which, depending on their polarity, seem to hinder or support the radial expansion of the discharge. Potential-probe measurements in low and high current carbon arcs are in good agreement with this theoretical analysis and prove the transitional region between the distorted potential field in the arc and the undistorted potential field outside of the discharge to be a fairly thin one.

I. INTRODUCTION

THE potential distribution in and around any electric arc has a considerable influence on the axial as well as radial motion of electrons and ions, and thus on the arc mechanism. The same applies, to an even larger extent, to the potential drop regions immediately in front of the electrodes, i.e., the cathode and anode drops. Surprisingly little experimental evidence has been reported on the potential distribution in and around an arc, and scarcely anything is known about the spatial extension of the cathode and anode drops which determine the electric field strength in front of the electrodes.

In order to improve this situation, we have tried to explore the potential fields of carbon arcs by means of thin metal probes which were covered up to their tips by insulating glass (Fig. 1). These probes were whipped through or shot into the arc, while the potential they picked up in the plasma was recorded by a Hathaway oscillograph. Simultaneously, the position of the probe's tip with respect to some reference point (e.g., the anode surface), as well as the arc current and the arc voltage, were recorded by the same instrument.

One part of our results, published recently,[1] concerns the potential gradient in the high current arc stream and the plasma properties derived from it. In the present paper, results pertaining to two further problems, the spatial extension of the cathode and anode drop regions and the potential fields around the arcs, are presented. For the major part of this investigation, a pure carbon, low current arc was used, in order to permit a sufficiently slow probe motion without the danger of damaging probe tips or insulation. Supplementing experiments with high current carbon arcs, however, proved that all of our results described subsequently apply to the high current arc as well as to the low current arc.

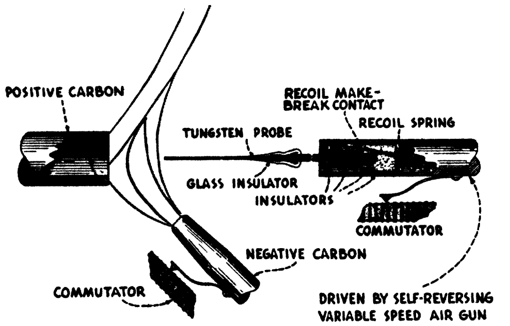

FIG. 1. Probe arrangement for measuring the spatial extension of the anode fall region.

II. THE THICKNESSES OF THE CATHODE AND ANODE DROP REGIONS

In order to measure the spatial extension of the anode and cathode drop regions, the probe, guided by a machined groove, was moved by hand or an air-gun mechanism until it contacted the anode, and was then retracted. A metal contact (Fig. 1), attached to the probe, moved with it over a commutator, and the recorded voltage pulses (trace No. 2 on Fig. 2), corresponding to an actual spacing of 0.45 mm, allowed the determination of the position of the probe and the correlation with the potential record. In a supplementary set of experiments, the negative carbon was used as a probe. It was moved by hand until it made contact with the positive carbon, and was then retracted, while the arc voltage was recorded, together with the arc current, as a function of the distance between the carbon tips. In these experiments, the position indicator (metal contact sliding over commutator of Fig. 1) was attached to the negative carbon.

In both arrangements, a sharp breakdown of the probe potential or arc voltage, respectively (trace No. 1 of Fig. 2), was observed when the probe or the negative carbon pierced a thin plasma sheath immediately in front of the anode, or anode and cathode, respectively, and a corresponding sharp potential rise when the probe broke its contact with the anode. From Fig. 2, where the vertical lines are 1/100-sec marks, it

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[1] W. Finkelnburg and S. M. Segal, Phys. Rev. **80**, 258 (1950).

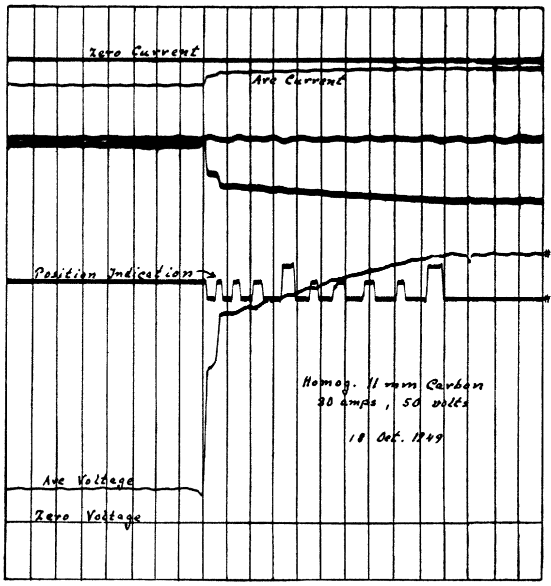

FIG. 2. Sample oscillograph record used for determining the spatial extension of the anode fall region.

is evident that, even with the slowest possible probe motion, the breakdown occurred within a time of the order of 1/1000 of a second, which, unfortunately, was the limit of resolution of our oscillograph elements. Our measurements, therefore, can give only an *upper limit* for the distance d, across which the breakdown occurred. A comparison with the position markers in Fig. 2 showed that the potential drop occurred over a distance which is small compared with that of one marker period (0.45 mm). Careful measurements on a number of records of probes of sufficiently slow motion showed that the thickness of either potential drop region was below 0.1 mm, and in at least one case, even below 0.05 mm. This result seems to be of interest; it means that the increase in temperature by nearly 3000°K from the electrode temperature of scarcely 4000°K to the arc stream temperature (approximately 6800°K for the low current arc stream in air) occurred over a distance of the order of only 10 mean free paths of the electrons.

We shall try to improve our method in order to obtain a better accuracy for this figure which is of decisive importance for any detailed theory of the cathode and anode drop.[2] Quantitative results concerning anode and cathode drop voltages will be given in a later paper for low and high current carbon arcs, after the problem of the contact potential between plasma and probe has been studied in more detail.

III. DISCUSSION OF THE POTENTIAL DISTORTION AROUND AN ARC STREAM

Little consideration seems to have been given in the literature to the distortion of the potential field around a discharge which inevitably is caused by the nonuniform space charge distribution along the axis of the discharge. Only Loeb[3] has pointed to the corresponding radial electric fields and has discussed their effects in relation to the phenomena of the negative point corona discharge.

A sketch of a conventional carbon arc, Fig. 3, may serve to explain the theoretically expected potential field around the arc. Suppose we have a potential difference of 70 volts between the electrodes of a low-current arc; assume, furthermore, a cathode drop of 10 volts and an anode drop of 30 volts. This last figure seems a little high, but we may use it for our example. Knowing, finally, from our probe measurements,[1] that the potential gradient within the arc stream decreases slowly from the cathode towards the anode, we can draw the equipotential lines in the arc stream as indicated in Fig. 3. The potential field distortion with the sharp drops in front of the electrodes is, of course, a consequence of the excess space charges in these regions and thus depends on the current density. In Fig. 3, the potential across the arc stream is assumed to be constant. This is probably not quite true, but is of secondary importance for the present discussion. Far outside of the arc, there is no reason for any distortion of the potential field. Here, therefore, we must have the normal constant distance between consecutive equipotential surfaces.

It follows that in the outer boundary region of the arc stream we must have a transition from the unperturbed potential field, outside of the arc, to that within the arc stream. For theoretical reasons, we believe this boundary region to be rather thin. The temperature decreases fairly rapidly with increasing distance from the apparent arc stream surface. The electric conductivity, moreover, depends exponentially on the temperature and thus decreases even faster with increasing distance from the arc surface. The arc

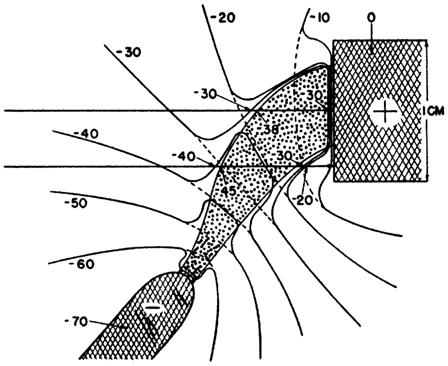

FIG. 3. Schematic sketch of the potential distribution in and around a carbon arc. The arrows indicate the directions of the probes piercing through the arc in anode drop measurements.

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[2] W. Finkelnburg, *Hochstromkohlebogen* (Springer-Verlag 1948), p. 172 f. W. Finkelnburg, J. Appl. Phys. **20**, 468 (1949).

[3] L. B. Loeb, J. Appl. Phys. **19**, 882 (1948). The senior author is indebted to Dr. Loeb for directing his attention to this work, after the present paper had been presented at the Gaseous Electronics Conference in New York City on October 20, 1950.

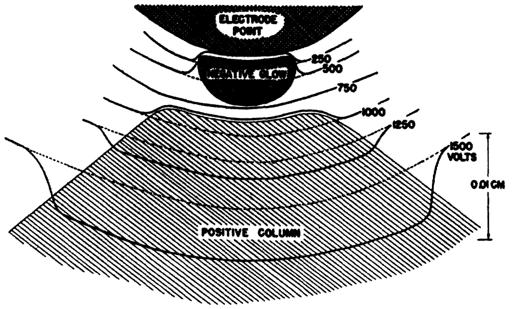


FIG. 4. Schematic sketch of the potential distribution in and around a negative point cornea discharge, based on data by L. B. Loeb.

stream, consequently, is a region of high electric conductivity with a fairly well defined outer boundary. It will be shown in a forthcoming theoretical paper that for such a conductor the surrounding potential field is approximately that indicated in Fig. 3.

Loeb, in his aforementioned paper,[3] had arrived at very similar conclusions, without using the concept of equipotential surfaces, for the entirely different corona discharge. By quantitative considerations about the potential distortions along the discharge axis, to be expected as a consequence of the space charges produced by ionization, and by comparing them with the undisturbed potential, Loeb drew conclusions to the necessary existence of radial electric fields. He further explained the radial contraction of his discharge near the negative point, and its radial expansion farther away from it, as a consequence of these fields. We have used Loeb's data (Figs. 4 and 7 of his paper) to draw a picture (Fig. 4) of the potential distortion in the essential region of a negative point corona. The similarity of Figs. 3 and 4 is striking in spite of the fact that we are dealing with entirely different discharges and different orders of magnitude in linear dimensions and potential gradients.

As potential field distortions of this kind are to be expected near the electrodes of *all* discharges, direct evidence for the correctness of a distortion like that of Fig. 3 and for the thickness of the transitional regions seems of considerable interest.

IV. EVIDENCE FROM POTENTIAL-PROBE MEASUREMENTS FOR THE FIELD DISTORTION AROUND AN ARC

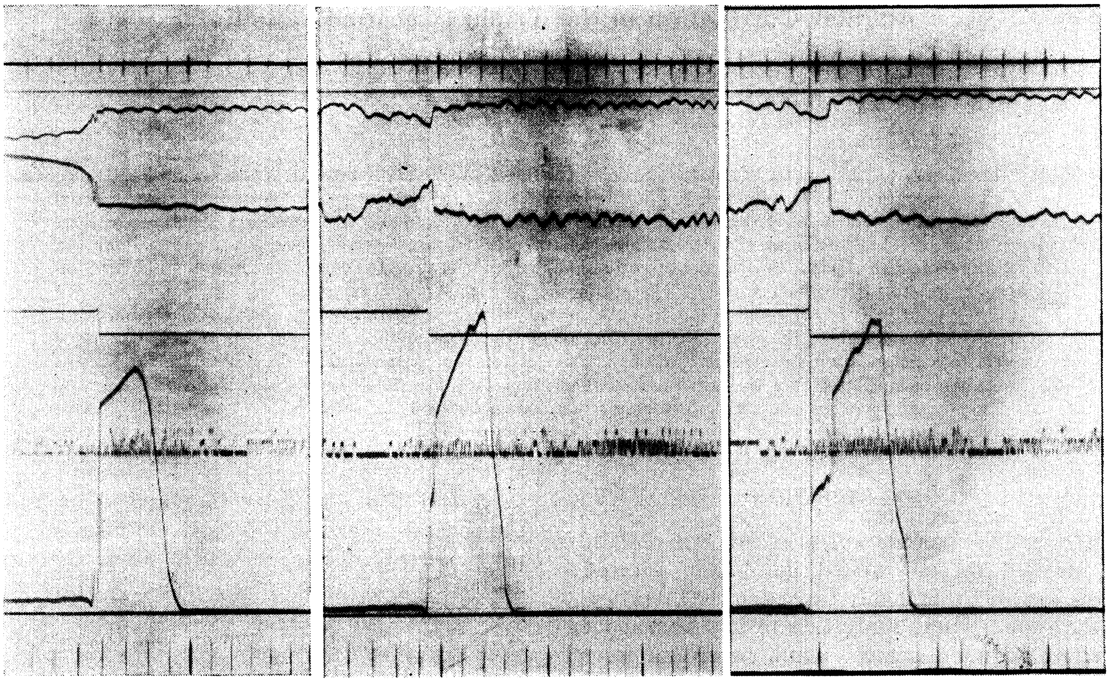
We believe that our probe measurements furnish fairly direct experimental evidence for potential distortions of the kind discussed. To prove this, we compare a number of representative records, of the low current carbon arc, which appeared very surprising at first, with what we expect theoretically from Fig. 3.

Consider first the probe being shot into the arc along the path indicated by the upper arrow. The probe, of course, cannot pick up any potential before it reaches the conducting plasma of the boundary region around the arc stream. The potential here will be, in our assumed example, about 30 volts negative with respect to the anode. It should increase to approximately 38 volts when the probe reaches the arc stream proper, then decrease slowly while the probe proceeds through the arc stream towards the anode, and finally drop sharply to zero when the probe makes contact with the anode—this last potential drop representing the anode drop. This is exactly what is observed (Fig. 5(a)) when the probe hits the center of the anode spot.

However, if the probe happens to reach the outer region around the anode spot, i.e., if it proceeds along the lower arrow in Fig. 3, the probe potential record should look quite different. When reaching the conducting boundary region, the probe should pick up a potential of approximately 40 volts negative with respect to the anode. This potential should increase to 45 volts when the probe reaches the arc stream proper and then exhibit a slow decrease to 35 volts reached at the point where the probe leaves the arc stream. Then the probe proceeds through a region, in our assumed example, where the potential drops suddenly by about 15 volts. In the last few millimeters, before reaching the anode, there should be a second slow decrease and then a final sharp drop of the potential of the order of 10 volts. In this region the conductivity should stem from the high temperature in the neighborhood of the hot anode surface. We may regard the last 10-volt drop as the anode drop corresponding to the small current density in this outer region of the arc; this requires, according to our ideas of the anode drop,[2] a much smaller production of positive ions and thus a smaller anode drop than the arc proper.

This expected probe potential record again agrees well, in all details, with the observed records, such as Fig. 5(c). If the probe hits the anode somewhat closer to the actual anode spot, the spatial distance, in millimeters, between the two sharp potential drops, decreases, as may be seen, for instance, in Fig. 5(b). If, on the other hand, the probe hits somewhat lower, in a regions where the closest equipotential surface begins to move away from the anode surface, this last drop, on our records, becomes much less sharp. To summarize: Depending on the direction of the probe's path with respect to the anode spot, we expect and find a variety of probe potential records which all agree excellently with the theoretical picture presented here. From the steepness of the first potential drop in Figs. 5(b) and 5(c), which was attributed to the potential drop in the boundary region around the arc stream, we conclude that this boundary region is very thin indeed.

There is further evidence for the correctness of our interpretation. By shooting probes through the arc stream, in a direction perpendicular to its axis, and near either the cathode or anode, we find in low current arcs as well as in high current carbon arcs radial changes of the probe potential which agree well with our theoretical picture. Furthermore, simultaneous records of the arc voltage and arc current allow us to determine



(a) (b) (c)

FIG. 5. Oscillograph records of potential probes piercing a carbon arc. (a) Record of probe shot into the arc along the path indicated by the upper arrow in Fig. 3. (b) Record of probe shot into the arc along a path intermediate between the two arrows indicated in Fig. 3. (c) Record of probe shot into the arc along the path indicated by the lower arrow in Fig. 3.

the perturbation of the arc by the probe, and to correlate the probe's position with the occurrence of the perturbation. If the probe follows the upper arrow in Fig. 3, Fig. 5(a) clearly shows a sharp perturbation of the arc at the moment when the probe hits the anode surface, this point being indicated by the step in the third curve from the top in Fig. 5. This perturbation seems to be caused by the fact that the probe here disturbs the anode drop region which is so essential for the production of the positive discharge ions. If, on the other hand, the probe follows the lower arrow in Fig. 3, there is no disturbance of the arc when the probe hits the anode surface, because this outer region of the anode is not essential for the discharge mechanism. Surprisingly, however, in the latter case a strong disturbance of the arc is observed when the probe pierces the sharp potential boundary layer (of Figs. 5(b) and 5(c)), thus apparently upsetting the well-balanced potential and temperature fields in this important region close to the anode.

V. SUMMARY

It is generally known that in all high pressure arc discharges sharp potential drops occur close to the electrodes, called the cathode and anode drops. Our potential probe measurements indicate that these are confined to plasma sheaths of less than 0.1 mm extension, i.e., to distances from the electrode surfaces of the order of only 10 mean free paths of the electrons. We believe to have shown, furthermore, that fairly sharp potential drops exist also in the outer boundary region around an arc stream, at least near the electrodes. These distortions of the potential field should be the more pronounced, the larger the cathode and anode drop voltages are compared with the undistorted potential gradients, and the larger the conductivity of the discharge plasma is. As a result of this potential distortion, the discharge regions close to the electrodes are surrounded by a fairly thin plasma sheath in which a large radial electric field strength exists. Near the cathode, this radial field drives the electrons back toward the axis of the arc stream, and thus changes the normal mechanism of the ambipolar diffusion of the charge carriers, thereby obviously restricting the discharge to a smaller diameter. Near the anode, conversely, the radial electric field attracts the mobile electrons, influences the ambipolar diffusion in the reverse direction and favors a radial expansion of the discharge. These radial fields, to our knowledge, have not been taken into account in all hitherto published theories of arc streams, but we believe they should not be neglected.

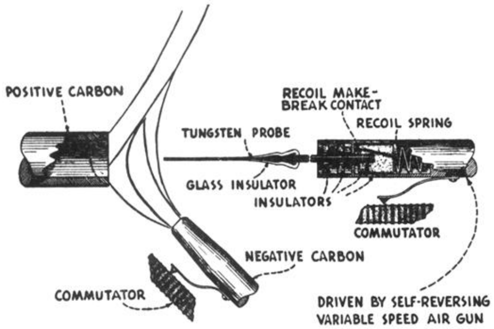
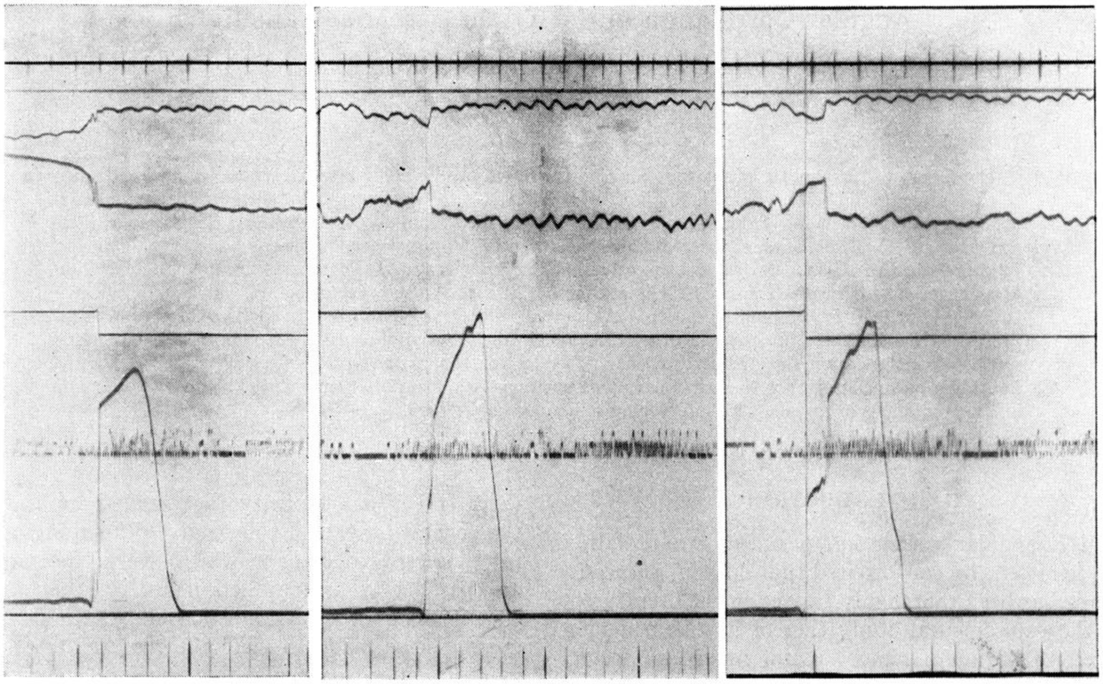


FIG. 1. Probe arrangement for measuring the spatial extension of the anode fall region.



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