outside a closed shell, the alkali metals, and those with an almost completed shell, the halogens, is not surprising. The fields of both of these groups of elements must spread out much farther than those of any of the other elements. The ratio of the energies at which the high maxima occur in K and in Cl_2 corresponds roughly to the ratio of their ionization potentials. Here, however, any conclusion is difficult inasmuch as the process in Cl_2 is much more complicated than in K.

Even at very low velocities one would hardly expect to check with the theory of elastic scattering for here the probability of capture to form a negative ion would be large. The remainder of the cross section curve must be accounted for by a number of probable events: dissociation (the energy required being but 2.47 V) with the formation of negative ions, ionization, excitation, and excitation of vibration and rotation. It would be interesting to explain by a direct calculation these high and unexplained peaks in the Na, K, Cs, Rb and Cl_2 curves. These involved calculations require approximate wave functions, which at present are not available.

Comparison of the cross section curves of H_2, HCl, and Cl_2 is interesting. H_2 has a maximum of about 60 of these atomic units at 1.5 $\sqrt{V}$, whereas Cl_2 has the value of $Q=2100$ at 2.65 $\sqrt{V}$. HCl, on the other hand, has a peak at 3.5 $\sqrt{V}$ of some 80 sq. atomic units. This comparison only lends weight to the previous conclusion of Brüche[3] that the cross section is determined by the nature of the external shell of electrons; HCl being very like argon.

The author is indebted to Professor E. S. Lamar and to Doctors R. P. Johnson and P. T. Smith for teaching him the technique of experiment. Professor W. B. Nottingham and Dr. E. B. Jordan have kindly supplied the author with clues to the overcoming of several difficulties.

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Probe Measurements on High Pressure Arcs

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The introduction of a probe in a carbon arc in air at atmospheric pressure has been found to increase the arc voltage by several volts, the increase being almost independent of the velocity with which the probe is moved, but being a function of probe perimeter. Observation showed that the probe was surrounded by a dark space, with a fairly definite boundary several times the diameter of the probe, which was uninfluenced by the potential applied to the probe. The gas temperature fell from several thousand degrees at the outer boundary of the dark space to a few hundred degrees at the probe surface. The rate of flow of energy to the probe was measured to be about 50 watts per cm length of probe, for a 0.03 cm diameter probe at the center of a 6-amp. arc; calculations show about half the energy was carried by thermal conduction across the dark space, and about half came from recombination of dissociated molecules upon the probe surface.

The interpretation of the probe current voltage characteristic, valid at low pressures, does not apply at high pressures because ions reaching the probe must travel from the arc through the dark space. An insulated probe must have a potential several volts negative with respect to the cathode side of the dark space boundary; from this interpretation, the cathode fall of the arc lies above 10 volts, and the anode fall is about 20 volts. In a 6-amp. arc, the current density in the positive column is about 20 amp. per cm^2; the gradient, 33 volts per cm; and the ion density, above 10^{14}.

KNOWLEDGE of low pressure gas discharges has been greatly advanced by numerous investigations in the dozen years since Langmuir showed how the current voltage characteristics of probes could be made to yield information about the distribution of potential, ion density, and electron temperature in such discharges. In attempting to apply the Langmuir probe methods, however, to the study of high pressure positive columns (pressure of a few millimeters or greater) one encounters experimental difficulties at once: the melting of the probe used, or the attainment of a temperature sufficient for thermionic emission. Nottingham overcame these by moving a probe through the arc at a speed so great that the probe never attained a high temperature. Meas-

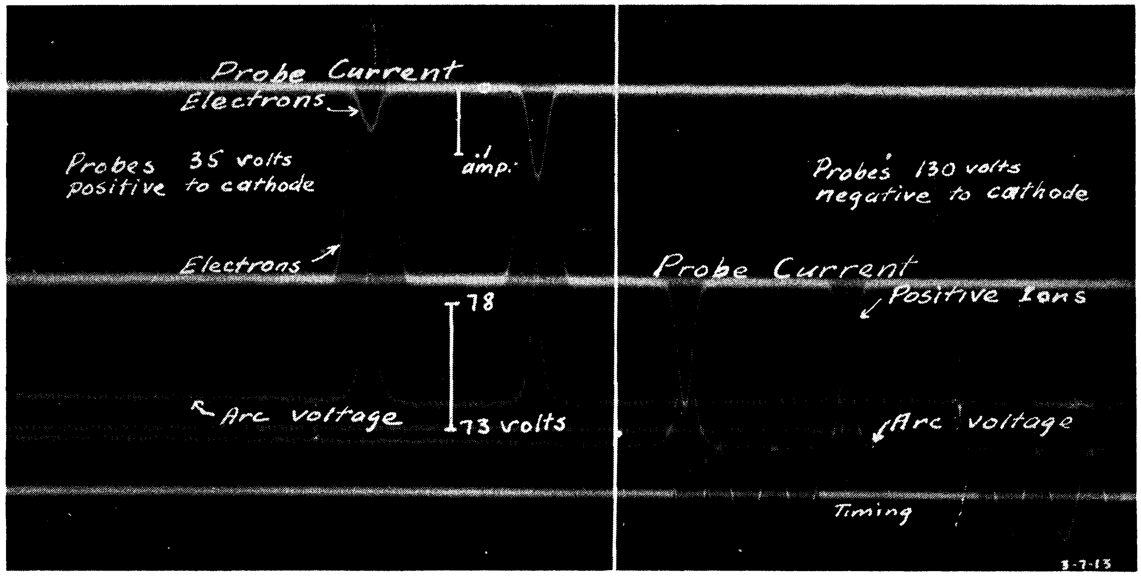

FIG. 1. Passage of two 0.025 cm diameter probes through 6-amp. arc.

uring the charge collected by the probe for different voltages, he applied the usual Langmuir theory, and from his results believed he had obtained the electron temperature and the potential distribution in a number of arcs at atmospheric pressure.[1] Following Nottingham, Bramhall[2] and Myer[3] used essentially the same methods in studying other arcs, obtaining results not always in agreement.

Experiments with a moving probe in a carbon arc at atmospheric pressure, in which an oscillograph was used to record currents and voltages, revealed a large change in arc voltage when the probe passed through the arc.[4] Since so great a change must have been due to a profound disturbance of the arc by the probe, which might vitiate the usual interpretation placed upon the probe characteristics, extensive experiments have been undertaken to find the cause of the disturbance, and to determine its effect upon probe measurements at high pressures.

This paper, in reporting the results of these experiments, first describes the effect of probes of different geometries and speeds. Photographs, made with a special design of probe, show the probe to be surrounded by a large dark space. Primarily, the origin of the disturbance seems to lie in the cooling of the arc by the probe. Next, this idea is advanced further by actual measurements of the energy received by a probe in the arc. Rough calculations show that about half this energy is conveyed by thermal conduction; the remainder must come from the recombination of dissociated molecules on the probe surface.

With the nature of the disturbing effect of the probe in mind, the difficulties of interpretation of the probe current voltage characteristic, and the contrast with the low pressure case, are discussed fully. It is shown that the presence of the dark space around the probe makes an exact description of the motion of ions to the probe almost impossible, but a qualitative explanation of the

TABLE I.

PROBE SECTION	MAXIMUM INCREASE IN ARC VOLTAGE
0.01×0.046 cm	
Broad side parallel to arc axis	8.25
Broad side perpendicular to arc axis	8.24
0.02×0.09 cm	
Broad side parallel to arc axis	10.57
Broad side perpendicular to arc axis	10.64
0.0056×0.092 cm	
Broad side parallel to arc axis	9.17
Broad side perpendicular to arc axis	9.39

[1] Nottingham, J. Frank. Inst. **206**, 43 (1928); **207**, 299 (1929).
[2] Bramhall, Proc. Camb. Phil. Soc. **27**, 421 (1931); Phil. Mag. **13**, 682 (1932).
[3] Myer, Zeits. f. Physik **87**, 1 (1933).
[4] Mason, Phys. Rev. **40**, 1045 (1932).

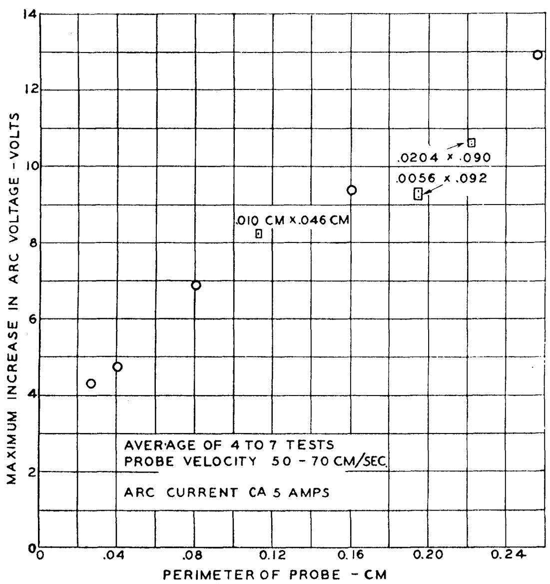

FIG. 2. Increase in arc voltage caused by probe swinging through arc.

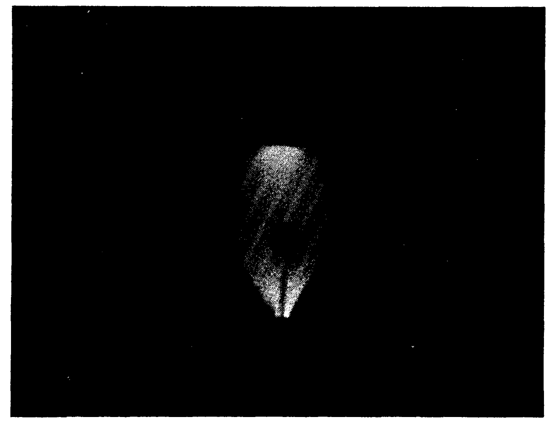

FIG. 3. Photograph of 6-amp., 0.89 cm long, arc with 0.025 cm probe wire 0.38 cm from cathode (lower) electrode.

nature of the probe characteristic is developed from the form of the potential and ion distributions which must set up about the probe. In this way, a rough idea of the potential distribution in the arc is secured, but no information about the electron temperature results. Finally, a critique of earlier investigations with probes at high pressures is given, and general conclusions about the use of probes are drawn.

I. Disturbance Caused by a Probe

Effect on arc voltage

In these investigations electrodes, 13 mm in diameter, of Siemens "E Homogenkohle E" brand carbon,[5] were mounted so that the arc axis was vertical, with the cathode below. A fine copper probe wire, on a long radius arm revolved in a plane perpendicular to the arc axis. On one of the probe passages through the arc, an oscillographic record of currents and voltages was made. A typical oscillogram is shown in Fig. 1, upon which are recorded two separate exposures, the first being represented in the part to the right of the vertical line, and the second in the part to the left. Two 0.025 cm diameter probes followed one another in rapid succession, through a 6-amp. arc 0.89 cm long. The first probe, reading from left to right, was 0.38 cm from the cathode and the second, 0.13 cm from the cathode. The upper trace in the left picture shows the electron current collected by the probes when they were about 35 volts positive with respect to the cathode. The next trace gives the probe current on a much larger scale, obtained by a vacuum tube amplifying circuit. In the left half of the figure, the saturation of one tube for large probe currents resulted in a constant deflection during most of the probe passage. When the probes were 130 volts negative with respect to the cathode, in the right half of the figure, the positive ion current collected is given, on an arbitrary scale. The third trace shows the arc voltage, and the bottom trace records the closing of timing contacts on the probe arm from which the probe velocity can be obtained. The arc length and arc voltage were slightly greater on the second exposure. It will be noted that the arc voltage increased as the probe moved into the arc, and the maximum increase, when the probe was in the center, amounted to about 6 volts. In addition, the increase in arc voltage was the same when the probes were negative as when they were positive.

One cause of the increase in arc voltage which suggested itself was mixing in of cold gas carried along by the rapid motion of the probe. In order to test this point, the probe velocity was varied between wide limits, and probes of different sizes and shapes were used. No consistent effect of

[5] The electrodes were kindly furnished by the Siemens Planiawerke.

probe speed was found: for 0.025 and 0.051 cm diameter probes, the maximum increase in arc voltage was about 20 percent smaller at 120 than at 10 cm per sec., while for a 0.081 cm probe, the increase was 10 percent greater at the high velocity.

Next, probes of rectangular cross section were tried, both with the broad side of the probe parallel to the arc axis, and with it perpendicular. Very nearly the same increase in arc voltage was noted in either case. The averages of several tests for different probes are tabulated in Table I. As any turbulent gas flow would be expected to be influenced by probe velocity, or in particular by the orientation of the flat, rectangular probes, it must be concluded that such effects are not responsible for the increase in arc voltage.

When the increase in arc voltage is plotted against probe perimeter as in Fig. 2, a direct correlation is seen, the voltage rise being almost directly proportional to probe perimeter. The values for round wires are indicated by circles, and the points for the rectangular probes, by rectangles. Thus it is strongly suggested that conduction of heat to the probe, or some other diffusion phenomenon, is primarily responsible for the increase in arc voltage.

In order to see distinctly any change in appearance of the arc produced by the probe, and as well to obtain current voltage characteristics more conveniently, a different type of probe was devised. A small copper wire was wound from one spool to another, passing horizontally through V grooves in maple guides mounted on a movable carriage. Then with the wire moving along its own axis at a speed sufficient to prevent melting when in the arc, the carriage could be moved so as to introduce the probe into the vertical arc. In this way, it was possible to move the probe wire very slowly through the arc, or even to hold it at any desired position in the arc. With this type of probe, which produced only a few tenths of a volt greater change in arc voltage than the revolving probe, it was observed that the arc voltage increased markedly only after the probe entered the central intense core of the arc.

Though the increase in arc voltage was virtually independent of the probe potential, very large negative potentials resulted in an additional few tenths of a volt increase. The type of supply circuit had a considerable effect on the increase of arc voltage with a revolving probe: if no inductance was included in the circuit, the increased arc voltage produced by the entrance of the probe caused a reduction in the arc current; the reduced current through the undisturbed parts of the arc required a higher arc voltage, so the measured increase in arc voltage included the effects of both factors. From the extensive data collected, it was possible to construct a volt-ampere curve for an arc with a 0.025 cm probe passing through its center, and to compare it with the characteristic of an undisturbed arc. The increase in arc voltage caused by the probe alone was larger the smaller the current, being 3.5 volts at 11 amps. and 7 volts at 3 amps.

Visual observations

When the continuous wire probe was used, it was seen that a large dark space surrounded the probe. The boundary of the dark space was quite sharp, being as definite as the outer boundary of the arc itself. The diameter of the dark space, within the accuracy with which it could be measured, was independent of the potential applied to the probe within very wide limits. In photographs, the dark region appeared exactly the same, whether the probe was over a hundred

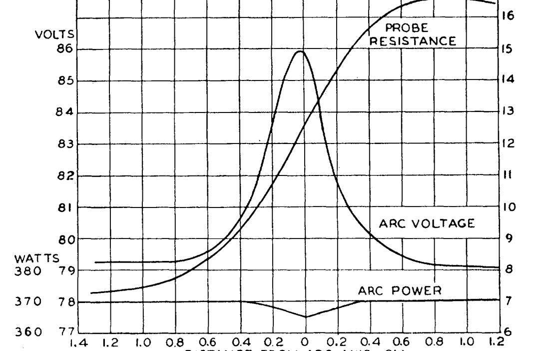

FIG. 4. Thermal probe in arc.

volts negative and collecting several milliamperes of positive ion current, or was sufficiently positive to receive several hundred milliamperes of electrons; but for very large negative voltages, above 200 say, a distinct bluish spark passed from the probe to the arc. The dark space surrounding the probe is thus nothing like the dark space at the cathode of glow discharges, or that surrounding negatively charged Langmuir probes in low pressure discharges; but because of its descriptive character, the term "dark space" will be used herein to apply to the region devoid of light which has been found about cold wires in atmospheric arcs.

A photograph of the arc and probe is shown in Fig. 3. A continuously moving 0.025 cm copper wire was held in the center of a 6-amp. arc, 0.38 cm from the cathode (lower) terminal. The lower part of the arc is hidden by the guide, the V groove in which can be seen.

From photographs, the following dark space diameters were found for a 0.025 cm diameter insulated probe at different positions in a 6-amp. arc: 0.086 cm diameter dark space at 0.13 cm from the arc cathode; 0.112 cm, at 0.25 cm; 0.128 cm, at 0.38 cm; and 0.168 cm, at 0.51 cm. Approximately the same dimensions were obtained when the dark space was measured by projecting an enlarged image on a screen, and by observing through a measuring telescope. Substantially the same results were found for currents up to 12 amps. The dark space size was independent of the velocity of the probe wire, which was usually between 20 and 50 cm per sec., and of the radial position of the probe in the arc core. Some measurements of the projected image of the dark space surrounding other sizes of probes were made, but with not as great accuracy as the above determinations. The results are: for a 0.013 cm diameter probe, a dark space 0.083 cm diameter; for a 0.051 cm probe, a dark space 0.143 cm, at 0.38 cm from the cathode.

At the center of the arc, or near the cathode, it was possible to make the continuous wire run perfectly steadily through the axis of the arc, with no motion of the arc core; but near the anode, such a position was one of unstable equilibrium, the arc moving quickly to one side or the other. Presumably, the arc behaved similarly when the revolving probe was used; so, near the anode, the relative velocity of the probe and the arc core varied widely as the probe passed through the arc, even though the probe velocity may have been constant. For other positions of the probe in the arc, the relative velocity was probably always nearly equal to the probe velocity; some nonuniformity occurred as may be seen from the slight dissymmetry in Figs. 1 and 4.

II. Heating of Probe

Experimental

As the increase in arc voltage caused by the introduction of a probe has been clearly shown to be unaffected by turbulent gas flow around the probe, but to be a function of probe perimeter, loss of energy from the arc by diffusion of particles through the dark space to the probe could explain the increased power input required. In order to test the idea quantitatively, an experiment was arranged to measure directly the heat input to a probe. Consider a revolving probe passing once through an arc. Since the arc is circular in section, different parts of the probe will be in the arc different lengths of time and will attain different temperatures. If $W(t)$ represents the power input to the probe at any time t, then the total energy input up to t, measured from $t=0$ at some time prior to the entrance of the probe into the arc, will be

$$\int_0^t W(t)dt = c\delta A \int_0^l T ds, \qquad (1)$$

where c is the specific heat; δ, the density; and A, the cross section of the probe; s is measured along the probe; and T, the temperature rise of the probe at time t, is a function of s. The integral on the right must be taken not over the length of the probe in the arc, but over the total length, as there will be conduction of heat along the probe. It is assumed, however, that there is no loss of energy *from* the wire. Likewise, the *increase* in resistance of the probe due to the change in temperature is

$$\Delta R = ((\rho_0\alpha_0)/A)\int_0^l T ds, \qquad (2)$$

where ρ_0 is the resistivity at room temperature, and α_0 its temperature coefficient. It will be more convenient later to express W as a function of x, the distance of the probe from the axis of the arc at any time t; thus, from (1) and (2), if v is the probe velocity

$$W(x) = (c\delta A^2/\rho_0\alpha_0)v(d/dx)\Delta R. \quad (3)$$

As a probe, a one-inch length of the filament from a 60-watt Mazda lamp, seasoned by several hours burning, was chosen. The filament was a coil, 0.0297 cm outside diameter, wound of 0.0046 cm tungsten wire, 145 turns per cm. The probe was placed in one arm of a wheatstone bridge, which was approximately balanced with the probe out. The unbalance in current when the probe was in the arc was obtained by an oscillograph. The cold resistance of the probe was about 8 ohms; the bridge current through it was a little over 1 ma. An oscillogram, showing the resistance of the probe, the arc voltage, and the power input to the arc is reproduced in the lower part of Fig. 4 with time translated into distance from the arc axis; the probe was midway between the electrodes. It was found that the decrease of resistance after the probe emerged from the arc was very slow, so it is proper to neglect the cooling of the probe while it is in the arc. From the slope of the resistance curve, the total power input to the probe, $W(x)$, was calculated as above.

Before any calculations can be made on heat flow, it is necessary to find the heat input per unit length of the probe. This may vary from point to point in the arc, so it would not be correct merely to divide the total power by the arc diameter. Fig. 4 gives further evidence on this point; one sees that the probe is being heated before it enters the core of the arc at about $r=0.3$; in fact almost half the total input comes from regions about the arc in which the presence of the probe causes almost no change in the arc voltage. If the power input per cm length of the probe, $H(r)$, is expressed as a function of the distance from the center of the arc, then

$$W(x) = 2\int_x^\infty H(r)\frac{rdr}{(r^2-x^2)^{\frac{1}{2}}}. \quad (4)$$

Eq. (4) is very similar to Abel's equation, so a solution for $H(r)$ may be found readily.[6]

[6] Cf. Bocher, *Integral Equations*, second edition, p. 8.

$$H(r) = -\frac{1}{\pi}\int_r^\infty W'(x)\frac{dx}{(x^2-r^2)^{\frac{1}{2}}}. \quad (5)$$

From Fig. 4, and similar curves, $W(x)$ was obtained, and Eq. (5) solved for chosen values of r by mechanical integration. In the upper part of Fig. 4, $H(r)$ is plotted for the experimental data given below it. Considerable variability was exhibited in the values of $H(r)$ obtained, as might be expected since a double graphical differentiation of an experimental curve was involved. For $r>0.3$ all tests gave about the same $H(r)$, but values of $H(0)$ between 44 and 138 watts per cm were obtained. The most reliable gave approximately 50 watts per cm for the power input at the center of the arc. Likewise the maximum total power inputs to the probe, $W(0)$ were scattered, values between 55 and 90 watts being found; probably the best figure is 55.

Effect of probe on arc energy

In Fig. 4, it will be seen that where the arc voltage increase was about 10 percent of the maximum, corresponding to a probe position just outside the central core, the power input to the probe was $\frac{1}{3}$ to $\frac{1}{2}$ the maximum. Most of the arc energy is developed within the central core and lost from it to the surrounding medium. Parts of the probe lying outside the core, though receiving a large amount of heat from the hot gas, do not cause any additional energy loss from the arc; what they receive would be lost from the core even if the probe were not present. Energy given to the portion of the probe inside the core represents an additional loss which must be made up by an increase energy input to the arc. From the curve for $H(r)$ such as Fig. 4, the total energy received by the part of the probe within the core, for a probe passing through the arc axis, was found by integrating $H(r)$ from $r=0$ to $r=$radius of the core.

With a noninductive circuit, the total power input sometimes actually decreased, as in Fig. 4, when the probe was in the arc, despite the energy abstracted by the probe, because of the large decrease in arc current resulting from the rise in arc voltage. When a heavy inductance was included in the circuit, then the measured arc power rose when the probe entered the arc. From experimental volt-ampere characteristics, it was possible always to calculate the reduction in the arc power input caused by the decrease in arc current; this added to the actual measured effect on arc power by the probe, should give the change in the rate of energy input to the arc caused by the presence of the probe. The increase in arc watts due to the presence of the probe, calculated in this way for a number of tests, agreed well with the integral of $H(r)$ over the arc core.

From the energy standpoint, then, the effect of a probe upon a high pressure arc is to produce artificially an added surface, much larger than the probe wire itself, through which energy flows from the arc. The increased losses from the arc require additional energy input, and hence a higher arc voltage, in order to maintain the arc.

Methods of conveyance of energy to probe. Radiation

Energy may be conveyed to the probe by three ways: radiation, thermal conduction, and recombination upon the probe of dissociated particles (both atoms and positive ions and electrons). The radiant energy received is probably negligible: Holm and Lotz[7] from measurements of the total radiation from the positive column of a long carbon arc with large a.c. currents flowing, give the fraction of total energy loss appearing as radiation as 5 percent at 30 amperes. Extrapolation of their curve to below 10 amp. would carry the radiation loss to zero. This factor can thus be neglected.

Thermal conduction

The appearance of the dark space around the probe suggests that the gas at the outer boundary is at the temperature of the positive column, while the temperature of the probe is always quite low. Under this assumption, the heat flow to the probe may be calculated from the conduction equation

$$k(\partial T/\partial r)2\pi r = H_K, \qquad (6)$$

where k is the thermal conductivity, T the temperature in °K at any point and H_K the energy conducted per cm per sec. Now the temperature has such wide limits it will not be correct to take k as a constant. Neglecting variation of specific heat and mean free path with temperature, simple kinetic theory makes the thermal conductivity proportional to $T^{\frac{1}{2}}$. In order to get an idea of the magnitude of the transport by thermal conduction, it will be assumed for the present $k = k_0 T^{\frac{1}{2}}$. Eq. (6) may be integrated then, with the boundary conditions that $T = T_0$ = temperature of probe for $r = r_0$ = probe radius and $T = T_R$ = temperature of arc core for $r = R$ = radius of dark space, with the result

$$H_K = (T_R^{\frac{3}{2}} - T_0^{\frac{3}{2}})((4\pi k_0)/(3 \log R/r_0)). \qquad (7)$$

The temperature rise of the tungsten coil in passing through the arc, gotten from the total change in resistance, was not over 200°; thus, roughly $T_0 = 500$°K. The temperature of the arc may be taken as 6000°K.[8] Putting in Eq. (7) these values, together with $2R = 0.13$, $2r_0 = 0.0297$, $k_0 = 1.45 \times 10^{-5}$ watt-sec. per cm^2 per degree from the value for air at room temperature, H_K comes out 18.5 watts per cm.

Since the gas in the dark space is largely atomic the value of k_0 used should be modified: the smaller specific heats of the atoms and the increased specific heat of the remaining molecules at high temperatures would have opposite effects, however. Through the Sutherland correction for variation of mean free path with temperature, k_0 should be increased. A rough estimate of the net effect of all these factors raises the energy transported by thermal conduction to 20 to 25 watts per cm at the arc axis—about one-half the total input to the probe.

Recombination

In these heating experiments the probe was insulated so that the only electrical heat input came from direct recombination of positive ions and electrons on the surface. From direct measurements, the current of positive ions, and of electrons, was less than 1 ma per cm, so the heat of recombination amounted to not over 0.015 watts—entirely negligible compared with the total of 50.

[7] Holm and Lotz, Wis. Veroff. a.d. Siemens-Konzern **13** (2), 87 (1934).

[8] The temperature of the gas in the positive column has been measured in a variety of ways in the past few years: Ornstein, Physik Zeits. **32**, 517 (1931); Ramsauer, E. u. M. **51**, 189 (1933); v. Engel and Steenbeck, Wis. Veroff. a.d. Siemens Konzern **10** (2), 155 (1931); Suits, Phys. Rev. **47**, 335 (1935). Only Ornstein had experimental conditions like those in this paper (pure carbon electrodes, 2 to 12 amp.), so his value of 6000°K has been adopted.

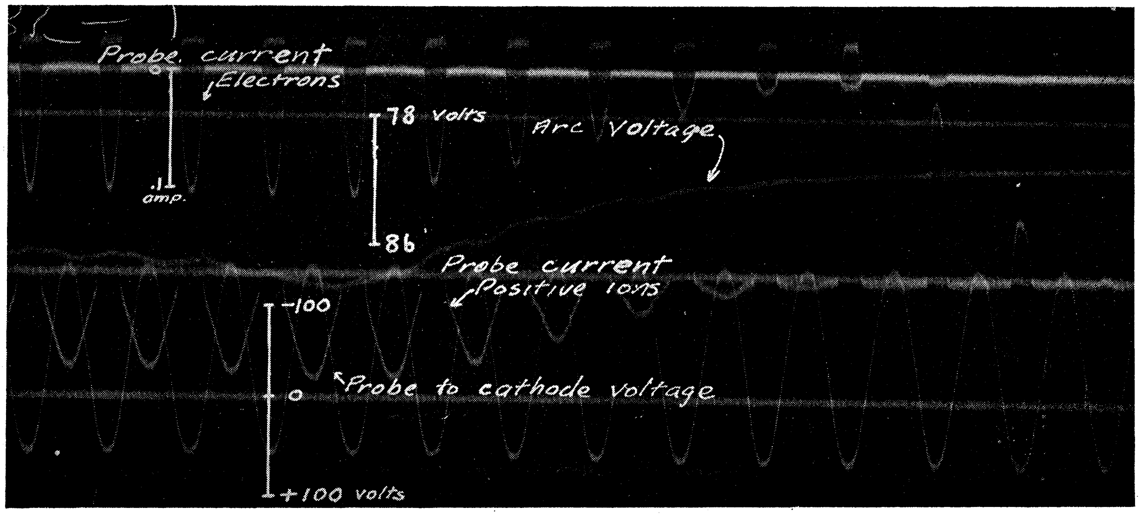

FIG. 5. Probe 0.51 cm from cathode of 6-amp., 1.14 cm long, arc. Probe moved through arc during exposure of film.

At the high temperature of the arc, complete dissociation of O_2 and about 80 percent dissociation of N_2 may be expected.[9, 10] It is likely no recombination of atoms occurs within the dark space.[11] Atoms diffuse, then, from the boundary of the dark space to the probe wire, where they recombine, giving up the heat of dissociation to the probe. From the previous rough calculations, it seems that roughly half, or a little over, of the total energy input to the probe must come from this source. A solution of the diffusion problem for the four-component gas in the dark space is impossible for the present state of diffusion theory. It is entirely plausible, however, that recombining atoms should contribute so largely to loss of energy from the arc to the probe.

Temperature distribution in the arc

From the measurement of the rate of heat flow to the probe and the assumed temperature at the arc axis of 6000°K, it is possible, with some uncertainty, to calculate the temperature distribution in the arc. If the diameter of the dark space remains constant, if the effective thermal conductivity does not change, if the ratio of the heat carried by thermal conduction to the total heat delivered to the probe is the same everywhere, then the temperature at any radius may be found, for by Eq. (7) $(T^{\frac{3}{2}}-T_0^{\frac{3}{2}})\propto H(r)$. It seems likely these conditions may be met within the arc core, where the temperature is high; it is observed that the dark space diameter is constant throughout the core. Outside the core, the temperature may be very different. Such calculations may indicate the trend of the temperature, however; and in Fig. 4, $T(r)$ found in this way is plotted. The temperature does not fall much within the dark space around the arc core.

III. PROBE CURRENT VOLTAGE CHARACTERISTICS

The effect of the probe on the arc from an energy standpoint having been considered, this section discusses the direct electrical consequences of the introduction of a probe, and the modifications which must result in the interpretation of the probe current voltage characteristic. The use of the continuous wire probe described above offered the great advantage of enabling one to measure quickly the current collected by a probe at a known position in the arc for a whole series of probe voltages. The probe potential, applied between the probe and the cathode, was derived from a d.c. battery in series with a 15-cycle a.c. generator. The magnitude of the voltages was adjusted so that during one cycle the probe current would vary from a large positive ion current to a large electron current. The currents and voltages are recorded by an oscillograph. Positive ion currents to the

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[9] Lewis and v. Elbe, J. Am. Chem. Soc. **57**, 612 (1935) and literature there cited.
[10] Mulliken, Phys. Rev. **46**, 144 (1934).
[11] Kassel, *Kinetics of Homogeneous Gas Reactions* (Chemical Catalog Co.), p. 131.

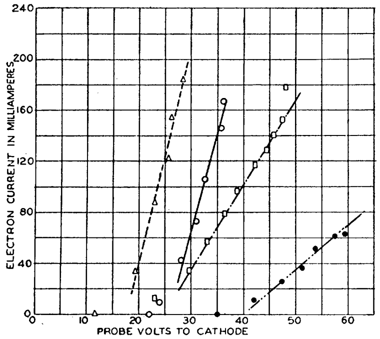

FIG. 6a. Probe current voltage characteristics. Triangle, probe 0.13 cm from cathode, arc 6 amp.; open circle, probe 0.38 cm from cathode, arc 8.7 amp.; square, probe 0.38 cm from cathode, arc 5.9 amp.; closed circle, probe 0.38 cm from cathode, arc 3.2 amp.

probe were measured by means of a two-stage vacuum tube amplifier, the saturation of one tube of which protected the oscillograph element from damage by the large electron currents. The electron currents were measured by another less sensitive element.

A typical oscillogram obtained is shown in Fig. 5. The top trace shows the probe current; when the probe was collecting positive ions, the sensitivity of the element was so low no deflection shows. The next trace gives the arc voltage, which decreased as the probe moved slowly from the center to the outside of the arc. The third trace also gives the probe current, but on an arbitrary scale, as it is actually the output current of the vacuum tube amplifier which is shown. Saturation of the amplifier resulted in a constant deflection when large electron currents were collected, but when positive ions were collected, the deflection was almost directly proportional to the positive ion current. The bottom trace gives the potential of the probe with respect to the cathode.

Current voltage records were attempted with the probe at several positions in the arc, for currents from 3 to 12 amp., and for three arc lengths. Because of the motion of the arc when the probe was introduced near the anode, described before, it was not possible to get a complete record with the probe near the arc axis for these positions. Some results are shown in Figs. 6a, b.

Theoretical difficulties at high pressures

Some of the reasons why the methods of analysis of probe current voltage characteristics applicable for low pressures break down at high pressures may be pointed out. In the first place, the potential drop over a length of the arc equal to the dark space thickness amounts to several volts; so, to speak of the "potential of the probe to space" has no meaning unless some particular point is specified. Because of the changes brought about by the probe, the potential distribution when the probe is in the arc is not at all like that in the undisturbed arc.

Within the dark space, it seems likely no ions are being produced, and none are lost except at the probe surface. Consequently, the current collected by the probe depends on the motion of the ions through the dark space from their point of origin in the arc. Changes in the probe potential, and in the absorption of ions by the probe, have a direct effect on the ion distribution throughout, and around, the dark space. In a low pressure discharge, the mean free paths of the ions are so long, the collection of ions by the probe has little effect on the discharge outside the space charge sheath around the probe.

At low pressures, it is assumed that the point of zero field marks the space charge boundary, and that all the potential applied to the probe is taken up within the space charge sheath. Practically it makes little difference exactly where the sheath boundary is located, or whether the field there is precisely zero, for it is assumed the random motion of the ions is responsible for carrying them up to and across the sheath boundary. To speak of the simple hypothetical case of a sharp boundary, with zero field, and current limited by space charge is sufficiently exact. In probe measurements at high pressures, however, where all ions which arrive at the probe must travel through the dark space, weak fields may have a large influence on the current collected. There may be *no* point

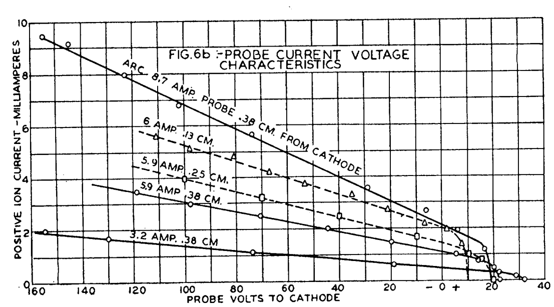

FIG. 6b.

of zero field where one may say the space charge sheath terminates. In high pressure discharges, one may still divide the region about the probe into two parts, in one of which the ions move under the influence of strong electric fields and in the other, the ions are carried by weak fields and diffusion, with the boundary between the two defined in some arbitrary fashion. The first may be termed the space charge sheath; for the calculation of the current flowing through it, it will make little difference exactly where the boundary is located or what the field there is. The second may be called the weak field or diffusion region; the field at, and the location of, the boundary will be extremely important in determining the current which flows through the dark space up to the sheath boundary. In other words, at low pressures the potential applied to the probe has no effect on the current density at the sheath boundary for it is only the random motion of the ions which bring them up to the boundary; at high pressures, the influence of the potential applied to the probe extends far beyond what one would ordinarily think of as the sheath boundary, because weak fields and diffusion carry ions up to that boundary.

For precise determination of the current, then, it would be necessary to consider the whole of the dark space, and even beyond, as one region, and calculate the motion of the ions under diffusion and electrical forces. Even the approximation of breaking the region up into a strong field, or space charge, part and a weak field part still leaves the problem too complicated for solution: cylindrical symmetry does not occur because the ion density and fields are not constant around the probe; one must use diffusion and mobility constants which are functions of position through the variation of the temperature and field. A further complication is that the dark space boundary is not an equipotential surface. Though one could set up the differential equations describing the relations between the ion density, current and probe potential, their solution would be extremely difficult if not impossible.

The contrast between the regime to which the Langmuir theory applies and the high pressure discharge will be brought out more clearly by considering the results of some orienting calculations which have been made. Under the assumption that diffusion alone governs the motion of ions through the dark space, it has been found that diffusion velocities over most of the dark space are so much smaller than the velocities of the electrons and ions under even moderate fields, such as exist in the positive column, that the effect of electrical fields are predominant. Accordingly, it is incorrect to assume that the dark space boundary is an equipotential surface; the motion of ions across the boundary and in the outer part of the dark space will, in most cases, be determined largely by the fields there. Further confirmation may be adduced from the data for large negative probe potentials, which show positive ion currents many times the calculated diffusion currents. In some cases, however, particularly when the probe receives about equal numbers of positive ions and electrons, the diffusion of electrons must be important.

If the energy received from the electric field is neglected, rough calculations show that for high electron drift velocities through the dark space, the electron temperature at the probe surface must be almost the temperature possessed outside the dark space, while for low electron velocities, virtual thermal equilibrium with the gas will always exist. If the energy received from the electric field is considered, it is much more difficult to estimate the electron temperature near the probe. An electron, starting from rest in a uniform field, traverses a distance of about 100 mean free paths in the direction of the field before acquiring 90 percent of its terminal energy —a distance equivalent roughly to the dark space thickness. Consequently, if the field varies much within the dark space, the electron temperature may lag behind considerably. The electron temperature will not necessarily be the same at all points the same distance from the probe, depending as it does both upon the field, the time spent in the dark space, and the gas temperature. The temperature of the electrons at the probe surface, or at the boundary of any region of strongly attracting forces about the probe, may be higher, or lower, than their temperature outside the dark space, depending upon the path followed by the electrons in reaching the probe. Since the electron temperature is not a constant, the Boltzmann equation has no applicability. The positive ions in the dark space may be expected to be in thermal equilibrium with the gas, except in very strong fields, or space charge regions, near the probe.

Other calculations, while not exact, are of sufficient accuracy for one to draw the following conclusions: all space charge sheaths, or strong field regions, about the probe are small in extent compared to the dimensions of the dark space. Recombination of ions within the dark space is negligible under most conditions, but the possibility exists that sometimes recombination may occur near the probe; in which case, the effect is merely to increase the probe diameter slightly.

Summarizing, the usual concepts applicable to the explanation of probe characteristics at low pressures have no force at high pressures, because the ions reaching the probe must travel through the dark space from the arc. Since their motion through the dark space is influenced by the fields present there, the effect of the change in voltage applied to the probe is not confined to a narrow space charge sheath about the probe, but is felt throughout the dark space. For the same reason, the current density at the sheath boundary is not constant but depends upon the probe voltage.

Qualitative explanation of probe characteristic

In the light of the ideas developed above, it is possible to explain the general shape of the probe characteristic. Since no ions are generated or lost within the dark space, except at the probe, there can be no potential maxima or minima within the dark space. When the probe has a large negative potential with respect to all surrounding space, it can collect only positive ions. As all electrons which reach the probe are turned back, the potential distribution within the dark space must so adjust itself that the field opposes the motion of electrons toward the probe. In Fig. 7a, the potential distribution over a section through the arc axis is shown. The drawing is not to scale, but is exaggerated in order to portray more clearly the fields. With large negative potential on the probe, there is *no* electron current to the probe; hence the field is negative all the way from the probe to the dark space boundary. As the electrons advancing from the cathode cannot halt abruptly, a negative space charge develops at the cathode side of the boundary which diverts the current around the probe. In Fig. 7b is shown the space charge distribution and lines of current flow around the probe for a negative probe potential. The space charges shown are the *net* charges and do not indicate the presence of ions of one sign alone. The gas in the dark space is cooler than in the arc, so the mobilities of the positive and negative carriers are lower there than in the arc core. Under the same field, ions move slowly in the dark space; hence there will be an accumulation of positive ions on the anode side of the dark space, and electrons on the cathode side, until most of the carriers are turned around the dark space. The space charges push away from the axis the electrons on the cathode side, and pull them together again on the anode side, and conversely for the positive ions. The resulting lines of flow are as shown. With sufficiently large potential on the probe, the field along the center line might be large enough to move the ions in to the probe as fast as they come up to the boundary, and hence prevent the development of the space charges, but apparently this condition was not attained experimentally. With a large negative voltage, the current of positive ions collected was much larger than field free diffusion would give, so

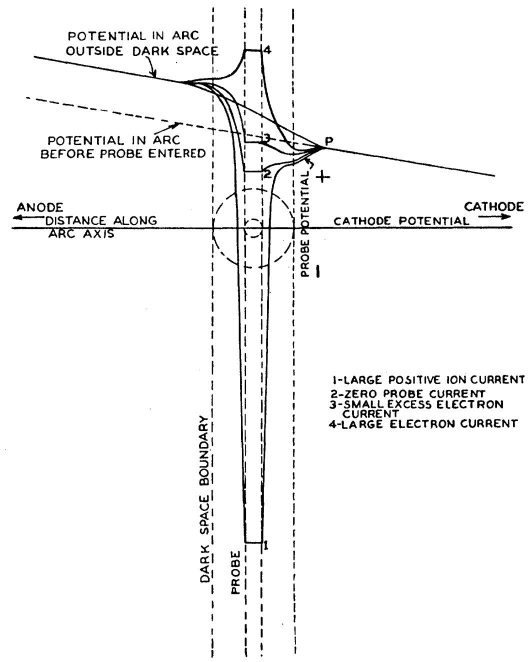

FIG. 7a. Potential distribution around probe.

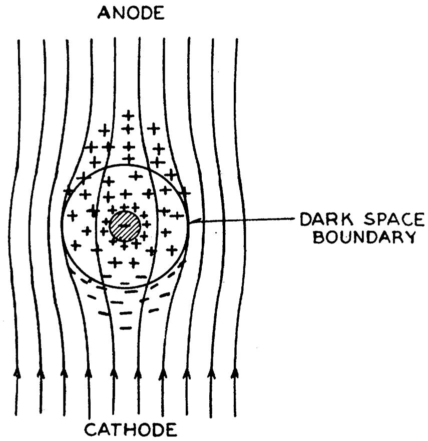

FIG. 7b. Space charges and lines of current flow around probe. Section perpendicular to probe.

actually accelerating fields must have carried positive ions to the probe from all sides.

The figure shows conditions for several probe potentials. Suppose the potential is reduced from the high negative value. Since in a space charge sheath, a reduction in voltage across the sheath causes a reduction in current, larger than the change in the sheath dimensions, a decrease in current to the probe must result. This can come about only through a change in the electric field all the way from the probe to the dark space boundary. No pronounced effect outside the boundary can occur for it is observed that changing the probe potential scarcely affects the disturbance caused by the probe.

As the probe is made more positive with respect to the cathode, finally a point is reached where the net current to the probe becomes zero; then the probe receives equal numbers of electrons and positive ions. As the electrons move so much more rapidly than the positive ions, the zero current condition will be attained when the probe receives a few electrons at the point nearest the cathode, but only positive ions over the rest of the periphery. The zero current point corresponds to a probe potential a little negative with respect to the arc at the point P. A slight negative field occurs from the probe all the way to P, but electrons are able to diffuse against this field in sufficient numbers to balance the positive ions attracted to all other sides of the probe.

For higher probe potentials, the electron current increases quite rapidly; even with zero field on the cathode side, diffusion will carry electrons to the probe far in excess of the positive ions arriving elsewhere. With still higher probe potentials, the electron current increases rapidly, and a region of electron space charge develops about the probe. It is possible for the probe potential to be considerably above all the surrounding space, and still the current to the probe to be limited by the reduced mobility in the cold dark space to a value less than the drift current to it would be if a dark space did not form.

Fig. 6 shows a considerably larger total probe current, and a faster increase of current with voltage, the larger the arc current. Some increase should occur merely from the longer length of probe immersed in the larger arcs and some should be caused by the slight increase of ion density with current, but these two do not seem quite adequate to explain the large difference noted. The current collected was also the larger the closer the probe approached the cathode. Because of the decreased section of the arc near the electrodes, the ion density probably is actually higher there: in addition, the dark space around a probe near the cathode was smaller than in the body of the arc, so both the fields and concentration gradients in the dark space would be higher.

Potential distribution in the arc

From the points of zero current for the probe in different positions, some idea of the potential distribution in the arc may be secured. The average values of the voltage between probe and cathode for zero current, for a few conditions, are given in Table II.

For zero current, the probe potential is probably 1 or 2 volts negative with respect to the dark space boundary nearest the cathode. The boundary itself must be negative with respect to adjacent parts of the arc, which remain undisturbed by the probe,—sufficiently negative to produce fields of the same magnitude as the longitudinal fields in order to redistribute the current flow around the probe. Possibly the boundary is 4 to 6 volts negative with respect to the same point in an undisturbed arc. The actual potential of an undisturbed arc at a point corresponding to the probe axis, measured from the cathode, will be the sum of these two potentials, plus the potential for zero current and the voltage drop in the undisturbed arc over a distance equal to half the dark space diameter. In round numbers, for a probe at the center of a 6-amp. arc, something like 8 volts must be added to the figures in Table II in order to give the space potential. More must be added near the cathode, where the field is higher; for the same reason, the addition must be greater the smaller the current. The probable space potential distribution for different currents is shown in Fig. 8. It should be realized that this is merely a rough approximation, representative only in magnitude. The cathode fall seems to be a little over 10 volts, and the anode fall of the order of 20 volts.

Ion density and distribution in the arc core

Quite apart from any probe measurements, it is possible to get a rough estimate of the ion density in the positive column of the arc from observed current density and the gradient, which was obtained from volt-ampere characteristics for different length arcs. For a gas temperature of 6000° and a field of 33 volts per cm, for a 6-amp. arc, the equivalent value of E/p is 1 volt per cm per mm pressure. By the Compton theory of terminal velocities,[12] the energy of electrons making only elastic collisions in N_2 would be 4.24 volts, and the corresponding drift velocity, using the Langevin mobility formula[12] comes out 4.88×10^5 cm per sec. Townsend[13] has measured the energy of electrons in N_2 for $E/p=1$, but at room temperature, and found 0.778 volt (6000°) for the terminal energy, and 8.5×10^5 for the drift velocity. In the present case, the high gas temperature will probably make the terminal energy larger, and hence the drift velocity

TABLE II. *Potential from probe to cathode for various arc currents.*

Distance of the probe axis from cathode	3 amp.	6 amp.	9 amp.	12 amp.
0.13 cm	14 volts	11.5 volts	7.5 volts	9 volts
.25	22.7	20	12	10
.38	32	22.5	18	17
.51	37	28.5	23	21
.63	39	35.5	25.5	23

[12] Compton and Langmuir, Rev. Mod. Phys. **2**, 220 (1930).
[13] Townsend, J. Frank. Inst. **200**, 586 (1925); Phil. Mag. **42**, 883 (1921).

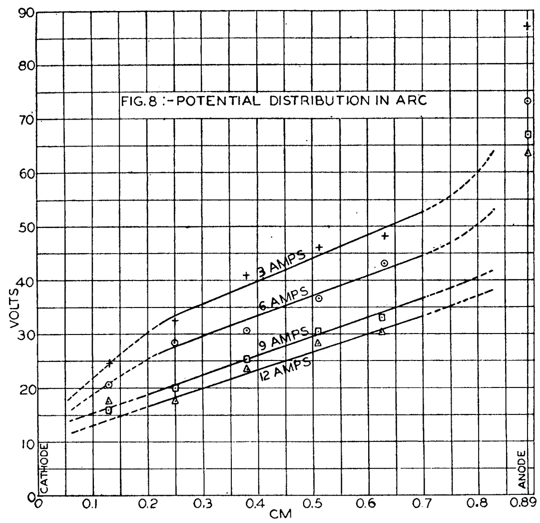

FIG. 8.

smaller, than Townsend's values. If one uses a velocity 8.5×10^5, then a value of electron density will be found which is too low, but of the correct order of magnitude. Taking the current density as 20, the electron density comes out 1.48×10^{14} per cm^3. If one uses the value of velocity calculated above, then the density would be almost twice as large. Since no large space charges are present, the positive ion density in the positive column must be about the same. As the gradient has been found to vary only 25 percent for a change in current by a factor of 4, while the current density remained substantially constant, the ion density must change not over 25 percent in the same range.

From the total current measured by a revolving probe, with constant voltage applied, the current collected per unit length of the probe at different radii from the arc axis may be found, just as the exactly similar energy input to the probe was gotten previously. If $i(x)$ represents the total current for the straight probe at a distance x from the arc axis, and $i(r)$, the current per unit length for a point r from the axis, then

$$i(r)=-\frac{1}{\pi}\int_r^\infty i'(x)\frac{dx}{(x^2-r^2)^{\frac{1}{2}}}. \qquad (8)$$

From this equation $i(r)$ was calculated from measured $i(x)$. Since positive ion current varies more slowly with probe potential than does

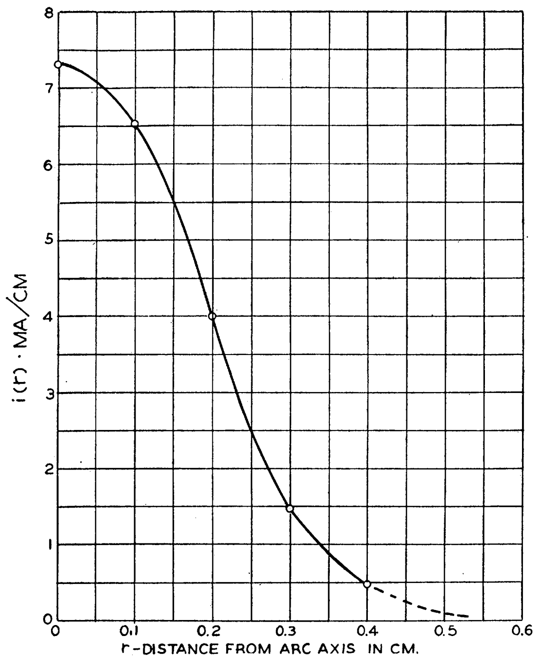

FIG. 9. Positive ion current collected per cm length of probe.

electron current, the consequence of different radii in the same transverse plane of the arc being at different potentials has less effect on the positive ion results. Fig. 9 represents $i(r)$ for a 0.025 cm diameter probe, passing 0.51 cm from the cathode of a 5.85 amp., 1.15 cm long arc, with the probe 130 volts negative to the cathode. The curve gives some indication of the radial distribution of ion density in the arc, but $i(r)$ is not necessarily directly proportional to the ion density: the current collected must also depend on the temperature distribution around the probe, which in turn changes with r. The curve does show, however, that the ion density falls to a low value outside the intense central core of the arc ($r=0.3$ cm).

IV. Critique of Other Investigations

Although the errors into which other investigators have fallen will be obvious from the above results, perhaps a brief mention of some specific points may be worthwhile in view of the wide acceptance in the literature of their work.

From the point of zero probe current, the electron current to the probe rises rapidly with increase in probe to cathode voltage. The rate of increase of current bears no obvious relation to the electron temperature in the positive column, for in order to reach the probe the electrons must travel from where they are produced a long distance through a gas with varying temperature to a probe whose immediate surroundings are at a low temperature compared to the arc. In this part of the characteristic, it is the change in drift velocity of the electrons to the probe which is responsible primarily for the change in current, so whatever the temperature of the electrons finally arriving at the probe, their temperature is not constant throughout the dark space. Furthermore, a change in slope of the current voltage characteristic at a few volts positive with respect to the point of zero current cannot arbitrarily be called the space potential for an undisturbed arc. The interpretation of results which Nottingham[1] used led him to space potentials which are certainly much too low near the cathode—giving a cathode fall of only 5 volts for the carbon arc—and probably too high near the anode.

Bramhall[2] observed the increase in arc voltage caused by passage of the probe, but he failed completely to realize the significance of the disturbance caused, making the same errors that Nottingham did in interpretation of data. Some inconsistencies into which he was led may be pointed out: for instance, he gives the volt equivalent of the electron drift velocity as 0.64, and of the random velocity as 2.7; from these, the random electron current should be about twice the drift current. In other parts of his paper, however, from his interpretations, he gives the random current density as from 1 to 5 amp. per cm^2, and the drift current density 70 to 310 amp. per cm^2. Again, in his attempt to determine the recombination coefficient from the decrease of probe current after extinction of an arc, Bramhall also falls into serious errors, though finally arriving at reasonable results, through his misinterpretation of the probe characteristic, and through neglect of the production of ions. Here, this internal inconsistency may be pointed out: using Bramhall's figures, and graphically integrating his probe current curve, one finds that in the period after arc extinction in which ions were supposed to disappear only by volume recombination, the total number of ions collected by the probe was over 200 times the total number existing in the whole arc initially. The probe measurements of previous investigators of high pressure arcs must be considered as of little value.

V. General Discussion

From experiments on a carbon arc at atmospheric pressure, this paper has brought out the restrictions in the use of probes for investigating high pressure discharges. In a discharge at low pressures, the gas temperature is not much above room temperature and the discharge substantially fills the containing vessel. At high pressures (above a few millimeters) the positive column of the discharge contracts to a definite section, independent of the dimensions of the vessel, if these are larger than the natural section of the discharge. The contraction of the positive column is accompanied by, or more likely, is *caused* by an increase in the gas temperature to several thousand degrees. The positive column may be expected to take that section for which the losses are a minimum. Now if by any means the section of the arc is changed from the minimum, without any change in current, the energy necessary to maintain the discharge increases. As the energy in a self-maintained discharge is supplied only from the electrical power source, a change in section necessitates an increase gradient in the positive column, and a larger arc voltage.

If a solid probe of finite size is placed in the arc, then the arc voltage must increase. As the temperature of the probe, if it remains a solid, is only a fraction of the gas temperature in the arc (around 6000°K at atmospheric pressure), there will not be a sudden transition of temperature, but a region around the probe in which the gas temperature falls from the several thousand degrees of the arc to the few hundred degrees of the probe. Within the transition region, which appears as a dark space around the probe, probably very few ions are produced, so the effect of the probe on the arc cross section extends over a distance several times the probe dimensions, with consequent greater increase in the voltage required for the arc. Put in other words, from an energy standpoint, the introduction of a probe cools the arc and increases the energy input necessary for maintenance of the arc; the effect of the probe extends far beyond the probe surface because of the lowering of the gas temperature around the probe. From an electrical standpoint, the presence of a region of lowered gas temperature impedes the flow of ions and develops space charges which divert most of the current around the dark space.

The interpretation of probe current voltage characteristics which has been developed for the use of probes in low pressure discharges, does not apply at high pressures. The ions or electrons which reach the probe must travel a long distance through the dark space from the point of their generation in the arc. The current which the probe collects depends not only upon the strong fields, or space charge sheaths which develop about the probe, but also upon the weak fields and concentration gradients which move the ions through the dark space. Since it is likely no ions are lost within the dark space except at the probe, when the net probe current is zero, the probe potential must be negative with respect to the part of the dark space boundary nearest the cathode. From this condition, the distribution of potential in an undisturbed arc may be estimated. An exact mathematical formulation of the probe current voltage relations appears difficult, if not impossible, so that the use of probes in high pressure discharges probably can never bring such exact information about the nature of the discharge as it can at low pressures. Through a study of the thermal as well as electrical characteristics of probes, together with observations of the general properties of the arc, perhaps some knowledge of high pressure discharges can be gained.

The writer is indebted to Professors H. D. Smyth and G. P. Harnwell for criticizing this paper, and to Dr. Joseph Slepian for helpful discussion throughout the course of the experiments.

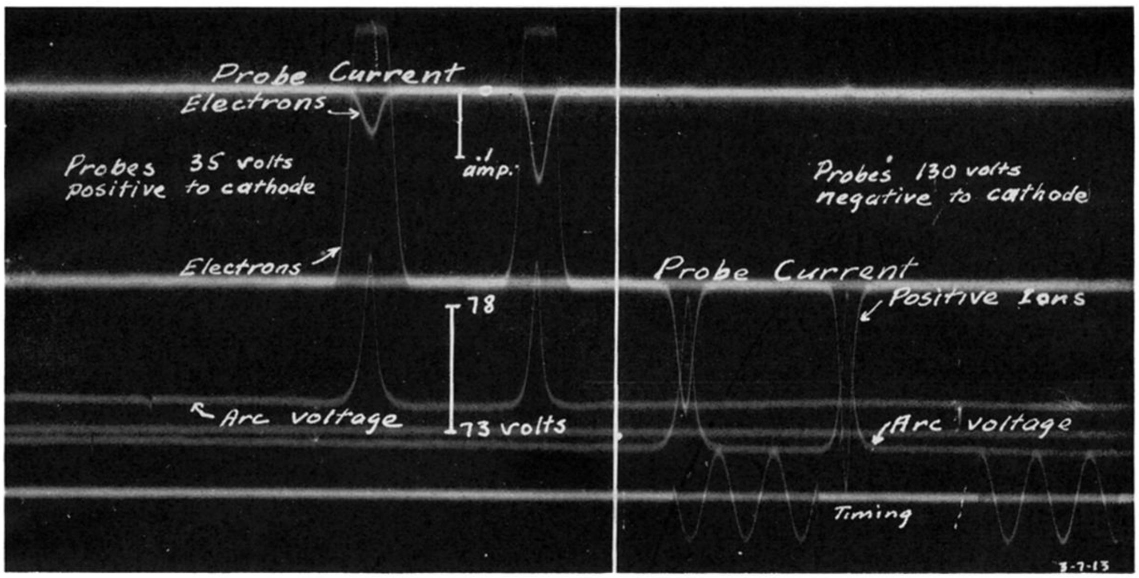

FIG. 1. Passage of two 0.025 cm diameter probes through 6-amp. arc.

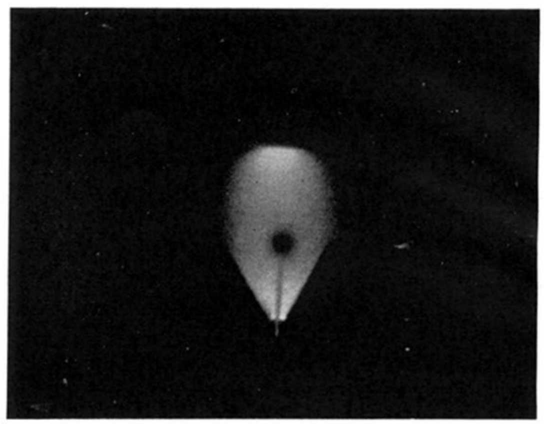

Fig. 3. Photograph of 6-amp., 0.89 cm long, arc with 0.025 cm probe wire 0.38 cm from cathode (lower) electrode.

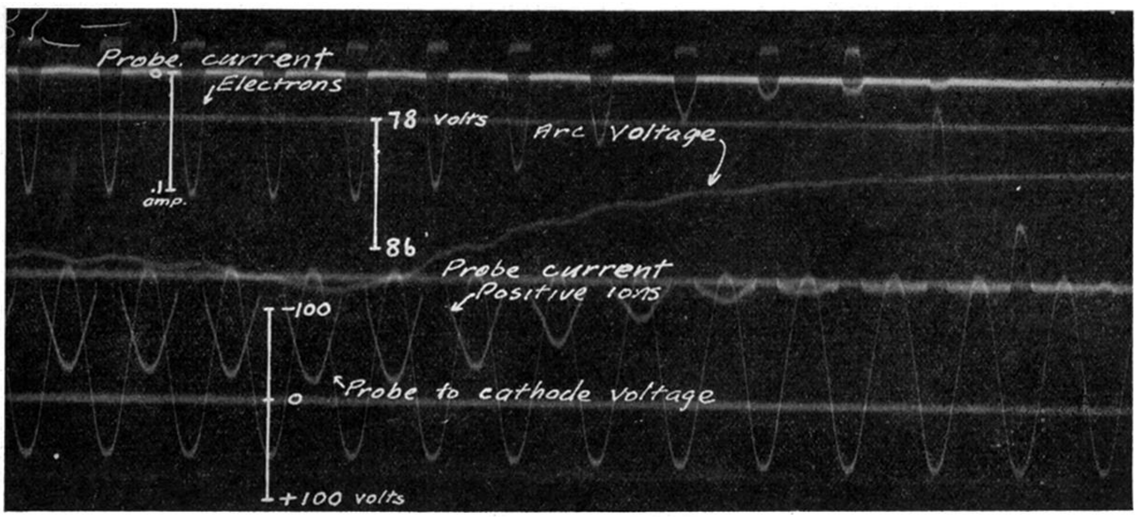

FIG. 5. Probe 0.51 cm from cathode of 6-amp., 1.14 cm long, arc. Probe moved through arc during exposure of film.