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PROBE MEASUREMENTS IN THE NORMAL ELECTRIC ARC

W. B. NOTTINGHAM

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PROBE MEASUREMENTS IN THE NORMAL ELECTRIC ARC.

BY

W. B. NOTTINGHAM, B.S., M.A.,

Bartol Research Fellow.

BARTOL RESEARCH
Foundation
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Abstract. Probe measurements have been made in cadmium, thallium and carbon arcs by sweeping the probe through the arc at a constant velocity and measuring the current collected by the throw on a ballistic galvanometer with different probe potentials applied. The voltage-current characteristic was analyzed to get a measure of the positive ion concentration, the average electron temperature and the space potential by the Langmuir method. The cathode falls found were each equal to, or only slightly higher than, the ionization potential of the active gas, and were 9.0 volts in the cadmium arc, 6.5 volts in the thallium arc and 5.0 volts in the carbon arc. The last value is to be compared with the ionization potential of the cyanogen molecule of 4.4 volts. The anode fall found in the carbon arc was 16.5 volts. These values for the carbon arc agree almost exactly with the "forward" and "back" E.M.F.s measured by Duddell and others at the cathode and the anode but not identified by them as the cathode and anode falls. The electron velocities were found to be Maxwellian with average velocities sufficiently high to account for the ionization known to exist. Over parts of the arc stream where the fields were found to be large the electrons showed corresponding increases in average temperature and evidence that only about three-quarters of the energy gained by the electrons from the field between collisions is lost by the lectrons while the remaining quarter is retained and made evident by the steady increase in the electron temperture. As the current flowing through the arc was increased, the radiation per unit volume and also the positive ion current per unit length of the probe were found to increase very rapidly indicating an increase in the efficiency of the ionization process as the current increases. It is thought that this observation is closely related to the fact that the voltage drop across the arc decreases as the arc current increases.

THE Langmuir probe method of determining the electronic energy distribution and the positive ion concentration in low pressure arc discharges, has been used to explore certain normal arcs operating at atmospheric pressure. The new facts concerning the detailed mechanism of the electric arc which were revealed by these probe measurements seem to be of sufficient importance to warrant this advance report being made before the entire project has been completed. More extensive explorations of a number of different arcs are now being prepared, the results of which will also be published in this JOURNAL.

THE LANGMUIR PROBE METHOD.

The theory of the use of probes for measuring space potentials, electron energies, etc., has been presented in a series of papers by Langmuir and Mott-Smith [1] along with examples of experimental results. Although the details of procedure were a little different in the case at hand, the general method was the same as that developed by the above writers and can be outlined as follows.

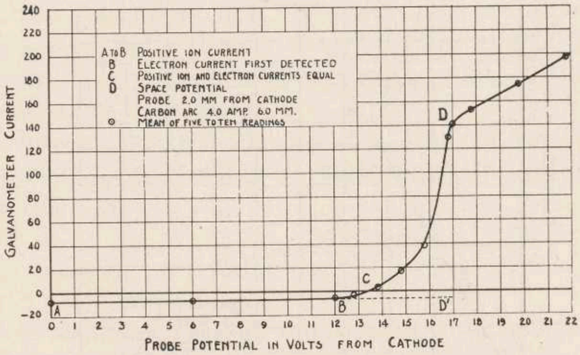
The direct current arc is usually operated by power furnished the electrodes from a battery or generator through a suitable resistance which stabilizes the discharge at the preassigned current flow. The potential drop over the arc, measured at the electrodes, is usually thought of as being divided into three parts, namely, (1) the cathode fall very close to the negative electrode surface, (2) the arc stream fall in potential supposedly distributed uniformly along the arc stream, and (3) the anode fall at the surface of the positive electrode. Thus the potential of the space at any given distance from one of the electrodes, for instance, the cathode, is made up of the cathode fall plus that part of the arc stream fall between the point in question and the cathode. In order to measure this space potential it is not sufficient simply to immerse the probe in the discharge and measure its potential by means of an electrometer or a high resistance voltmeter. The result can only be gotten in the more indirect way of studying the voltage-current characteristic of the probe when it is immersed in the discharge and maintained at definite potentials with respect to one of the electrodes by means of a battery. The potential of the cathode will be taken arbitrarily as zero and a current of positive charges coming to the probe will be called a negative current in order to be consistent with the accepted practice. If the probe potential is negative with respect to the space, a positive ion sheath will form around the probe. Within this sheath perfect reflection will take place of all the electrons which enter it with insufficient velocity to penetrate to the probe against the adverse field set up, due to the charge maintained on the probe by the battery. Positive ions which happen to enter the sheath find themselves in a field of force which carries them through the

[1] *G. E. Rev.*, **27**, 449, 538, 616, 762, 810 (1924).

sheath to the probe and the rate at which these ions come to the probe is indicated by the current flowing in the probe circuit.

This positive ion current, AB of Fig. 1, is seen to change very little as the probe potential changes. What change there is observed is due to the change in the surface area of the sheath as the probe potential is altered. When the probe is slightly negative with respect to the space, enough fast electrons are able to penetrate the sheath and strike the probe to give an electron current large enough to be measured, superimposed on the positive ion current. This point is indicated by B in Fig. 1. At C on the same curve, the electron

FIG. 1.



Voltage-current characteristic of probe in carbon arc.

current exactly equals the positive ion current making the total current registered in the probe circuit zero, and thus showing the potential which would be found if the probe were connected to a high resistance voltmeter and allowed to "float." At potentials higher than C the electron current exceeds the positive ion current. If it happens that the electrons which come to the probe have a Maxwellian distribution of velocities, a plot of the ordinates representing the difference between the curves BCD and BD' on semi-logarithmic paper will give the average temperature of the electrons because of the well known relationship

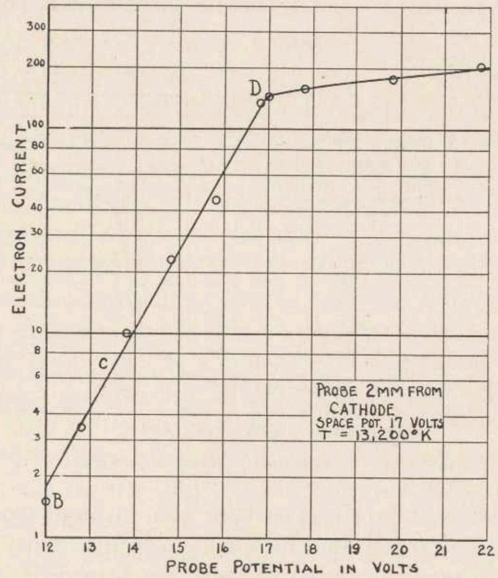
$$i = a\epsilon^{\frac{eV}{kT}} \qquad (1)$$

which applies to this case. Since

$$\log_e i = \frac{e}{kT} V + \log_e a, \tag{2}$$

the slope of the straight line part of the curve BCD of Fig. 2 must be e/kT and with e/k known ($e = 4.774 \times 10^{-10}$ e.s.u. and $k = 1.372 \times 10^{-16}$ ergs per degree) the temperature T can be calculated. The theory of the Langmuir probe method predicts that the "current-voltage" characteristic will show

Fig. 2.



Semi-logarithmic plot of electron current.

a change in slope when the probe potential equals the space potential. It is on this basis that the bend of the curve at D in Fig. 2 is taken as an indication of the true potential of the space.

Probe measurements following the general method described above have been successfully carried out in low pressure discharges with the probe continually immersed in the discharge space. Such a procedure is not possible in the high pressure arc because the bombardment of the probe is so violent that it soon heats up to the melting point or else it becomes hot enough to give off electrons in sufficient number to invalidate the results. The method adopted, therefore, has been to swing the probe by a mechanical means at practically a constant velocity, through the discharge so rapidly that it does not heat up sufficiently to cause trouble. The potential was maintained on the probe by means of a low resistance battery and the current measured by the throw of a ballastic galvanometer properly shunted. To use the measurements to indicate the space potential and the average energy of the electrons, it is not necessary to know the area of the arc stream swept over by the probe but in order to compare the positive ion currents collected at various parts of the arc or in arcs with different currents flowing, it is necessary to know the area swept out. Photographic measurements of the light given off by the arc show that the conditions in the arc over any plane perpendicular to the axis of the arc can be considered to be uniform. It is possible to show that if a probe is moved through the arc at a uniform velocity v, the quantity of current Q which flows through the galvanometer circuit is

$$Q = \frac{\pi r^2 i}{v}, \tag{3}$$

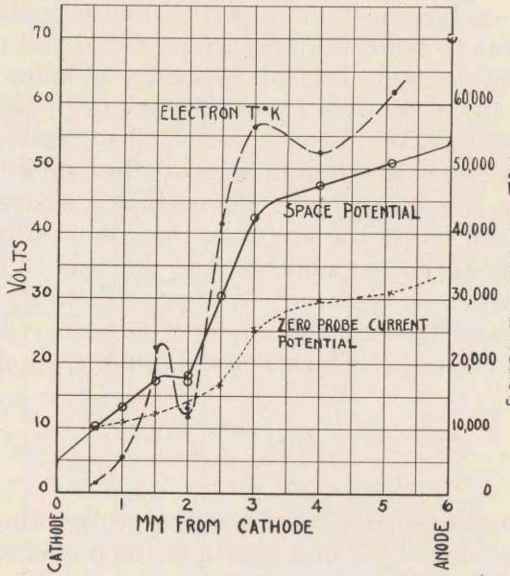
where r = radius of the arc where the probe swings through, and i = the current per unit length of the probe, and depends on the condition of the gas within the arc.

RESULTS OF MEASUREMENTS.

The arc materials studied so far have been (1) cadmium in argon, (2) thallium in argon, and (3) carbon in air.

Cadmium Arc.—The results of the measurements on the cadmium arc in argon at atmospheric pressure showed that the cathode fall was exactly equal to, or very slightly greater than, the ionization potential of cadmium which is 8.9 volts and that the anode fall was of the order of one volt. The field along the arc stream was uniform and about one volt per millimeter. These measurements were made on 4 mm. arcs carrying currents of 1 to 4 amperes. The average energy of the electrons half way between the electrodes increased slightly as the current was increased. The electron temperatures found were 5400° K. for 1.0 and 2.0 amperes, and 6100° K. for 4.0 amperes. The average electron energies corresponding to these temperatures expressed in equivalent volts are 0.7 and 0.79 volt respectively. A tungsten probe 0.2 mm. diameter was used.

FIG. 3.



Distribution of potential and electronic temperature along the carbon arc.

Thallium Arc.—Measurements of a 2.0 ampere 4 mm. thallium arc in argon showed also that the cathode fall was exactly equal to or slightly higher than the ionization potential of thallium of 6.08 volts. The field along the arc stream in this case was about 1.5 volts per mm. and the average temperature of the electrons 7750° K. which is the equivalent of 1.0 volt. Whether or not this average energy of 1.0 volt is in any way related to the known metastable electron level of 0.96 volt for the thallium atom, is a point we hope to settle by further measurement.

Carbon Arc.—The results obtained on the carbon arc have proved to be by far the most unexpected. The carbons studied were furnished by Gebrüder Siemens & Co., Berlin, and classified by them as "+ E + HOMOGENKOHLE + E +." Spectroscopically these were found to be the purest of all of the carbons tried out preliminary to the beginning of this study. A very faint trace of sodium was found to be present along the entire length of the arc stream and a trace of iron impurity showed in the spectrum in the immediate neighborhood of the cathode. Since it has been impossible to obtain carbons of greater purity than these, we have not been able to prove that the irregularities in the carbon arc stream disclosed both by the photographs and the probe measurements, are really inherent in the carbon arc or were found in this case as a result of the traces of impurities. A carbon probe burned to 0.4 mm. in dia. was used for the measurements.

The curves on Fig. 3 serve to illustrate the general results so far obtained with the carbon arc. The solid line (heavy over the range of measurement, light in extrapolation) shows the distribution of potential along the arc from the cathode taken as zero to the anode at 70.5 volts, a result in good agreement with the Ayrton [2] value of 69.6 for pure carbons. A straight line extrapolation of the line through the observed points from 0.6 to 1.5 mm. from the cathode gives a cathode fall of about 5.0 volts which is lower than that given by other observers.[3, 4] This value agrees with the estimated value, 4.4 volts, of the ionization potential of the cyanogen molecule given by Mullikan [5] and extends the general observation mentioned above that the cathode fall is equal to or slightly greater than the ionization potential of the gas actively involved. Between 1.5 mm. and 2.0 mm. from the cathode there was no increase in potential while over the range 2.0 mm. to 3.0 mm. the potential increased 25.0 volts. From this point on no irregularities were found. The field of 40 volts per cm. agrees with that found by Hagenbach and Wehrli.

The anode fall of 16.5 volts is lower than that measured by

[2] Ayrton, "The Electric Arc," p. 185.

[3] Ayrton, "The Electric Arc," p. 218. Cathode fall 11.0 volts.

[4] Hagenbach and Wehrli, *ZS. f. Phy.* **26**, 23 (1924). Cathode fall 7.1 volts.

[5] *Phys. Rev.*, **25**, 291 (1924).

Ayrton [6] (34.0 volts) and that calculated by Hagenbach and Wehrli [4] (33.7 volts).

It is interesting to note that the values for the cathode and the anode falls as found by the Langmuir probe exploration coincide almost exactly with the "forward" and the "back" E.M.F. measurements of the cathode and the anode spaces published by Duddell [7] in 1904 and by Hagenbach and Wehrli [4] in 1924. In both cases small intensity high frequency currents, 100 and 190 kilocycles, were used and determinations of an apparent E.M.F. and an IR drop from the probe to the electrode were made. The cathode E.M.F. was found by Duddell to be − 5 to − 6 volts and Hagenbach found − 6.1 volts. The anode E.M.F. was measured as 15 to 17 volts by the former and as 16.7 volts by the latter. The numerical values agree almost perfectly with those now found by the Langmuir probe method to be the true cathode and anode falls.

The measured electron temperatures showed an interesting relationship to the electric fields accelerating the electrons. At the termination of each rise in voltage, namely at 1.5 mm. and 3 mm. there was a maximum temperature of the electrons, and immediately following, over the range of smaller field the electron temperature dropped. This drop was particularly noticeable at 2.0 mm. from the cathode. At the maximum at 1.5 mm. from the cathode, the average energy of the electrons expressed in equivalent volts was about 3.0 volts, thus allowing for many electrons with sufficient energy to ionize the *CN* molecule in a single impact. Over the entire range from 2.5 mm. on, the electrons on the average had acquired sufficient energy to ionize the *CN* molecule easily. Thus it can be said that it is an experimental fact that the electrons have acquired sufficient energy from the field to produce the ionization required for the maintenance of the electric arc in spite of the fact that the fields are small. This observation should make it unnecessary to invoke the indirect explanation based on Saha's equation as given by Compton [8] to explain the ionization known to exist.

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[6] Ayrton, "The Electric Arc," p. 215.

[7] *Phil. Tran.*, **203**, 305 (1904).

[8] *Phys. Rev.*, **21**, 286 (1923).

The consistency with which the electron temperature rises while traversing a region of the arc where the field is high suggests that the electrons gain their high temperatures by their acceleration in the field. We shall assume that electrons after collision with molecules come off with a Maxwellian distribution of velocities and that they communicate on the average a fraction α of the energy which they have gained from the field since the last impact. If, under these conditions, X is the field, u the average velocity of the electrons along the axis of the arc, e the electronic charge, and n the number of electrons per c.c., the energy converted into heat per second will be $neuX$. The amount which goes into temperature energy of the electrons, is according to the above hypothesis $(1 - \alpha)neuX$. Thus if T is the temperature of a group of electrons whose motion we follow

$$(1 - \alpha)neuX = \frac{3}{2}kn\frac{dT}{dt} = \frac{3}{2}kn\frac{dT}{dx}u, \tag{4}$$

where k is the molecular gas constant. On integration between two points along the arc we find

$$(T_2 - T_1) = (1 - \alpha)\frac{2e(V_2 - V_1)}{3k}. \tag{5}$$

We can convert an electron energy corresponding to a given temperature T into equivalent volts v by taking

$$\begin{aligned} v &= \frac{3}{2}\frac{k}{e}300T \\ &= 1.293 \times 10^{-4}T. \end{aligned} \tag{6}$$

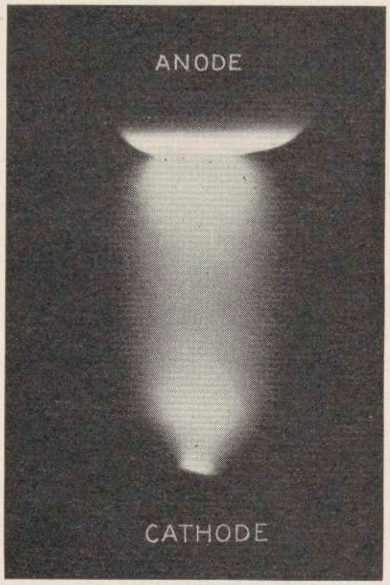
Solving equation (5) we get

$$(1 - \alpha) = \frac{v_2 - v_1}{V_2 - V_1}. \tag{7}$$

The application of this result to the range 2.0 mm. to 3 mm. in Fig. 3 gives $\alpha = 0.78$ while over the range from the cathode fall to 1.5 mm. we get $\alpha = 0.763$. This seems to show that electrons moving along the arc under the influence of the field lose on the average only about three-quarters of the energy gained over their free paths by impact on molecules.

In order to illustrate the error involved in probe measurements, before the Langmuir analysis was proposed, the points showing the probe potentials for which no current flowed to the probe are plotted along the dotted line in Fig. 3. It is easy to see how the irregularities which have been observed above were not detected.

Fig. 4.



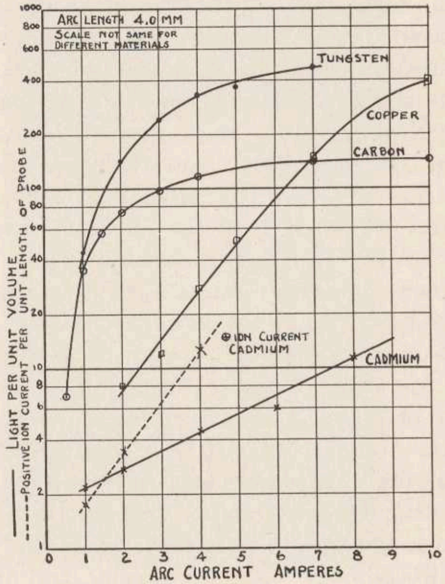
Photograph of 4.0 amp., 6 mm. carbon arc.
Light from 4216 Å cyanogen band.

Figure 4 is a reproduction of a photograph taken of an arc 6 mm. long carrying 4 amperes which shows quite clearly the fact that maxima and minima in the light given off the arc stream follow exactly at the points of irregularity as shown by the probe. In particular the maximum of light intensity at 1.5 mm. from the cathode has a direct counterpart in the potential curve of Fig. 3 because at this point there is a marked change in slope in the direction to indicate a region of positive space charge, and therefore, a region of high positive ion concentration.

CORRELATION BETWEEN POSITIVE ION MEASUREMENTS AND LIGHT INTENSITIES.

Probe measurements in the cadmium arc showed that the positive ion current *per unit length* of the probe increased very rapidly with an increase in the current flowing in the arc although the current density over any cross section of the arc has been found to be constant and independent of the current. This observation seems to indicate an apparent increase in the efficiency of the ionization process as the current is increased. Such an increase in efficiency might conceivably be brought about because the volume occupied by the arc stream is directly proportional to the current flowing. The larger volume results in a greater radiation flux and absorption of the resonance radiation in each element of volume and thus increases the efficiency. It is perhaps along these lines that we must look for an explanation of the fact that the voltage drop across the arc decreases as the current flowing increases. Selected radiation, not including resonance radiation, has been found to be emitted without appreciable absorption in passing through the arc. A photoelectric cell has been set up with an appropriate lens system to measure the radiation of a selected wave-length (or range of wave-lengths) which comes from a little cylinder of the arc stream formed by passing two planes perpendicular to the axis of the arc and including 0.5 mm. of the arc stream's length. From previous measurements it is known that the light per unit volume is uniform over such a cylinder and therefore if the total light recorded by the cell is divided by the known area, the light per unit volume will be known and this can be compared with the positive ion current per unit length of the probe. The light intensity measurements showed the same type of rapid increase of intensity per unit volume when the arc current was increased as was found for the positive ion current. Copper, carbon and tungsten arcs also were measured and found to show a great increase in light per unit volume as the current increases. The carbon and the tungsten arcs showed a marked tendency for the light per unit volume to reach a "saturation" value. In view of the fact that the areas of cross section of these arcs are greater than the others measured, a more rapid approach of the emitted radiation to a saturation value with increasing current is to be expected because of the larger absorption of the light in the arc itself. The curves shown in Fig. 5 serve to illustrate the rapid increase in positive ion current and light per unit volume and also the tendency towards light saturation in the carbon and tungsten arcs.

FIG. 5.



Light intensity and positive ion measurements.

Qualitatively, this increase in radiation has been known by the medical profession for some time and measurements of A.C. arcs between impregnated electrodes summing the radiation along the axis of the arc instead of at right angles to its axis, have been published by Coblentz,[9] Dorcas and Hughes. Their results are qualitatively much the same as the writer's, showing a tendency to saturate at slightly higher currents, although they did not express their results in such a way as to make this point obvious.

It is apparent from the results presented that the use of

[9] Sci Papers of Bureau of Standards No. 539, Nov. 19, 1926.

the Langmuir probe and the correlation of the probe measurements with other physical measurements of the arcs, such as light intensity, ionization potential, etc., opens a whole new field of research, the outcome of which promises to fill in many details of the mechanism of the electric arc which have evaded discovery for a long time.

To Professors W. F. G. Swann and K. T. Compton, I am greatly indebted for many valuable suggestions.

The Liter and the Cubic Decimeter. H. W. BEARCE. (*Science*, May 18, 1928.) In the establishing of the metric system it was intended to derive the units of length, area, volume and mass from the meter which was to be the ten-millionth part of the length of the earth's quadrant from pole to equator. A cube a tenth of a meter on a side was the unit of volume and the mass of this volume of water at its maximum density was the kilogram. Difficulties were encountered in making these plans concrete. It was a task beset by serious obstacles to measure accurately a quadrant of the earth and the meter was later defined by reference to a definite material standard. Furthermore masses could be compared with greater accuracy than was obtainable by deriving a mass from volume measurements, so that the kilogram also was defined by reference to a concrete standard. An additional step was taken by defining the liter as the volume of a kilogram of water at maximum density. The liter as thus defined is 27 parts in a million larger than the cubic decimeter specified by reference to the earth's quadrant, and the milliliter is in the same proportion larger than the cubic centimeter.

The author, who is in the Bureau of Standards, regrets this existing confusion in units and decries the use of 'cubic centimeter' in measuring the volume and density of liquids instead of the correct 'milliliter' (ml.). For the abbreviation of 'cubic centimeter' he prefers 'cm^3' to 'cc.'

G. F. S.

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