Experiments with Arcs at Atmospheric Pressure

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In the equation for the static characteristic of the electric arc at atmospheric pressure, $E = A + B/I^n$, the exponent n has been interpreted by Nottingham and others as a constant independent of arc length and dependent linearly upon the boiling point of the anode material. This view is criticized from a consideration of new experimental data showing that the spread in measurements of n is necessarily very large. The conclusion that "n varies directly as the boiling point of the electrode (anode) material" is not given support by these experiments.

In a comprehensive investigation of the steady state volt-ampere characteristics of atmospheric pressure arcs between metallic electrodes, Nottingham[1] proposed the relation,

$$E = A + B/I^n, \tag{1}$$

between the arc voltage E and the current I, where A, B and n are constants. It was found experimentally that the exponent n was independent of arc length but not of electrode material. In particular, n depends upon the material of the anode and is numerically greater for materials like W and Pt than for Sb, Pb, Cu and Au. In the case of a 3 mm copper arc, for example, $n = 0.665$, while the average value for ten arc lengths, between 1 mm and 10 mm, is given as $n = 0.670$. The data suggest that there may be some fundamental dependence of this exponent n on the boiling point of the anode material, as shown for example by Fig. 1, where values given by Nottingham,[1] Anderson and Kretchmar,[2] and Myers[3] are plotted. The original data lie remarkably close to a straight line. It should be pointed out, however, that (1) in the case of Ni, Al, Cu and Zn, it was necessary to use the boiling point of an oxide to provide agreement, and (2) more recent determinations of the boiling points of W, Pt and Ag take these points well off the curve, particularly in the case of W.

If the relation of Nottingham between the boiling point and n could be confirmed and extended, it would be of practical importance to the study of arcs, in spite of the fact that it has absolutely no theoretical background. In view of the importance of this work, and the firm root it has taken in the literature on atmospheric arcs, it has seemed desirable to investigate the foundations on which this arc equation rests.

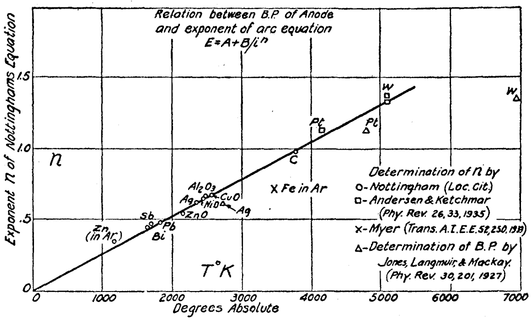

FIG. 1.

EXPERIMENTAL METHOD

For the first series of measurements the method of Nottingham was duplicated as nearly as possible. In this method the arc voltage is obtained by a voltmeter in parallel with the electrodes; the arc current (plus the v.m. current) was obtained from an ammeter in series with the arc; and the arc length was adjusted and measured by projecting an enlarged image on a suitably calibrated screen. The current limiting element in series with the arc was nominally a pure resistance. The voltage supply was in some cases a 500 volt battery, and in other cases a 1500 volt d.c. generator.

The electrodes ($\frac{1}{2}''$ diameter cylinders) were turned smooth on a lathe after every reading for the high currents, but were used for several readings at the low currents where the electrode

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[1] Nottingham, J. A. I. E. E. **42**, 12 (1923); Phys. Rev. **28**, 764 (1926).

[2] Anderson and Kretchmar, Phys. Rev. **26**, 33 (1925).

[3] Myers, Zeits. f. Physik **87**, 1, 2 (1933).

burning was less. Three observers, located respectively at the ammeter, voltmeter, and screen, took simultaneous readings. The time required to take a reading, after starting the arc, varied between three seconds to a minute or more.

Although the arc current is maintained at a relatively constant value, the arc voltage shows large random fluctuations so that the spread of the measurements is very great. An enormous number of readings were taken of different arc lengths, electrode diameters, electrode surfaces, electrode materials and positions. An oscillogram illustrating the case is shown as Fig. 2, which was obtained by a method to be described in detail later. In this method the current through the arc was increased in steps by a commutator in such a manner that the complete volt-ampere data were obtained in a relatively short time. The arc voltage is given at (*A*), as it appeared to the standard, low sensitivity, high frequency (8000 cycle) galvanometer. The trace (*B*) is the arc voltage which one would observe on a conventional laboratory d.c. voltmeter. For this record (*B*), the time constant of the galvanometer circuit was increased, with an inductive shunt, to agree with the time constant of the mechanical system of a laboratory voltmeter. It should be noted that this oscillogram was taken after the arc had burned for some minutes, or in approximately the time required to take a reading by the voltmeter-ammeter method. It can be observed from both traces of this oscillogram that (1) changes in arc voltage are large (15–45 percent); and (2) random in character.

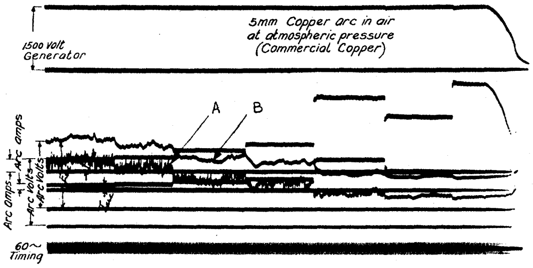

FIG. 2.

From a great deal of data it is concluded that the spread of the measurements, due to the random nature of the arc voltage variations, is such as to preclude the possibility of an accurate determination of *n* by this method.

NEW MEASUREMENTS OF *n* BY AN OSCILLOGRAPHIC METHOD

To eliminate the human element and to shorten the time required for readings and hence electrode heating, burning and associated errors, a completely automatic method for taking the volt-ampere data was used. The oscillograph trip mechanism is used to start a motor driven commutator which successively short-circuits portions of the current limiting resistance to increase the arc current and decrease the arc voltage in steps. Two current elements are used on the oscillograph so that both high and low current ranges are read with accuracy. The high sensitivity current element is shorted by the commutator to protect it from the heavy current. The arc length is adjusted by a thickness gauge with cold electrodes before starting the arc. The total change in arc length due to electrode expansion during the course of a run (*circa* 5 sec.) leads to a negligible error. Some errors in arc length occur if the arc travels to the edges of the electrodes and forms an outward bow. Records for which this was observed were thrown out.

For electrodes three kinds of pure copper were used, one with known analysis, together with one sample of commercial purity for comparison purposes. The electrode surfaces were lathe turned, except for a series of records taken with highly polished surfaces—to be described in a separate publication. The method of taking data is automatic and rapid so that an enormous number of records, each a complete volt-ampere characteristic, may be taken quickly and with a high order of accuracy. The arc voltage was in some instances taken with a galvanometer element employing an inductive multiplier (trace (*B*), oscillogram Fig. 2), and in some cases with a non-inductive multiplier, as noted. In the case of the copper records, where the changes in arc voltage appear to be random in character, the inductive element was used. In this case the *average value* of arc voltage throughout each current step was the recorded value.

3 mm Copper Arc

A typical record for a 3 mm copper arc is shown as Fig. 3. Data taken from 15 oscillographic records of 4 kinds of copper are summarized in Fig. 4. It can be seen from these data that (1) the spread is relatively small, and (2) there are no systematic differences which may be ascribed to the type of copper used. In particular, the vacuum melted copper gave the same performance, within the spread of the measurements, as the same copper not so treated, and all pure samples agreed with commercial copper as far as the volt-ampere characteristic was concerned. From the volt-ampere curve of Fig. 4, one might determine n graphically, as in Fig. 5. Depending upon the choice of the asymptote A, the value of n lies some place in the range $0.1 < n < 0.4$. One could state quite certainly that it is not greater than 0.5, but a determination to the first significant figure is somewhat questionable, and a value of n carried to the third decimal place, as $n = 0.665$ (3 mm Cu arc, Nottingham[1]), would appear to be decidedly unwarranted. It is important to point out that the lack of accuracy is not fundamentally due to the graphical method used in determining n, but to the nature of the phenomena being investigated. If, for example, n is calculated by fitting three experimental points to a curve, the numerical value will vary greatly with the choice of the points.

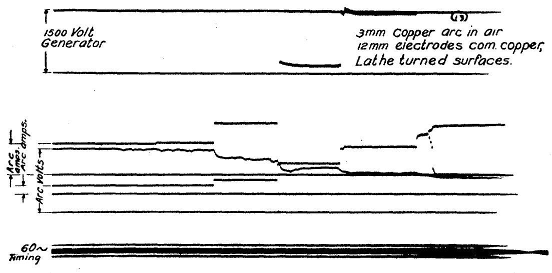

FIG. 3.

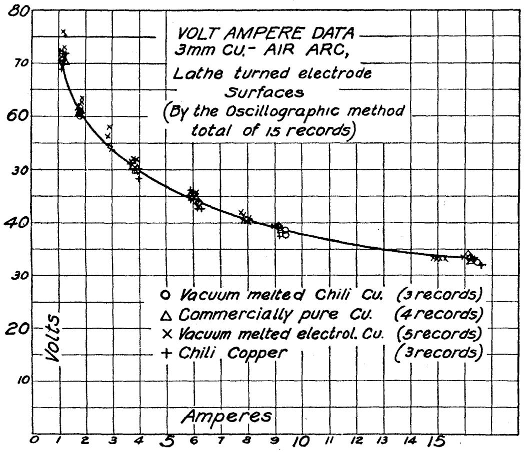

FIG. 4.

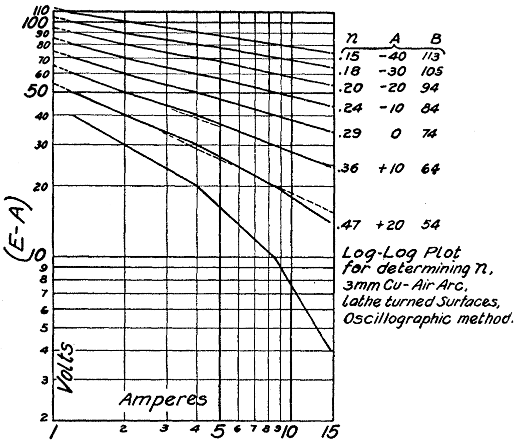

FIG. 5.

No question is raised as to the possibility of representing the experimental arc characteristic of Fig. 4 by an equation of the form of (1). The difficulty lies in the fact that n is not a sensitive constant. It is believed from these experimental data and from the considerations given that the evidence does not warrant the interpretation "the exponent n varies directly as the boiling point of the electrode (anode) material."[1]