SHORT-LENGTH TUNGSTEN ARC CHARACTERISTICS

By S. H. Anderson and G. G. Kretchmar

Abstract

The method used was a dynamical one. Oscillograms were taken giving the current through the arc and the p.d. across the electrodes (4 mm in diam.) as the latter were uniformly separated. This was accomplished by connecting the cam which separated the electrodes directly to the shaft of the oscillograph drum so that the exposure on the film was made while the arc gap was being lengthened. From the measurements of the oscillograms, curves are plotted giving p.d. as a function of current for constant gap length of from 0.005 mm to 0.4 mm, also curves giving p.d. against gap length for different constant current values from 2 to 12 amp. The intercepts of these latter curves on the voltage axis give the "minimal length" characteristic. It is found that (1) for an arc length 0.4 mm, and for shorter gaps where the current is 4 amp. or more, the characteristics are expressed by Nottingham's equation, $E=A+B/i^n$ where $n=1.49$; (2) the value of n for tungsten fits roughly the linear relation of n to the absolute temperature of the boiling point of the anode material, suggested by Steinmetz; (3) the minimal length characteristic is expressed by $E=13.2+1.05/(i-1.75)$, which makes it possible to compute the constants of an ignition or relay circuit so as to eliminate sparking between tungsten contact points.

I. Introduction

THERE has been renewed interest recently in the investigation of the characteristics of electric arcs for two reasons. (1) Information regarding the processes of ionization and values of ionizing potentials have become available so that a more detailed theory of the arc is possible; (2) a knowledge of the characteristics of arcs between metallic contact points is necessary in order to calculate the current potential-difference relations which occur upon opening circuits, such as the primary of an induction coil or an ignition circuit or a relay. K. T. Compton[1] has fully discussed the theory of the electric arc. Nottingham[2] has investigated the characteristics of a number of metallic arcs (copper in particular) and has extended the empirical equation of Ayrton. H. E. Ives[3] has shown the importance of the "minimal length" characteristics of arcs in computing the current potential-difference relations occurring in the discharge as contact points are opened, and has determined these characteristics for gold and platinum. Of all materials used for contact points tungsten is

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[1] K. T. Compton, Phys. Rev. **21**, 266 (1923).

[2] Nottingham, J. Am. Inst. Elec. Eng. **42**, 12 (1923).

[3] H. E. Ives, J. Franklin Inst. **198**, 4 (1924).

the most common, and apparently the most satisfactory yet found. So it is highly important to have information of the characteristics of arcs between tungsten electrodes.

II. METHOD AND EXPERIMENTAL ARRANGEMENT

The method used was a dynamical one. By means of an oscillograph a record was obtained of the current and the potential difference across tungsten contact points as they were uniformly separated. Fig. 1 shows some of the details of this method. An interrupter housing from a Bosch automobile ignition system was mounted on the frame of the oscillograph so that the cam operating the interrupter lever L could be directly connected to the shaft of the oscillograph drum. The cam C was made specially for this work. It was cut in the form of an Archimedean spiral so that for each revolution the contact points opened once. In operation the cam rotated against the fiber friction block of the interrupter lever, thus separating the contact points T_1, T_2 and producing a gap which could be predetermined from the form of the cam and the angular position. By means of a screw N and lock nuts the interrupter lever could be adjusted to secure proper bearing against the cam. The contact points were 4 mm in diameter, with the contact surfaces flat and carefully polished. Before each oscillogram was taken the surfaces were renewed.

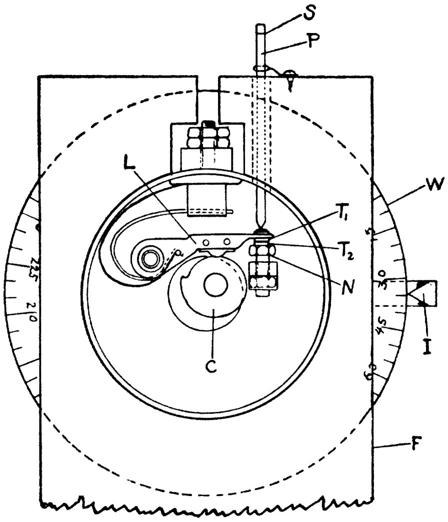

Fig. 1. Arrangement used to separate the tungsten contacts at a uniform rate.

The maximum separation produced was about 0.5 mm and was produced by a rotation of 225° after the initial separation, or in other words, the curves on the oscillogram were distributed over 225/360ths of the film length. The circular scale W marked in degrees was attached to the drive pulley on the shaft to give the angular position of the cam while making the calibration. The opening of the contact points was indicated by the motion of the pin P which rested on the interrupter lever just above T_1. The movement of P was read by a micrometer microscope.

Fig. 2 is a diagram of the electric circuits. The current through the arc was recorded on the oscillogram by means of a standard vibrator V_1 used in connection with the usual external shunt arrangement for current measurement. Three shunts were provided, each allowing a deflection of about 6 cm on the film for its rated capacity. The capacities were 5, 10, and 15 amp. respectively.

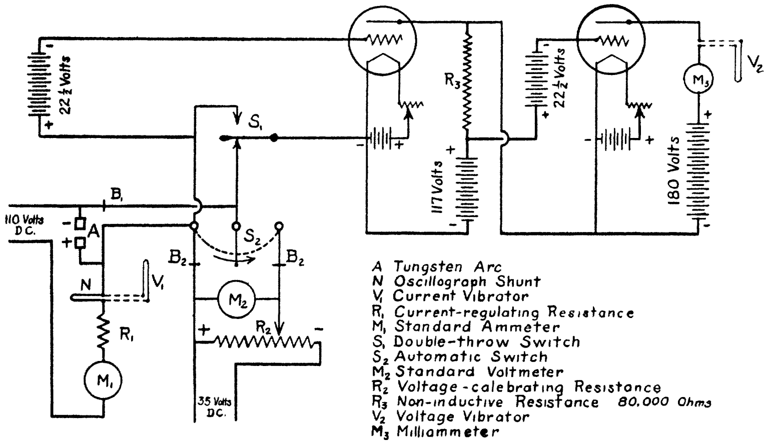

Fig. 2. Diagram of electric circuits

The voltage curve was taken simultaneously with the current on the same oscillogram, by means of a high sensitivity vibrator V_2 and a thermionic tube relay. The thermionic tube arrangement was used in order to give an electrostatic measurement of voltage, so that no current would be diverted from the arc for energizing the voltage vibrator. It consisted of a U.V.201A tube in combination with a Western Electric V.T.2. These were resistance coupled, and the resistance as well as the grid and plate voltages of the tubes were adjusted by trial, so as to give very little deflection for the first 10 volts, and to spread the voltage range from 10 to 30 volts over as great a distance on the film as possible. The values of resistance and voltage used are shown on the diagram.

Oxidation of the tungsten was reduced to a minimum by allowing the current to flow through the arc for about one-half second only, while the exposure was being taken. This was accomplished by means of an automatic switch S_2 which was connected across the arc terminals and was opened simultaneously with the shutter by means of an electromagnetic arrangement. A hand-operated switch (not shown in the diagram) was also connected across the arc terminals, and this was closed, shorting the tungsten contacts again immediately after pulling the string which opened the shutter of the oscillograph. The interval between the opening of the automatic switch and the closing of the hand switch was equivalent to about 3 revolutions of the cam and film drum, as the speed of the drum was about 400 r.p.m. throughout the tests.

The current for the arc was taken from a 110 volt storage battery and adjusted to the proper value by means of the usual regulating resistance in series. The external voltage was maintained at 110 volts throughout the tests. The oscillograph motor and field coils were supplied with 110 volts d.c. from the laboratory motor-generator set.

III. Calibration and Operation

Before making any oscillograms, accurate calibrations of the current vibrator and external shunts were made. This was done by sending the current through a standard ammeter in series with a regulating resistance and the shunt undergoing calibration. The deflection produced by the oscillograph vibrator on the ground glass was then carefully marked for a series of current values through the shunt, taking from three to five readings for each shunt. The deflections were then carefully measured and the resulting current-deflection curve was drawn as a calibration curve for the shunt. This was checked by the straight portions of the current curves on the final arc oscillograms.

The standard ammeter was checked with a potentiometer and standard cell, and was found to be correct within from 1/4 to 1/2 percent over the range used.

It was early apparent that the factors which would limit the accuracy of the work were (1) the measurement of the very small arc lengths, and (2) the oxidation of the tungsten contacts. The tungsten points were always carefully adjusted so that their flat surfaces made a close well-fitting contact. Each renewal of tungsten points made necessary a new calibration of the cam setting. The cam was set to open at the same point for each of the films. The calibrations were made by reading the gap width for each 15° for the first 75°, and then for each 30° up to the maximum value of the cam lift at 225°. This work was always carefully done in duplicate and the curves always showed a good agreement, the variation being less than .01 mm between the two sets of readings. To make sure that oxide was absent, new tungsten contacts were installed for each value of arc current used, except in a few cases where the same contacts were used the second time when a small current had been used at first which did not appreciably oxidize the tungsten.

The voltage calibration data were obtained by running calibration oscillograms. Because of the possibility of variation of the high voltage dry batteries used for the plates of the tubes, it was thought best to take these before, after, and during the operation of taking the arc oscillograms. This was accomplished easily by a special system of wiring which is shown in Fig. 2. When running a calibration oscillogram the arc was disconnected at B_1, and the automatic switch connected to the potentiometer resistance R_2 through the connections B_2. The standard laboratory voltmeter was connected across the potentiometer resistance at M_2. Each calibration line was obtained by setting the automatic switch in the open position, and adjusting the resistance R_2 until the meter M_2 indicated the voltage desired. The oscillograph shutter was then opened, closing the circuit through the automatic switch at the same time, thus throwing the voltage indicated on M_2 against the constant negative grid bias of the first tube, and giving a line on the film corresponding to the applied voltage. The switch S_1 was kept closed on the side of the $22\frac{1}{2}$ volt negative grid bias all the time of making the calibration, except during the time of taking the exposure, thus keeping the continuous output of the tubes down to a safe small value. Table I shows the average measurements taken from four calibration oscillograms.

TABLE I

Average measurements for voltage calibration curve.

Taken from oscillograms Nos. 4, 8, 11, 14 at positions 10° to 155°

Voltage	10°	32°	81°	120°	155°
0	0				
10	.10	.11			
12	.43	.43			
13	.73	.73			
14	1.07	1.07			
15	1.31	1.31			
17	1.69	1.69	1.69	1.67	1.67
19	2.34	2.33	2.33		
20	3.07	3.07	3.06	3.05	3.04
21	3.54	3.55	3.53	3.53	
23	4.16	4.15	4.14	4.12	4.11
25		4.54	4.52	4.50	4.48
26		4.74	4.72	4.72	4.70
30		5.36	5.34	5.32	5.30

The data of Table I show the effect of the space charge. The space charge seemed to exercise a reservoir effect giving slightly augmented values of the tube output until the excess electrons were used up, which occurred, for a speed of 400 r.p.m., after the drum had traveled 150°.

The effect was observable only for the larger voltage values used, appearing as a slight increase in the amplitude of the calibration line for voltages above 20 volts, and on the first part of the film record. The effect was taken into account on the calibration curve.

The operation of making an arc film was as follows. (1) The new tungsten points were properly adjusted and the cam setting calibrated. (2) The automatic switch was closed, thus short-circuiting the arc. (3) The oscillograph arc light was started and the adjustment of the vibrators tested. (4) The oscillograph shutter was set. (5) The thermionic tube filament currents were turned on and adjusted to the proper values by means of the ammeters in the filament circuits. (6) The film drum was attached and the motor started. (7) Exposure was made for the zero lines. (8) The current through the arc was adjusted to the value desired and the value recorded as observed on the standard meter M_1. (9) Making sure that the arc light was burning satisfactorily and that the tube filaments had remained constant, the shutter string was pulled making the exposure and then the hand-operated switch was closed. (10) The circuits were all opened and the film developed.

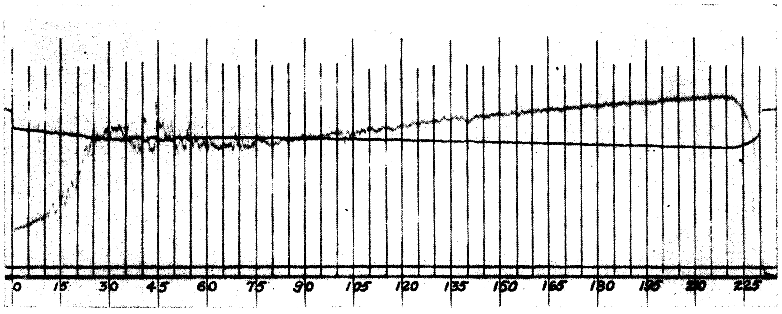

Fig. 3. Typical oscillogram and scale.

A typical oscillogram is shown in Fig. 3 which shows a film taken with the 5-ampere shunt and an initial current of 3.8 amp. The ruled scale shows the form used under the oscillograms during measurements.

IV. Results

1. *Arc characteristics.* In Fig. 4 are shown the arc characteristics obtained by plotting the potential difference against current. The lowest curve is the "minimal length" characteristic, obtained as described below. From this set of curves potential differences corresponding to different gap lengths for a constant current value were read off and plotted in

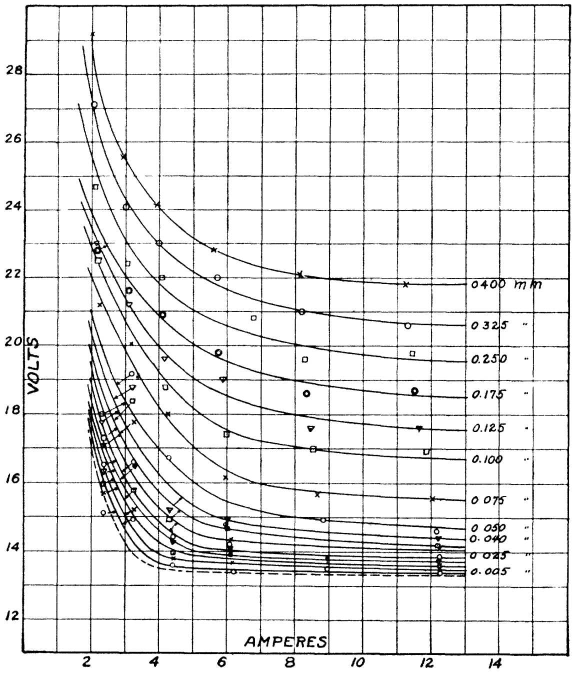

Fig. 4. Arc characteristics for constant length.

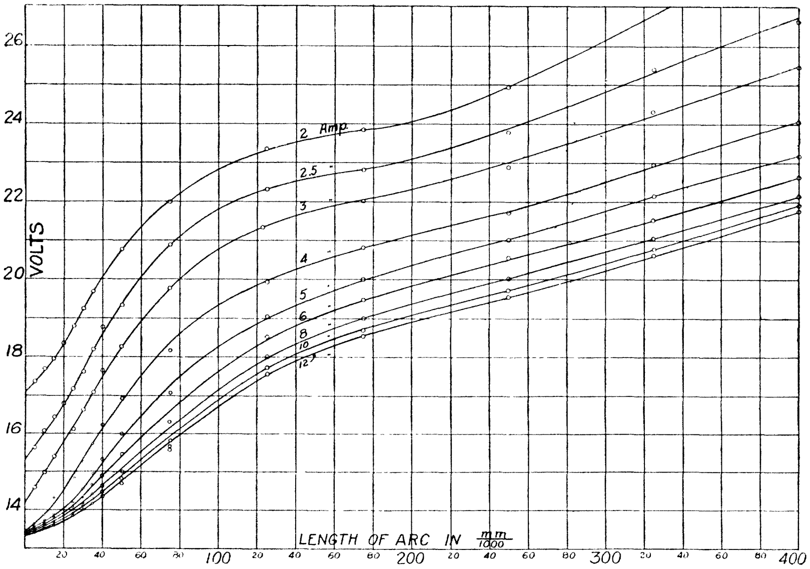

Fig. 5. Characteristics for constant current.

Fig. 5. It is interesting to note that while the general form of the curves in this set is similar to that found by other observers (for example Nottingham), the lower portion shows an upward inflection. This method has made it possible to obtain data for smaller gap lengths than previously reported, so that the intercepts of these curves on the voltage axis are given with considerable certainty. These intercepts, which are potential differences corresponding to currents of 2, 4, 6, 8, and 10 amp. respectively for zero arc length, were read off and plotted in Fig. 4 as the dashed line. *This is the "minimal length" characteristic for the arc between tungsten electrodes.* The convergence of the curves of Fig. 4 to the dashed curve is in agreement with the observation of Ives[3] for gold and platinum, that "the minimal length characteristic . . . . is obviously a member of the family of finite length characteristics."

2. *Equation for arc characteristic.* Nottingham[2] has proposed the following empirical equation for arc characteristics

$$E=A+B/i^n$$

in which E is the potential difference across the arc, i the current, A and B constants for a given arc length and electrode material, and n a constant characteristic of the material but independent of the length. This may be considered a more general form of the equation found by Mrs. Ayrton[4] to hold for carbon arcs. The constants of this equation can be evaluated only by a semigraphical method.[5] Values of A were found for ten gap lengths from 0.4 mm to 0.03 mm, and then log $(E-A)$ plotted against log i (Fig. 6). For two larger gaps, 0.4 mm and 0.325 mm, the points are uniformly distributed about a straight line and the two lines are nearly parallel. So we may conclude that for gaps of the order of 0.4 mm (and probably larger) Nottingham's equation holds for the tungsten arc in air. The slopes of these lines gives the value of n. The average for the two upper lines is 1.487. For gaps smaller than 0.325 mm the upper points depart considerably from a straight line, but the lower points ($i>4$ amperes) lie very close to a straight line parallel to those of the larger gap. Using the straight portion of the first five logarithmic graphs, the average value is nearly the same, 1.48. An inspection of Fig. 4 suggests that, while the lower curves differ in form from the upper, the whole set is one family of curves and it should be possible to find an equation which would hold for all. However, an attempt to do this will be

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[4] Hertha Ayrton, The Electric Arc, The Electrician Printing and Publishing Co., London, 1902.

[5] Lipka, Graphical and Mechanical Computation, John Wiley & Sons, New York, 1918, p. 140.

deferred until a redetermination of the characteristics is made with greater precision. In the present work the possible error in the potential difference is ±1.0 volt which makes the exact form of the curves rather uncertain.

3. *Equation for minimal length characteristic.* Ives found that the minimal length characteristics for carbon, gold, and platinum can be satisfactorily represented by the following equation

$$E = a + \gamma/(i - c).$$

Furthermore, this equation is well adapted to the calculations involved in determining the constants of a circuit such that the arcing is a minimum at the opening of contacts. Within the limits of experimental error this equation will also serve for the tungsten minimal length characteristic, the equation after determining the constants being given by

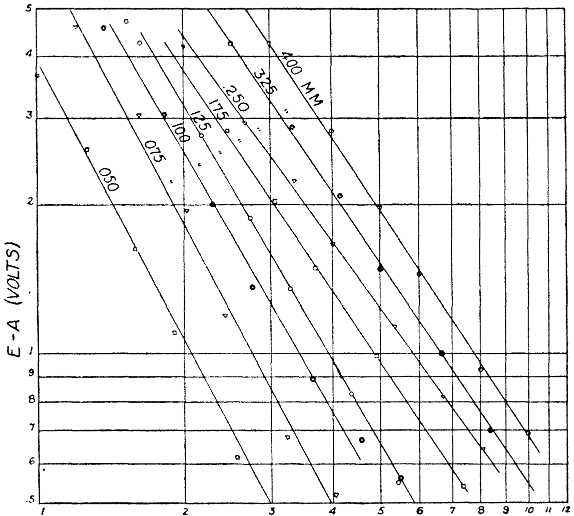

Fig. 6. Log $(E - A)$ as a function of log i.

$$E = 13.2 + 1.05/(i - 1.75).$$

From this it is seen that *the arc will not persist when the current is 1.75 amperes or less, no matter what potential difference is applied at the electrodes.* This agrees with observations made for small current values. No oscillograms of a persisting arc were obtained when the initial current was less than the above value.

4. *Relation of* n *to the temperature of the boiling point of the electrode metal.* Steinmetz[6] suggested that the temperature of the vapor in the arc is a constant depending upon the boiling point or sublimation point of the material of the anode. Nottingham, following out this suggestion, proposes that the constant *n* of his equation is a linear function of the absolute temperature of the boiling point or sublimation point of the material of the anode, and obtains a table of values that fit a straight line very well. However, for the anode of aluminum, cadmium, and zinc respectively he uses the boiling point of the metallic oxide rather than the metal. We have extended Nottingham's graph by two points, computing *n* for platinum from Ives curves[3] and *n* for tungsten from our own work. This is shown by Table II and Fig. 7.

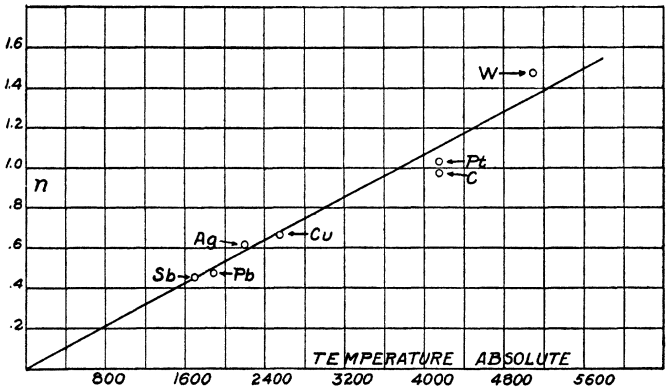

Fig. 7. Constant *n* of Nottingham's equation as a function of boiling temperature.

TABLE II

Cathode	Anode	*n*	Authority	Boiling point	Authority
carbon	antimony	0.460	Nottingham	1710°K	Greenwood 1910
carbon	lead	0.480	“	1883	Van Liempt 1920
carbon	silver	0.624	“	2214	“ “ “
copper	copper	0.670	“	2562	“ “ “
copper	carbon	0.985	“	4187	“ “ “
platinum	platinum	1.15	Ives (Anderson)	4180	Langmuir 1914
tungsten	tungsten	1.487	Anderson & Kretchmar	5100	“ “

The temperatures used were taken from Landolt-Bornstein Physikal-ischen-Chemische Tabellen, Fifth Edition, 1923 (except for platinum and tungsten) and are not quite the same as those given in Nottingham's paper. The questionable materials, aluminum, cadmium, and zinc are omitted from Table II and Fig. 6. Within the limits of experimental

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[6] Steinmetz, Radiation, Light and Illumination, McGraw-Hill, New York, p. 140.

error the points fit a straight line. If more precise determinations verify the validity of Nottingham's equation and the linear relation of n to the absolute temperature of the boiling point of the anode, we shall have a new method of finding the boiling points of metals.

We wish to express our appreciation of the assistance given in this experimental work by the Bosch Magneto Corporation who furnished materials and by Mr. L. F. Curtis, Chief Engineer, who gave valuable advice and suggestions from his experience with ignition circuits. The oscillograph used was kindly loaned by the Department of Electrical Engineering, University of Washington.

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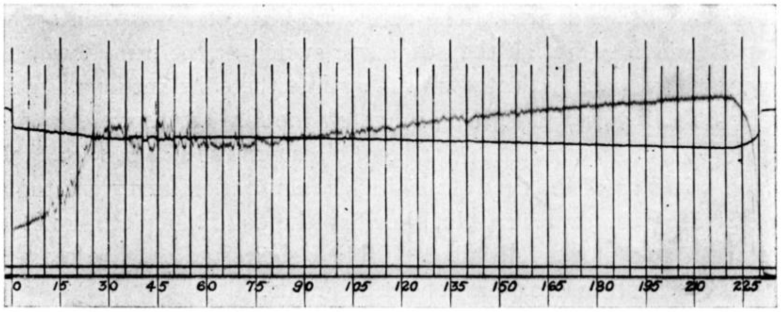

Fig. 3. Typical oscillogram and scale.