MC 0241 . Publications, 1923 - 1930

BOX 7 FOLDER 34

1926

NORMAL ARC CHARACTERISTIC CURVES: DEPENDENCE ON ABSOLUTE TEMPERATURE OF ANODE

A DISSERTATION

PRESENTED TO THE
FACULTY OF PRINCETON UNIVERSITY
IN CANDIDACY FOR THE DEGREE OF
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W. B. NOTTINGHAM

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Abstract

The equation $V=A+(B/I^n)$ for normal arc characteristic curves has been verified and the temperature range over which n has been found to be proportional to the absolute temperature of the boiling point of the anode material has been extended to include the zinc arc in argon at 1180°K with 0.345 for n and the tungsten arc in air at approximately 5100°K with $n=1.38$.

The static characteristic curves of the normal electric arc can be measured with the simple circuit shown in schematic in Fig. 1. After the electrodes have been brought into contact and separated a given distance, the current I flowing through the arc and the voltage V across the arc can be measured at a number of different current intensities. The graphical representation of such a series of measurements is usually called the "characteristic curve" of the electric arc. Four typical curves are shown in Fig. 2. The top-most curve shows measurements taken by Mrs. Ayrton on the carbon arc, the next two are from measurements on tungsten and zinc arcs in air and the lowest shows the zinc arc in argon.

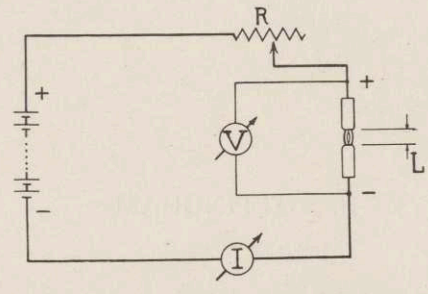


Fig. 1. Circuit for measuring arc characteristics.

It is obvious that these curves are hyperbolic in form and are apparently asymptotic to zero current on the left hand and to some value of voltage other than zero, below. The most natural assumption therefore is that these data can be represented by a simple empirical equation[1]

$$V=A+(B/I^n).$$

A and B are constants dependent on the length of the arc, the electrode

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

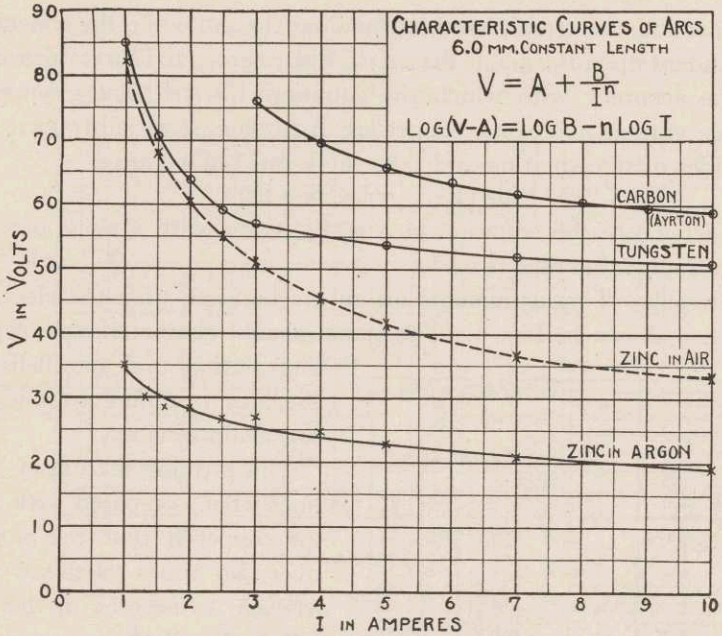
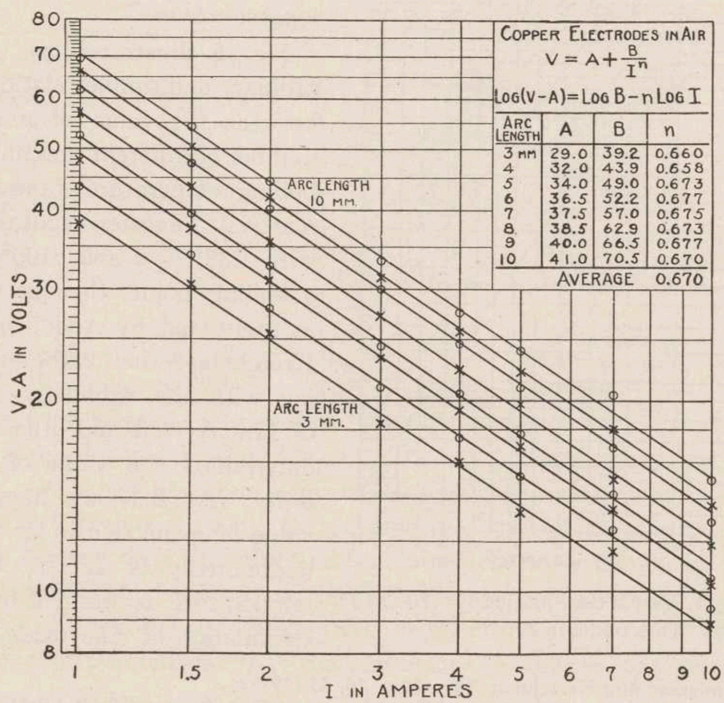


Fig. 2. Characteristic curves of arcs; 6.0 mm constant length.



ARC LENGTH	A	B	n
3 MM	29.0	39.2	0.660
4	32.0	43.9	0.658
5	34.0	49.0	0.673
6	36.5	52.2	0.677
7	37.5	57.0	0.675
8	38.5	62.9	0.673
9	40.0	66.5	0.677
10	41.0	70.5	0.670
		AVERAGE	0.670

Fig. 3. Test of the equation $V = A + (B/I^n)$ for copper electrodes in air.

materials and the atmosphere surrounding the arc while the constant n is dependent upon the anode material. Fig. 3 serves to illustrate graphically the accuracy with which the equation $V=A+(B/I^n)$ represents the observations made on a copper arc in air since if we subtract A from both sides of the equation and take the logarithm we have

$$\log (V-A) = \log B - n \log I$$

which is simply the equation of a straight line with a slope of $(-n)$. The average value of n is 0.67.

The results of measurements on an arc between tungsten electrodes in air are shown in Fig. 4. The same general characteristics of point distribution and parallelism of the lines for different arc lengths are again obvious.

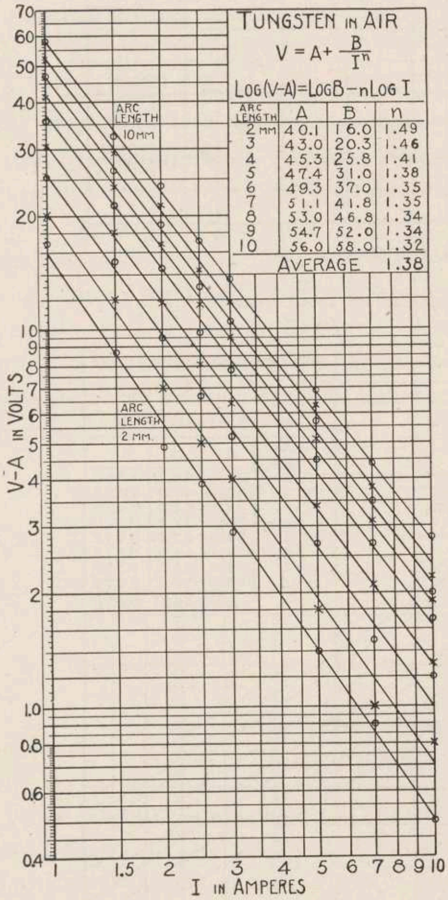


Fig. 4. Test of the equation $V=A+(B/I^n)$ for tungsten electrodes in air.

The striking feature of these lines when compared with those for copper is that the slope is over two times as great. The average value of n in this case is 1.38 for all of the arc lengths and 1.34 if we average the six longest curves.

Fig. 5 illustrates an extraordinary and simple relationship between the value of n for a number of different arcs and the boiling temperature of the anode material. Tungsten heads the list with 1.38 for n and 5100°K for a boiling point; then platinum as calculated by Anderson and Kretchmar;[2] then carbon agreeing with the exhaustive work of Mrs. Ayrton[3] and others who determined the value of n as unity. At 0.57 we have the value of n for zinc in air which undoubtedly is an arc whose temperature is limited by the sublimation of zinc oxide. The

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

[3] Heartha Ayrton, The Electric Arc: "Electrician" Printing & Publishing Co., London.

value of 0.345 has been determined for zinc from a few preliminary measurements in argon and fits fairly well on the curve with a boiling temperature of 1180°K.

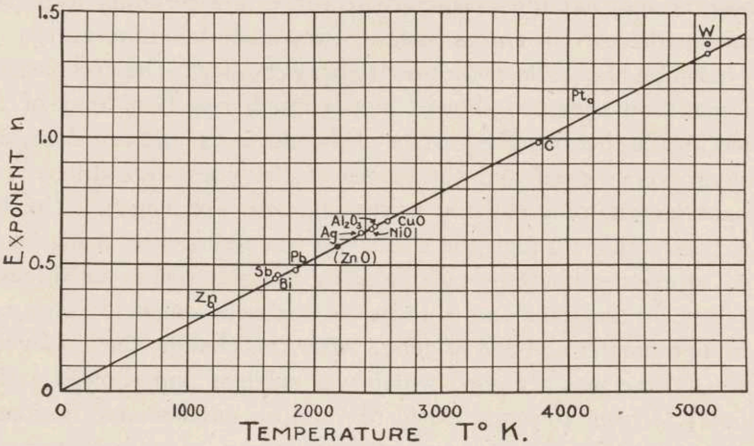


Fig. 5. Illustrating the variation with anode temperature of the exponent n in the equation $V=A+(B/I^n)$

TABLE I

The exponent n depends on the anode temperature.

Anode	Cathode	n	T° K	Authority
Tungsten	Tungsten	1.380	5100	Langmuir
Platinum[2]	Platinum	1.150	4180	Langmuir
Carbon[3]	Carbon	1.000	3770	Van der Waals
Carbon[1]	Copper	0.985	3770	Van der Waals
Copper[1]	Copper	0.670	2580	Greenwood
Aluminum[1]	Carbon	0.650	2480	Ruff-Schmidt
Nickel[1]	Carbon	0.640	2450	Hagenbach-Langbein
Nickel	Nickel	0.640	2450	Hagenbach-Langbein
Silver[1]	Carbon	0.624	2370	v. Wartenberg
Zinc(air)[1]	Carbon	0.570		
Zinc(air)	Zinc	0.570		
Lead[1]	Carbon	0.480	1850	v. Wartenberg
Antimony[1]	Carbon	0.460	1710	Greenwood
Bismuth[1]	Carbon	0.445	1690	Greenwood
Zinc(argon)	Zinc	0.345	1180	Braune

This relationship $n=2.62\ (10)^{-4}T$, where T is the temperature of the anode is so simple and thus seems to be so well borne out by these points, eleven in all, that it should be recognized as one of the observed facts of the electric arc. It unifies certain divergences of opinion as to the true form of the characteristic curves and may possibly point the way, or serve as a test for a comprehensive theory of the arc. In 1907 Malcom and Simon[4] pointed out that the power curves, that is, curves plotted

[4] Malcom and Simon, Phys. Zeits. **8**, 471 (1907).

with power as the ordinate and current as the abscissa for all arcs measured by them were concave toward the current axis, with the exception of carbon which was straight. Steinmetz[5] stated as a result of his observations that the characteristic curves are certainly hyperbolic in form but the current enters with a power much less than unity.

The question may arise, is the anode always boiling? The first measurements made on tungsten showed slopes much less than that of 1.34 required by the theory. The surface of the electrodes did not show signs of having even melted and the slopes of the lines were different for every arc length, progressively increasing with arc length. The heat lost by conduction through the electrodes was reduced by using "collar button" electrodes made by cutting away the material so as to leave a disk 1/2 in. in diameter and 3/16 in. in thickness supported on a neck 3/32 in. in diameter and 3/8 in. long. After this change, the log I versus log $(V-A)$ line was obtained which was straight and showed a slope of about 1.34 from 10 amps. down to 4 amps., but deviated noticeably from the straight line for currents below 4 amps. It was necessary to reduce the heat lost by conduction even more before the data shown by Fig. 4 were taken which shows the lines to continue straight even for currents as low as 1 amp. All of these measurements prove that the characteristic curves can be represented by $V=A+(B/I^n)$ only when the temperature is stabilized at some point throughout the series of measurements. The boiling or sublimation of the anode performs this function in the normal arc, and Fig. 5 illustrates in a very convincing manner the universality of the relationship $n=2.62(10)^{-4}T$ where T is the stabilized temperature of the anode.

To the New Jersey Zinc Company, The Driver Harris Company, and the Research Department of the General Electric Company, I am indebted for supplying some of the materials used, while to the Department of Physics of Princeton University, and in particular to Professor K. T. Compton, I am grateful for the privilege of carrying on this research.

Palmer Physical Laboratory
Princeton University,
Princeton, New Jersey.
June 12, 1926.

[5] Steinmetz, Chem. and Met. Eng. **22,** 455 (1920).