High Pressure Arcs in Common Gases in Free Convection

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An oscillographic method is described for measuring the electric gradient E (volts cm^{-1}), current density I (amp. cm^{-2}), total voltage e (volts) as a function of current i in the discharge. The method is applied to arcs in the 0–10-ampere range under conditions of free convection in N_2, A, and He in the 1–50-atmosphere pressure range, and to air, CO_2, and steam at atmospheric pressure. The exponent n and B in $E=Bi^{-n}$ are determined for these cases. The range of n is $0.54<n<0.73$, and some dependence on pressure is observed. The exponent m in $E=B_0p^m$ is measured for N_2, H_2, He, and A, and is found to be 0.31, 0.32, 0.20, and 0.16, respectively, with some dependence on current. The method is applied to arcs between electrodes of a number of common metals in air.

INTRODUCTION

THERE exists nowhere in the literature a comprehensive set of measurements of the important electrical quantities in the positive column of the arc in common gases. This information must be reckoned as fundamental to the understanding of the mechanism and to the development of the theory. For the purpose of this study we consider the following measurables: E—electric gradient (volts cm^{-1}); I—current density (amp. cm^{-2}); i—arc current (amp.); in the region of the positive column as described below. By the method of measurement the total arc voltage e is also recorded, but since e is determined partly by electrode properties and phenomena, it is of secondary importance for the present purpose.

EXPERIMENTAL METHOD

Previous measurements of arcs at atmospheric and higher pressure[1] have indicated that the pressure range up to 100 atmospheres was sufficiently great to develop prominent changes in the electrical constants of the arc and that in this pressure range some new measurement methods would have to be developed, especially for E. In an arc in N_2 (at one atmosphere, 10 amperes, and 10 mm), $e=73$ volts, while E is only 21 volts cm^{-1}. Thus the 7-mm portion of this arc which represents the positive column accounts for only 20 percent of the total arc voltage. In view of the fact that the spread in e under the best measurement conditions is 10 percent, the difficulty of determining E as a difference in arc voltage for a change in arc length is apparent.

A very satisfactory solution of this problem was found in a vibrating electrode. It is the change of voltage Δe resulting from a change in arc length Δl at constant current from which the gradient E is calculated, as $E=\Delta e/\Delta l$. Comprehensive experiments were undertaken to discover how rapidly the change in arc length can take place without altering Δe. It was found that for arc lengths in the 10-mm range and for Δl of one- or two-mm Δe is independent of the frequency at which the arc length is changed for frequencies at least as high as 30 per second. More recent measurements under a variety of experimental conditions confirm this conclusion. The interpretation of this experimental fact is that the steady state in the thermal and electrical process is established in a time short compared to the period of the vibrating electrode. This equilibrium time, or thermal time constant, is known from numerous experiments[2, 3] and is approximately 0.001 second in arcs in air at atmospheric pressure.

Measurement of gradient by means of the vibrating electrode is accomplished as follows. The vibrating mechanism is driven by a synchronous motor at 30 vibrations per second. The resulting 30-cycle component of voltage is selected by a 30-cycle band-pass filter and amplifier system and applied to a galvanometer of the oscillograph. This filter has a time constant of about one cycle at 30 cycles, so that its response to gradient changes is very rapid.

[1] C. G. Suits, J. App. Phys. **10**, 203 (1939).

[2] C. G. Suits, Gen. Elec. Rev. **39**, 194 (1936).

[3] H. Witte, Zeits. f. Physik **88**, 415 (1934).

The procedure of selecting only the 30-cycle component in the arc voltage permits a great improvement in the accuracy of measuring E, since it suppresses much of the random variation in arc voltage.

Very little appears in the literature on the causes of the random voltage variations (r.v.v.) which characterize the high current, high pressure arc with nonthermionic cathodes. It is known that in air at a pressure of one atmosphere (1) the arc voltage at constant current shows a random variation around a mean value for all electrode materials at some values of current and electrode diameter; (2) the r.v.v. is entirely absent in the 1–10-ampere range if electrode dimensions are so chosen that the cathode becomes incandescent for pure carbon, cored carbon, tungsten, and possibly some other electrode materials in air, nitrogen, hydrogen, argon, helium, and mercury; (3) the r.v.v. is absent in mercury vapor in the 1–30-atmosphere range for oxide-coated cathodes in the 0.5-ampere range; and (4) of the nonthermionic metallic electrodes, the r.v.v. is a minimum with polished copper.

TABLE I. *Arc gradient E as function of length l.*

E (v cm^{-1})	125	71	60	54	53	53	53
l (mm)	0	1	2	3	4	6	8

As a result of investigation, pure carbon electrodes were chosen as the best from the standpoint of r.v.v. in the subsequent experiments in the 50-atmosphere pressure range. It was found necessary to adjust the electrode diameter from 1.5 mm at one atmosphere to 6 mm at 30 atmospheres for best results in nitrogen. Above 30 atmospheres no electrode condition was found which would eliminate r.v.v. in the 10-ampere current range. Precise measurements of arc electrical properties, therefore, do not extend much above this pressure. By the vibrating electrode method which has been described, and by the use of pure carbon electrodes of a size adjusted to the pressure range, the measurement of E can be carried out to a satisfactory degree of accuracy.

It appears that the only high pressure arcs free from r.v.v. are those which have stable thermionic cathode emission capable of accommodating the cathode current densities imposed by gas pressure, and that above 30 atmospheres (in N_2) there is no thermionic cathode material which can provide sufficient emission in the 10-ampere range.

There remains the question of the dependence of gradient on arc length. This is shown by the data of Table I, which were taken for an arc in air with a maximum amplitude in electrode vibration of 4.6 mm. The gradient of 125 v/cm at zero arc length means that this is the total voltage change divided by 0.46 cm when the vibrating electrode just failed to short-circuit the arc. In this region the apparent gradient would be higher if the amplitude of vibration were smaller. The characteristic feature shown by Table I, however, is that in air (and in most common gases) the gradient is constant when the arc length exceeds approximately 3 mm. Observations of the diameter also show that the arc column assumes a constant maximum cross section when the length is greater than 3 mm. This region of constant diameter, constant gradient is analogous to the positive column in a

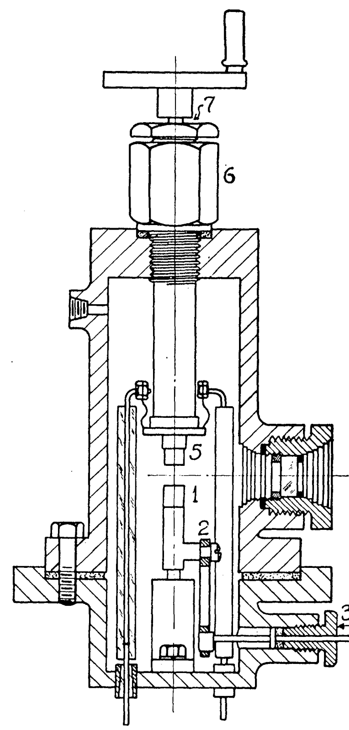

FIG. 1. Arc chamber with vibrating electrode.

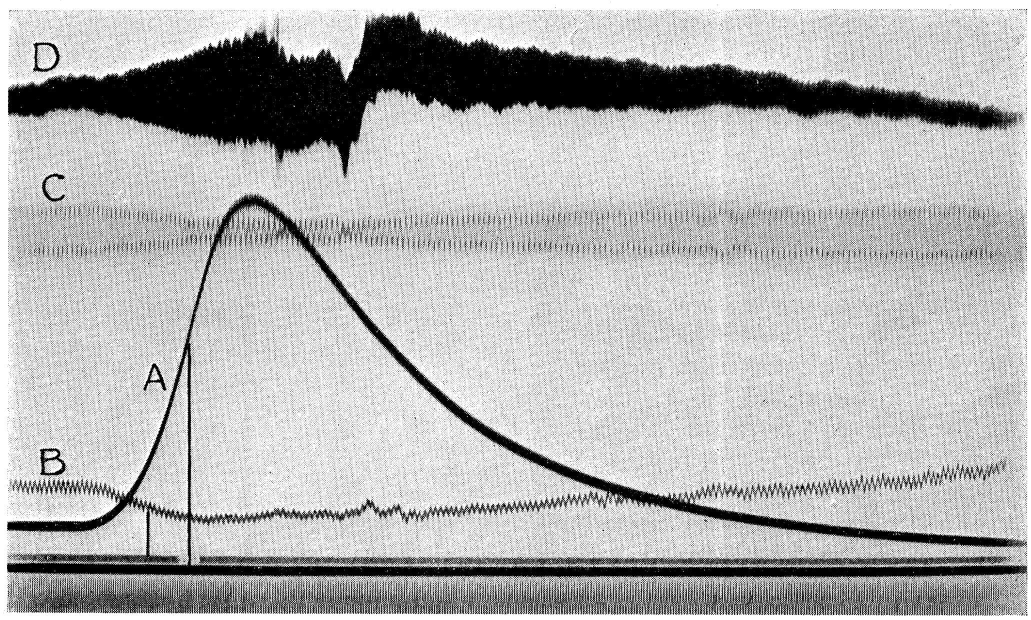

FIG. 2. Oscillographic record of an arc in nitrogen at one atmosphere pressure in the vibrating electrode chamber. A, arc current. B, total arc voltage. C, gradient in positive column. D, diameter (proportional to width of trace) of the arc column midway between electrodes.

low pressure discharge, and for convenience will be referred to as the positive column here. The measurements reported below were made at a mean arc length of 10 mm in all gases, and they are therefore properly interpreted as the gradient in the positive column of the high pressure arc in the above sense.

The diameter of the arc column is the next important quantity in the high pressure arc. In the present experiment it is measured photographically by forming an image of the arc on the film with a lens mounted on the oscillograph. This image is taken through a slit system which selects a section through the arc perpendicular to the axis and midway between the electrodes. To minimize photographic errors the exposure is adjusted at the maximum current to give a density of approximately one on the film with a set of neutral density filters and by adjustment of lens aperture. Errors due to a *variation* of exposure within a given record are discussed below.

The method therefore measures on a single record the arc voltage e, gradient E, and oscillographic diameter D as a function of current and yields the approximate luminosity.

An arc chamber with a vibrating electrode is shown in Fig. 1. Two observation windows are provided, and the strength of structure is sufficient for use up to 200 atmospheres pressure. The lower electrode, 1, can be vibrated through a total amplitude adjustable from zero to 5 mm by means of an arm, 2, and eccentric operated through the bushing, 3, by shaft, 4. The upper electrode, 5, is adjustable vertically through a range of 20 mm by a worm and pin arrangement, which can be operated externally at the highest pressures by rotating the shaft, 7, in the bushing, 6. Starting the arc is accomplished by bringing the electrodes in contact. This design of chamber has been very satisfactory for this pressure range.

An oscillographic record of the arc in nitrogen at a pressure of one atmosphere in the vibrating electrode chamber is shown in Fig. 2. Trace A is the arc current, B the total arc voltage, C the gradient in the positive column, and D the diameter (proportional to the width of the trace) of the arc column at a point midway between the electrodes. Thus a single oscillogram records the chief electrical measurables as a function of current for a given experimental condition.

The current density, lumen efficiency, and brightness data of this study form the subject matter of a separate paper. We now proceed to consider the gradient measurements.

Experimental Results

E and *e* for nitrogen

The chief results obtained with the vibrating electrode chamber are given below. In Fig. 3 the total arc voltage e and the gradient E are plotted for the same set of eight records for nitrogen at one atmosphere pressure. Individual points are shown for the purpose of illustrating the spread in the measurements. The spread in E is much greater than in e, although the absolute deflections on the oscillograms were from two to three times greater for E than for e. This spread in E must, therefore, represent a real variation in the gradient, possibly because the mid-portion of the arc column is most sensitive to convection forces. Within the spread of the measurements the log $E-$log i relationship is linear; hence

$$E=Bi^{-n}, \tag{1}$$

where $B=84$, $n=0.6$, for nitrogen at $p=$one atmosphere.

In fact the gradient data for all of the gases studied (with the possible exception of air), over the entire pressure range at which accurate measurements can be made, fit an equation of the form (1), which can therefore be regarded as a general equation for the gradient of the steady-state high pressure arc. The values of B and n for different gases and pressures appear below.

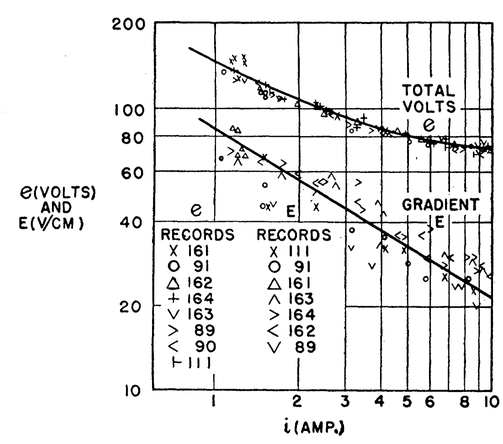

Fig. 3. Total arc voltage e(volts) and electric gradient $E(v/\mathrm{cm})$ for an arc between pure carbon electrodes in N_2 at one atmosphere (arc length one cm).

The log $e-$log i relation is definitely not a straight line, but can be made so quite closely by adding a constant A to the ordinate; this involves the assumption of an $e-i$ expression of the form

$$e=A+B/i^n. \tag{2}$$

The A can be determined by a number of methods, but if (2) is valid, it must allow a choice of an A which is constant for the values of B and n previously determined by direct experiment. We therefore substitute values of $B=84$, $n=0.6$, and determine A from Fig. 3, with the results shown in Table II. It can be seen that for currents in the 2–10-ampere range A is constant within ± 4 percent. We conclude that

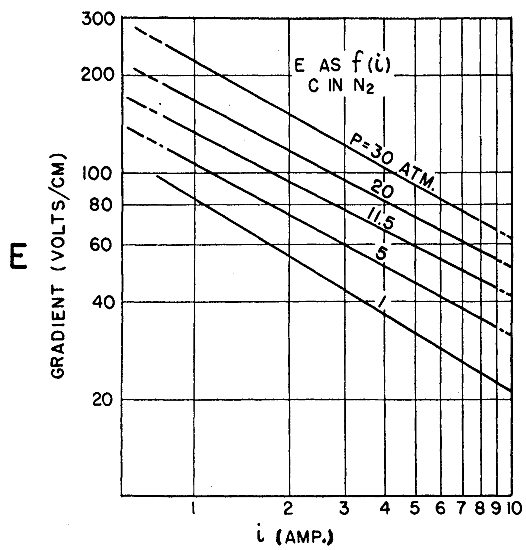

Fig. 4. Gradient as a function of arc current for nitrogen at various pressures (carbon electrodes).

$$e=51+84/i^{0.6}$$

is a satisfactory approximate expression for the total arc voltage of the one atmosphere nitrogen arc of length 1 cm.

An alternative method of determining the constants of an equation of the form of (2) is to plot log $(e+A)$ and log i, adjusting the value of A to obtain the best straight line.[4, 5] The n is

[4] C. G. Suits, Phys. Rev. **46**, 252 (1934).
[5] W. B. Nottingham, Phys. Rev. **28**, 764 (1926).

then calculated for the selected value of A. For the present case a value of 0.9 ± 0.2 is obtained by this method. This value should be compared to the direct experimental value of $n=0.6$. The example points out the fallacy of interpreting n in terms of gradient from $\log(e+A)-\log i$ plots, since the method fundamentally lacks sufficient accuracy for this purpose.

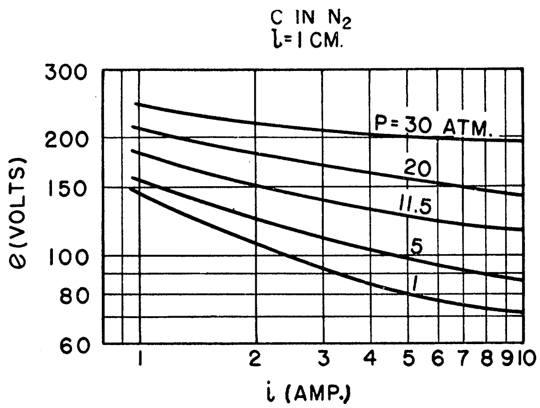

FIG. 5. Arc voltage as a function of arc current for nitrogen at various pressures (carbon electrodes).

The $\log E - \log i$ characteristics for nitrogen at 1, 5, 11.5, 20, and 30 atmospheres are given in Fig. 4; the values of n (Eq. (1)) for these pressures are shown by Table III. Although n shows an extreme range of 0.51 to 0.60, an average value of $n=0.55$ would be consistent with the results over the whole range of pressure. The family of curves for $e-i$ for the pressure range up to 30 atmospheres is shown as Fig. 5.

E for helium and argon

By the method outlined above, the gradient in steady-state arcs between pure carbon electrodes has been determined for He, A and H_2. Fig. 6 shows the $\log E - \log i$ curve for He between 1 and 48 atmospheres. The dotted portions of the curves represent extrapolations beyond the best experimental points. The arc in He is stable and reproducible and resembles the N_2 arc in many respects. The gradient in He is somewhat higher than in N_2; the difference becomes less at higher pressure. The exponent n (Eq. (1)) is given in Table IV over this pressure range.

TABLE II. *Values of* $A = e - 84/i^{0.6}$.

e	145	107	84	77	74	73
i	1	2	4	6	8	10
A	61	52	48	49	50	52

TABLE III. *Values of n for nitrogen, 1–30 atmos. pressure.*

p (atmos.)	1	5	11.5	20	30
n	0.60	0.53	0.51	0.52	0.54

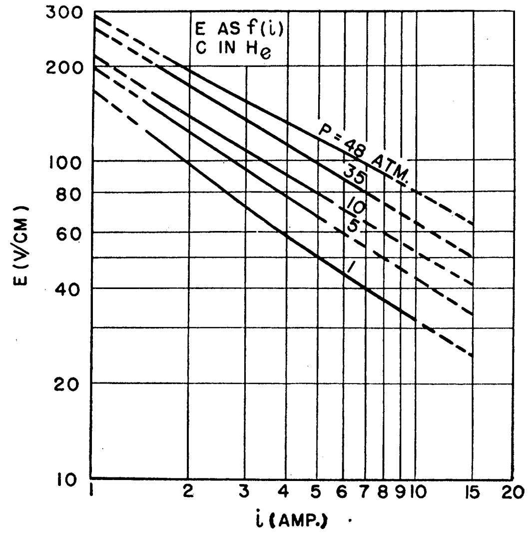

FIG. 6. Gradient as a function of arc current in helium at various pressures (carbon electrodes).

Similar data for argon are given by Fig. 7 and Table V. The arc in argon is characterized by a low gradient and a very small change of E with p, particularly at low current.

Because the hydrogen arc shows some unusual features not found in the case of N_2, He and A, these results are being reported in a separate paper. In a summary of results at the end of the present paper, however, the gradient for the normal arc state of hydrogen is included.

Arc gradient for metallic electrodes in air

The gradient data above apply to cases of pure carbon electrodes in gases of 98 percent purity, that is, to metal-vapor-free arcs in which the thermal ionization of the gas provides the electron density required for current conduction. One may expect the above results to be correct for arcs between metallic electrodes in cases in which, because of high thermal conductivity and low vapor pressure, the metal vapor concentration is low. Favorable electrode materials in this respect are tungsten, molybdenum, clean (for

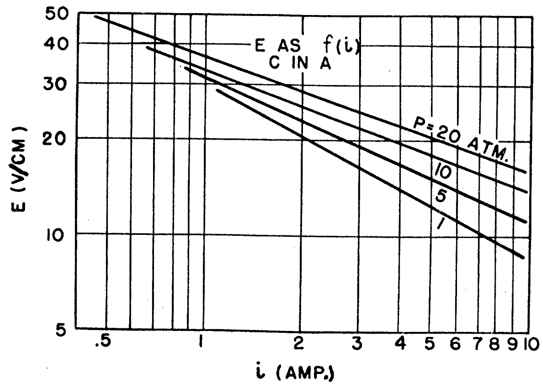

FIG. 7. Gradient as a function of arc current in argon at various pressures (carbon electrodes).

example, polished) copper and silver. In these arcs in this current range the gradient E cannot be distinguished from pure carbon. In the case of other metals the effect of the metal vapor is such that it lowers the gradient by an amount which is greater than the uncertainty of measurement.

The spread in the measurements is large, however, because of the random voltage variation and other causes. When the data are taken in air, the absence or presence of the oxide and the condition of the surface influence the results. This is illustrated in the case of copper by Fig. 8 where gradient E (measured with a vibrating electrode) is plotted as a function of current. Three surface treatments were used, as indicated. The gradient is consistently lower for electrodes which are heavily coated with oxide, higher for freshly turned surfaces, highest for electrodes with polished surfaces. Also the effect is most pronounced at high currents. It is not immediately evident from this result that discrete states for the Cu arc, characterized by relatively small voltage differences, could be identified as reported by White[6] and Fry.[7]

TABLE IV. *Values of the exponent n in Eq. (1) for helium.*

p (atmos.)	1	5	10	35	48
n	0.72	0.66	0.61	0.61	0.56

TABLE V. *Values of the exponent n in Eq. (1) for argon.*

p (atmos.)	1	5	10	20
n	0.53	0.45	0.38	0.35

TABLE VI. *Exponent n of the gradient equation for various gases.*

Gas	Hg	A	N_2	Air	CO_2	He	H_2O	H_2
n	0.26	0.54	0.60	0.60	0.60	0.73	0.59	0.70

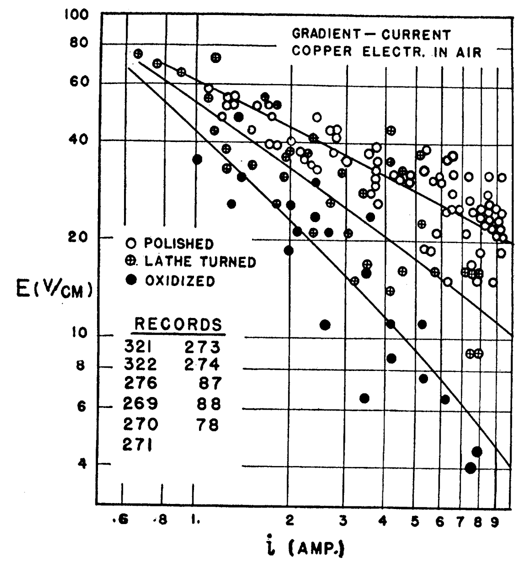

FIG. 8. Gradient as a function of arc current for copper electrodes in air.

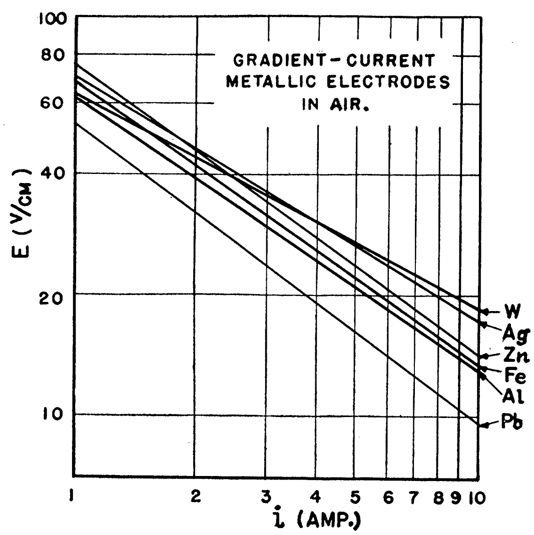

FIG. 9. Gradient as a function of arc voltage for various metallic electrodes in air.

Curves for a number of additional metals are shown in Fig. 9. At 10 amperes one might form three groups on the basis of gradient. In the first group, characterized by high gradient, are W,

[6] A. B. White, Phys. Rev. **53**, 935 (1938).
[7] A. S. Fry, Phys. Rev. **51**, 63 (1937).

Ag, Cu and C. In the second group one can place Zn, Fe and Al; and, finally, the lowest gradient grouping would include Pb.

Comparison of Gradient Data for Various Gases

The plot of Fig. 10 shows the log $E-\log I$ data for the gases He, N_2 and A, discussed above, together with the H_2 data and some additional measurements on steam and CO_2, and Elenbaas'[8] results for mercury vapor at one atmosphere. In Table VI the values of n for arcs in these gases are given.

A detailed discussion of this gas effect together with the pressure effect will be deferred to another paper, in which it is shown that[9] the changes in gradient correlate with the conduction-convection heat transfer properties of the gaseous medium.

From the approximate proportionality between log E and log i we have determined m in

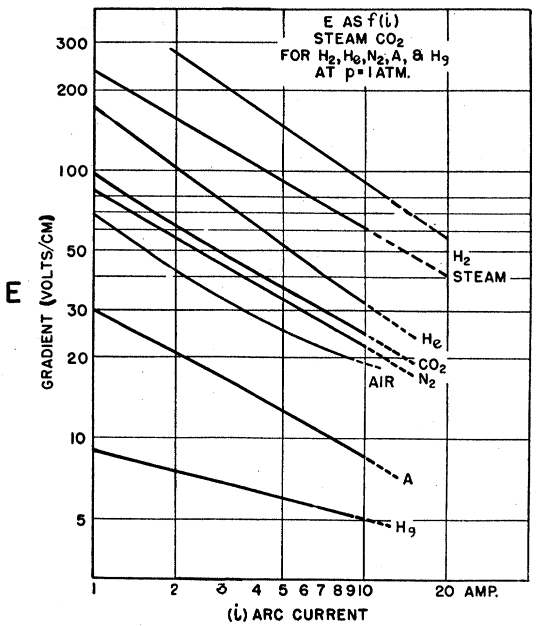

Fig. 10. Gradient as a function of arc current for various gases.

the relation

$$E \sim p^m$$

as an average value for the range $1 < p < 30$, for N_2, He, and A. Comprehensive pressure data are not available for H_2, but from a single measurement at $p = 0.014$ atmos. and the H_2 one atmosphere data, an approximate value of m has been calculated.

These results are given in Table VII.

Table VII. *Exponent m in the gradient-pressure relation.*

N_2 i	N_2 m	H_2	He i	He m	A i	A m
1	0.29	$m=0.32$	1	0.15	1	0.06
2.5	.30	(approx.)	3	.20	2.5	.12
5	.31		5	.20	5	.21
10	.32		15	.24	10	.27
Av. =	.31		Av. = 0.20		Av. = 0.16	

[8] W. Elenbaas, Physica **2**, 787 (1935).
[9] C. G. Suits and H. Poritsky, Phys. Rev. **52**, 136 (1937).

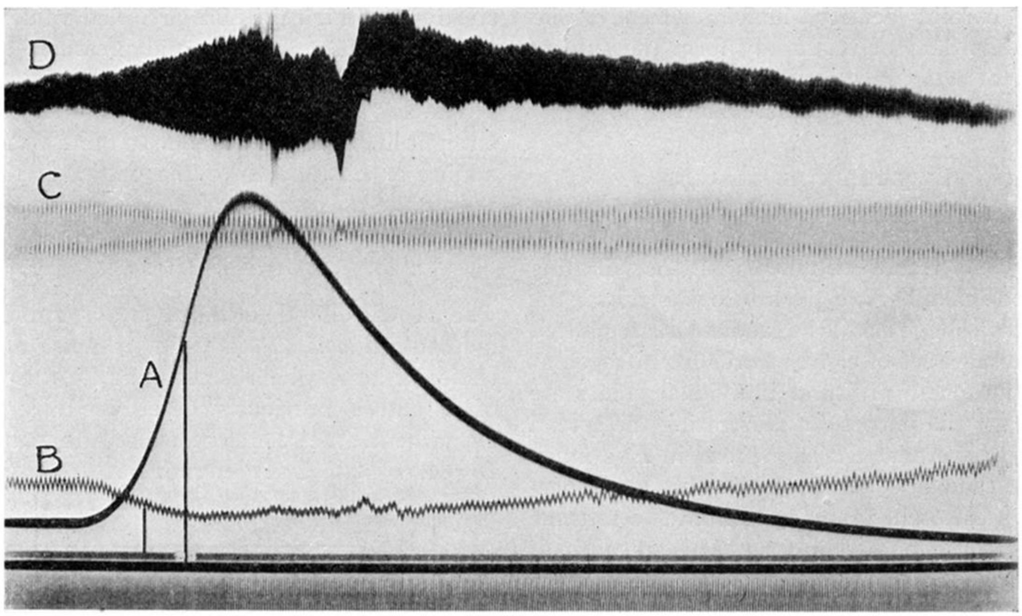

FIG. 2. Oscillographic record of an arc in nitrogen at one atmosphere pressure in the vibrating electrode chamber. A, arc current. B, total arc voltage. C, gradient in positive column. D, diameter (proportional to width of trace) of the arc column midway between electrodes.