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A Condition on Uniform Field Breakdown in Electron-Attaching Gases*

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The usual form of breakdown potential curves indicates that at large pd an asymptotic value of E/p seems to exist, below which breakdown does not occur. A study of the equation for steady-state current in electron-attaching gases suggests that this $(E/p)_{\lim}$ is nearly that for which the ionization and attachment coefficients are equal. Substantial agreement is found in CCl_4, CF_3SF_5, CCl_2F_2, SF_6, air, and O_2 between values of $(E/p)_{\lim}$ so determined and those found experimentally. The order of $(E/p)_{\lim}$ for these gases corresponds closely to that of their dielectric strengths.

THE general form of the curve that relates breakdown potential to the product of electrode separation and pressure (pd) in gases between plane-parallel electrodes is well-known.[1] A curve of this kind can be converted into one relating E/p for breakdown (where E is the electric field strength) and pd, assuming uniformity of field. As pd increases, the latter curve falls rapidly at first, but eventually more slowly and seems, where it has been carried sufficiently far, to approach an asymptotic value below which breakdown does not occur.[2,3] It is the main purpose of the present note to suggest an interpretation of this limiting E/p for breakdown in gases that form negative ions by electron attachment.

Since the existence of an asymptote seems common to all gases its explanation would appear to depend on the mechanism of breakdown. In particular it might be related to the failure of some secondary ionizing process at low E/p. However, the breakdown mechanism is incompletely understood at present, and it is difficult to make even a qualitative statement. In spite of this limitation the characteristics of attaching gases permit certain conclusions to be drawn.

An equation for steady-state pre-breakdown current in attaching gases has been presented previously.[4]† That equation is appropriate when secondary ionizing processes such as photoelectric effect or positive ion bombardment are unimportant. Discussions of breakdown, however, must include such processes. Assuming a secondary process at the cathode, one finds

$$i/i_0=\frac{[\alpha/(\alpha-\eta)]\exp[(\alpha-\eta)d]-\eta/(\alpha-\eta)}{1-\{\gamma\alpha/(\alpha-\eta)\}\{\exp[(\alpha-\eta)d]-1\}}, \qquad (1)$$

where the symbols are to be interpreted as follows: i = total discharge current, i_0 = electron current produced at the cathode by an external source, α = number of ionizations/cm electron = the ionization coefficient, η = number of attachments/cm electron = the attachment coefficient, d = electrode separation, and γ = probability per positive ion or photon of liberating an electron from the cathode.

A threshold for a self-sustaining current is obtained by requiring the denominator of Eq. (1) to vanish, i.e.,

$$\{\gamma\alpha/(\alpha-\eta)\}\{\exp[(\alpha-\eta)d]-1\}=1. \qquad (2)$$

It is well-known[5] that for non-attaching gases ($\eta=0$) Eq. (2) can be fitted to observed breakdown potentials within experimental error. In addition it has been shown recently[6] that a nearly equivalent procedure can be used to represent formative times of sparks at low overvoltages. If we suggest that Eq. (2) is equally valid for breakdown in attaching gases we note that when $\alpha/p \geqslant \eta/p$, breakdown is possible for sufficiently large pd regardless of the values of α/p, η/p, and γ. Under this condition the breakdown criterion always has a pd dependence. However for $\alpha/p<\eta/p$ Eq. (2) approaches, with increasing pd, an asymptotic form which is independent of pd, i.e.:

$$\alpha/p=(\eta/p)/(1+\gamma). \qquad (3)$$

Equation (3) is a condition on E/p alone and fixes a limit for this parameter, $(E/p)_{\lim}$, below which no sparking should be possible regardless of the magnitude of pd. In the following we shall compare, for several gases, values of $(E/p)_{\lim}$ obtained from these considerations with asymptotic limits derived from experimental studies of breakdown potentials.

Values of α/p and η/p are now available in a number of attaching gases.[4] In all cases thus far α/p is the smaller at low E/p but grows more rapidly with increasing E/p and overtakes η/p. Values of E/p for equality vary widely from gas to gas, ranging from 30 to 300 volts/cm/mm. They are believed accurate within 5 percent.

Values of γ will vary with gas and electrode material.

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[1] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, Inc., New York, 1939), Chap. X.

[2] M. J. Druyvesteyn and F. M. Penning, Revs. Modern Phys. **12**, 88 (1940).

[3] L. B. Loeb and J. M. Meek, *The Mechanism of the Electric Spark* (Stanford University Press, Stanford, 1941), p. 74.

† *Note added in proof:*—Dr. J. D. Craggs has kindly called our attention to an article by F. M. Penning, Ned. T. Natuurkde **5**, 33 (1938) in which this equation is derived.

[4] R. Geballe and M. A. Harrison, Phys. Rev. **85**, 372 (1952); M. A. Harrison and R. Geballe, Phys. Rev. **91**, 1 (1953); M. L. Reeves and R. Geballe (to be published).

[5] See references 1–3.

[6] G. A. Kachikas and L. H. Fisher, Phys. Rev. **88**, 878 (1952).

TABLE I. Comparison of predicted and observed $(E/p)_{\text{lim}}$.

Gas	$(E/p)_{\text{lim}}$ Pred.	Obs.	% dev.	Dielectric strength	Ref.
CCl_4	305	294	3	6	a
CF_3SF_5	186	160	15	3	b
CCl_2F_2	126	110	14	2.4	c
SF_6	117	103	13	2.2	d
Air	31.5	36.5	15	1	e
O_2	35.5	36.5	3	0.95	f

[a] B. M. Hochberg and E. J. Sandberg, J. Tech. Phys. (U.S.S.R.) **12**, 65 (1942).
[b] R. Geballe and F. S. Linn, J. Appl. Phys. **21**, 592 (1950).
[c] Trump, Safford, and Cloud, Trans. Am. Inst. Elec. Engrs. **60**, 132 (1941).
[d] Wilson, Simons, and Brice, J. Appl. Phys. **21**, 203 (1950).
[e] L. H. Fisher, Phys. Rev. **72**, 423 (1947).
[f] L. H. Fisher (private communication).

Its order of magnitude has been found in air[7] to be less than 10^{-3} near the asymptotic E/p for this gas. At high E/p, Hale,[8] using H_2 with electrodes of Pt and Na, found γ to lie below 0.05 for E/p below 600 except for a peak of no present concern. The magnitude of γ is expected, in general, to be sufficiently small that this quantity can be neglected in Eq. (3), a simplification further justified by uncertainties in the values of $(E/p)_{\text{lim}}$ available from experiment. Thus, we are led to adopt the relation

$$\alpha/p = \eta/p \tag{4}$$

as a working condition for the limiting E/p.

Comparison with experiment can be made through Eq. (2). The substitution of values of α/p and η/p yields, as for the non-attaching case, a relation between breakdown potential and pd with one parameter to be determined. In CCl_2F_2 and oxygen, for which the most extensive checks can be made at present, experimental curves are duplicated as closely as those of non-attaching gases. However, this is at best an insensitive test.

A direct test of Eq. (4) is illustrated in Table I. Here values of $(E/p)_{\text{lim}}$ predicted from this equation by the use of data from reference 4 are compared with those deduced from measurements of breakdown potentials. It is important to point out two principal causes of error in the latter. If measurements are not made under conditions of strict uniformity of electric field, breakdown will occur at abnormally low E/p. On the other hand, if measurements are not carried out to sufficiently large pd, the limiting E/p cannot be estimated accurately and will generally be given too high a value. Best conditions of uniformity seem to have been achieved in CCl_2F_2, oxygen and air. Only for the first two of these do measurements permit of reliable extrapolation to the asymptotic limit. It should be pointed out, in addition, that a failure of the kind described in the second paragraph might cause the observed $(E/p)_{\text{lim}}$ to lie above the predicted value. In view of these uncertainties, the agreement exhibited in Table I indicates the essential correctness of the proposed interpretation of Eq. (4). It can be seen from the table that an ordering according to $(E/p)_{\text{lim}}$ corresponds closely to relative dielectric strength as generally quoted.

The authors are grateful to Professor L. H. Fisher for supplying breakdown potential data in oxygen prior to publication.

[7] F. Llewellyn Jones and A. B. Parker, Proc. Roy. Soc. (London) **A213**, 185 (1952).
[8] D. H. Hale, Phys. Rev. **55**, 815 (1939).