II. MICROWAVE GASEOUS DISCHARGES

Prof. S.C.Brown	B.Lax
Prof. W.P.Allis	A.D.MacDonald
M.A.Biondi	D.J.Rose
Donald E.Kerr	L.J.Varnerin,Jr.

A. A-C BREAKDOWN

A generalized picture of a-c breakdown has been derived which applies not only to microwave gas discharges but to the general behavior of a-c breakdown. The discussion is based on proper variables from dimensional analysis, using the parameters $p\Lambda$ $p\lambda$, and $E\Lambda$ where p is the pressure, Λ the characteristic diffusion length, λ the wave length and E the magnitude of the breakdown field. The limits of applicability of diffusion theory have been derived from elementary kinetic-theory considerations and lead to a standing-wave limit, a mean-free-path limit and an oscillation-amplitude limit. These limits are plotted for hydrogen in Figure II-1. Within these limits, a single ionization coefficient correctly predicts breakdown fields for all published data tested, covering a wave-length range from 16,700 cm to 10 cm, as shown in the last progress report.

A classification is suggested in which the ultra-high-frequency discharges are those in which the electron makes many oscillations per collision, and high-frequency discharges are those controlled by diffusion

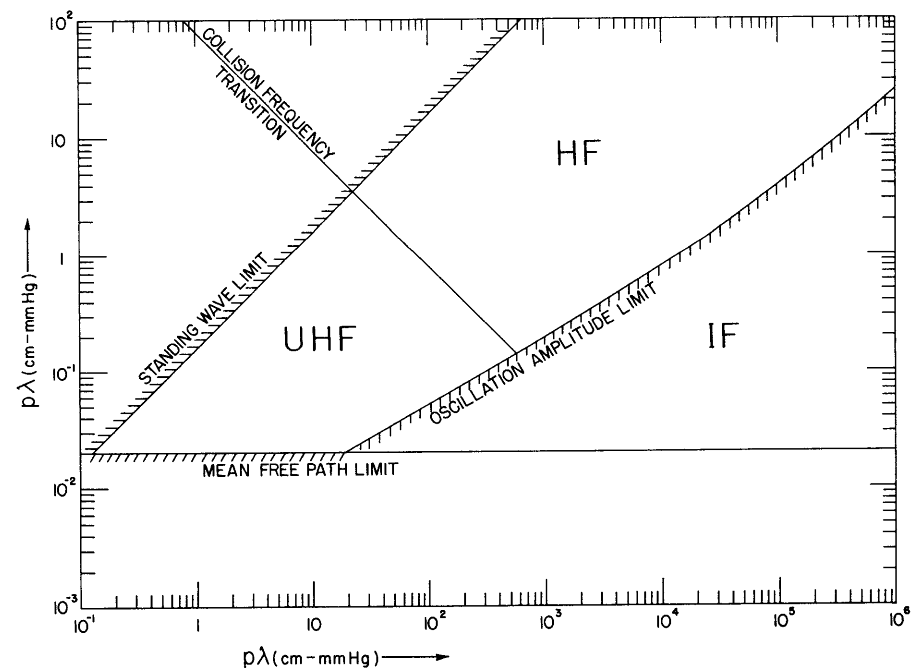

Fig. II-1. A plot of the limits of the diffusion theory for breakdown at high frequencies in terms of variables derived from dimensional analysis.

in which the electron makes many collisions per oscillation. Intermediate-frequency discharges occur when the drift distance of the electron under the action of the field per half-cycle is greater than the diffusion length, but the positive-ion loss is by diffusion. Low-frequency discharges occur when both electrons and positive ions collide with the walls every half-cycle. These regions are marked on Figure II-1.

All of the measured and published values of high-frequency-breakdown phenomena for a particular gas may be put on a single three-dimensional plot of $E\Lambda$, $p\Lambda$, and $p\lambda$. Such a surface has been constructed from the available breakdown data for hydrogen and is shown in Figure II-2. A technical report on this subject is forthcoming.

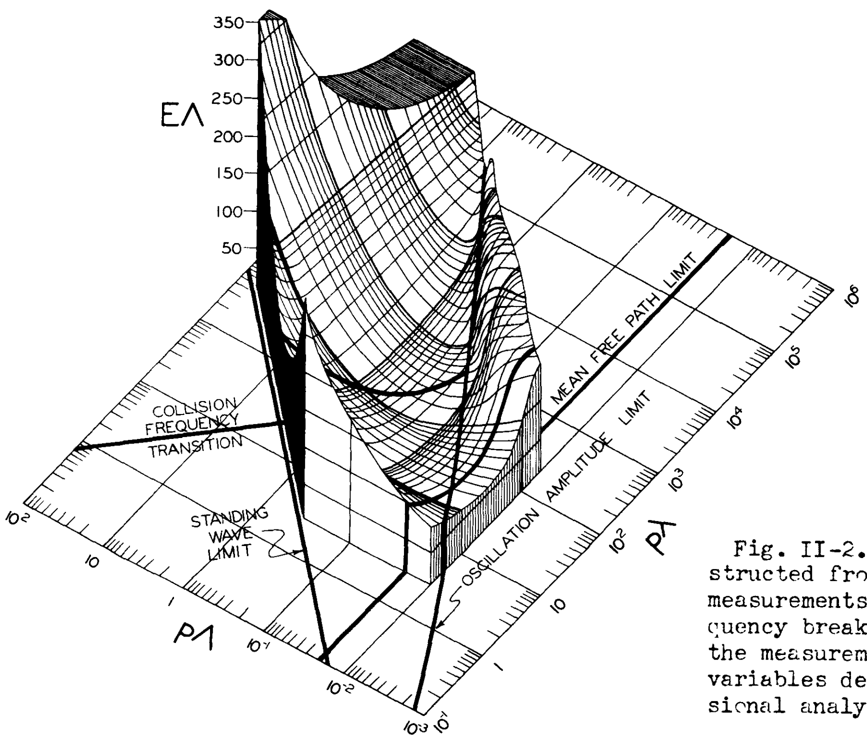

Fig. II-2. A surface constructed from experimental measurements of high-frequency breakdown, correlating the measurements in terms of variables derived from dimensional analysis.

B. MICROWAVE BREAKDOWN IN HELIUM

Breakdown electric fields have been theoretically predicted and experimentally checked for helium containing traces of Hg vapor.

The theory is based on a derivation of the electron-energy distribution function from the Boltzmann transport equation. Energy gain and loss in phase space is accounted for in setting up the transport equation which is the phase-space continuity equation for electrons. There results a second-

1. R.B.Brode, Rev. Mod. Phys. 5, 257 (1933).

order linear homogeneous differential equation in which collision cross section is hyperbolic in velocity, and the collision frequency, ν_c, is given by

$$\nu_c = 2.37\ 10^9 p,$$

where p is the pressure in mm of Hg. Diffusion is the removal process for electrons produced by the field. The solution of the differential equation gives for the distribution function

$$f_o = e^{-(1 - \frac{2}{3}\alpha)w} \left\{ M(\alpha;\tfrac{3}{2};w) + Cw^{-\frac{1}{2}} M(\alpha - \tfrac{1}{2};\tfrac{1}{2};w) \right\}, \qquad (1)$$

where M is the confluent hypergeometric function,

$$w = \frac{0.820\ 10^4\ u_i}{(E\lambda)^2}\, b \left[1 + \left(\frac{p\lambda}{79.6}\right)^2 \right],$$

$$b = \left[1 + \left(\frac{E\lambda}{p\Lambda}\right)^2 \frac{3.77\ 10^{-4}}{\left[1 + \frac{p\lambda}{79.6}\right]^2} \right]^{\frac{1}{2}},$$

$$\alpha = 0.75\ \frac{b-1}{b}$$

u is the electron energy in volts, p the pressure in mm of Hg, λ the free-space wave length, E the rms value of the electric field strength, and Λ the diffusion length of the cavity. C is a constant to be determined by the initial conditions. Helium has a metastable level at 19.8 volts and transitions from this level to the ground state by radiation are forbidden. Since metastable states have mean lives of the order of milliseconds, practically every helium atom which reaches an energy of 19.8 volts will collide with a mercury atom and lose its energy by ionizing the mercury. Therefore each inelastic collision will produce an ionization, and the effective ionization potential u_i will be the first helium excitation potential. This then provides a boundary condition on the differential equation and determines C. f_o goes to zero at the ionization potential, therefore

$$C = -\frac{(w_1)^{\frac{1}{2}} M(\alpha; \frac{1}{2}; w_1)}{M(\alpha - \frac{1}{2}; \frac{1}{2}; w_1)}. \tag{2}$$

Having determined the distribution function we may compute the ionization rate, ν, and the diffusion coefficient, D, from standard kinetic-theory formulas:

$$n\nu = -\frac{2\pi}{3}\left(\frac{E}{\omega}\right)^2 \frac{\nu_c}{\left[1 + \left(\frac{p\lambda}{79.6}\right)^2\right]} \left(\frac{2e}{m}\right)^{\frac{5}{2}} \left[u^{\frac{3}{2}} \frac{df_o}{du}\right]_{u = u_1} \tag{3}$$

and

$$nD = \frac{2\pi}{3\nu_c}\left(\frac{2e}{m}\right)^{\frac{5}{2}} \int_0^{u_1} f_o u^{\frac{3}{2}}\, du. \tag{4}$$

The breakdown condition, derived from the diffusion equation, is that $\nu/D = 1/\Lambda^2$ (1). Combining this condition with Eqs. (3) and (4) we have the breakdown equation

$$M(\alpha; \tfrac{3}{2}; w)e^{-\frac{2}{3}\alpha w} = 2. \tag{5}$$

The expression ν/D has been simplified by using the Wronskian of the differential equation. Figure II-3 shows the theoretical fields predicted from Eq. (5), and the experimentally measured fields. A technical report on the subject will appear soon.

1. M.A.Herlin and S.C.Brown, RLE Technical Report No. 60; also Phys. Rev. 74, 291 (1948).

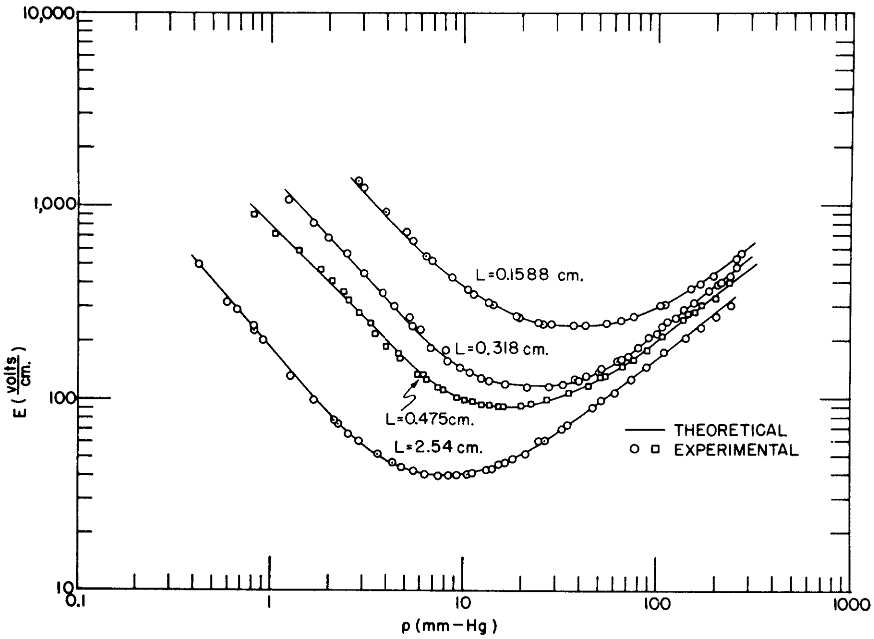

Fig. II-3. Experimental and theoretical breakdown fields.

C. TRANSIENT-DISCHARGE CHARACTERISTICS: AMBIPOLAR DIFFUSION AND ELECTRON-ION RECOMBINATION

The energy dependence of the ambipolar diffusion coefficient for helium has been measured. Kinetic theory defines the diffusion coefficient as

$$D = \left(\frac{\ell v}{3}\right)_{av.}$$

where D is the diffusion coefficient, ℓ is the mean free path and v is the velocity of the particle.

For the conditions present in the experiment the ambipolar diffusion coefficient, D_a, is given by:

$$D_a \simeq 2D_+ = 2\left(\frac{\ell_+ v_+}{3}\right)_{av.}$$

where the + refers to positive ions. The mean free path, ℓ, is defined by:

$$\ell = \frac{1}{n_g \sigma(v)}$$

where n_g is the gas density and $\sigma(v)$ is the collision cross section. For positive ions in helium

$$\sigma_+(v) \sim \frac{1}{v_+}$$

so that at constant pressure and with $T_+ = T_{gas}$ as is the case experimentally

$$\ell_+ \sim T^{3/2}$$

where T is the absolute temperature of the gas. Thus at constant pressure

$$D_a \sim T^2.$$

The experimental data are shown in Figure II-4. The slopes of the curves yield values of D_a which are plotted against T^2 in Figure II-5. The theoretical dependence on energy is checked very accurately.

Preliminary studies of ambipolar diffusion in neon have been made. The large recombination present permits measurements only in the 0.5 - 3 mm pressure range (where the diffusion might be expected to outweigh the recombination). At 0.039 e.v. energy, the value of $D_a p$ is found to be about 130 (cm^2/sec - mm Hg).

Studies of the pressure and energy dependence of the recombination coefficient, α in neon have been made. The results of a typical pressure run are shown in Figure II-6. The recombination is found to be independent of pressure over the measured range. The effect of the variation of positive ion and electron energy is shown in Figure II-7. Points taken at $T = 400^\circ K$ also fall on the curve. The recombination appears to be independent of both pressure and energy in the measured range.

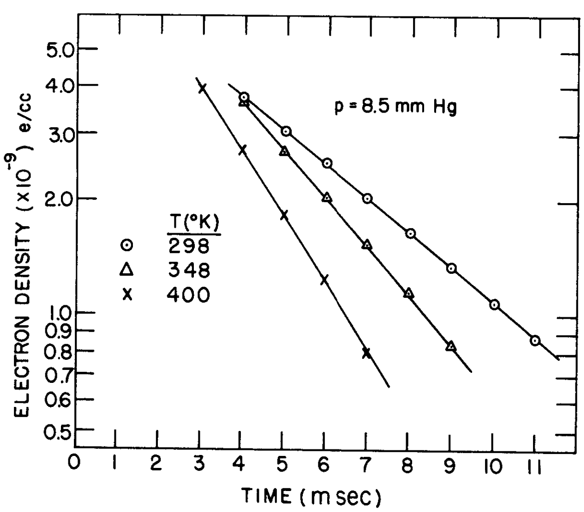

Fig. II-4. Rate of removal of electrons as a function of gas temperature.

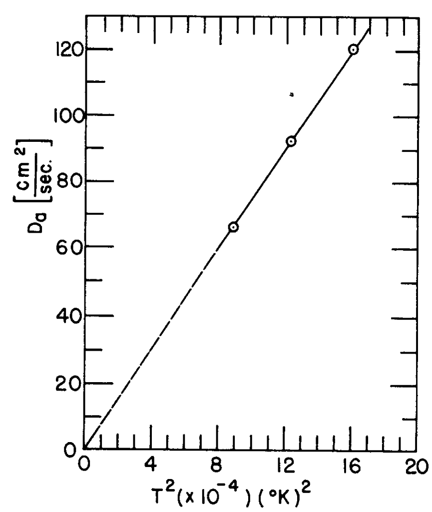

Fig. II-5. Variation of the ambipolar diffusion coefficient with temperature.

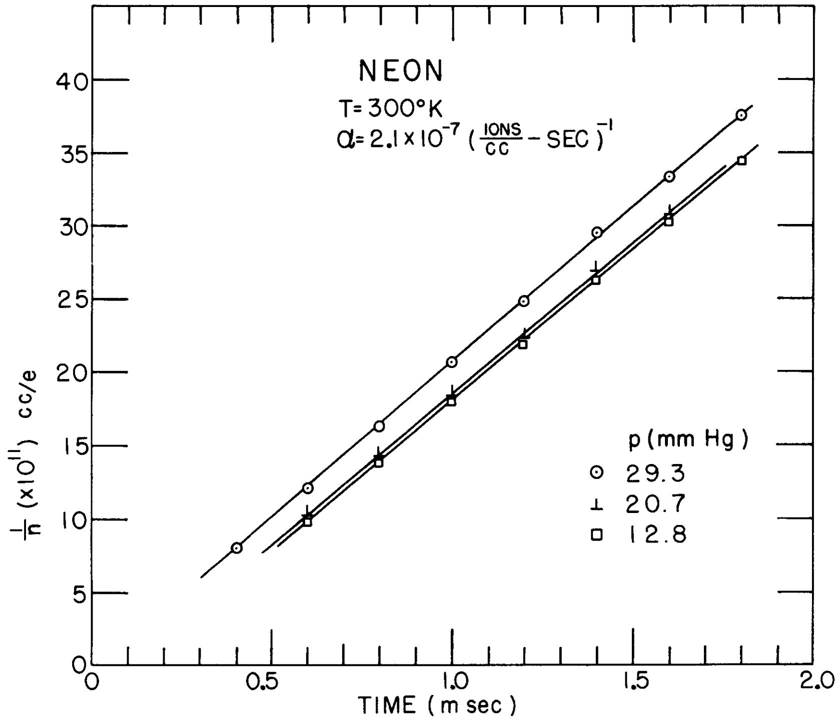

Fig. II-6. Recombination in neon as a function of pressure.

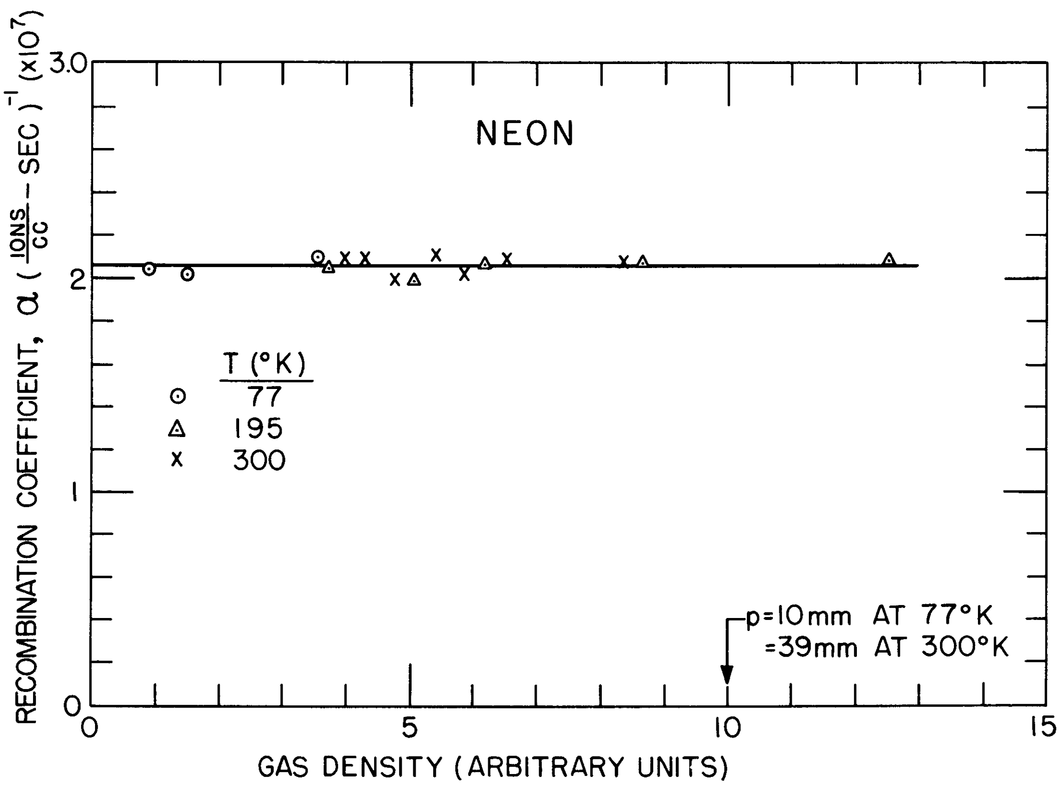

Fig. II-7. Recombination in neon as a function of pressure and temperature.