Breakdown and Maintenance of Microwave Discharges in Argon

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The breakdown fields for argon have been measured in a resonant cavity at 3000 megacycles/sec. over a pressure range from 3 to 100 mm Hg. The discharge gap approximates the case of a uniform field between parallel plates. The results are compared with predicted values derived from Holstein's theory; the agreement is quite good, about 5 percent. Measurements taken with the discharge in the cavity permit determination of the voltage-current characteristics of the argon microwave discharge. These are given for a set of pressure values. These characteristics are compared with results on positive column gradients in d.c. discharges.

INTRODUCTION

AN important reason for the study of microwave discharges is their relative simplicity as compared with d.c. or low frequency discharges. There are two reasons for this relative simplicity: first, electrode phenomena need not play a role in the high frequency discharge and second, an electron need not undergo a net drift motion to receive energy from the high frequency field. These differences between the d.c. and high frequency case may be illustrated by a qualitative description of the breakdown process for the two cases.

In the d.c. case[1] a chance electron formed in the gas volume between the two electrodes drifts toward the anode under the influence of the applied field, gaining energy from the field and losing it chiefly through inelastic collisions with gas molecules. Some of these will be ionizing collisions; the resulting electrons also move toward the anode producing still more electrons. Thus the original chance electron produces an exponential increase in electron density with position toward the anode. As Townsend has pointed out, however, this alone cannot result in a self-sustained discharge. For a discharge to occur it is necessary that all the physical phenomena resulting from the passage of the original electron through the gas to the anode shall result in the formation of at least one additional electron in the volume at a potential no greater than that at which the original chance electron started. This regenerative process generally occurs at the cathode through electron emission due to impinging ions, photons and excited atoms. Thus Townsend's d.c. breakdown theory involves two distinct features. These are volume ionization by electrons depending on the gas, gas pressure, and applied field and cathodic emission depending upon all of the above factors plus the nature of the cathode surface.

An electron in a region of high frequency field[2] has an oscillatory motion at the field frequency plus a rectilinear motion whose magnitude and sign depend on the phase of entry of the electron into the field. The maximum energy that can be acquired by a free electron is determined by the field amplitude and frequency. The presence of a gas alters the situation profoundly, however, for now the electrons may make elastic collisions with the gas molecules. In such a collision the electron energy is only slightly reduced because of the disparity in masses, while the electron velocity after collision is more or less randomly directed with respect to the field. As a result of this random orientation of velocity after collision, the electron energy will, on the average, grow with successive collisions until the electron can make excitation and ionizing collisions with gas molecules. Thus the number of electrons will grow with time provided that an electron produces at least one other electron before it is lost. For breakdown considerations the important loss mechanisms are attachment to molecules and diffusion out of the field region. Thus for a non-attaching gas the breakdown criterion is simply this: rate of production of electrons by ionization must exceed rate of loss of electrons by diffusion.

These ideas were developed by Holstein in an unpublished report[3] and formed the basis of his theory of high frequency breakdown in a non-attaching gas.[4] This theory is based on two points the first of which is the breakdown criterion stated above. The second is his observation—in a paper on electron energy distribution functions[5]—that in the pressure region in which the field frequency is less than the frequency of elastic collisions of electrons with the gas and greater than the frequency of inelastic collisions, the electron distribution in energy for the high frequency field is very nearly the same as that in a d.c. field whose value equals the r.m.s. value of the high frequency field. The breakdown case treated by Holstein is that of a uniform field between parallel metal plates; for this geometry the r.m.s. breakdown field E is related to the pressure p and plate separation d by the expression

$$(pd)^2=\frac{\pi^2kT_e}{e(E/p)(\alpha/p)},\tag{1}$$

[1] M. J. Druyvesteyn and F. M. Penning, Rev. Mod. Phys. **12**, 88 (1940).

[2] For these and the following remarks to apply, the drift motion per cycle of an electron in the high frequency field must be small compared to the linear dimensions of the discharge region. At microwave frequencies ($f>10^9$ sec.$^{-1}$) and usual geometries this condition is easily met.

[3] Westinghouse Research Report, R-94411-9A, "The TR switch," Chapter III, *Theory of the TR Switch*, by T. Holstein.

[4] T. Holstein, Phys. Rev. **69**, 50(A) (1946).

[5] T. Holstein, Phys. Rev. **70**, 367 (1946).

where α is Townsend's first coefficient for a d.c. field E and pressure p and T_e is the electron temperature for the same field and pressure. k is Boltzmann's constant and e is the electronic charge.

Some years ago Townsend and Gill[6] summarized certain related remarks as well as pointing out the close similarity between the high frequency discharge and the positive column of a d.c. discharge. Recently microwave breakdown measurements as well as theoretical work have been reported for air with flat plate and cylindrical geometry by Herlin and Brown[7] and for helium with mercury admixture by MacDonald and Brown.[8]

A primary purpose of the work reported here was experimental verification of Eq. (1) above. For this purpose we studied the breakdown field in argon at 3000 megacycles/sec. argon was chosen partly because values of α/p and T_e are known over a suitable range of values of E/p but mainly because the Penning effect[9] with argon is limited to certain chemically active molecules which may be readily removed.

The experiment approximated the idealized case of the theory by providing as the discharge region the space between the ends of two cylindrical reentrant noses in a cylindrical resonant cavity. The input of the cavity was coupled to a generator, the output to a load. Figure 1 illustrates the behavior of the power transmitted by the cavity as the power incident on the cavity is varied.

In the absence of a discharge the power transmitted by the cavity is a linear function of the incident power; this is illustrated by the line OF. The cavity gap field rises as the square root of the incident power, and with a gas at an appropriate pressure in the cavity breakdown may occur. If this occurs at an incident power H, the cavity transmission falls from A to B, and simultaneously a luminous glow appears in the cavity. We use this sudden fall in transmitted power as the breakdown criterion.

The discharge loads the cavity and detunes it, the relative importance of the two depending on the pressure. The net effect of either, however, is to reduce the cavity transmission. The characteristic of the discharge is such that an increase in incident power from H to K causes a fall in transmitted power from B to C. Reducing the incident power toward G, the transmitted power rises, and at G a sudden increase from D to E is observed. This corresponds to extinction of the discharge. Thus the discharge is always present for powers above H, never present for powers below G and may or may not be present for powers between G and H.

Breakdown measurements consist of determining the transmitted power at A. Knowing this power and the electromagnetic properties of the cavity, one may compute the gap voltage at breakdown. Maintenance measurements consist of determining curves such as DBC; with this data plus information on the cavity circuit properties, the discharge conductivity and the voltage-current characteristics of the discharge may be computed.

DESCRIPTION OF APPARATUS

I. Microwave Equipment

The generator used for the experiment was a Sperry 410-R klystron mounted in a water-cooled bath of transformer oil. It was operated as a self-excited oscillator, powered from a regulated supply, with r-f output powers usually around ten watts. The transmission line used was standard $1\frac{1}{2}$ inch$\times$3 inch rectangular brass waveguide (RG-48/U), the various sections being coupled with standard choke-flange points (UG-53/U, UG-54/U).

The high power variable attenuator was especially designed for the experiment and is described in detail elsewhere.[10] It was a variable position tapered vane type, the vane being a hollow Lucite chamber through which an ethelyne glycol and water mixture was circulated. This liquid served as attenuating medium as well as coolant in a closed system using an air cooled heat exchanger. Attenuations from under a db to about 40 db could be obtained with a maximum voltage standing wave ratio of 1.07.

The resonant cavity was specifically designed to satisfy the high frequency requirements of the experiment and to permit bakeout at over 400°C. The cylindrically symmetrical cavity is shown in Fig. 2. The cavity was coupled to the input and output waveguide with identical circular rises 0.562 inch in di-

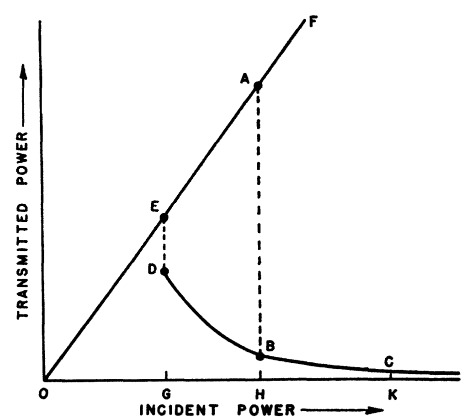

FIG. 1. Diagram illustrating the effect of the discharge on the cavity transmission. OF is the characteristic without a discharge, DBC that with the discharge. AB is the breakdown line, DE the extinction line.

[6] Townsend and Gill, Phil. Mag. **26**, 290 (1938).

[7] M. A. Herlin and S. C. Brown, Phys. Rev. **74**, 291, 910, 1650 (1948).

[8] A. D. MacDonald and S. C. Brown, Phys. Rev. **75**, 411 (1949).

[9] This effect is the ionization of impurity molecules by metastable atoms of the main gas constituent when the energy difference between the ground state and metastable state of the principal gas exceeds the ionization energy of the impurity. Penning, Naturwiss. **15**, 818 (1927).

[10] D. Alpert, Rev. Sci. Inst. (to be published).

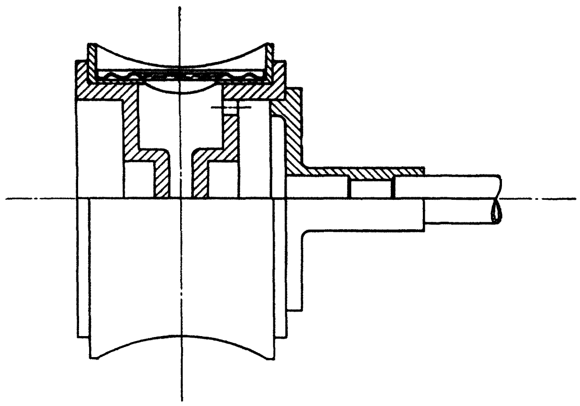

FIG. 2. The resonant cavity used for the experiment.

ameter. The window seals were wide corrugated rings stamped from sheet Kovar to which glass disks were sealed. The noses of the cavity were polished with the edges turned to 0.040 inch radius to eliminate local fields in excess of the central field.[11] The cavity itself was made of OFHC copper. The cavity and seals were assembled by silver brazing in a hydrogen atmosphere. The pumping connection to the interior of the cavity was a series of 8 holes, $\frac{1}{8}$ inch in diameter spaced equally around the bottom of the cavity near the cylinder wall. The technique of making the window seals as well as assembly methods for the cavity have been described in an unpublished report.[12] Figure 3 gives the essential interior dimensions of the cavity.

The cavity mounting was such as to permit the waveguide to be removed during bakeout. The exterior of the cavity was a circular cylinder of height equal to that of the waveguide. The waveguide was bored through to clear the cavity which was rigidly clamped to it by a collar and flange arrangement. Good electrical contact top and bottom was made by using special gaskets of 3-mil copper ribbon, corrugated by rolling between two lengths of gear stock, then bent into a circle in the plane of the ribbon. Electrical measurements indicated an effective and reproducible joint. A vertical slit 0.150 inch wide between the cavity and side walls of the waveguide contributed no significant leakage.

Power was measured by 10 ma Littlefuses used as bolometers in a mount developed at our laboratory during the war by a group under J. E. Hill.[13] These were used with resistance bridges measuring fixed power levels in a conventional manner. The power levels measured by the bolometers were around 1 milliwatt with attenuators used to measure higher powers; for certain maintenance data powers as low as 0.1 milliwatt were measured.

Incident power and higher levels of transmitted power were measured with Bethe hole directional couplers.[14] The two couplers used had attenuations of 15 and 22 db. The low power variable attenuators were of standard design using tapered resistance card vanes.[15]

Figure 4 shows the microwave equipment in block form. The low power attenuator just preceding the discharge cavity was used at very low incident powers. This permitted measurement of a suitable power level in the directional coupler. For lower values of transmitted power the cavity output was connected directly to a low power variable attenuator and bolometer.

All the measuring equipment had voltage standing wave ratios under 1.07 and almost all were better than 1.05. Attenuation of the low power attenuators and directional couplers was known to ± 0.02 db. The directivity of the couplers was better than 20 db. The relative short time error in the bolometers due to temperature drift, bridge sensitivity, etc., was five to ten microwatts at most. Six bolometers of the same design when intercompared gave power measurements within 1 percent. Further, a comparison made during the war between this type of bolometer mount and a M.I.T. Radiation Laboratory thermistor mount gave agreement within 1 percent.

The loaded Q of the cavity was measured by a special sweep frequency technique developed at this laboratory during the war by McCoubrey, Packard, and Krasik for measurements on radar beacon standard frequency cavities. This technique has been described elsewhere.[16] Insertion loss of the cavity was measured by a substitution method using a calibrated attenuator. Cavity measurements were made in the mount used for the discharge experiments either just preceding or immediately following discharge measurements. We estimate the loaded Q of the cavity to have been measured to 3 percent in absolute value and the inser-

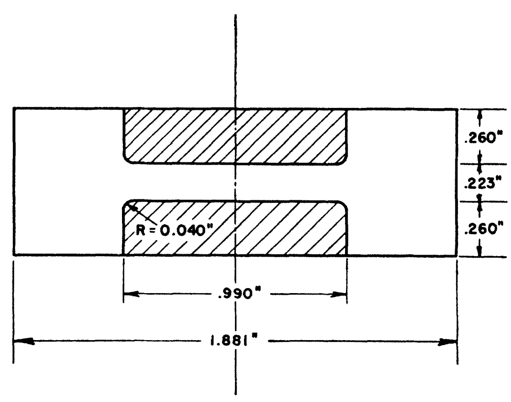

FIG. 3. The interior dimensions of the resonant cavity used for the experiment.

[11] Rogowski and Rengier, Arch. R. Elekt., **16**, 73 (1926).
[12] Westinghouse Research Report, R-94411-9A, "The TR switch," Chapter IV, *The 1B24 Design* by D. Alpert.
[13] T. Miller, Proc. I.R.E. **36**, 380(A), (1948).
[14] Montgomery, *Technique of Microwave Measurements* (Radiation Laboratory Series), Vol. 11, pp. 858–866.
[15] Reference 14, pages 748–751.
[16] Reference 14, pages 396–403.

tion loss to 0.1 db. These absolute errors are due principally to small residual standing waves; the reproducibility of the measurements was several times better than the estimated errors. Two similar cavities were used in the experiment; the measured values are given in the table below. Most of the breakdown data was taken on cavity No. 1.

	Cavity No. 1	Cavity No. 2
Loaded Q	2780	2890
Insertion loss	8.9 db	8.9 db
Frequency	2950 megacycles/sec.	2950 megacycles/sec.

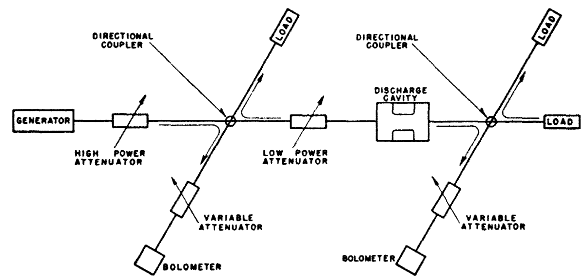

FIG. 4. Line diagram of the microwave equipment used for breakdown and maintenance measurements.

II. Pumps and Gas Handling Equipment

The pumping and gas handling system is shown schematically in Fig. 5. The discharge cavity, ion gauge and an auxiliary d.c. discharge tube form a central system protected from the oil diffusion pumps and grease stopcocks by liquid air traps. The system is made of Pyrex connected to the cavity through a Kovar-glass seal and a section of annealed copper tubing. The auxiliary discharge tube was used to clean the gas after filling; it had two closely spaced cylindrical electrodes made of magnesium alloyed with some few percent of cerium. The ion gauge was standard with the usual residual air calibration (1μa.$=10^{-5}$ mm Hg).

After the system had been opened to air, the central system and liquid air traps were baked at 425°C for at least 24 hours. Following this the ovens on the traps were removed, and liquid air was placed on the traps while bakeout of the central system proceeded for some hours. After bakeout a shut-off test was made by closing stopcocks S_1 and S_2; an ion gauge current of 10^{-9} amperes was obtained which showed no change in 24 hours.

Pump No. 1 was connected to the central system through a standard type of reentrant liquid air trap. Pump No. 2 was used chiefly for the gas system, which was connected to the central system through two reentrant liquid air traps in series. These traps were of special design and were made in the following way. A sheet of three mil copper foil, six inches wide and about 40 inches long, was corrugated diagonally by rolling it between two lengths of gear stock. The copper sheet was then wrapped around the inner tube of a standard reentrant type liquid air trap so as to fill completely the space between the inner and outer tubes of the trap. The corrugations thus formed a large number of small diameter tubes in parallel spiralling around the inner tube of the trap. This design aimed at a trap which would be effective in removing condensible vapors from gas at fairly high pressures as it entered the central system. A detailed description and performance analysis will be published in a later article by one of the authors (D. A.) in the *Review of Scientific Instruments.*

Pressure was measured with an oil manometer using Octoil S. The manometer read pressures up to 60 mm Hg directly; a stopcock was provided for evacuating the closed side of the manometer or pressurizing it to extend the pressure range. We estimate the error in pressure to be 0.06 mm Hg at most, which is under 1 percent except for the two lowest pressures in the breakdown data.

The argon used was of the highest purity obtainable commercially. It was obtained from the two primary suppliers in one liter flasks with break-off tips. Except for possible contamination of the gas itself by the manufacturer, no mercury was present in the system.

Following bakeout gas was admitted to the system to the maximum pressure desired. The auxiliary d.c. discharge was then started and operated continuously during the run and for at least 24 hours preceding any measurements. This discharge operated at about 150 ma and 100 volts from the 60-cycle power line.

BREAKDOWN MEASUREMENTS

For breakdown measurements only the transmitted power at breakdown is required. From this the breakdown voltage may be obtained by a straightforward analysis. The definition of "external" or "transmission" shunt resistance[17] R_2 associated with the output coupling is given by the equation

$$V=(2R_2P_2)^{\frac{1}{2}},$$

where P_2 is the power transmitted to a matched load

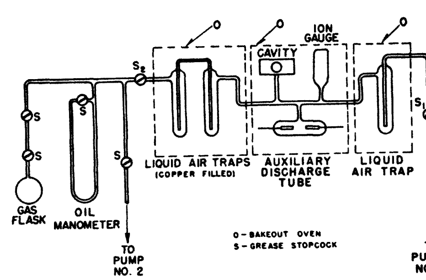

FIG. 5. Diagram of the pumping and gas filling equipment.

[17] The cavity parameter Q is $\omega U/P$ where ω is the circular frequency, U the energy stored in the cavity and P is a power loss. The shunt resistance R is $V^2/2P$ where V is the time peak of the gap voltage. The power P may be the dissipation in the cavity walls, the power transmitted to a coupled circuit or the total power loss of the cavity and associated lines. Corresponding to each power loss a Q and shunt resistance may be defined. Clearly the ratio R/Q is independent of this choice.

TABLE I. Microwave breakdown fields for argon.

Pressure (mm Hg.)	Transmitted power at breakdown (milliwatts)	pd (mm×cm)	E/p (Peak volts/cm×mm)
113.2	266	64.2	10.9
106.0	246	60.1	11.1
103.3	240	58.6	11.3
98.6	224	55.9	11.4
94.5	213	53.6	11.6
89.9	199	51.0	11.8
85.4	186	48.4	12.0
81.0	174	45.9	12.3
76.5	163	43.4	12.6
71.7	152	40.7	13.0
67.7	141	38.4	13.2
63.1	129	35.8	13.6
58.6	117	33.2	13.9
54.4	107	30.9	14.3
49.9	95.3	28.3	14.7
45.3	83.9	25.7	15.3
41.0	74.6	23.3	15.9
36.9	65.6	20.9	16.5
31.0	54.6	17.6	18.0
26.6	46.4	15.1	19.3
22.4	38.4	12.7	20.9
18.1	30.9	10.3	23.2
13.8	23.7	7.83	26.6
9.6	18.1	5.43	33.5
5.45	14.4	3.09	52.4
3.25	14.0	1.84	87.0

and V is the peak gap voltage in the cavity. For a cavity with equal input and output couplings[18, 19]

$$Q_2/Q_L = 2/(T)^{\frac{1}{2}},$$

where Q_L is the loaded Q of the cavity and T is the fractional transmission of the cavity at resonance. Further since

$$R_2 = (R/Q)Q_2, \quad V = 2[(R/Q)Q_L P_2]^{\frac{1}{2}}(T)^{-\frac{1}{4}}. \qquad (2)$$

In this expression if P_2 is the power transmitted at breakdown, V is the gap breakdown voltage. The value of R/Q for the cavity was calculated for us by T. Holstein who obtained the value 58.9 ohms. The breakdown voltages may be computed by using this and the measured values of Q_L, T and transmitted power. The circuit analysis used here assumes the cavity has a single resonant mode with loaded $Q \gg 1$.

The measurement procedure was as follows: with no discharge in the cavity the incident power level was set somewhat below that causing breakdown. The bridge reading the transmitted power was then balanced and maintained in balance continuously as the incident power level was slowly raised. At breakdown the bridge unbalanced sharply; the power reading at which it had been balanced just previous to breakdown was then noted. This value we call the transmitted power at breakdown. Three successive trials were taken, the agreement in general being better than one percent. Breakdown measurements at various pressures of Argon were obtained by starting with the highest pressure desired and evacuating through pump No. 2.

The results of our breakdown measurements in argon are given in Table I and the solid curve of Fig. 6. The data given are values of breakdown field over pressure *vs.* the product of pressure and gap spacing. The theoretical curve was given by Holstein in an unpublished report.[3] It was obtained using the published data for α given by Kruithof and Penning[20] and the electron temperature data of Townsend and Bailey[21] in Eq. (1). The experimental curve lies from 4 percent to 8 percent below the theoretical curve; we consider such agreement to be satisfactory verification of the breakdown theory over the region of applicability.

From our maximum error estimates of 3 percent for Q_L, 2.5 percent for T, 0.5 percent for P and Holstein's estimate of 1 percent for his value of R/Q we estimate the error limit in breakdown voltage to be about 3 percent. This excludes the question of absolute bolometer calibration; in view of the intercomparisons made, we believe this question to be satisfactorily resolved. Data taken with cavity No. 2 gave agreement to within 1 percent of the solid curve of Fig. 6 over the range of comparison with theory; the departure was as much as 5 percent for lower values of E/p.

Our gap geometry deviates from that of a uniform field between parallel plates assumed in the theory in at least two respects. First, because the gap diameter is an appreciable fraction of a wave-length, the field decreases from the axis of the cylinder to the outer edge. Second, there is a sidewise diffusion of electrons out of the gap region. Both effects should cause the measured breakdown voltage to be higher than that for an ideal gap geometry. Concerning the first point we find that at the outer boundary of the gap the field is down to about 85 percent of its value at the center; hence the average field does not deviate by over 7 percent from the extreme values and is probably better. Concerning the sidewise diffusion loss out of the gap region, Hol-

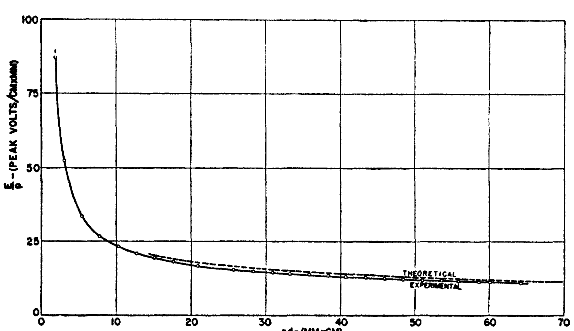

FIG. 6. Breakdown fields in argon. The ordinate is peak breakdown field over pressure, the abscissa pressure times gap spacing. The theoretical curve is by Holstein.

[18] T. Holstein, *Transmission Characteristics of Resonant Cavities in Microwave Systems* (unpublished report, Westinghouse Research Report R-94318-F).

[19] Cf. Smullin and Montgomery, *Microwave Duplexers* (Radiation Laboratory Series), Vol. 14, Chapter II. Also reference 14, 286–293.

[20] Kruithof and Penning, Physica 4, 430 (1937).

[21] Townsend and Bailey, Phil. Mag. 44, 1033 (1922).

stein, in an unpublished calculation, has shown it to be a negligible fraction of the total diffusion loss.

In these measurements a number of argon samples were used. Before cleaning with the auxiliary discharge, two or three of the samples gave essentially identical breakdown *vs.* pressure curves while the remainder of the samples gave curves lying below this common curve by varying amounts. Differences of as much as 20 percent were observed at the higher pressures—above 40 mm Hg. At pressures below 10 mm Hg there seemed to be little difference among samples, however. For a sample giving low breakdown voltage, operation of the cleaning discharge for an hour produced a marked rise in breakdown voltage, and operation for 24 hours brought it into agreement (better than 1 percent) with the common top curve. Further operation of the auxiliary discharge for 24 hours and longer periods had no measurable effect; moreover, the cleaning discharge had no effect on the breakdown voltage of those samples originally giving the common top curve. We conclude that a contaminant removable by a cleaning discharge and measurably affecting the breakdown voltage of argon is present to a varying extent in the gas samples furnished us; apparently our own gas handling system introduced no such contaminant.

To reduce the statistical spread in breakdown voltage measurements we found it necessary to use a radioactive source to provide a sufficient electron density. We used a 100 microcurie ampule of radium which was placed on top of the cavity; the cavity copper thickness in this region was 9/64 inch.

MAINTENANCE MEASUREMENTS

With the discharge present in the cavity we may assume that the cavity is loaded with a gas discharge admittance Y_G at the gap. If the generator frequency is the resonant frequency of the cavity without the discharge, with the discharge the following expression of Holstein's[3] for the ratio of incident power P_i to transmitted power P_2 may be used.

$$P_i/P_2 = 1/T\,|1+Y_G R_L|^2. \tag{3}$$

Here R_L is the loaded shunt resistance of the cavity (without the discharge), and T is defined as before. By measuring the incident and transmitted powers with the discharge present we know all the quantities in Eq. (3) except Y_G. To obtain the magnitude of Y_G from this equation we must know the phase of Y_G or make some reasonable assumption about it. We chose the latter procedure for reasons to be discussed later. Having the magnitude of Y_G and the gap voltage at any transmitted power from Eq. (2), we may obtain the gap current and thus the voltage-current characteristics of the discharge.

The procedure used to obtain incident and transmitted powers was the following: with the cavity filled with argon at the desired pressure, the discharge was started and the incident power increased to the maximum value used, about six watts. The bridges reading incident and transmitted powers were balanced and the values noted; a set of such readings were then taken reducing the incident power in steps. In order to obtain the point at which the discharge was extinguished we proceeded as follows: at an incident power slightly above that at which the discharge was extinguished, the bridge reading transmitted power was balanced and maintained in balance continuously as the incident power was lowered slowly. At extinction the bridge

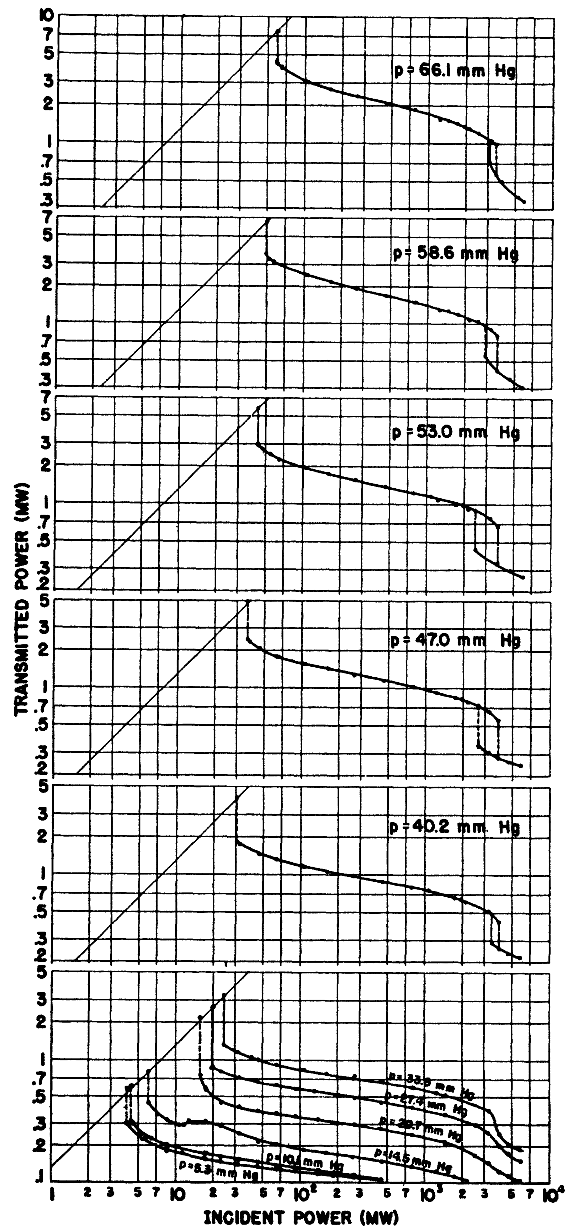

FIG. 7. Maintenance data for the argon discharge; the abscissa is incident power in milliwatts, the ordinate transmitted power in milliwatts. The range of incident powers is from 1 to 10^4 milliwatts. The line at the left with 45° slope is the line of cavity transmission without the discharge.

suddenly unbalanced; the value at which it had just previously been balanced was noted, after which it was rebalanced for the higher value of transmitted power. At the same time the bridge reading incident power was balanced and the value noted. This procedure, similar to that used to obtain the breakdown voltage, was also used to locate the discontinuities in the maintenance characteristics. Following each run, a set of check points was taken which included the extinction point. Reproducibility better than 2 percent was considered satisfactory. Incident powers below 20 milliwatts were measured by inserting the low-power attenuator in the main line as shown in Fig. 4.

In these measurements the generator was carefully tuned to within 0.05 bandwidth of the cavity resonance preceding each run and each set of check points. There was no measurable detuning of the generator with variation in attenuator setting. As with the breakdown measurements the cavity was filled with gas to the highest pressure desired with runs taken at successively lower pressures by exhausting through pump No. 2. Again we found that cleaning of the gas with the auxiliary discharge was necessary for reproducible data; after cleaning, various samples of gas gave maintenance data within the limits of reproducibility of measurements on a given sample.

The maintenance data which we obtained is given in Fig. 7 in the form of curves of transmitted power *vs.* incident power for a series of 11 pressures from 5.3 to 66.1 mm Hg. The curves lie above one another in the order of increasing pressure; because of the discontinuities in the curves for the higher pressures at incident powers between 3 and 4 watts, they are given as separate plots. At pressures below those given here, the curves of transmitted power *vs.* incident power lie above one another as the pressure is reduced since 5.3 mm Hg gives about the minimum value of transmitted power over the range of incident powers examined. At each discontinuity in the data including extinction we have connected initial and final transmitted powers with a vertical dashed line. All measured points in the runs given, including check values, are shown.

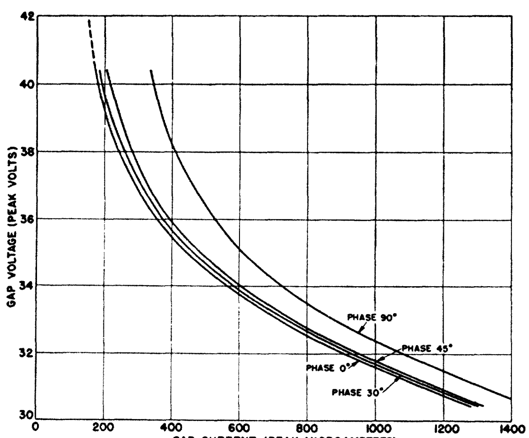

FIG. 8. Voltage-current characteristics of the argon discharge at 27.4 mm Hg assuming phase angles for the discharge admittance of 0, 30, 45 and 90 degrees.

The breaks in the maintenance data curves are reproducible as is the indicated hysteresis effect in changing from one condition to the other. Accompanying the sudden transition, the discharge, which on the higher curve appears to be a more or less uniform luminous region across the entire gap, develops a bright luminous ball at the center of the gap while the remainder of the glow appears reduced in intensity. At the lower pressures, 33.8, 27.4, and 20.7 mm Hg, where the transition is gradual, the development of the luminous ball is likewise gradual. It has been suggested that this phenomenon is similar to "contraction" in the d.c. positive column.[22] The curious bump in the curve for 14.5 mm Hg near extinction is not understood. The effect is definitely connected with the discharge and is independent of the measuring equipment; it is quite reproducible although it occurs only around this pressure.

We have previously remarked that reduction of the power data to discharge characteristics requires some information about the phase of Y_G. Because the particular cavity we used was very loosely coupled to the transmission lines, measurement of the phase of Y_G directly was not easy. By the following considerations, however, we can make a sufficiently good estimate of the phase angle ϕ associated with Y_G. Townsend and Gill[6] have pointed out that the minimum value of discharge field as a function of pressure corresponds to $\omega\tau$ of the order of magnitude unity, ω being the circular frequency of the generator and τ the mean time between collisions. An order of magnitude calculation for the relation between ϕ and τ gives $\tan\phi=\omega\tau$, and if the distribution function does not change very much with pressure, $\tan\phi$ varies as $1/p$.[23] To be conservative let us assume $\tan\phi=2$ at 5 mm Hg;[24] for 20 mm Hg we

[22] Reference 1, page 170.

[23] If we define a high frequency electron mobility K as the average over all the electrons of the ratio to the field of the electron velocity component in the field direction, the phase of this mobility and the phase of the discharge admittance are the same. For electrons of a given speed v this mobility may be calculated by simple mechanics. For a single electron the result is

$$K=(1/i\omega)e/m\{1-\exp[i\omega(t_0-t)]\},$$

e/m being the charge to mass ratio of the electron, t the time considered and t_0 the time previous to t at which the electron suffered its last collision. Next K is averaged over all the electrons of speed v by introducing the probability that the electron has gone for a time $(t-t_0)$ without a collision; this probability may be written in terms of the mean free path $\lambda(v)$ and v. The resulting average K is a real factor times the complex number $(1+i\omega\tau)$, τ being $\lambda(v)/v$. Thus for electrons of velocity v, $\tan\phi=\omega\tau$. For an electron distribution in energy τ must be averaged over the distribution and in general will not be equal to $\lambda/\bar{v}$ where λ and $\bar{v}$ are averaged independently. For helium $\lambda(v)/v$ is essentially independent of v, thus $\tan\phi=\omega\tau$ is true even in the average; for other gases for which the phase varies with electron energy, a factor, presumably of the order of magnitude of unity, is involved. Whatever this factor, if the electron distribution in energy does not vary greatly with pressure, $\omega\tau$ will vary as $1/p$.

[24] We may estimate $\omega\tau$ at 5 mm Hg directly. Suppose we take the average electron energy to be about 1/3 the ionization poten-

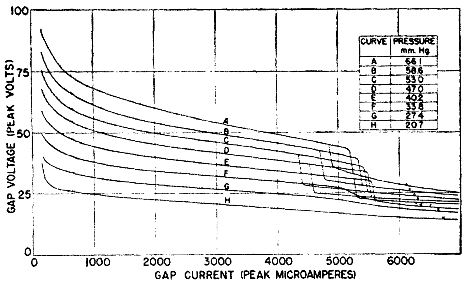

FIG. 9. Voltage-current characteristics of the argon discharge over a range of pressures. We calculated these from the data assuming the gap current to be in phase with the gap voltage.

would thus expect ϕ to be under 30°. The very small effect of such phase angles on the voltage-current curve is illustrated by Fig. 8.

Here we have reduced the data for 27.4 mm Hg assuming phase angles 0, 30, 45, and 90 degrees. The effect of phase angle is clearly greatest at low currents. Around 200 microamperes, which is practically extinction, the difference in voltage between phase angles of zero and 30 degrees is only about 1 percent and between zero and 45 degrees less than 5 percent. At 500 microamperes the difference in voltage from zero phase angle is 0.5 percent for 30 degrees, 1 percent for 45 degrees, and 5 percent for 90 degrees. In view of these results we have computed voltage-current characteristics for our discharge for pressures of 20.7 mm Hg and higher assuming the phase of Y_G to be zero. These are given in Fig. 9.

The operating point of the discharge in a given circuit with a given incident power may be determined graphically in a manner similar to the procedure used with d.c. discharges. The results are quite simple for the case of Y_G real. From Eqs. (2) and (3) we get

$$V=2(2P_i/R_2)^{\frac{1}{2}}(R_L/1+R_LY_G).$$

We can get an equation for I, the peak gap current, by multiplying this by Y_G. These two equations represent a relation between V and I in terms of the parameter R_LY_G. Solving, we obtain

$$V=2R_L(2P_i/R)^{\frac{1}{2}}-IR_L. \quad (4)$$

This is the equation for a straight line in the $V-I$ plane with a slope $-R_L$ and intercept for $I=0$ equal to the gap voltage without a discharge. This straight line is the locus of all possible gap currents and voltages for the particular cavity with a given incident power. The result is illustrated by Fig. 10. P_{i1}, P_{i2}, P_{i3}, and P_{i4} represent four successively higher values of the incident power. The intersections, A and B, of the discharge characteristic with the line labeled P_{i4} presumably represent two possible operating points of the discharge in the cavity with incident power P_{i4}. However, by the usual stability arguments,[25] only A is a stable operating point. Lowering the incident power to P_{i3} moves the operating point to C; still lower incident powers move the operating point to E, the point of tangency and extinction. Thus at extinction the slope of the discharge characteristic is $-R_L$. The portion of the characteristic above E, EDB, can be explored only with a cavity with higher value of R_L.

In Fig. 11 we have plotted the discharge characteristic for 47.0 mm Hg to illustrate this behavior, the points representing values calculated from our data while the straight lines are drawn with a slope $-R_L$. At both extinction and the transition points the agreement of the slopes is quite good.

The close similarity between the high frequency discharge and the d.c. positive column has been pointed out.[6] In the high frequency discharge between parallel plates the applied high frequency field produces ionization while loss occurs by a diffusion motion to the plates. In a positive column in a cylindrical tube, ionization is produced by the longitudinal gradient due to the applied d.c. field while the loss is by radial diffusion to the tube wall. To compare the high frequency data with positive column data, account must be taken of the relative rates of ionization by the d.c. and high frequency fields and the geometry difference which affects the diffusion rate. Concerning the first point it has already been pointed out[5] that a d.c. field of amplitude E and high frequency field of r.m.s. value E result is essentially the same electron energy distribution over the range of frequency to pressure ratios which we use. The diffusive loss in a plane geometry with plate separation d is equal to that in a cylindrical tube of radius R for[3]

$$\pi/d=2.405/R.$$

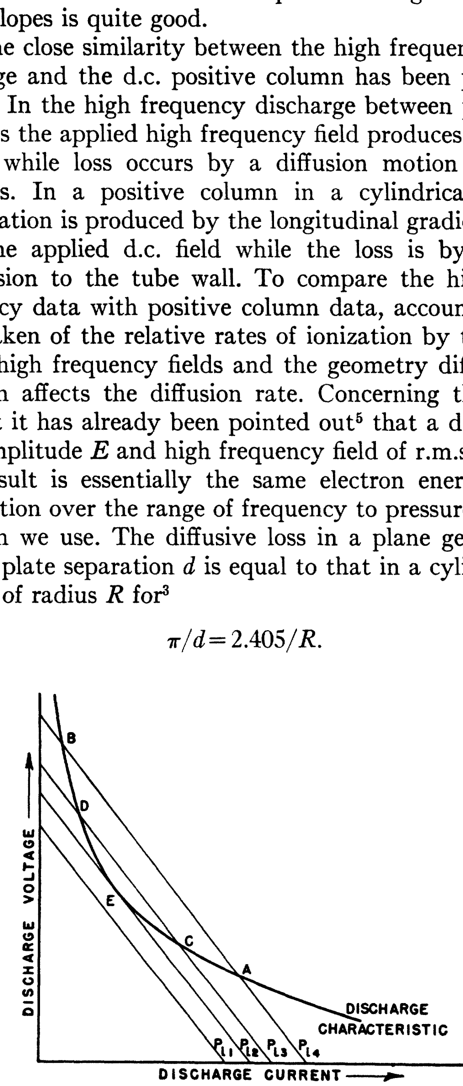

FIG. 10. Diagram illustrating the location of the operating point by the intersection of the circuit characteristic with the discharge characteristic.

tial or 5 volts (see reference 5 page 381). This corresponds to $\bar{v}$ of about 1.4×10^8 cm/sec. We may take as a conservative estimate $\lambda=(1/30p)$ cm in the average (see Kollath, Physik. Zeits. **31**, 997 (1930)), p being the pressure in mm Hg. This gives about 0.9 for $\omega\tau$.

[25] Engel and Steenbeck, *Elektrische Gasentladungen* (J. Springer, Berlin, 1932), **II**, 170–175.

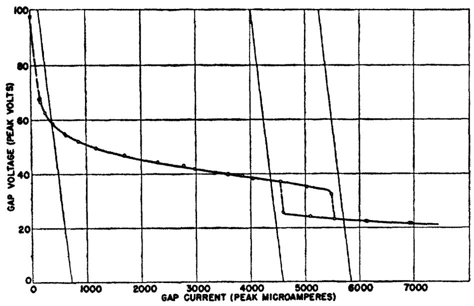

FIG. 11. Voltage-current characteristic of the Argon discharge at 47.0 mm Hg showing the characteristic slope at extinction and at the transitions. The straight lines are drawn with slope $-R_L$.

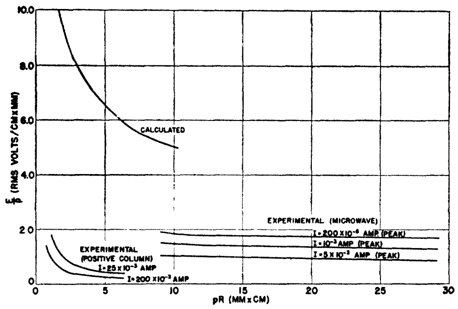

FIG. 12. Comparison of the longitudinal gradient in the d.c. positive column with high frequency maintenance fields. The calculated curve is by Holstein and is based on ambipolar diffusion. The experimental positive column data is from Klarfeld. The ordinate E/p is either longitudinal gradient in the positive column or the r.m.s. maintenance field over the pressure.

In Fig. 12 we compare our maintenance data taken at selected values of current from Fig. 9 with positive column measurements by Klarfeld[26] taken in a tube of radius 1 cm and a calculation by Holstein[3] the calculation being made in a manner very similar to that for breakdown. The maintenance calculation differs from that for breakdown in that the densities are presumed to be sufficiently high so that the electron diffusion is ambipolar rather than free. The electron energy distribution is taken to be the same at all radii and equivalent to the distribution for a d.c. field equal to the r.m.s. value of the high frequency field. Numerical values are obtained using published values of the parameters.

While the range of the abscissas for the various curves do not overlap well, it would seem that the high frequency discharge is more nearly represented by the calculation than is the positive column data. Presumably cumulative ionization processes are extremely important in the positive column; the fact that the high frequency data lies below the calculation suggests that these cumulative processes are also important here.

We may estimate our density by assuming the current uniformly distributed over the area of the gap and further that the mobility in the high frequency field is the same as for a d.c. field of the same magnitude as the r.m.s. value of the high frequency field. Using published values of mobility,[27] we estimate densities of 3×10^8, 2×10^9 and 10^{10} per cc. for peak gap currents of 200, 1000, and 5000 microamperes, respectively. At densities of 10^8 per cc we should expect the diffusion rate of electrons to be greater than the ambipolar rate[28] so that surprisingly enough the difference to be ascribed to cumulative processes is even greater than is indicated by Fig. 12. The other possibility, of course, is that the space charge field does have an appreciable effect on the energy distribution of the electrons.

In conclusion we wish to thank Dr. T. Holstein of this laboratory for proposing this experiment and assisting in interpretation of the results.

[26] Klarfeld, Tech. Phys. U.S.S.R. **5**, 725 (1938).

[27] R. A. Nielsen, Phys. Rev. **50**, 950 (1936).

[28] T. Holstein, Phys. Rev. **75**, 1323A (1949).