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C. E. Muehe

AC Breakdown in Gases

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Group 46

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ABSTRACT

The breakdown potential of helium, neon, argon and xenon was measured over the frequency range from DC to 1000 Mcps, and the pressure range from 10^{-8} to 600 mmHg employing a glass breakdown cell with 1-cm spacing. Graphs showing contours of constant breakdown potential as a function of pd and d/λ are presented. These graphs show three distinct breakdown regions: (1) the diffusion-controlled region, (2) the secondary-electron-emission (multipactor) region, and (3) the low-frequency region. The breakdown mechanism in each of these regions is explained. An extensive bibliography on AC breakdown in gases is included.

Accepted for the Air Force
Stanley J. Wisniewski
Lt Colonel, USAF
Chief, Lincoln Laboratory Office

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AC BREAKDOWN IN GASES

I. INTRODUCTION

The breakdown potential of a gas, when subject to an AC electric field, has been the topic of a very large number of experimental and theoretical investigations as evidenced by the extensive bibliography included in this report. Unfortunately, each of these investigations covers only a small range of experimental variables so that it is difficult to get an over-all picture of AC breakdown. This was clarified somewhat by Brown[1,2] who recognized that the experimental data for a given gas and geometry could all be displayed on one graph if a set of proper variables were used. This is the approach followed in the present investigation.

We will consider breakdown in a uniform field between two parallel plates. If we assume that the plate diameter is large compared to the spacing and that edge effects are somehow avoided, then the only experimentally adjustable parameters are the spacing between the plates d, the pressure p, the wavelength λ, the nature of the plate material, and the gas used. Figure 1, the breakdown of hydrogen between brass or copper plates, results from plotting the data of several experimenters[3-7] using proper variables that are well established and are in conformity with the usual similarity laws for gas discharges.[8] We used a slightly different set of proper variables from those used by Brown for the simple reasons that the resulting graph displays more vertical and horizontal lines in the contours of constant breakdown voltage, and the graph is more compact (extends over fewer orders of magnitude of the proper variables) than Brown's. A horizontal or vertical line in one of the contours indicates that the breakdown voltage is independent of one of the parameters in a certain region. Thus the horizontal lines to the left of Fig. 1 indicate that the breakdown voltage is independent of pressure as one approaches a vacuum. We normalized all other variables to the spacing d. This particular normalization is also useful from an experimental point of view, since the distance d usually is fixed in a given experiment while the pressure and wavelength are allowed to vary.

We measured the high-frequency breakdown potential in helium, neon, argon and xenon using experimental methods described below (Figs. 2 through 5*). Before discussing the experiments, we will briefly review the various types of AC breakdown. This discussion will center on Fig. 1, although from the similarity in the shapes of the curves it could equally apply to Figs. 2 through 5.

II. THREE BREAKDOWN REGIONS

Figure 1 can be broken into three regions. The upper and lower halves of the figure are divided by the oscillation amplitude limit, which starts at the left of Fig. 1 in a horizontal line

* Enlarged copies of these figures may be obtained from the author.

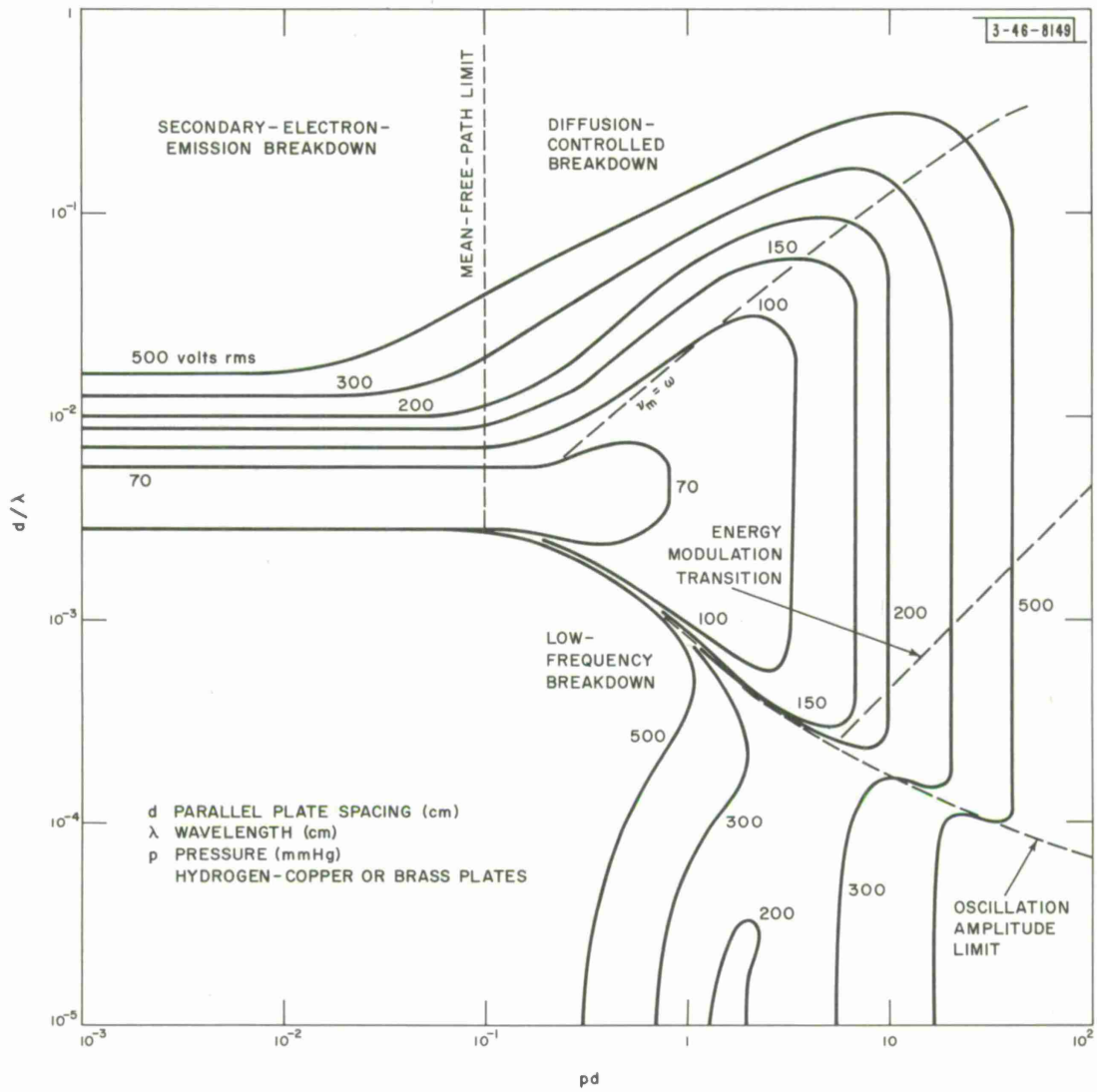

Fig. 1. Contours of constant breakdown voltage for hydrogen.

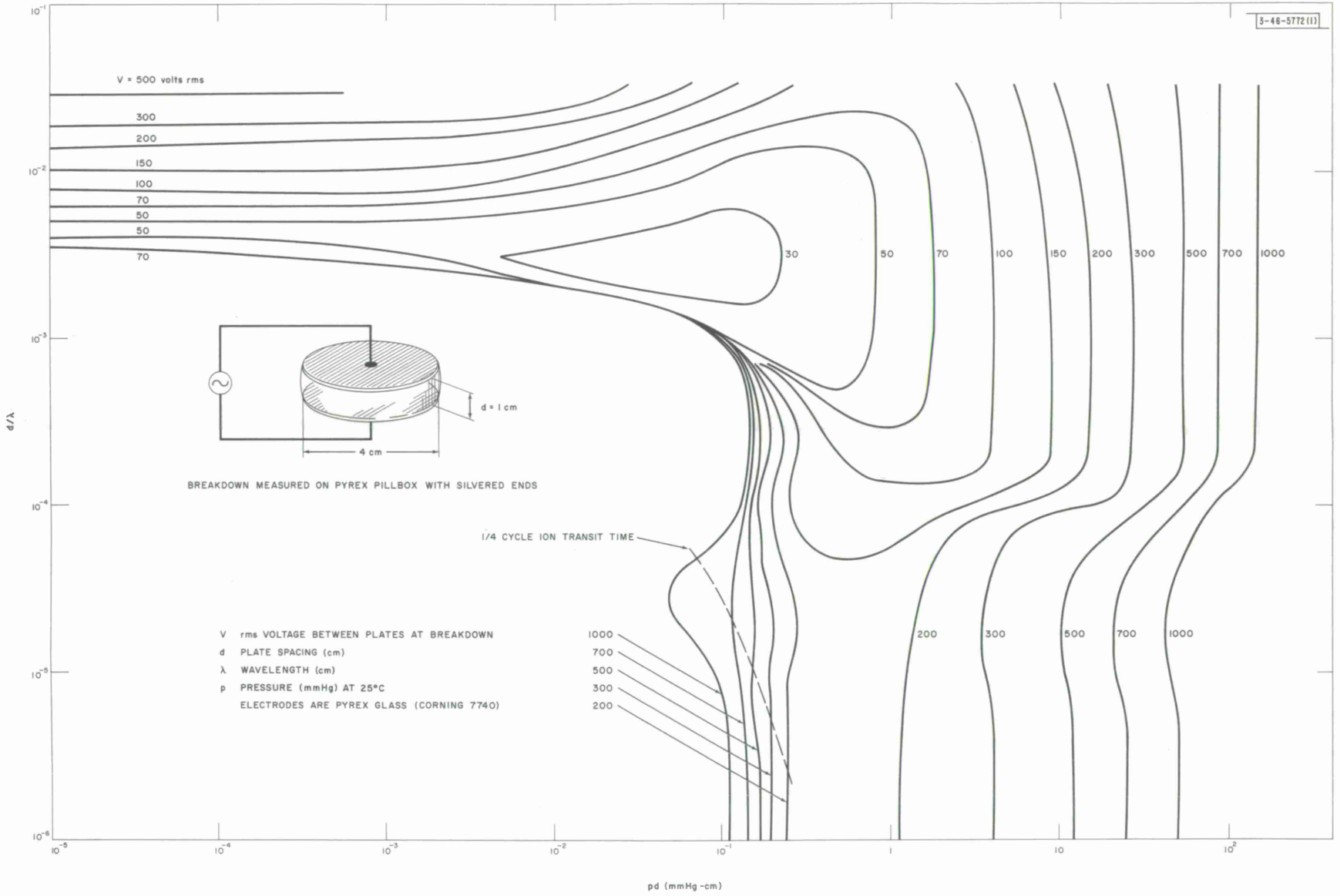

Fig. 2. Experimental AC breakdown of xenon.

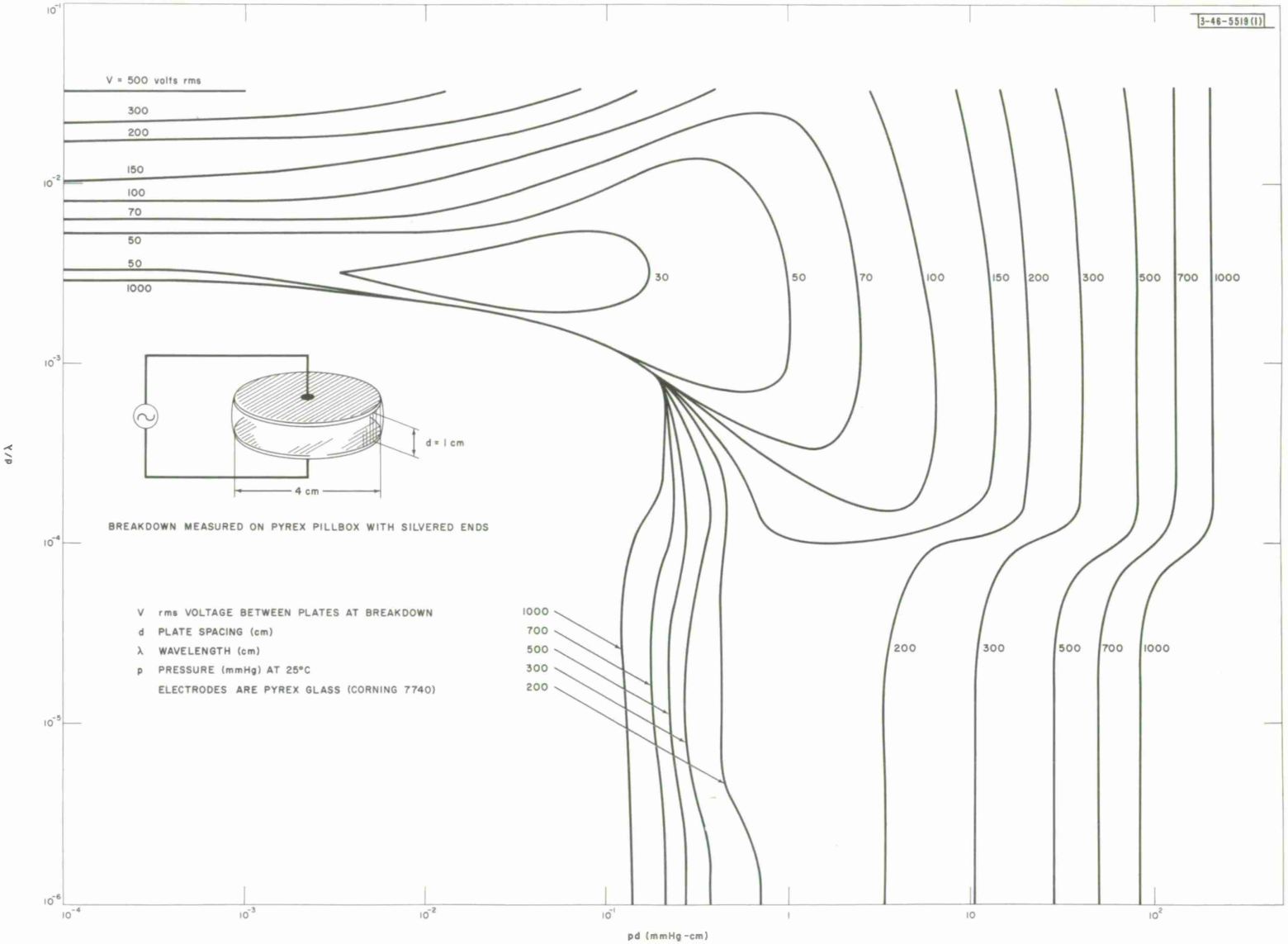

Fig. 3. Experimental AC breakdown of argon.

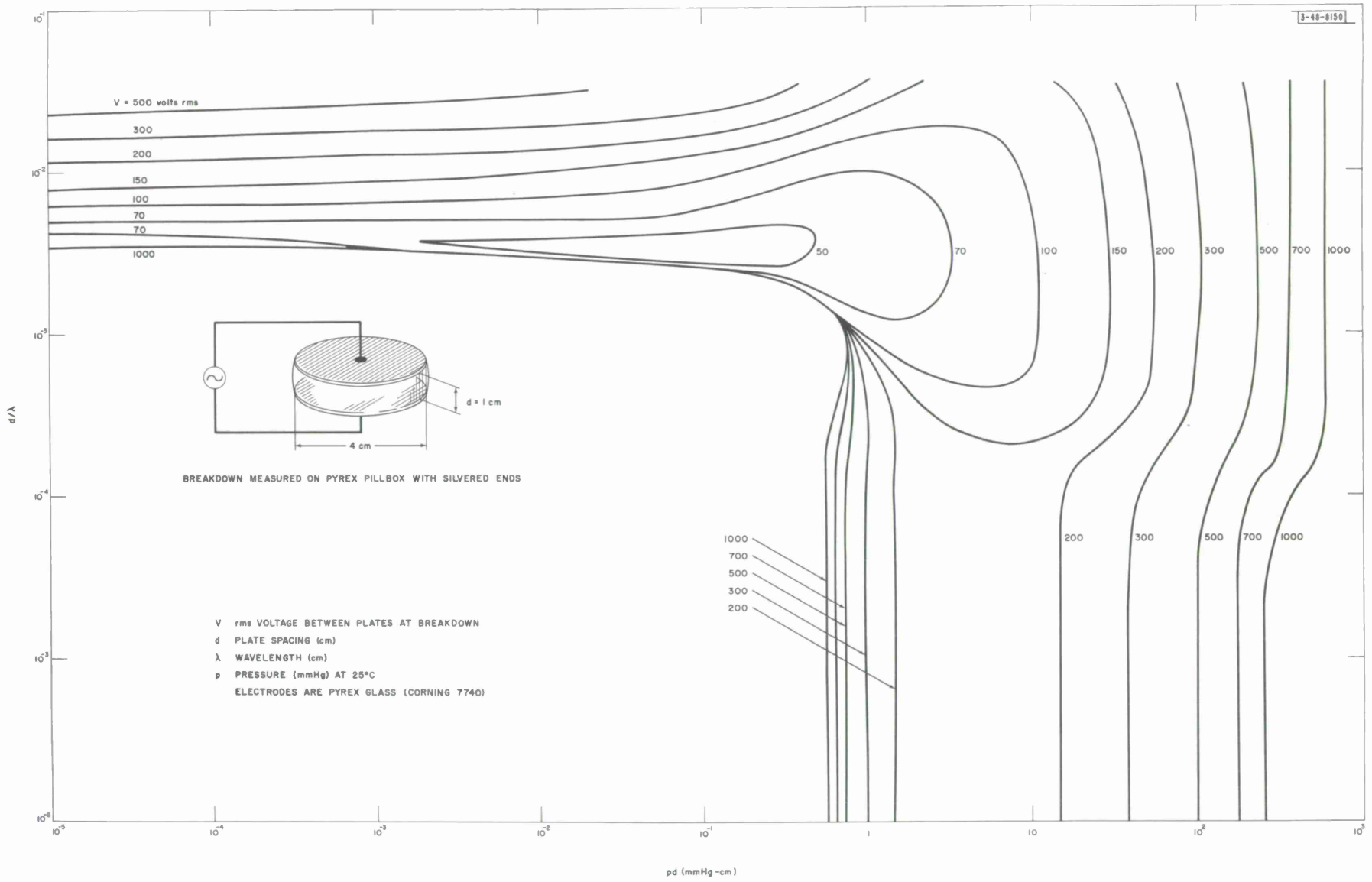

Fig. 4. Experimental AC breakdown of neon.

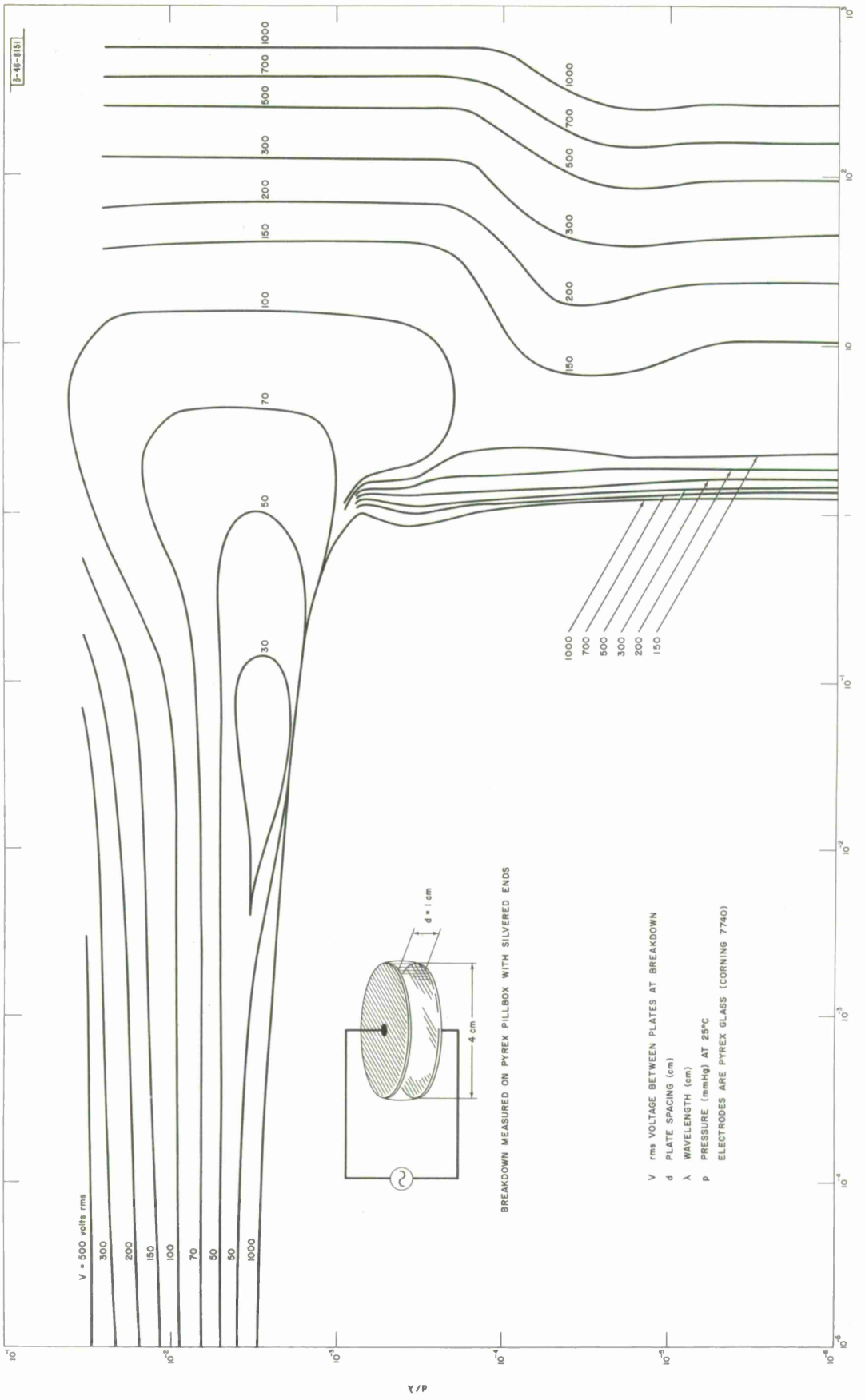

Fig. 5. Experimental AC breakdown of helium.

at a d/λ value of 0.0027 and extends into the dashed line marked "oscillation amplitude limit." The upper half of the figure is further subdivided into two parts by the "mean-free-path limit." The three different regions into which the breakdown diagram is divided are characterized by various electron production and loss mechanisms. If a very slowly increasing AC field is applied to the region between the plates, any electrons present will either multiply or be lost. When the rate of gain exceeds the rate of loss, breakdown occurs.

A. Diffusion-Controlled Region

When the experimental parameters are adjusted to be in the upper-right-hand corner of Fig. 1, the breakdown is said to be "diffusion controlled." In this region electrons are produced by ionizing collisions between electrons and gas molecules, and are lost by diffusion to the walls. Where the equipotential lines in this region are straight and vertical, the breakdown potential is independent of frequency. Moving vertically upward (increases the frequency, decreases the wavelength) along one of these lines, one notices that they bend to the left because the efficiency of energy transfer from the electric field falls off with increasing frequency. An effective field is often defined[2] as $E_e = E\nu_m/\sqrt{\nu_m^2 + \omega^2}$ (where ν_m is the collision frequency for momentum transfer), which would transfer the same energy to the electrons as a DC field of the same value. Examining the above expression we see that when $\nu_m = \omega$ the effective field equals $E/\sqrt{2}$. With this in mind we can determine the curve of $\nu_m = \omega$ in Fig. 1 by projecting the vertical straight-line portions of the curves to a point where the voltage is $\sqrt{2}$ times the value for each equipotential curve. The above procedure is valid since we have not varied p or d in the projection so that the loss of electrons by diffusion is still the same, and we must merely have a higher electric field in order to heat the electrons enough to produce the needed ionization.

If we examine what happens in the diffusion-controlled region when the pressure is varied while holding the spacing d and the wavelength λ constant (movement along a horizontal line), we observe that the minimum potential occurs to the left of the $\nu_m = \omega$ line at high values of d/λ as one might expect if the above-mentioned effect alone were acting. But, at low values of d/λ, the minimum occurs to the right of the $\nu_m = \omega$ line. This can be explained by the fact that the same effect which causes the minimum in the DC Paschen curve, as explained under low-frequency breakdown, is also active.

Actual breakdown voltages in the diffusion-controlled region have been calculated theoretically for helium (Ref. 9), neon (Ref. 10), hydrogen (Ref. 11), and in a helium-mercury mixture (Ref. 12). These theoretical investigations utilized Boltzmann's equation and experimentally measured elastic and inelastic collision cross sections. Good agreement exists between theory and experiment.

By use of measured uniform-field breakdown data, diffusion-controlled breakdown fields have been predicted correctly for several nonuniform-field situations: coaxial geometry,[13] spherical geometry,[14] around a small hemispherical boss,[15] and for cavities with $d/\lambda > 0.1$ (Ref. 16).

In electron-attaching gases such as air, electrons are lost by attachment as well as diffusion. Attachment predominates at high pressures where diffusion losses are small; then the breakdown becomes a volume process occurring when a certain value of E/p is exceeded.

Also, in the diffusion-controlled region when the pressure is high enough and the frequency low enough, the breakdown field is altered because the electron energy is modulated. At each collision with a gas molecule, an electron loses some small fraction g of its energy.

If the collision is elastic, g is about 2m/M (where m is the electron mass and M is the molecular mass). If the collision is inelastic, a larger portion will be lost. A simple analysis shows that if ν_c/ω is much less than 2/g, the electron energy will remain practically constant throughout the AC cycle. If ν_c/ω is much greater than 2/g, then the electron energy will closely follow the electric field. The transition $\nu_c/\omega = 2/g$ is approximately a 45° line running upward to the right, marked "energy modulation transition" in Fig. 1. We have taken g = 0.01 for hydrogen.* Figure 1 shows no change in breakdown voltage in crossing this transition for two reasons. First, the expected change in voltage is probably quite small for hydrogen. Gould and Roberts[17] calculated that the breakdown field for air increased by 20 percent when this transition is crossed vertically by going from longer to shorter wavelength. The change depends to a large extent on the slope of the ionization-vs-field curve which is steeper for air than hydrogen. Second, Fig. 1 was drawn using the data from five experimenters. There was about 10-percent scatter between the various sets of data, and no single experimenter gave enough data to detect the change in voltage in crossing this transition. It would be interesting to take several vertical experimental runs in this region for some polyatomic gas to find the exact effect of the energy modulation. If plotted, we would find this energy modulation transition off to the right of our graphs (Figs. 2 through 5) everywhere above the oscillation amplitude limit. Below this limit the energy modulation transition is not important because the electrons themselves are swept out of the breakdown region during each half cycle, as explained in Sec. B below.

B. Low-Frequency Region

The dividing line between the diffusion-controlled and low-frequency breakdown regions is the "oscillation amplitude limit," so called because at voltages corresponding to the diffusion-controlled breakdown voltage along this line, the amplitude of oscillation of the electron motion equals half the plate separation d. Thus during one cycle all the electrons will hit the walls of the container. Below this line the breakdown takes place much like a DC breakdown with each electrode acting as cathode during half the cycle. At high pd the oscillation amplitude limit approaches a horizontal straight line for attaching gases, but continues to slope gently downward with increasing pd for nonattaching gases.

In the low-frequency breakdown region, because the electrons are rapidly swept to the anode, a secondary (γ or β) process such as electron emission due to bombardment of the cathode by positive ions or photons is required for breakdown. At low and medium pressures, breakdown occurs when the equation $\gamma(e^{\alpha d} - 1) = 1$ is satisfied.[2] Here α is the number of electron-ion pairs produced by one electron as it drifts 1 cm in the applied field. The quantity $(e^{\alpha d} - 1)$ is the number of ions formed by one electron in crossing the gap d. The quantity γ_i is defined as the probability that one ion so formed will produce one new electron at the cathode, and γ_p is the probability that the photons formed in one ionizing collision will produce one new electron at the cathode. At high pressures, the β_p process seems to be important wherein the photons produce ionization in the gas. At very low frequencies, breakdown occurs at the peak of each cycle and the peak AC voltage for breakdown equals the DC breakdown voltage. For this reason the curves of Fig. 1 become vertical straight lines at the bottom of the graph with pd values corresponding to the normal Paschen curve for DC breakdown.

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* L. B. Loeb, Basic Processes of Gaseous Electronics (University of California Press, Berkeley, California, 1955), p. 325.

The Paschen curve of DC breakdown voltage vs pd is concave upward with a single minimum. Breakdown voltage rises with increasing pressure at higher pressures because of the increasing collision frequency. The electrons lose energy more rapidly due to collisions so they require a higher electric field to raise their average energy sufficiently to ionize the gas. At low pressures the breakdown voltage rises with decreasing pressure because the collision frequency is so low that ionizations are rare before the electrons are lost from the discharge. Thus their average energy must be raised higher so that an electron has a better chance of ionizing before being lost.

As the frequency is raised (movement along a vertical line in Fig. 1) from DC, the time it takes to initiate the discharge becomes important.[18,19] If the breakdown time is more than a small fraction of a cycle, the voltage will not remain near its peak value long enough for breakdown to take place. Then, during the next quarter cycle, the charged particles will be swept out of the gap. Thus when the breakdown time is long, usually at low pressures, the peak voltage must be raised with increasing frequency to cause breakdown. (See the low-pressure curves in Fig. 6.)

If the frequency is increased still further, a point will be reached at which some ions generated at the positive peak of the RF cycle will remain in the gap at the next peak. If the ions can just cross the gap in $\frac{1}{4}$ of the RF cycle, many ions generated near the anode at the positive peak will traverse the gap twice before the negative peak and bombard the cathode at just the right time to produce new electrons. Thus simultaneous multiple avalanches will take place at the negative peak. A reduction in breakdown voltage can then be expected much as if the cathode were bombarded by intense ultraviolet.*

At low pressures, where the γ_i process is important, the breakdown voltage will first rise with increasing frequency because there is insufficient time at the peak of the cycle for the ions to reach the cathode and then fall when the gap transit time is $\frac{1}{4}$ cycle. This course of events is seen to exist for argon at low pressure in Fig. 6, where the $\frac{1}{4}$ cycle transit time points are marked. At higher pressure, where the γ_p process dominates, no transition is apparent. This effect is very marked in xenon. A dashed line in Fig. 2 shows where the transit time is $\frac{1}{4}$ cycle. Similar results were observed by Fuchs[19] in hydrogen. The distance ions travel in $\frac{1}{4}$ cycle is $\mu_i\sqrt{2}E/\omega$, where μ_i is the ion mobility.

If the frequency is increased above the point where the ion transit time is $\frac{1}{2}$ cycle ($d = 2\sqrt{2}\mu_i E/\omega$), ions can accumulate in the gap from one cycle to the next. In this case breakdown will take place if the number of ions produced exceeds the number lost by diffusion per cycle.

Breakdown of air at atmospheric pressure with increasing frequency usually between various-sized spheres has been the subject of a number of investigations.[20] A downward departure from the 60-cps breakdown value is observed when the transit time is $\frac{1}{4}$ to $\frac{1}{2}$ cycle (see especially Lassen[21]). It is not clear which of the above mechanisms is causing this departure. Because of the very short breakdown times with small overvoltages at high pressure, associated with the fact that breakdown takes place in a single avalanche, it is hard to explain breakdown as being due to the accumulation of ions after many cycles. We prefer the explanation involving the production of simultaneous multiple avalanches by the ions bombarding the cathode at the peak of the pulse when the ion transit time is greater than $\frac{1}{4}$ cycle.

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* T. F. Godlove, "Nanosecond Triggering of Air Gaps with Intense Ultraviolet Light," J. Appl. Phys. 32, 1589 (1961).

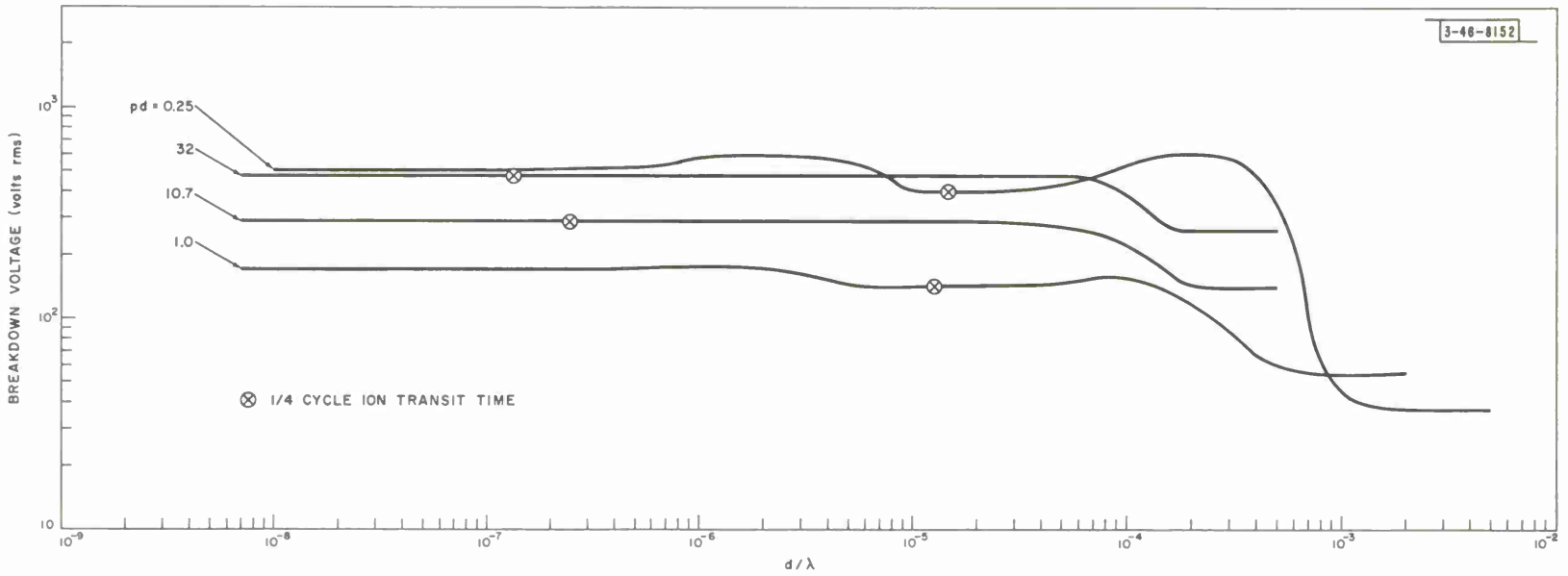

Fig. 6. Low-frequency breakdown in argon.

C. Secondary-Electron-Emission Region

The "secondary-electron-emission" and "diffusion-controlled" breakdown regions (Fig. 1) are separated by the "mean-free-path limit." Left of this limit, breakdown becomes independent of the nature of the gas or the gas pressure so that the constant breakdown voltage lines become horizontal, and ionization in the gas is no longer important. Instead, new electrons are produced by secondary-electron emission at the walls of the container. The theory of secondary-electron-emission (multipactor) breakdown is well understood.[2,22] For breakdown to occur, the walls must have a secondary-emission ratio greater than one in the energy range of the incident electrons, and the transit time must be an odd number of half periods of the applied RF. A fairly well-defined sheet of electrons travels back and forth between the electrodes, reconstituting itself through secondary emission as it strikes each wall. The density of the electron sheet grows with each wall encounter and is finally limited principally by space-charge repulsion forces. For values of d/λ less than 0.0027, no voltage exists for which the secondary emission is greater than one and the transit time is one-half period, even if all starting phases are examined. Below this value of d/λ, the amplitude of oscillation of electrons in a field sufficiently large to give a secondary-emission ratio greater than one is much larger than the plate spacing so that no breakdown will occur. Thus the line $d/\lambda = 0.0027$ is a natural extension of the oscillation amplitude limit of higher pressures.

Several geometries, other than the parallel-plate geometry described above, can lead to multipactor breakdown. A magnetic field,[2] an applied DC field,[23] or an electrostatic field[24] can be used to return the electron to the secondary emitting surface. Multipactor discharges can also take place between irregular-shaped electrodes.[25,26]

III. EXPERIMENTAL PROCEDURE

The tube used for breakdown measurements was in the form of a Pyrex pillbox (see Fig. 2). Electrodes were external and were applied to the flat ends of the tubes. Internal spacing between the flat ends was 1 cm. Voltage given on the figures is the internal, rms voltage. The tube diameter was chosen so that it would not change the diffusion length by more than 8 percent from a tube with infinite radius.

The pillbox was placed at the high-voltage point of various cavities tuned to the frequency of operation in order to increase the applied voltage and filter out any harmonics from the oscillator output. The cavity most often used was a piece of $3\frac{1}{8}$-inch coaxial line with the tube mounted between the end of the center conductor and an end plate. The other end of the cavity had an adjustable shorting plate and a small adjustable loop for coupling in power. Voltage was measured using a power meter and a carefully calibrated directional coupler mounted on the cavity wall. At lower frequencies, the tube still in the $3\frac{1}{8}$-inch coax mount was incorporated into a lumped-element tuned circuit coupled to the oscillator through a short piece of coaxial line and a swinging loop coupling. Voltage was measured using a vacuum-tube voltmeter. At still lower frequencies, audio amplifiers supplied the signal and an oscilloscope was used to assure proper wave shape.

A square, flat cavity whose height was just that of the tube spacing was built for the highest frequency (1000 Mcps) because the R/Q could be calculated quite accurately. The input coupling matched a 50-ohm coaxial line, and the output coupling was much smaller. Thus with the measured Q and insertion loss, the relation between output power and tube voltage could be calculated.

The gas-handling system was made completely of metal and glass following the design used for ultrahigh-vacuum systems. Bakeable metal valves were used for connections to the oil diffusion pump and the bottle of spectroscopically pure gas. Gases used were Airco Reagent grade; some were Airco Assayed Reagent grade. All pressures were measured at room temperature and no corrections were made. Three different pressure gauges were used depending on the pressure range. From about 1 mmHg upward, a metal diaphragm gauge incorporated into a capacitance bridge was used. The metal diaphragm separated the clean gas system from an auxiliary system which included a conventional mercury U-tube manometer and a McCleod gauge. The capacitance bridge was balanced with both gas systems evacuated, then balanced again with gas in both systems. The pressure in the clean system was then the same as that read in the auxiliary system.

In the pressure range from about 3 microns to about 20 mmHg, a Pirani (hot-wire) gauge was employed as one arm of a DC bridge circuit which was always kept in balance by adjusting the voltage supplied to the bridge. The Pirani gauge was surrounded by an aluminum block which was kept within 0.1°C at 40°C by means of a heating element and a mercury contact thermometer, both embedded in the block. Special low-temperature coefficient resistors were used in the other arms of the bridge and a precision ($\frac{1}{2}$-percent) meter was used to read the bridge voltage. The hot wire was maintained at a constant 140°C. In separate calibration tests using a CVC-type, GM-100, triple-scale McCleod gauge and a conventional mercury manometer, the following equation for the calibration curve was found to hold within the experimental accuracy over the whole range of pressures for which the Pirani gauge is useful:

$$p = p_o \frac{V^2 - V_1^2}{V_2^2 - V^2} \quad ,$$

where p is the pressure corresponding to any voltage V. Of the three parameters in the above equation, two (p_o and V_2) vary with the nature of the gas. V_1 is the voltage necessary to balance the bridge in a good vacuum; V_2 is the bridge voltage at pressures high enough so that the heat conductivity of the gas is constant, independent of pressure; and p_o is the pressure where the bridge voltage has fallen off to $V_2/\sqrt{2}$. A transparent overlay of a log-log graph of $V^2 - V_1^2$ vs p of the above equation was made letting $p_o = 1$, and $V_2^2 - V_1^2 = 1$. Then calibration points in the high-pressure range (>1 mmHg) were obtained using the diaphragm pressure gauge. A log-log plot of $V^2 - V_1^2$ vs p for the experimental points was overlaid with the previously prepared transparency. The best fit was obtained and the (1, 1) point of the transparency covered the $(V_2^2 - V_1^2, p_o)$ point on the experimental plot. This had to be done for each gas and each Pirani gauge used. It was found that the gauge could be relied on to hold its calibration as long as the voltage V_1, necessary to balance the bridge in a vacuum, stayed the same. A change in V_1 indicates a surface change in the tungsten wire of the gauge, usually the formation or reduction of oxides.

At pressures below 10^{-2} mmHg, an M. I. T. -modified Bayard-Alpert gauge was employed, calibrated* for each of the gases used with the aid of the CVC McCleod gauge. The ionization gauge calibration is probably not very accurate (~ 20 percent) but the breakdown voltage turns

* W. B. Nottingham and F. L. Torney, Jr., "A Detailed Examination of the Principles of Ion Gauge Calibration," Seventh National Symposium on Vacuum Technology Transactions (Pergamon Press, New York, 1960).

out to be quite independent of pressure in its range anyway (see Figs. 2 through 5). Using the three pressure gauges described above, we were able to measure the pressure from 10^{-9} to several hundred mmHg without introducing condensible vapors of any description into the system under test.

The experimental procedure was to outgas the whole system using a torch until a pressure in the 10^{-9}-mmHg range was achieved. The ion gauge was outgassed and a multipactor discharge was run in the experimental tube for several hours. At this point the valve to the diffusion pump could be closed off and the pressure would not exceed 10^{-7} after about six hours even without ion-gauge pumping. With ion-gauge pumping, the pressure would remain much lower. Gas was then admitted and a pressure measurement made. RF voltage was brought up very slowly, and the voltage at which breakdown occurred was noted. The darkened tube was viewed with a 1P21 photomultiplier tube to detect breakdown. Under some experimental conditions, breakdown produced no change in the electrical circuits and could only be detected by eye in a darkened room. The photomultiplier was perfectly reliable in detecting breakdown. After an initial determination of the breakdown voltage, the RF power was lowered and raised even more slowly through the suspected breakdown voltage. After several such trials the scale reading for breakdown was determined with great precision. A pressure run was made across the limits shown in Figs. 2 through 5 at each frequency; the frequencies were varied in steps of 1.5 to 1. At several low pressures, where the lines are nearly horizontal, the pressure was fixed and the frequency was varied so as to progress along a vertical line in the graphs. Oscillators delivered at least 50 watts at all frequencies from 300 cps to 1000 Mcps. At least 1000 volts could be produced across the experimental breakdown tube. Frequencies were measured using a Beckman counter.

Xenon:— Our xenon breakdown measurements agree very well with those reported by Bradford, et al.[27] ($d/\lambda = 0.0297$) for pressures up to 10 mmHg. Above this pressure our breakdown fields are lower than theirs, lying between their "pure" and "impure" xenon curves. The discrepancy probably comes from their use of a Pirani gauge to measure pressures. Above 10 mmHg for xenon, the Pirani gauge used in a bridge circuit is very inaccurate. When calibrating this gauge any impurities in the gas, particularly condensibles, would lead to a higher voltage reading than for pure xenon. This effect, coupled with the flat voltage-pressure calibration curve, would introduce large, systematic errors in reading the pressures above 10 mmHg. The large scatter in their experimental points seems to confirm this suspicion.

Argon:— Our argon breakdown measurements agree well with those of Krasik, et al.[28] ($d/\lambda = 0.0555$), MacDonald and Matthews[29] ($d/\lambda = 0.0442$), and Vlaardingerbroek[30] ($0.00034 < d/\lambda < 0.00101$) except for the low-pressure end of the latters curves, where our breakdown potentials are generally lower. This can easily be explained by the fact that Vlaardingerbroek used nickel electrodes and his curves approached the oscillation amplitude limit at their low-pressure ends. Since our electrodes were glass with a much higher secondary-emission ratio than nickel, their electron contribution due to secondary emission would be much larger, resulting in a lower breakdown voltage. This difference should not appear at higher pressures where the experimental agreement is quite satisfactory.

Neon:— Our results for neon are not in agreement with other workers (Fig. 7 illustrates the discrepancies). We have plotted various reported results for diffusion-controlled breakdown; all results should fall on the same curve. The most logical explanation of these discrepancies

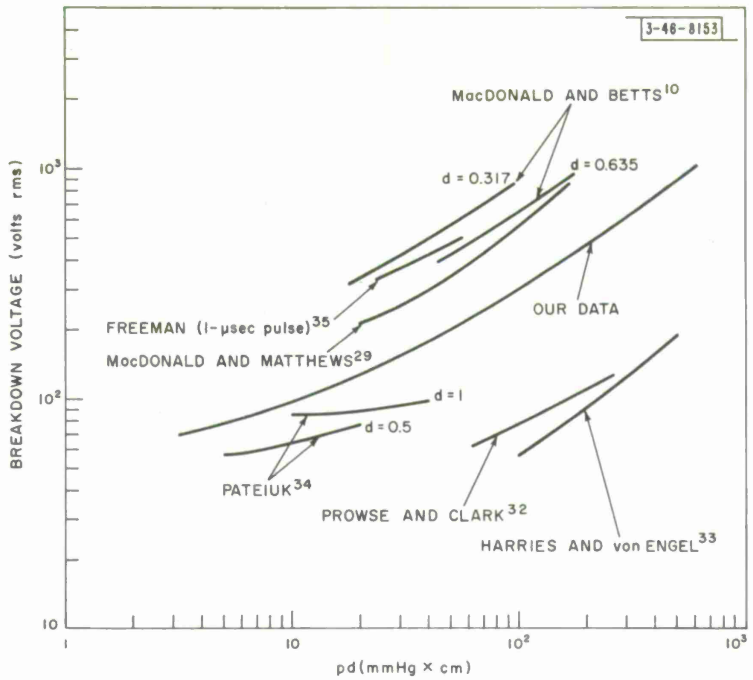

Fig. 7. Diffusion-controlled breakdown in neon. Results of several experimenters.

is that neon can form a Penning mixture with most likely impurities. An argon impurity content of only one part in 10^5 can cause a large reduction in the breakdown potential.[29,31] Most other impurities would also form Penning mixtures with neon, whereas xenon and argon will not form Penning mixtures with most impurities. Prowse and Clark[32] recognized this fact when they compared their neon results with those from known argon-neon Penning mixtures. On the other hand, Harries and von Engel[33] invented a new mechanism involving light quanta to explain their extremely low breakdown potentials. Their measurements in the low-frequency region are much lower than ours, and they find a transition to higher breakdown values as d/λ is reduced below 2×10^{-7}. If the Penning effect explains their low breakdown voltages in the diffusion-controlled region, then this transition near $d/\lambda = 2 \times 10^{-7}$ might be explained in terms of a change in impurity content or some other interesting mechanism involving the Penning effect. Until experiments are made with known, well-controlled mixtures over the whole wavelength range, any discussion would be mere speculation.

Our low results, compared with those of MacDonald and Matthews[29] ($d/\lambda = 0.0442$), are probably due to a small impurity in our gas. One batch of neon showed much lower breakdown potentials so the results were discarded. Aside from the efforts already described to ensure a clean gas-handling system, we made no other attempt to purify the gas. There was more scatter in the experimental points for neon than for any other gas we used. It would be interesting to use getters and cataphoresis tubes to remove impurities.

MacDonald and Betts'[10] results for two different spacings ($d/\lambda = 0.0297$ and 0.595) do not agree with themselves or with the results reported later.[29] We cannot explain this discrepancy. Pateiuk's[34] low results ($d/\lambda = 0.00263$, 0.00525) are probably due to impurities. Freeman's[35] rather high results ($d/\lambda = 0.095$) are probably due to the short pulse (1 μsec) used in her breakdown studies because the experimental apparatus used almost surely had a high impurity content.

Helium:– Parallel-plate breakdown data for pure helium are reported by Reder and Brown.[9] The same data are reported in Brown's book (Ref. 2, pp. 144 and 150). Our electric fields lie consistently a factor of 1.4 lower than these. There may be some confusion between peak and rms values since the argon breakdown fields plotted on p. 150 of Brown's book and taken from Krasik, et al.,[28] are definitely peak fields, but the graph is merely labeled E_e. We are led, in other parts of the book (p. 142), to believe that E_e represents an rms value. All we can say is that our values are all rms values.

Our breakdown voltages for helium are a factor of about two higher than those reported by Francis.[8] Again, as in our discussion of the neon results, the difference may be attributed to impurities in the gas since helium also forms Penning mixtures with various impurity gases. Our disagreement with Reder and Brown may also be due to impurities in our gas.

IV. CONCLUSION

We have measured the breakdown potential in four inert gases over an extremely wide range of the experimental parameters. Three breakdown regions are easily discernible on each graph: (a) the diffusion-controlled region, (b) the low-frequency region, and (c) the secondary-electron-emission (multipactor) region. The dividing lines between these regions are easily discernible on all the graphs. The constant breakdown potential lines flow smoothly from one region to the next. Agreement with previous theory and experiment is good for all gases except neon where large discrepancies, probably due to impurities, appear among all investigators.

An interesting effect was observed in the low-frequency region for low pressures in argon and xenon. When the transit time of the positive ions is approximately $\frac{1}{4}$ cycle, the breakdown voltage is reduced. The effect is similar to that observed by Fuchs, et al.,[19] in hydrogen. An extensive bibliography for AC breakdown in gases follows.

ACKNOWLEDGMENTS

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13. ABSTRACT

The breakdown potential of helium, neon, argon and xenon was measured over the frequency range from DC to 1000 Mcps, and the pressure range from 10^{-8} to 600 mmHg employing a glass breakdown cell with 1-cm spacing. Graphs showing contours of constant breakdown potential as a function of pd and d/λ are presented. These graphs show three distinct breakdown regions: (1) the diffusion-controlled region, (2) the secondary-electron-emission (multipactor) region, and (3) the low-frequency region. The breakdown mechanism in each of these regions is explained. An extensive bibliography on AC breakdown in gases is included.

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