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VOLTAGE BREAKDOWN IN IONIZED AIR AT FREQUENCIES FROM ZERO TO 10,000 MEGACYCLES

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for

THE PURDUE RESEARCH FOUNDATION
Lafayette, Indiana

April 30, 1959

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Sponsor: The Martin Company
Denver Division
Denver 1, Colorado

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Under Prime Contract
AF 04 (645) 56

Report Prepared
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The Purdue Research Foundation
Lafayette, Indiana
Fund: 1785-61-780

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1. Introduction

a. Background

During the summer of 1957, The Martin Company, Denver Division, expressed a need for experimental data which would enable more exact design of surface-mounted antennas on missiles which would avoid corona and voltage breakdown in the higher atmosphere. Inasmuch as some experimental data were then available, a request was also made for a literature search on voltage breakdown in air as a function of pressure, frequency, pulse length, electrode spacing, and degree of ionization.

Contract No. DEN 57-5652, under Prime Contract AF 04 (645) 56, was initiated with the Purdue Research Foundation in January, 1958, to obtain (1) a literature search and (2) experimental data covering a range of the parameters listed above. The literature search was delivered to The Martin Company on November 25, 1958. The experimental data are the subject of this report.

b. Experimental Data Required

The experimental data requested in the contract are shown as curves of electric field intensity at voltage breakdown plotted as a function of pressure in air. The breakdown is to occur in an essentially uniform field, and measurements are to be made at the frequencies, pulse lengths, and electrode spacings listed:

Zero frequency:

pulse length:	continuous
electrode spacing:	1 mm and 4 mm

200, 500, and 1000 mcs:

pulse length:	10 μsec. or longer
electrode spacing:	4 mm

3000 and 10,000 mcs:

pulse length:	0.25 and 2.0 μsec.
electrode spacing:	1 and 2 mm

For each frequency, pulse length, and electrode spacing combination, three values of ionization density are to be used: the ambient ionization present in the laboratory environment, artificial ionization sufficient to reduce the breakdown field strength by at least a factor of two, and one intermediate value.

2. Ionization Sources

a. Cobalt 60

Ten millicuries of the artificial radioactive isotope cobalt 60 were procured and installed in a specially designed, lead shielded container. The construction of this container was such as to produce a reasonably collimated beam of gamma rays vertically downward from the bottom of the vessel. Provisions were also made to allow for two different intensities by the movement of the isotope within the sample holder.

Following the methods used on pages 232-233 of "Microwave Transmission Circuits", vol. 9, Radiation Laboratory Series, a crude estimate of the ion density may be made. Ten millicuries of cobalt 60 gives 3.7×10^8 disintegrations per second; perhaps one per cent, or 3.7×10^6 gamma rays, are emitted in the desired direction; of these, some three per cent are effective in producing secondary electrons from the brass cavity walls and, therefore, about 10^5 ionizing events per second result. Each secondary electron produces perhaps 100 ion pairs per centimeter of path length, and, if an effective cross section of 3 cm^2 is assumed, the ionization intensity is roughly 3×10^6 ion pairs per second per cubic centimeter.

Since the generation and recombination of ion pairs is governed by the steady state relationship,

$$n_o = \beta n^2$$

where n_o is the rate of generation (ion pairs per second per cm^3), n is the ion density (ion pairs per cm^3), and β is the recombination coefficient, about 10^{-6} in air at atmospheric pressure, a value of 3×10^6 for n_o leads to about 2×10^6 ion pairs per cm^3. This is only a crude estimate and is most applicable for the 10,000 mcs equipment at atmospheric pressure. The lower frequency experiments employed physically larger devices and consequently had somewhat smaller ionization rates and densities. The ionization rate also drops with the pressure.

Without any artificial means of creating an appreciably ion density, it is estimated by the Radiation Laboratory that natural sources, such as cosmic rays and natural radioactivity, produce a rate of generation of 10^{-1} ion pairs per second per cm^3 and a resultant ion density of 3×10^2 ion pairs per cm^3. Judging from the long periods of time that it was necessary to spend waiting for breakdown to occur when no ionization was used, this estimate appears to be on the high side.

b. Point Discharge

Ionization of better known and more easily controlled intensity was also obtained from a point discharge. A negative voltage of a few thousand volts was applied through 18 megohms to a finely sharpened platinum-iridium point. A grounded ring surrounding and just ahead of the point produced a high electric field intensity at the point and a resultant electron current. A small, controlled, air leak behind the point assisted the electric wind effect in moving the electrons into the region of the gap. Above a pressure of about 1 mm Hg, an air flow of approximately 100 cm^3/minute was used, both to help propel the electrons and to insure removal from the gap of nitrogen compounds produced during the breakdown.

In order to estimate the electron density produced by this point discharge, a special vacuum chamber was constructed in which the electron current could be measured in a relatively small portion of the cross section of the beam. Provisions were made to allow this current density to be determined at various distances from the point. Knowing the current density J, then the relationship

$$J = \rho v \qquad (a/cm^2)$$

was used to determine the charge density ρ (coul/cm^3) or electron density (electrons/cm^3) in terms of the mean velocity v. This velocity was obtained by using an electrostatic voltmeter to measure the potential of the collecting screen. From the potential, the velocity was easily found by

$$v = 5.93 \times 10^7 \sqrt{V} \qquad (cm/sec)$$

where V is in volts.

Breakdown data were taken for nominal currents of 10 and 50 microamperes from the high voltage supply. The electron densities varied with the pressure and cavity geometry between 10^2 and 3×10^6 electrons/cm^3. Figures 1 to 4 show the logarithm of the electron density in electrons/cm^3 as a function of the logarithm of the pressure in mm Hg for the five different resonant sections.

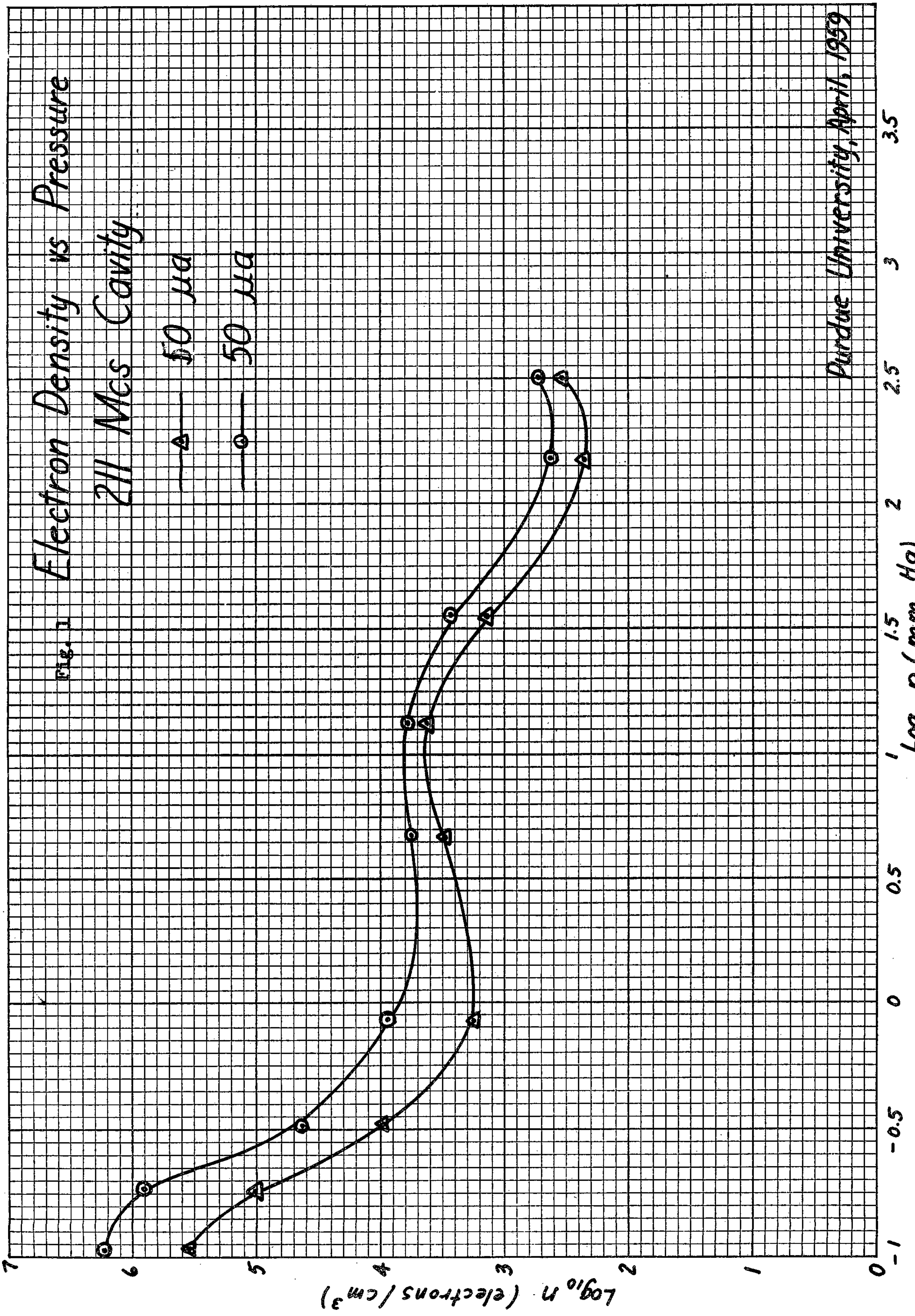
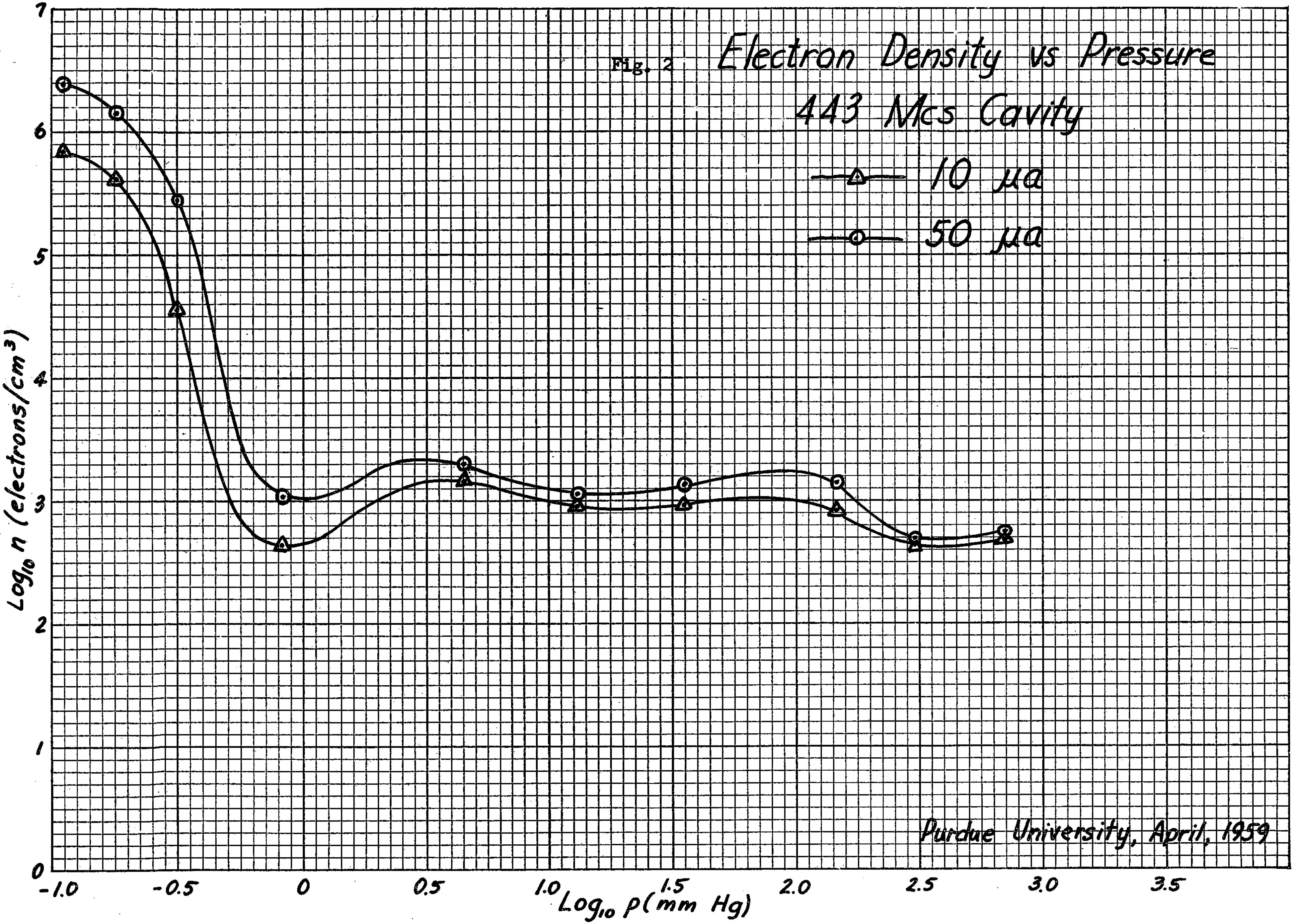


Fig. 1
Electron Density vs Pressure
211 Mcs Cavity
50 μa
50 μa
Purdue University, April, 1959
Log₁₀ p (mm Hg)
Log₁₀ n (electrons / cm³)
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
0
1
2
3
4
5
6
7

Fig. 2



Electron Density vs Pressure
443 Mcs Cavity
10 μa
50 μa
Purdue University, April, 1959
Log₁₀ n (electrons/cm³)
Log₁₀ p (mm Hg)
-1.0
-0.5
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
1
2
3
4
5
6
7

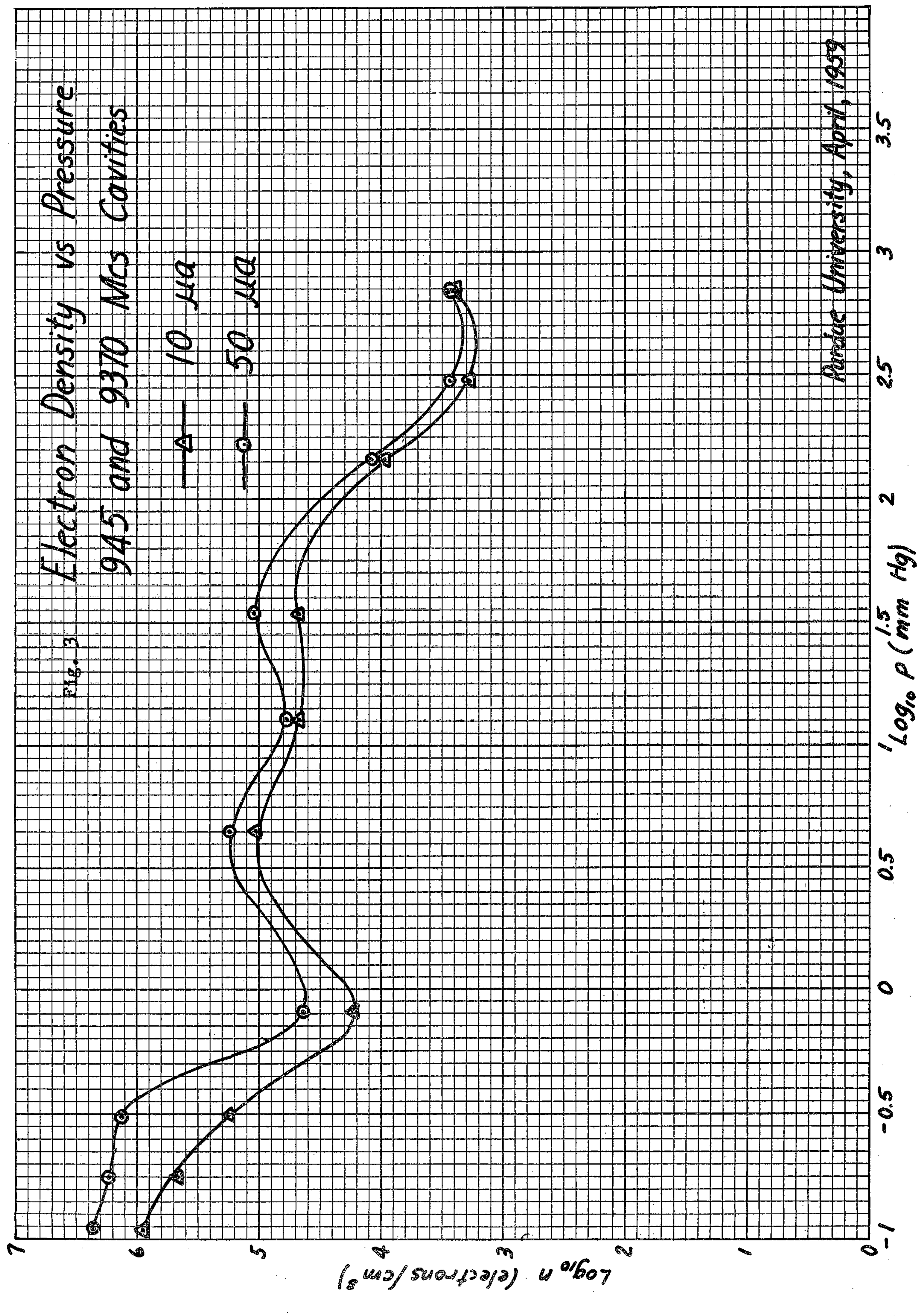


Fig. 3
Electron Density vs Pressure
945 and 9370 Mcs Cavities
10 μa
50 μa
Purdue University, April, 1959
Log₁₀ p (mm Hg)
Log₁₀ n (electrons/cm³)
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
0
1
2
3
4
5
6
7

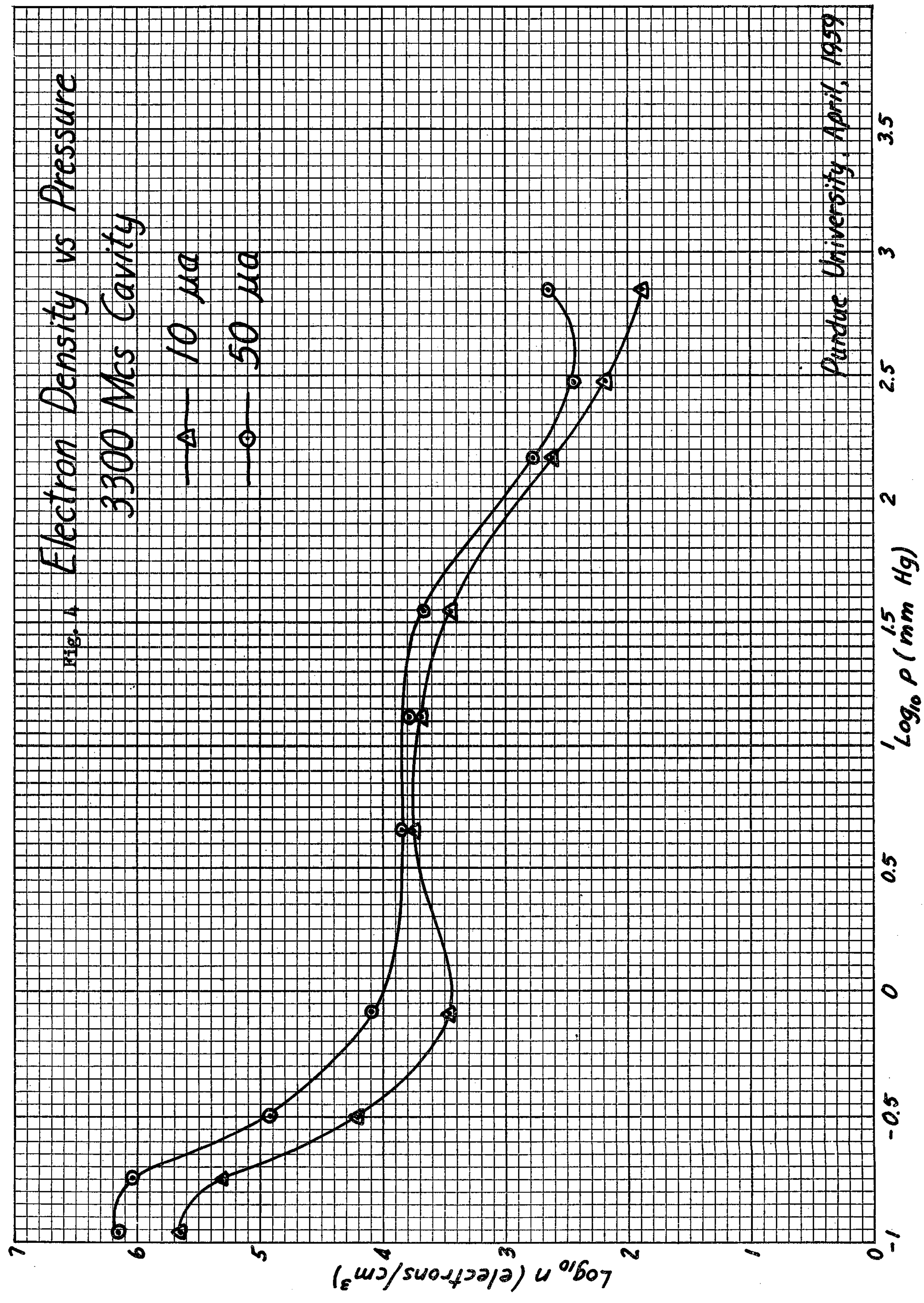


Fig. 4
Electron Density vs Pressure
3300 Mcs Cavity
10 μa
50 μa
Purdue University, April, 1959
Log10 p (mm Hg)
Log10 n (electrons/cm3)
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
0
1
2
3
4
5
6
7

The curves for 945 mcs and 9370 mcs are identical.

3. Experimental Methods

a. 211, 443, and 945 mcs

The frequencies, 211, 443, and 945 mcs, correspond to the three frequencies given in the specifications, 200, 500, and 1000 mcs, and were determined by the exact dimensions of the resonant cavities described below.

Figure 5 is a diagram of the experimental equipment and Fig. 6 shows a representative resonant cavity in more detail. The dimensions applicable to each of the three frequencies are tabulated on the figure.

The Q of such a cavity is high and therefore a relatively small power input at the resonant frequency produces a large electric field intensity across the gap.

A crystal detector and wide-band oscilloscope, together with suitable coaxial attenuators, were used to monitor the field strength in the gap by sampling the cavity fields at the output connection. After converting the oscilloscope deflection to voltage, applying the experimentally determined crystal detector and attenuator calibrations, and using the measured ratio of cavity input power to output power, the peak power input to the cavity was obtained. The gap field strength was related to the input power by using Slater's perturbation theorem for a cavity with a matched input,

$$E = \sqrt{240\, Q\, P_{in} \frac{d\lambda_o}{dv}} \qquad (v/cm)$$

where Q = cavity Q with input matched

P_{in} = peak input power (watts)

$\frac{d\lambda_o}{dv}$ = shift in resonant wavelength (cm) per cubic centimenter of inserted volume of perturbing plunger.

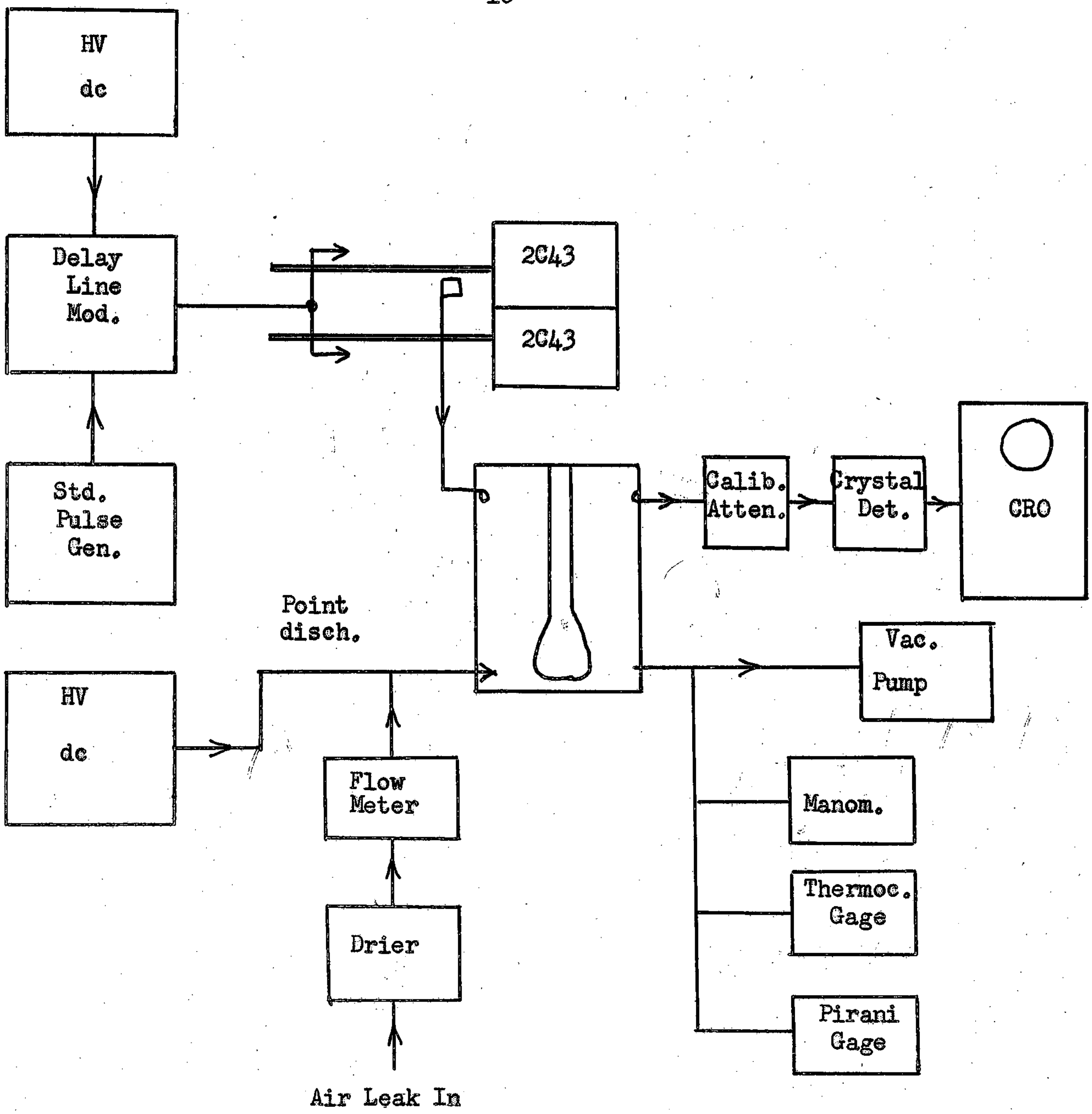
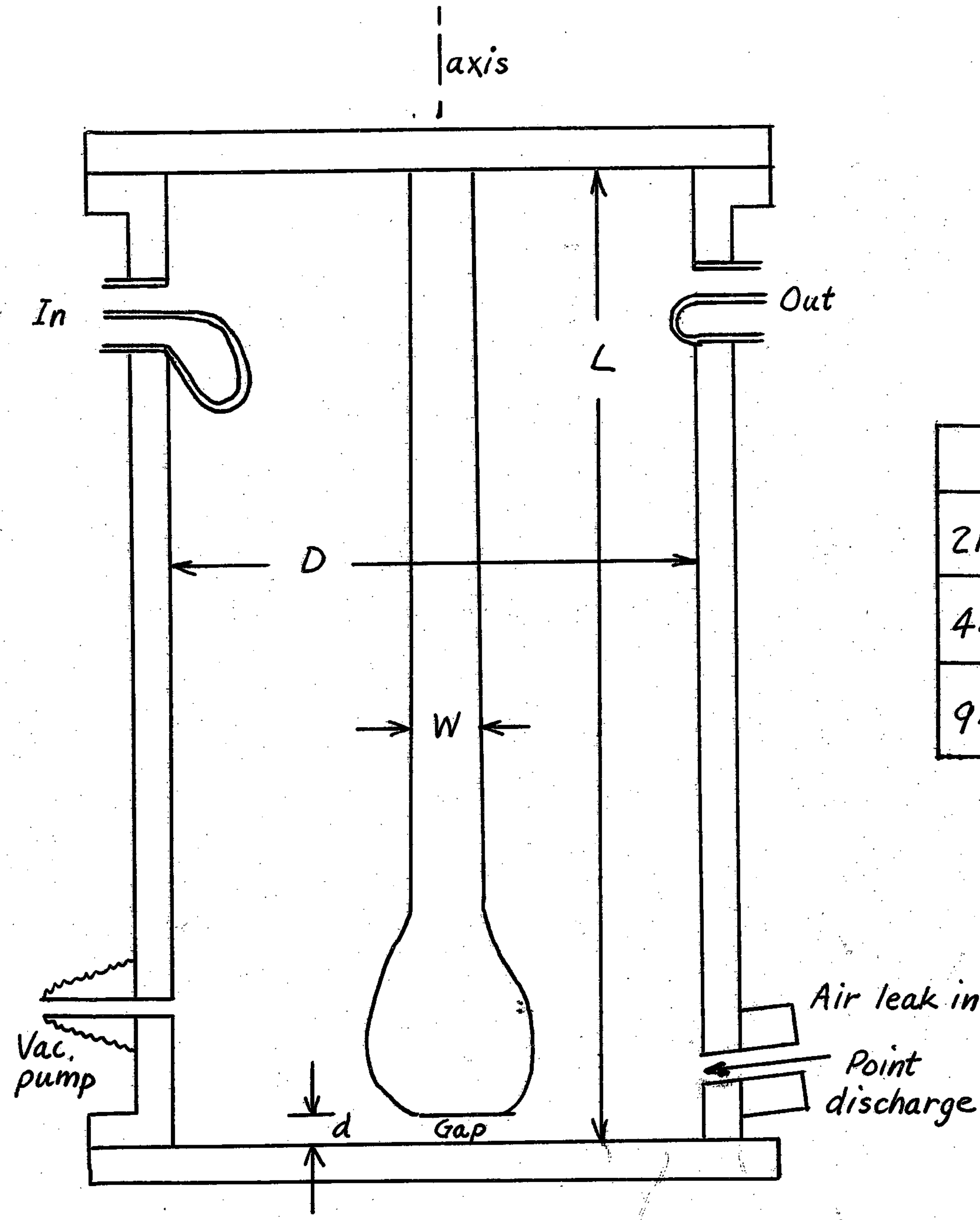


Fig. 5

Equipment block diagram for voltage breakdown measurements at 211, 443, and 945 mcs.

Purdue University, April, 1959



	d	D	L	W
211 mcs	4 mm	$11\frac{1}{2}$ in	4 in	$\frac{3}{4}$ in
443	4	$5\frac{3}{4}$	$1\frac{15}{16}$	$\frac{3}{8}$
945	4	$2\frac{5}{8}$	1	$\frac{3}{16}$

Fig. 6

Details of the 211, 443, and 945 mcs cavities.

Cylindrical plungers were installed in the long center conductor and the change in resonant frequency determined as the plunger was advanced 1/80 inch into the gap and withdrawn an equal distance from the flush position. The Q and resonant frequency were measured by conventional methods.

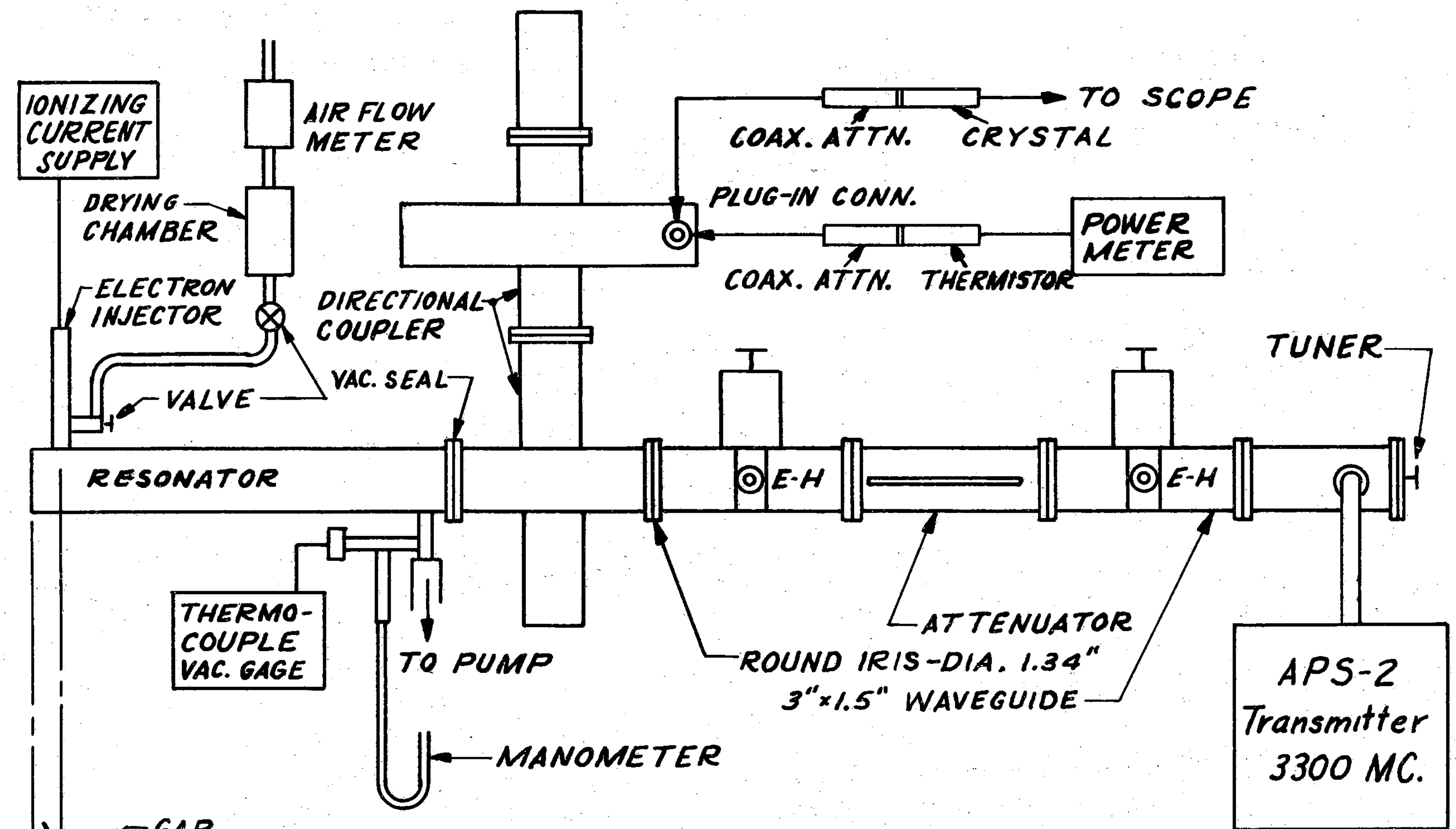
Peak power inputs of the order of 200 watts were required to produce voltage breakdown at atmospheric pressure with some ionization in the 4mm gap. Since the pulse repetition rate for the 10 microsecond pulses was 200 ppsec, the average power required was only about one-half watt.

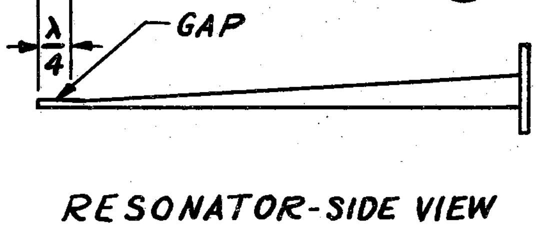
b. <u>3300 and 9370 mcs</u>

At each of the two microwave frequencies, the resonant cavities consisted of short-circuited waveguide sections which tapered down to a shorter section, approximately one-half guide-wavelength long and having a "b" dimension equal to the desired electrode spacing. Sketches of the experimental equipment arrangement for 3300 mcs and 9370 mcs are shown in Figs. 7 and 8, respectively. Each evacuated section contains the point discharge, an air drying chamber, a metered air leak, provisions for manometer, thermocouple, and Pirani vacuum gages, and the exhaust line to the pump. The Co^{60} container is placed immediately above the gap when it is being used.

The field strength in the gap at breakdown is determined by using a directional coupler to measure the circulating power in the resonant waveguide section, which extends from the short circuit to an iris following the E-H tuner. The relationship between the peak transmitted power and the peak electric field intensity in the center of a matched guide excited in the TE_{10} mode is given by

$$P = \frac{ab}{480\pi} E_{yo}^2 \sqrt{1 - \left(\frac{\lambda}{2a}\right)^2} \qquad \text{(watts peak)}$$





Equipment Set-up for Voltage Breakdown in Air at 3300 Mc. per sec.

Figure 7

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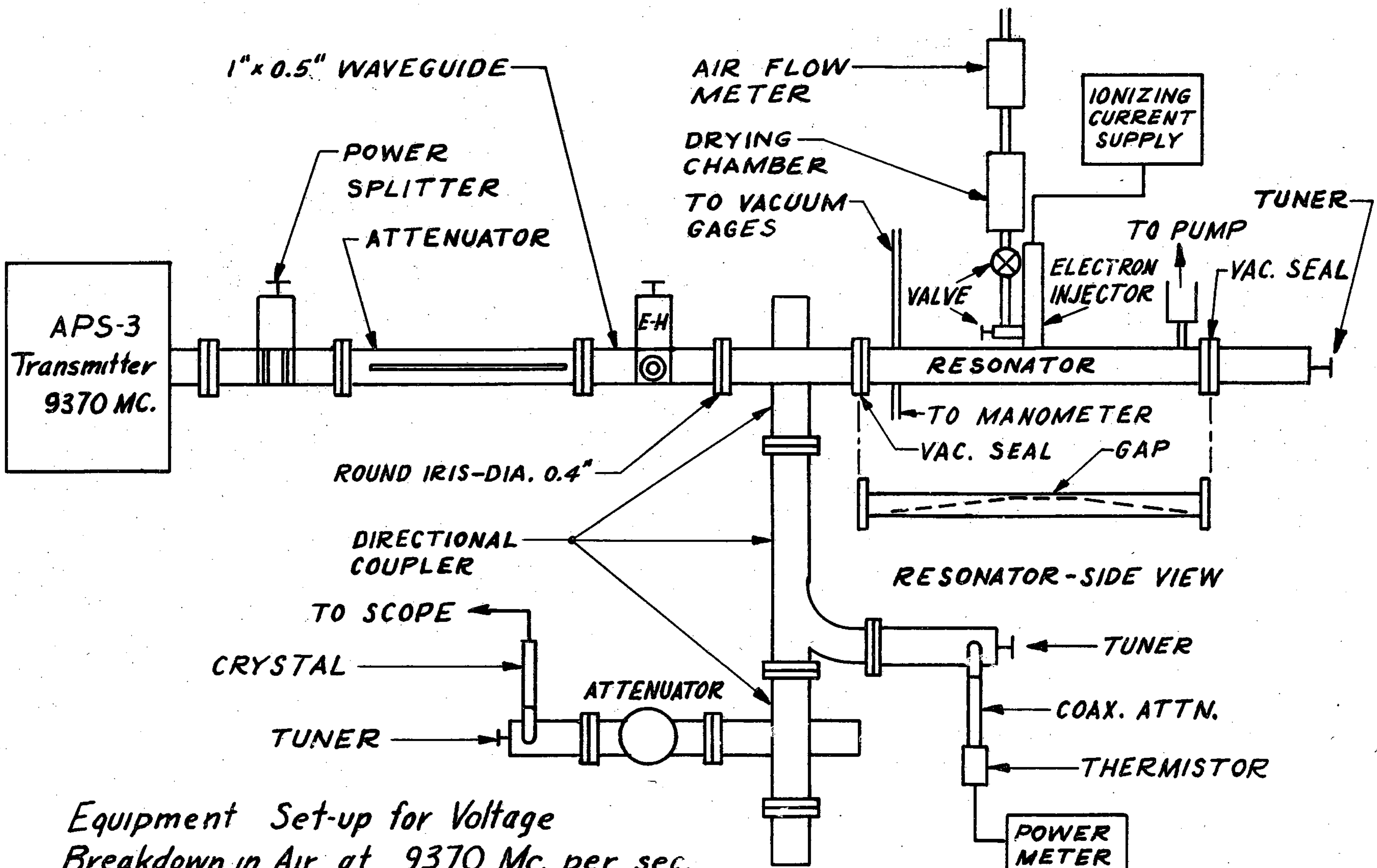


Equipment Set-up for Voltage Breakdown in Air at 9370 Mc. per sec.
Fig. 8

where,

E_{yo} = maximum peak electric field intensity (v/cm)

a = wave-guide width (larger dimension) (cm)

b = wave-guide height (cm)

$_o$ = free space wavelength (cm)

In a short-circuited section, the maximum peak electric field strength is twice E_{yo}, and, therefore,

$$E_B = \sqrt{\frac{1920 \pi P_{ave}}{f_p \tau a b \sqrt{1-(\lambda_o/2a)^2}}} \qquad \text{(v/cm)}$$

where,

$P_{ave} = f_p \tau P$ = average power (watts)

f_p = pulse repetition frequency (pps)

τ = pulse length (sec)

E_B = gap field strength (v/cm)

P_{ave} is determined by a thermistor and thermistor bridge connected to the directional coupler through calibrated attenuators or other directional couplers. For breakdown at atmospheric pressure, an average power input of about 40 watts was necessary.

Neither the available 3300 mcs or 9370 mcs radar transmitters were designed for pulse widths less than a nominal one-half microsecond, which was actually measured as being closer to 0.6 microseconds between 90% amplitude points. Shorter pulse lengths lead to greater possible field strengths before breakdown.

c. Zero Frequency

Figure 9 is a diagrammatic sketch of the equipment assembled for the tests

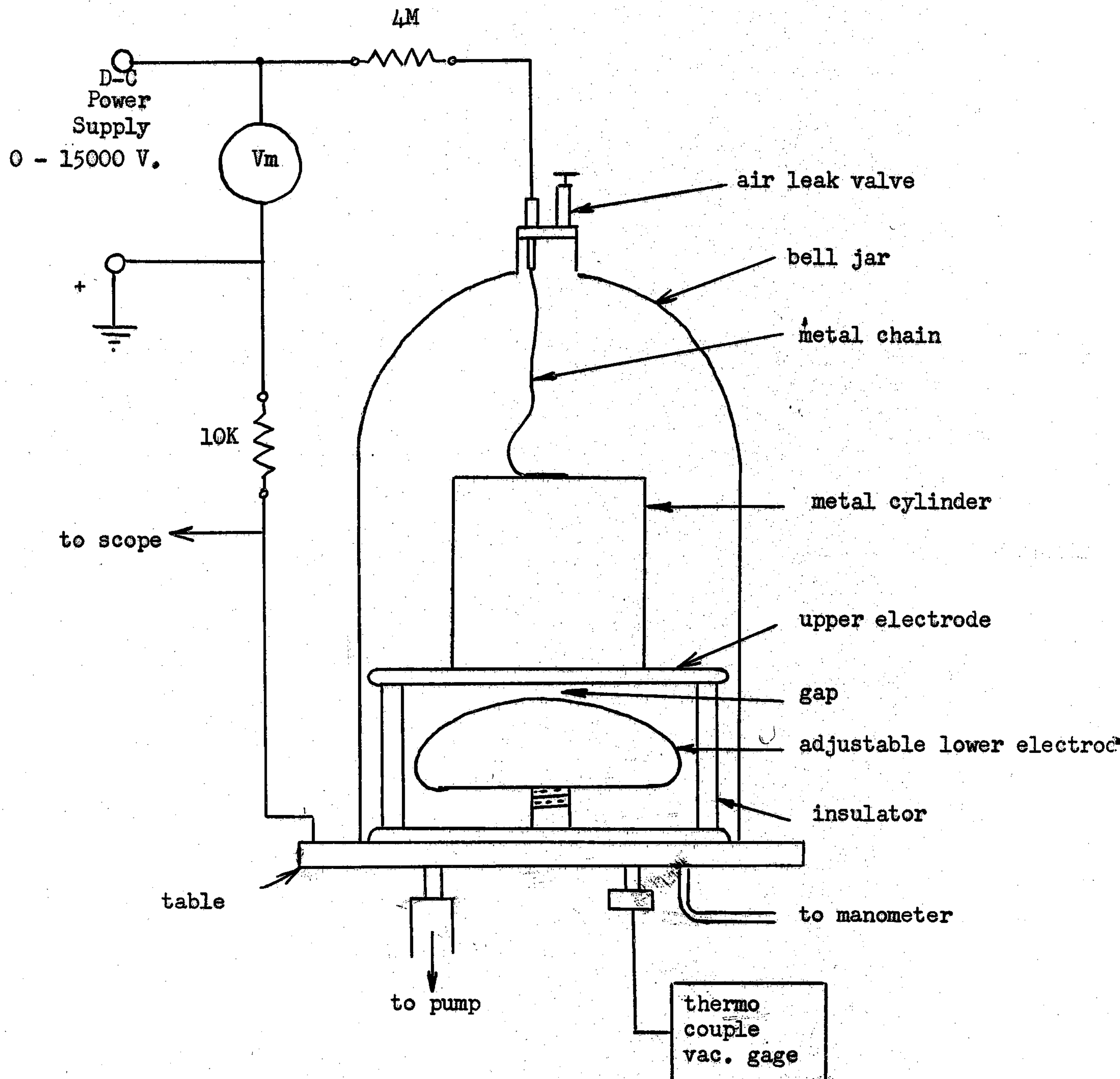


Fig. 9

Equipment Set-up for Voltage Breakdown

in Air at Zero Frequency

Purdue University

April 1959

at zero frequency. The electrode assembly consists of a flat upper plate mounted above the adjustable mushroom-shaped lower electrode which rests on a brass plate. Both electrode surfaces in the gap are silver-plated and polished, and the entire assembly is surrounded by a conventional glass bell jar. A second plate containing the electrical connection to the upper electrode and an air leak valve seals off the upper opening of the bell-jar, while the lower opening is covered by the brass table containing the pump, manometer, and vacuum gage connections. Whenever Co60 was used, the container was centered on the top of the upper electrode, and when the isotope was not being used, it was replaced by a metal cylinder of the same dimensions.

The d-c power supply, continuously adjustable from zero to 15,000 volts, is connected as shown in Fig. 9. The four megohm resistor serves to limit the current and the ten thousand ohm resistor is used to provide an indication of incipient breakdown on an oscilloscope.

Data for the curves in Figs. 10 to 12 were obtained over the full range of air pressure, from about 750 mm Hg to a few microns, for the three electrode spacings of 1, 2, and 4 mm. Ionization of the gap, when used, was achieved by means of the cobalt 60 only and was always the maximum obtainable from the available 10 millicurie source. For each observation made, the voltage was raised slowly and noted at the point of incipient or of complete breakdown. The incipient value was always recorded when observable. The field strength was easily obtained by dividing the recorded voltage by the known electrode spacing.

4. The Experimental Curves

The curves appearing on Figs. 10 to 23 show breakdown electric field in-

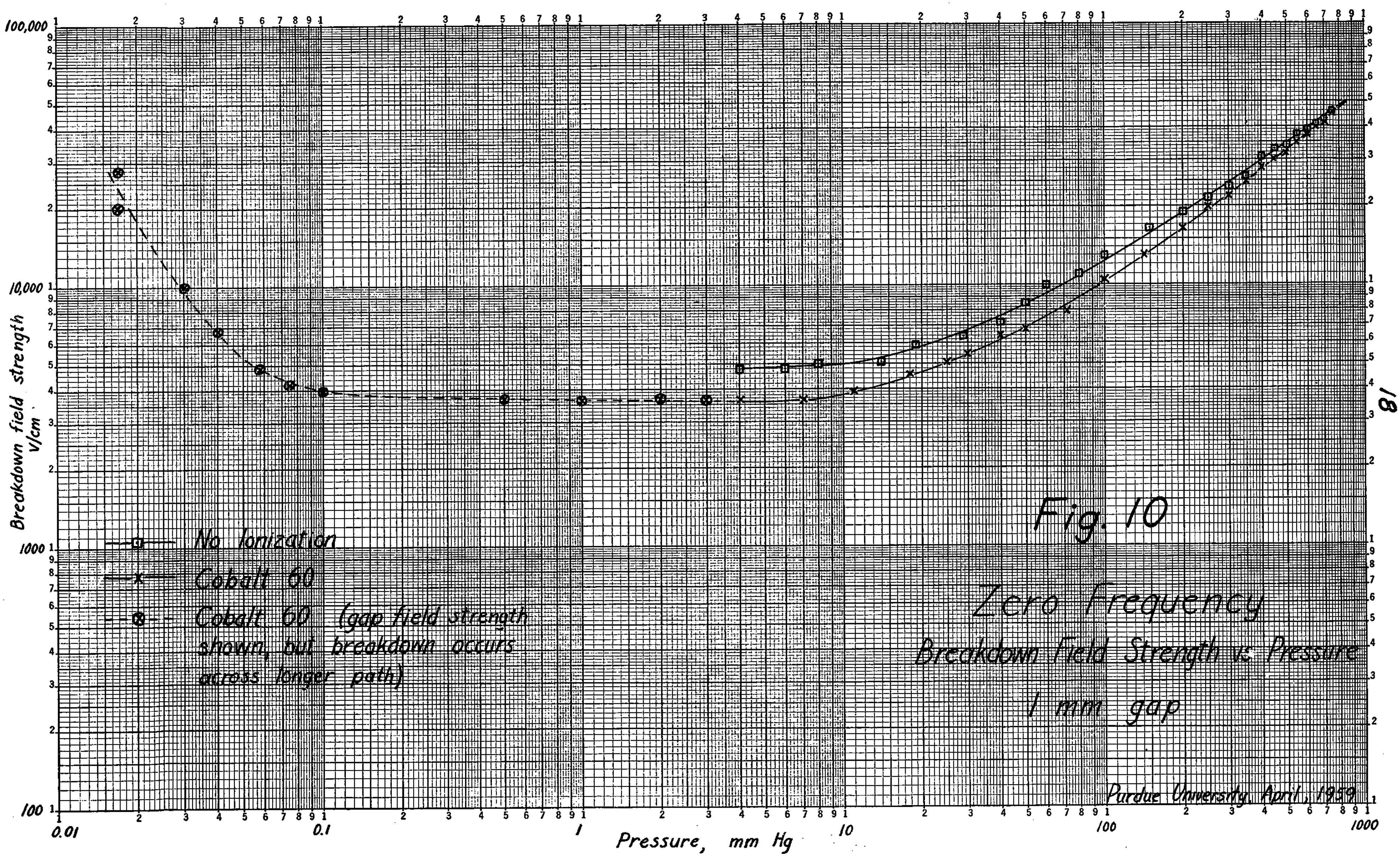

Breakdown field strength V/cm
100,000
10,000
1000
100
0.01
0.1
1
10
100
1000
Pressure, mm Hg
No Ionization
Cobalt 60
Cobalt 60 (gap field strength shown, but breakdown occurs across longer path)
Zero Frequency
Breakdown Field Strength vs. Pressure
1 mm gap
Purdue University, April, 1959

Fig. 10

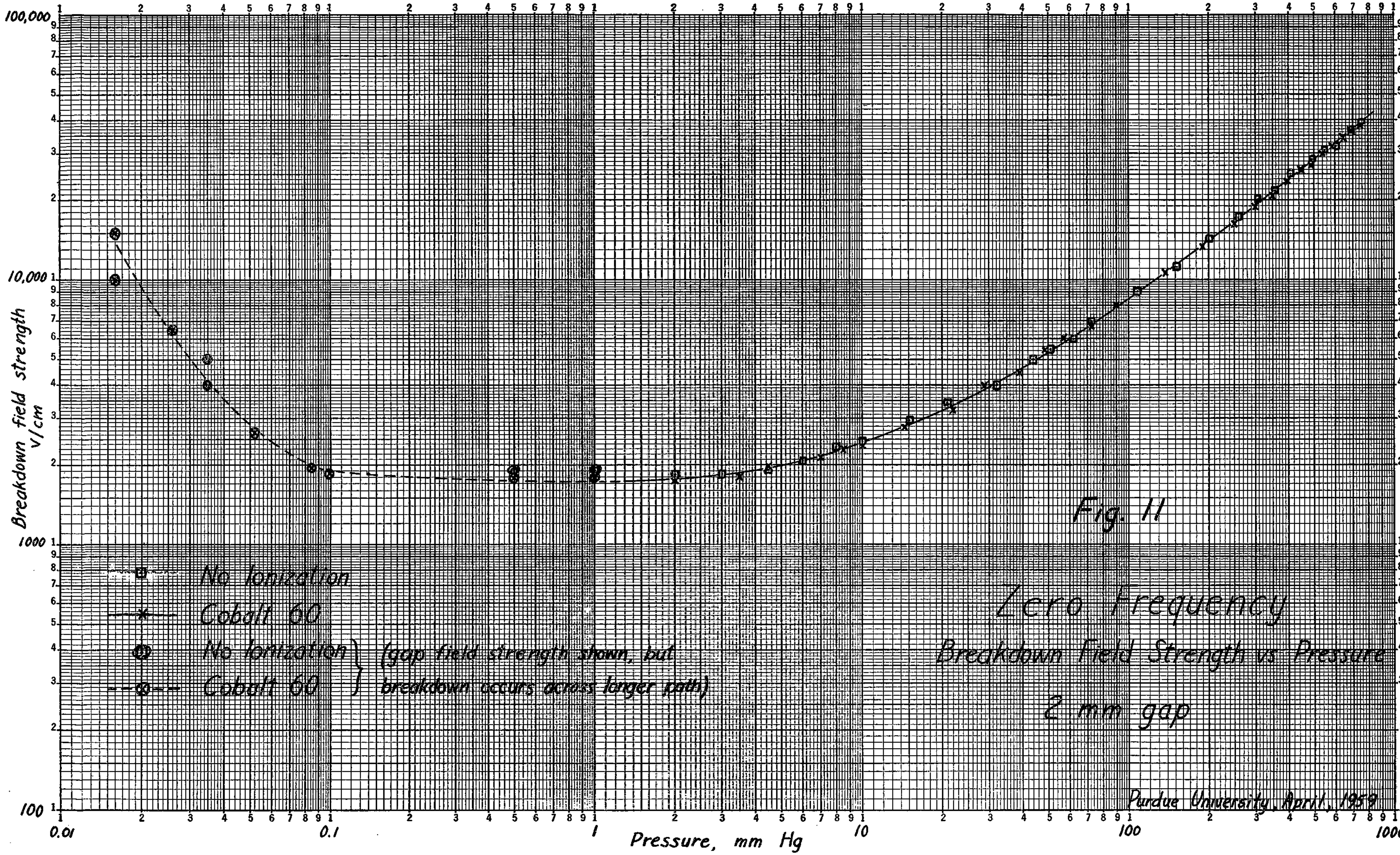


Fig. 11
Zero Frequency
Breakdown Field Strength vs Pressure
2 mm gap
Breakdown field strength
V/cm
Pressure, mm Hg
No Ionization
Cobalt 60
No Ionization
Cobalt 60
(gap field strength shown, but breakdown occurs across longer path)
Purdue University, April, 1959

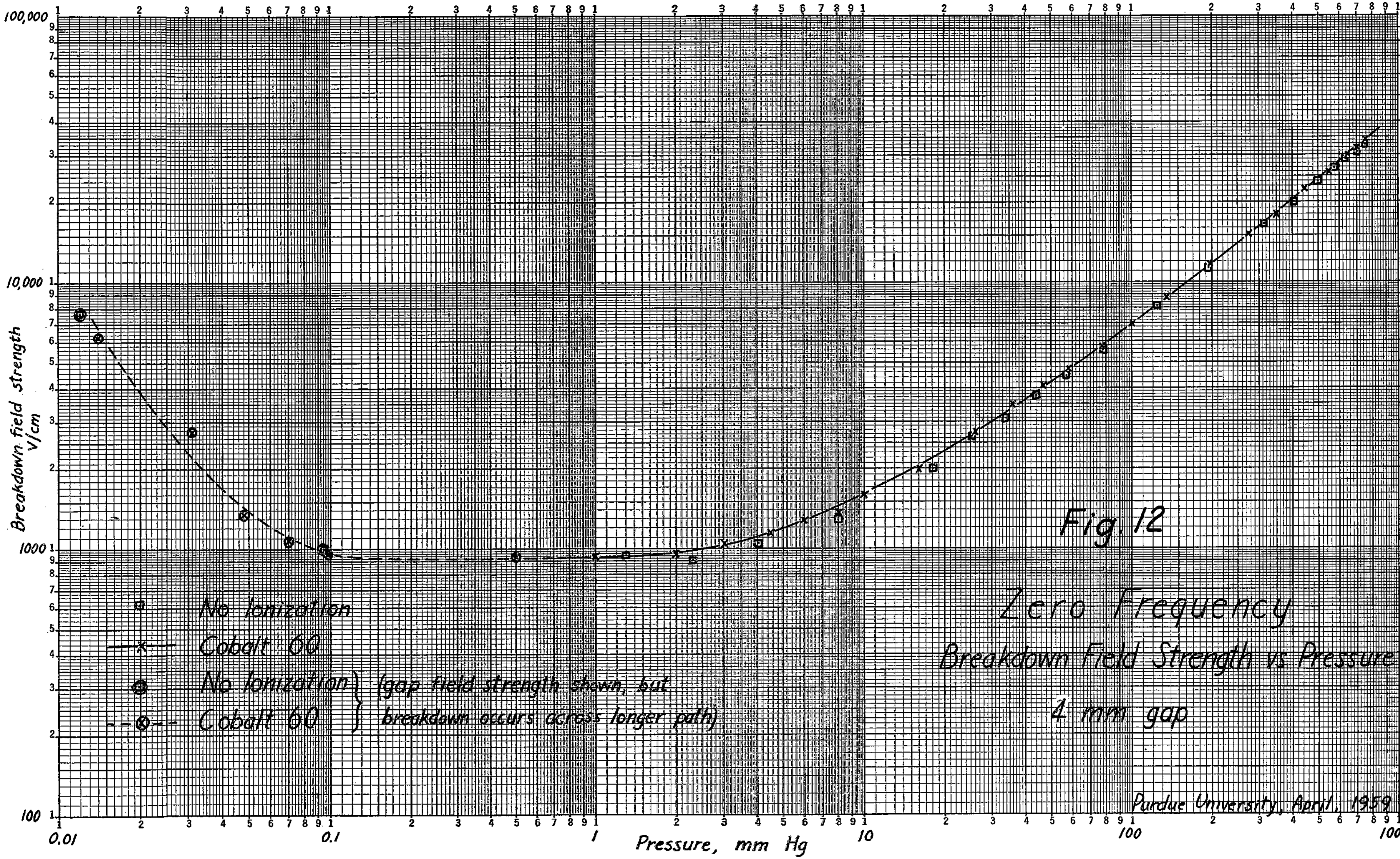
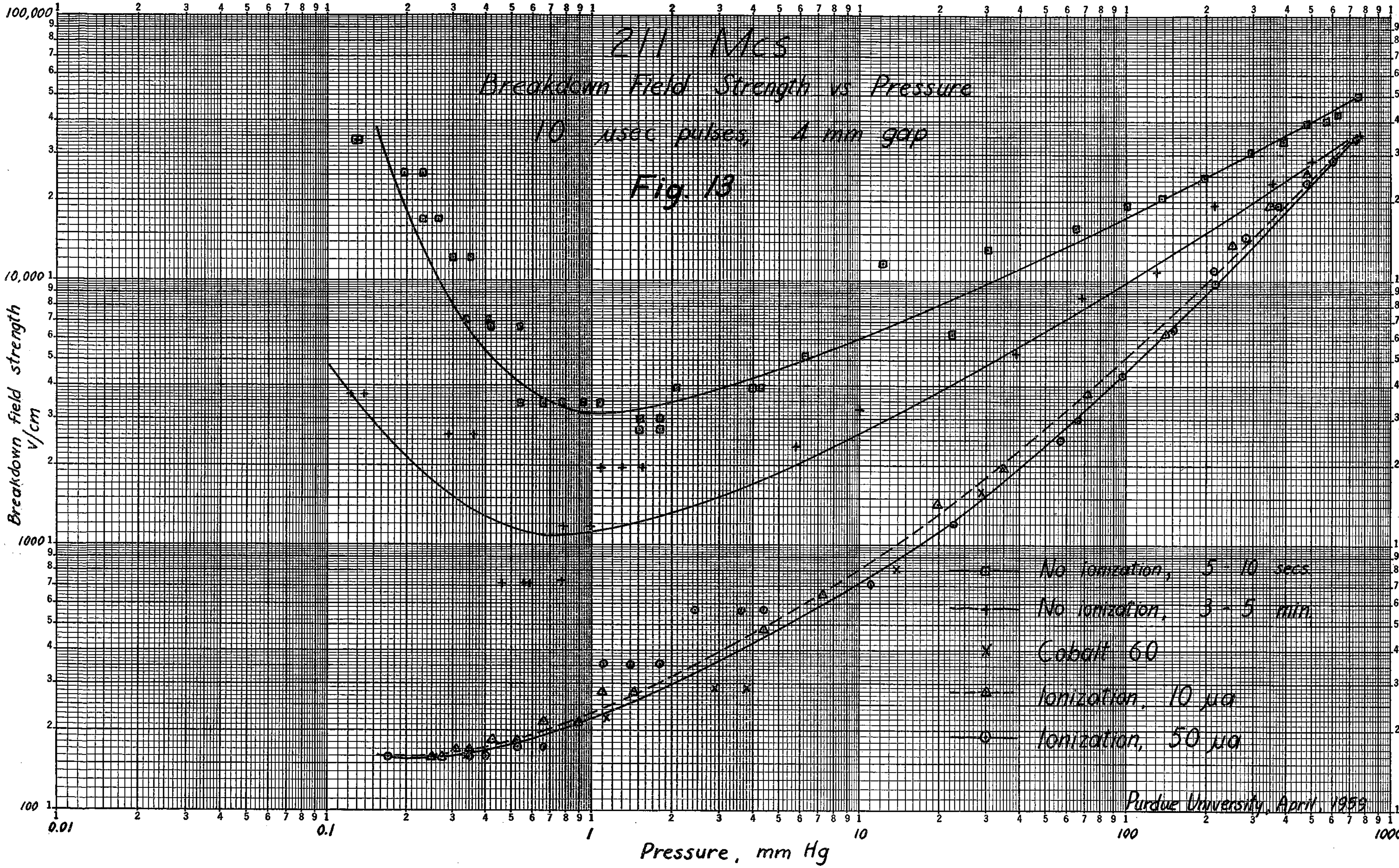
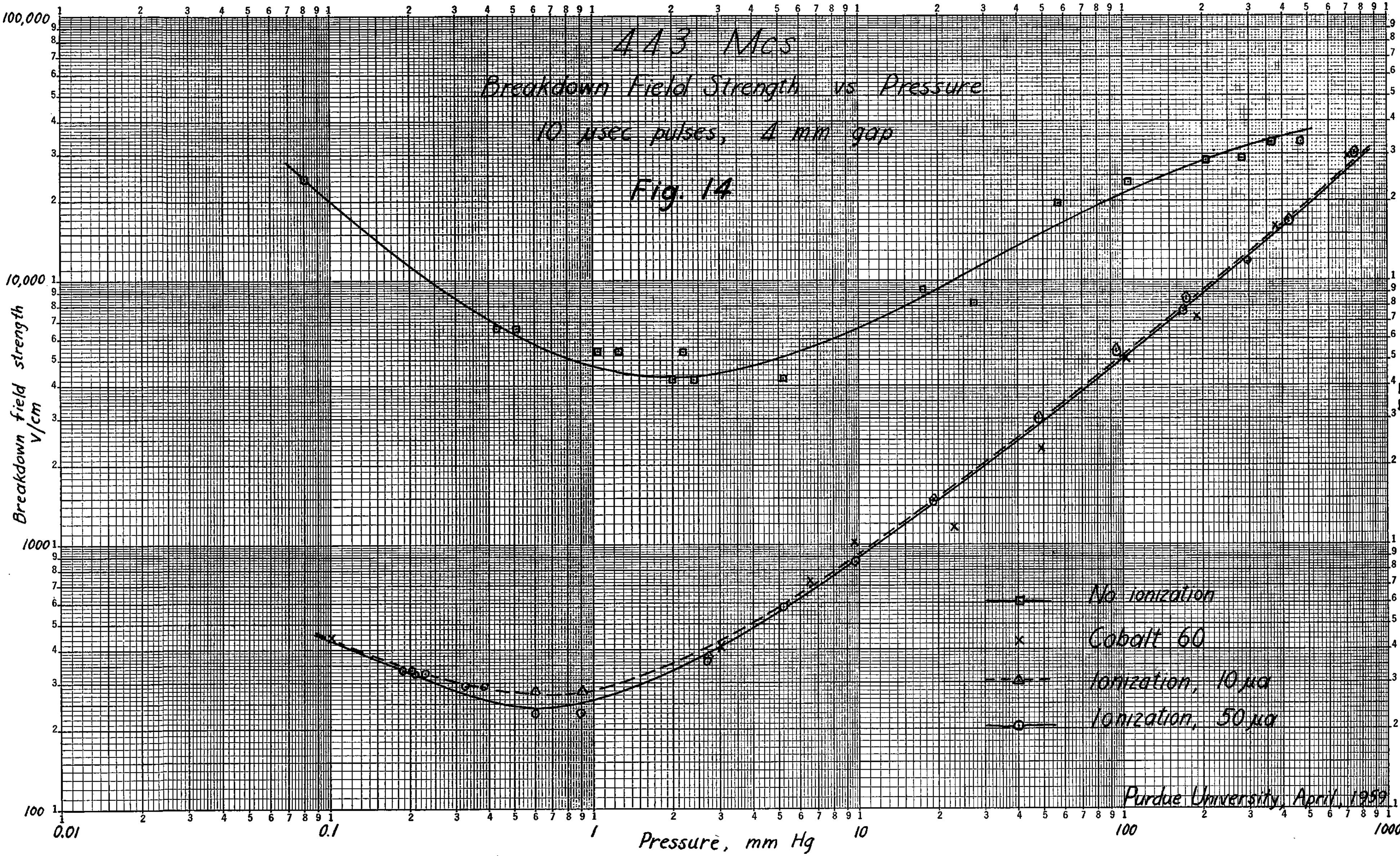

Breakdown field strength V/cm
100,000
10,000
1000
100
0.01
0.1
1
10
100
1000
Pressure, mm Hg
No Ionization
Cobalt 60
No Ionization } (gap field strength shown, but
Cobalt 60 } breakdown occurs across longer path)
Zero Frequency
Breakdown Field Strength vs Pressure
4 mm gap
Purdue University, April, 1959

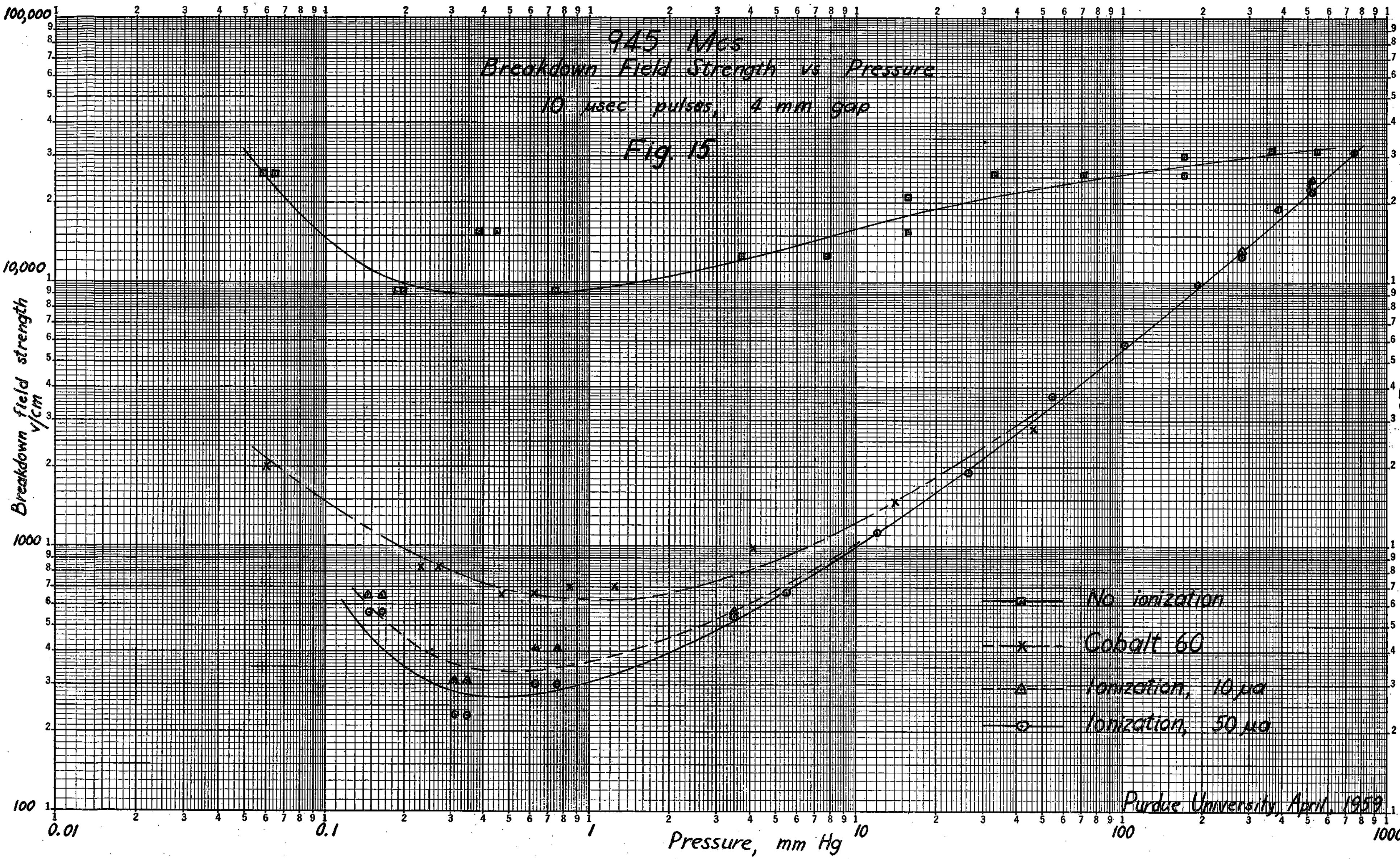
Fig. 12

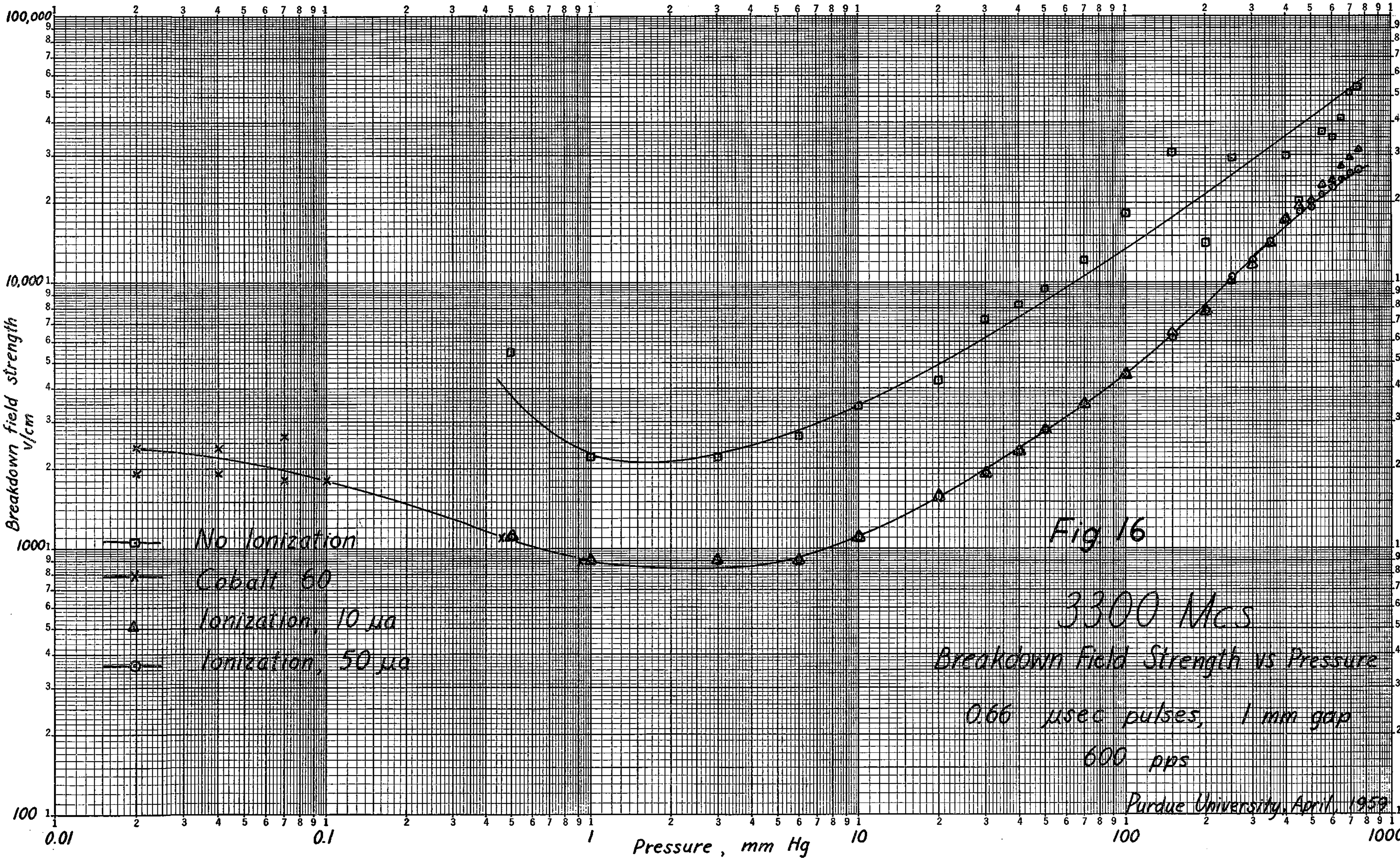

211 Mcs
Breakdown Field Strength vs Pressure
10 μsec pulses, 4 mm gap
Fig. 13
Breakdown field strength V/cm
Pressure, mm Hg
No ionization, 5 - 10 secs.
No ionization, 3 - 5 min.
Cobalt 60
Ionization, 10 μa
Ionization, 50 μa
Purdue University, April, 1959

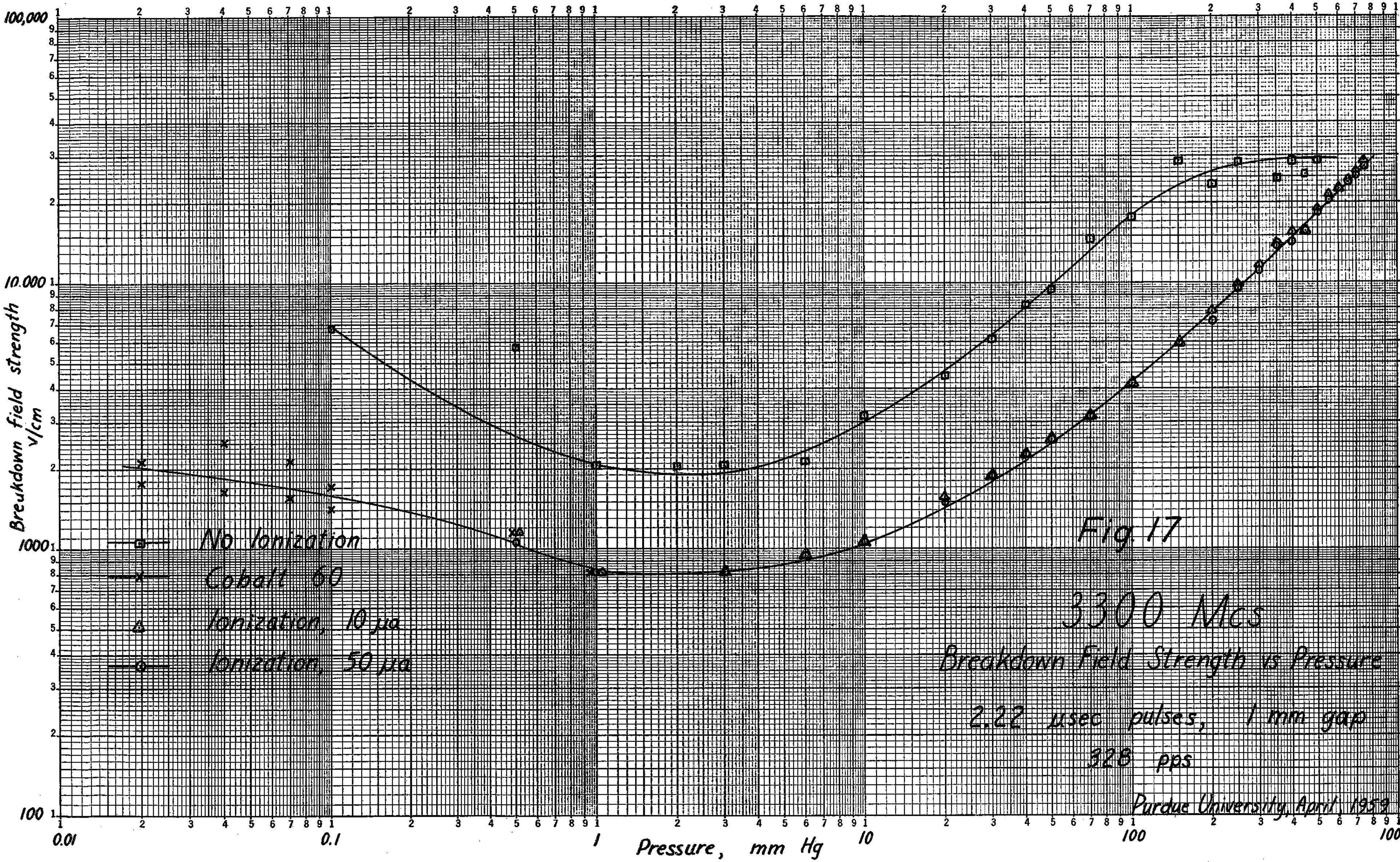


443 Mcs
Breakdown Field Strength vs Pressure
10 μsec pulses, 4 mm gap
Breakdown field strength V/cm
Pressure, mm Hg
No ionization
Cobalt 60
Ionization, 10 μa
Ionization, 50 μa
Purdue University, April, 1959

Fig. 14


945 Mcs
Breakdown Field Strength vs Pressure
10 μsec pulses, 4 mm gap
Fig. 15
Breakdown field strength v/cm
Pressure, mm Hg
No ionization
Cobalt 60
Ionization, 10 μa
Ionization, 50 μa
Purdue University, April, 1959


Breakdown field strength v/cm
Pressure, mm Hg
No Ionization
Cobalt 60
Ionization, 10 μa
Ionization, 50 μa
Fig 16
3300 Mcs
Breakdown Field Strength vs Pressure
0.66 μsec pulses, 1 mm gap
600 pps
Purdue University, April, 1959


No Ionization
Cobalt 60
Ionization, 10 μa
Ionization, 50 μa
Fig 17
3300 Mcs
Breakdown Field Strength vs Pressure
2.22 μsec pulses, 1 mm gap
328 pps
Purdue University, April, 1959
Breakdown field strength v/cm
Pressure, mm Hg
100,000
10,000
1000
100
0.01
0.1
1
10
100
1000

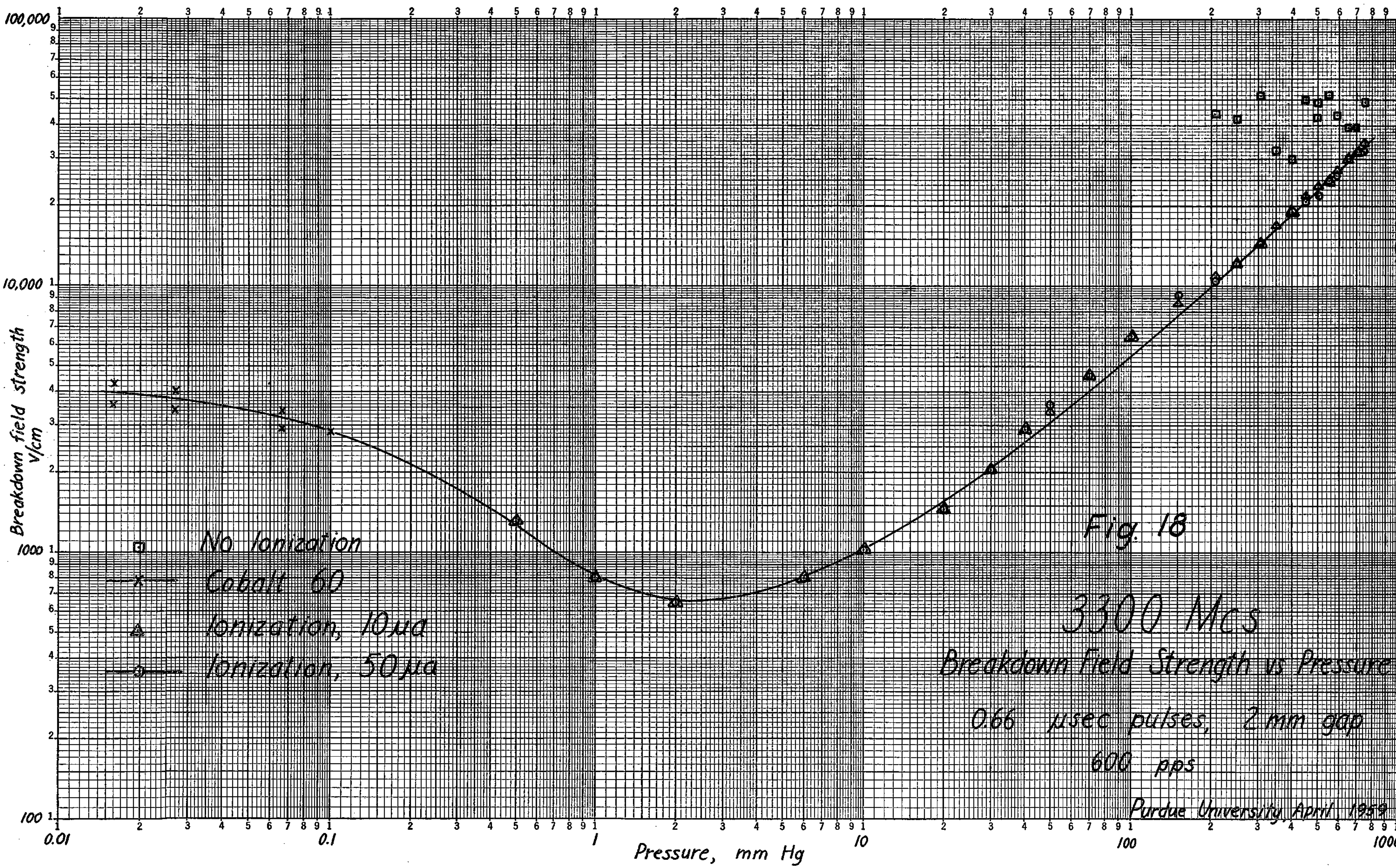


Fig. 18

3300 Mcs

Breakdown Field Strength vs Pressure

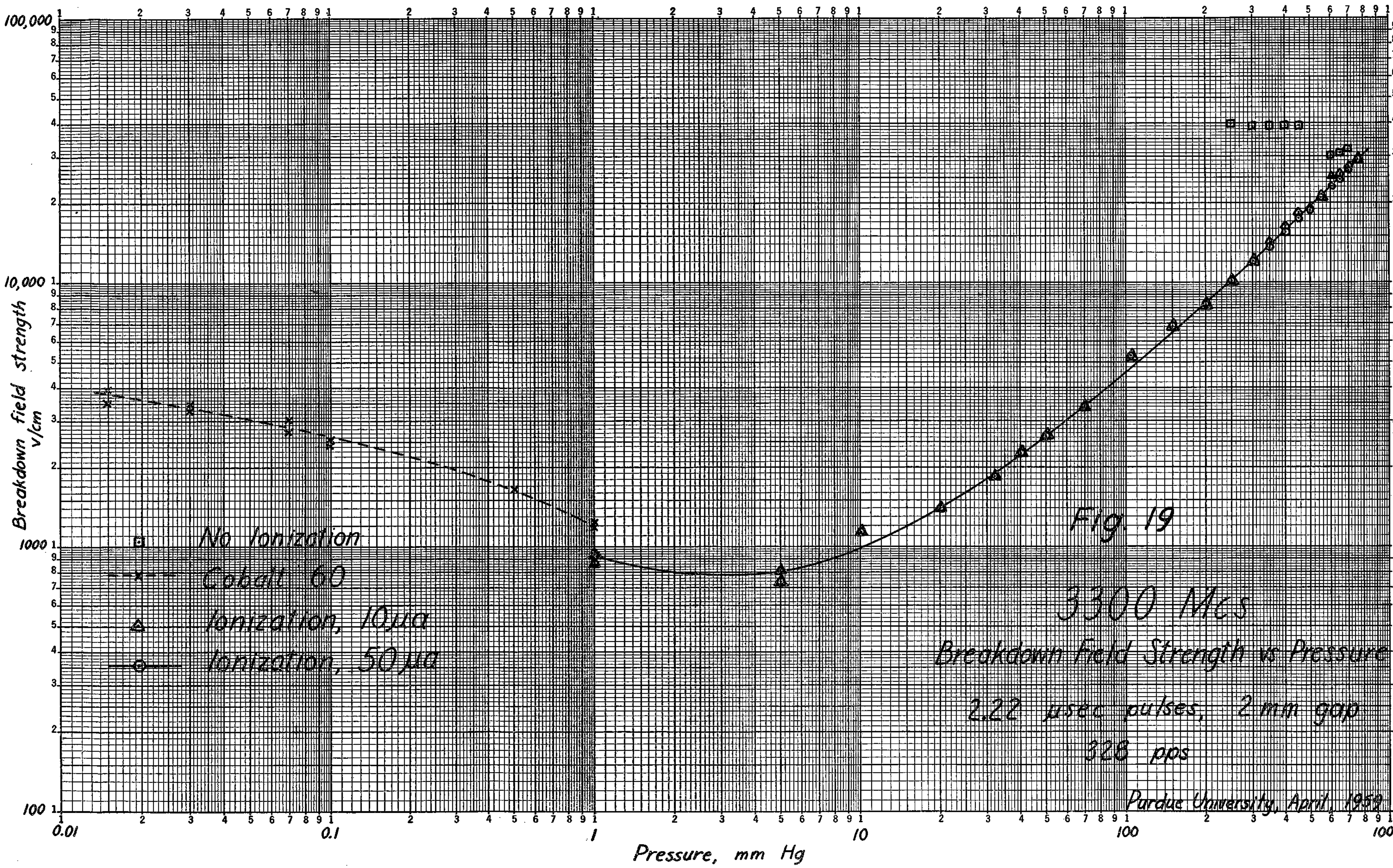
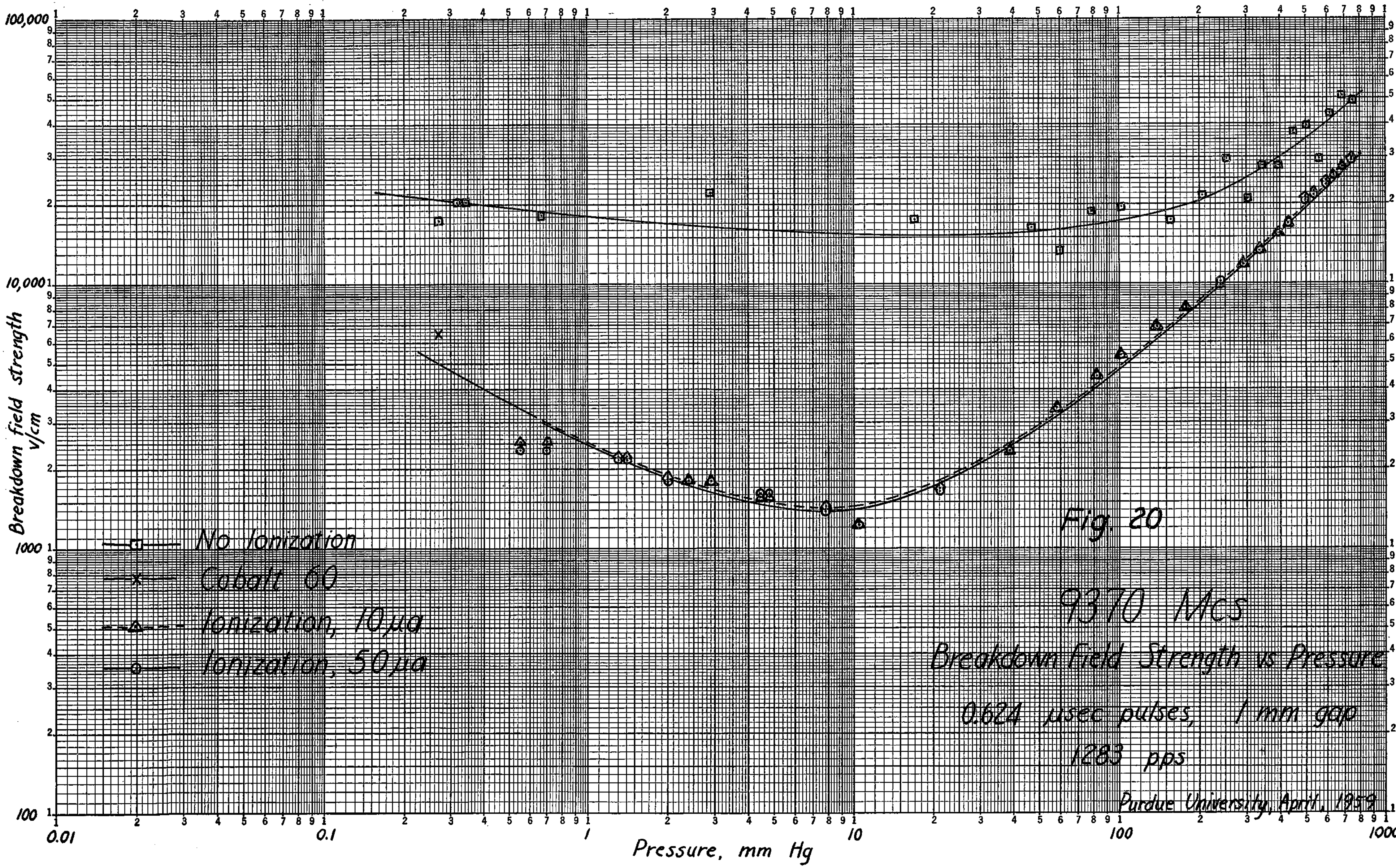
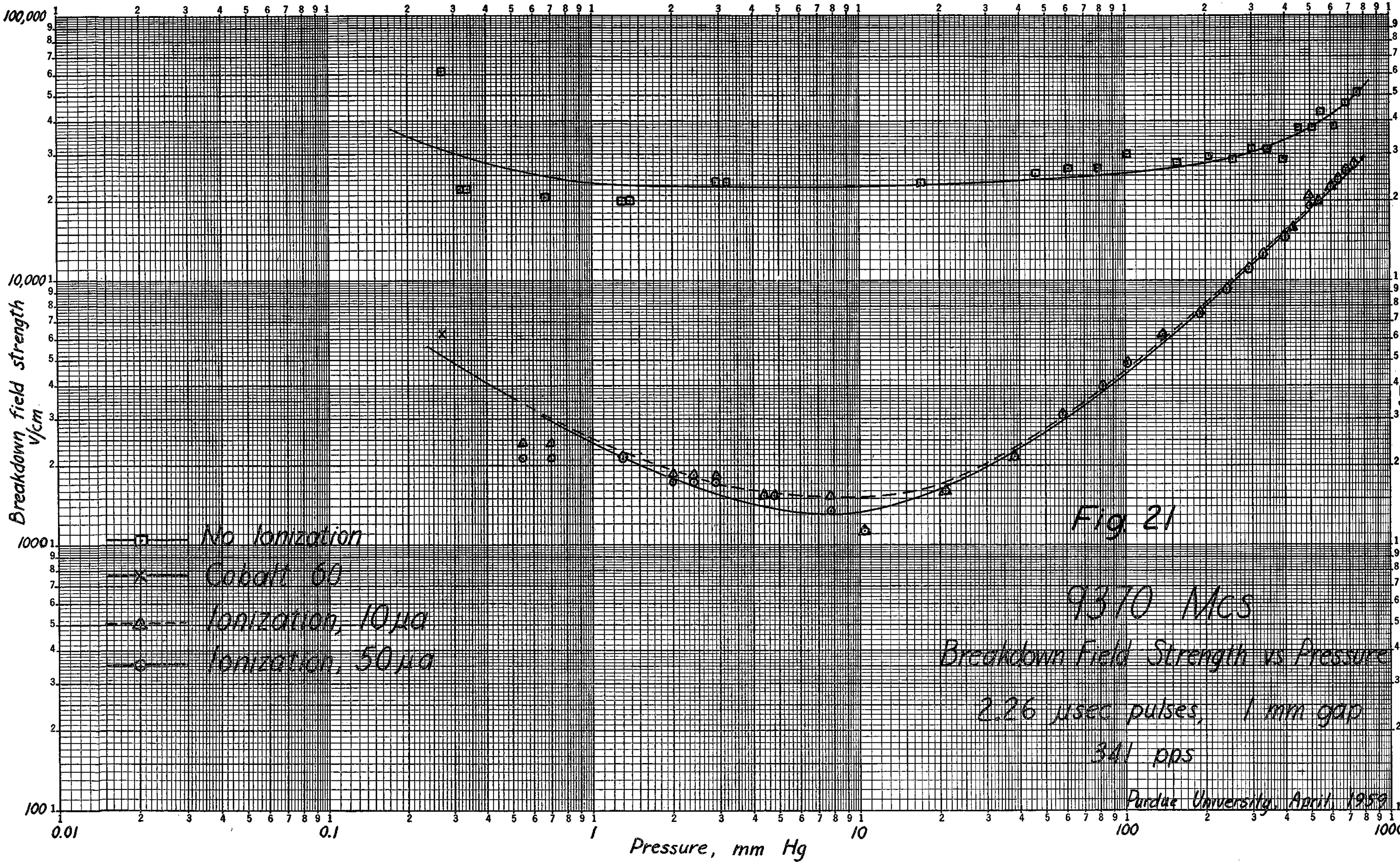


Fig. 19
3300 Mcs
Breakdown Field Strength vs Pressure
2.22 μsec pulses, 2 mm gap
328 pps
No Ionization
Cobalt 60
Ionization, 10μa
Ionization, 50μa
Breakdown field strength v/cm
Pressure, mm Hg
100,000
10,000
1000
100
0.01
0.1
1
10
100
1000
Purdue University, April, 1959



Breakdown field strength v/cm
Pressure, mm Hg
No Ionization
Cobalt 60
Ionization, 10 μa
Ionization, 50 μa
9370 Mcs
Breakdown field Strength vs Pressure
0.624 μsec pulses, 1 mm gap
1283 pps
Purdue University, April, 1959

Fig. 20


Breakdown field strength V/cm
Pressure, mm Hg
No Ionization
Cobalt 60
Ionization, 10 μa
Ionization, 50 μa
Fig. 21
9370 Mcs
Breakdown Field Strength vs Pressure
2.26 μsec pulses, 1 mm gap
341 pps
Purdue University, April, 1959

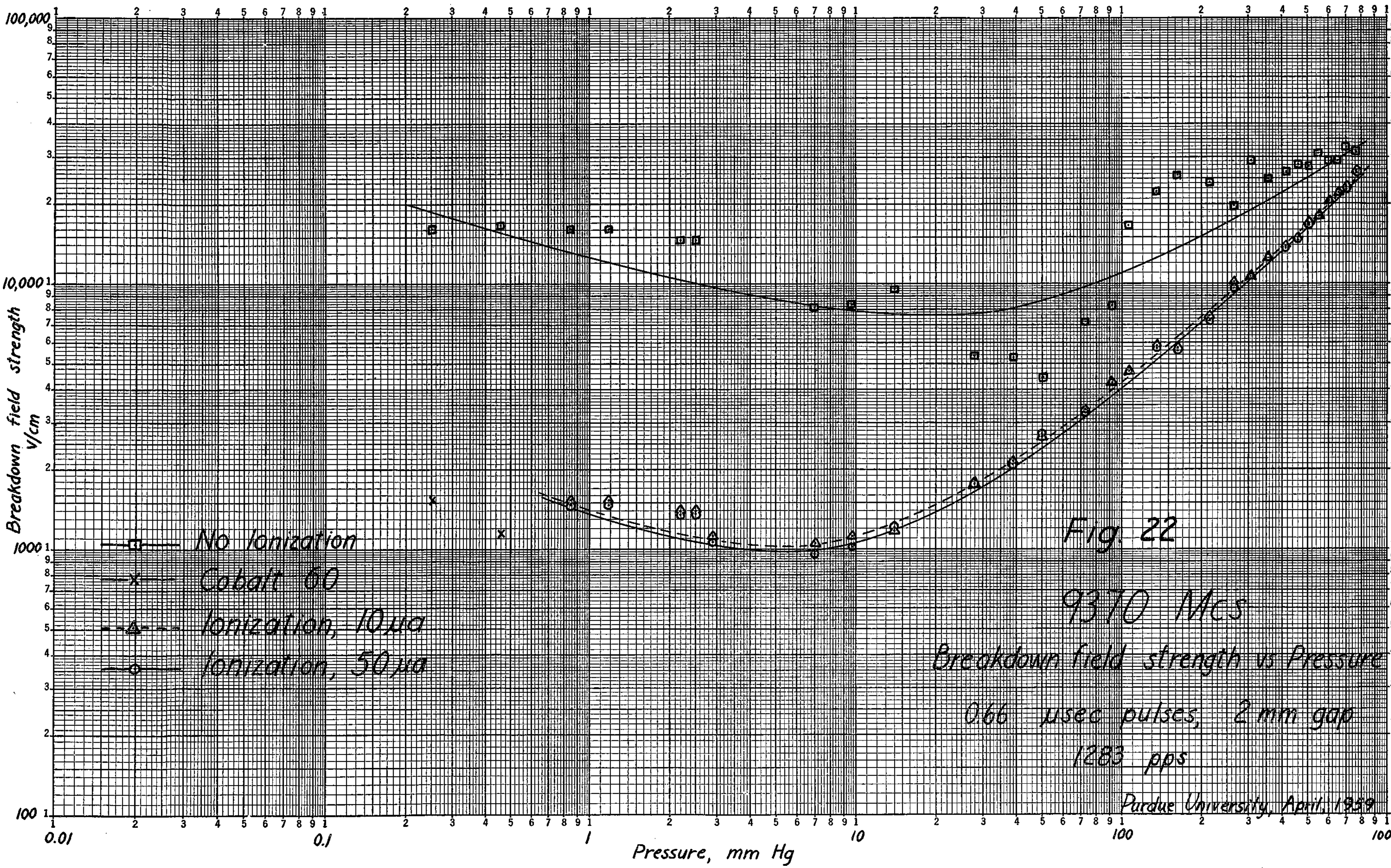


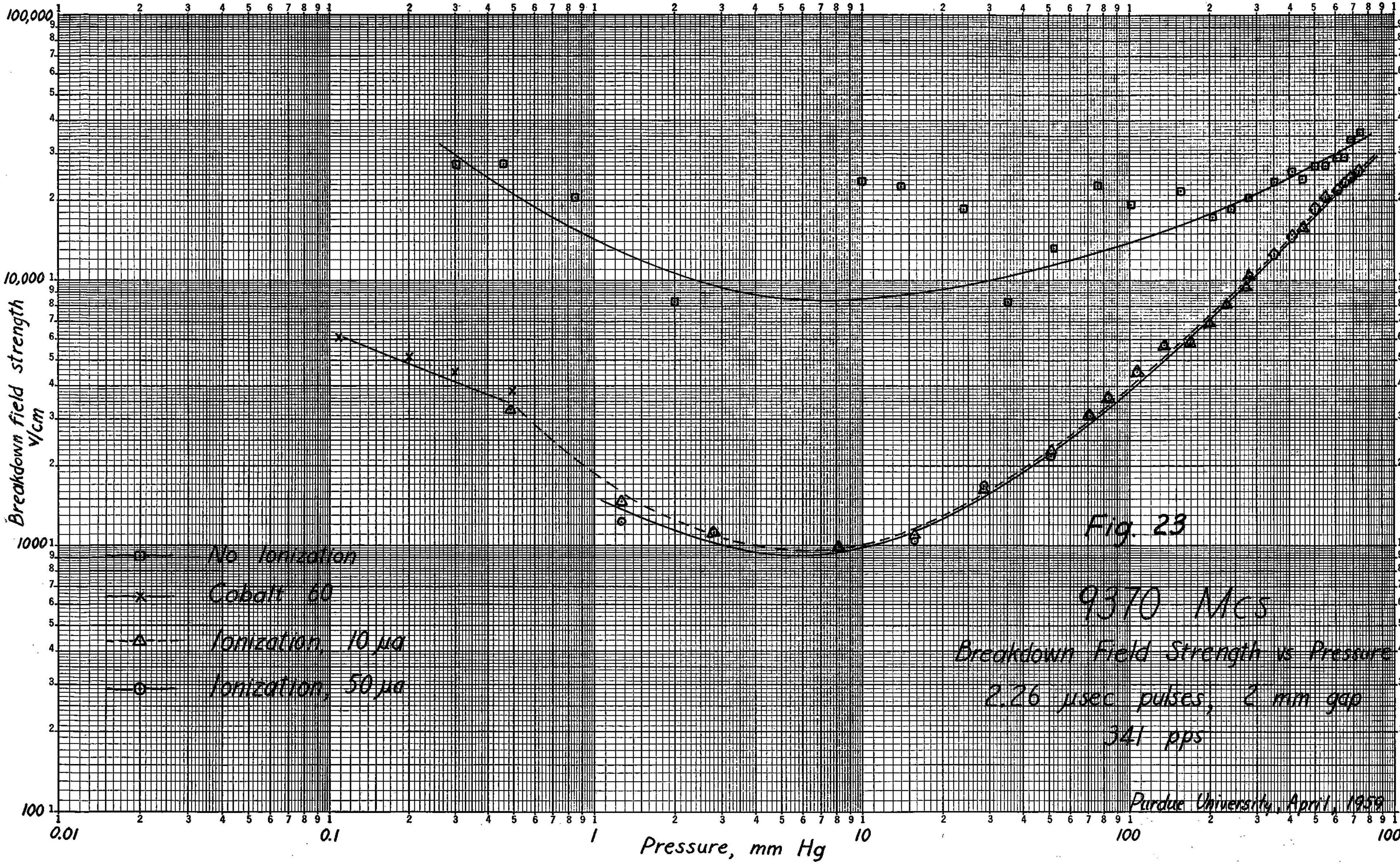
Fig. 22

9370 Mcs

Breakdown field strength vs Pressure

0.66 μsec pulses, 2 mm gap

1283 pps


Breakdown field strength V/cm
100,000
10,000
1000
100
0.01
0.1
1
10
100
1000
Pressure, mm Hg
No ionization
Cobalt 60
Ionization, 10 μa
Ionization, 50 μa
Fig. 23
9370 Mcs
Breakdown Field Strength vs Pressure
2.26 μsec pulses, 2 mm gap
341 pps
Purdue University, April, 1959

tensity in volts/cm as a function of pressure in mm of mercury for the various frequencies, pulse lengths, electrode spacings, and ion densities given on the figures. The curves are arranged by increasing frequency first, then by increasing electrode spacing for each frequency, and finally by increasing pulse length.

Several general (and, in some cases, obvious and familiar) statements may be made which apply to all of the curves:

a. Breakdown at atmospheric pressure occurs at about 30,000 v/cm.

b. The minimum breakdown field strength occurs within the approximate pressure range of 1 to 10 mm Hg.

c. The effect of cobalt 60 and of both values of point discharge ionization is about the same.

d. Smoother curves with less scattering of the points are obtained with some ionization. Such ionization has been aptly termed "stabilizing" ionization or radiation.

e. Without ionization, the field strength required for breakdown is larger than that needed with some stabilizing ionization. However, this larger value may be reduced somewhat if the field is applied for a longer period of time. Stated another way, it is apparent that, in a given interval of time, the probability of breakdown decreases as the voltage is reduced. The breakdown field intensity must, of course, be larger than that required with ionization. When stabilizing ionization is employed, breakdown occurs simultaneously with the application of the field or of the ionization.

Some of the data at pressures below the point of minimum breakdown field intensity are not directly applicable to the electrode spacings indicated because the breakdown moves away from the center of the gap and occurs across a longer path. This will also occur in any system in practice, such as in the region surrounding a slot antenna. This effect was readily observed at zero frequency because the gap was visible inside the bell jar at all times. The curves at zero frequency are drawn with a solid line in the pressure range for which the discharge occurred in the gap, and with a broken line for the lower pressures where the discharge moved out across a longer path.

All of the curves at the other frequencies show the field strength in the gap at all pressures, but breakdown is probably taking place across a longer path for pressures below the curve minimum. Thus, if the breakdown were restrained to occur in the gap, the curve obtained would lie above the one shown for that gap by an amount dependent on the geometry of the cavity. Safe designs are achieved by designing for the minimum breakdown field strength.

A comparison of the several figures indicates these general conclusions:

a. Higher field strengths are possible with smaller electrode spacings.

b. The safe maximum field strength before breakdown for large electrode spacings is somewhat less than that indicated for the largest spacing used, 4 mm.

c. Greater field strengths are permissible with shorter pulse lengths.

d. Greater field strengths are permissible with lower pulse repetition rates.

e. The breakdown field strength shows little change when the product of pulse width and repetition rate is maintained constant.

f. Breakdown at atmospheric pressure is relatively independent of frequency.

g. The maximum safe field intensity in the neighborhood of 1 mm Hg is smallest at 200 mcs and has a value of about 160 V/cm for the 4 mm gap.