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EXPERIMENTS IN MICROWAVE BREAKDOWN

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EXPERIMENTS IN MICROWAVE BREAKDOWN

Abstract

Experiments were conducted on electrical breakdown at microwave frequencies using several sizes of air gaps in waveguide. The variation of breakdown was studied as a function of a number of parameters with the following findings. (1) Pressure. At atmospheric pressure, the peak breakdown power varies directly with pressure; at pressure from $\frac{1}{2}$ atmosphere to 5 cms Hg, approximately as the square of the pressure; and when the natural ionization is augmented by the radiation from a 3-millicurie radioactive source (Co*), as the square of the pressure from 5 cms to 2 atmospheres. (2) Initial Ionization. The use of the Co* also lowers breakdown power at atmospheric pressure by 1/3 and at lower pressures by a factor of 4 or 5. (3) Gap Width. At K-band the breakdown field strength depends on the gap width particularly at lower pressures and for narrower gaps, but at X- and S-band no significant dependence was found except at very low pressures. In general, the breakdown field is larger for the narrower gap. (4) Pulse Width. Over a large pressure range the peak breakdown power varies inversely (from a fraction of a microsecond to approximately two microseconds) as the square root of the pulse width. (5) Repetition Rate. A decrease in breakdown power accompanies an increase of repetition rate. At K-band for an increase in prf from 500 to 2,000 the decrease in breakdown power is 25% at atmospheric pressure. (6) Humidity. No significant dependence of breakdown power on humidity exists. (7) Surface Points. At X-band brass filings 2 to 5 mils in diameter lowered the breakdown power by a factor of 3 within a 40-mil gap. In general, repeatability in breakdown data was achieved through the use of extra ionization supplied by the Co*.

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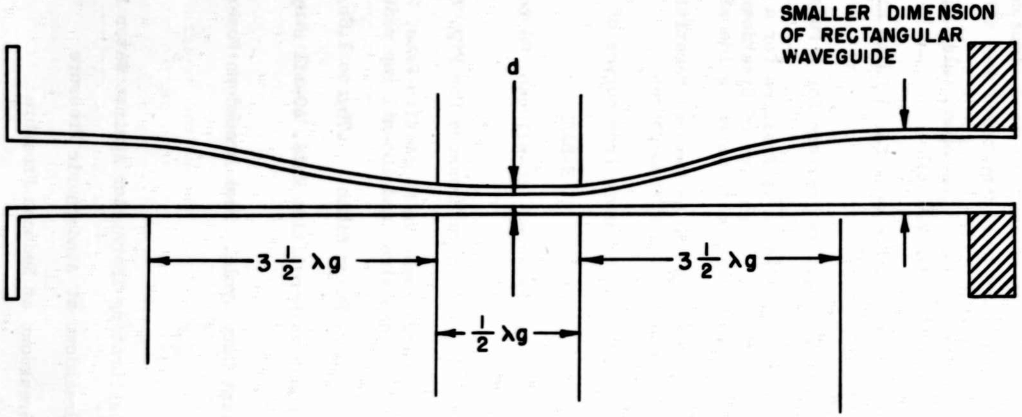

DIAGRAM I

EXPERIMENTS IN MICROWAVE BREAKDOWN

I. INTRODUCTION.

The fact that high power breakdown tests made on various radar components had for long been extremely erratic led to a program designed to investigate the causes of the irregularity. Once a systematic program of investigation was initiated, it became clear that the erratic breakdown performance was of a dual nature: (1) On successive trials a given test piece broke down at widely differing values indicating an existence of a pure high power or breakdown instability such as surging line power or statistical gap breakdown or both, (2) Lack of duplication of controllable parameters in making successive tests on the unconscious assumption that these parameters, like pulse width and repetition rate, were of no consequence in determining the breakdown level.

II. BASIC CONSIDERATIONS.

In solving the problem of unrepeatable breakdown behavior it was necessary to first achieve repeatable data while all significant parameters were controlled and then to change these parameters one at a time to observe their effect on peak breakdown power.

A. Achieving Repeatability.

The experiments were conducted on a prepared waveguide gap within a constricted section of guide called a "swayback," shown in Diagram 1 (discussed in the Appendix). Fig. 1 illustrates an actual run of fourteen successive trials in which the peak power to break down the swayback was determined. The arrows on two values indicate that the power to break down the guide would have been higher than the magnetron could give at all or without strain at the time. The results clearly may be called "erratic," the lowest value being about 65% of the highest. In view of such results, an attempt to run a pressure-power curve could only result in some haphazard data, such as that actually obtained and shown in Fig. 2. It was recognized of course that if a number of such curves were obtained and averaged, one might obtain a smooth curve, such as that shown in Fig. 3, where an average of four runs is depicted. Ordinarily, however, three or four runs would be far too few to give a smooth progressive curve. Fig. 4 illustrates this point and shows that for another test piece three runs were insufficient to give a unique average.

The problem of repeatability was solved by irradiating the test gap with the gamma rays of radioactive cobalt, Co*, thus providing enough background ionization to eliminate the gross statistical effects, which result frequently in such a long time lag, during which we await the appearance of chance electrons, that we are led by impatience to raise the voltage beyond the minimum necessary sparking value. Presumably the ionization produced by the Co* makes it unnecessary for the gap to await ionizations due to cosmic rays, or fluctuations in the line power, before a favorable (and random) condition amenable to sparking occurs; that is, before an electron appears in the gap. The Co* was prepared at M.I.T. and was sealed into a brass capsule. The strength of the Co* that was finally used was that equivalent to the gamma rays from 6.4 milligrams of radium or 3.2 millicuries (1 millicurie corresponding to 3.7×10^7 disintegrations per second). The half-life of the Co* is five years. In use, the capsule is placed on the outside of the test piece and may frequently be used to locate the weak spot in a device which is being high-power tested. The steps in this procedure are first, without the capsule, to raise the line power until a spark occurs; then to lower the power just out of reach of sparking; and, finally, to run the capsule of Co* along the various portions of the test piece until the weakest spot is reached, whereupon a spark passes inside. Naturally, due to the considerable width of the beam of gamma rays, it is not possible to isolate a weak "spot" but only a weak area.

The fact that the "Co* data" yields a smoother curve is demonstrated by Fig. 5 which for contrast also includes the non-Co* curve for the same test piece. The data were taken in the stagger manner, breakdown power being determined at a given pressure first with the Co* and then without, and so on, alternately. These curves are averages for a few runs. Figures 6, 7, and 8 present results of similar experiments for other widths of swayback sections as indicated on the diagrams. Although the average non-Co* curve shown in Fig. 8 is smooth, any component single run curve resembled the upper one shown in Fig. 9. As already stated, any single Co* curve was always smooth.[1]

It is true, of course, that the Co* curves are always lower than the others, and thus one does not obtain the "correct" value of breakdown power when the Co* is used. On the other hand, many problems in breakdown are of interest when there is a more than normal initial ionization in the gap. Furthermore, inasmuch as in the present study curves have been obtained both with and without the Co*, we may be able to estimate how a smooth non-Co* curve might lie from the Co* result or be satisfied with the lower conservative answer.

B. Effect of Various Parameters.

The factors whose influence on power breakdown were studied after the smoothness of the data was assured through the use of the Co* irradiation were: Pressure, Width of the Breakdown Gap, Humidity, Surface "Roughness," Wavelength, Repetition Rate, Pulse Width, and Duty Cycle. The part played by each of these is considered in some detail for each of the three frequency bands.

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[1] At first, ultraviolet light was used as a source of "extranormal" ionization; the light was focused down a horn termination and was observed to stabilize breakdowns but was not as convenient as a radioactive capsule.

III. K-BAND STUDIES.

A. Pressure and Width of Breakdown Gap.

By making use of the relation

$$P_{max.} = E^2_{max.} \times 6.63 \times 10^{-4}\, ab\, \frac{\lambda_o}{\lambda_g} \qquad 2.$$

and by applying it to such data as that of Figs. 6, 7, and 8, we obtain the curves of Fig. 10. These curves represent field strength (kilovolts/cm) vs pressure. In view of the fact that Paschen type curves have been found to be of significance from DC up to X-band[3] it was considered desirable to plot such curves for the data of the present experiments. For K-band this is done in Fig. 10a.

B. Humidity.

The ordinates of Fig. 15, in which the solid lines are for "dry" air (relative humidity about 10%) and the dotted lines are for wet air (relative humidity about 80%), indicate that there is no substantial difference in peak power that a waveguide will tolerate for the two cases.

C. Surface "Roughness."

The reason for the quotation marks in the title of the present section is found in the fact that actual solid rough surfaces were not used in the experiment. The study was carried out in the following manner: (a) peak breakdown power was measured for a 40-mil swayback of ordinary internal smoothness, the power required being 33 units; (b) brass filings 2 to 5 mils in diameter were now spread throughout the swayback, forming a thin layer on the bottom; the power

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2. RL Report T-9, Waveguide Handbook, N.H. Frank, October 2, 1942, p. 13, ($P_{max.}$ is the peak or maximum power in watts which flows through the waveguide at the threshold of breakdown, $E_{max.}$ is the corresponding peak or maximum tolerable field in volts/cm, a and b are the internal cross-sectional dimensions in cms, of the rectangular guide section which is breaking down, λ_o is the free-space wavelength, and λg is that in the guide).

3. At X-band, see report of L. E. Hunt, Bell Telephone Laboratories, Inc.; MM-42-160-112. For frequencies up to 10^7 see account of work of Gutton, Thomson, Reukema and others in Fundamental Processes of Gaseous Discharge, L. B. Loeb, pages 552-558. A report on Microwave Breakdown (theory) is in preparation by the senior author, and among other questions that of Paschen curves is considered in mathematical detail.

to crack the gap now was only 11 units; (c) the swayback was disconnected from the line and then was bounced upright on the table to remove the brass filings; after replacement in the line, the peak power for breakdown was measured again and found to be still 11 units; (d) the swayback was again removed from the line and this time blown out by a violent airstream in order to rid it as best possible of all brass filings; upon replacement in the line the peak power rose to its original value of 33 units. These results are shown in Fig. 16, and although it may not be fair to interpret them as applying to a rough surface, they nevertheless indicate the prudence of thoroughly cleaning parts which are newly-arrived from the machine shop; likewise, they serve to emphasize the well-known need of rounding sharp edges and corners to eliminate concentrated fields.

D. Repetition Rate.

The effect of repetition rate on peak tolerable power was investigated for K-band swaybacks only at atmospheric pressure. It has been found that, for a given field strength, a spark that just manages to occur when the repetition rate is R_1 does not occur when the repetition rate is $R_2 < R_1$ even if we wait for it indefinitely; in addition to the great amount of data shown in our curves which have some bearing on this point, we may also cite certain specific experiments especially designed to test the matter: at K-band a certain gap broke down at 14 units of average power when the repetition rate was 1,000 pps; the power was then lowered and the repetition rate set at 500; then the power was raised until the average power read 14/2 or 7 units; this made the two peak powers equal but no spark passed now even after a wait of three minutes. When the power was raised a certain amount, the spark came. The experiment was performed a number of times and the average increase in peak power necessary to crack the gap in the 500 pps case was about 20%. The results for a .25-microsecond pulse depicted in Figs. 17, 18, and 19 indicate that a safe conclusion for full-width K-band guide probably is this: a four-fold increase in repetition rate (500 to 2,000 pps) lowers the peak breakdown power by about 30%. (It will be seen presently that much more extensive data, valid over a large pressure range, were gathered at X-band.) It should of course be remembered that in view of the quadratic relationship between power propagated and field strength ($P_m = KE_m^2$), the lowering of the field strength for the condition stated above is not 30% but about 16%. These are considered conservative values.

E. Pulse Width.

A rather complete study of pulse width effect on peak breakdown power was made on X- and S-bands. The conclusion reached there, as will be shown, is that $P_m \propto \frac{1}{\sqrt{\mu}}$, where μ is the pulse width; this relation holds for μ up to a certain limiting value (about 1 microsecond at atmospheric pressure). Some time ago this relation was stated to hold for K-band also, as the theoretical treatment indicates that the pulse effect is independent of frequency. Recently, in testing K-band rotary joints, it has been confirmed that this inverse square root law holds. These tests were made on pulses of .3 and .65 microsecond for several pressures. The inverse square root law was studied for several gap widths, and for a large range of pressures and pulse widths.

IV. X-BAND STUDIES.

A. Pressure and Width of Breakdown Gap.

Experiments at X-band were carried out with swaybacks of 6, 17, and 38 mils. Figures 20 to 25 give the results of pressure and gap width runs at certain constant values of repetition rate and pulse width. The figures contain both power and field strength results. As at K-band, besides being interested in the nature of the Power-Pressure law and the absolute values, we are also interested in whether or not the breakdown powers at a given pressure are proportional to gap width, and whether or not the field strengths are independent of gap width. It will be recalled that some deviation from these expectations was encountered at K-band. However, the situation is more nearly "normal" at X-band, especially at the higher pressures; this may be seen in Figs. 26 and 27 where comparisons are effected for the three swayback sizes used.

Extrapolations to regular X-size are shown in Figs. 26 and 27 (of course, the E_m curve is the same as that for the 38-mil curve). In connection with these results convenient recourse may be made to the pressure-altitude scale of Fig. 13.

It must be remembered that Figs. 26 and 27 are for one definite pulse width and one definite repetition rate. Values at other pulses and rates may be obtained from the ones given by suitable transitions such as those given in the X-band summary in the Appendix. It should further be remarked that the laboratory pressure appearing on the graphs is that at 20° C, and the obvious transformation involving $\frac{(273 + 20)}{(273 + t)}$ should be resorted to when other laboratory temperatures are considered. At the risk of repetition, we mention again the fact that Fig. 13, relating laboratory pressure at 20° C to altitude above ground has already taken temperature variation with altitude into account.

Figure 28 gives the results of extending to two atmospheres the type of studies presented in Figs. 26 and 27. Paschen curves, such as those shown in Fig. 29, may be plotted at X-band, but again as for K-band, there is no unique Paschen curve for pulsed microwaves. In view of the flattening of the power-pulse width curve shown in Figs. 35 and 36, it would seem that for pulses wider than about 4 μseconds one unique Paschen curve is expected to exist, namely, the same as the cw one. Thus, for pulses less than about 4 μseconds, we have a Paschen curve for every pulse width and repetition rate. However, it is true that if we decrease the pulse width by a certain amount and increase the repetition rate by a special amount then we can get the same Paschen curve back again. The values of pulse width and repetition rate which thus counter-balance each other are those which maintain the breakdown field or power constant. If, for example, the breakdown power may be expressed as

$$P_m = \frac{C}{\sqrt{\mu}} \quad (a-R) \quad p^n$$

as was the empirical situation at K-band, and is the case also at X-band, then, for constant pressure the counter-balancing pulse width and repetition rate (which maintain the same Paschen curve or sparking curve) are related by

$$\frac{a - R}{\sqrt{\mu}} = \text{constant}$$

$$\text{Thus,} \quad \frac{a - R_1}{\sqrt{\mu}_1} = c, \qquad \frac{a - R_2}{\sqrt{\mu}_2} = c$$

$$\text{and} \quad \frac{a - R_1}{\sqrt{\mu}_1} = \frac{a - R_2}{\sqrt{\mu}_2}, \quad \text{where}$$

the value of a is known (for K-band it is 5,500). For X-band a will be shown to be 8,000, in the Appendix.

We have then

$$\sqrt{\frac{\mu_2}{\mu_1}} = \frac{8000 - R_2}{8000 - R_1}$$

Remembering the limits within which these empirical relations are valid, we may illustrate with an example the counter-balancing values of pulse width and repetition rate:

if $R_1 = 2{,}000$ pps, and is changed

to $R_2 = 500$ pps, then

$$\sqrt{\frac{\mu_2}{\mu_1}} = \frac{7500}{6000}$$

or, μ_2 should be $1.56\ \mu_1$

B. Repetition Rate and Single Pulse Breakdown.

The effect on breakdown power of a two-fold or four-fold change in repetition rate is visible in Fig. 30, for a 6-mil gap, at .2 microsecond. It is seen that the repetition rate effect depends on the operating pressure, and for a four-fold increase in the repetition rate the decrease in peak breakdown power runs from 30% at the lower pressures through 16% at atmospheric and down to 13% at two atmospheres. The corresponding field strength curves are shown in Fig. 31. The repetition rate effect is also shown for 1 microsecond, for pressures up to two atmospheres in Fig. 32. These particular curves, which also are for the 6-mil swayback, again demonstrate the effect of changing the repetition rate by a factor of four. The curves are parallel, indicating again that the percentage lowering of the breakdown power decreases at the higher pressures. Figure 33 shows the field strength vs pressure relationship derived from one of the curves of Fig. 32. Another study which demonstrates the effect of repetition rate is presented in Fig. 34, obtained for the 38-mil gap, at .43-microsecond pulse. An analysis reveals that both the 500 pps curve and that at 1960 pps are not too far from being parabolic, as was indicated previously to be the case in general for the larger gap width curves. For the particular curves discussed, the change in peak breakdown power at atmospheric pressure (for the four-fold change in repetition rate) amounts to about 13%.

The experiments in which a single pulse was sent down the waveguide to cause breakdown at the narrow gap are shown in the series of Figures 36a to 36e. Included in some of the Figures are also breakdown values at a wide variety of repetition rates. One of the most significant features evident is that for small pulse widths breakdown at zero repetition rate (single pulse) requires a much higher peak power than at say 1000 pps. These matters are discussed more amply in the next section.

C. Pulse Width.

The lowering of peak breakdown power with increasing pulse width is shown in Figs. 35 and 36a to 36e for atmospheric pressure. Preliminary studies were first made up to a maximum pulse width of 1 microsecond. The preliminary studies consisted of investigations on two gap widths, 17 mils and 6 mils. These early results may be tabulated as follows:

Pulse Width	17-mil gap Peak Breakdown Power (kw)	6-mil gap Peak Breakdown Power (kw)
.2 μ	114	34
.43 μ	72	23
1.0 μ	52	16

(It may be noted that here the peak breakdown power is fairly closely proportional to the short dimension of the swayback or gap width.)

The table given immediately below shows that the peak breakdown power (P_m) is very closely proportional to the inverse square root of the pulse width, as was found to be the case at X-band also.

17-mil gap P_m		6-mil gap P_m	
$1\,\mu$	52	$1\,\mu$	16
$\sqrt{.43\mu} \times 72$	47	$\sqrt{.43\mu} \times 23$	15
$\sqrt{.2\mu} \times 114$	49	$\sqrt{.2\mu} \times 34$	15

We may, therefore, conclude with some degree of certainty, that for X-band (as well as for K), in general, $P_m \sim \frac{1}{\sqrt{\mu}}$ where μ is the pulse width, up to at least 1 microsecond. From 1 to 2 microseconds there is still a falling off of P_m with a definite flattening setting in at about 4 microseconds, as was previously mentioned. The significance of this limiting value of 4 microseconds, beyond which no power lowering occurs is argued in detail in the theoretical report. Figures 36a to 36e reveal more curves of this type, all at X-band and extending in pulse width up to 5.24 microseconds. These curves reveal the effect of repetition rate from 2,000 pps actually to 0 pps. The 0 pps of course refers to single shot experiments, which reveal in a striking manner the important role of repetition rate in determining the level of power breakdown. All the curves of the 36 group taken collectively reveal an approach to a final independence of power breakdown of pulse width. This seems to occur at about 4 microseconds.

Figures 37 to 41 give indication of how effective a change of pulse width is at various pressures. The curves are drawn for the three sizes of swaybacks used. In a specific problem it is recommended that a particular curve should be consulted when it is desired to know the effect of changing from one pulse to another at any pressure. However, the inverse square root law given above will serve not too badly over nearly all of the pressure range. Figures 42, 43, and 44 present the effect of both pulse width and repetition rate over the usual pressure range.

V. S-BAND STUDIES.

A. <u>Pressure</u>.

The power-pressure curve, from atmospheric pressure to 114 cms. H_g, shown in Fig. 45 is an extrapolation to full size guide from results for a 40-mil gap. This curve may be taken as being nearly parabolic in nature. The corresponding field strength curve is shown in Fig. 46.

B. Repetition Rate.

The repetition rate effect at S-band, shown in Fig. 47 is of considerable interest inasmuch as a curve obtained by scaling down results for the 105-mil gap to 40 mils, coincides closely with the results of an actual 40-mil swayback curve, over the region 450 pps to about 1,000 pps. On the higher values the two curves are rather close up to about 1,000 pps which is approximately as far as the 105-mil curve goes. However, at the lower end of the scale, that is, to the left of 450 pps the two curves diverge slightly to the end of their ranges, namely, 200 pps for the 105-mil curve and 300 pps for the 40-mil curve. Over its entire range of 300 to 2,000 pps the 40-mil curve is essentially a straight line, whereas the 105-mil curve, as a whole, shows curvature except in the region mentioned previously. For the present, the best procedure would seem to be to use that curve which corresponds more closely to the dimensions of interest in any problem. The equation of the 40-mil straight line is

$$\underline{P_m = 378 - .059R}$$

where P_m is in kilowatts, R is in pps, and is not to be outside the limits 300 to 2,000 pps. The data was taken at a pulse width of .76 microsecond. For gaps up to about 70 mils one might use the following formula:

$$P_m = (378 - .059R)\frac{x}{40}, \text{ where x is the gap width.}$$

For gaps greater than about 70 mils the curve for the 105-mil swayback may be used.

At a pulse width of 1.29 microseconds some data was taken which indicated, as expected, a lowering of power with increasing repetition rate. However, it must be remarked that at a pulse of 1.84 microseconds the power for breakdown seemed to increase with increasing repetition rate. Not much stress is being placed on this seeming effect at the moment, pending further investigation. One recalls at this point that, at least for X-band, it is in the general neighborhood of this pulse width that the lowering of peak breakdown power with pulse width declines considerably. Fig. 49 shows in more usable form, the peak power vs repetition rate curve already discussed and used in Fig. 47.

C. Pulse Width.

Figure 48 shows a plot of the effect of pulse width on peak breakdown power for a range extending between .76 microsecond and 1.86 microseconds. The straight line which seems to fit this data has the following equation for the 40-mil gap:

$$P_m = 408.6 - 63.6\mu$$

at a repetition rate of 500 pps and atmospheric pressure. It is desirable to lower the above values by about 6% in view of the following fact: data taken on another run (unextrapolated value of Fig. 45) gave a value of 325 kw. breakdown for the 40-mil gap at atmospheric pressure, for the same repetition rate and pulse width; the data for the straight line, however, gave a value of 345 kw. for the same situation. Accordingly, we choose the lower value, to be on the side of conservatism, and therefore use the following relation for the 40-mil gap:

$$P_m = .94\,(408.6 - 63.6\mu), \qquad \text{or}$$

$$P_m = 384 - 60\mu;$$

40-mil gap, atmospheric pressure
500 pps, valid for pulse range
of .76 microsecond to 1.86 microseconds.

D. Duty Cycle.

Figure 50 presents a run taken at a constant duty cycle of 1 in 700, and reveals the marked decline in peak breakdown power attendant upon an increase in pulse width when the duty cycle remains unchanged. The experiment was performed on a 105-mil gap.

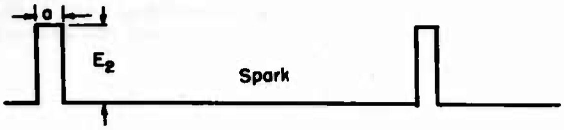
VI. CONCLUSION.

In closing this report we might take occasion to remark in general on certain points of interest which arose during the investigations; we might also suggest future directions of worth-while investigation:

1. A study of breakdown due to multiple pulses

would be of value in helping to establish the nature of the decay law after a pulse. Of course, comparison would be made with breakdown results from single pulses. Thus,

$E_2 > E_1 > E_3$



and

2. A direct inquiry would be of interest into the question of whether or not ionizing radiation exists in the gas, i.e., excitation or recombination radiation liberating electrons by photoionization of the gas at high pressure (much absorbing material), and photoelectrons from the metallic walls at low pressure (radiation less attenuated by the intervening gas). This question is of fundamental importance in that it examines the possibility of the existence of a secondary electron-creating mechanism. In the writer's opinion such a mechanism is not mathematically necessary at microwave frequencies inasmuch as it has been shown in the theoretical report that a sparking sequence can be formulated utilizing only electron ionization by collision.

3. The effect of n_o, the initial number of ions/cc in the gap could be studied more purposefully. Only a few different concentrations were used in the present experiments. Such an investigation would be of considerable value in solving TR box problems and the like.

4. The increase in standing wave ratio occurring when breakdown occurs (which was observed in these experiments) could be investigated more closely with a view to utilizing this change as an indication of the occurrence of breakdown.

5. At S-band, during certain pressure measurements when a manometer was connected to the sealed-off swayback, a spark produced very marked pressure changes in the manometer. This effect, which is doubtless a sudden heating of the gas due to the discharge, could be profitably examined closely with a number of purposes in mind, one of which might well be the determination of the heat component of the quantity of dissipated energy in particular types of breakdown.

6. A study of other gases as microwave dielectrics could be of some value. Carbon tetrachloride has occasionally been used by some workers as a discharge extinguisher.

7. A suggestion has also been made that it would be desirable to obtain breakdown values without extrapolation for full size guide experimentally, and with only moderate power, by introducing standing waves of known magnitude and then raising the power to breakdown.

8. More work should be done in studying the breakdown power change with a change of repetition rate. Anomalous effects were supposed to have been found for the ordinary repetition rate range for pulse widths of about 1.84 microseconds or greater. One certainly expects an end to repetition

rate effect if the pulse width is as long as the time necessary to generate a spark, or longer, for then the breakdown should occur on the first pulse. But one does not expect an inversion of the repetition rate effect at any pulse width. This inversion may nevertheless be occurring, in view of certain evidence, and the question should, therefore, be examined without prejudice, unattractive though the conception may seem. This applies to S-band.

9. A similar point of interest is that of further inquiry into the effect of pulse width on peak breakdown power at constant duty cycle.

10. It would probably be worthwhile to investigate carefully the validity of the following: break down a test piece of arbitrary design, consider the power and pressure at which this occurs and from the data given in this report, calculate the width of an equivalent parallel plate gap. From this, predict from the curve the subsequent behavior of the "test gap."

11. Likewise, when the breakdown occurs across a dielectric window, investigate the validity of the process described in 10, above.

12. For some particularly troublesome device, that is, one which breaks down too easily, one might resort to the construction of plane sections whose 60-cycle fields may be studied by the probe method in an electrolytic solution. Success has even been reported in the study of three-dimensional models by this technique, though not for devices for microwave work.

13. As in d.c. work, investigation of breakdown between a point and a plane should be of great interest and value at microwave frequencies. The results for microwaves would not be expected to be very similar to those at d.c., for in the microwave case, the extremely-rapid alternations of the field render the point neither positive nor negative, insofar as pre-spark ion build-up is concerned.

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It is a pleasure to report the help of Alice Reynolds in making the runs, the interest in the work exhibited by George Yevick, Walter Aron, Harold Webster, and Gerald Heller, and the cooperation of members of the Main Drafting Room.

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APPENDIX I

USEFUL BREAKDOWN VALUES AND FORMULAS

A. K-BAND.

1. Peak Power at
   atmospheric pressure
   repetition rate 500 pps
   pulse width 1 microsecond
   full size waveguide (170 x 420 mils, inner)

   is <u>187 kilowatts</u>

   (extrapolating from 59-mil gap, and .25-microsecond pulse)

2. Peak Field Strength for above condition

   is <u>27 kilovolts/cm</u>

3. For any other gap, of Width W in mils, the power is

$$187 \times \frac{W}{170} \text{ kilowatts}$$

4. For any Repetition Rate between 500 and 2,000 pps, at atmospheric pressure, and for 1-microsecond pulse,

$$P_m = \frac{187}{5000} (5500 - R) \text{ kilowatts}$$

5. For any Pulse Width up to 2 microseconds

$$✓\ P_m = \frac{187}{\sqrt{\mu}}, \quad \begin{array}{l} 500 \text{ pps} \\ \text{pres.} = 1 \text{ atmosphere} \end{array}$$

6. For any Pressure, p, in atmospheres,

$$✓\ P_m = 187\ p^n \quad \text{at}$$

   n between 1 and 2; 500 pps; 1 microsecond; and above $\sim$ 5 cms. Hg.

   for regions above about half an atmosphere n $\simeq$ 1.

7. Combining the separate parameter effects we have the following empirical formula:

$$P_m = \frac{187}{\sqrt{\mu}} \frac{(5500 - R)}{5000}\ p^n \text{ , or}$$

$$P_m = \frac{3.7 \times 10^{-2}}{\sqrt{\mu}} (5500 - R)\ p^n \times \frac{W}{170}$$

   n between 1 and 2 as in point 6, above.

$\underline{\mu}$ is in microseconds, $\underline{p}$ is in atmospheres, $\underline{R}$ is in pps; $\underline{P_m}$ is in kilowatts, $\underline{W}$ is in mils (for the width of a gap).

Limits in the parameters for which the formula is valid, are:

μ , 0 to 2 microseconds
R, 500 to 2,000 pps
p, 5/76 to 2 atmospheres

The above empirical formula should not be used if the curves given in this report are at hand, for the curves are important in that they cater to special gap characteristics (recall Fig. 10); moreover, the formula is not valid in the region of pressures below 5 cms. Hg.

B. X-BAND.

1. Peak Breakdown Power at $\begin{cases}\text{atmospheric pressure}\\ \text{repetitition rate 500 pps}\\ \text{pulse width 1-microsecond}\\ \text{full size waveguide (400 x 900 mils, inner)}\end{cases}$

   is <u>1.2 megawatts</u>

   (extrapolating from 38-mil gap)

2. Peak Field Strength for above condition

   is <u>34 kilovolts/cm</u>

3. For any other gap, of width $\underline{W}$ in mils, the power is

$$1.2 \times \frac{W}{400} \text{ megawatts}$$

4. For any Repetition Rate between 500 and 2,000 pps, at atmospheric pressure, and for 1-microsecond pulse,

$$\underline{P_m = .16\ (8000 - R)}\ \text{kilowatts}$$

5. For any Repetition Rate between 500 and 2000 pps, for any pressure in atmospheres up to about 2, and above (5/76); and for any pulse width under 2 microseconds,

$$P_m = \frac{.16\ p^n}{\sqrt{\mu}}\ (8000 - R) \qquad n \text{ between 1 and 2;}$$

   above about 1/2 atmosphere $n \eqsim 1$.

6. For the above conditions, but for any gap of width $\underline{W}$ in mils,

$$P_m = \frac{4W\ p^n}{\sqrt{\mu}}\ (8000 - R) \times 10\text{-}4 \text{ kilowatts}$$

   n between 1 and 2;

   as in point 5, above.

7. For the above conditions, the field strength

$$E_m = \frac{.38 \sqrt{p^n} (8000 - R)^{\frac{1}{2}}}{\sqrt[4]{\mu}} \quad \text{kilovolts/cm;}$$

n as in point 5, above.

$$\left(\text{using } \underset{\text{watts}}{P_m} = \underset{\text{volts/cm}}{E_m{}^2} \times 6.63 \times 10^{-4} \frac{\lambda_o}{\lambda_g} \underset{\text{cms}}{ab}\right)$$

C. S-BAND.

1. Peak Breakdown Power at $\left\{\begin{array}{l}\text{atmospheric pressure}\\ \text{repetition rate 500 pps}\\ \text{pulse width 1 microsecond}\\ \text{full size waveguide (1.34" x 2.84", inner)}\end{array}\right.$

is <u>10.8 megawatts</u>

(extrapolating from either 40-mil gap or 105-mil gap)

2. Peak Breakdown Field for the above conditions

is <u>30 kilovolts/cm</u>

3. For any other gap of width <u>W</u> in mils, (for the above conditions)

$$P_m = 10.8 \times \frac{W}{1340} \quad \text{megawatts}$$

4. For any pulse width, but a repetition rate 500 pps, at atmospheric pressure

$$P_m = 12.8 - 2\,\mu \quad \text{megawatts;}$$

valid for $.76\,\mu$ to $1.86\,\mu$

5. P_m in terms of repetition rate, pulse width, and pressure:

$$P_m = cp^2 \quad (6300 - R) \quad (6.4 - \mu)$$

When $p = 1$ atmosphere, $R = 500$ pps, and $\mu = 1$ microsecond, P_m should be 10.8 megawatts; $c = 3.45 \times 10^{-4}$

$$\underset{\text{megawatts}}{P_M} = 3.45 \times 10^{-4} \underset{\substack{\text{atmospheres}\\ 1 \text{ to } 1.52}}{p^2} \underset{\substack{\text{pps}\\ 500 \text{ to } 2000}}{(6300 - R)} \underset{\substack{\text{microsecond}\\ .76 \text{ to } 1.86}}{(6.4 - \mu)}$$

APPENDIX II

A. EXPERIMENTAL PROCEDURE.

To get a controlled, measurable field, at microwave frequencies, requires either a method of directly measuring the field, or methods of computing the field from indirect measurements. In the present experiments, the latter procedure was adopted. Inasmuch as it was desired that the breakdown take place across a definite gap, (of known width), the gap had to be narrower than other sections of waveguide. For this purpose, the technique here used is the familiar one of gradually narrowing a waveguide in its small dimension until this is quite small, extending the waveguide for a short distance with these dimensions, and then gradually tapering out again to normal dimensions (Diagram I). The gradual taper minimizes reflections, and since the same power must now pass through a smaller guide, the field is increased in proportion to the square root of the factor by which the guide is made smaller.[4] A measured amount of power was fed into this section, and thus, it became possible to compute the field, at any power level.

In operation, the power was increased until a spark passed in the narrow section of the waveguide, whereupon measurement of the power permitted computation of the field required to cause the breakdown. The power source used in each case was a magnetron of appropriate frequency, driven by a hard tube or hydrogen-thyratron modulator.

B. METHODS OF POWER MEASUREMENT.

The primary standard of power measurement was the water load. In general, this consists of a glass tube inserted in a waveguide using some form of taper to eliminate or minimize reflections. Water is circulated through this glass tube, at an accurately known rate of flow, and the difference between input and output temperatures is indicated by thermocouples. In order to reduce errors due to radiation and conduction, the temperature of the input water is maintained as nearly as possible at room temperature, and high flow rates resulting in small differences in temperature are used. The small temperature difference reduces the thermal leakage to a value which has been estimated to average about 0.3 to 0.5%. The probable deviation from this average is ±0.3 to 0.5%.

---

[4] $P_M = \cdot KE_M^2 \frac{\lambda_o}{\lambda_g} ab$

A sensitive Rubicon galvanometer (0.5-microampere full scale) measures the small thermocouple voltages involved. Its voltage sensitivity is varied by means of a series resistance (G.R. decade, 0-1000 ohms). Calibration of the thermocouples and the galvanometer is accomplished by substituting for the glass tube in water load, a tube containing a coiled heating element, which is then excited by 60-cycle power applied through a wattmeter. The probable errors in connection with the galvanometer (non-linearity, zerodrift, etc.) are about ±0.3% to ±0.5%.

The water load is an absolute method of measuring power, and when used with care gives fair accuracy, but it has two disadvantages: it must terminate the line after the power has passed through the object under test, which is sometimes inconvenient; and it is inclined to be rather slow in response (15 seconds to a minute, mostly due to galvanometer lag). Since breakdown is a practically instantaneous phenomenon, it is desirable that the power measuring device be as fast as possible, to follow momentary fluctuations in magnetron power output. It was found convenient to use for this purpose, a thermistor coupled to the line by means of a directional coupler. The thermistor bridge is known as the "W" bridge, type TBN 3EV, which can be individually calibrated by applying a d.c. signal to the thermistor. Although the thermistor power monitor may be used in an absolute manner, by measuring the coupling of the directional coupler, and calibrating the bridge for a known sensitivity at the thermistor, discrepancies observed when using this system with the water load (especially on K-band) lead to the calibration of all directional-coupler monitors against water loads. The arrangement of the apparatus is shown in Diagram A. The probable error of these power monitors is estimated to be, with careful handling, about 2% from true reading, after calibration.

All methods of power measurement using thermal devices measure average power, from which, of course, it is necessary to compute peak power by calculating from the repetition rate and pulse width. The repetition rate is determined by using a common oscilloscope, placing the modulator trigger voltage pulse on the vertical plates, and a sine wave from an accurately calibrated audio oscillator on the horizontal. The frequency of the latter is varied until it is observed on the scope that one trigger occurs each cycle. The probable error in this measurement is estimated at 0.3 to 0.5%.

The pulse width (for purposes of power measurement) is measured as the time from the center of the rise of the current pulse to the center of the fall of the pulse, as in standard procedure for pulse width measurements. The measurements are made on synchroscopes calibrated with the standard range calibrators of the indicator group. The probable error of the measurement is estimated at about 2% for long pulses and 6% on short (.25-microsecond) pulses.

For certain measurements involving single pulses, thermal methods of power measurements cannot be used. At the time of these experiments, high-level detectors were not yet available, and crystal plus broad-band video amplifier combination is hard to get, and not strongly trusted to hold calibrations very long. A simple method of getting the power level in such cases is by observing the current pulse. The power output of a magnetron operating at a given magnetic field is found to be approximately proportional to the magnitude of the current pulse. At any rate it seems reasonable to assume that current pulses of the same magnitude correspond to the same power whether single, or at some repetition rate. Thus, one can, by using a water load with a steady train of pulses, calibrate the height of the current pulse against the power output as observed by the water load. Actually, in those portions of the present experiments where single pulse breakdown was compared to rep rate breakdown, as well as other single pulse experiments, only relative powers were of interest, and hence, merely comparisons were made of heights of magnetron current pulses.

C. SWAYBACK SECTIONS.

A generalized drawing of the tapered waveguide section used is shown in Diagram I at the front of this report. The actual gap dimension d and probable error in its measured value is as follows for the three bands:

Band	Guide width inches	Guide height inches	probable error in height in %
S	2.840	0.110	3
		0.040	8
X	0.900	0.0065	8
		0.0175	3
		0.0385	2
K	0.420	0.0065	8
		0.0165	3
		0.0395	2
		0.0595	2

Since for a given power transmitted the field strength is proportional to the square root of the height d, the percentage errors in estimate of breakdown field is about half these values. But the estimate of breakdown power for the height assumed will be in error by the full value of gap error.

In the above measurements, the swayback section is followed by a dry load, and preceded by the directional coupler used in power monitoring. In all cases, the voltage standing wave ratio of the dry load was kept as low as possible, being commonly around 1.05, and in all cases, as good as 1.10. Allowing for a possible additional standing wave ratio of up to 1.05 in the taper, the maximum v.s.w.r. in the half-wave long constricted section would be about 1.15. This would lead to breakdown at a computed power 15% lower than with no standing wave. Hence, our estimate of breakdown power will be in error by up to -15%, because of this standing wave. It is estimated that on the average, the standing wave was such as to lead to our estimate of power for breakdown being low by about 3 to 6%. The probable deviation from this average is estimated as about plus or minus 2 to 4%.

D. WAVEGUIDE LOSSES.

In the S-band work, the losses in waveguide are so low (about .013 db per foot) that they are entirely negligible. In the X-band work, the losses are about .08 db (or 2%) per foot. As may be seen from Diag. A, the power level at the thermistor coupling exceeds that at the water tube of the water load by a certain non-negligible amount (of the order of 2 or 3%). But an almost identical relation exists between power level at the thermistor coupling and that at the swayback section in Diagram C. Hence, if the lengths involved in the two cases are the same within about three inches, as they usually were, the error is of the order of 0.5%. In the reduced pressure measurements, allowance for the extra length of line involved was made.

In the K-band work, guide losses were considerably larger, but lengths were shorter. A difference of length of about 2 inches, which is probably typical, gives rise to an error of about 1% (since the loss is about 3/4 db per meter, or 0.5% per inch).

E. SUMMARY OF THE ABOVE PROBABLE ERRORS

	Probable Errors			
	Worst Cases		Best Cases	
	average error ±		average error ±	
(a) Water load - Heat leakage	-0.5	0.5	-0.3	0.3
(b) Galvanometer errors in water load readings		±0.5		±0.3
(c) Thermistor error (or scope error in single pulse work) besides water load calibration errors		±0.8		±0.4
(d) Repetition rate measurements		0.5		0.3
(e) Pulse width measurements		6.0		2.0
(f) Standing wave effect	-6.0	4.0	-3.0	2.0
(g) Waveguide losses		±1.0	0	0
(h) Swayback height		8.0		±2.0
Over-all probable errors:	-6.5	10.8	-3.3	3.6

Probable errors given are our estimate of the error which will be exceeded about half the time, i.e., with 50% probability. In item (e), "worst case" is for short pulse work (0.1 to 0.3 microsecond) while "best case" was for 2 to 5 microseconds. In item (h), "worst case" refers to the swayback section of smallest height d (for a given wavelength), while "best case" refers to the largest height sections. On the other items, best and worst represent upper and lower limits on our estimate of probable error. The overall probable error is taken as the square root of the sum of the squares of the individual probable errors. It should be noted that the final estimate of power is the result of multiplying together all the separate items listed.

F. SPARK DETECTION.

Breakdown usually was detected by the sound of the spark and occasionally by its light. However, there were certain cases for which detection of this type was not easy. Obviously, when a piece of plumbing under test is being evacuated, at low pressures, the discharge makes very little sound, and since it is enclosed, detecting it by its light is either difficult or impossible. Under such circumstances, two methods were used: a stethescope or a contact microphone was used to detect the very soft sound made by discharge; or, alternatively, a directional coupler with power detecting device was used to pick up the sudden increased reflections made by the spark acting as an abrupt termination. In the last method, it is highly desirable that some device showing instantaneous power be used, as the reflections from occasional sparking would not show up on an average power indicator. In this case a crystal, amplifier, and synchroscope were used; and a spark would be indicated by a sudden increase in height of the pulse appearing on the scope. This system was correlated with the system of detection by sound, and seemed to check out quite well. However, it received only limited usage, since most breakdown could be heard easily. Occasionally also, the occurrence of a breakdown was detected by noting the increase in the standing wave ratio in a slotted section located between the magnetron and the spark.

G. TUBES AND MODULATORS USED.

The tubes and modulators used in these experiments were the following:

S-Band: 720 with G.E. 3 Megawatt Hard Tube Modulator.

X-Band: 725-A with Model 12 Hydrogen Thyratron Modulator
4J50 with Model 11D Hydrogen Thyratron Modulator for single pulse measurements
K-Band: 3J31 with "Link" Model 4 Hard Tube Modulator

In the case of the hydrogen thyratron modulators, some difficulty was experienced in the X-band work with the pulse shape at low levels. The pulse shapes at both S- and K-band (using hard tube modulators) were flat-topped.

D. Q. Posin
Ina Mansur
H. Clarke

November 1, 1945

K-Band

The Problem of Obtaining Reliable and Repeatable Data in Breakdown

Successive determinations of the peak power that a test piece could stand differed so widely that small reliance could be placed on most results. This experiment shows "normal" erratic breakdown of waveguide.

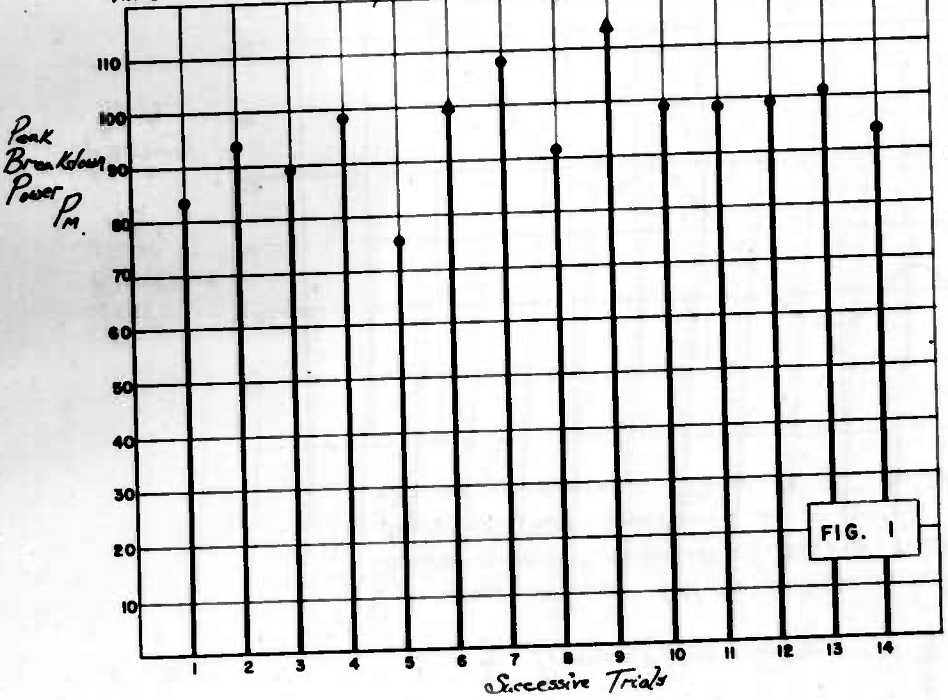


FIG. 1

Experiment was performed on 36-mil gap of a swayback section; at atmospheric pressure.

K-Band

Erratic Pressure-Power Curve

Such behavior had to be eliminated before controlled experimental studies could begin of power breakdown as a function of various parameters. (Curve is for 59-mil swayback)

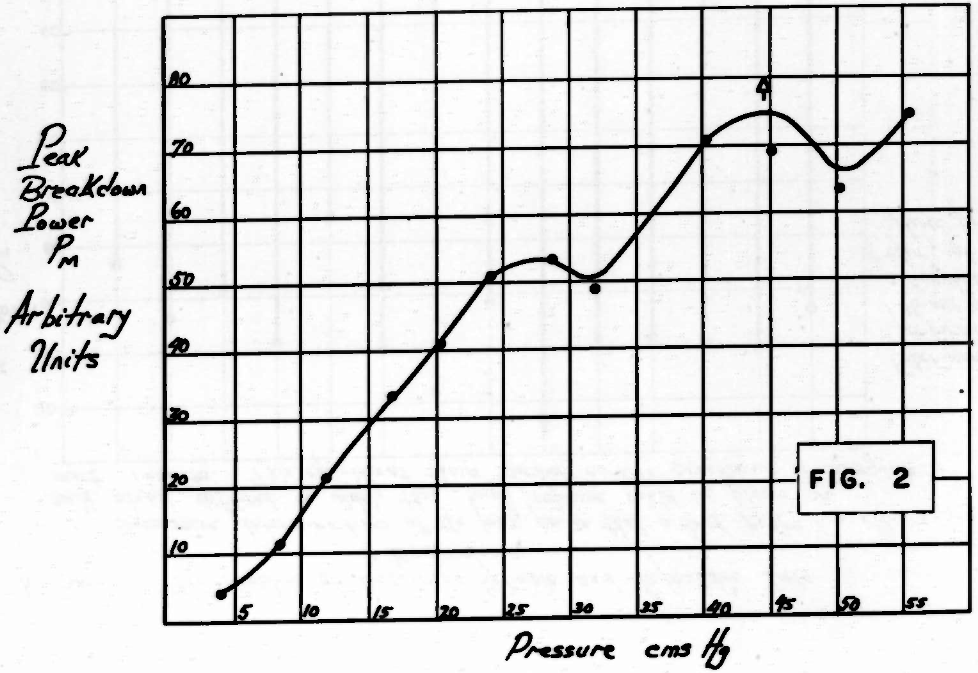


FIG. 2

K-Band

An Average of 4 Runs, here yields reasonably smooth breakdown-pressure curve.

(59-mil swayback)

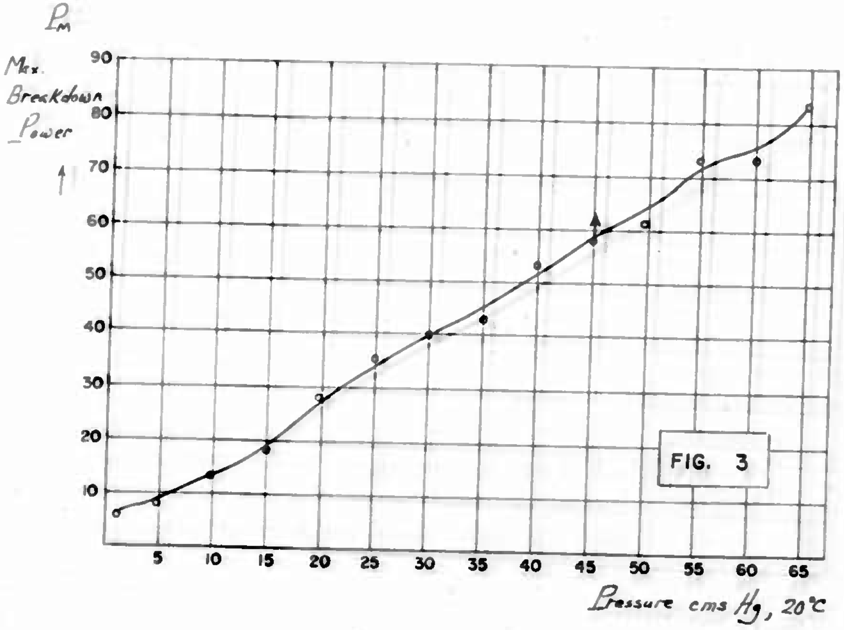


FIG. 3

K-Band

Average of 3 Runs here fails to yield believable curve; 4 or even 8 Runs would not have sufficed in this particular session.

36-mil swayback or gap

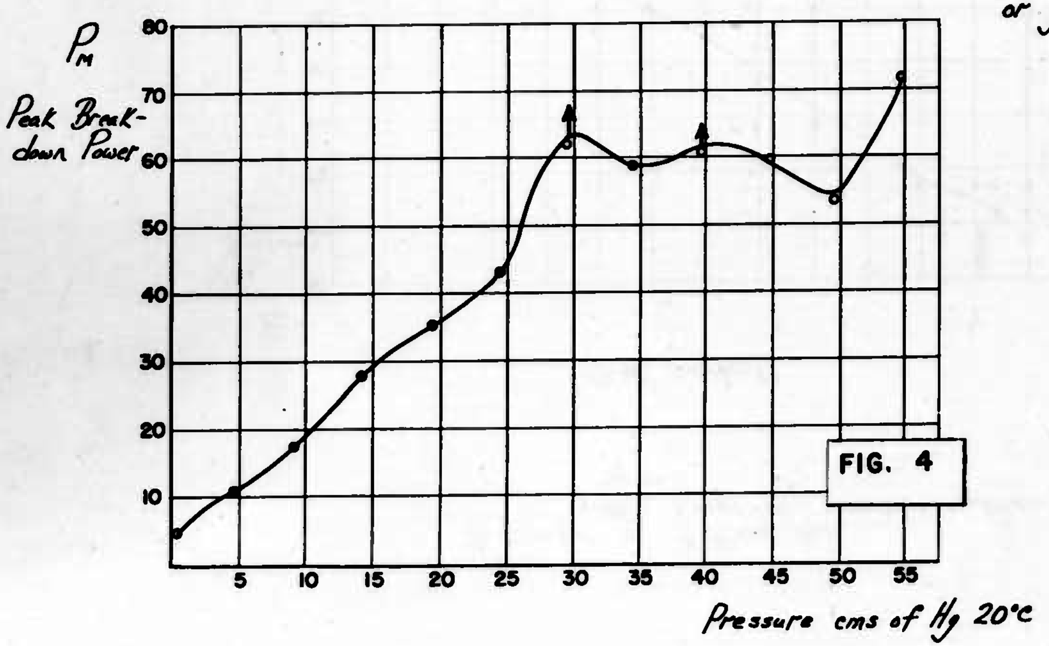


FIG. 4

K-Band

Pulse .25μ
500 p.p.s.

Smoothing the Pressure – Power Curve

Radioactive Cobalt (C_o^*) placed on top of Swayback makes possible smooth pressure-power curve, presumably by supplying sufficient ionization to remove the possibility of a spark from the realm of statistical behavior...

curves for
6-mil gap

Capsule of C_o^* (half life 5yrs)

Extreme lowering of breakdown power with C_o^* is later corrected for, when "normal" but smooth breakdown values are needed.

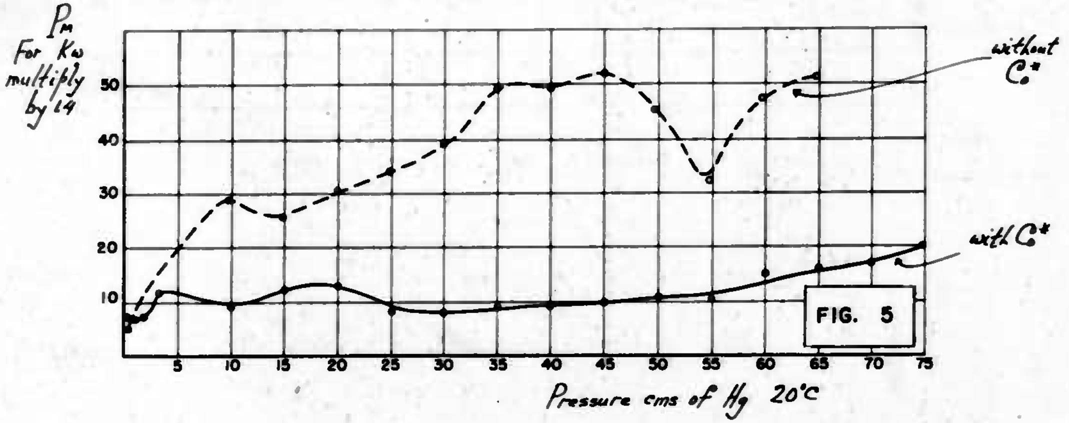


FIG. 5

K-Band

Pulse .25µ
500 p.p.s.

Effect of
Irradiation by Co*
Curve for 16-mil gap (swayback)

Each curve is an average for 3 Runs

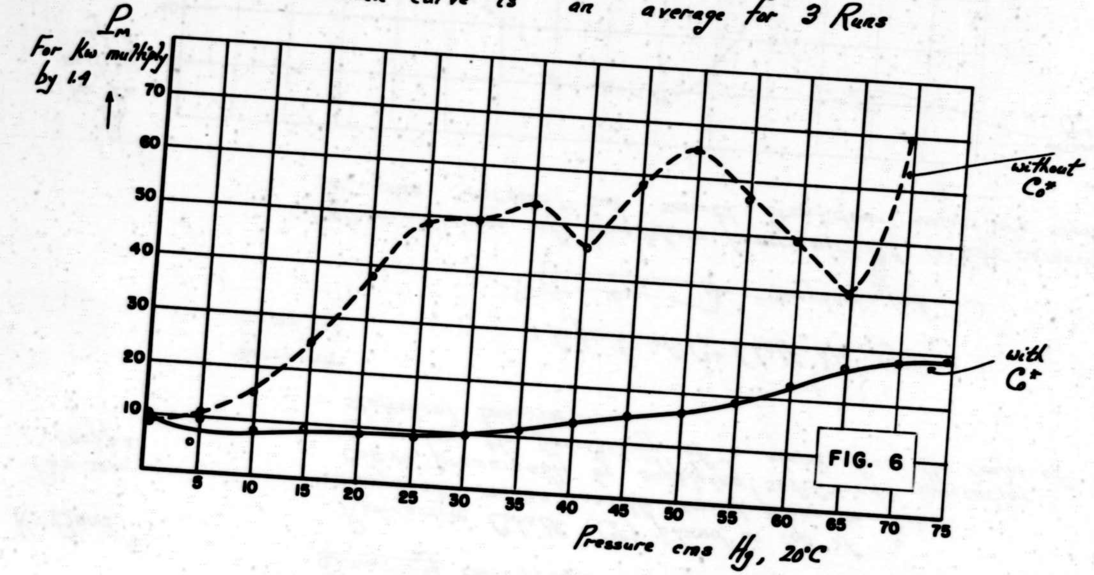


FIG. 6

K-Band Smoothing the 36-mil gap Pressure-Power Curve

Each curve is an average for 3 Runs

Curves for 36-mil gap

.25μ
500 pps

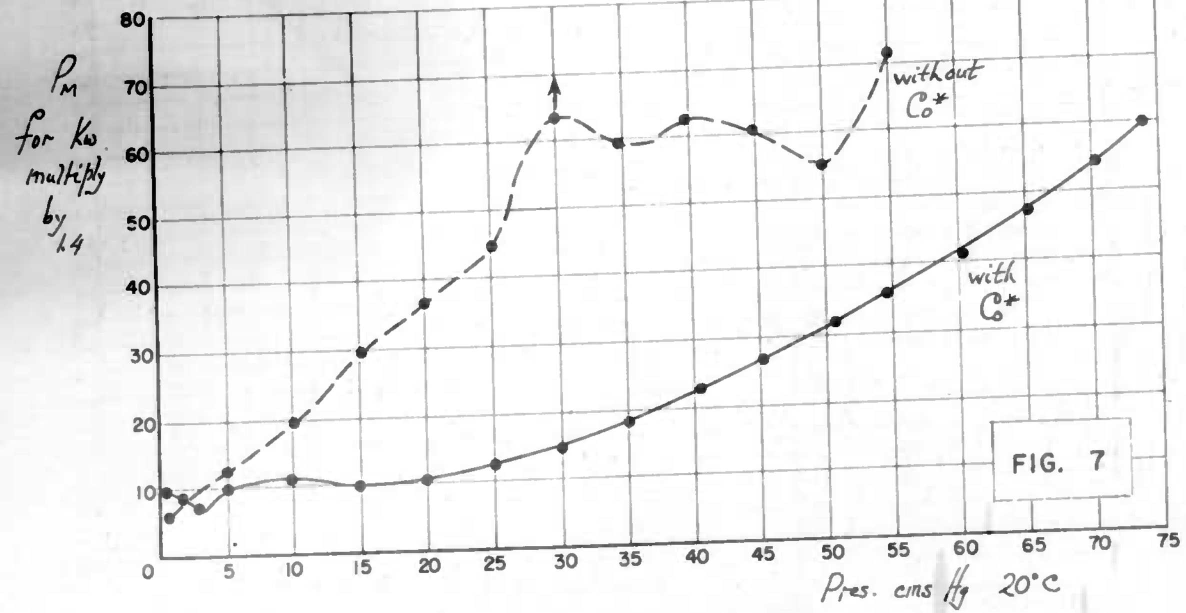


FIG. 7

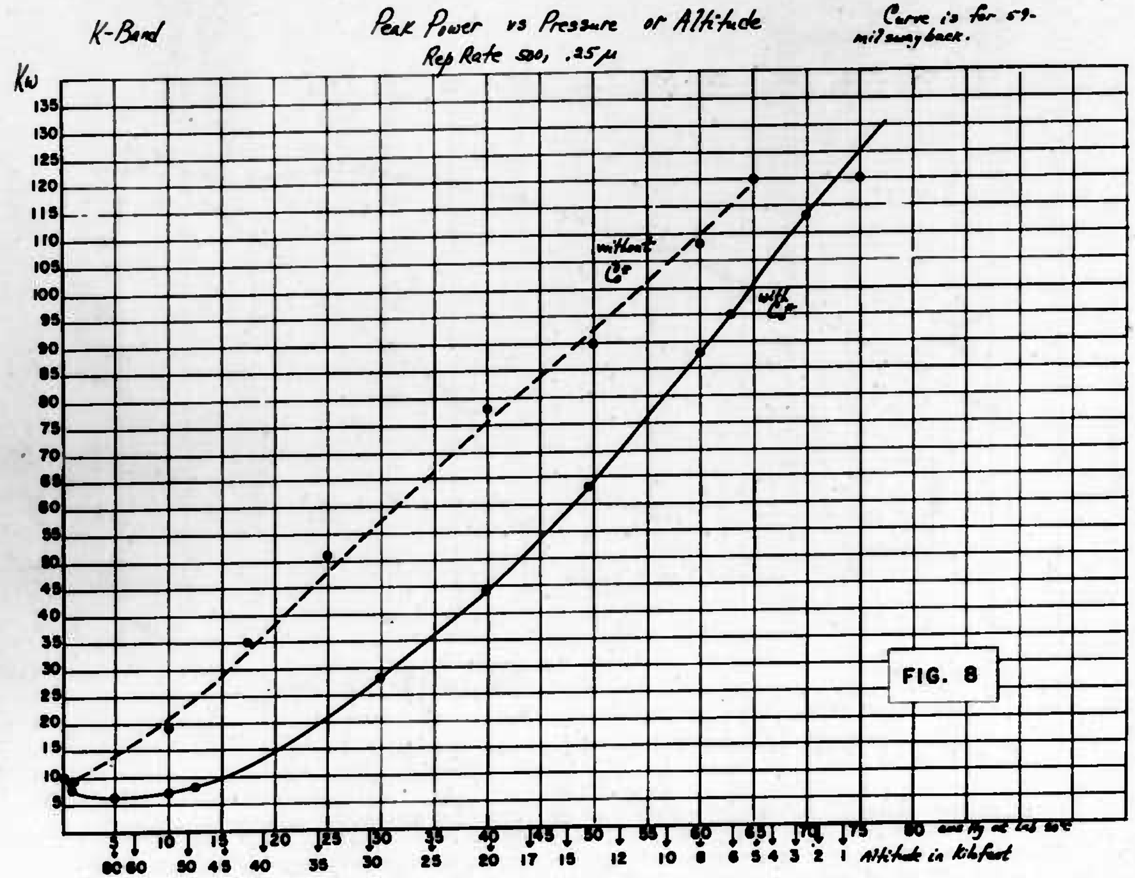

K-Band
Peak Power vs Pressure or Altitude
Rep Rate 500, .25 μ
Curve is for 59-
mil swayback.
Kw
135
130
125
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
without
C°
with
C°
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80 cm Hg at sea level
80 60 50 45 40 35 30 25 20 17 15 12 10 8 6 5 4 3 2 1 Altitude in kilofeet

FIG. 8

K-Band

Pulse .25µ
500 pps

One Run With C_o^* Compared to One Run Without C_o^*

Showing that although both the C_o^* and the non-C_o^* curves were smooth in Fig. 8 where 4 Runs for each were averaged, here, on the other hand, when only 1 Run was taken for each curve, only the C_o^* gave a smooth curve.

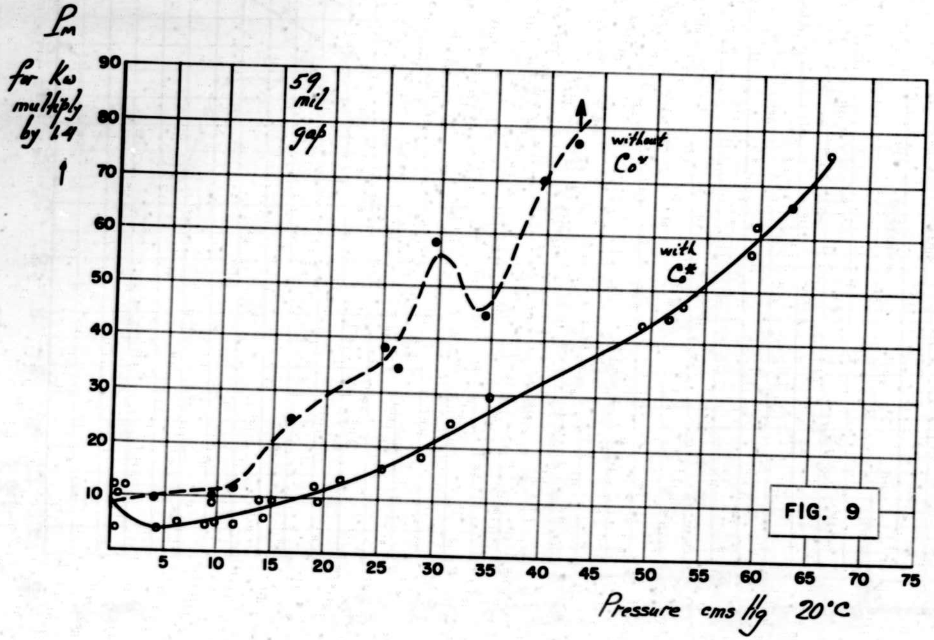
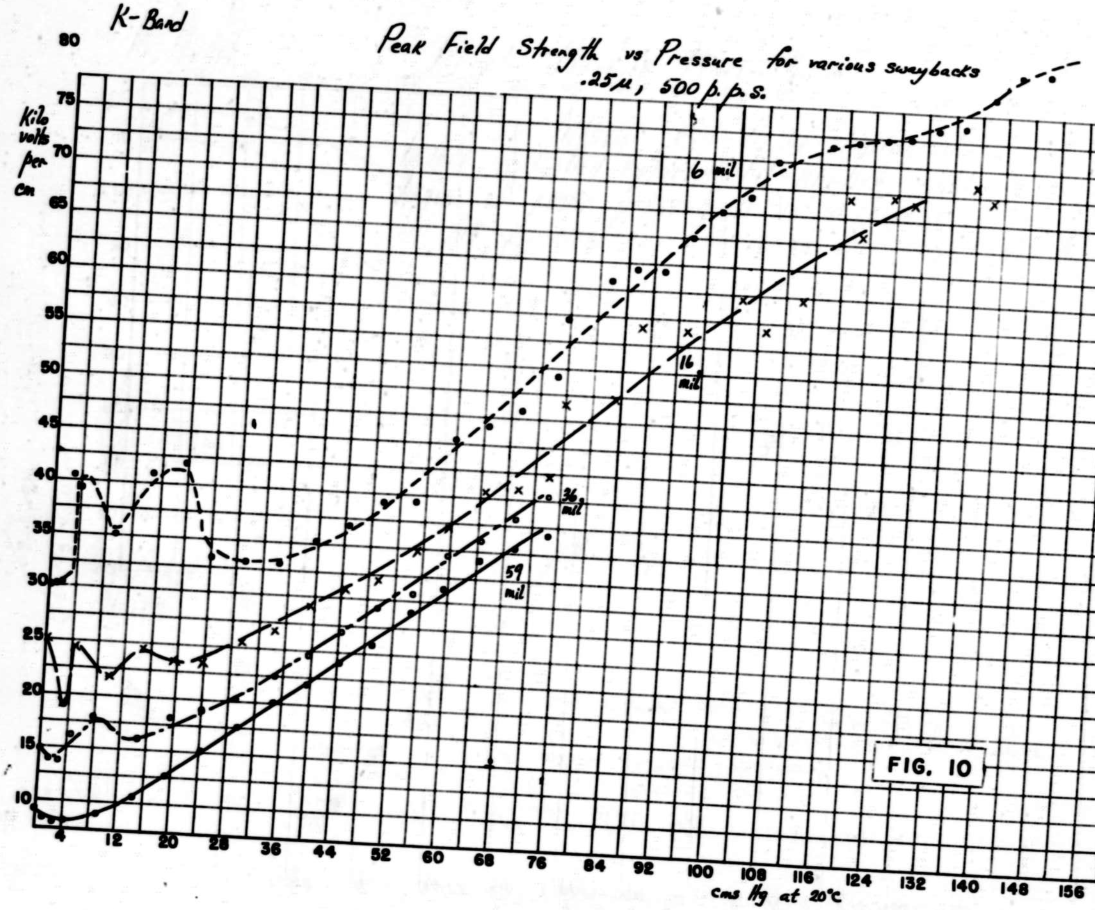


FIG. 9



K-Band
Peak Field Strength vs Pressure for various swaybacks
.25μ, 500 p.p.s.
Kilo volts per cm
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
4
12
20
28
36
44
52
60
68
76
84
92
100
108
116
124
132
140
148
156
cms Hg at 20°C
6 mil
16 mil
36 mil
59 mil

FIG. 10

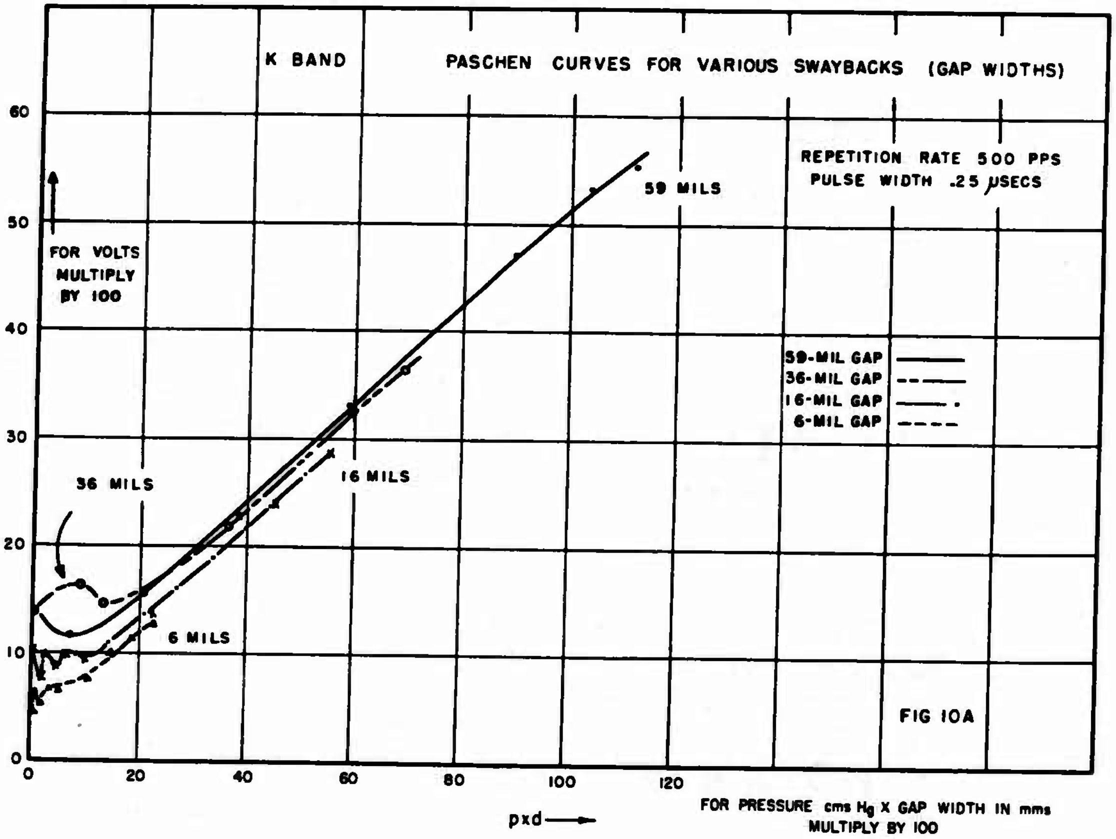

K BAND
PASCHEN CURVES FOR VARIOUS SWAYBACKS (GAP WIDTHS)
REPETITION RATE 500 PPS
PULSE WIDTH .25 μSECS
59 MILS
36 MILS
16 MILS
6 MILS
59-MIL GAP
36-MIL GAP
16-MIL GAP
6-MIL GAP
FOR VOLTS MULTIPLY BY 100
0
10
20
30
40
50
60
0
20
40
60
80
100
120
pxd
FOR PRESSURE cms Hg X GAP WIDTH IN mms MULTIPLY BY 100

FIG 10A

K- Band

At Atmospheric Pressure

Variation of Field Strength With
Swayback Size

.25µ , 500 pps

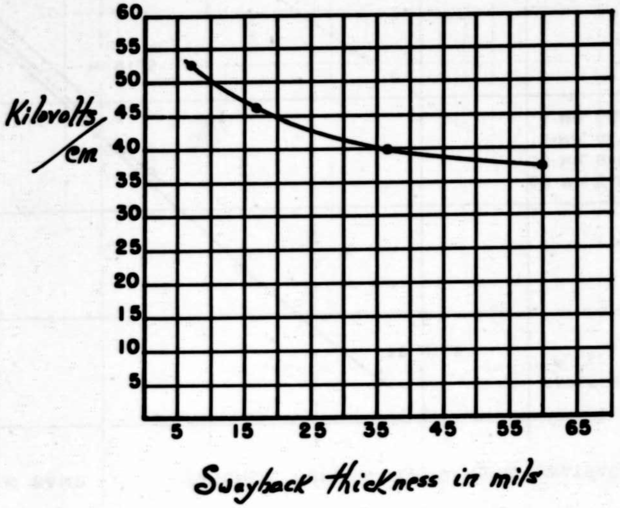
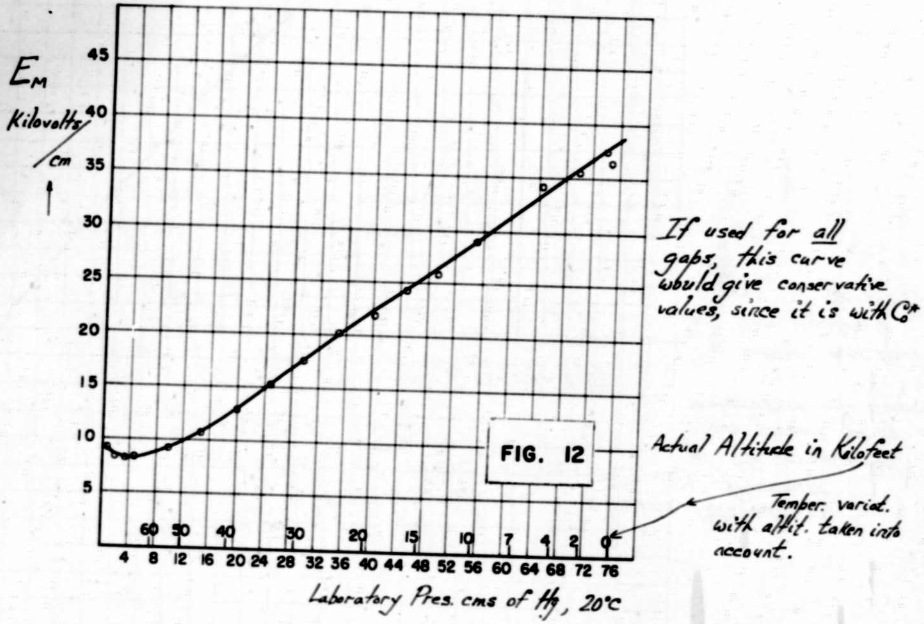


FIG. 11

K-Band

Pulse .25μ, 500 p.p.s.

Field Strength vs Pressure
or Altitude
(Curve taken from 59-mil data)



If used for all gaps, this curve would give conservative values, since it is with C_o^*

Tember. variat. with altit. taken into account.

FIG. 12

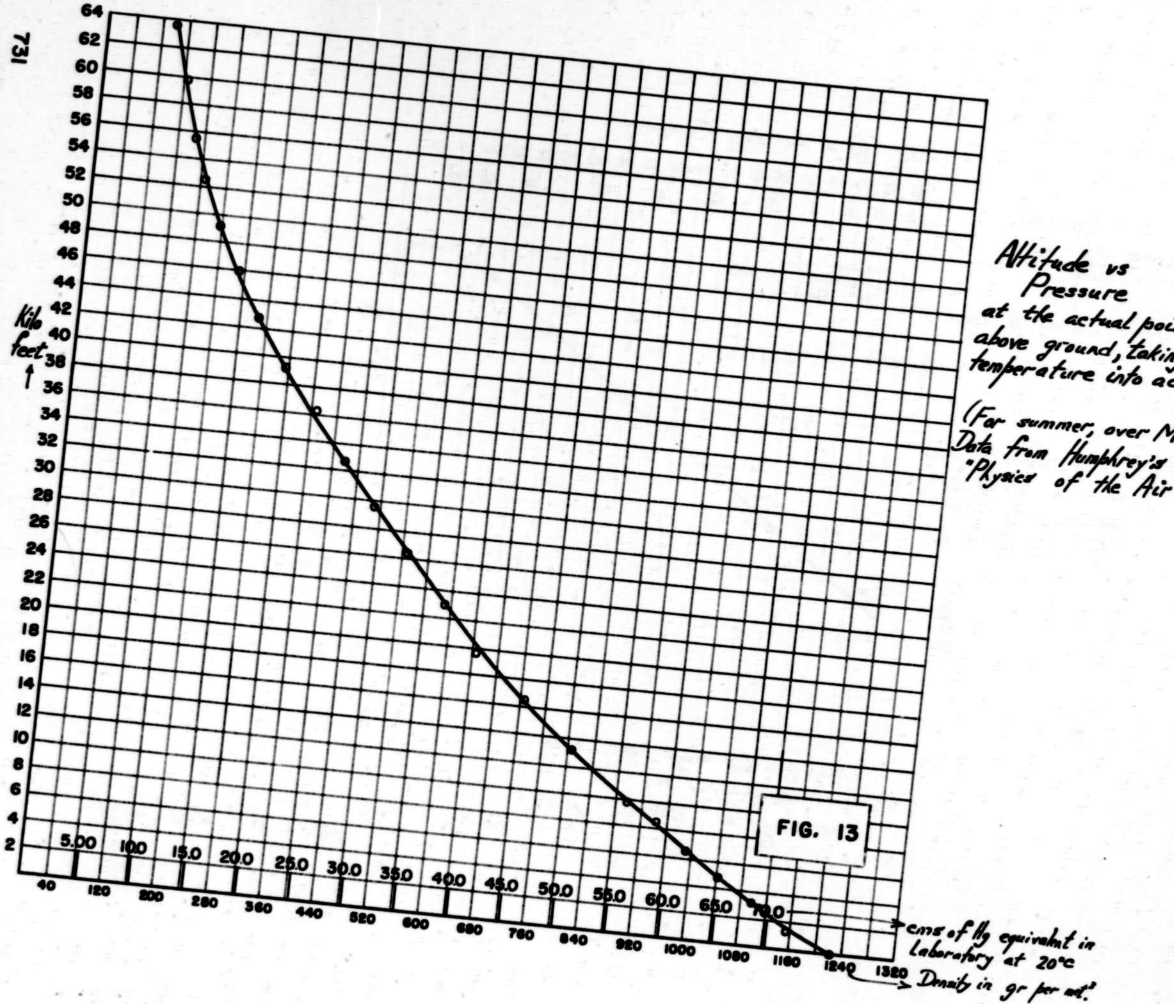
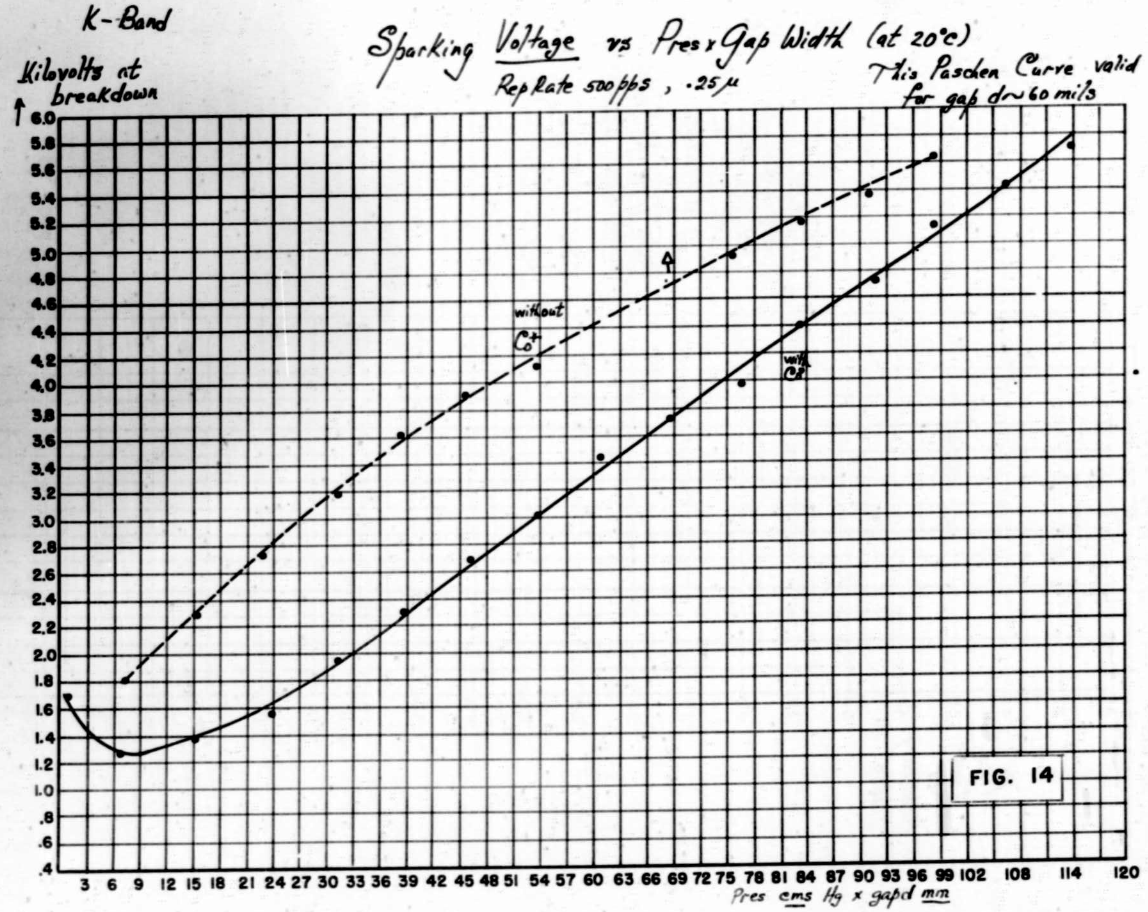


FIG. 13

Altitude vs
Pressure
at the actual point
above ground, taking
temperature into account

(For summer, over Munich.
Data from Humphrey's
"Physics of the Air")

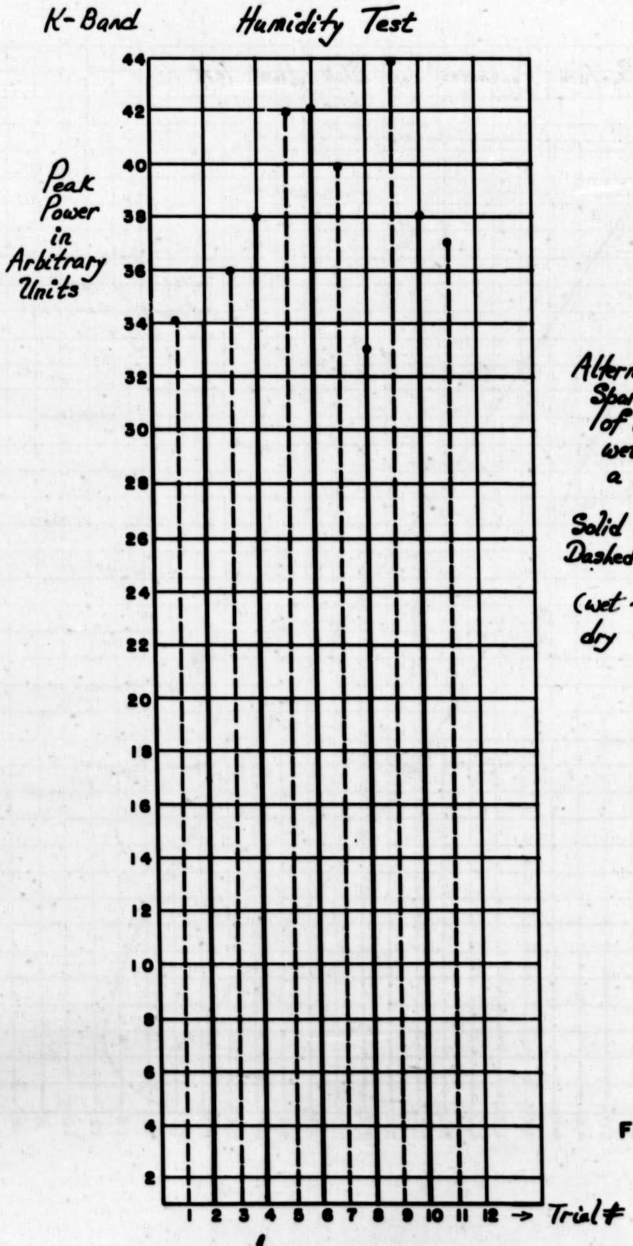

K-Band

Sparking Voltage vs Pres x Gap Width (at 20°c)

Rep Rate 500pps , .25μ

This Paschen Curve valid for gap d~60 mils

FIG. 14



Alternate Sparking of dry and wet air in a Swayback

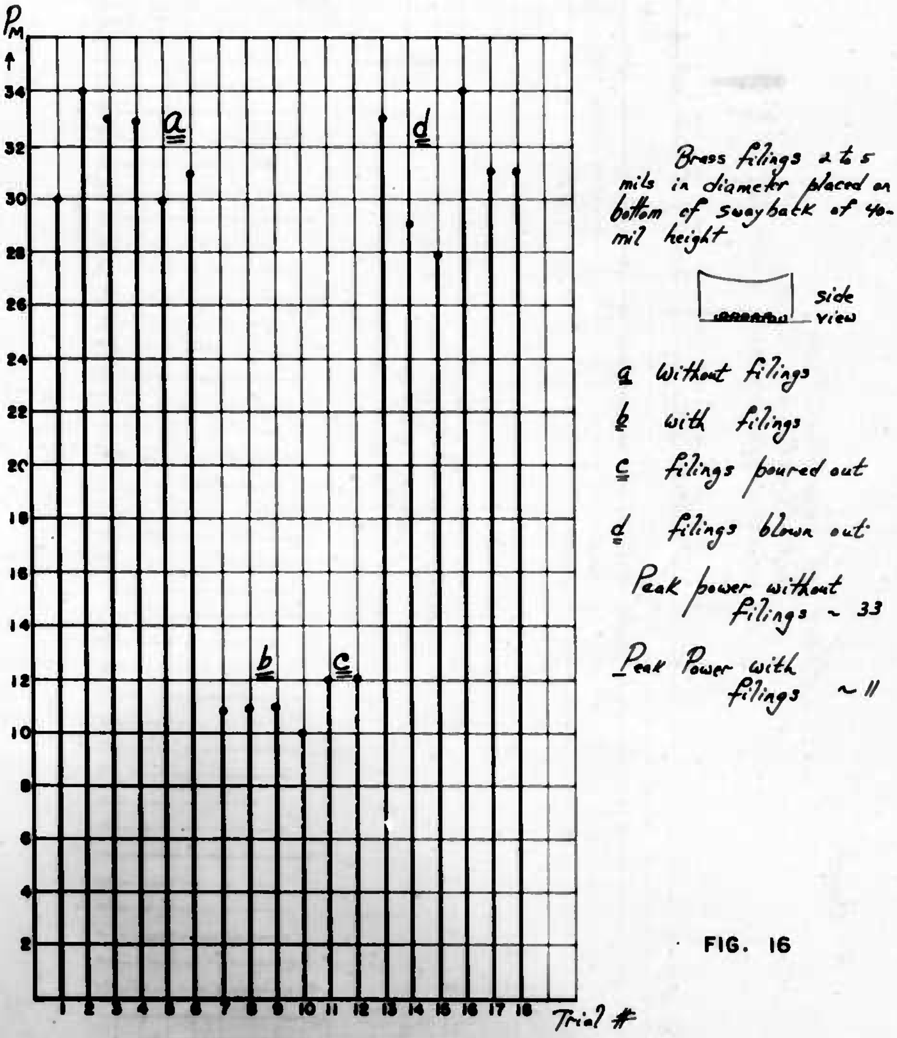
Solid lines: wet air
Dashed lines: dry air

(wet ~ 80% r.h.
dry ~ 10% r.h.)

FIG. 15

K-Band

Surface "Roughness" or Shop-Dust Test



Brass filings 2 to 5 mils in diameter placed on bottom of swayback of 40-mil height

a without filings

b with filings

c filings poured out

d filings blown out

Peak power without filings ~ 33

Peak Power with filings ~ 11

FIG. 16

731

K-Band

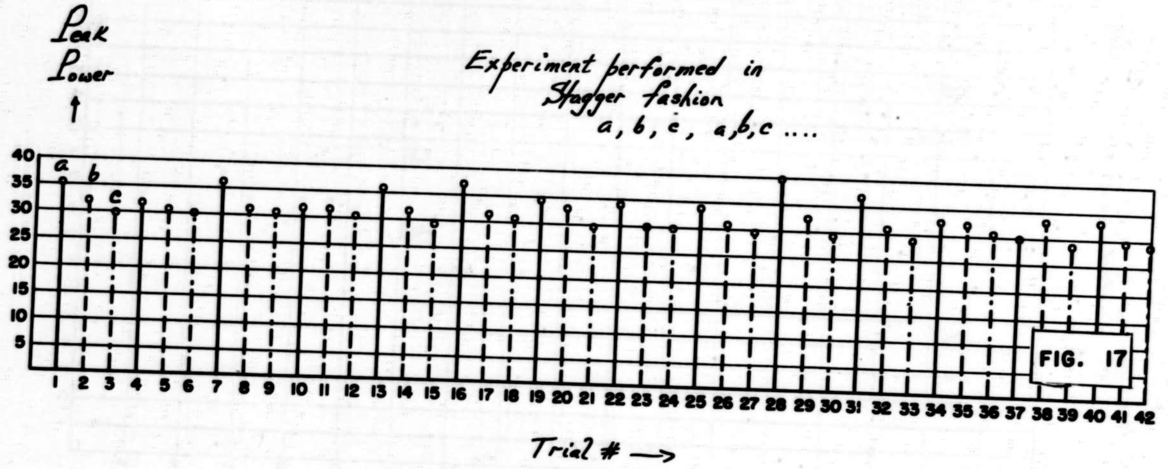
Effect of Repetition Rate
on Peak Breakdown Power
at atmospheric pressure (with C_o^*)

16-mil gap

a : At rep. rate 447
b : " " " 905
c : " " " 1760

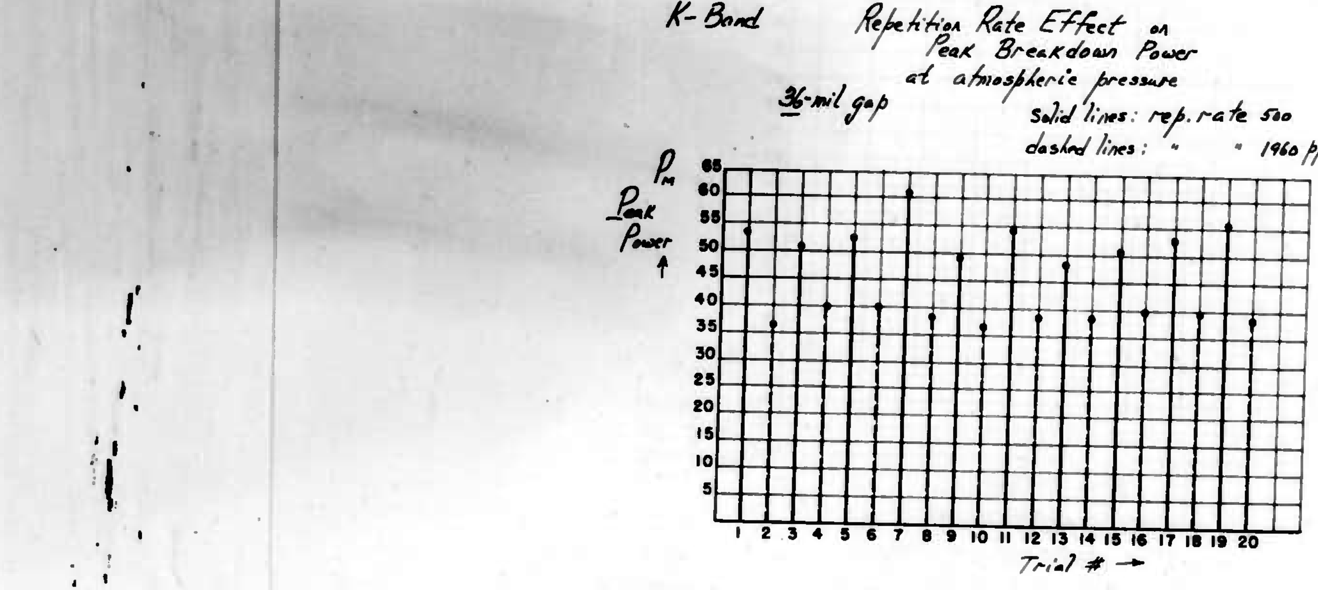
Average of a 34 → 16% higher
" " b 31 → 7% higher
" " c 29 –

If 1760 Taken as base



Experiment performed in
Stagger fashion
a, b, c, a, b, c ....

FIG. 17



Average Lowering
~30%

FIG. 18

K-Band

Effect of Repetition Rate
at atmospheric pressure
59-mil gap

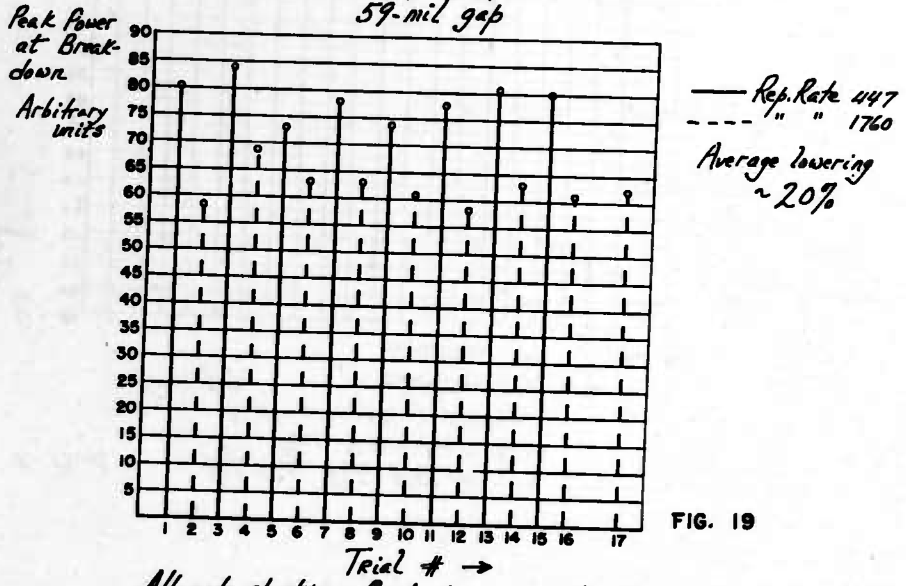


FIG. 19

Alternate sparking - first at one rep. rate, then at the other.

X-Band

Breakdown As a Function of Pressure At 20°C

Above ~ 24 cms Hg the curve is closely parabolic

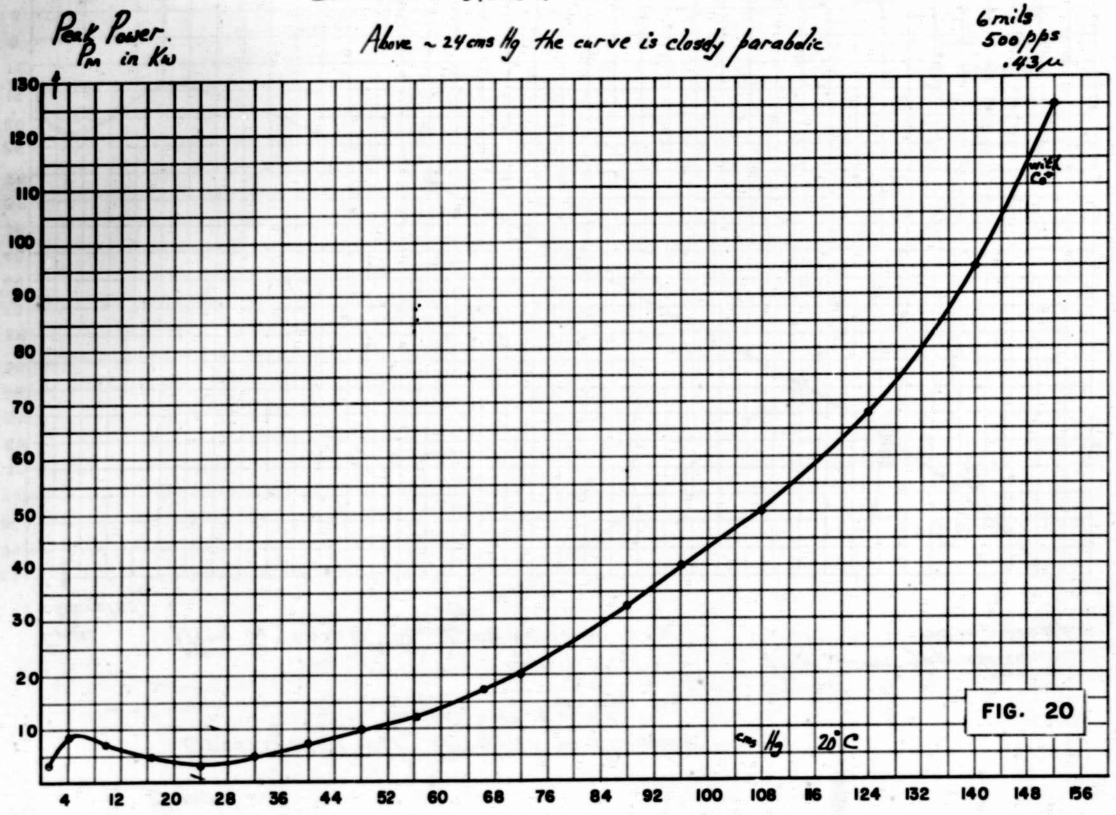


FIG. 20

·X-Band

Breakdown Field Strength vs Pressure
for previous figure

(from $P_M = 6.63 \times 10^{-9} E_M^2 \frac{\lambda_g}{\lambda} ab$)

from 6-mil gap data
.43 μ, 500 p.p.s.

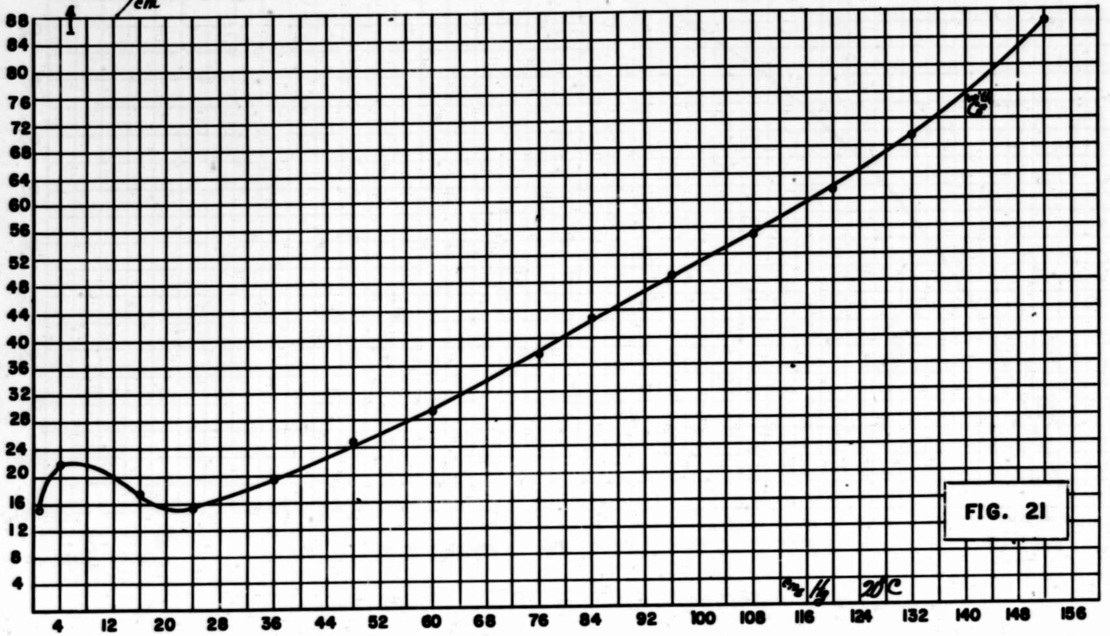


FIG. 21

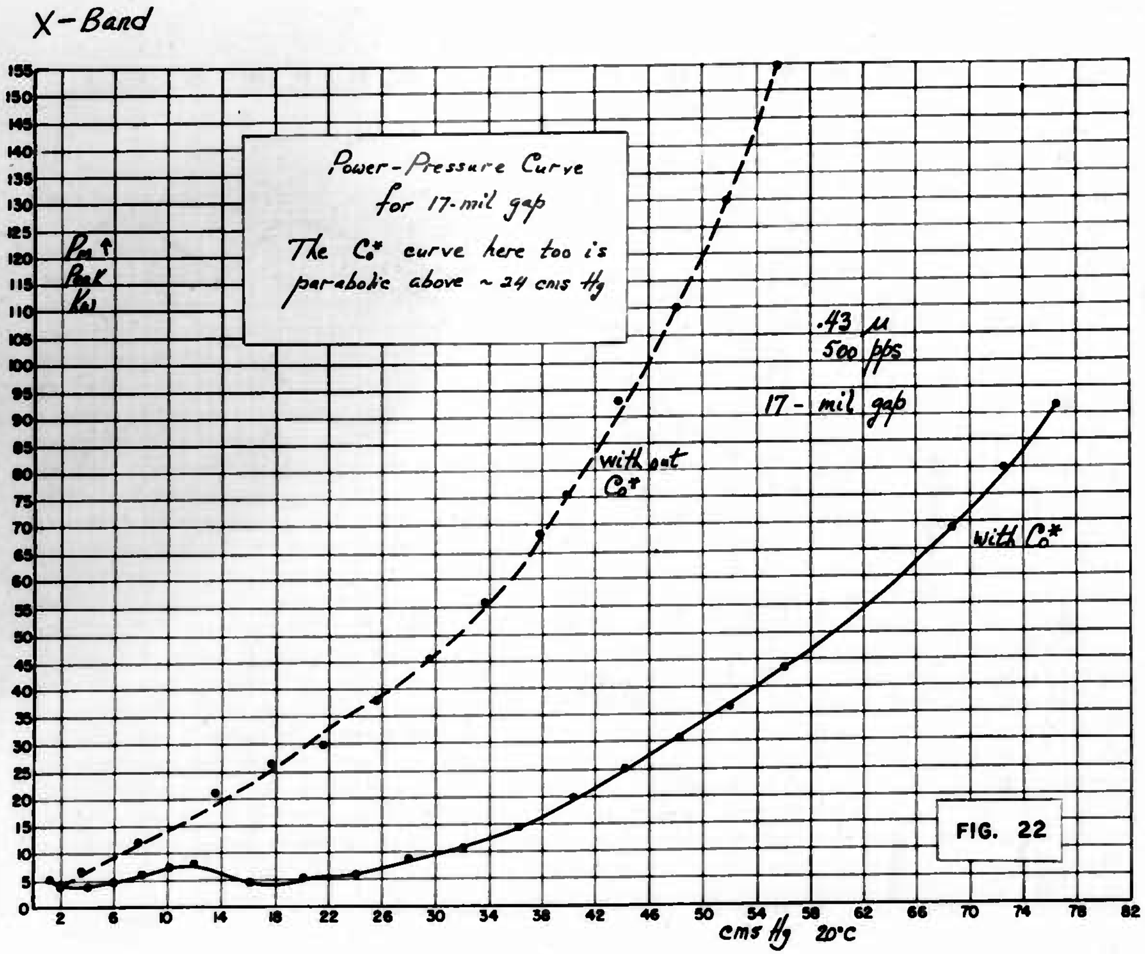

X-Band
Po ↑
Peak
Kw
Power-Pressure Curve
for 17-mil gap
The Co* curve here too is
parabolic above ~ 24 cms Hg
.43 μ
500 pps
17 - mil gap
without Co*
with Co*
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
2
6
10
14
18
22
26
30
34
38
42
46
50
54
58
62
66
70
74
78
82
cms Hg 20°C

FIG. 22

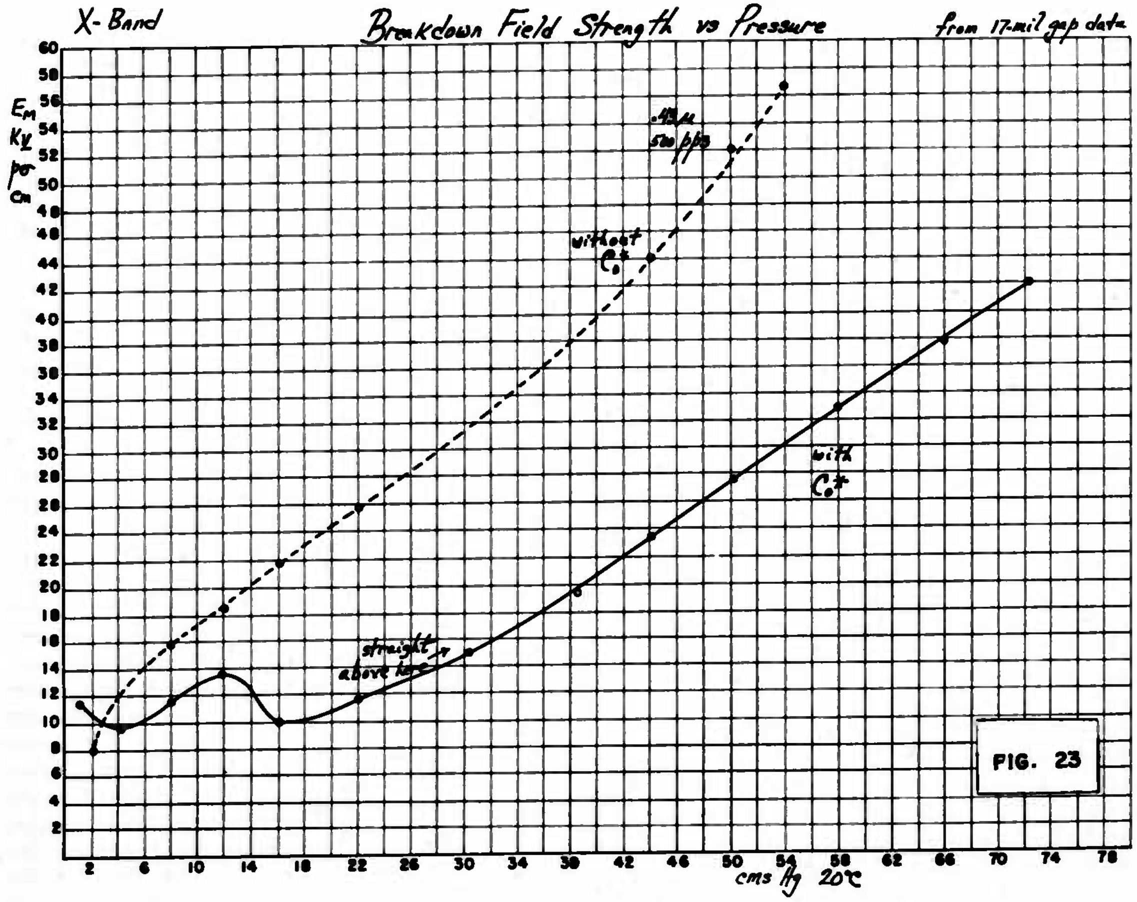

X-Band
Breakdown Field Strength vs Pressure
from 17-mil gap data
Em
kv
per
cm
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
2
6
10
14
18
22
26
30
34
38
42
46
50
54
58
62
66
70
74
78
cms Hg 20°C
.45μ
500 pps
without
C_o^*
with
C_o^*
straight above here

FIG. 23

X-Band Power-Pressure Breakdown Behavior for 38-mil gap. Curve parabolic above ~24cms Hg

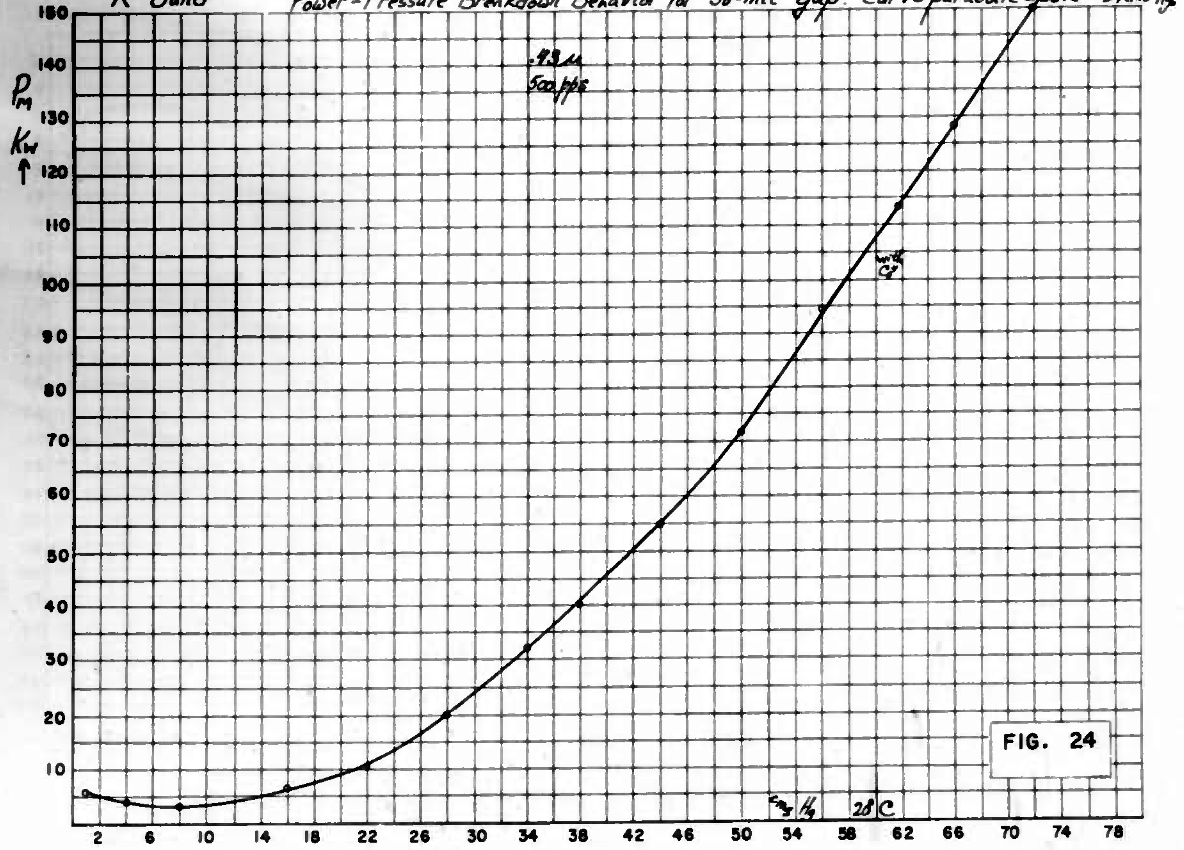


FIG. 24

X-Band

Field Strength vs Pressure From 38-mil gap data

.43μ, 500 p.p.s.

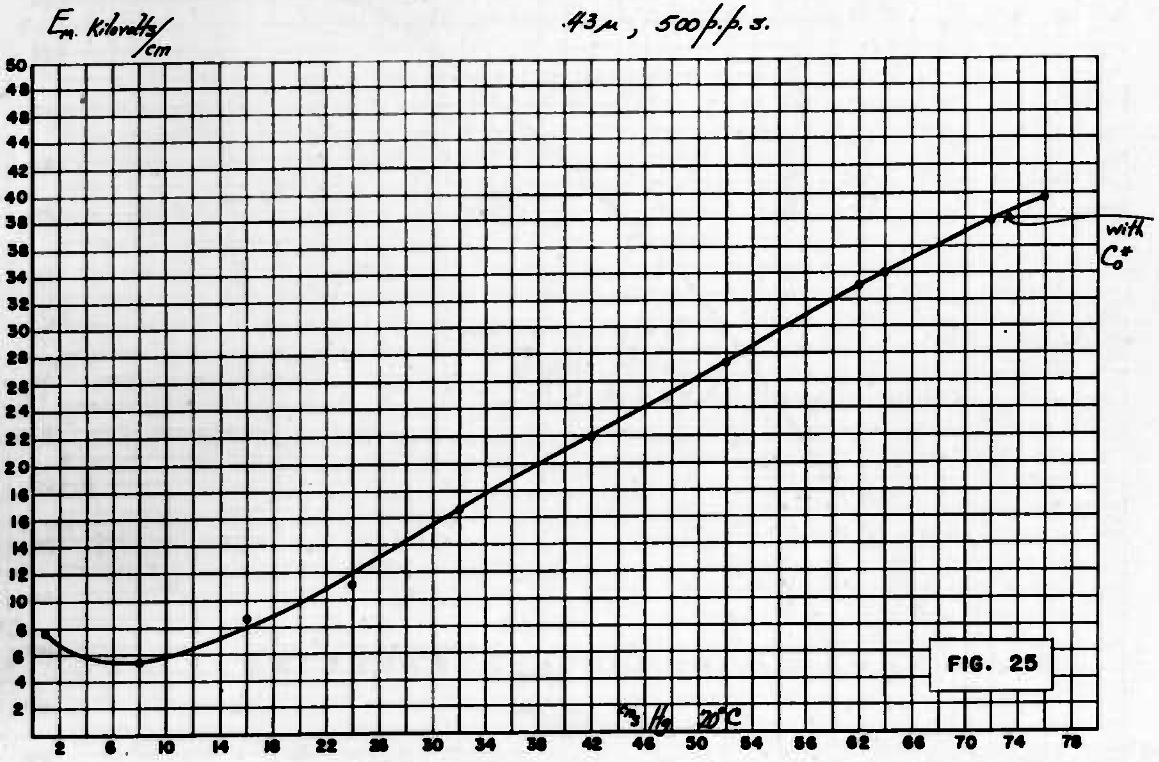


FIG. 25

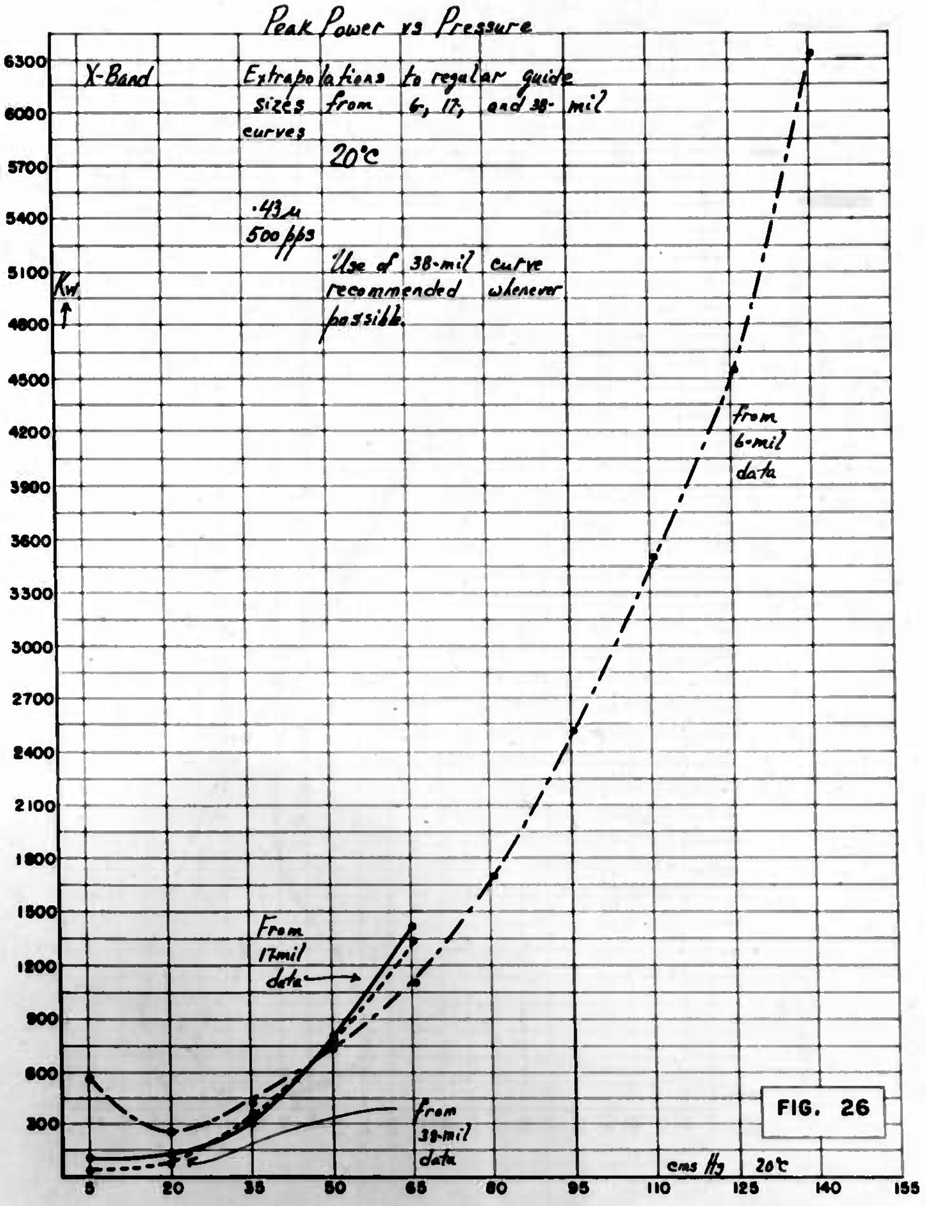

Peak Power vs Pressure
X-Band
Extrapolations to regular guide sizes from 6, 17, and 38-mil curves
20°C
.43 μ
500 pps
Use of 38-mil curve recommended whenever possible.
Kw.
From 17mil data
from 38-mil data
from 6-mil data
cms Hg
20°C
6300
6000
5700
5400
5100
4800
4500
4200
3900
3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
5
20
35
50
65
80
95
110
125
140
155

FIG. 26

2.

X-Band

Field Strength vs Pressure
for 3 gap widths
.43µ, 500 p.p.s.
For use, 38-mil curve is recommended
for any gap width

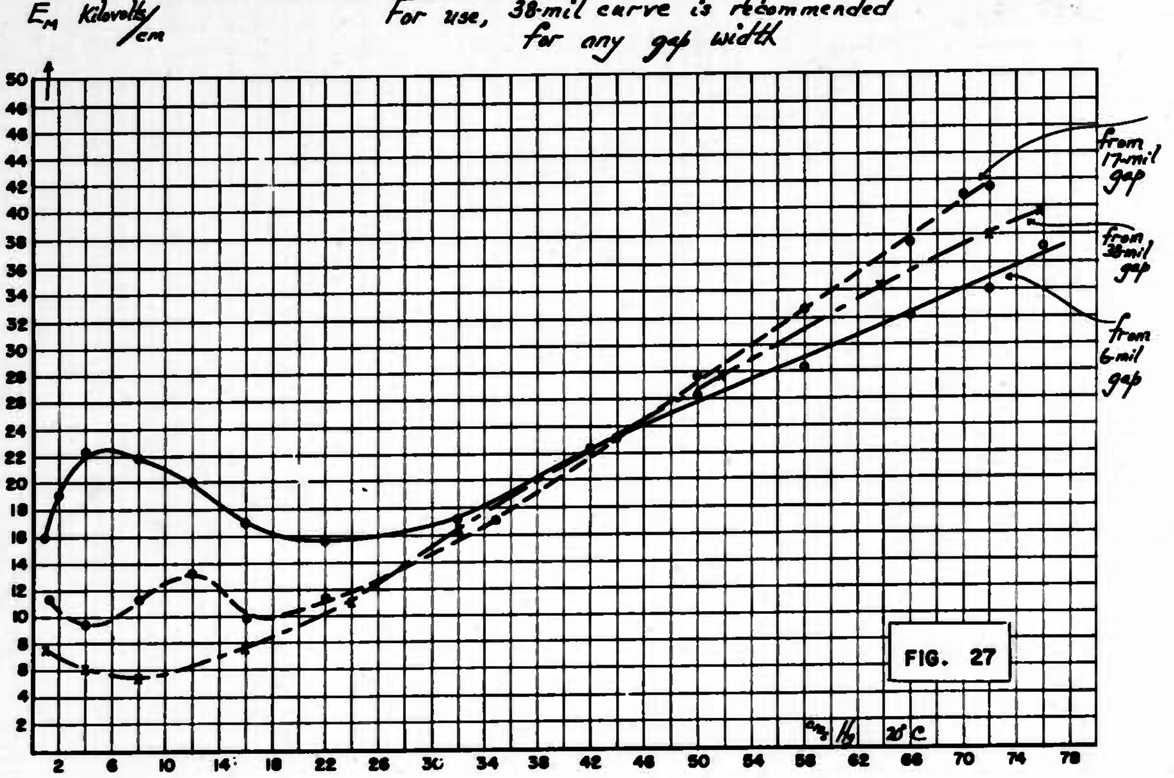


FIG. 27

X-Band

Breakdown Field Strength vs Pressure
Up to 2 Atmospheres . .43 u, 500 p.p.s.
From 6-mil gap data
Below 76 cms Hg it is recommended
that results from 38-mil curve be used.

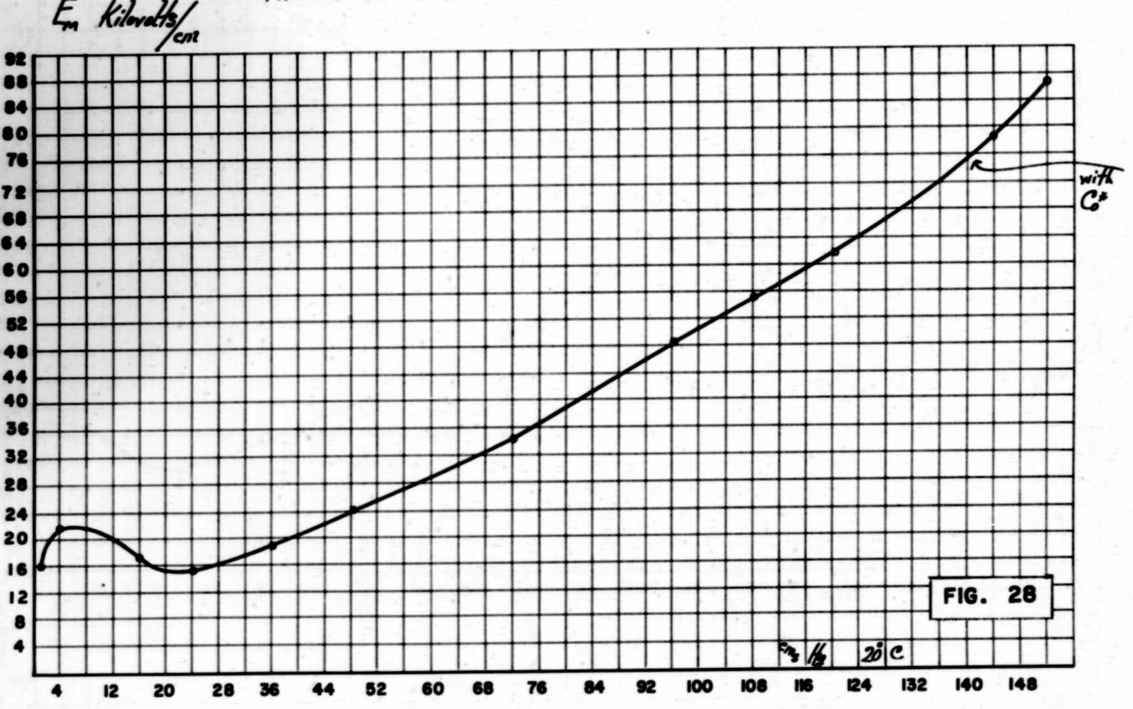


FIG. 28

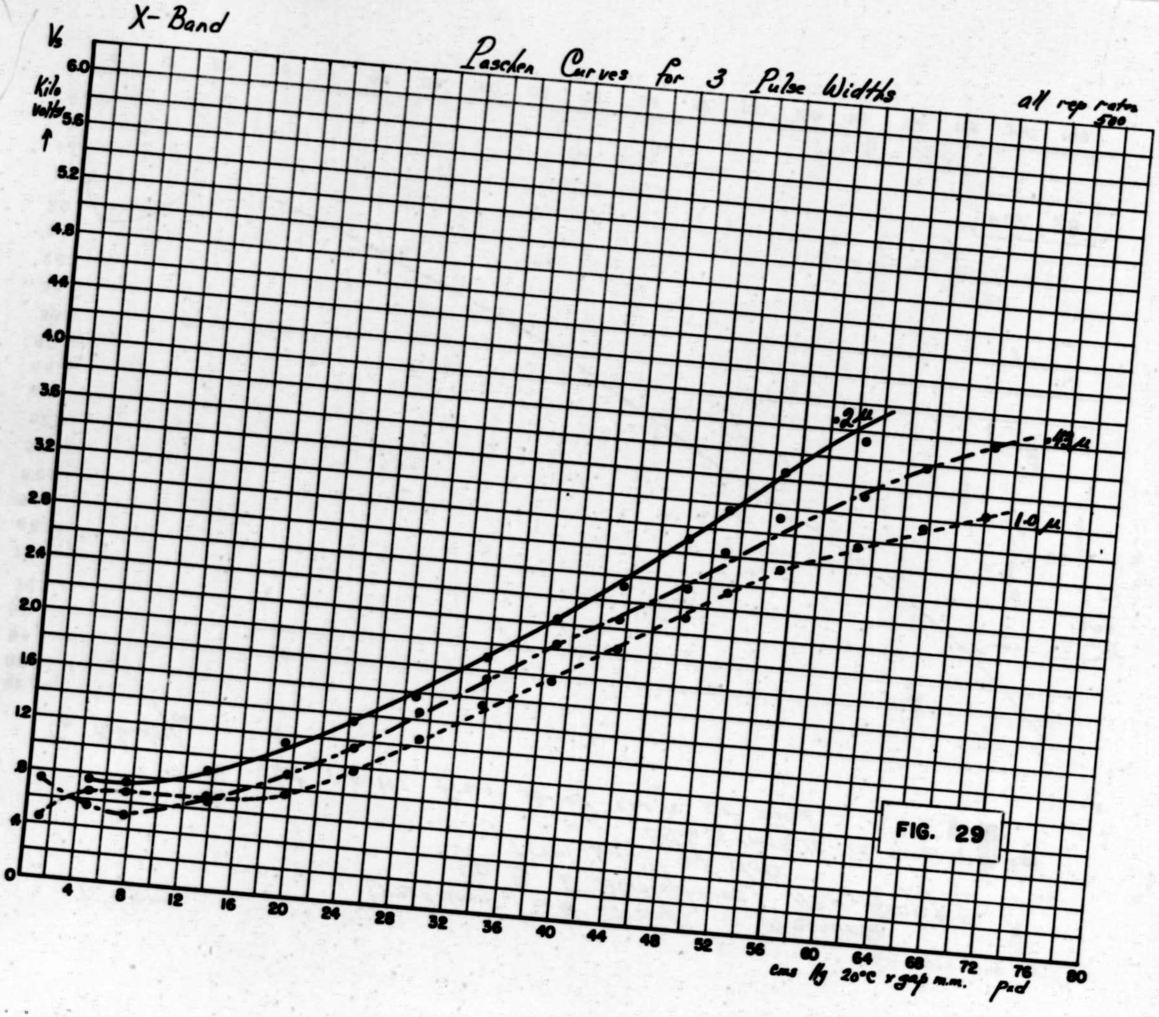

X- Band
Paschen Curves for 3 Pulse Widths
all rep rates 500
Vs
Kilo Volts
↑
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
.8
.4
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
cms Hg 20°C × gap m.m.
Pxd
.2 μ
.43 μ
1.0 μ

FIG. 29

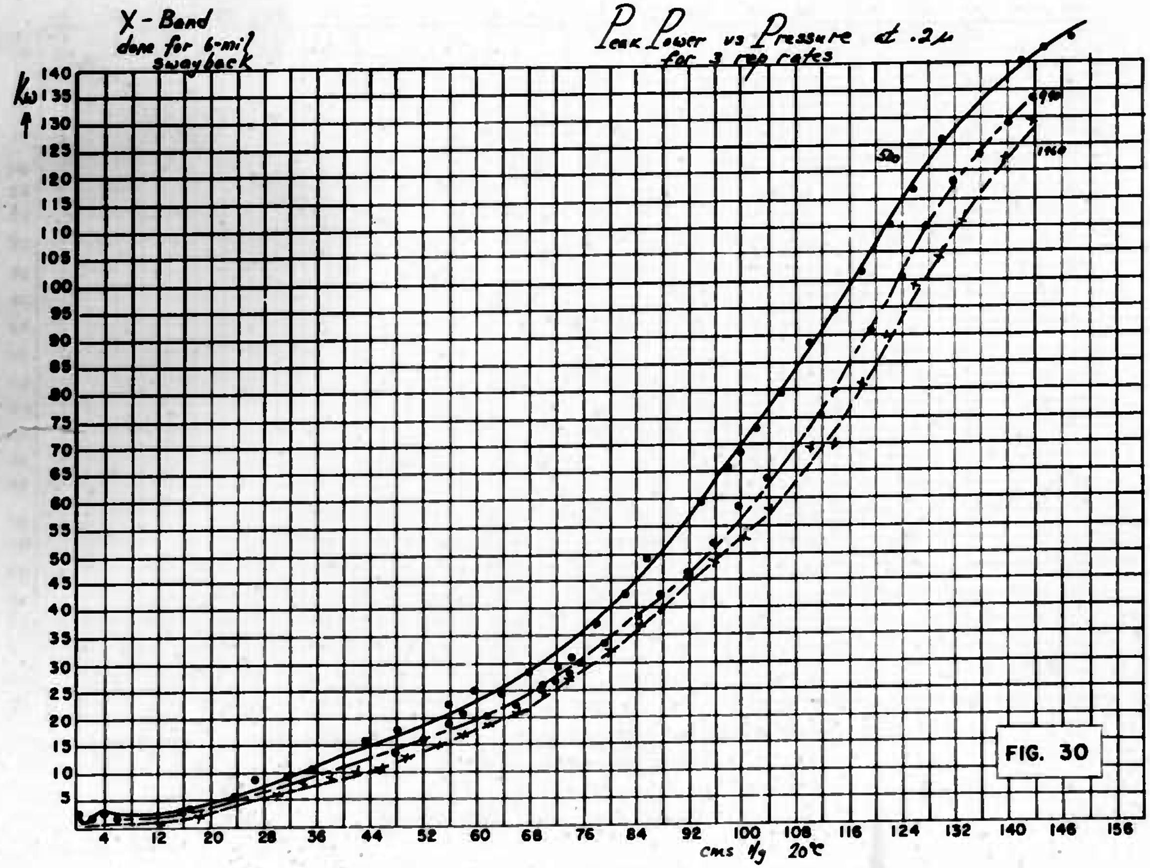

X - Band
done for 6-mil
swayback
Peak Power vs Pressure at .2μ
for 3 rep rates
Kw
140
135
130
125
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
4
12
20
28
36
44
52
60
68
76
84
92
100
108
116
124
132
140
146
156
cms Hg 20°C
500
990
1960

FIG. 30

X-Band

Breakdown Field Strength
vs Pressure
For 3 Different Rep. Rates
All curves at .2 μ ; from 6-mil swayback data

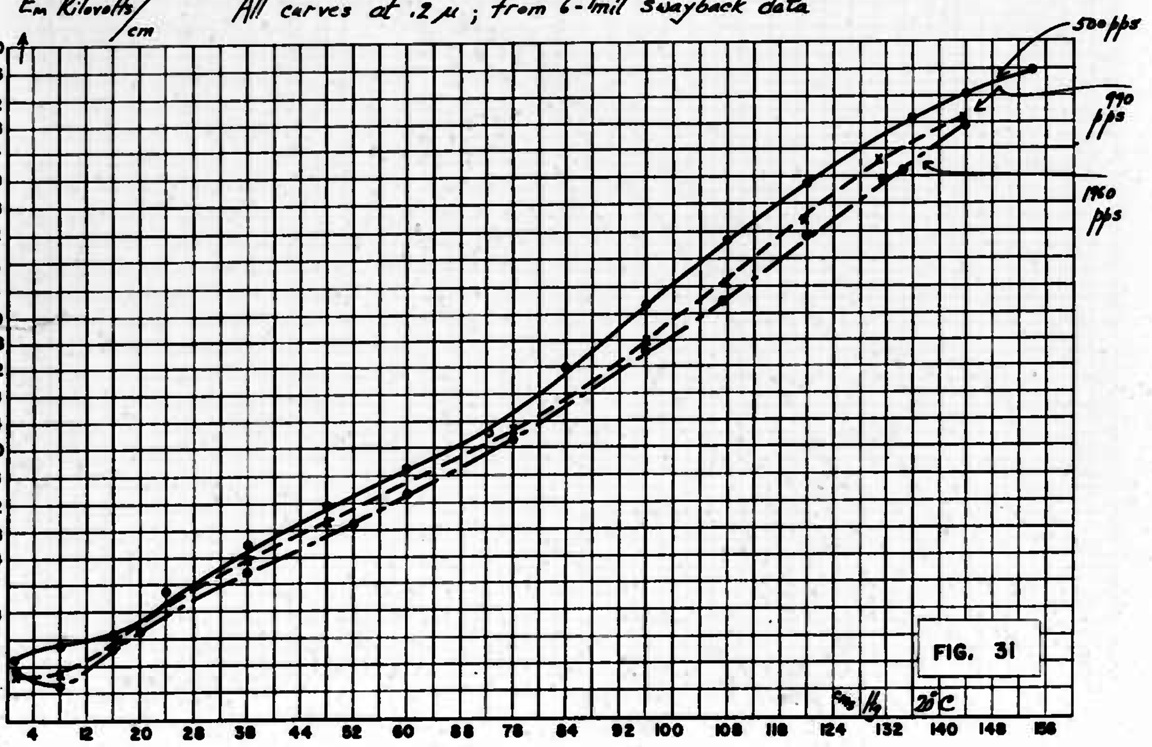


FIG. 31

X-Band

Breakdown Power vs Pressure Up to 2 Atmospheres
For 2 Different Rep. Rates
at a pulse of 1 μ sec

Data for 6-mil gap

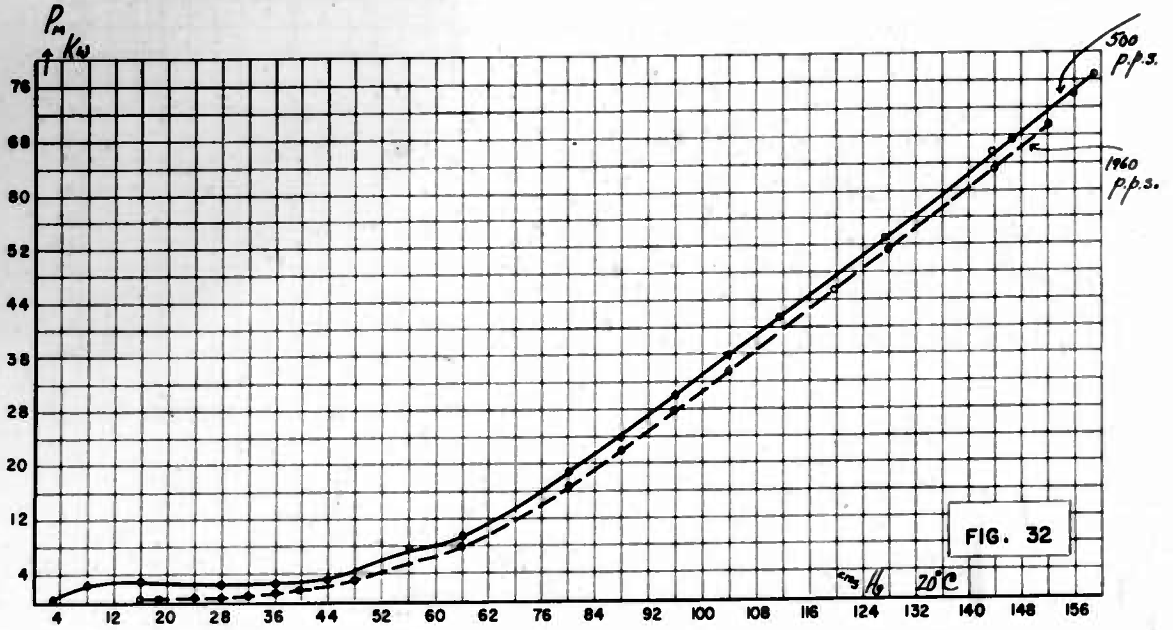


FIG. 32

X-Band

Breakdown Field Strength vs Pressure
Up to 2 Atmospheres. Pulse 1 μ sec, 500 p.p.s.

From 6-mil gap data, but valid for any gap for pressure above ~ 24 cms Hg
See curves for other gaps

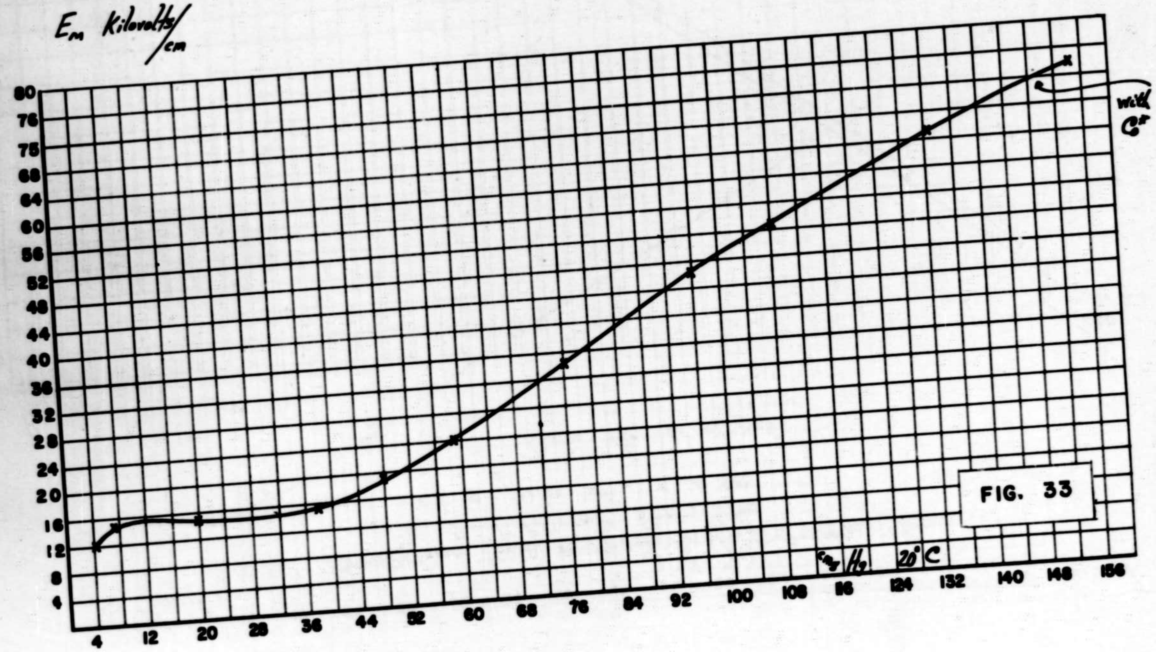


FIG. 33

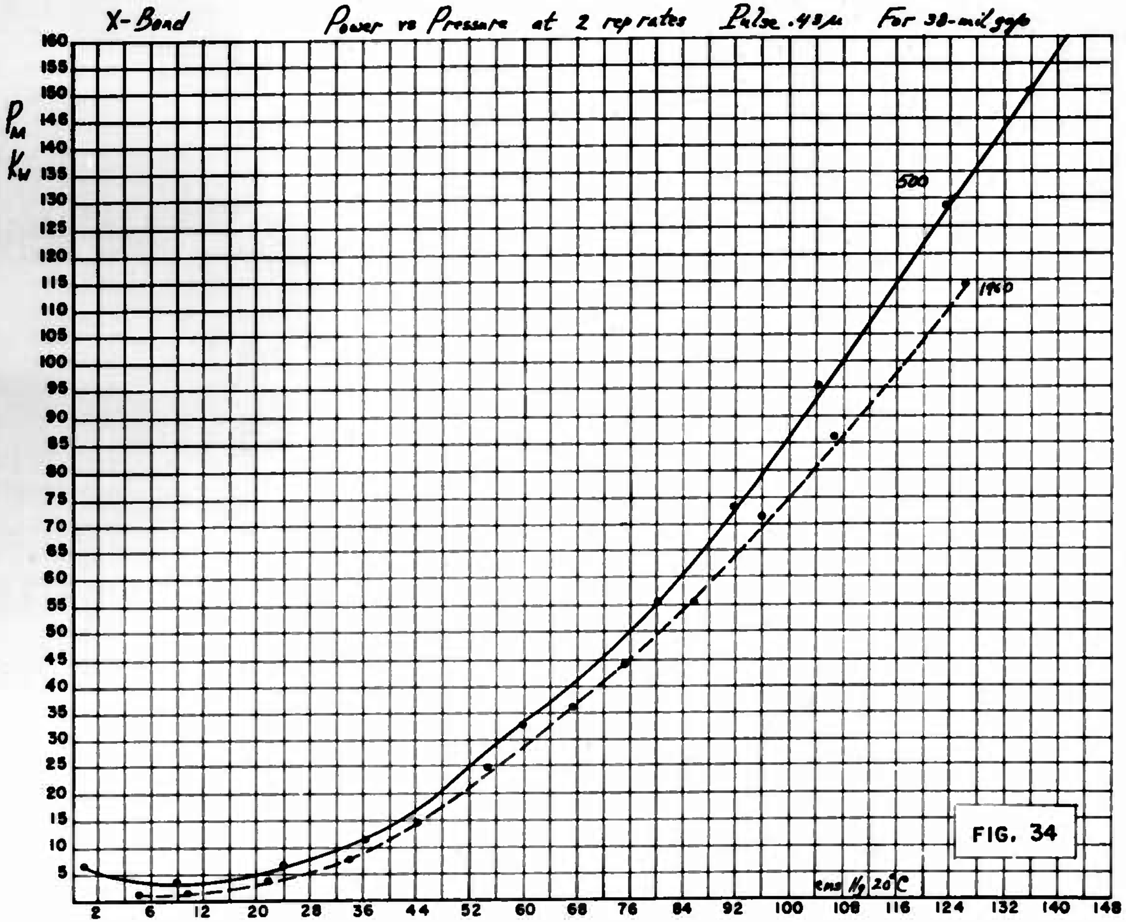

X-Band
Power vs Pressure at 2 rep rates Pulse .43μ For 38-mil gap
P_M
KW
160
155
150
145
140
135
130
125
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
500
1960
cms Hg 20°C
2
6
12
20
28
36
44
52
60
68
76
84
92
100
108
116
124
132
140
148

FIG. 34

X-Band
500 pps

Effect of Pulse Width
at atmospheric pressure
20°C
For 6-mil gap

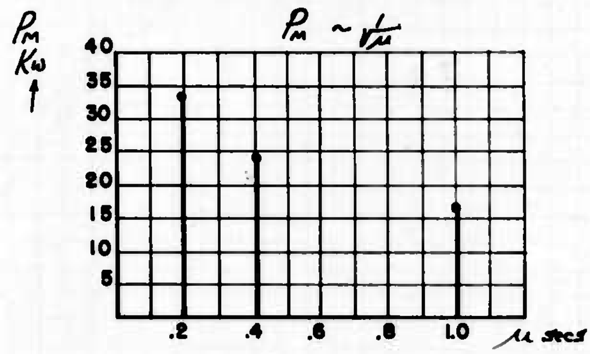


FIG. 35

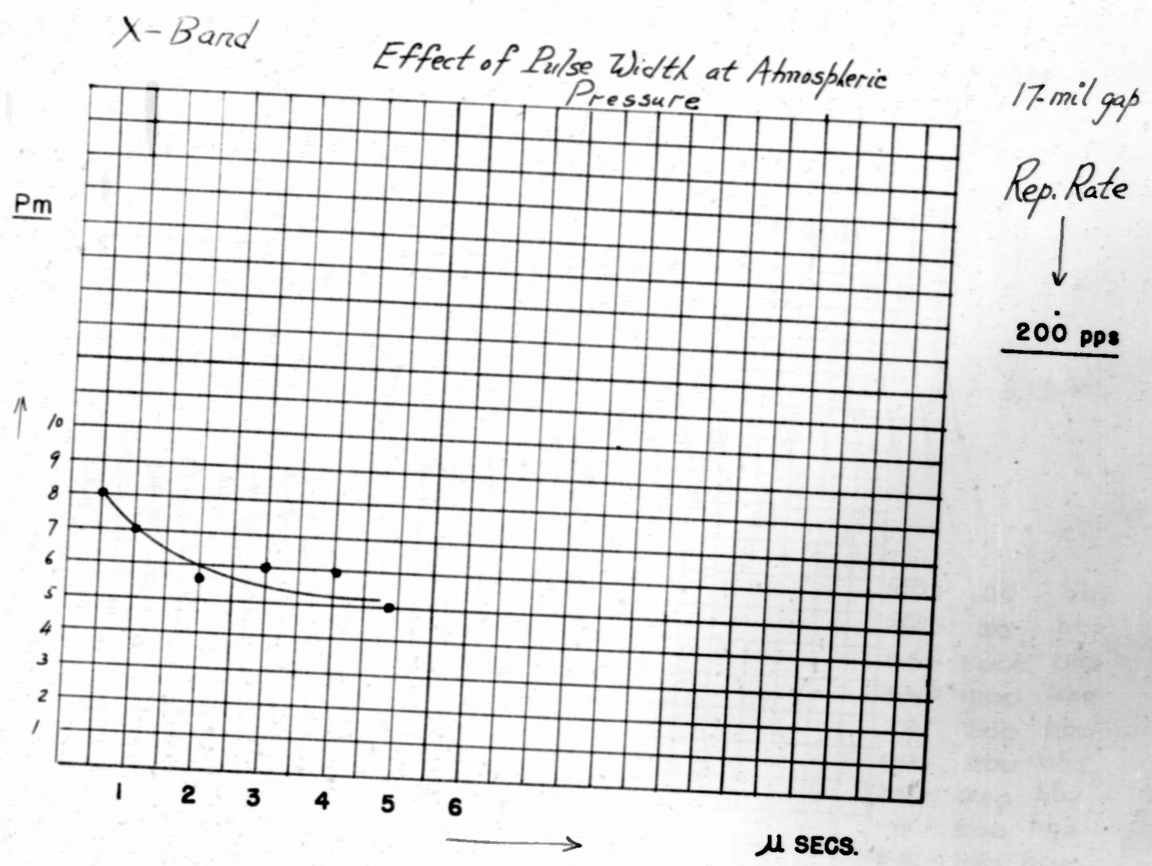
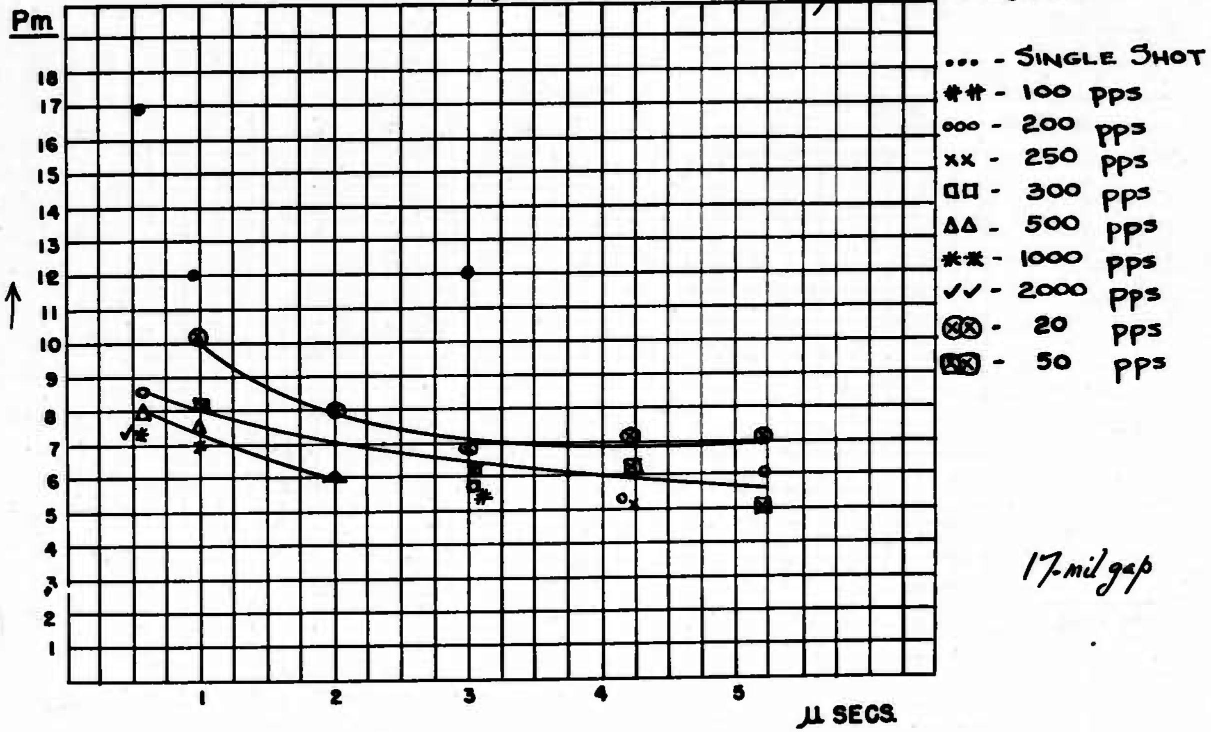

X-Band
Effect of Pulse Width at Atmospheric Pressure
17-mil gap
Rep. Rate
200 pps
Pm
1
2
3
4
5
6
7
8
9
10
1
2
3
4
5
6
µ SECS.

FIG. 36 a

X-Band Lowering of Breakdown Power With Increasing Pulse Width For a Number of Repetition Rates:



17-mil gap

FIG. 36b

X-Band

Peak Power as a Function of Pulse Width
Atmospheric Pressure, and a Rep. Rate of

100 pps

17-mil gap

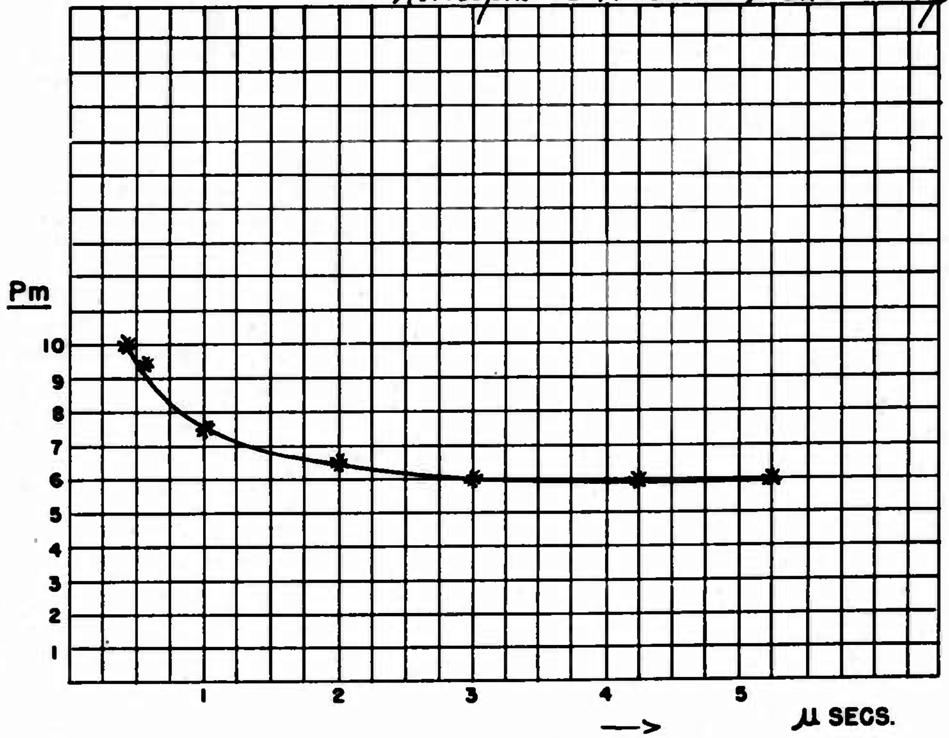
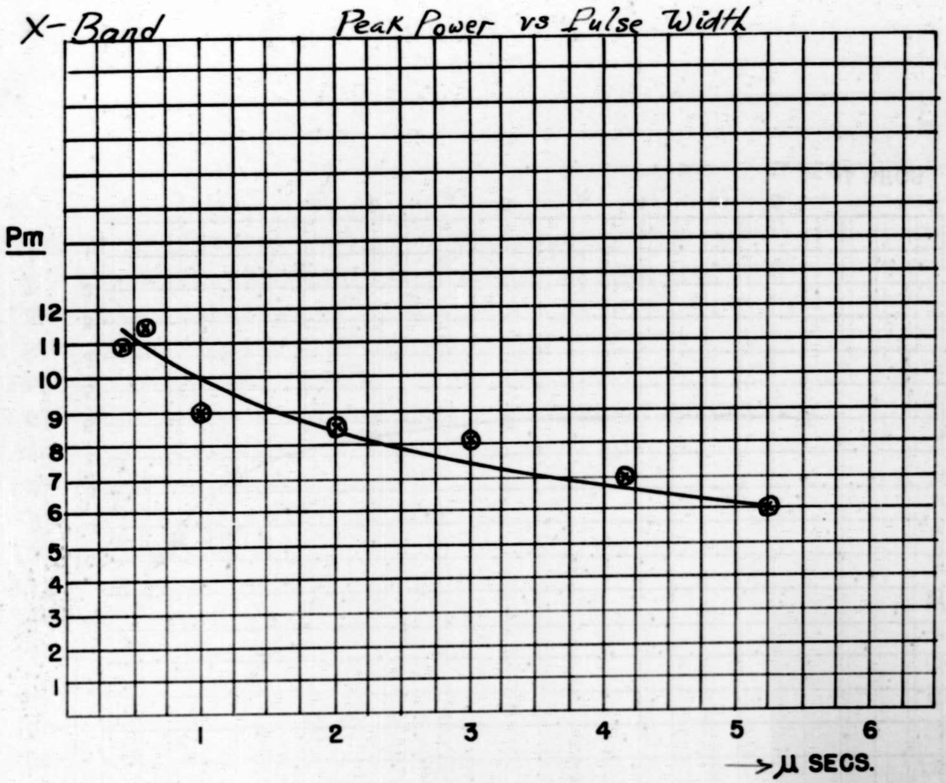


FIG. 36c



Rep. Rate
↓
20 pps

17-mil gap

A single run

FIG. 36 d

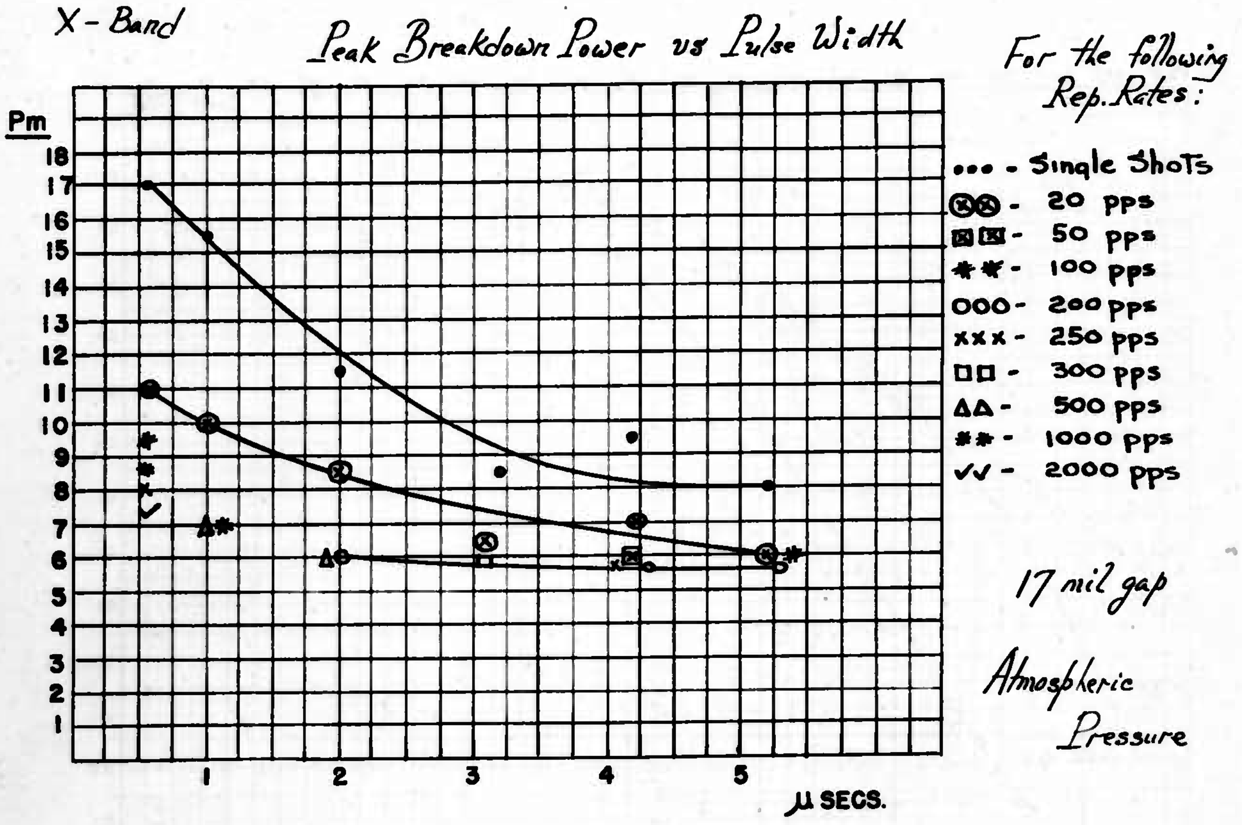
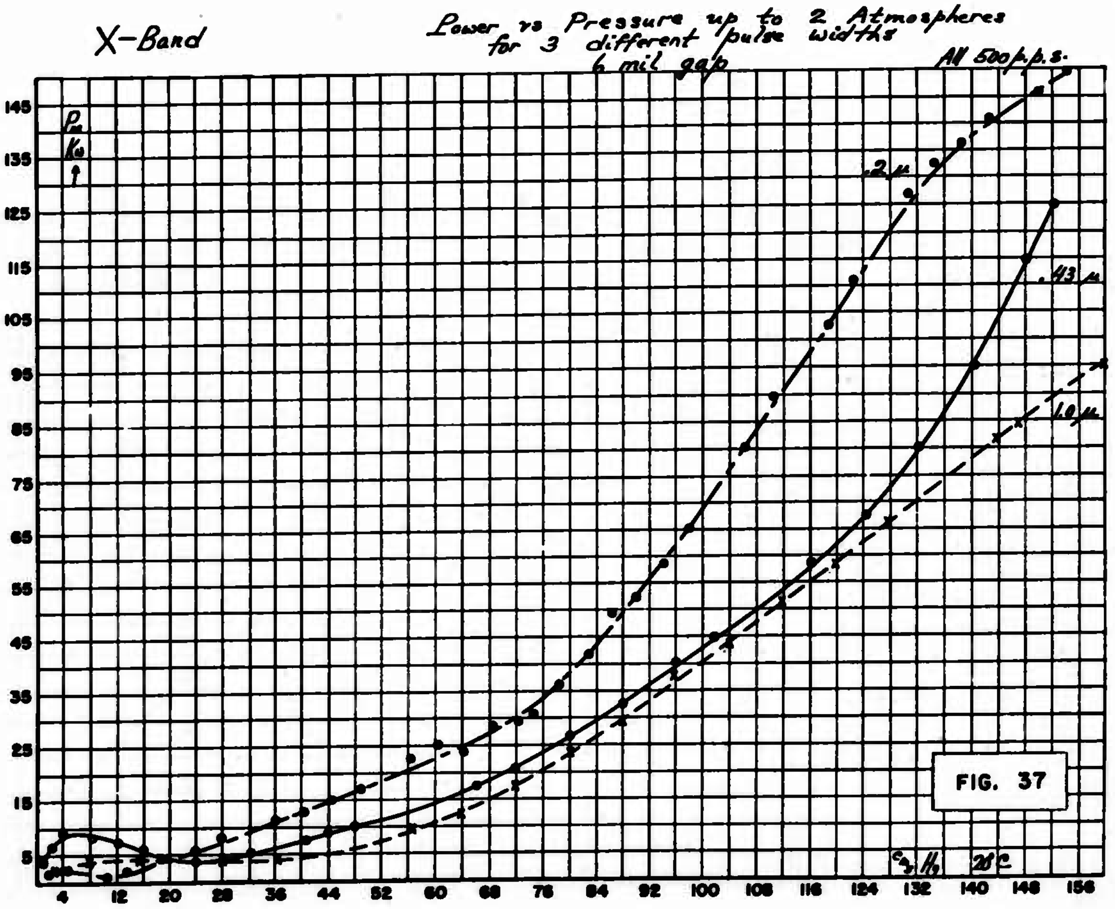

X - Band
Peak Breakdown Power vs Pulse Width
For the following Rep. Rates:
••• - Single Shots
⊗⊗ - 20 pps
⊠⊠ - 50 pps
✱✱ - 100 pps
○○○ - 200 pps
xxx - 250 pps
□□ - 300 pps
ΔΔ - 500 pps
- 1000 pps
✓✓ - 2000 pps
17 mil gap
Atmospheric Pressure
Pm
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
1
2
3
4
5
μ SECS.

FIG. 36 e



X-Band
Power vs Pressure up to 2 Atmospheres for 3 different pulse widths
6 mil gap
All 500 p.p.s.
P_m Kw ↑
145
135
125
115
105
95
85
75
65
55
45
35
25
15
5
4
12
20
28
36
44
52
60
68
76
84
92
100
108
116
124
132
140
148
156
.2 μ
.43 μ
1.0 μ
C_3H_8 28 C

FIG. 37

X-Band

Field Strength vs Pressure Up to 2 Atmospheres
for 3 different pulse widths

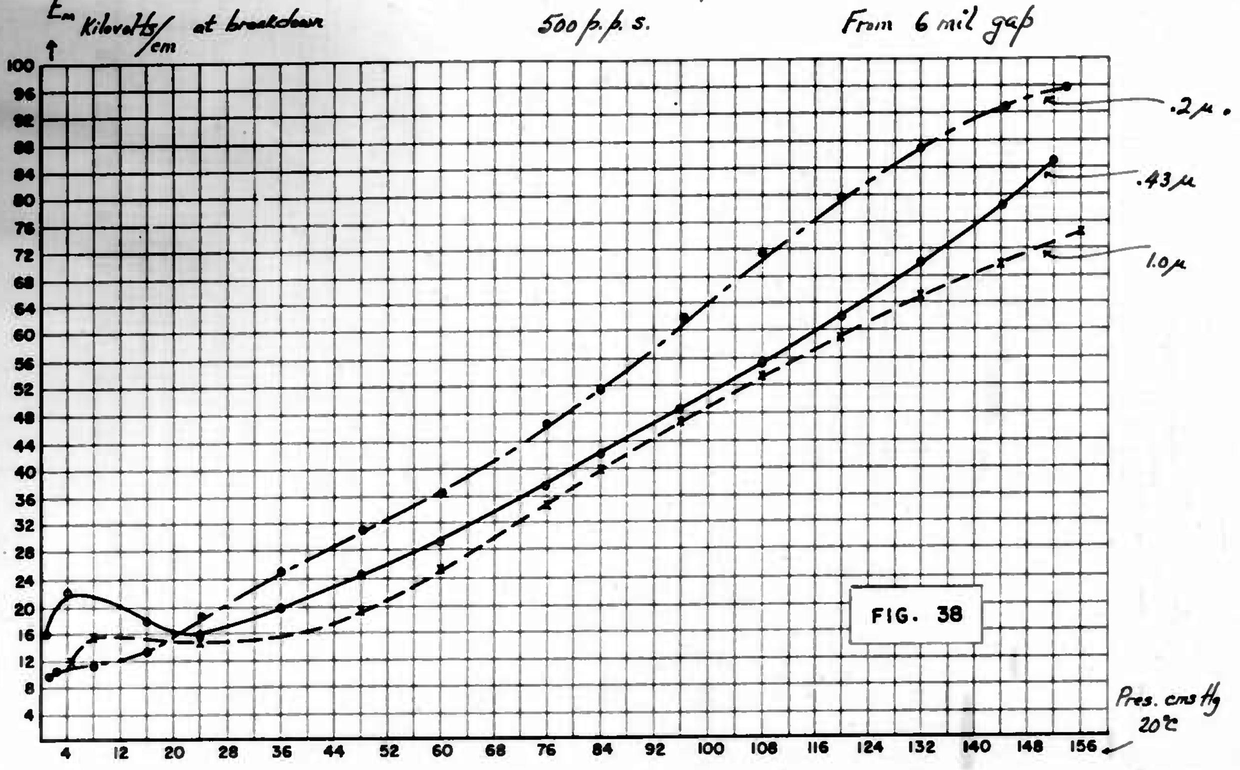


FIG. 38

X-Band

Power vs Pressure for
3 different pulse widths

For 17 mil gap

500 pps

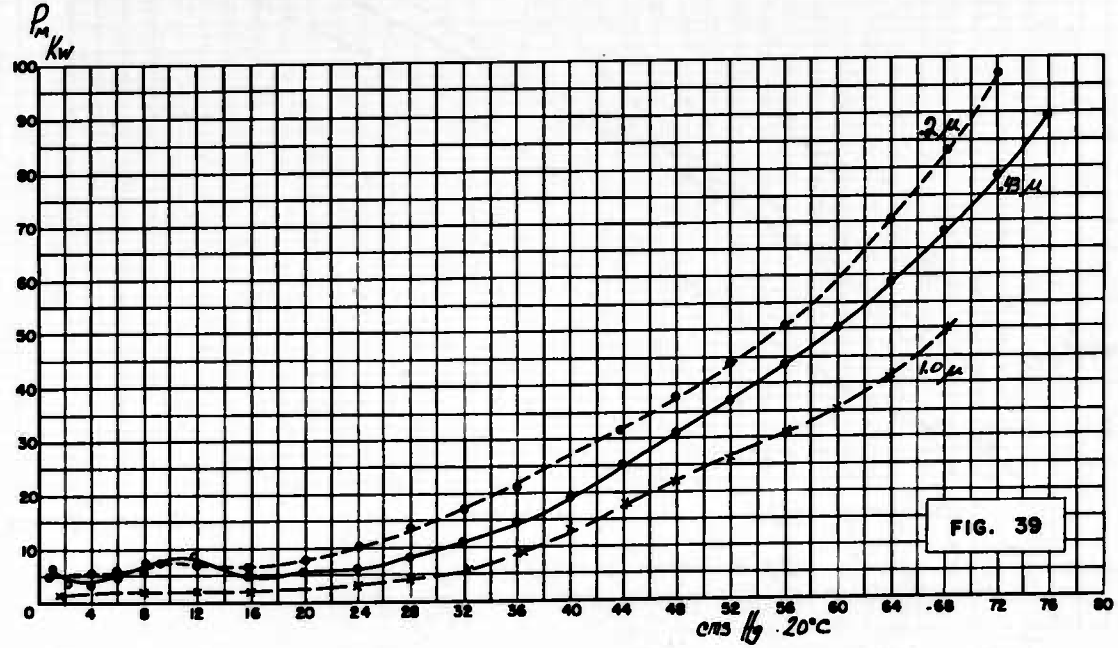


FIG. 39

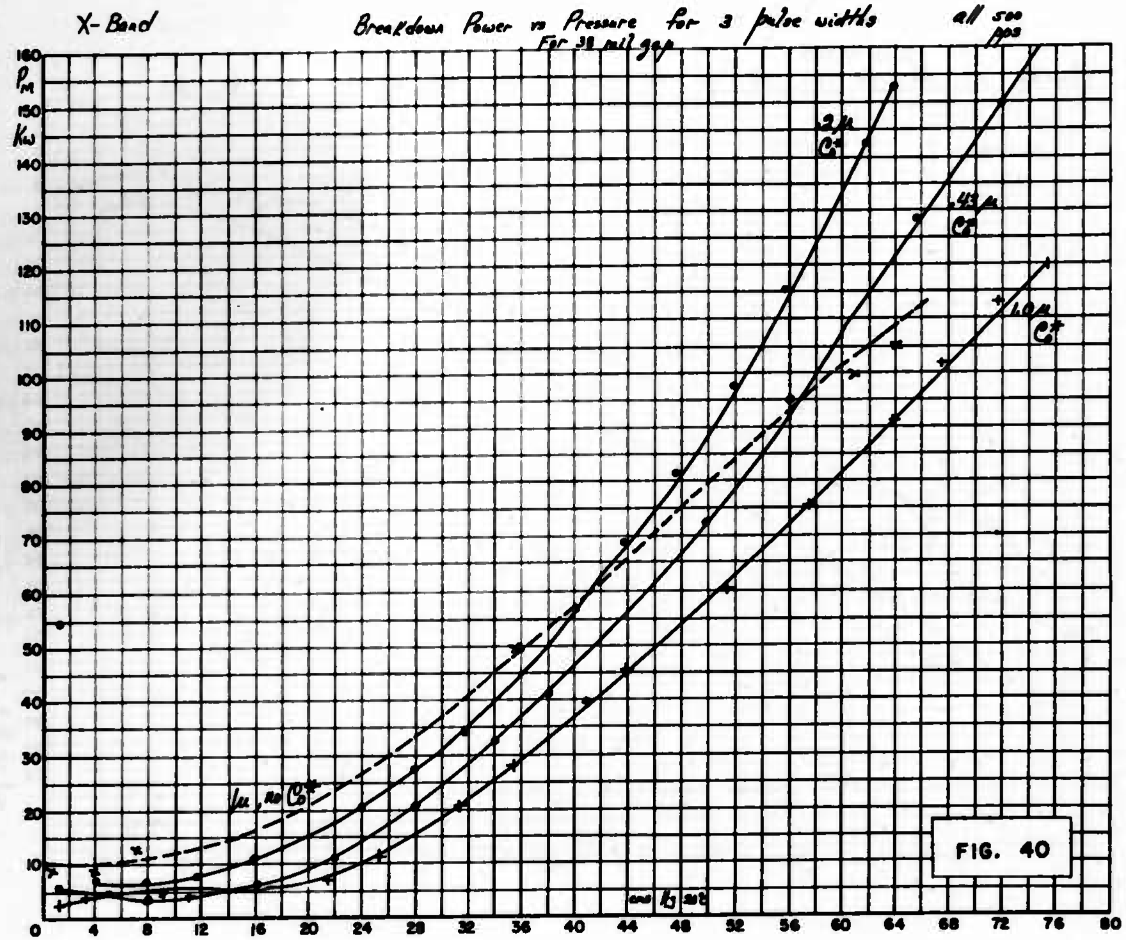
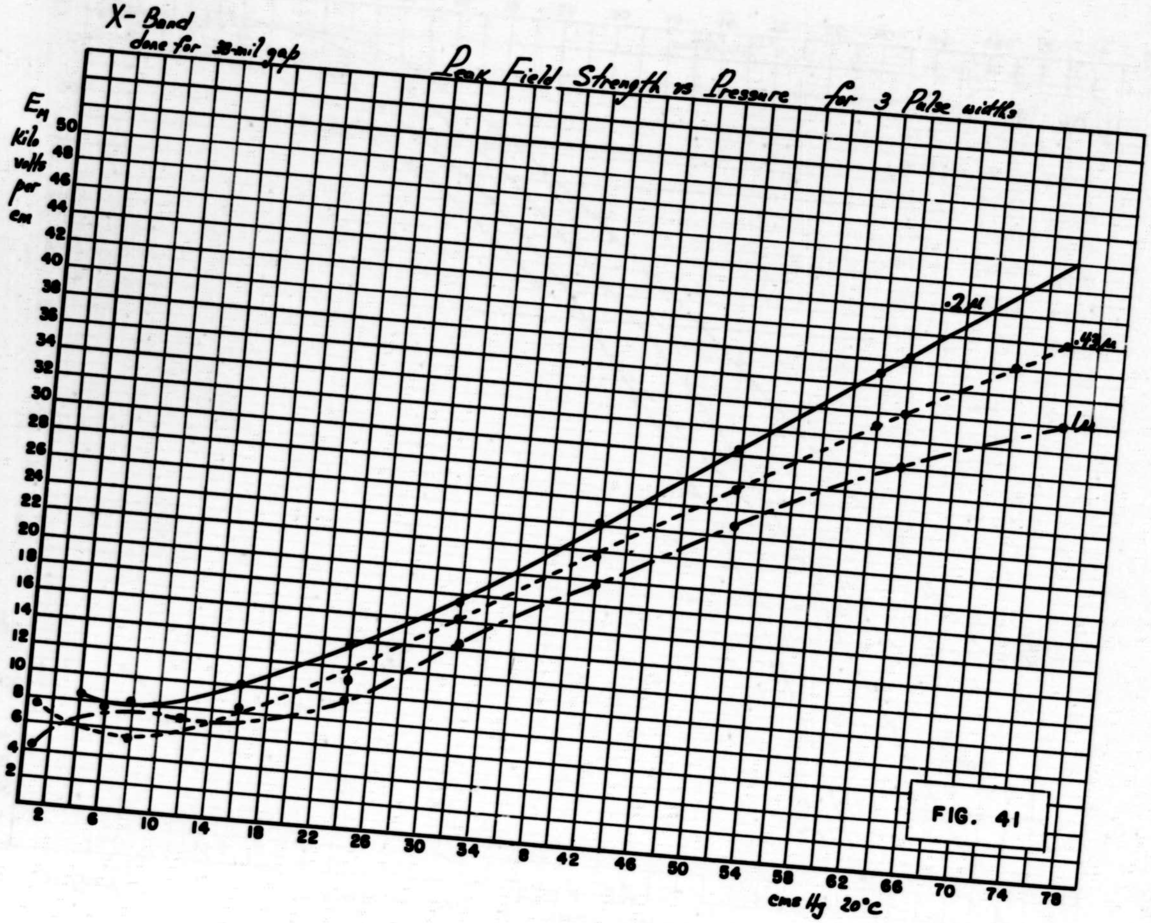

X-Band
Breakdown Power vs Pressure for 3 pulse widths
For 38 mil gap
all 500 pps
P_M
Kw
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
mm Hg
.2μ C_0^+
.43μ C_0^+
1.0μ C_0^+
1μ, no C_0^+

FIG. 40



Peak Field Strength vs Pressure for 3 Pulse widths

FIG. 41

X-Band done for 38-mil gap
Fo regular X size multiply by $\left(\frac{400}{38}\right)$ → perhaps not too risky

Peak Power at Breakdown vs Pressure for a number of rep rates and pulse widths.

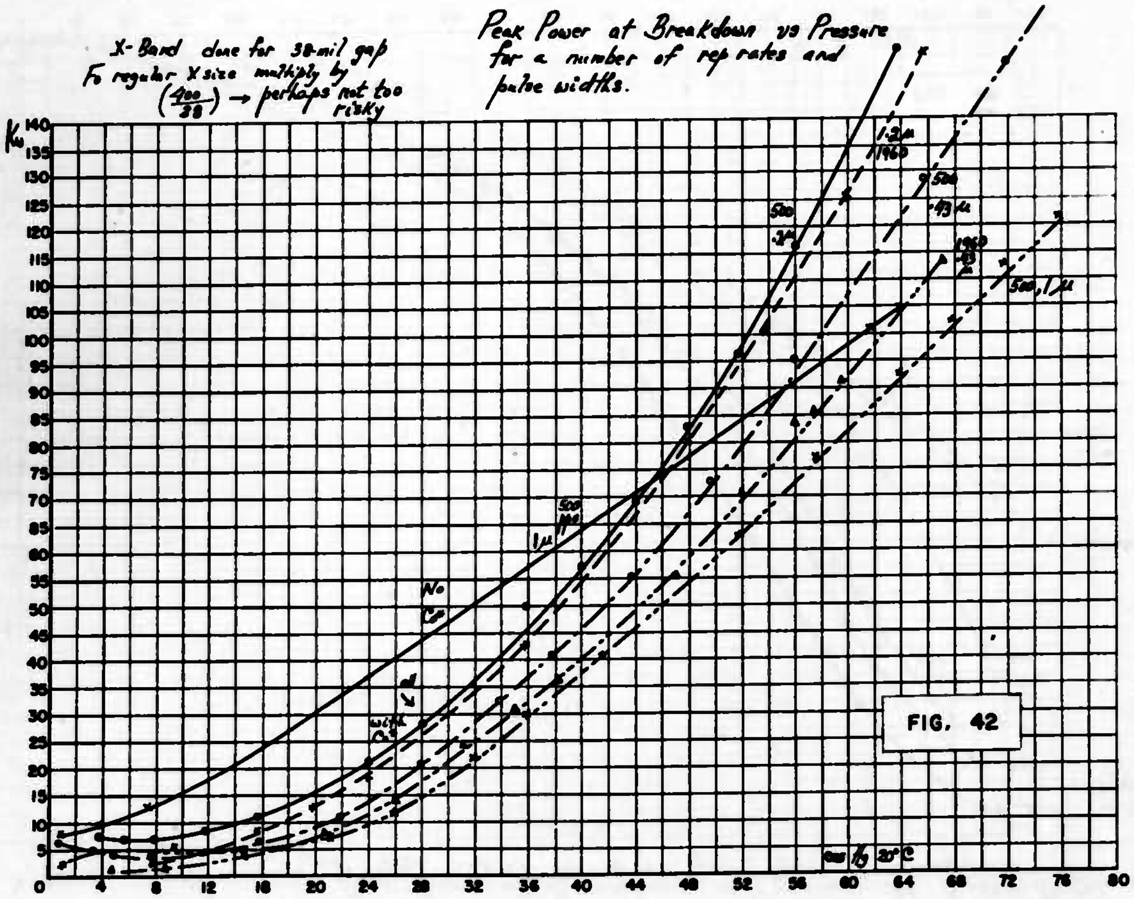


FIG. 42

X-Band

Peak Power at Breakdown vs Pressure At 3 Rep. Rates, and Pulse Widths for 6-mil gap; Up to 2 Atmospheres

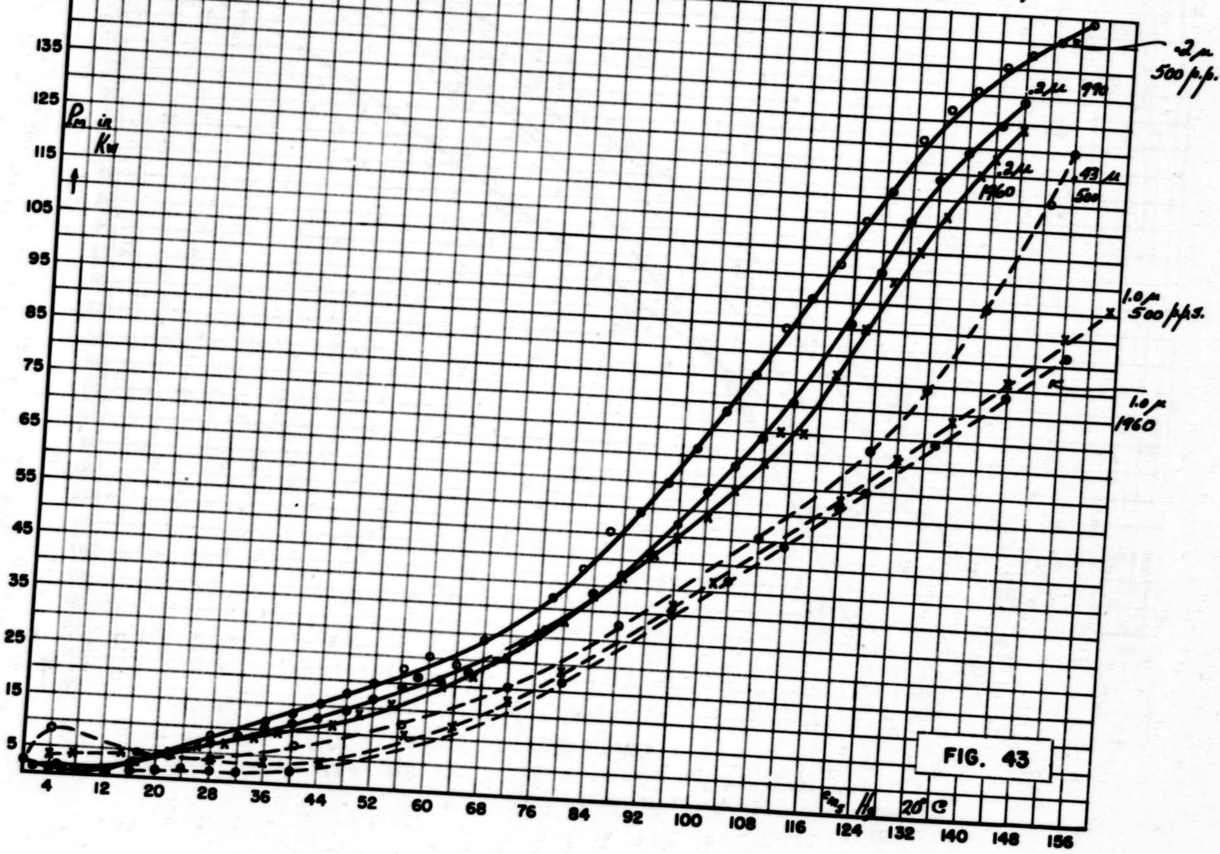


FIG. 43

X-Band

Field Strength vs Pressure, For Various Rep. Rates
and Pulse Widths
Up to 2 Atmospheres
From 6-mil gap Curves of Previous Figure

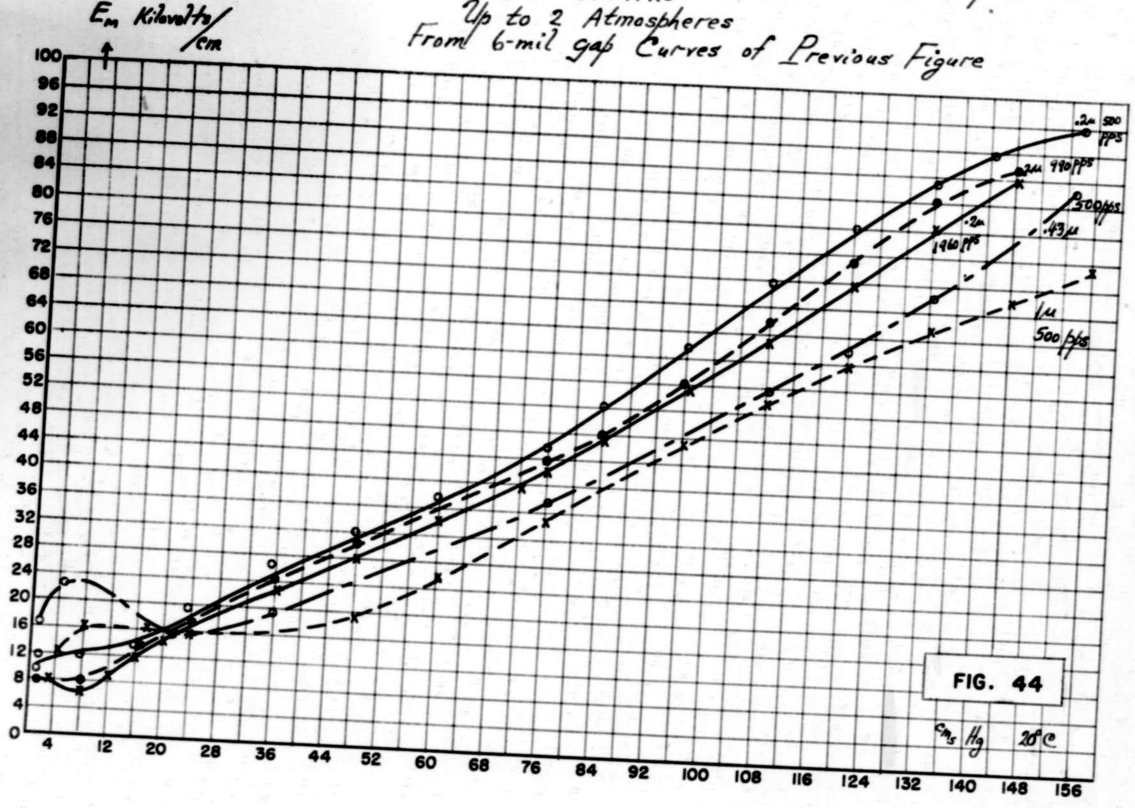


FIG. 44

S-Band

Peak Field vs Pressure

This curve is derived from that of the Power - Pressure by means of

$P_m = 6.63 \times 10^{-4} E_m^2 \frac{\lambda_0}{\lambda_g} ab$ P_m in watts, E_m in volts/cm

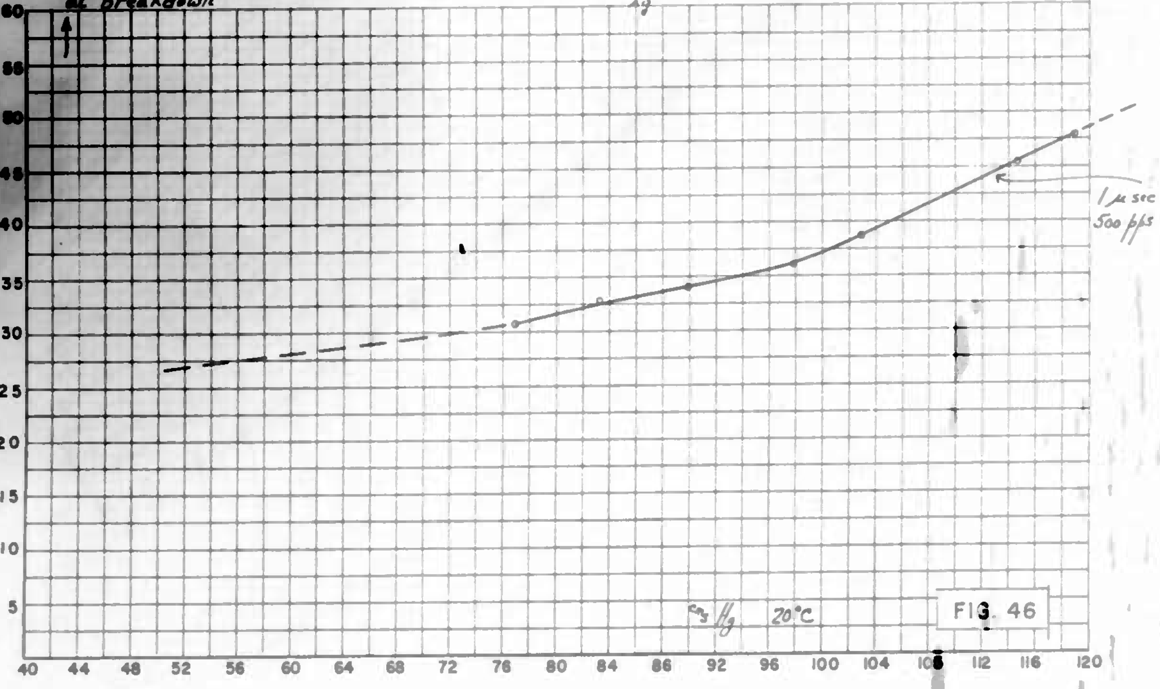


FIG. 46

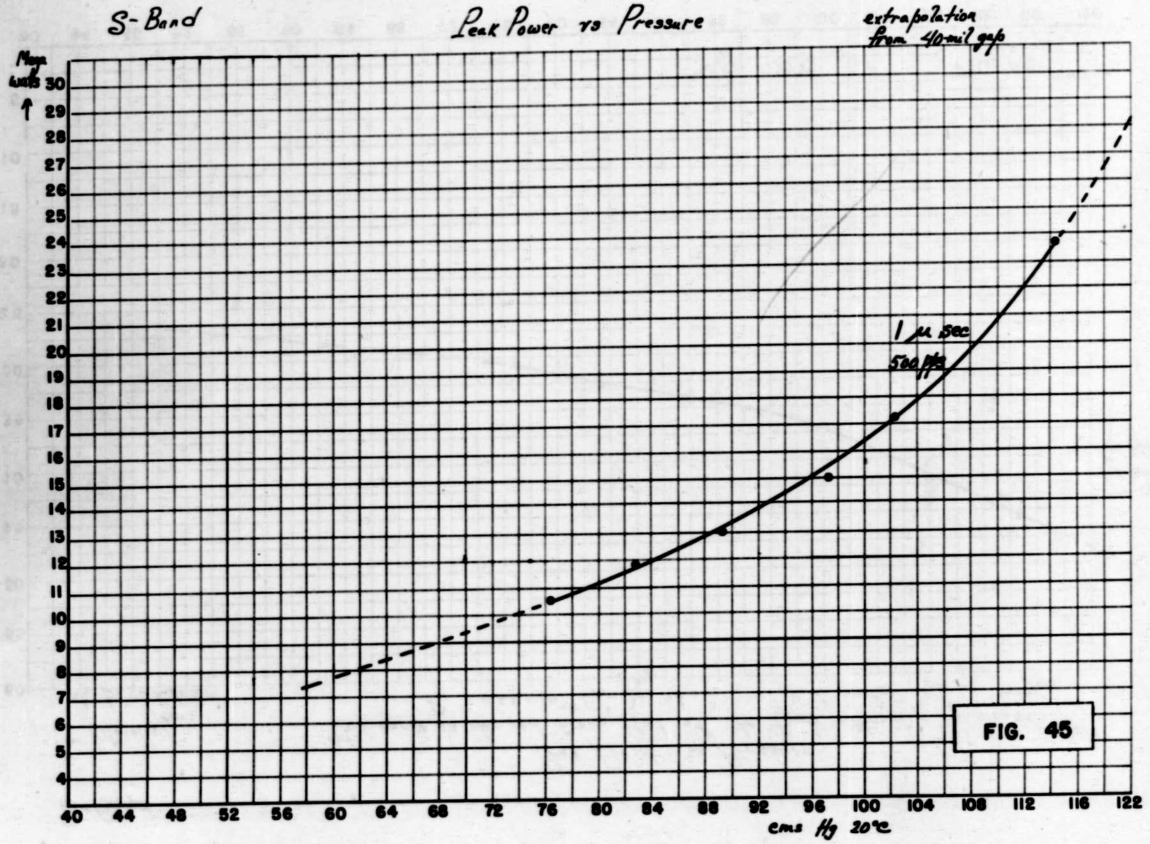

S-Band
Peak Power vs Pressure
extrapolation from 40 mil gap
Mega watts ↑
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
104
108
112
116
122
cms Hg 20°C
1 μ sec
500 pps

FIG. 45

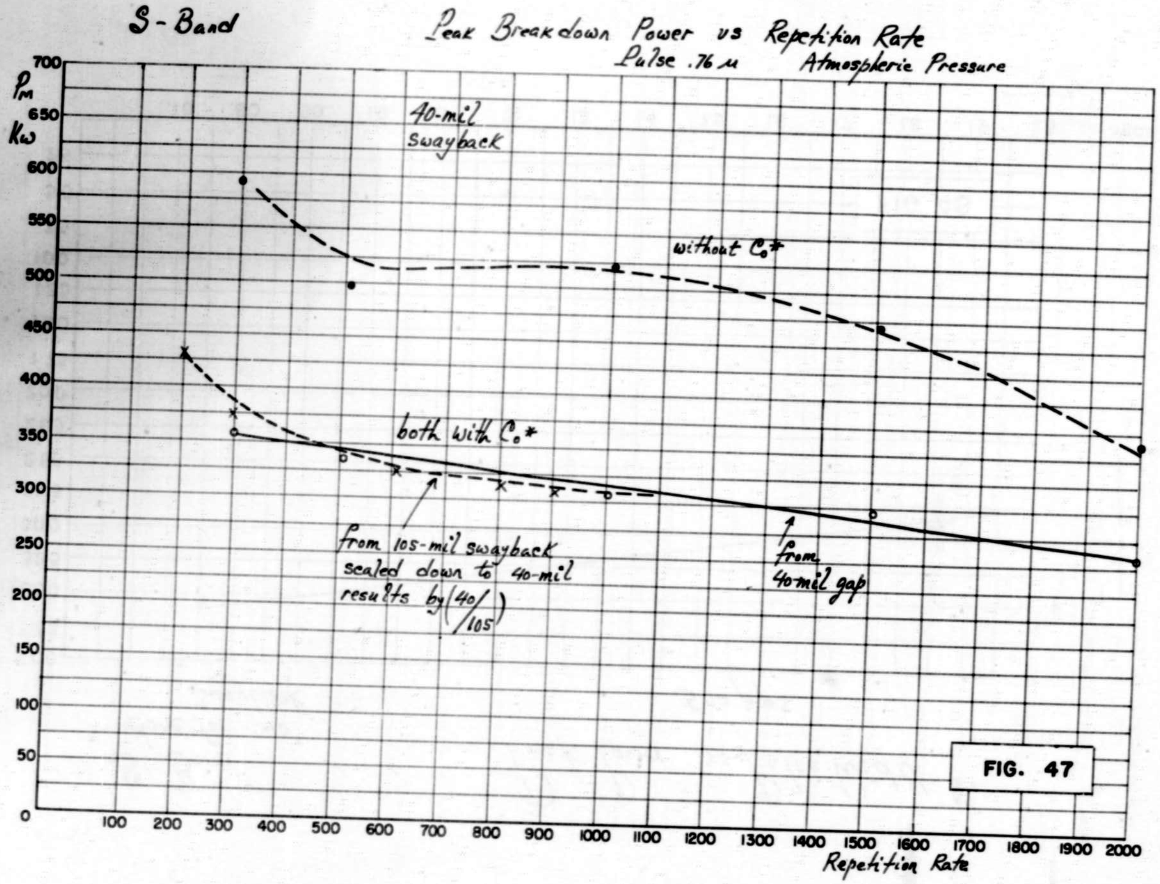

S-Band
Peak Breakdown Power vs Repetition Rate
Pulse .76 μ Atmospheric Pressure
P_M Kω
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Repetition Rate
40-mil swayback
without C_o*
both with C_o*
from 105-mil swayback scaled down to 40-mil results by (40/105)
from 40-mil gap

FIG. 47

Peak Power vs Pulse Width

500 pps

S-Band
done for .040"
Swayback

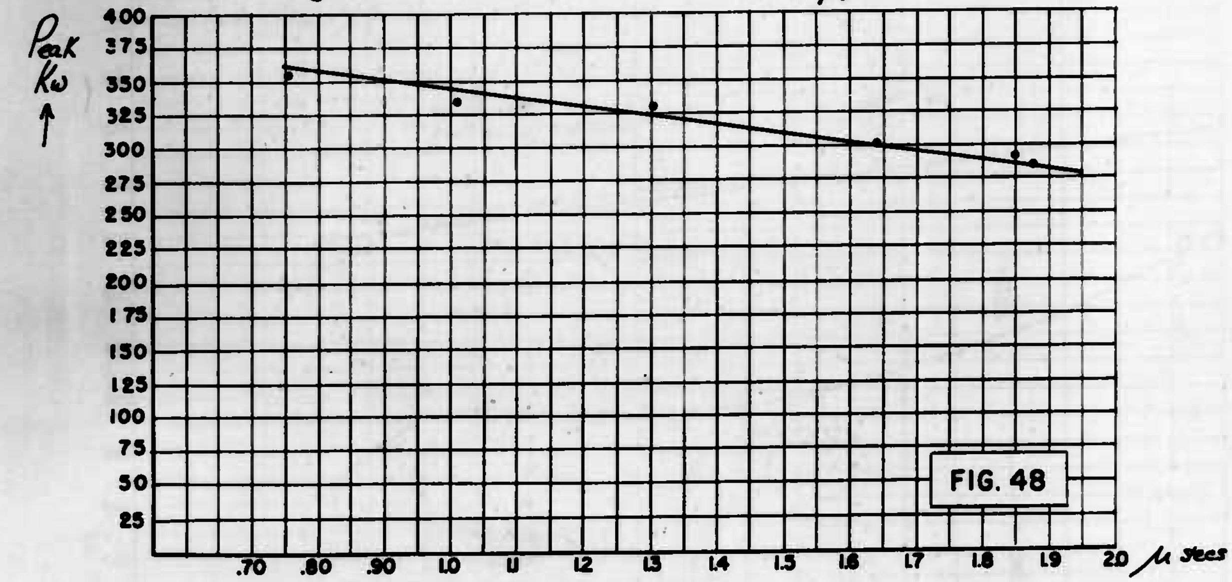


FIG. 48

S-Band
done for 40-mil swayback

Peak Power vs Rep. Rate

.76 μ sec

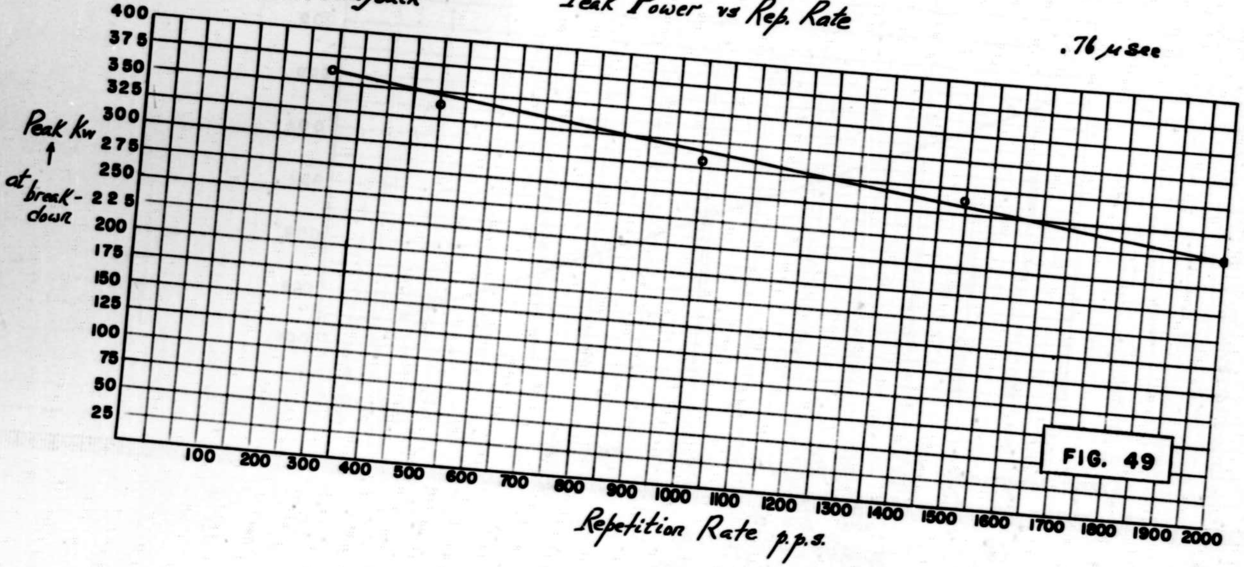


FIG. 49

S- Band

Constant Duty Cycle : 1 in 700
Peak Breakdown Power
vs Pulse Width
105-mil gap
Showing the relative importance of pulse width and
repetition rate in changing the breakdown level

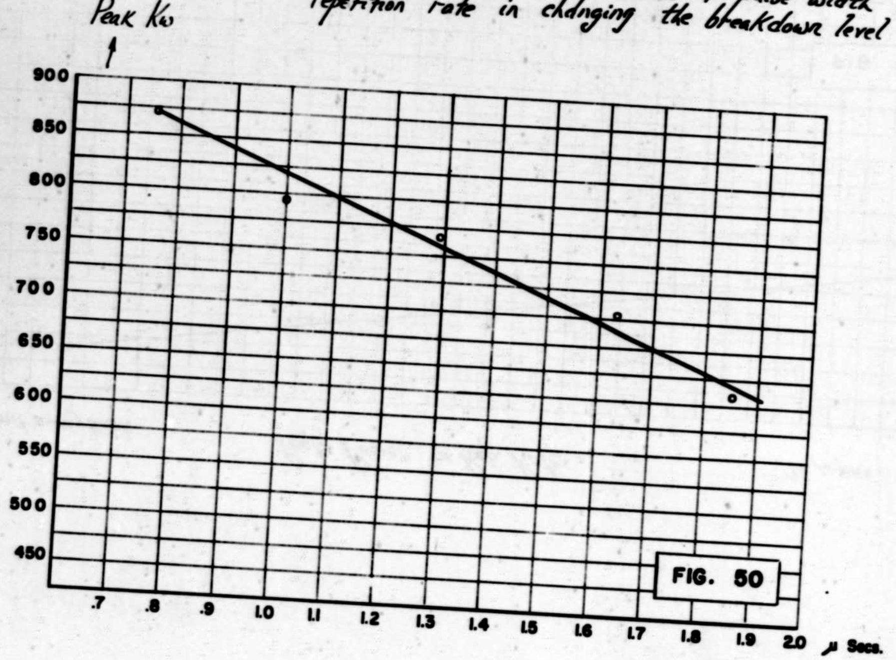


FIG. 50

For calibrating thermistor against water load

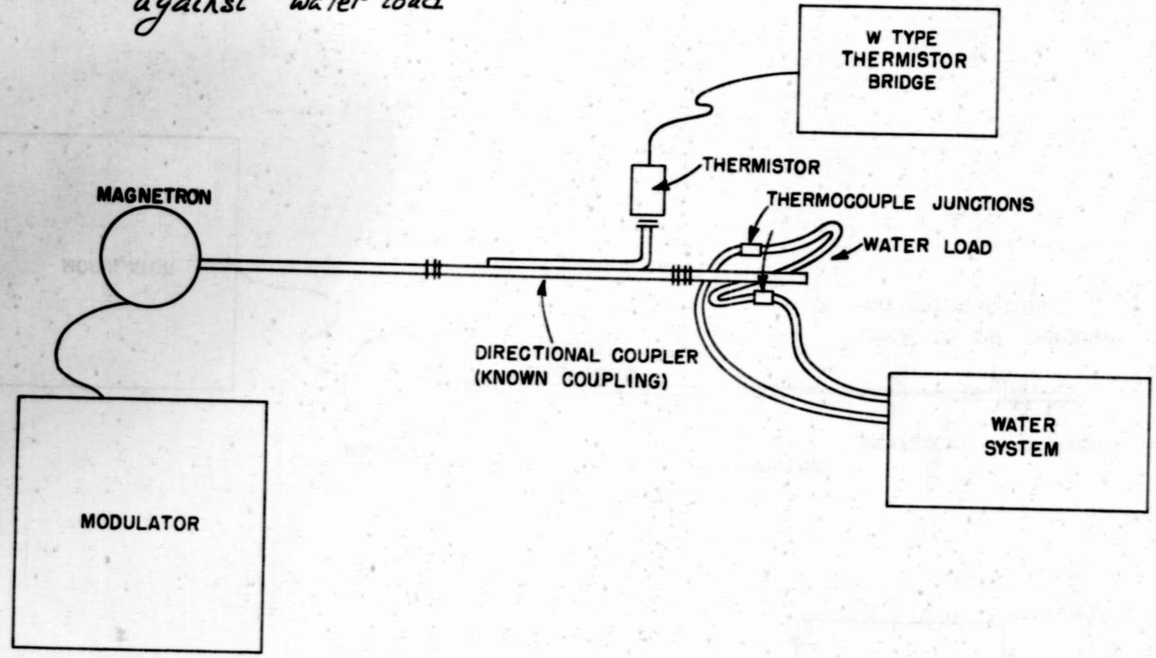


DIAGRAM A

For Breakdown at
Atmospheric Pressure

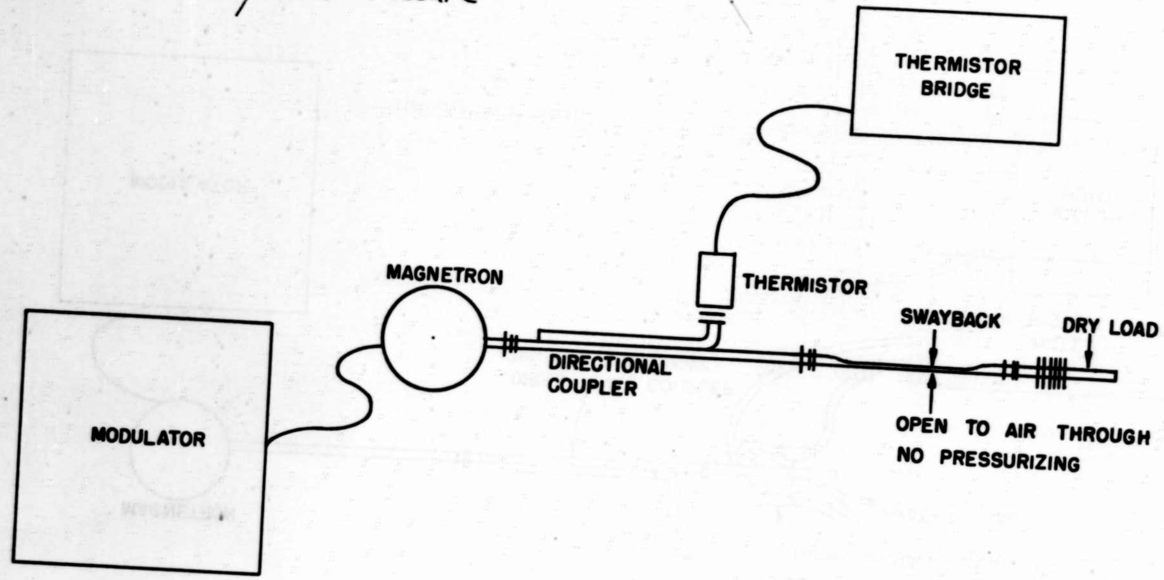


DIAGRAM B

For Breakdown at
Reduced Pressure

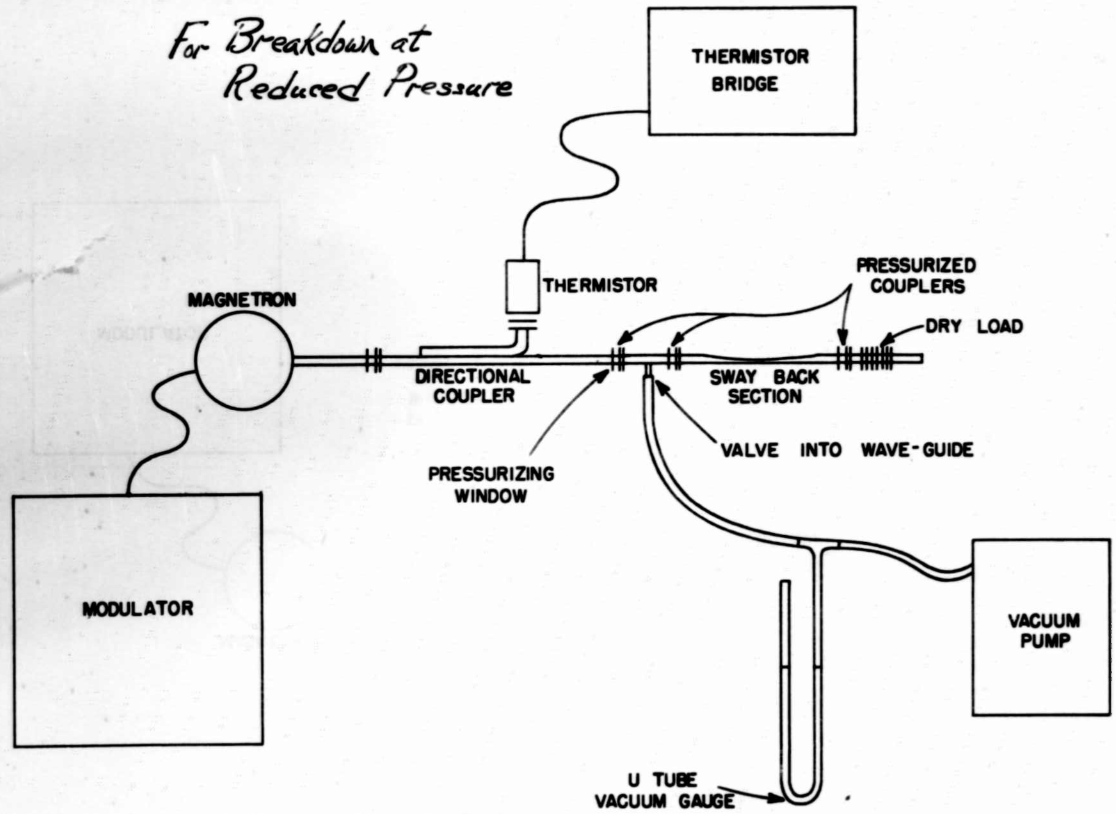


DIAGRAM C

For Breakdown at Increased Pressure

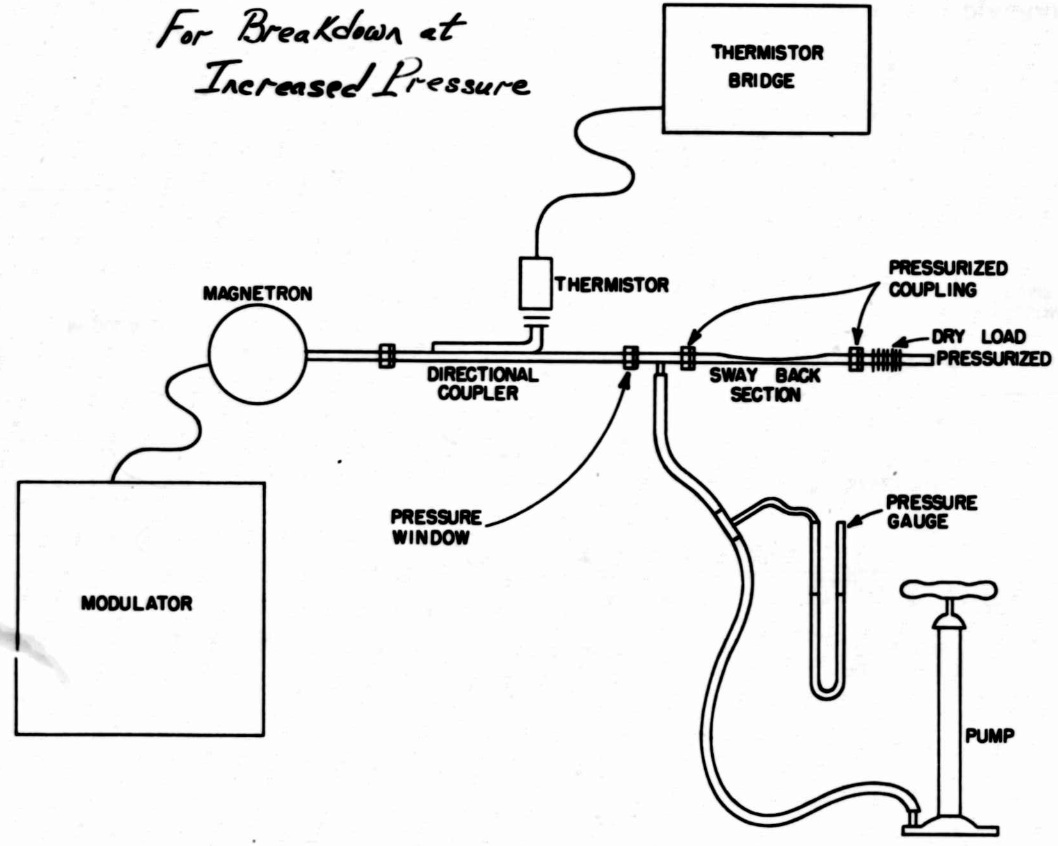


DIAGRAM D

REEL – C

483

A.T.I.

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ABSTRACT:

Experiments were conducted on the electrical breakdown at microwave frequencies using several sizes of air gaps in waveguide. The variation of breakdown was studied as a function of a number of parameters. The relations are given between the peak breakdown power and pressure, pulse width, and repetition rate. A 3-millicurie radioactive source was found to lower the peak breakdown power, and the breakdown field was larger for narrower gap widths.

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