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Microwave Associates INC.

First Interim Development Report
on
Microwave High Power Breakdown Study

This report covers the period March 20, 1953 to December 1,1953

MICROWAVE ASSOCIATES, INC.
22 Cummington Street
Boston, Massachusetts

NAVY DEPARTMENT, BUREAU OF SHIPS, ELECTRONICS DIVISION
CONTRACT NObsr - 63295, INDEX NO. NE - 111616

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ABSTRACT

This report presents a proposed approach and experimental procedure for determining microwave breakdown. The theory for microwave breakdown is developed on a qualitative basis and the mechanisms determining breakdown are discussed. The dependence of the breakdown field on pressure, pulse width, repetition rate, diffusion length, and initial density in the region of breakdown is presented. The theory shows that the experimental data must be determined from a plot of sparking probability as a function of electric field. Experimental data are cited to substantiate its use. The experimental arrangement and the associated components are described.

PART I

SECTION A

PURPOSE

1. Purpose of Development

This contract is concerned with the accumulation of high power microwave frequency, breakdown data of various microwave components, the establishment of design parameters and criteria useful and necessary to design microwave units for high power application, and the construction of a high power microwave test source.

2. Study and Work Phases

The objectives of this development shall be as follows:

Task I: Review Phase: Study and review all available data concerning existing high power microwave sources. The desired high power microwave source shall be at S band.

Task II: Constructional and Theoretical Phase: Construction of the laboratory source decided in Task I.

Task III: Theoretical and Measurement Phase: Both actual breakdown and the phenomena which precedes breakdown shall be considered. The method chosen shall be fully applicable by others.

Task IV: Theoretical and Measurement Phase: Investigate the problem of determination of the region of breakdown.

Task V: Application of Results: Apply the results of the previously described work to the investigation of the dependence of peak power capacity on the values of the more important parameters. The parameters investigated shall include the following unless otherwise specified by the Bureau of Ships:

(a) Pulse Length

(b) Pulse Shape

(c) Pulse Repetition Frequency

(d) Pressure

(e) Nature of the gas

(f) Mechanical Finish

(g) Plating Material

(h) Microwave Frequency

Task VI: Component Measurements: Measure the peak power capacity of the following microwave units, of designs commensurate with the latest state of the art:

(a) Termination

(b) Directional Coupler

(c) Interlocked flexible waveguide

(d) Convoluted flexible waveguide

(e) Waveguide to type "N" adapter

(f) Series Tee

(g) Shunt Tee

(h) Flange to choke joint

(i) Flange to flange joint

(j) Joint, circular waveguide type, rotating

(k) Joint, rectangular waveguide type, rotating

(l) Window

(m) Switch

(n) Duplexer

(o) Other

Task VII: Correlation of Results: Correlate the data obtained at frequency desired in Task I with data obtained at X or L band. These data shall be obtained in the same manner as for the S band specified in Task VI.

SECTION B

GENERAL FACTUAL DATA

3. References

The following references are used in the report.

(1) Final report on Contract Number NObsr-56261 Wheeler Laboratories, Inc. January, 1953

(2) First and Second Interim Report on Contract Number NObsr-52227, Sperry Gyroscope Company, June, 1951.

(3) Cooper, R., Experiments on the Electrical Strength of Air at Centimetre Wavelengths, Journal of the Institution of Electrical Engineers, vol. 94, Part III, p. 315, 1947.

(4) Posin, D.Q., Masur, I. and Clarke, H., Experiments in Microwave Breakdown, M.I.T. Radiation Laboratory, Technical Report No. 731, Nov.28, 1945

(5) Lathrop, J.W. and Brown S.C., The Relationship of Pulsed to C.W. Breakdown of a Gas at Microwave Frequencies, M.I.T. Research Laboratory for Electronics, Technical Report No. 146, Dec.1, 1949.

(6) Pim, J. A., The Electrical Breakdown Strength of Air at Ultra-High Frequencies, Proceedings of the Institute of Electrical Engineers, Vol.96, Part III. p. 117, 1949.

(7) Herlin, M.A. and Brown, S.C., Breakdown of a Gas at Microwave Frequencies, Physical Review, vol.74, p. 291, 1948.

(8) S.C. Brown & D.J. Rose, Methods of Measuring the Properties of Ionized Gases at High Frequencies, Journal of Applied Physics, 23, 711 (1952); 719 (1952); 1028 (1952).

SECTION C

DETAIL FACTUAL DATA

4. Introduction

A comprehensive survey of all available technical information on the subject of breakdown has been reported by Wheeler Laboratories, Inc.[1] and Sperry Gyroscope Company.[2] Rather than to review the material discussed in these reports, the object of this report is to develop the breakdown criteria and limits for high power pulsed breakdown at microwave frequencies on a qualitative basis which can later be extended to a quantitative basis. The experimental approach and procedure are also discussed.

5. Theory of High Power Breakdown

In a high frequency gas discharge breakdown, the primary ionization due to the electron motion is the only production phenomenon which controls breakdown. The electron can gain energy from the field only by suffering collisions with the gas atoms, in which case the electron's ordered oscillatory motion is changed to random motion on collision. The electron gains random energy on each collision until it is able to make an inelastic collision with a gas atom. The gas discharge breakdown occurs when the gain in electron density due to ionization of the gas becomes greater than or equal to the loss of electrons by diffusion, recombination, or attachment.

The breakdown conditions for a region bounded by walls which absorb electrons will be developed. A radioactive source near the discharge tube provides a small amount of ionization, S , in the tube. A detailed study of the build-up of the discharge is obtained from considering the continuity equation for electrons

$$\frac{\partial n}{\partial t} = \nu_i n - \nu_L n + S \qquad (1)$$

where n is the electron density, ν_i is the frequency of ionization, and ν_L is the frequency of loss given by

$$\nu_L n = \nu_a n - D_- \nabla^2 n + \alpha_r n_+ n_- \qquad (2)$$

where ν_a is the frequency of attachment of electrons to gas molecules, D_- is the electron diffusion coefficient, $\nabla^2 n$ can be approximated by $\frac{n}{\Lambda^2}$ where Λ is the diffusion length, α_r is the positive ion-electron recombination coefficient, and n_+ is the positive ion density. The coefficients ν_i and ν_L will, in general, be functions of E_o , the peak electric field, p , the gas pressure, and the nature of the gas. These quantities can be given theoretically only by taking into account the electron energy distribution function. The evaluation of ν_i and ν_L will not be attempted at this time. For air, at pressures from 200 mm to 1000 mm Hg, it is believed that the dominant loss mechanism is attachment, although recombination may become important depending upon the values of the positive ion and electron densities in the neighborhood of breakdown. As yet, the important loss mechanisms have not been verified experimentally. In Equation (1), the production of electrons in the gap or at the walls owing to photo-electric action caused by excitation of molecules by electron impacts has been neglected.

The solution of Equation (1), assuming S to be negligible except in determining the initial electron density, n_o, is given by

$$n = n_o e^{\gamma t} \qquad (3)$$

where $\gamma = \nu_i - \nu_L$.

the condition for CW breakdown is that $\gamma = 0$, i.e. $\nu_i = \nu_L$. For a value of γ slightly larger than 0 , the density can build up to the electron density required for breakdown, n_b. Therefore, the minimum breakdown field, E_{bcw}, is determined from the condition that $\gamma = 0$. When pulsed operation is considered, breakdown within a given pulse will take place when the pulse width, τ, of the pulse is of sufficient length so that the electron density, n_b, can be produced. The condition for single pulse breakdown is

$$\gamma = \frac{1}{\tau} \ln \frac{n_b}{n_o} \qquad (4)$$

For multiple pulses, it is possible for breakdown to occur even though $\gamma < \frac{1}{\tau} \ln \frac{n_b}{n_o}$. Electrons produced in one pulse, although not sufficient to produce breakdown, can increase the initial electron density for the next pulse, and, hence eventually a pulse will occur in wh'ch breakdown can take place. The condition that such a process is possible, depends upon the decay of electrons between pulses in the afterglow. If attachment or diffusion is the dominant loss mechanism between pulses, the electron density as a function of time in the afterglow can be written as

$$n = n_o + (n_\tau - n_o) e^{-\beta(t-\tau)} \qquad (5)$$

where n_τ is the electron density at time τ and β is the decay time constant. If recombination should be the dominant loss mechanism, then Equation (5) would have to be modified. In general, β is not the same as ν_L, since the average electron in the afterglow is of the order of .04 electron volts while the average electron energy during the pulse may be of the order of 5 to 10 electron volts and ν_L is, probably, a function of electron energy.

Equations (3) and (5) are combined to yield the density obtained after k pulses have elapsed. When the repetition frequency of the pulses is f, the time between pulses is then $T = 1/f$. The density after the first pulse is $n_{\tau_1} = n_0 e^{-\gamma\tau}$ and the density at the beginning of the second pulse is $n_2 = n_0 + (n_{\tau_1}) e^{-\beta/f}$ when $T \gg \tau$ and $n_\tau \gg n_0$. The density after the second pulse is $n_{\tau_2} = n_0 e^{\gamma\tau}(1 + e^{(\gamma\tau - \beta/f)})$. By continuing this process, the density after k pulses is

$$n_{\tau_k} = n_0 e^{\gamma\tau}\left(1 + e^{(\gamma\tau - \beta/2)} + e^{2(\gamma\tau - \beta/f)} + \cdots + e^{k(\gamma\tau - \beta/f)}\right) \qquad (6)$$

Using the expression for the sum of a geometric series, the above equation becomes

$$n_{\tau_k} = n_0 e^{\gamma\tau}\left[\frac{e^{k(\gamma\tau - \beta/f)} - 1}{e^{(\gamma\tau - \beta/f} - 1}\right] \qquad (7)$$

The condition that the gas breakdown after k cycles is that $n_{\tau_k} = n_b$. If we assume $e^{(\gamma\tau - \beta/f)} > 1$, then Equation (7) becomes

$$\gamma\tau = \left[\frac{1}{k}\frac{n_b}{n_0} + \frac{\beta}{f}\frac{(k-1)}{k}\right] \qquad (8)$$

Equation (7) or (8) determines the general breakdown condition. For CW operation, *i.e.* f or τ approaches infinity, we have the condition $\gamma = 0$. For a single pulse breakdown, *i.e.* $k = 1$, we have $\gamma\tau = \ln \frac{n_b}{n_0}$. The curve for $\gamma\tau$ as a function of $1/k$, the reciprocal of the number of pulses required before breakdown takes place, has the general shape shown in Figure 1. It is seen that $\gamma\tau$ has the value of $\ln \frac{n_b}{n_o}$ when $k = 1$, and the asymptotic value of β/f when $k = 0$. Therefore, the minimum breakdown field is determined by $\gamma\tau = \beta/f$ and is independent of $\ln \frac{n_b}{n_o}$. However, when β/f is greater than $\ln \frac{n_b}{n_o}$ breakdown will occur every pulse and $\gamma\tau$ will be independent of k and β/f. A plot of $\gamma\tau$ as a function of β/f is shown in Figure 2.

The problem consists of transforming $\gamma\tau$ to the corresponding value of E_o and p at breakdown. Since the exact relation between γ and E_o, p, and Λ is not precisely known, only qualitative results will be obtained. The condition $\gamma = 0$ for C.W. breakdown determines a curve for E_{bcw} vs p. For pulsed conditions, one must first explain how the factor k enters into the picture. The experiments of Cooper(3) indicate that a plot of sparking probability versus power results in a reproducible value of breakdown voltage. His procedure involves counting the number of sparks and dividing this value by the number of applied pulses to obtain the sparking probability at a given microwave power. A typical curve of sparking probability as a function of the electric field at breakdown obtained by Cooper is shown in Figure 3. Comparison of Figure 3 with Figure 1, shows that the sparking probability, the number of sparks per pulse, should be related to $1/k$, the reciprocal of the number of pulse required for a spark, since $\gamma\tau$ is a function of the electric field at a given pressure. The exact relationship between the sparking probability and $1/k$ is not completely understood. However, measurements as a function of sparking probability at a given pressure should yield E_{bp}, the breakdown field at a sparking probability of zero and E_1, the field at a sparking probability of one. It is seen that if β/f is less than $\ln \frac{n_b}{n_o}$, E_{bp} determined from the sparking probability curve, should be independent of n_o. A typical curve for the pulsed breakdown field, E_{bp}, or a function of the repetition frequency is shown in Figure 4. The shape of the curve is derived from Figure 2. At low frequencies, the breakdown field is independent of frequency. At $f_1 = \beta / \ln \frac{n_b}{n_o}$, a discontinuity in the curve occurs and the breakdown field decreases since we are in a region in which electrons from one pulse can increase the initial electron density in the next pulse. Since β can be written as $\beta_o p$, it is expected that f_1 increases when the pressure and initial density, n_o, increases. At larger values of frequency, the breakdown field decreases and approaches the C.W. breakdown field value. In addition, when $f > f_1$, the pulsed breakdown field, E_{bp}, should be a unique function of $f\tau$ at a given pressure. However, care must be taken in determining the breakdown field at zero sparking probability.

The results discussed above are purely qualitative and depend upon which mechanisms are assumed important. Such a discussion is valuable since it indicates how the various mechanisms will affect the results and also what experimental measurements are important. It has been assumed here that attachment and diffusion are the dominant loss mechanisms.

However, the value of n_b/n_0 used by Posin[4] is 10^{14} electrons/c.c. which means that if n_0 lies between 1 and 100 electron/c.c., the density at breakdown lies between 10^{14} and 10^{16} electrons/c.c. This value of density is rather high and would mean that recombination is an important loss mechanism. Lathrop & Brown[5] used a value of 10^6 for n_b/n_0 and indicated that the density at breakdown is of the order of 10^9 electrons/c.c. which seems more reasonable than Posin's value of breakdown density. It should be remembered that Lathrop & Brown's data was taken at low pressures (1-20 mm Hg) while Posin's data was taken at high pressures (50-760 mm Hg). Obviously, the value of n_b/n_0 and its variation with pressure must be investigated in more detail.

From the discussion presented here, the most logical approach is, first, to determine E_{bcw} as a function of pressure, since the C.W. breakdown field is a lower limit on all the pulsed breakdown field data. The C.W. measurements will be taken for various gap lengths in order to determine the influence on the breakdown field of Λ, the diffusion length, given by L/π for a pair of infinite parallel plates separated by a distance L. Measurements will be taken for pulsed condtions, determining the breakdown field as a function of τ, f, Λ, p and n_0 using the sparking probability approach of Cooper. It is hoped that from these measurements, the important mechanisms involved may be determined. After these measurements for breakdown field are obtained, they will be used to predict the maximum power capacity of various waveguide components, which will be verified experimentally.

Measurements of C.W. Breakdown field as a function of pressure in air taken from the data of Pim[6] and Herlin and Brown[7] are shown in Figure 5. Pim's data was taken at 200 megacycles and a diffusion length of about 0.025 cm. The largest gap widths in Pim's measurements are used here, since for shorter distances the phenomenon of the electron oscillation amplitude becoming comparable to the diffusion length is important. At microwave frequencies, this phenomenon is negligible above distances of the order of 0.01 cm, hence, it is desirable to use that data of Pim in which the oscillation amplitude effect is negligible. The data of Herlin and Brown was taken at 3000 megacycles and a diffusion length of 0.2 cm, however, the maximum pressure they used was only 60 mm Hg. It should be noted that the data of Herlin & Brown are continuous with the data of Pim, despite the fact that the diffusion lengths vary over a factor of 10. This would seem to indicate that over this range of diffusion length the breakdown field is independent of diffusion length. From 150 mm to 760 mm Hg., the electric field is given by $E_{bcw} = 43P$ in volts per cm. Thus, the C.W. breakdown power is proportional to P^2.

Measurements of the pulsed breakdown field as a function of pressure in air taken from the data of Cooper[3] and Posin[4] are shown in Figure 6. The data were taken in both cases at a microwave frequency of 9800 megacycles per second, a pulse width of $1 \mu s$, and at essentially the same repetition frequency (400 c.p.s. for Cooper and 500 c.p.s. for Posin) and using essentially the same diffusion length (.046 cm for Cooper and .031 cm for Posin). The disagreement in the two curves is obvious, but no feasible explanation for this discrepancy is as yet available.

6. Proposed Experimental Procedure

Measurements of breakdown field are to be determined in a microwave resonant cavity, using the techniques similar to those of Herlin and Brown. The microwave cavity is cylindrical in shape, having a resonant frequency of 2800 megacycles per second. Cavities of different height are to be used so that the variation of breakdown field with diffusion length can be investigated.

The block diagram for the equipment to be used for the C.W. measurements is shown in Figure 7. An L3501 Litton C.W. magnetron feeds 500 watts power into a waveguide ring magic tee, which has a tuning plunger and a water load on the side arms. The power through the magic tee is varied by means of the tuning plunger. A directional coupler is used to introduce a fraction of the power from a QK59 Raytheon magnetron. The QK59 is used to measure the characteristics of the microwave cavity. The power level of the QK59 is small compared to that of the L3501. A directional coupler samples a fraction of the power incident on the cavity, which is measured by means of a thermistor and associated power bridge. A knowledge of the coupling of the directional coupler allows the line power to be calculated. The frequency is measured by a wavemeter which samples a fraction of the signal in the waveguide. A slotted section in conjunction with a movable probe and a spectrum analyzer is used to obtain standing wave ratio measurements as a function of frequency. These measurements are used to determine the unloaded Q of the cavity. The value of Q and the power absorbed in the cavity determine the electric field according to the method outlined by Brown and Rose[8]. The cavity is iris-coupled to the waveguide with a glass window so that the air pressure in the cavity can be varied. The cavity may be replaced by a waveguide water calorimetric load so that the power incident on the cavity can be measured and the calibration of the directional coupler and power bridge can be varied.

The block diagram for the equipment to be used for pulsed measurements is shown in Figure 8. A QK338 Raytheon pulsed magnetron furnishes 5 megawatt peak power into the waveguide ring magic tee. A square wave generator and audio oscillator are used to determine the frequency of the modulator output. The QK59 is introduced into the main waveguide through a duplexer. The duplexer protects the QK59 from the high power pulses. The remainder of the experimental arrangement is essentially the same as for C.W. measurements. The cavity has a small window so that using a photo cell and electronic counter enables the number of pulses per spark to be counted.

7. <u>Progress during Interval</u>

In addition to studying the theoretical aspect of breakdown, considerable preparatory work was performed during the interim. The design of many of the circuit components was chosen, and the components are at present in various stages of fabrication and test. The power supply for the QK59 is almost completed. The QK338, the L3501, and associated power supply and modulator have been ordered.

Section D

Conclusions

8. General Conclusions

The theory of high power breakdown developed here, although qualitative, indicates the expected behavior of the breakdown field as a function of pressure, pulse width, repetition rate, and initial electron density. The importance of determining the breakdown electric field from the sparking probability data is clearly evident. The theory shows that it is important to know the C.W. breakdown field in as much as the C.W. breakdown field places a lower limit on all pulsed breakdown measurements. It is hoped that the mechanisms of breakdown can be interpreted from the experimental measurements, provided the data is properly interpreted. Some of the available experimental data is given and the regions of agreement and disagreement are shown. The experimental arrangement to be used is presented and the various components are described.

Part II

Program for Next Interval

9. Program for Second Quarter

The objective for the next quarter is the completion and testing of the experimental set up. This involves the fabrication of several directional couplers, the waveguide ring tee, and microwave cavity. It will also be necessary to test or calibrate these components as well as the audio signal generator, the thermistor bridge, the waveguide water-load, the spectrum analyzer, the QK59 and associated power supply, and the QK338 and L3501 and their associated power supply and modulator. In addition, a further investigation must be conducted to determine a suitable means for detecting and counting the sparks. Work will be continued on the theory of high power breakdown and an attempt to put the theory on a quantitative basis will be initiated.

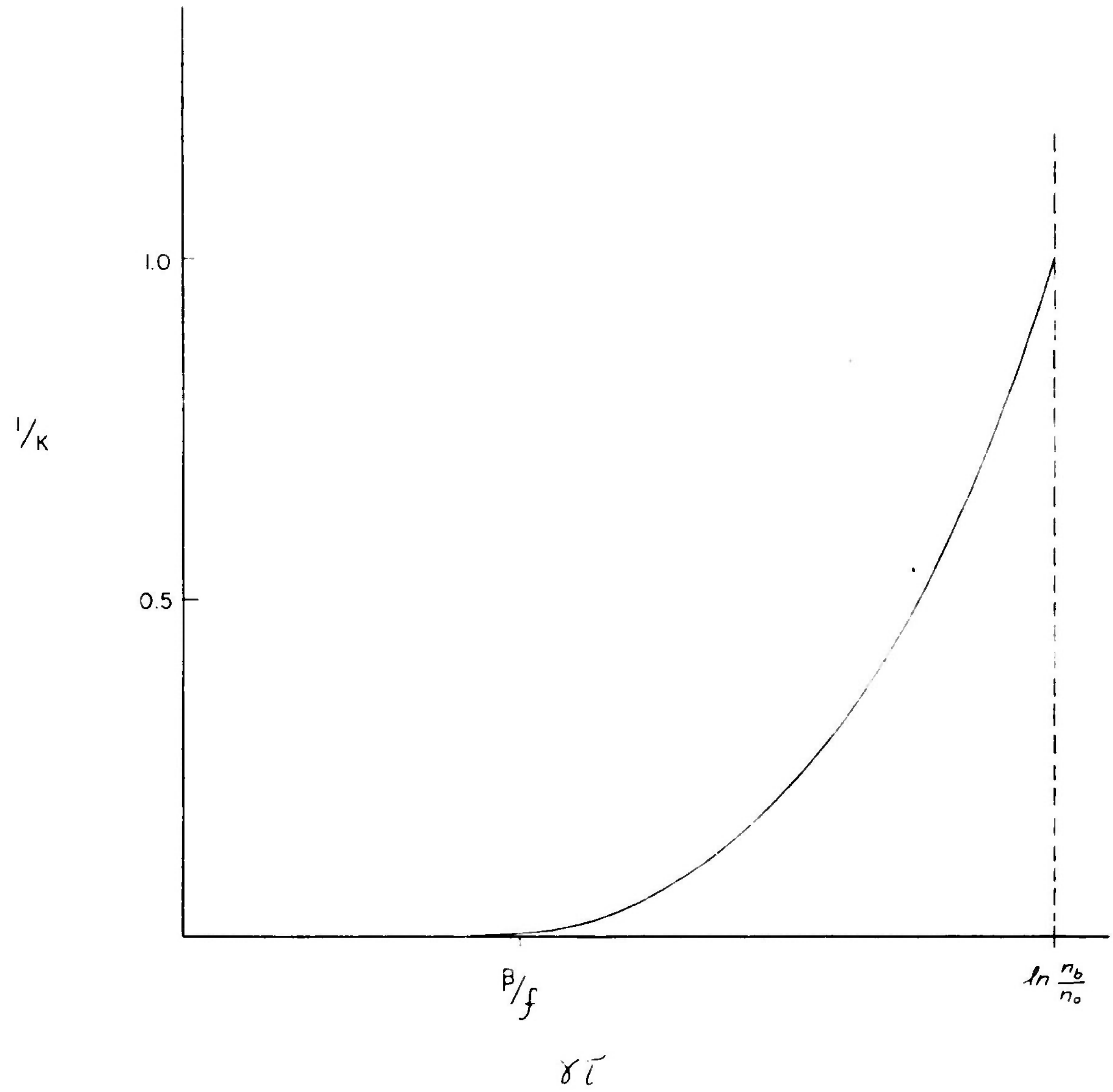

FIG. I - VARIATION OF $1/K$ WITH $\gamma\tau$

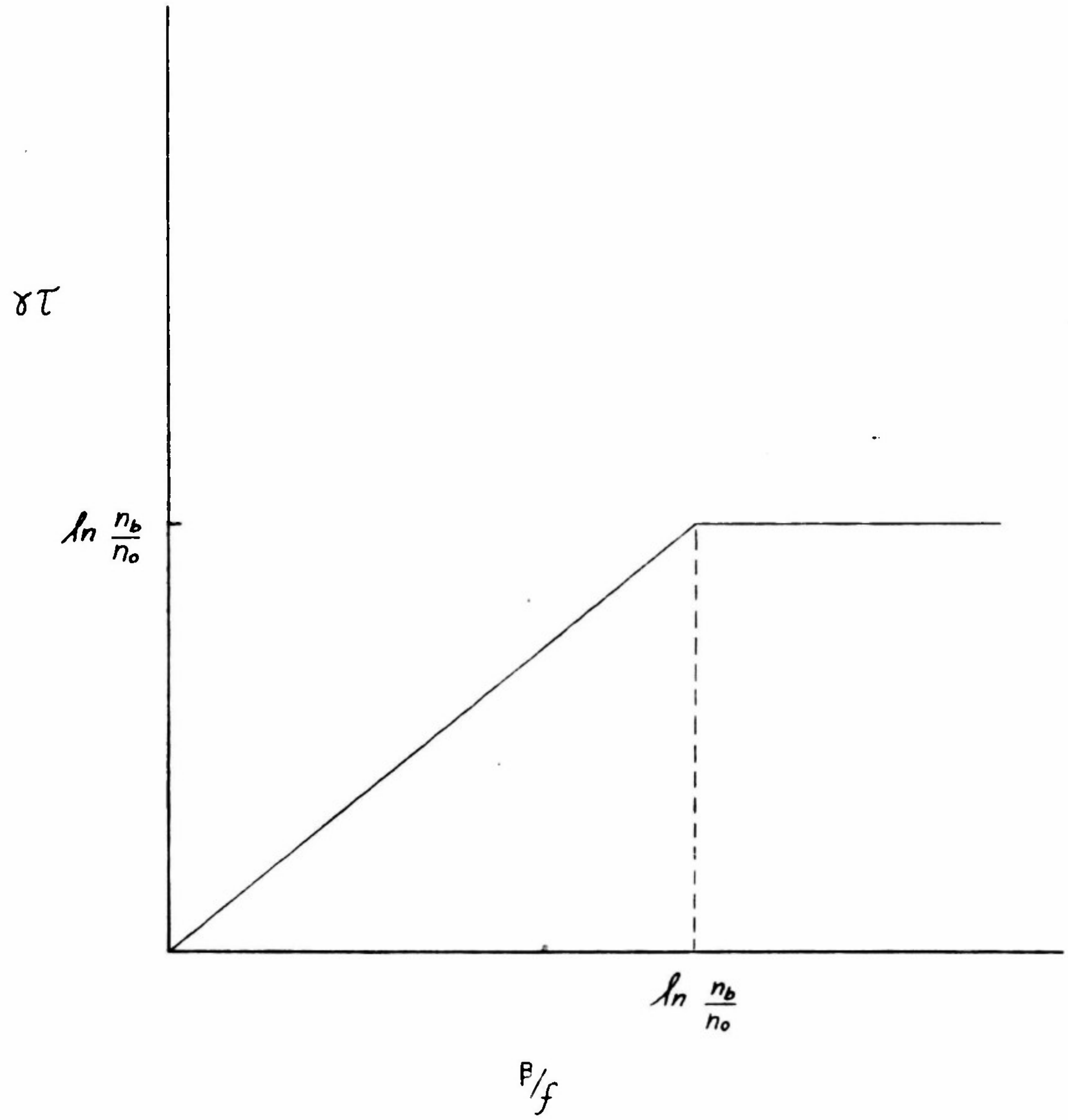

FIG. 2 – VARIATION OF $\gamma\tau$ WITH β/f

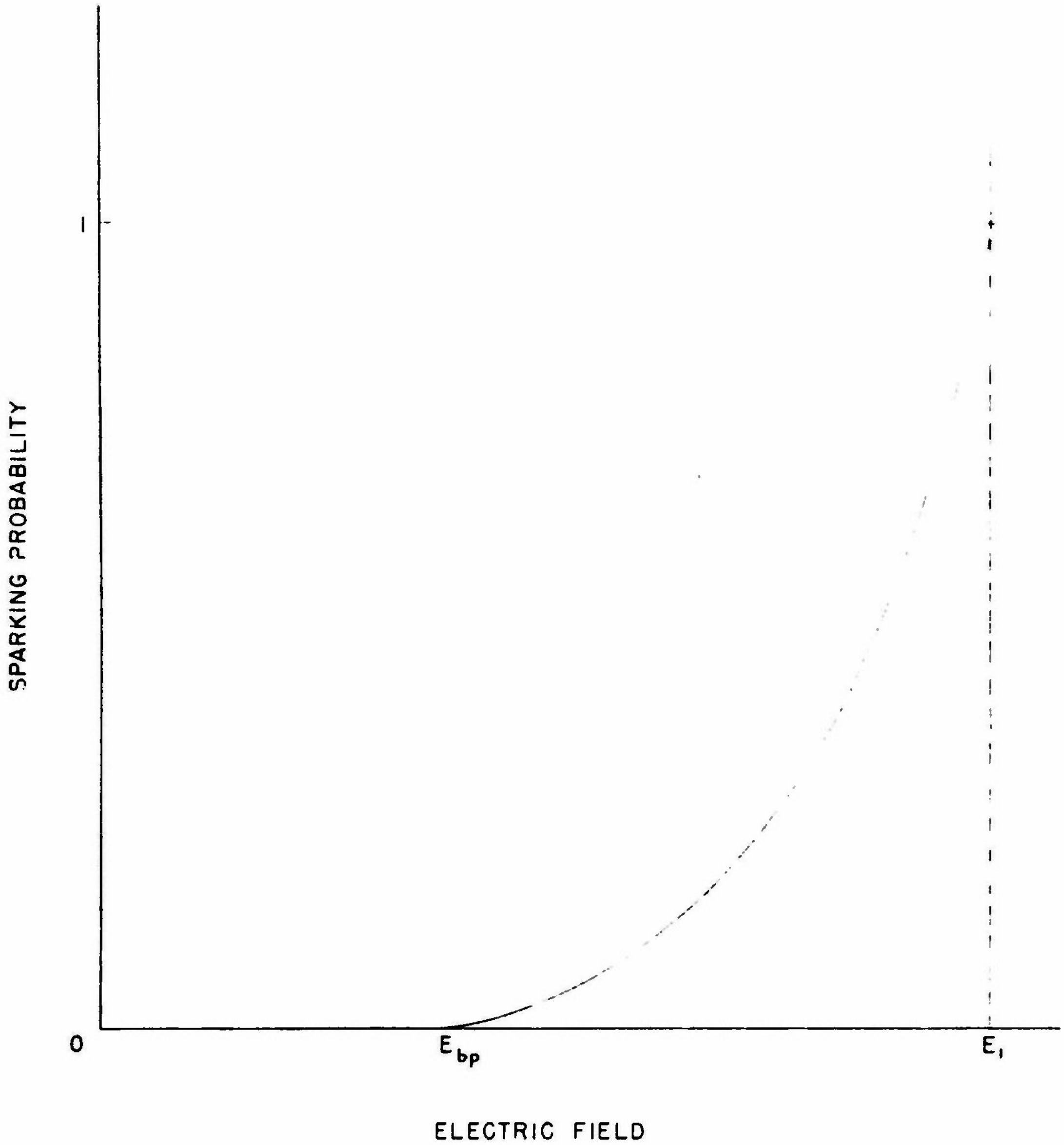

FIG 3 - VARIATION OF SPARKING PROBABILITY WITH ELECTRIC FIELD

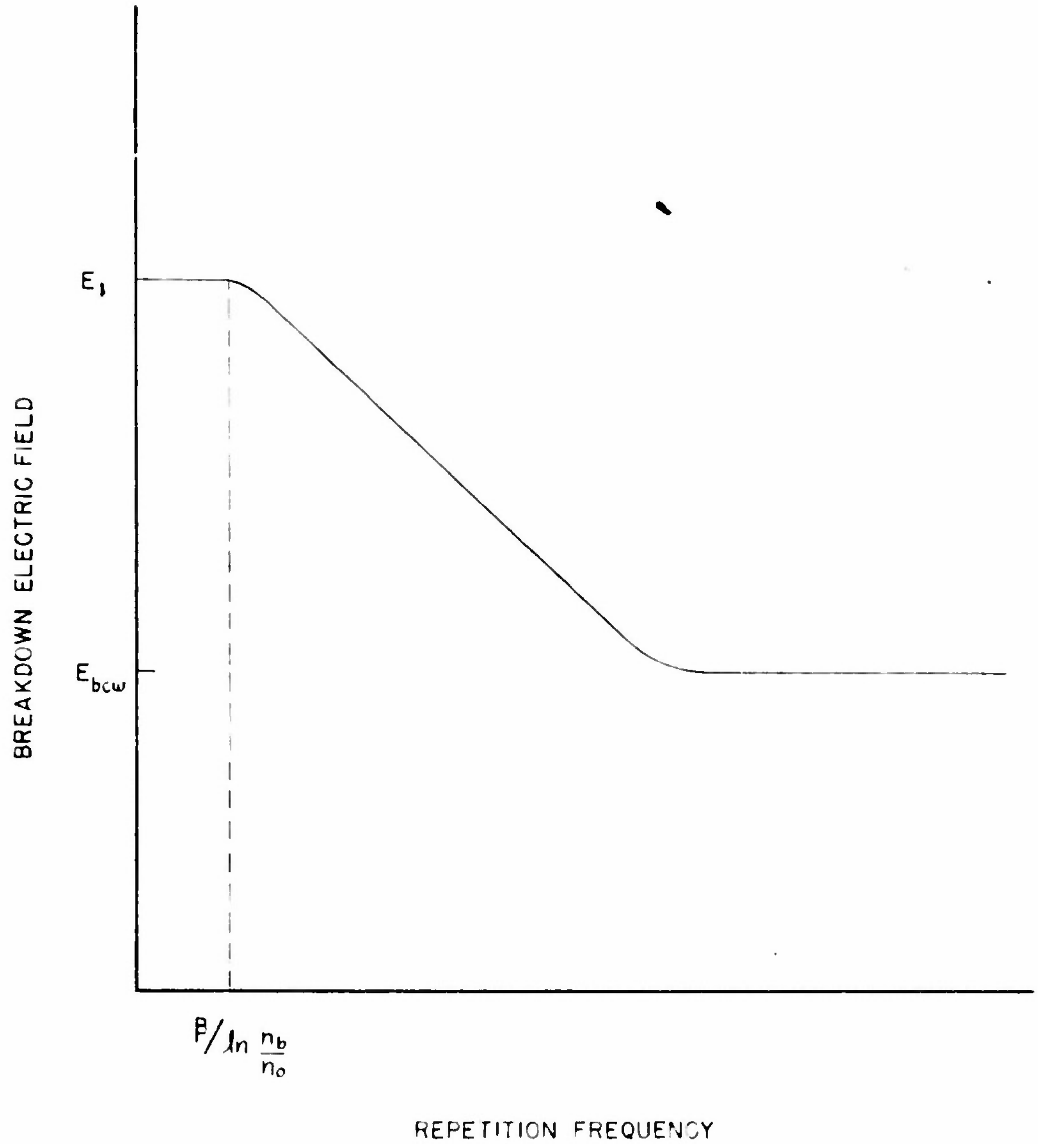

FIG. 4 – VARIATION OF BREAKDOWN ELECTRIC FIELD AS A FUNCTION OF REPETITION FREQUENCY

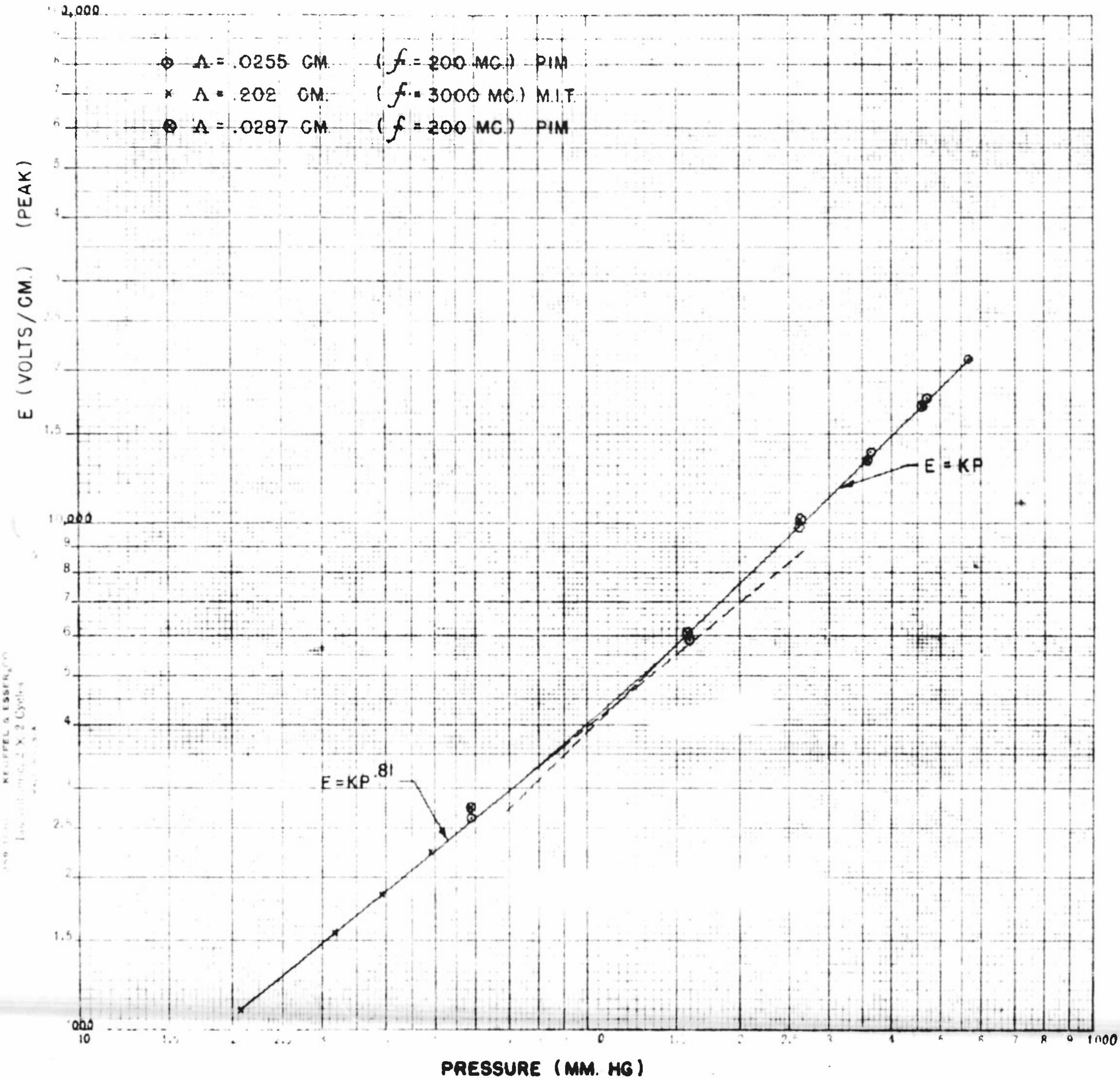

FIG. 5 - C.W. BREAKDOWN AS A FUNCTION OF PRESSURE

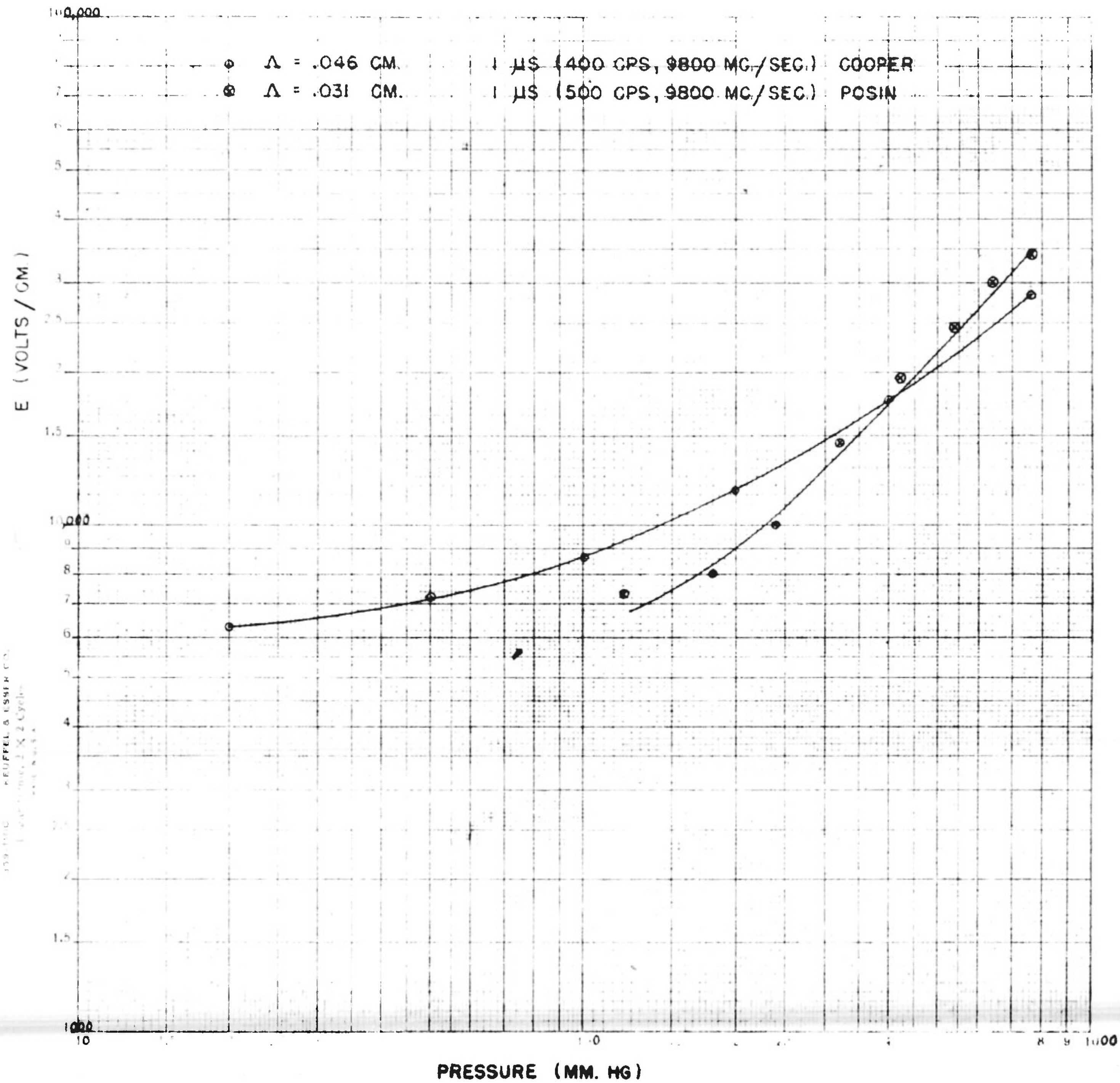

FIG. 6 - PULSED BREAKDOWN FIELD AS A FUNCTION OF PRESSURE

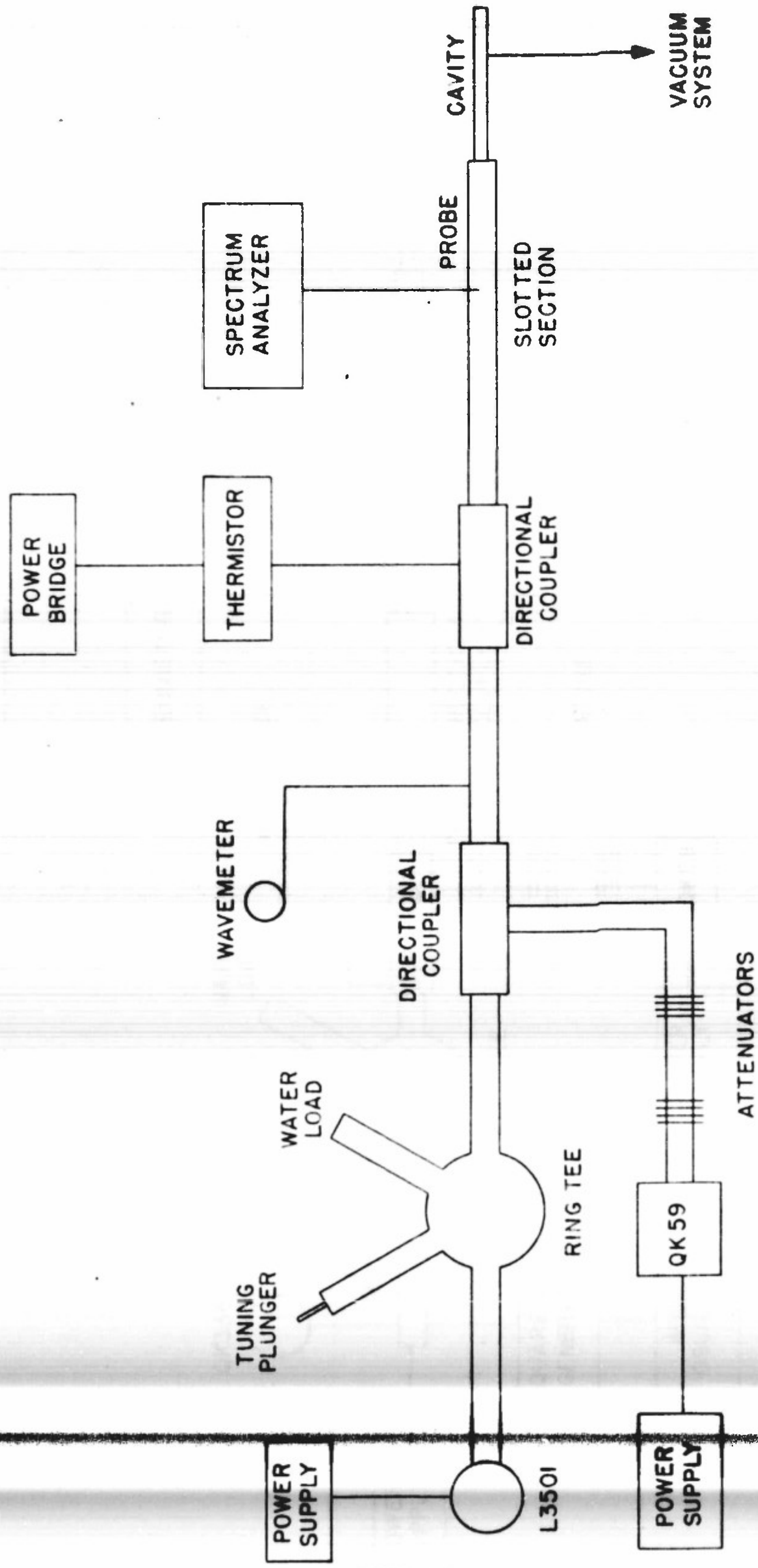

FIG. 7 - BLOCK DIAGRAM OF EQUIPMENT FOR C.W. MEASUREMENTS

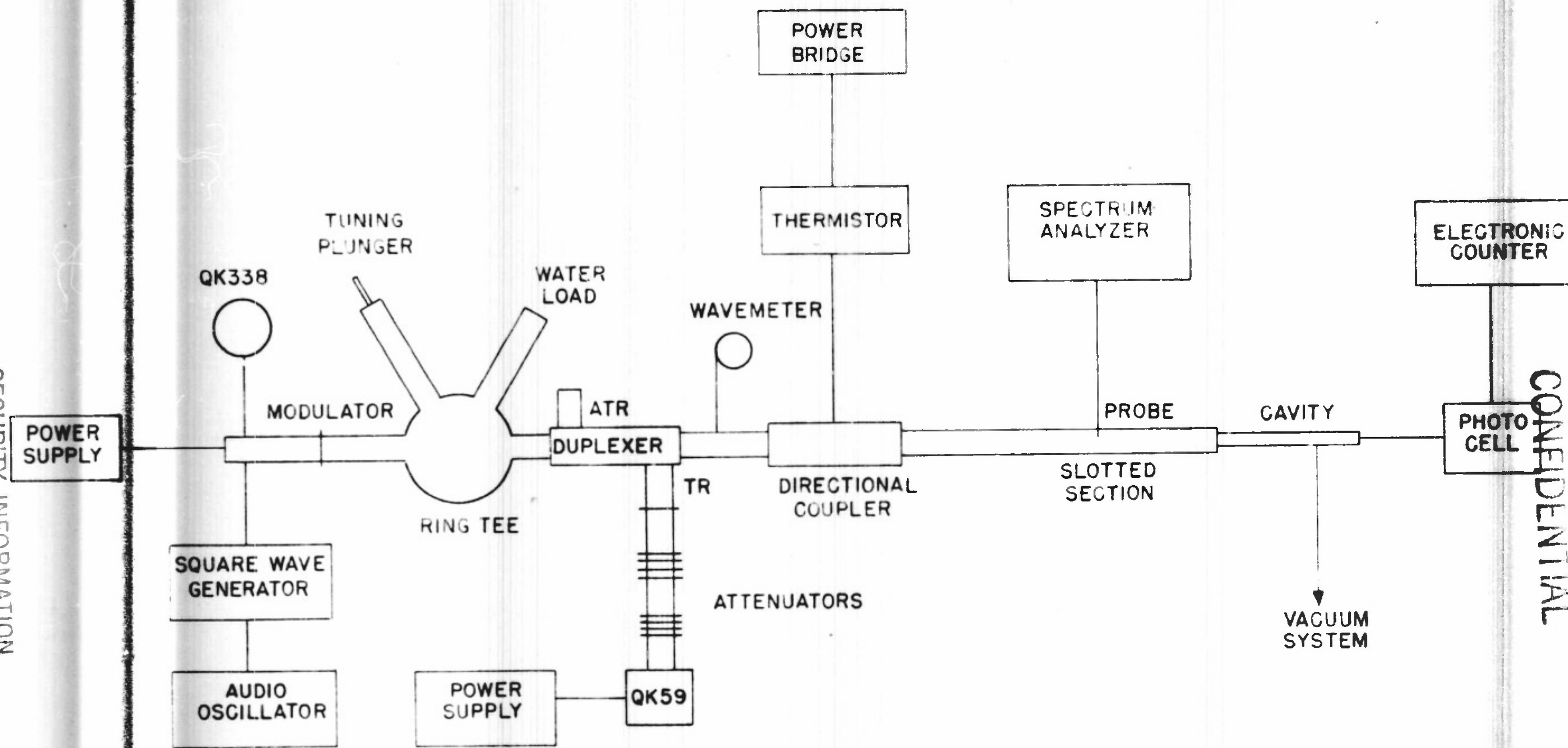

FIG. 8 - BLOCK DIAGRAM OF EQUIPMENT FOR PULSED MEASUREMENTS