THE DISCHARGE MECHANISM OF SELF-QUENCHING GEIGER-MUELLER COUNTERS

By

Sidney H. Liebson

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INTRODUCTION

The object of this investigation was to study the mechanism for the spread of the discharge along the length of the wire of a Geiger-Mueller counter. In proportional counting the pulses are localized and have amplitudes proportional to the primary ionization. The source of current amplification is ionization by electron impact, leading to the formation of a Townsend Avalanche.[1] The Geiger-Mueller region is characterized by the spread of the discharge along the length of the tube by a process previously shown to be photoelectric in nature.[2,3] The spreading of the discharge is supposed to depend on the excitation of certain spectral lines of the gas at a given field strength, corresponding to the threshold voltage.[4] Geiger-Mueller counting is also characterized by the self-quenching process resulting from the reduction of the field at the anode by the ion sheath.[5,6] At sufficiently high voltages a continuous corona discharge develops, which sets the limit to Geiger counting action.

1. M. E. Rose and S. Korff, Phys. Rev. 58, 850 (1941).

2. C. G. and D. D. Montgomery - J. Frank. Inst. 231, p. 447 and p. 509 (1941).
3. E. Greiner, Z. F., Phys. 81, 512 (1933).

4. L. S. Brown, Phys. Rev. 62 - 244 (1942).

5. C. G. and D. D. Montgomery, Phys. Rev., 57 - 1030 (1940).
6. Stever, H. G., Phys. Rev. 61 -38 (1942).

Several experiments have been conducted to determine the mechanism for the spread of the discharge. Greiner's experiments[3] on slow counters came closest to the intent of this investigation. He used two counters facing each other, in a common envelope. The anodes were separated at a fixed distance of about 1 cm. Measurements were made of the number of counts that originated in one counter and spread

across to the other, at different pressures. By means of these measurements he was able to deduce absorption coefficients for different gases. That the discharge depended on photon absorption was proven with the aid of ultraviolet absorbing films of celluloid. The most plausible explanation for the spread of the discharge through the film was photo-emission in the second counter produced by ultraviolet radiation penetrating the celluloid. In another experiment, insulating beads of different thicknesses and diameters spaced on the anode, localised the discharge between the beads.[7] In an experiment conducted by Ramsey,[8] two adjacent slow counters were triggered coincidentally when the discharge was initiated in one of the counters, but discharged randomly when a self-quenching gas mixture was used. Similar results were obtained by Curran and Strothers.[9] The arrangements in both experiments were such as to minimise the possibility that the discharge was being initiated by any mechanism other than photons. Another set of interesting experiments was performed by Stever[6] following earlier work by A. Brode. Stever used counters with divided cylinders and beads on the wire. In one most suggestive experiment, a glass bead on a wire served to stop the discharge spread at low values of E/p, but did not hinder the discharge at large values of E/p. This was interpreted to mean that the radius corresponding to the critical value of E/p was pushed out till the bead was well enclosed within it, and the discharge could then spread. The possibility of localization

7. M. H. Wilkening and W. R. Kanne, Phys. Rev. 62 - 504 (1942).

8. W. E. Ramsey, J. Frank. Inst. 321 - 393 (1941).

9. S. C. Curran and J. E. Strothers, Camb. Phil. Soc. Proc. 32 - 645 (1936).

of the discharge at the surface of the wire was ruled out by these experiments which indicated a mechanism in the gas, starting at the critical value of E/p. In another paper, Stever[10] used the divided

10. H. G. Stever, Phys. Rev. 59 - 762 (1941).

counter as a counter telescope where separate ionizing events were necessary in each segment to cause the segment to count. Other localization effects have been studied through the use of divided cathode cylinders with different voltages on each segment.[11] The

11. W. E. Ramsey, Phys. Rev. 61 - 96 (1942).

effectiveness of insulating beads in stopping the discharge from spreading was attributed by Wilkening and Kanne[7] to a combination of reduction of field intensity by accumulation of charge on the insulators, and to photon absorption by the vapor. Their results were interpreted to mean that the photon absorption in the gas was complete within a few electron mean free paths.

THEORY OF THE EXPERIMENTS FOR DETERMINING ABSORPTION COEFFICIENT AND NUMBER OF PHOTONS

The following work was undertaken to determine the nature of the process responsible for the spreading of the discharge. In order to measure the absorption coefficient of the spreading radiation, a double counter arrangement was used. One of the counters could be moved along its axis with respect to the other, in the same glass enclosure (See Fig. 1). The electronic circuits were so designed that a count could be kept of all discharges which spread from one counter to the other. Since the charge per unit length of a counter is a constant, those discharges which spread across the intervening gap, appeared as

pulses twice the size of those which developed in one of the counters. Assuming an absorption to take place, the probability of discharge spread must be a function of the total amount of intervening gas, or what amounts to the same thing, the probability of spread must depend on the constitution of the gas mixture, the distance between the counters, and the pressure. The ratio of the number of large (double-sized) pulses to the total number of pulses determines, w, the probability for spread of the discharge. In subsequent paragraphs it will be shown how this measurement can be used to derive both the absorption coefficient, μ, and the total number of photo-ionizations per unit length of the wire responsible for the spread of the discharge. Knowing the number of ions per unit length per discharge, the number of photo-ionizations produced per ion in the discharge, may be computed.

The absorption coefficient may be determined directly from measurements of w. If $e^{-\mu x}$ is the probability that a quantum appearing at the end of one counter wire will traverse a distance, x, then, $1 - e^{-\mu x}$ is the probability that a quantum will not traverse that distance. The probability that all of N quanta will be absorbed is $(1 - e^{-\mu x})^N$. It follows, therefore, that

$$w = 1 - (1 - e^{-\mu x})^N \tag{1}$$

is the probability that one or more will not be absorbed, or,

$$w = 1 - e^{-N e^{-\mu x}} \tag{2}$$

is the probability for a discharge to occur at large distances of x. Taking the logarithm twice, the result is

$$\log \left[- \log (1 - w) \right] = \log N - \mu x. \tag{3}$$

This is the equation of a straight line whose slope is given by $-\mu$,

and the y intercept by log N. To determine μ, the logarithm of $(1 - w)$ was plotted on a logarithmic scale as a function of x, and the slope determined from the experimental curves.

The value of N used in the calculations represented the total number of photons capable of photo-ionization, occurring at the end of the wire, and included the quantum efficiency, absorption, and related factors.

DESCRIPTION OF EQUIPMENT

The movable split counter was constructed of brass cylinders (Fig. 1) 5 cm. long and 2.07 cm. diameter, mounted in a pyrex glass envelope. The anodes were tungsten wires 0.031 inch in diameter, one of which was sealed directly to the pyrex envelope, and the other attached to a sylphon bellows and micrometer screw arrangement moving in a vacuum-tight brass housing to minimize side motion of the wire. The bottom cathode was movable through the same bellows. The brass housing was sealed to the pyrex envelope with de Khotinsky Cement. It was found necessary to provide another sylphon bellows system, coupled to that on the movable counter, so that the pressure was maintained constant, i.e., when the bellows in the counter was compressed, the compensating bellows expanded.

To correct for spurious effects in the determination of charge per pulse, the occurrence of point discharges, and errors in resetting the micrometer, control measurements of plateau, charge per pulse, and photon production were made on a split counter tube of the same general dimensions as the movable counter tube combination N, except that a fixed distance between cathodes of 1.4 cm. was employed, and the inner wire was continuous through the tube.

Figure 2 is a block diagram of the measuring circuits associated with counting the pulses, for absorption determinations. The output pulse voltage across resistance R was fed through a condenser to a cathode follower. A low value of grid leak (10,000 Ohms) was used in conjunction with a 50$\mu\mu$fd coupling condenser to differentiate the pulses, thereby accentuating changes in pulse shape. The purpose of the cathode follower was to isolate the counter tube from external circuits by virtue of the high input impedance typical of cathode followers, in addition to providing a low-impedance output for the input circuits of the two video amplifiers. The one video amplifier was used to amplify the signals which were fed to a self-triggered oscilloscope with sweep times of 5, 25, 100 and 500 microseconds. This served as a monitoring oscilloscope to indicate the shape and characteristics of the Geiger counter pulses. The band pass of the video amplifier was roughly 100 c.p.s. to 4 megacycles per second. The other amplifier output was connected to a conventional oscilloscope and to the input circuits of two scaler units. The scalers were conventional, Eccles-Jordon type scale of two multivibrators, giving 1 output pulse to every 16 input pulses. Mechanical inpulse recorders were operated by a thyratron tube used as output stage from each scaler. One of the scalers was supplied with an additional amplifier tube with adjustable gain, so that all pulses would register on its recorder, while the gain of the video amplifier was adjusted so that only the large pulses, those which propagated across the gap, could register on the other recorder. A mechanical timing control was connected to the scalers, so that the total number of large pulses, as well as the total number of all pulses, both large and small, could be recorded in the same time interval.

For each filling the data taken consisted of: the total number of counts per minute as a function of counter voltage for each counter; the average current flowing to the counter during the same time interval; and for the double counter, the number of double-sized pulses appearing per 16,000 total pulses.

Measurements of the current flowing through the counter were made in the ground return circuit of the counter anodes by means of a General Radio vacuum tube d-c amplifier, Model 715 A across whose input a 20μfd condenser was placed to minimize fluctuations. During a given time interval the number of pulses occurring were counted, thus giving the necessary data for calculating the charge per pulse.

MEASUREMENTS OF ABSORPTION COEFFICIENT

Figure 3 shows a typical curve of probability of propagation through the gas path between the cathodes of the movable double counter, filled with a mixture of 10 percent CH_2BR_2 and 90 percent argon at a total pressure of 10 cm. Hg., for different voltages between anode and cathode. Figure 4 shows the values of log (1 - w) plotted on semi-logarthmic graph paper as a function of distance between the cathodes of the movable counter system. From equation (3) it is easily seen that the slope of these curves determines the absorption coefficient for the spreading mechanism.

Table I tabulates three sets of absorption coefficients computed from the curves. The first set lists measurements of the slope. The second set consists of absorption coefficients, corrected to one cm. of pressure, assuming the absorption to be due only to the total amount of argon present. The third set consists of absorption coefficients,

TABLE I

ABSORPTION COEFFICIENTS

Pressure	Gas Mixture	Slope Measured From Curves		Absorption Coefficients Corrected for 1 cm. argon		Corrected for 1 cm. vapor	
		μ_1	μ_2	μ_{1A}	μ_{2A}	μ_{1B}	μ_{2B}
5 cm.	10% CH_2BR_2	7.0 cm^{-1}		1.25 cm^{-1}		14 cm^{-1}	
5	20 CH_2BR_2	5.2		1.73		5.2	
10	4 CH_2BR_2	13.5	5.8 cm^{-1}	1.41	0.6 cm^{-1}	33.7	15 cm^{-1}
10	10 CH_2BR_2	11.5	6.4	1.28	0.71	11.5	6.4
10	20 CH_2BR_2	12.1	5.5	1.51	0.68	6.1	2.8
20	10 CH_2BR_2	23		1.28		11.5	
10	5 C_2H_5OH		3.85*				
10	10 C_2H_5OH		5.8		0.64		5.8
10	20 C_2H_5OH		5.4		0.67		2.7
10	30 C_2H_5OH		5.8		0.83		1.6
20	5 C_2H_5OH		3.5*				

Weighted Average of μ_{1A} = 1.35

μ_{2A} = 0.69

* Low percentage of alcohol does not make counter with Geiger-Mueller characteristics.

corrected to one cm. of pressure, assuming the absorption to be due solely to the organic vapor.

The corrected values of μ_1 and μ_2 shown in Table I were obtained by dividing the values of μ_1 and μ_2 obtained from the curves by the associated partial pressures of argon. The weighted values were obtained by estimating the accuracy of each set of readings, assigning relative weighting factors to each, and averaging the results.

It may be assumed that the various errors involved in counting, filling to the correct pressure, and measurement of slope, were sufficient to account for the minor variations observed in both the absorption coefficients listed in Table I. That the geometrical arrangement did not introduce appreciable error in the measurements may be concluded from the fact that the data in general showed the same slope in spite of the different distances used, and that the slopes of the 5 cm., 10 cm., and 20 cm. total pressure, absorption curves yielded the same values of the absorption coefficient.

Measurements made on methylene bromide were based on a counting rate of about 20 per second, and a total count of about 16,000 counts, in order to minimize errors due to resolving time and limit the standard deviation of counts per seconds to about one percent. Measurements made on the alcohol counters were not as accurate and, in general, were conducted only as a control experiment to support the results obtained with methylene bromide. The poor results obtained with the five percent alcohol mixtures are in accord with results of Wilkening and Kenne[7] who found that counters made with less than five percent alcohol showed almost no localization effects.

The absorption measurements were repeated with fillings of neon-methylene bromide and helium-methylene bromide. The results with

these mixtures verified the conclusions that the absorption coefficient is a function of the gas alone. For a ten percent methylene bromide-neon mixture at 10 cm. pressure, the coefficient of absorption was 0.93 corresponding to 0.1 per cm. of neon. For helium, the coefficient was so small that accurate determination of the slope was not feasible.

Certain conclusions may be drawn from these data:

1. The absorption per unit pressure is constant, depending only on the amount of argon present. This data is overwhelmingly in favor of the assumption that absorption is due to the argon alone.

2. There are two different absorption constants indicating two different types of photons. At various percentages of CH_2BR_2 at 10 cm. total pressure both coefficients showed clearly. In alcohol-argon mixtures only one coefficient was observed from which it is concluded that the separation used during measurements was such that one type of photon had been almost completely absorbed when the separation was sufficient for readings to be taken. The larger value of the absorption coefficient is probably characteristic of the higher energy photon since it appeared more prominently as the voltage was increased.

3. From the shapes of the curves and their intersections with the log (1 - w) axis, it appears that the number of effective photons increased with voltage. As will be shown later, the function of the vapor seems to be to inhibit the production of photons in the discharge.

The diameter of the atom for the absorption process, C, may be defined by

$$\mu = N\pi\left(\frac{C}{2}\right)^2$$

where N is the number of atoms per c.c. Inserting a value of $\mu = 1.35/cm.$ for one absorption coefficient, and $\mu = 0.65/cm.$ for the other absorption

coefficient, the resulting values for the atomic cross-section of argon for the two types of photons are

$$\text{diameter } \sigma_{1.55} = 0.23 \times 10^{-8} \text{ cm.}$$

and

$$\sigma_{0.65} = 0.16 \times 10^{-8} \text{ cm.}$$

DETERMINATION OF THE RELATIVE NUMBER OF PHOTONS IN DIFFERENT MIXTURES

Equation (2) indicates that the experiment is well suited for the determination of N, the number of photons causing a photoelectric effect in the gas. Equation (2), rewritten as

$$\log (1 - w) = -AN \tag{4}$$

shows that for a fixed separation between counter cathodes, $e^{-\mu x}$ is a constant, A, and log (1 - w) is directly proportional to the number of effective photoelectrons. Accordingly, probability measurements were made on the double counter with fixed separation of 1.4 cm. as the voltage was increased throughout the plateau region. Typical results are shown graphically in Figure 5. The data in Table II clearly show the effect of the vapor on the number of photons available to propagate the discharge. The ionization data were obtained by measuring the average current flowing through the counter while the counts were being recorded, and converting to ions per cm. per discharge by dividing the charge per count obtained on one counter by 5.5 cm. (0.5 cm. allowance being made for end effects). In this experiment, the separation of the counters was such that only the $\mu = 0.65$ cm^{-1} type of photon was involved. More photons were produced in alcohol-argon mixtures than in equivalent proportions of methylene-bromide-argon mixtures. If the transition from the proportional region to the plateau region depends on the number of photons available for propagating the discharge, then

TABLE II

RELATIVE NUMBER OF PHOTONS PER DISCHARGE IN DIFFERENT MIXTURES

- MEASURED AT OVERVOLTAGE OF 100 VOLTS -

Pressure	Percent Vapor	Relative No. of Photons		Relative No. of Photons	
		C_2H_5OH	CH_2BR_2	C_2H_5OH	CH_2BR_2
5 cm.	5 %		16.5		35
5	10		12.0		28
5	20		8.0		12
10	5		9.1		30
10	10	17.0	8.0	45	24
10	20	23.0	6.4	43	19
10	30	36.0		110	

the results predicted that alcohol-argon counters should have lower thresholds, in agreement with observation. This was also borne out by the greater slope of photon increase in alcohol-argon counters. This greater increase of slope presumably is related to the fact that alcohol-argon counters have a smaller plateau before breaking into a continuous discharge. It was observed that the increase in rate of ion formation with voltage was almost a constant, independent of the type of vapor or percentage composition.

The data for alcohol-argon mixtures showed an increase in the number of photons relative to ions as the percentage of alcohol vapor was increased. A possible explanation might be that in alcohol, single ionization and dissociation occur, with the electron by-product of the ionization contributing to the further production of photons. However, the data for alcohol would not be consistent with the fact that the discharge may be heavily quenched by the further addition of alcohol.

CONCLUSION

To understand the role of the organic vapor and its effect on the spread of the discharge, let us first consider the action taking place in the slow counter, i.e., a counter filled with monatomic gas. In the course of the discharge, several types of photons are created. The first type consists of photons derived primarily from excited neutral atoms. These photons lie in the visible and near ultraviolet region, and help perpetuate the discharge by the ejection of photoelectrons at the cathode. These photons do not cause ionization within the gas itself because of their low energy. The second type of photon is derived from the excited singly or doubly ionized gas atom, and may either eject photoelectrons from the cathode cylinder, or what is more

probable, because of the opacity of the gas in the wave length region involved, cause photoelectric emission in the gas itself. The emitted electrons then serve to trigger the formation of new Townsend Avalanches. On the basis of previous hypotheses, it was assumed that the organic vapor served to absorb radiation in the ultraviolet, thus minimizing photoelectric action at the cathode and in the gas. The experiments conducted above invalidate these assumptions.

Many of the photons from excited argon, originating in the avalanches, lie in the range of 11.5 to 15.7 e.v., corresponding to 1070 $\mathring{A}$ to 790 $\mathring{A}$. The photoelectric threshold of the cathode in most cases is about 4 e.v. Thus, for localization of the discharge to the region in the immediate vicinity of the wire, either these photons must be strongly absorbed in the gas mixture, as hypothesized by Ramsey,[8] or the number of photons produced should be lowered to the point where photoelectric action at the cathode has a sufficiently low probability.

The results presented here show quite definitely that the mechanism of the spreading discharge, previously shown to be photoelectric in nature, is a function of the rare gas alone. The experiments suggest that ionization is also produced after the initial avalanche, by photons originating from A^+ excited ions, lying in the range of (43.3 - 15.7) e.v. = 27.6 e.v. The function of the vapor is to poison the production of photons in the discharge and does not contribute appreciably to photon absorption. This behavior could be explained by the electrons in the avalanche losing their energy through excitation and decomposition of the organic vapor molecules. This interpretation is in agreement with the experiments of Spatz[12] in which it is shown

12. W. D. B. Spatz, Phys. Rev. 61 - 236 (1915).

that the organic vapor is rapidly decomposed in the course of a discharge. That this process is so effective is due primarily to the fact that the energy necessary for excitation and decomposition of the vapor is considerably less than the energy required for the production of suitable photons to spread the discharge. Finally, the fact that the absorption coefficients are dependent only on the absolute amount of rare gas in the counter, definitely places the photoelectric action as a process occurring in the gas alone, and cannot be attributed to the vapor.

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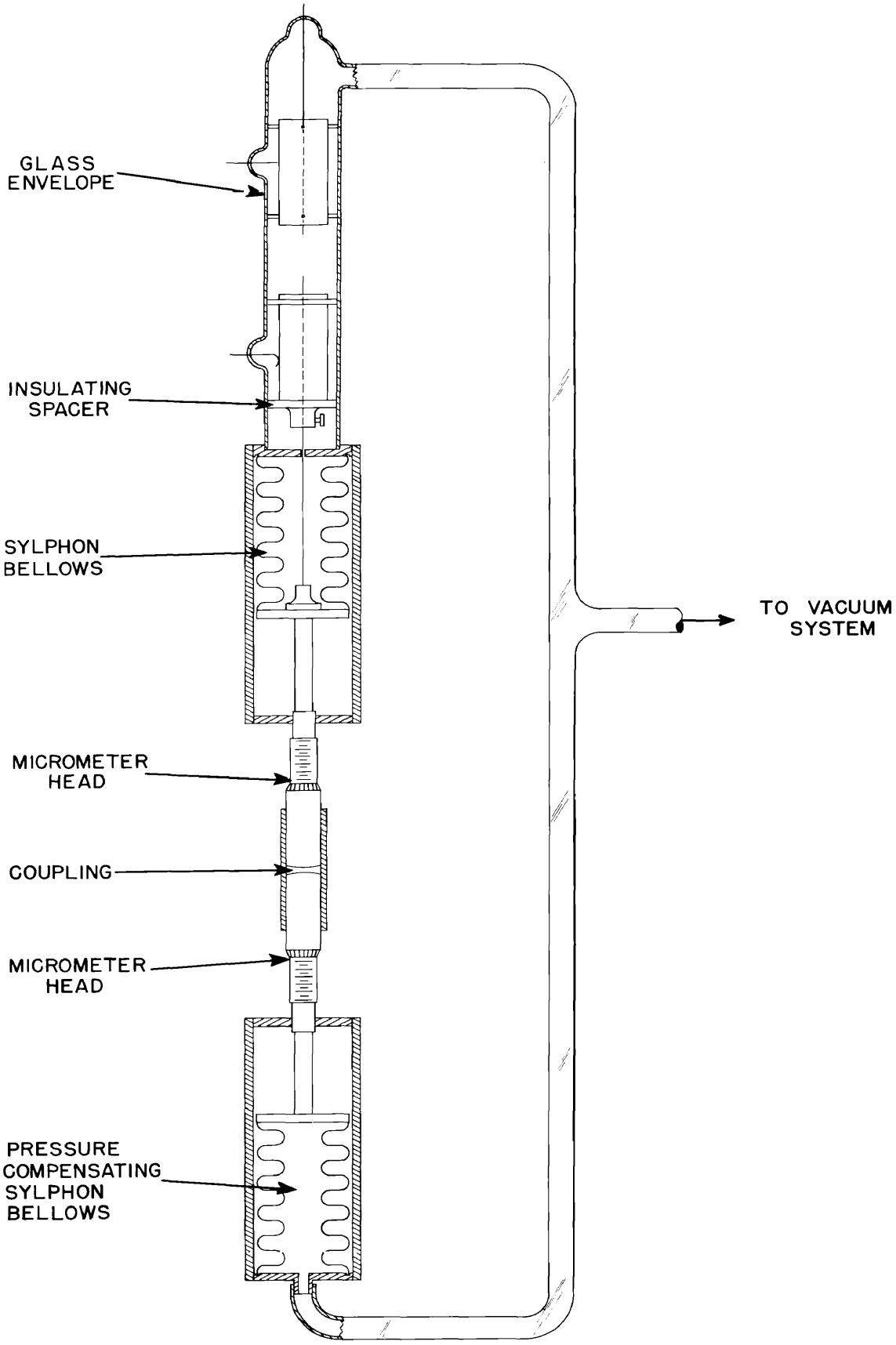

FIGURE 1 - THE MOVABLE DOUBLE COUNTER

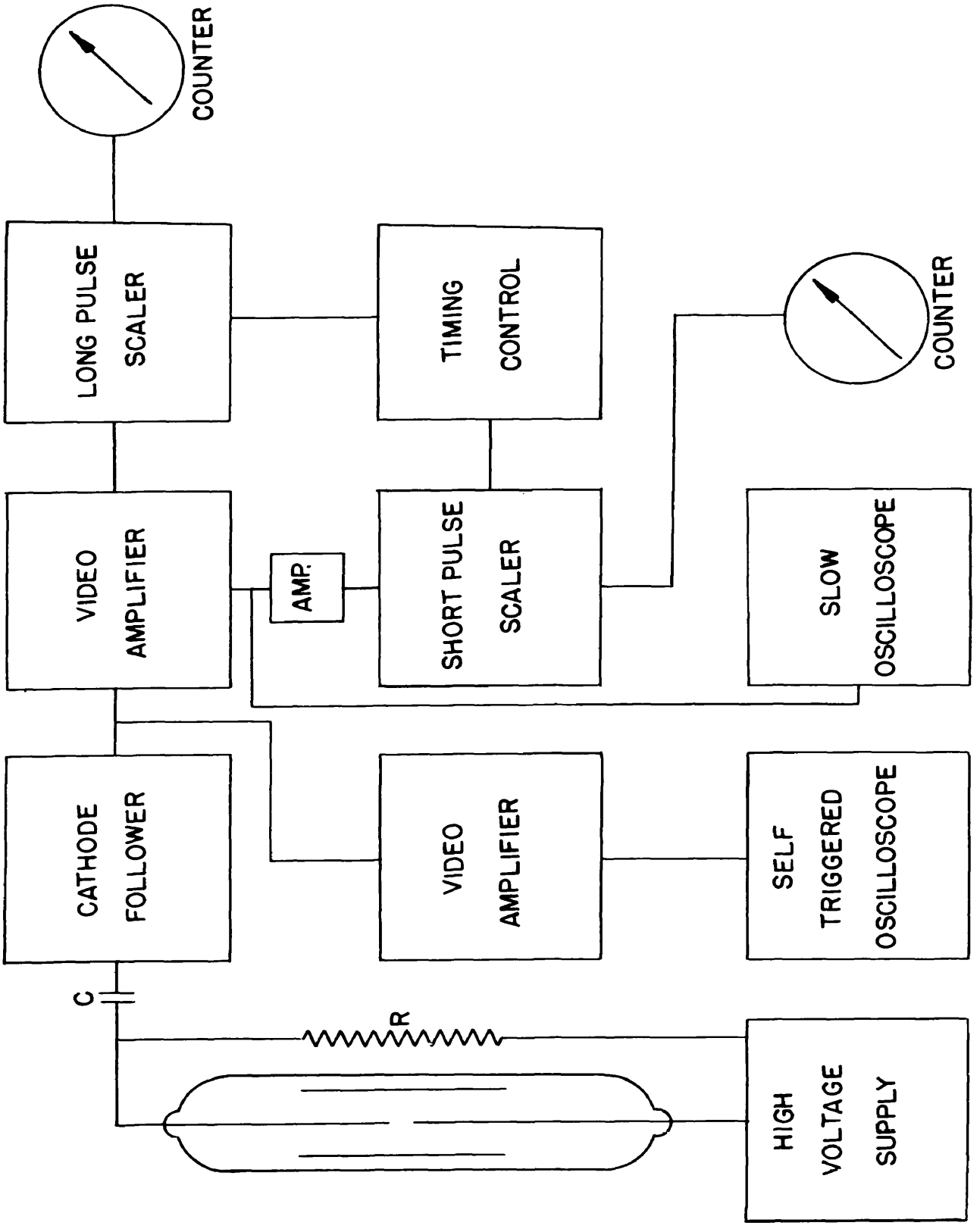

FIGURE 2 - BLOCK DIAGRAM OF ANALYZING CIRCUITS

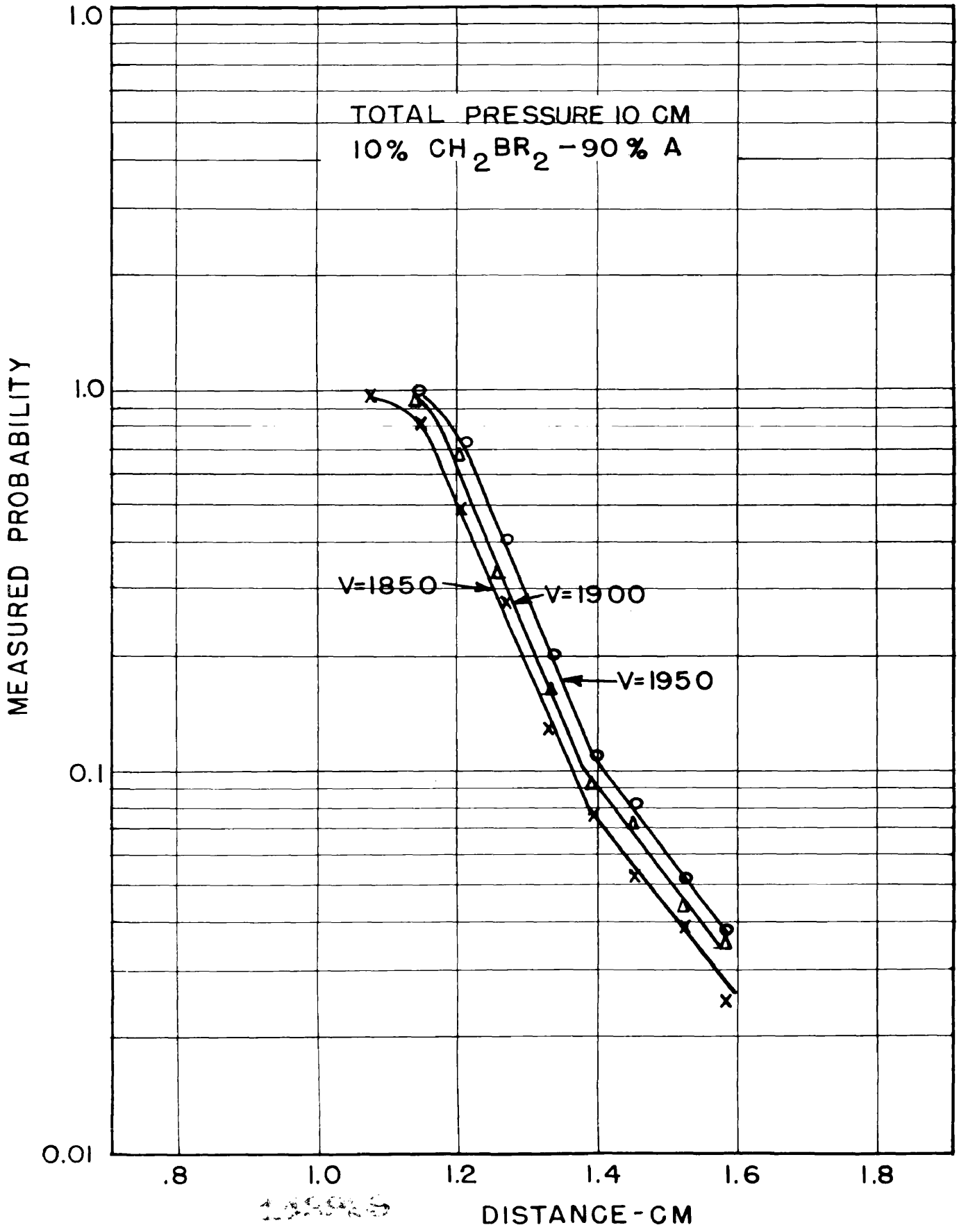

FIGURE 3 - TYPICAL PROBABILITY CURVE

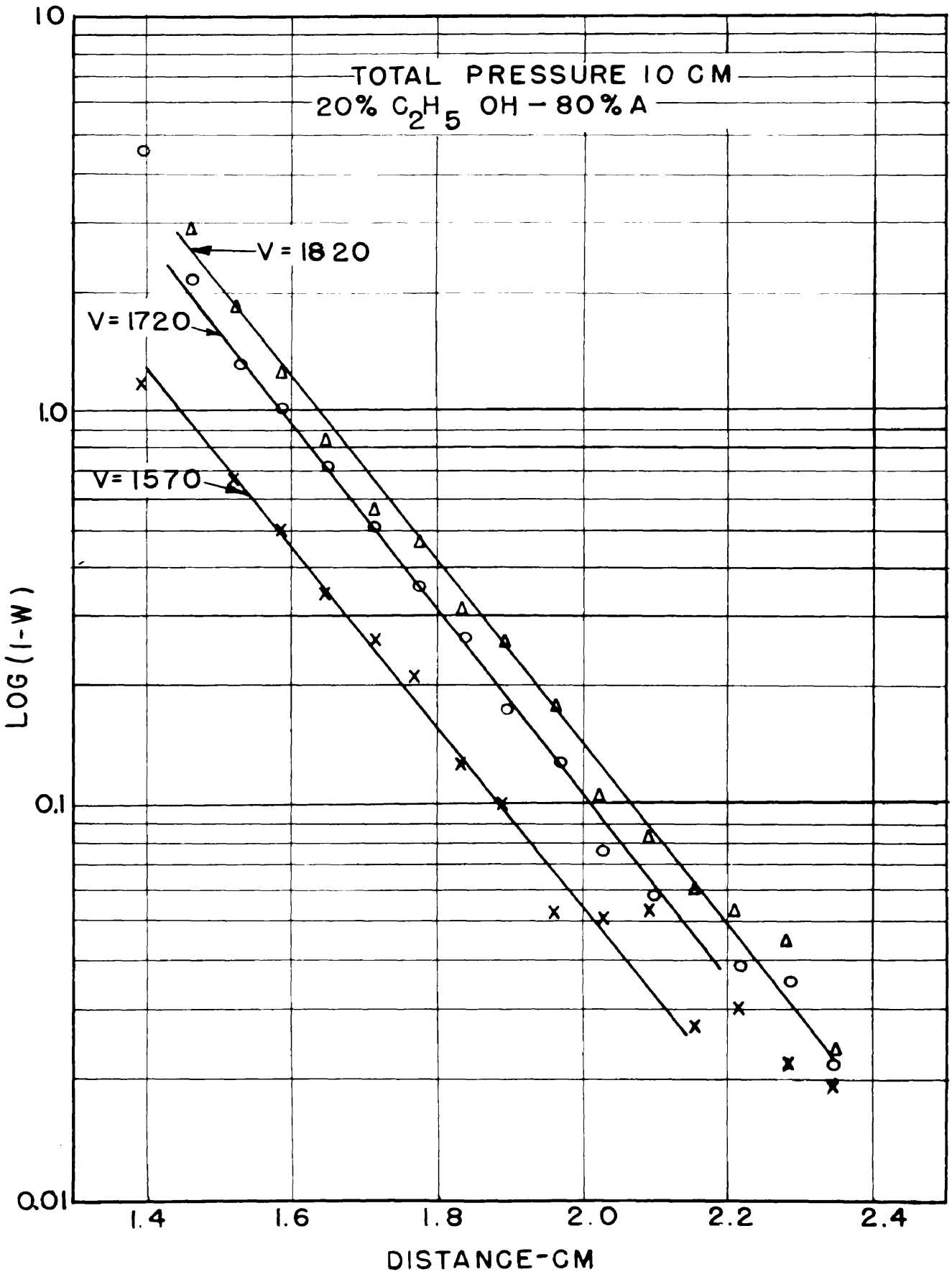

FIGURE 1 - TYPICAL ABSORPTION CURVE

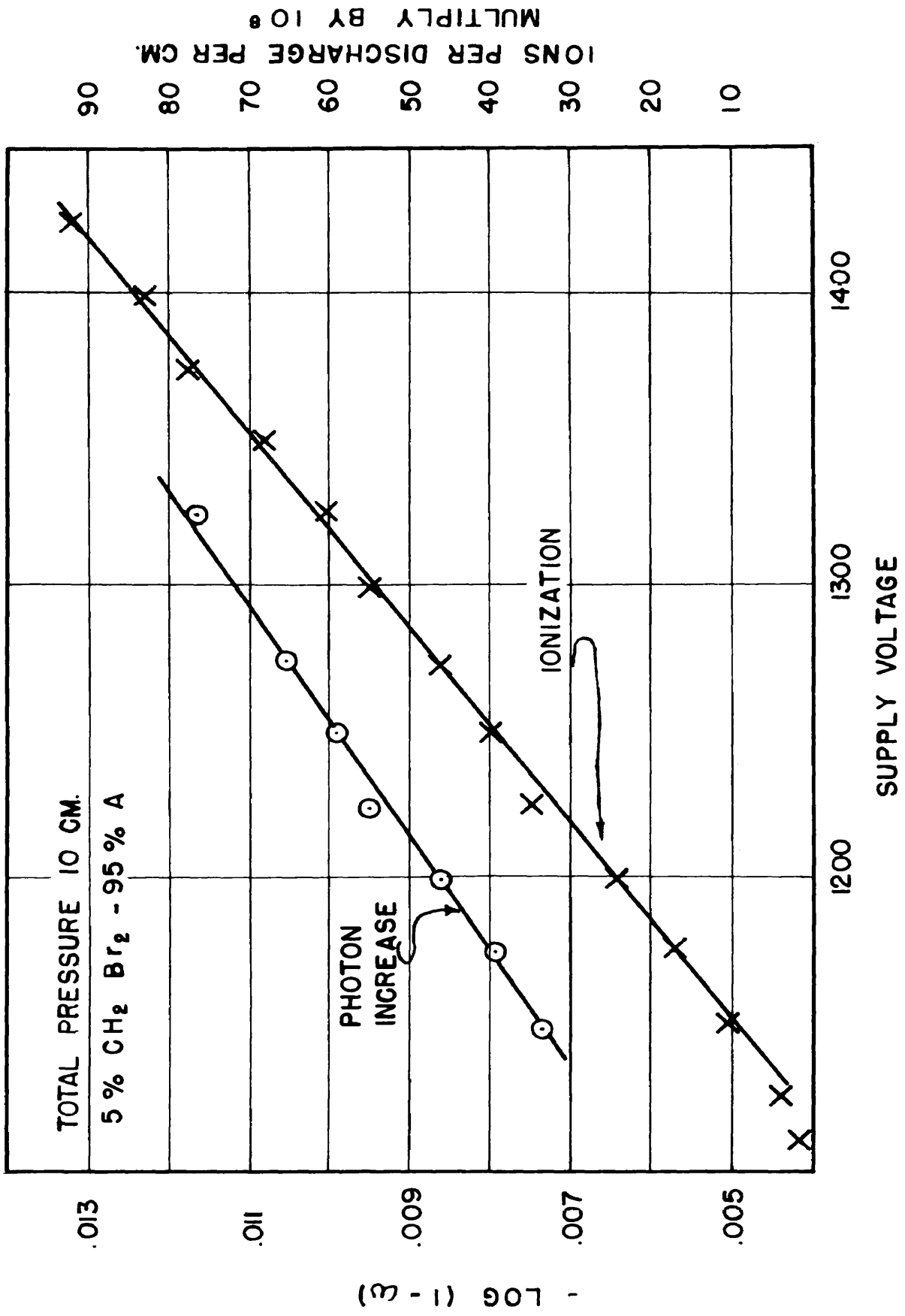

FIGURE 2 - IONIZATION AND PHOTON INCREASE CURVES