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# FORMATIVE TIME LAG AND PROBABILITY OF FIRING OF COHERERS

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## ABSTRACT

During the last five years there have been several studies of coherers as possible computer storage elements. These studies have for the most part been dropped on account of poor reliability or slow time constants. A study has been made of the cohering phenomenon to fix more accurately its statistical nature. The pre-breakdown current and its associated formative time lag plus its statistical time lag are measured for the dielectric breakdown and welding of coherers for different ranges of pulse length and repetition rates. The mean firing voltage is obtained over a range of pulse lengths from $10^{-6}$ to 100 seconds. A constant voltage effect is found at one stage in the pre-breakdown current growth. Sets of conditions are found for which coherers have a Gaussian probability distribution of voltage versus probability of firing.

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## TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

## I Introduction

Basically a coherer is a cell with two electrodes between which a quantity of metal powder is placed as illustrated in Fig 1 The metal powder particles are coated with an oxide or other tarnish film which makes the cell initially insulating A typical cell would have a resistance of the order of $10^9$ to $10^{11}$ ohms Above a critical voltage the oxide layers tend to break down so that the coherer fires or "coheres" After cohering the cell resistance is a few hundred ohms A sharp mechanical shock, such as the tap of a hammer on a relay armature will break up the cohered chain, restoring the cell to its original high resistance Shaking the particles during decohering turns most of the eroded spots to the side leaving principally fresh layers of oxide along the vertical paths

A coherer is a potentially cheap storage element for slow-speed computer applications, yet experimental models of coherer storage exhibit a percentage of errors which though small is enough to make them undesirable for use in the computer field where accuracy is imperative If the physical nature of cohering can be determined, then the limitations on the coherer can be better understood

Coherers were used as detectors in the early development of radio by Marconi[1] in England and Popoff[2] in Russia in the 1890's.

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[1] G Marconi, Application of Guglielmo Marconi for Improvement in Transmitter Electrical Impulses and Signal and in Apparatus Therefore "British Patent Specification No 12,039 (June 2, 1896)

[2] A. S Popoff, Journal of the Russian Physical and Chemical Society, 28 (1896) Partially reported in letter in Electrician, 40, 235 (1897)

In 1917 E. C. Green summarized the history of coherers from the early experimenters dating back to 1835, who demonstrated coherers as scientific curiosities, through extensive use as detectors in early radio communication development, and various secondary applications such as lightning arresters[3]. He outlined the conflicting theories of coherer action and stated that the real way in which coherence occurs was still a problem to be solved. R. Holm[4] narrowed down the alternative theories of coherer action by showing that the cohered state corresponded to welded bridges of metal. His work on coherer action was directed principally toward understanding the destructive welding of relay contacts and commutator bars.

The Mellon Institute[5] and the Harvard Computation Laboratory[6] made extensive tests of different metal powders and logical arrangement of coherer cells for computer storage and decoding logic. J. P. Eckert[7] in a survey of all known potential storage devices for computing included coherers as a possible low cost storage element restricted in application by its slow decohering time.

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[3] E. C. Green "The Development of the Coherer and Some Theories of Coherer Action". General Elec. Rev. 20, 369-374 (1917) also Sci. Am. S. 84, 2689 (Oct. 27, 1917)

[4] Ragnar Holm, Electric Contacts, Stockholm: Hugo Gebers Forlag (1946) pp. 131-143, 354-6.

[5] Mellon Institute of Industrial Research, Quarterly Reports of the Computer Component Fellowship, No. 347, Report No. 1, 2, 3, 4, 5, and 12 (1951 - 1953)

[6] Harvard University, the Computation Laboratory, Progress Report No. 8, "Electrochemical Computer Elements" pp. 8-XII-1 - 8-XII-10 (1951 ?) (Report numbers and date to be verified).

[7] J. P. Eckert, Jr., "A Survey of Digital Computer Memory Systems" Proc. IRE, pp. 1393-1406, Oct. 1953, p. 1405

Both the earlier studies and these more recent investigations of coherers tabulated the firing voltage as a d-c voltage. To carry out the postulate that coherer action is a dielectric breakdown phenomenon would require testing the coherers with varying pulse length and voltage. Since dielectric breakdown processes are physically statistical in nature, coherer tests should also be conducted under conditions to observe the possible statistical variation of the breakdown voltage.

The purpose of this study is to 1) check experimentally the firing characteristics of coherer cells to see if the voltage and time functions agree with the known characteristics of dielectric breakdown, 2) determine what type of probability function expresses the characteristics of firing plus welding in a form corresponding to the potential use as a storage element, 3) determine the shift in the probability curves with change in pulse length, and 4) measure the shift in the probability curves with time which would determine the useful life of coherers.

## II Pre-Breakdown Current, Non-Linear Resistance Region, Constant Voltage Region, and Total Time Lag.

A. Pre-Breakdown Current: The most plausible explanation of cohering is that the cohering is initiated as a dielectric breakdown phenomenon which may be enhanced by arcing through the oxide layers, electrostatic pulling of the powder particles, and plastic flow of metal into the holes in the oxide layers. After the breakdown current reaches a certain magnitude, the heat melts enough metal to form welds.

Experimental evidence supports the theory that a metal filament or bridge of metal is formed between adjacent metal spheres R Holm[8] for example, has reported on measurements of the temperature coefficient of resistance of the bridges, and found that it is positive as it should be for a metal wire Furthermore H, Singhaus[9] has obtained plots of pre-breakdown current in coherer cells as a function of time at constant voltage shown in Fig 2, which has the same form as those of von Hippel[10] for other dielectrics. This establishes that the pre-breakdown current has the same form as that obtained in dielectric breakdown

B <u>Non-Linear Resistance Region:</u> Tests were made of the pre-breakdown resistance using the experimental setup of Fig. 3 The results are plotted in Fig 4 Curve A shows the actual experimental points for a test in which the shunt resistor switch was set to A'' in Fig 3 while the voltage of the power supply $V_1$, was slowly increased After each increase in $V_1$, the electrometer voltage $V_2$ was recorded When the voltage $V_2$ reached the limit of the electrometer, the switch was turned to shunt resistors B, C, , H in turn The voltage across the coherer was calculated from:

$$V_c = V_1 - V_2 \qquad (1)$$

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[8] R Holm. op. cit. p. 134

[9] H. E Singhaus. private communication

[10] A Von Hippel. Phys Rev 54, 1096 (1938) also in Mott and Gurney, Electronic Processes in Ionic Conductors, second ed; Oxford (1948), p 196

[11] R. Holm. op cit. p 132

The current through the coherer was calculated from:

$$I = (V_2/R')(1 + R'/R_0), \qquad (2)$$

where $R_o = 10^{12}$ ohms and R' is the shunt resistor at the switch position B through H The resultant cohered state is shown as curve A' Additional curves B through H are plotted, which are for the condition of varying the power supply voltage $V_1$ over its full range while leaving the shunt resistance fixed at the indicated position.

The time of application of these voltages was held to a few seconds for each point, but was not accurately controlled These curves are equivalent to the RV-characteristic of R Holm, but are plotted in a more convenient form for comparison with non-linear characteristics of semi-conductors such as Silicon Carbide as reported by Schwertz and Mazenko[12]

The prefiring resistance is linear below $I = 10^{-10}$ amperes and is

$$I = K V^7 \text{ for } 10^{-10} < I < 10^{-5} \text{ amperes.}$$

C Constant Voltage Region: Examination of the peak of curves A, F, G, and H in Fig 4 indicates the possibility of a constant voltage reason possible for $10^7 \geq R' \geq 10^6$ ohms, provided the time of application of the voltage is controlled so the effect is not masked by the growing of the current with time shown in Fig 2 Curve F of Fig 4 was repeated with a fresh powder and was completed quickly to avoid the buildup of the pre-breakdown current at fixed total voltage The results are plotted on a trilinear graph in Fig 5 A second run was made with $R' = 2 \times 10^7$ ohms, which did not give as good a constant voltage

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[12] F A. Schwertz and J J Mazenko "Non-Linear Semi-Conductor Resistors" J A P 24, 1015 - 1024 (August 1953)

characteristic

The trilinear chart is a way of plotting a locus of the equation:

$$V_1 = V_c + V_R \tag{3}$$

This permits us to observe the region of any constant voltage effects Since the series resistance R is kept constant during the test, the $V_R$ scale can also be marked in current. This arrangement of the experimental data shows some correlation with the time delay effect shown in Fig 6 The oxide layer apparently must have a certain amount of energy put into it before breakdown can occur

Examination of Fig. 5 shows that this coherer must have its effective resistance reduced to three megohms before cohering can take place For cohering there are two independent conditions: the firing voltage and the critical resistance or the firing voltage and the pulse length. The constant voltage region shown on this tri-linear graph paper suggests an interesting application of coherers. The use of the coherer as a voltage regulator is indicated. The disadvantages of a coherer voltage regulator are that it has a very small current, and that if the voltage to be regulated goes too high the coherer will fire requiring a mechanical decohering shock to restore it When a coherer is placed in series with a limiting resistor of the right value and the total voltage is varied, there is a range where the coherer maintains an approximately constant voltage Where another regulator keeps the voltage below that at which the coherer fires, a coherer in series with an appropriate limiting resistor can provide a supplementary regulated voltage. Thus, additional regulated voltages with small current drain capacity can be added to a conventional voltage regulator by adding inexpensive coherers, but would be suitable for high impedance devices only.

Experimental tests were run on a coherer voltage regulator with 10-megohm series resistance. A regulated voltage of 54 ± 2 volts across the coherer was obtained as a total voltage varied between 100 and 160 volts. The usefulness of this coherer voltage regulator is restricted by the high probability of firing when the voltage is greater than 130 volts for long lengths of time.

D. Total Time Lag: Examination of the curves of H. Singhaus in Fig. 2 show that the pre-firing current plotted against time approaches a limiting time or total time-lag for cohering for any particular voltage. For example, at $V = 75$ volts, the total time lag $T_T = 73$ minutes for the NE-2-bulb cell coherer with nickel-powder. The curves of Fig. 2 are single tests at each voltage.

An experimental curve of firing voltage versus pulse length over extended range of pulse length from $10^{-6}$ to 100 seconds is given in Fig. 6. To simplify the experiments, the data was taken for 50 per cent probability of firing. This means that the firing voltages in this curve correspond to the mean firing voltages on the probability of firing curves discussed in the next section. The mean firing voltage for the particular coherer of Fig. 6 is empirically:

$$V = 70\,t^{-\,075}\ \text{(volts)},\ \text{for}\ 10^{-6} < t < 100, \qquad (4)$$

where t is the pulse length in seconds. This type of curve is similar to the variation of dielectric breakdown voltage of electric power line insulators as a function of pulse length.

## III Probability Distribution of the Firing of Coherers

Experiments were made in which a coherer cell was alternately pulsed with a fixed voltage and decohered An oscilloscope was connected across the coherer to observe the time interval required to cohere. A count was made of the number of pulses terminating during each one-hundred-micro-second block of time This gave the block distribution curve of Fig 7 These results suggest the existence of a basic time delay in the cohering process upon which is superimposed a statistical time delay, but the time intervals used in the experiment of Fig 7 are too coarse to permit an accurate separation of the two components of the time delay Therefore, a new experiment was designed to experimentally obtain these constants.

This new experiment used a series of pulses to determine the time to cohere by counting the pulses on a Brush recorder. The equivalent total time was taken as the product of the number of pulses times the basic pulse length. In the range of voltage and pulse length used in these experiments, a few points were checked by comparing the probability of firing for two cases: 1) a coherer subjected to one pulse of voltage V and pulse length $\tau$; 2) a coherer subjected to n pulses of voltage V and pulse length $\tau/n$. It was found that when the n separate pulse occurred within a period of one minute or less that the probabilities for the two cases were approximately the same. The experimental cam-operated cycling of a wheatstone bridge circuit is shown in Fig 8

By choosing a finer powder requiring a higher cohering voltage a series of curves of per cent failing to cohere was plotted against the number of pulses and are shown in Fig. 9 Plotting the experimental points in per cent failure to cohere enables us to find the formative time lag ($T_F$) and the statistical time lag ($\sigma$) as follows. By drawing a straight line approximation to the experimental points for a given voltage in Fig 9, the intersection of the line with N = 100 per cent failure gives the formative time lag ($T_F$). Then the time interval from N = 100 per cent down to N = 100/e = 36 per cent gives the statistical time lag ($\sigma$). These curves have the same form as those obtained by Inushi and Suita[13] for dielectric breakdown in KCl single crystals.

Earlier experiments of H E Singhaus[14] indicated a Gaussian probability distribution over a narrow range of variables. If this condtion were true over a very large range of the voltage with other conditions remaining fixed, it would be possible to determine the conditions for a specified error rate Next a set of experiments were designed to approximate the conditions under which coherers might be used Pulse lengths much greater than the sum of the formative time lag plus the statistical time lag were selected Experiments were run with a fixed pulse length and repetition rate, using the same wheatstone bridge to fire, read, decohere, and read. The experimental points are shown in Fig 10. Plotting on gaussian probability paper[15] shows that the experimental points distribute closely around a straight line which

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[13] Y Inushi and T. Suita, "Time Lag in Dielectric Breakdown of Single Crystals" J Phys. Soc. Japan 7. 641-693 (1952)

[14] H. E Singhaus. private communication

[15] Special graph paper with gaussian probability scales is available from: Codex Book Co , Norwood, Mass

shows the probability function is very close to gaussian for these condtions Drawing a straight line through the experimental points of Fig 10 corresponds to the following equation for the probability of the coherer firing:

$$P(R_c < R'/A) = (1/\sqrt{2\pi\sigma^2}) \int_{-\infty}^{V} \exp\left[-(v-\mu)^2/2\sigma^2\right] dv \qquad (5)$$

Where: $R_c$ = the resistance of the coherer after applying the pulse of voltage V and duration $t_o$

$R'$ = the reference resistance which is acceptable for the cohered state,

$\sigma$ = the standard deviation

v = the variable voltage,

$\mu$ = the mean voltage,

A = the conditions applicable to the particular coherer

In Fig 10 the specific values of the parameters are as follows:

A = Given the coherer cell is 0 200" long, filled with Bronze Powder MD-61HP, mesh -80 + 100, with 1/8" diameter electrodes, having a series limiting resistor of 30,000 ohms. with the pulse length, $t_o$ = 0 0052 seconds, and the repetition rate is 7 cycles per second

$R'$ = 10,000 ohms, meaning a cohered resistance of 10.000 ohms or less is satisfactory for reading the coherer as in the cohered state

$\mu$ = 92 volts; $\sigma$ = 10 volts; $\sigma^2$ = 100 (volts)$^2$

The resultant equation is:

$$P\ (R_c < 10k/A) = (1/\sqrt{200\pi}) \int_{-\infty}^{V} \exp\left[-(v-92)^2/200\right] dv \qquad (6)$$

In Fig 10 the circles "o" are actual experimental points, for example, the point at V = 38 volts and $P = 10^{-6}$ means that one misfiring was recorded in one million cycles The "sun" symbol "$-\phi-$" at V = 134 volts and $\overline{P} = 5 \times 10^{-6}$ means that a run of $10^5$ cycles was made with no failures to fire, so to be conservative a second run of $10^5$ cycles was assumed with one error making a total of one error in $2 \times 10^5$ cycles, giving an upper bound of $\overline{P} = 5 \times 10^{-6}$.

## IV. Reliability of Coherers

The reliability of coherers is dependent first upon the nature of the relationship between the probability of firing and the applied voltage and pulse length, and second upon how well this relationship remains constant throughout the life of the coherer. If we want to have a probability of error of less than one in 500,000 cycles with the bronze powder cell of Fig. 10, which has a Gaussian probability distribution, we specify a maximum probability of firing on reading of one in a million and a maximum probability of failing to fire on writing of one in a million For 0 0052 second pulses and other conditions as specified in Fig. 10, the required voltages are read off of the curve, showing that the reading voltage must be less than 43 volts and that the writing voltage must be higher than 140 volts to stay within the specified error probability We must then subtract and add tolerances to these values for the spread of the experimental points about the average curve Fresh powder from the vendor changes its probability of firing during the first hour of operation so that the powder must be processed before use The processing can consist of repeatedly firing the powder in a coherer cell until the firing voltage levels off, or it can consist of reducing the oxide layers of the powder particles by heating in hydrogen to remove the original oxide layer, allowing a more uniform but thiner oxide layer to grow

Simple oxide layers are variable in thickness depending upon the temperature of the original formation of the powders and its subsequent history The regrowth of the oxide on a bare spot starts out quickly and then tapers off slowly Simple oxide coated particles either increase or decrease their firing voltage with time The firing voltage increases if the oxide layers grow thicker at a rate faster than the material is removed in decohering. The firing voltage decreases, if the oxide is removed, either electrically or from mechanical abrasion faster than the oxide layers regrow

Experiments were made with ways of controlling the oxide layer on the spheres. Copper powder was reduced in hydrogen to remove the original layers of oxide and was then treated with corrosion inhibiting chemicals. A small layer regrows which is more uniform Coherers using copper which has been hydrogen reduced have given more reliable life test data A sample curve for such powder is given in Fig. 11 Examination of Fig 11 shows that the treated powder is still very close to the starting probability curve after 98,000 firings.

The examples shown in Figs 10 and 11 fit Gaussian probability curves very closely This is not always the case; experiments were run in which repetition rate was increased to the point that insufficient rest time was allowed after decohering These results are shown in Fig. 12 which shows that increasing the repetition rate from five to ten per second destroys the Gaussian probability distribution of cohering

## V. Conclusions

The coherer is an interesting device which has characteristics similar to certain basic physical phenomena, described as follows The pre-breakdown current growth with time with a fixed applied voltage has a form similar to dielectrics such as mica and KCl crystals. The pre-breakdown resistance of coherer cells is similar to the characteristic of semi-conductors such as cells of silicon carbide particles. There is a constant voltage region whereby the voltage across the coherer remains constant during an increase of the voltage across the coherer plus a series resistor of a certain magnitude. Study of the constant voltage curves indicates the pre-breakdown current must reduce the coherer resistance to a certain critical value, before dielectric breakdown takes place

The mean voltage for cohering decreases with increasing the pulse length as is the case for the dielectric breakdown of insulators. Conditions have been found for which the probability of cohering as a function of voltage, the pulse length remaining fixed, becomes a Gaussian probability function The existence of this probability of firing function makes it possible to predict the accuracy of a coherer design, provided the voltage and pulse length of all electric waves including transients to which the coherer will be subjected are known

Several tests of 100.000 cycles showed that the charge of the probability of firing curves remained within 15% of the original curves and that the standard deviation came back close to its original value after a breaking-in period

## Appendix -- Coherer Powder

No accurate measurements were made of the oxide film thickness of the coherer spheres. Approximate values of the film thickness have been calculated using electric field strength required for dielectric breakdown of oxides. As an example, consider the bronze powder used in Fig. 4.

The gap between the electrodes in 0.080 in. and average particle diameter is 0.0032 in. giving a minimum of 25 particles in the gap. Since each particle has two layers, there are 50 layers in the path. For $Cu_2O$ the breakdown field is approximately $0.4 \times 10^6$ volts per centimenter[16]. The total layer thickness for 80 volts at breakdown is $200 \times 10^{-6}$ cm. Dividing by 50 layers gives an approximate thickness per layer of $4.0 \times 10^{-6}$ cm or 400 Ångstrom units. In the absence of data on the proportion of tin and copper oxides in the oxide surface of bronze particles, the parameter for $Cu_2O$ have been used to obtain the order of magnitude.

In the case of the hydrogen reduced powder of Fig. 11, the average particle diameter is 0.0075 in. Dividing the 0.200 in. gap by the particle diameter gives 266 particles. The 114-volts mean firing voltage divided by 533 layers gives 0.214 volts per layer. This corresponds to a thickness of 53.5 Ångstrom units.

The different metal powders used in the experiments are identified in Table I.

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[16] R. Holm, op. cit., p. 142

# TABLE I

## Check List of Coherer Materials Used in Curves in this Report

| Figure No. | Material | Mfg. No | Lab No | Size | Surface Treatment | Cell Size |
|---|---|---|---|---|---|---|
| 2 | Nickel | | | | | NE-2 |
| 4, 5 | Bronze | MD-153-A | AA-49E | (-170+200) | | NE-2 |
| 6 | Bronze | MD-153-A | AA-49E | (-170+200) | | 0.200" |
| 9 | Bronze | | AA-49E | | | 0.200" |
| 10 | Bronze | MD-61HP | AA-14D | (-80+100) | | 0.200" |
| 11 | Copper | | AA-53 | (-72+80Sp) | Special | 0.200" |
| 12 | Copper | | AA-42 | | Reduced in Hydrogen | 0.150" |

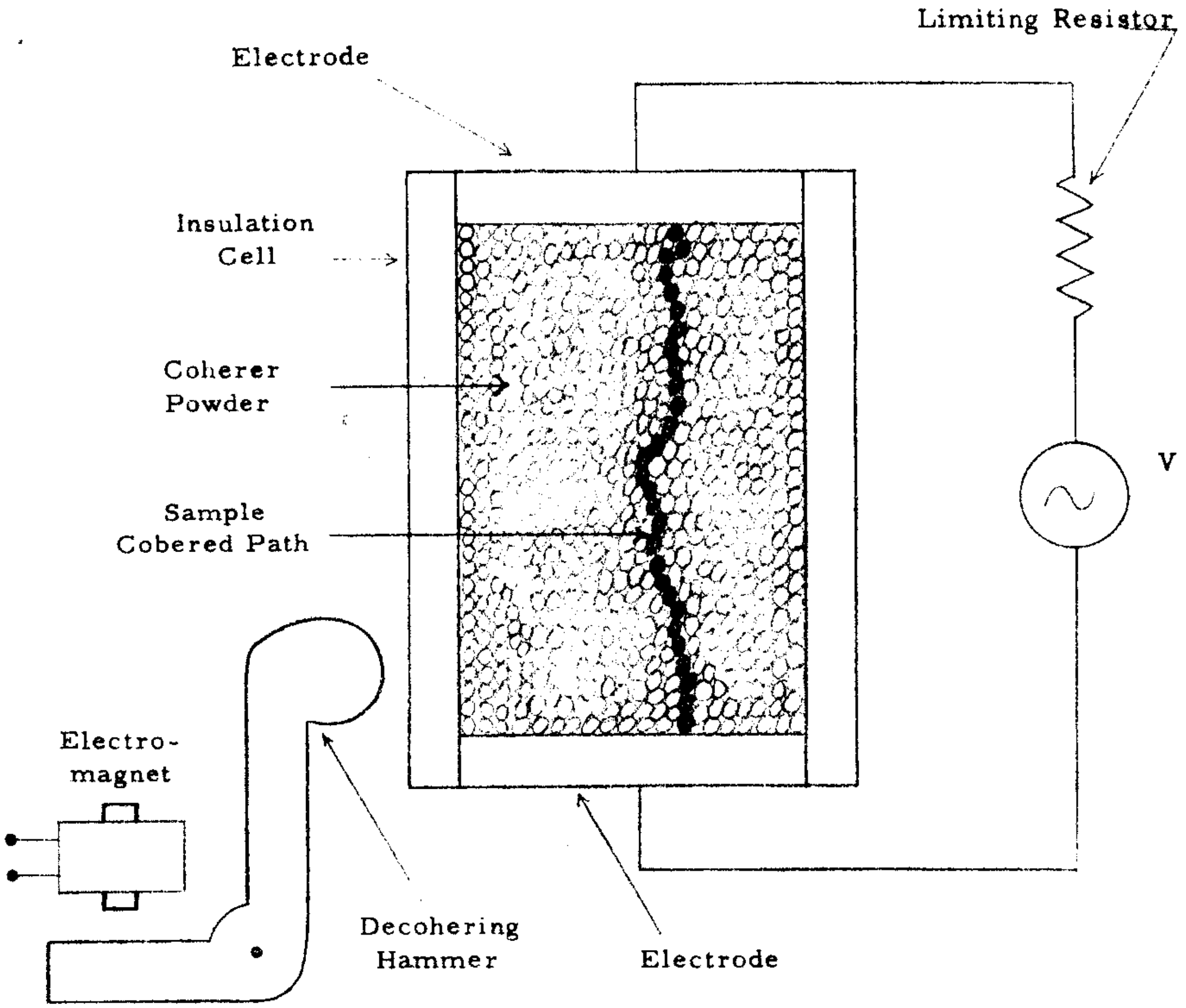


Fig. 1 -- Sample Coherer Cell

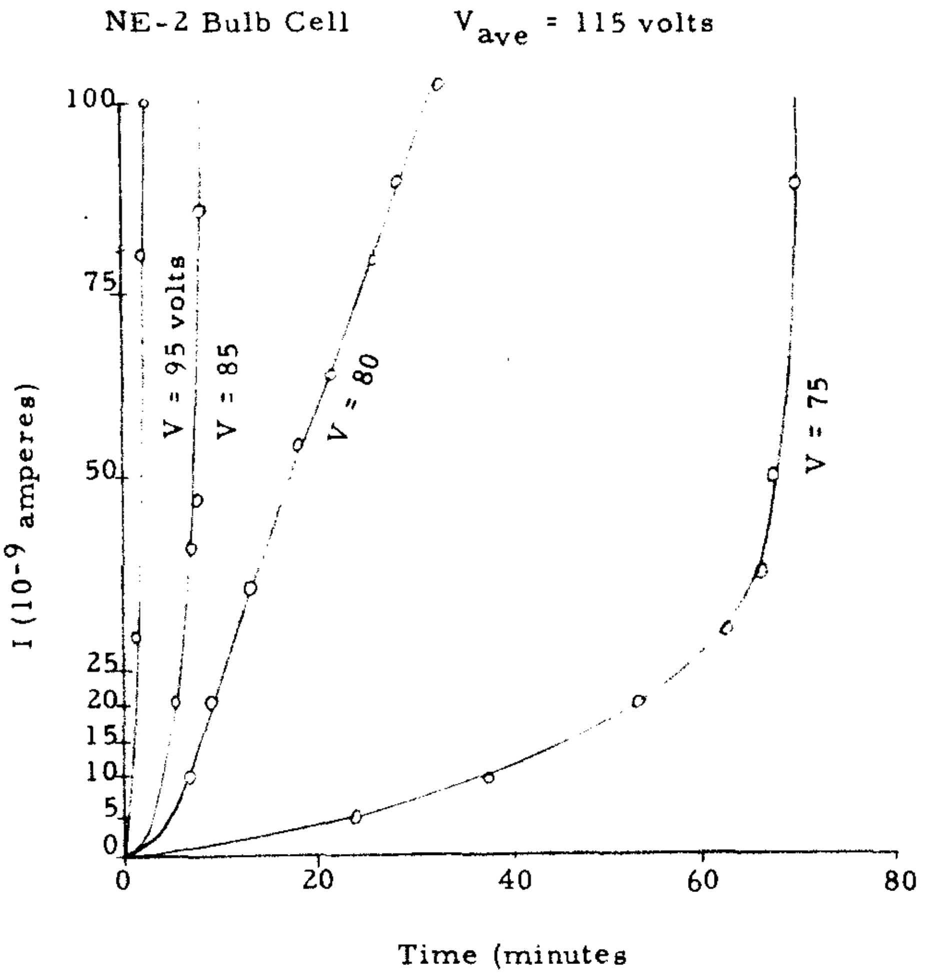


Fig. 2 -- Pre-Firing Characteristics of Nickel Powder Coherer

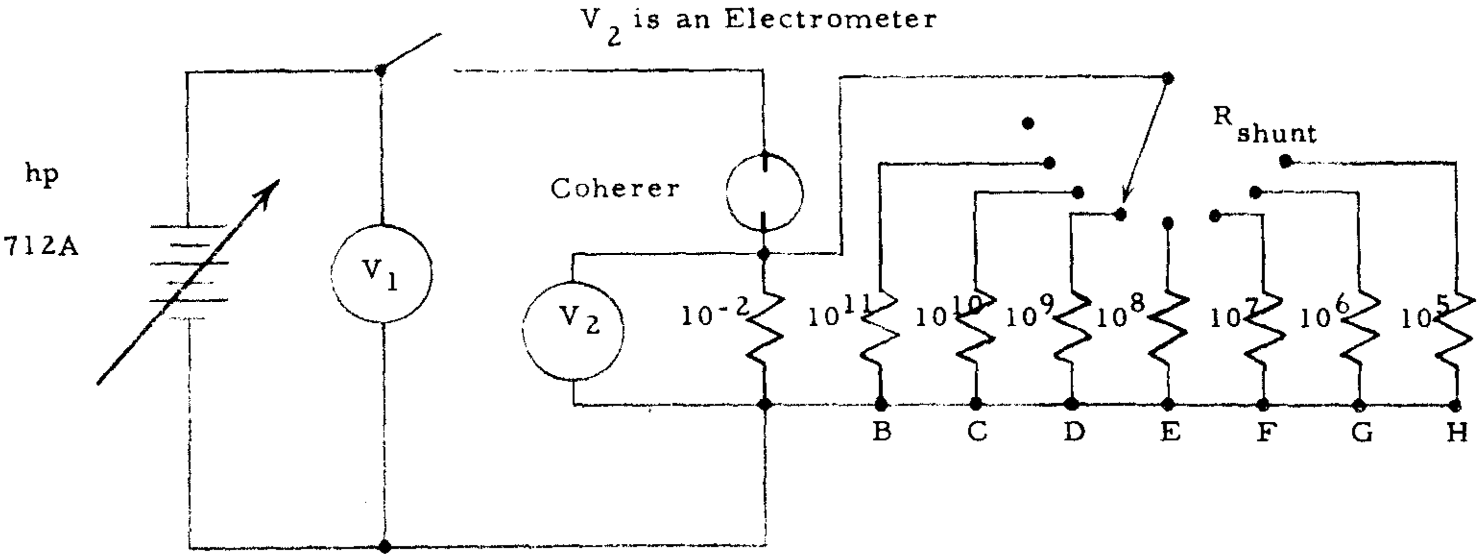


Fig. 3 -- Method of Measuring V-I Characteristics

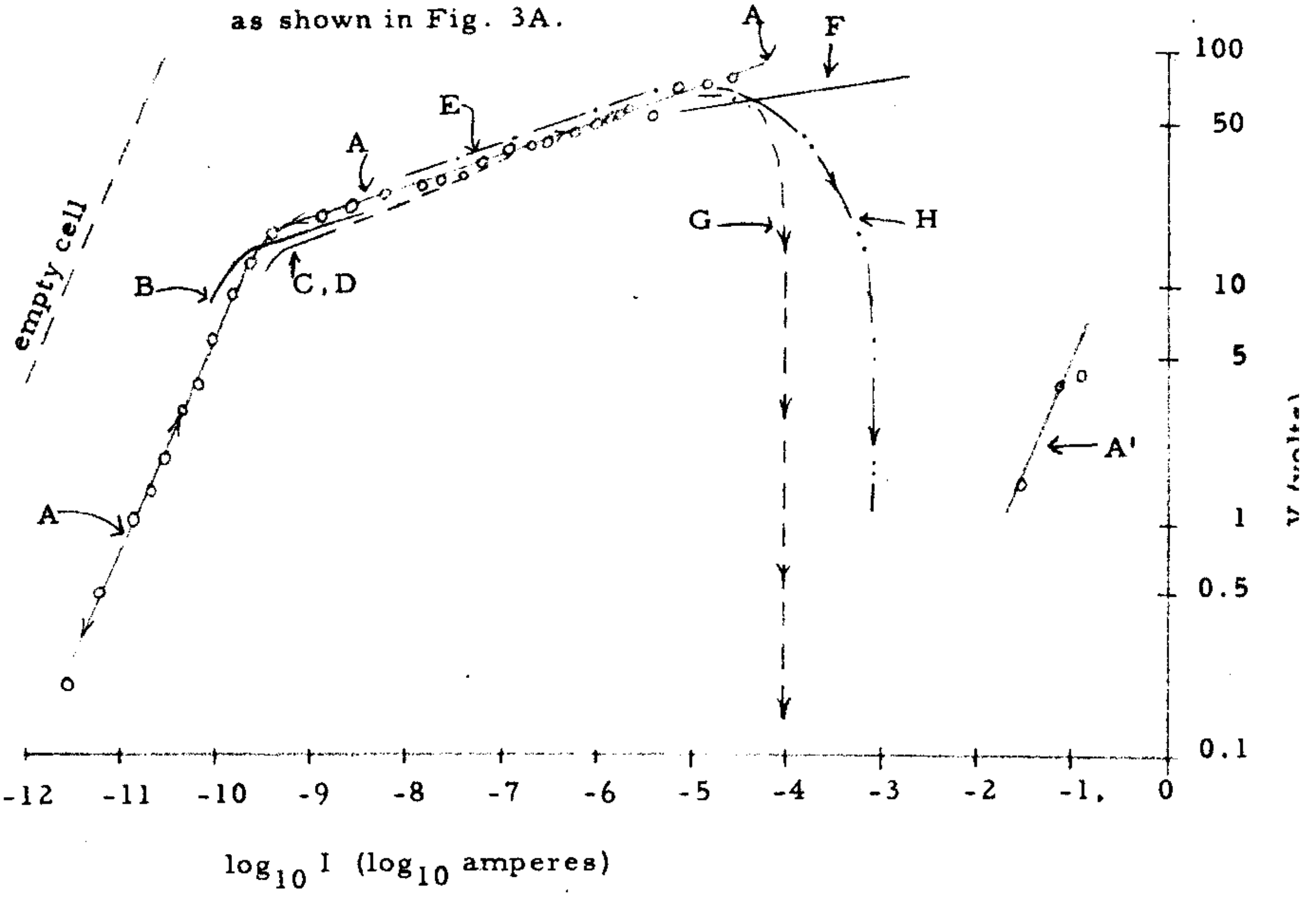

The letters A-H refer to the shunt resistance used as shown in Fig. 3A.

Fig. 4 -- Relation Between Voltage (V) and Current (I) in Process of Cohering

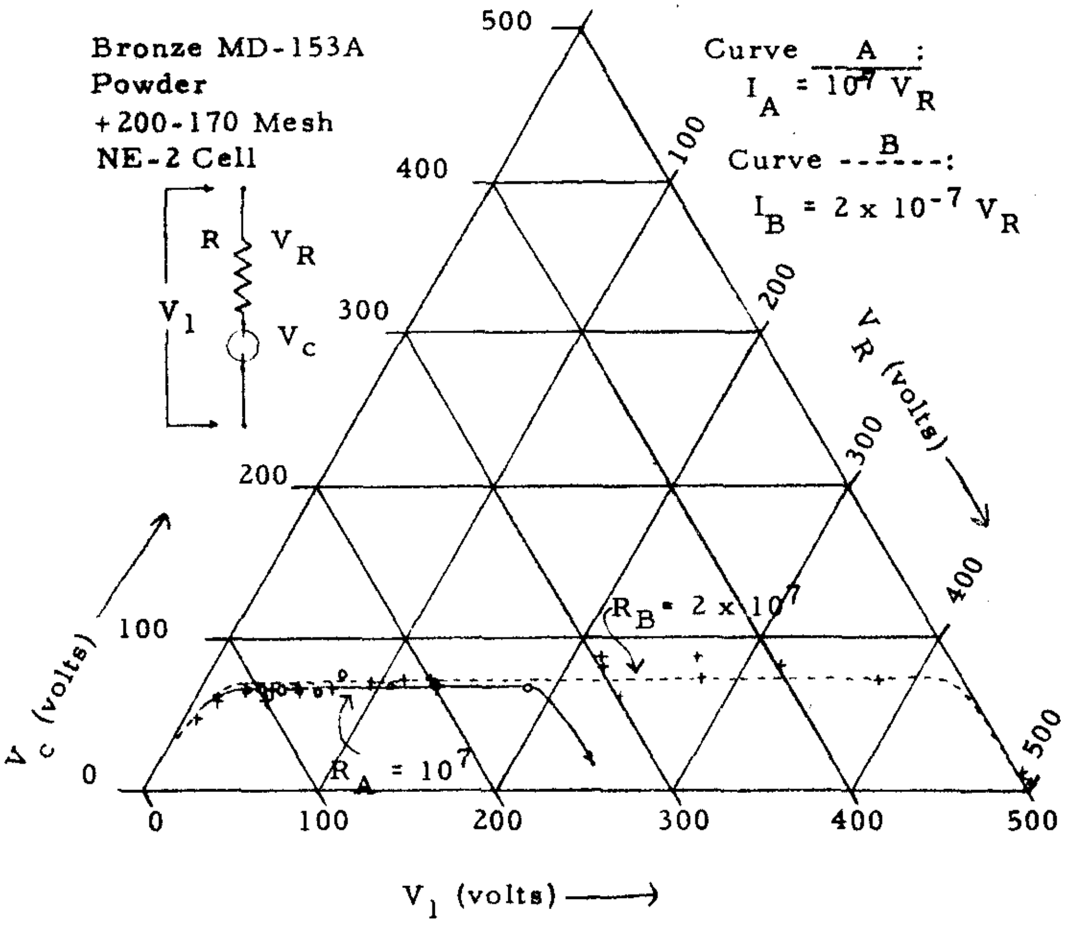


Fig. 5 -- Constant Voltage Characteristic of Coherers

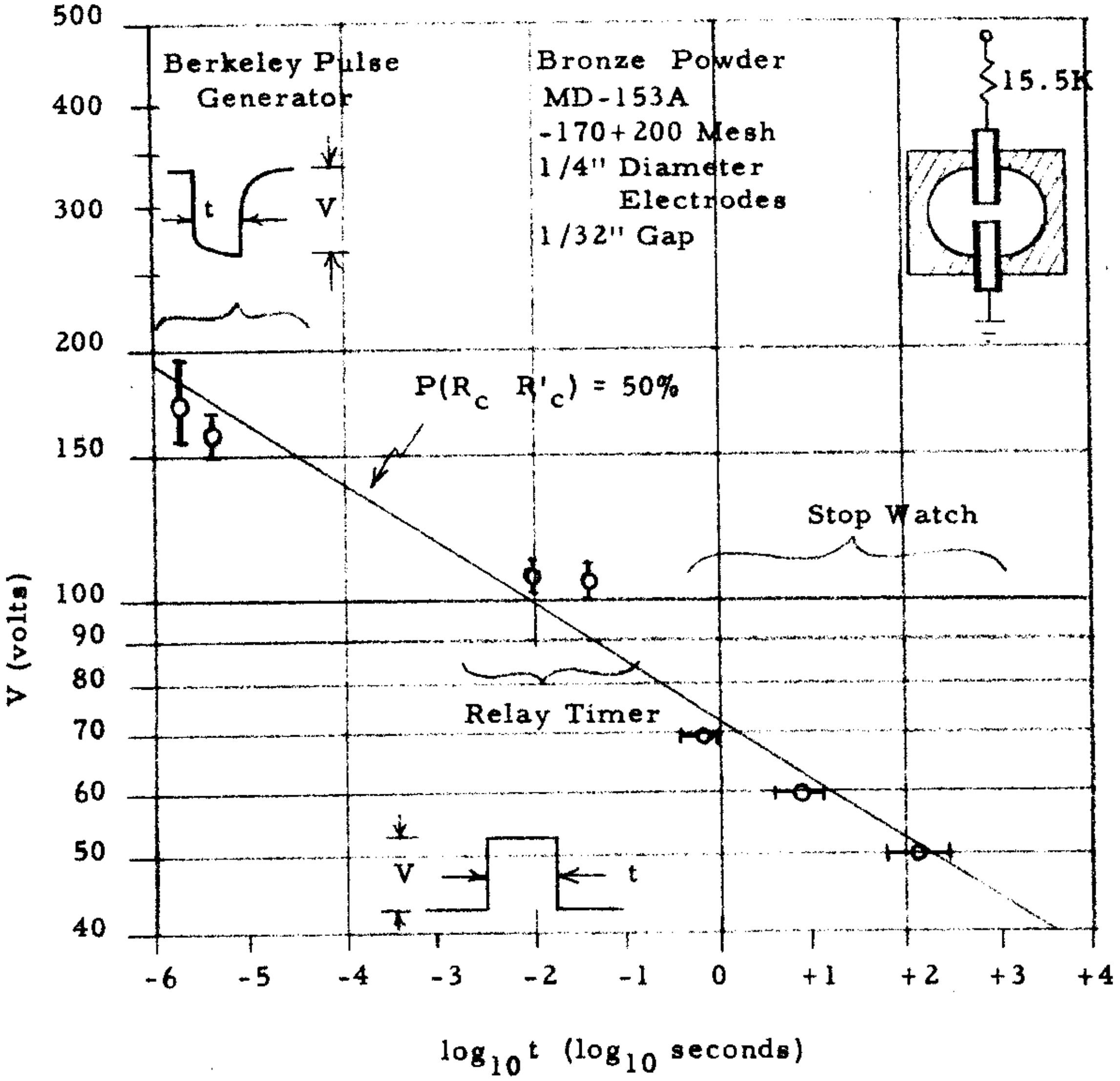


Fig. 6 -- Firing Voltage vs. Pulse Length

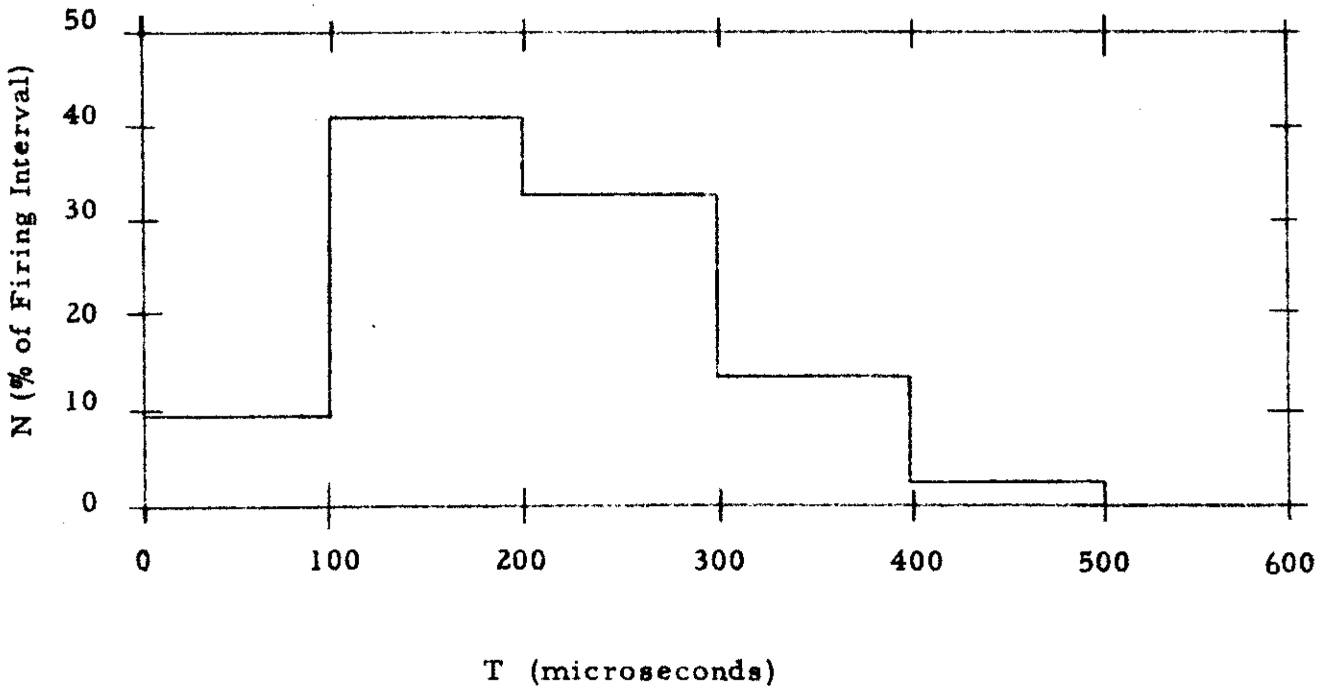


Fig. 7 -- Percentage Distribution of Coherer Firings Plotted Against Time Interval of Cohering

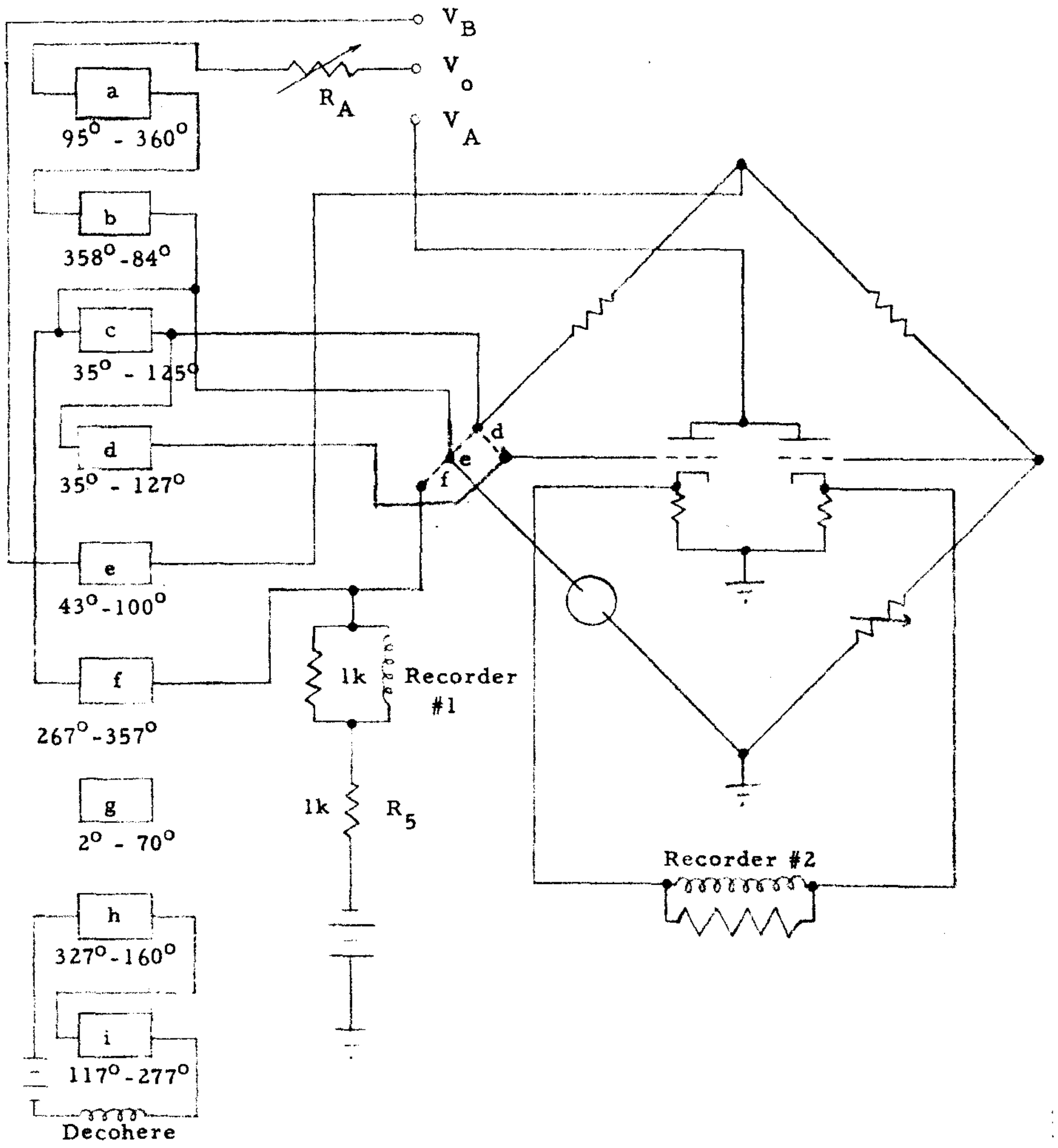
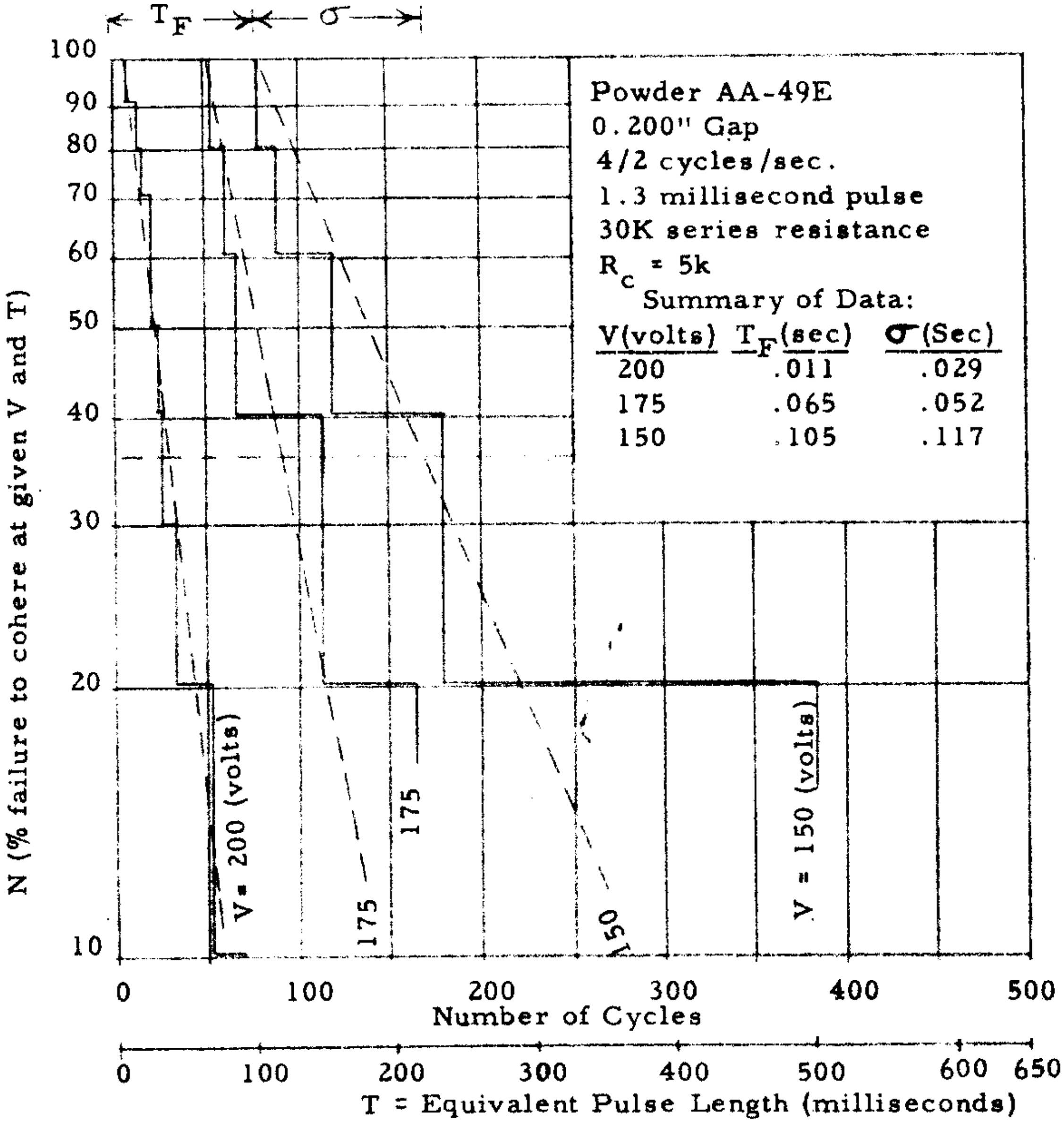


Fig. 8 -- Wheatstone Bridge Coherer Tester



| V(volts) | $T_F$(sec) | $\sigma$(Sec) |
|---|---|---|
| 200 | .011 | .029 |
| 175 | .065 | .052 |
| 150 | .105 | .117 |

Fig. 9 -- Formative Timelag ($T_F$) and Statistical Time Lag ($\sigma$) for a Typical Coherer.

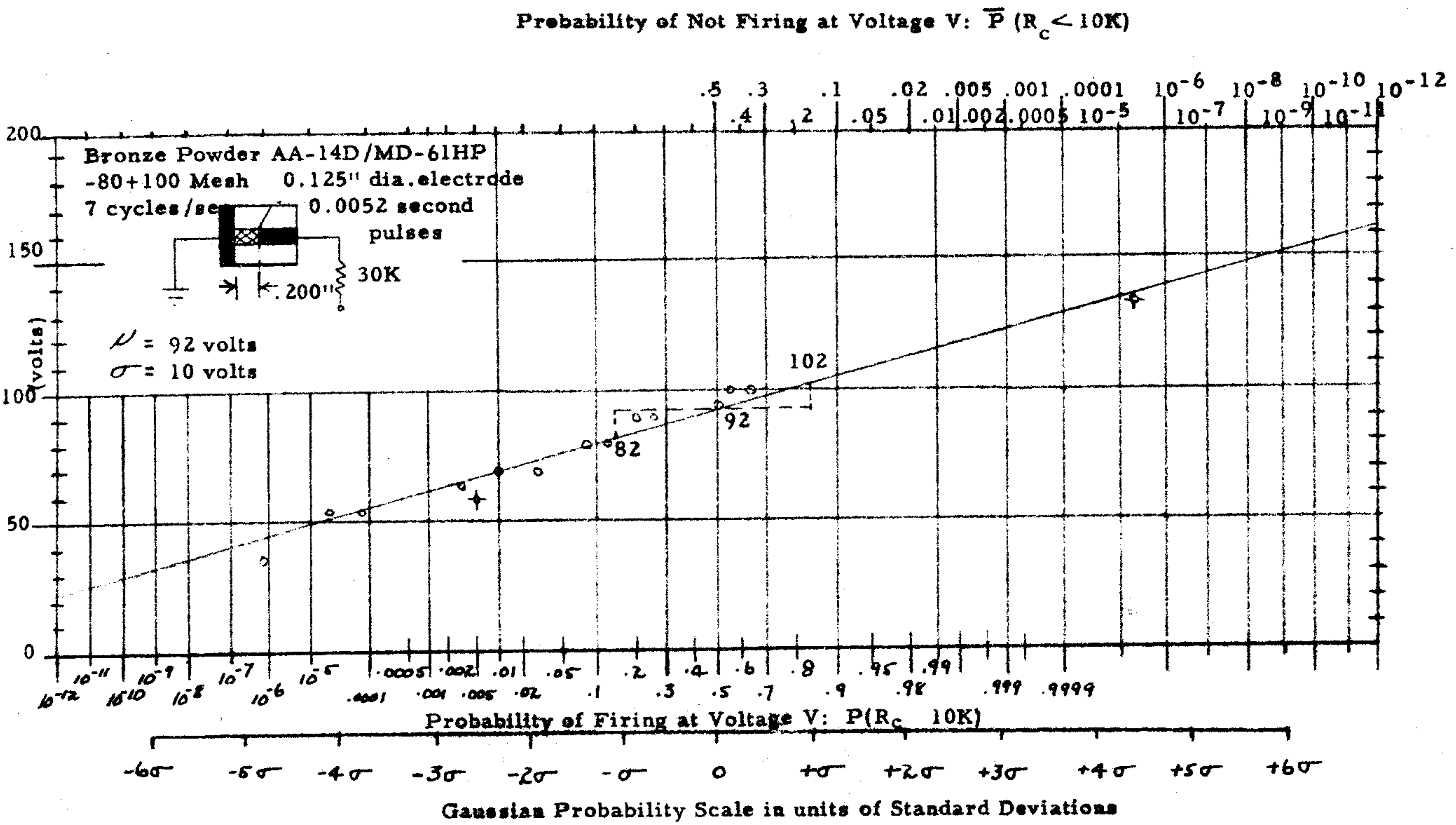


Fig. 10 -- Extended Probability of Firing Curve

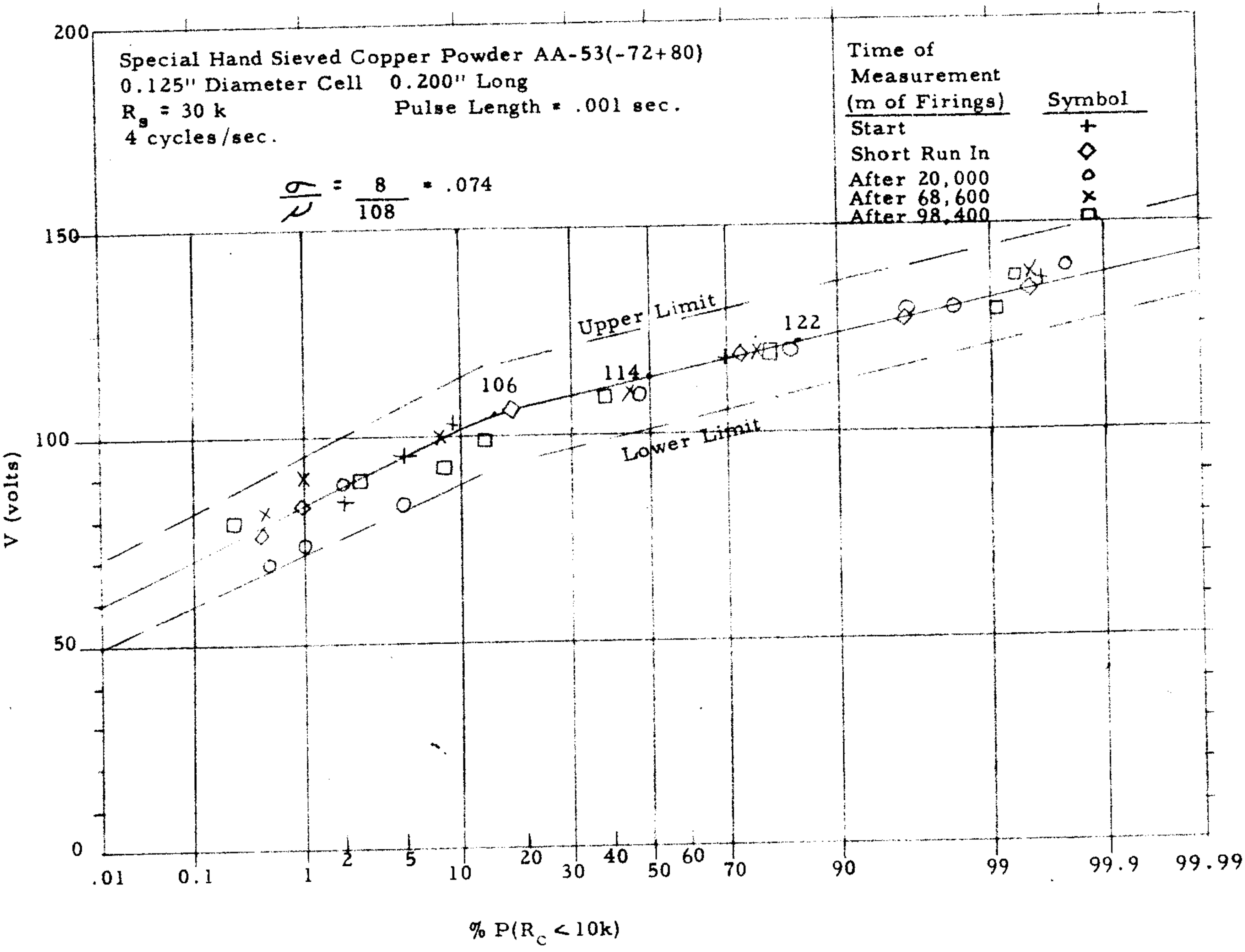


Fig. 11 -- Probability of Cohering For Copper Powder and

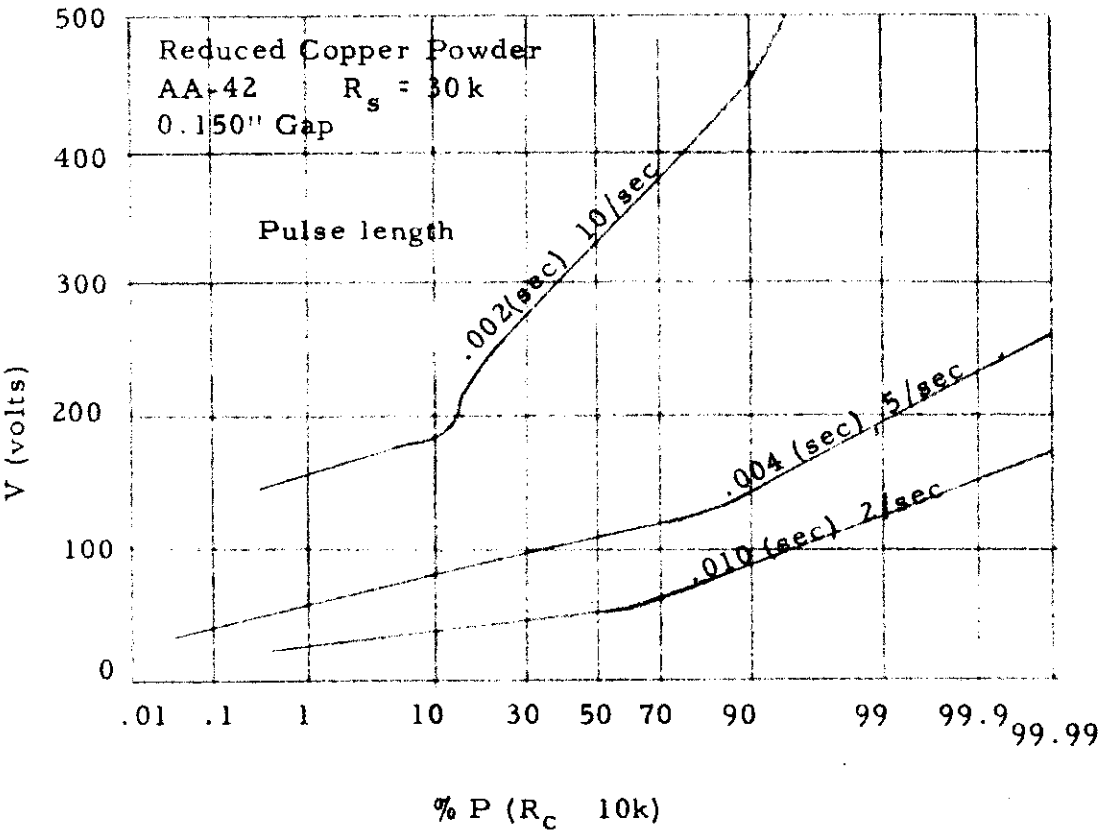


Fig. 12 -- Change in Shape of Probability Curve With Change in Pulse Length and Repetition Rate

## APPENDIX B

17 Nov. 1959

[illegible] R-IEDD

International Business Machine Corporation
Advanced Systems Development Division
590 Madison Avenue
New York 22, New York

Gentlemen:

Based on information contained in the feasibility study presented by Messrs. Bagget and [illegible] of IBM Corporation in November 1959, it is requested that IBM prepare and submit, at the earliest possible date, a formal proposal for the use of the IBM Image File in engineering drawing recovery.

The proposal should include such things as cost of hardware, delivery date, estimated conversion costs, assurance of acceptable legibility of each size drawing, and a detailed methods description of system implementation and operation.

In connection with this proposal, any money expended from government or company funds related to this project will create no obligation, moral or otherwise, direct or indirect, on the part of the government for future support of the project.

IBM is authorized to make additional studies at this agency, if necessary, to complete this proposal.

Sincerely yours,

H. H. [illegible]
Colonel, Ord Corps
Chief, Industrial Division