I. The Explosion of Ether - Air Mixtures by Electric Sparks

II. The Dynamic Resistance of a Spark

Thesis by

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TABLE OF CONTENTS

TABLE OF CONTENTS

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Thanks are also due to the many friends and members of the staff of California Institute of Technology who gave freely of their time and advice as the research proceeded.

To Mr. Edward Deeds I extend my thanks for being kind enough to handle the photographic work.

ABSTRACT

The work of previous investigators, on the initiation of explosion, is reviewed. Several researches are described in detail in order to indicate the basic requirements that must be satisfied by a coordinated theory of the explosion process.

The possibility that a correlation may exist between the ability of a "capacitor spark" to ignite a combustible mixture, and the electrical character of the discharge was investigated. The results of experiments with a 4% ether air mixture are presented and discussed.

It is shown that the energy dissipated in a spark is not by itself a measure of the ignitibility of the spark. Neither is the total charge passed during a discharge. The sparking potential, however, greatly affects the "exploding power" of a spark.

For sparking potentials between 2000 volts and 4000 volts no correlation has been found to exist between the igniting ability of a spark and the maximum, effective, or average discharge current.

The results of experiments with corona discharges of potentials up to 35,000 volts indicate that explosion could not be initiated by this type of discharge. The suggestion that current density in a spark may be a critical factor in determining its ability to cause explosion, is advanced. Further experiments are suggested.

REVIEW OF PREVIOUS WORK ON THE IGNITION OF COMBUSTIBLE MIXTURES

1.1 INTRODUCTION

The modern knowledge we have of the complex processes of combustion and explosion comes from experiments which fall into the following catagories:

I. Chemical action in electrical discharges.

II. Spontaneous explosions by self ignition.

III. Explosions and combustion induced by local heat or electrical sources.

Organized experimental study of the combustion problem probably began in the middle of the seventeenth century when the Oxford School of Chemistry came into being. (1)[1] Extensive and more detailed experimentation awaited the electron theory of matter.

In the last four decades the entire phenomenon of combustion and explosion has been re-examined a number of times. It has only been in the last fifteen years however that the complex nature of the underlying processes has been appreciated and for this reason progress toward a coordinated theory has been slow. At the present stage in fact, we await the development of better techniques, better methods of measurement, and finer understanding and control of the electro-chemical factors involved.

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[1]Bracketed numbers such as this one, refer to the bibliography at the end of this paper. Superscripts will always indicate footnotes.

The practical desire as well as the necessity, to be master of rather than servant to the explosion phenomena, has greatly stimulated research in this field. The elimination of dust explosions and the development of the internal combustion engine were two engineering problems about which something had to be done - even without the benefit of a complete understanding of the basic principles involved. The explosibility of modern anaesthetic vapors (2) on the one hand, and the development of new electrical instruments for use of the medical profession on the other, have led to serious problems.[1]

More recently, interest in the catalytic action of the electrical discharge (3) in certain chemical (4) and physical (5) reactions has opened a tremendous field of investigation, which has already shed new light on the fundamentals of combustion and explosion.

1.2 RESULTS OF EARLY INVESTIGATORS

It has not been possible to duplicate all of the results reported by early investigators of the explosion phenomena. Due to incomplete understanding of the electrical factors involved, experiments were frequently performed and conclusions drawn without regard for conditions we now consider critical. It is common to find disagreement on fundamental matters in the early literature.

[1]Fatal accidents in operating theatres have been caused by static spark discharges, use of the electric cautery, and a variety of other means. Substantial progress has been made in locating and eliminating these difficulties. See bibliography Reference No. (2)

With the passage of time, experimental results have tended toward greater consistency. Many probable mechanisms involved in initiating explosions are already known but they are not yet fully understood (6). In the not too distant future however it should be possible to develop a unified theory of the entire set of events that lead to an explosion.

The modern period of investigation can be set at the turn of this century. A wide range of researches developed when the Mining Association of Great Britian became concerned with finding means of preventing coal dust explosions (7) (8). The work of H. F. Coward and his associates (9) is of particular interest. It concerns the minimum pressure at which a $2H_2 + O_2$ mixture can be ignited when submitted to an electrical discharge.

To W. M. Thornton (10) however we owe the main "controlled" investigations of explosion by means of local heat and electrical sources. His interest was aroused by the problem of making electrical signalling devices, in mines, safe (11). This led to the problem of sparks in a combustible medium, and by a short step, to study of the complete problem of ignition by local sources. Much of Thornton's work has withstood the test of time (12) and a brief review of phenomena he reported and which has since been reinvestigated ~~with~~ will be useful.

1.3 THE INITIAL PERIOD (1900 - 1916)

Three convenient methods have been used to obtain sparks as a local source for ignition. They are:

I. Breaking an inductive circuit.

II. Discharging capacitors across a suitable gap.

III. Sparking the secondary of an induction coil by interrupting the primary current.

At one time or another Thornton tried all of these methods. Using sparks obtained by breaking an inductive circuit, he found that a critical current had to be interrupted before he could obtain an explosion (13). Further the current to cause explosion depended upon the voltage used in the circuit, the inductance, the composition of the explosive mixture and later (14) the series resistance in the circuit. The existence of a critical current led to the suspicion that ionization provided the initiating process of the explosion, while the effect of the inductance tended to indicate that energy $(1/2)LI^2$ might be a determining factor. In later investigations Thornton has modified this stand (14) showing that ignition depends more closely upon the product LI and in this way explosion by means of break sparks[1] can be explained on the basis of an "electric theory."

Thornton also investigated the explosion of gases by hot wires as local sources (13) (16). The temperature of the wire was controlled by the current it was allowed to conduct. Here again he found that a definite current was necessary before explosion

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[1] This matter is not yet settled. See reference (15) where LI^4 is reported to be the essential product.

occurred (14). It was at first felt that electronic emmission from the wire caused the explosion - but J. D. Morgan showed that explosion could be obtained with no emmission (17)[1].

Thornton was first to investigate the explosion of gaseous mixtures by a capacitor discharge (18) (19)[2]. It then became apparent that a given mixture could be exploded with much less $1/2\ CV^2$ than the $1/2\ LI^2$ that was necessary in the case of the "break sparks." This fact gave rise to a question which has been discussed for nearly 30 years: Is energy or ionization the motivating factor causing the explosion?

1.4 THE SECOND PERIOD (1916 - 1926)

During the period from 1916 to 1923 research was stimulated by the need of powerful engines. One of the many fine papers[3] published in this period was written by C. C. Paterson and N. Campbell (20). In addition to carefully describing the methods and difficulties involved in their own researches, they included a careful re-evaluation of the entire problem and the work that had gone before. Using capacitor sparks exclusively[4], they found that it was necessary to discharge a critical capacitor before

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[1]Other experiments involving explosions by hot surfaces will be mentioned later.

[2]Some of the difficulties experienced are discussed in reference (21).

[3]At least twenty papers appeared.

[4]A novel circuit arrangement was used. The first instance of "under running" the filament of a diode in order to use the tube as a current limiting device is here recorded.

explosion would occur. Further the $(1/2)CV^2$ that was "necessary" for explosion was shown to be a highly variable quantity - continually decreasing as the sparking voltage was raised. At a given voltage the capacitor required for explosion varied with the richness of the gaseous mixture - going through a minimum. No definite theoretical conclusions were drawn. Other papers notably (21) (22) by J. D. Morgan (23) (24) and R. V. Wheeler (25) (26) appeared during this period. These men independently came to the conclusion that explosion caused by electrical discharges was not due to processes of an electrical nature. Using theoretical and experimental considerations, they joined with E. Taylor Jones (27) (28) (29) (30) to put forth the theory that the explosion of gases was a purely thermal phenomena based upon the introduction of sufficient energy to maintain a necessary volume of gas at its explosion temperature for a sufficient length of time. It was shown theoretically that point sources were more effective than distributed ones[1] and also that the rate at which heat was supplied was a crucial factor - best results being obtained by instantaneous point sources[2].

1.5 THE THIRD PERIOD (1927 -)

In 1926 G. I. Finch and L. G. Cowen (31) began work on the combustion problem. Over a period of ten years, Finch and his

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[1]See however the discussion on page 9 of this thesis.

[2]Mathematical work on a modified thermal theory has been done more recently. See Page

co-workers have used induction coil sparks (32) the continuous direct current electrical discharge at low pressures, (33) as well as capacitor sparks (34) in their investigations. An extensive chemical, electrical, and physical (spectroscopic) (35) study of possible influencing factors was undertaken with a large measure of success[1]. The general conclusions[2] were such as to show that a complete thermal theory was untenable (36). Explosions were obtained under circumstances in direct contradiction to predictions based upon a thermal theory[3]. It was decided that explosion was due not to ionization but instead to the attainment of suitable molecular excitation. This was based partially on figure (1a) which shows the hyperbolic relation existing between igniting current and pressure. At a given pressure the current necessary for explosion was less for wider gaps apparently because the discharge is more concentrated for larger electrode separations.

In 1927 A. Kieth Brewer found (37) the explosibility of a carbon monoxide - oxygen mixture by a low voltage capacitor discharge depended upon the energy $(1/2)CV^2$ only. Working at reduced pressures, he found that for a given capacity, the voltage required for explosion varied inversely with the pressure of the gas. He showed that while ignition at any pressure depended only

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[1]The complete list of papers appears in Reference (38).

[2]The author gives an excellent review of the entire matter in reference (38).

[3]The reported effects of frequency of the discharge will be found interesting. See Reference (34).

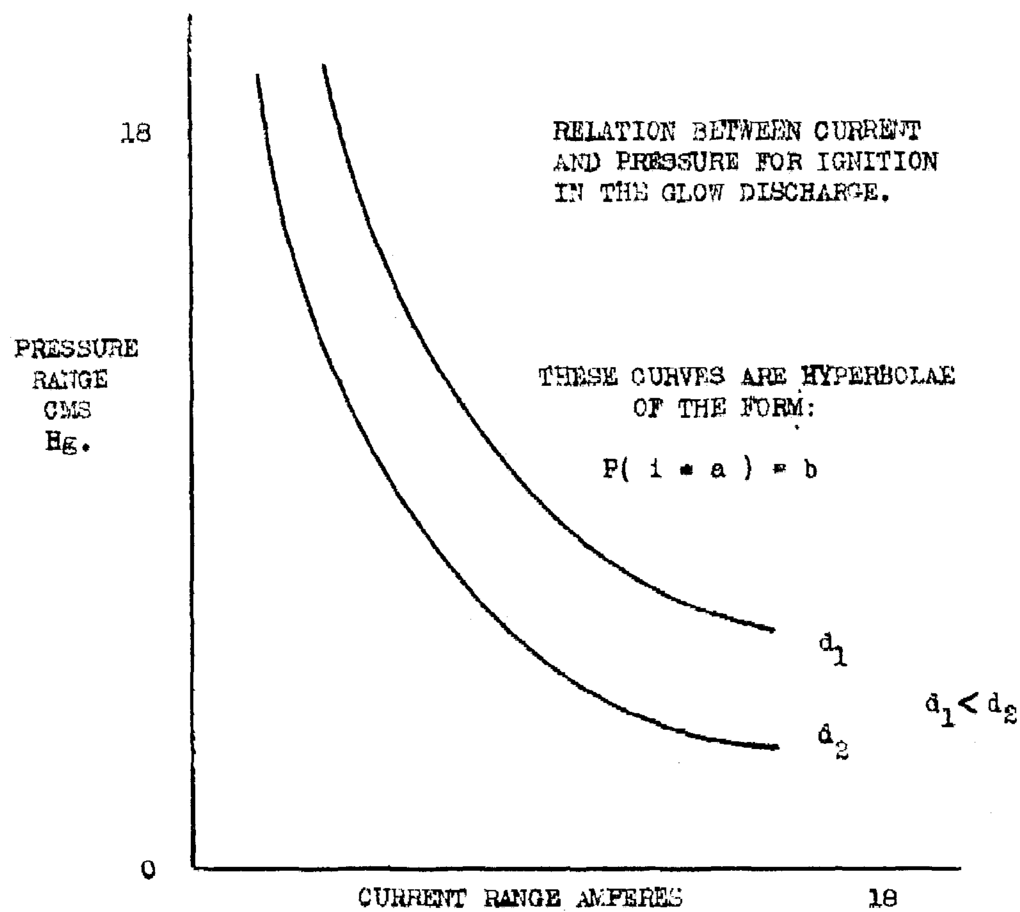

FIGURE 1a

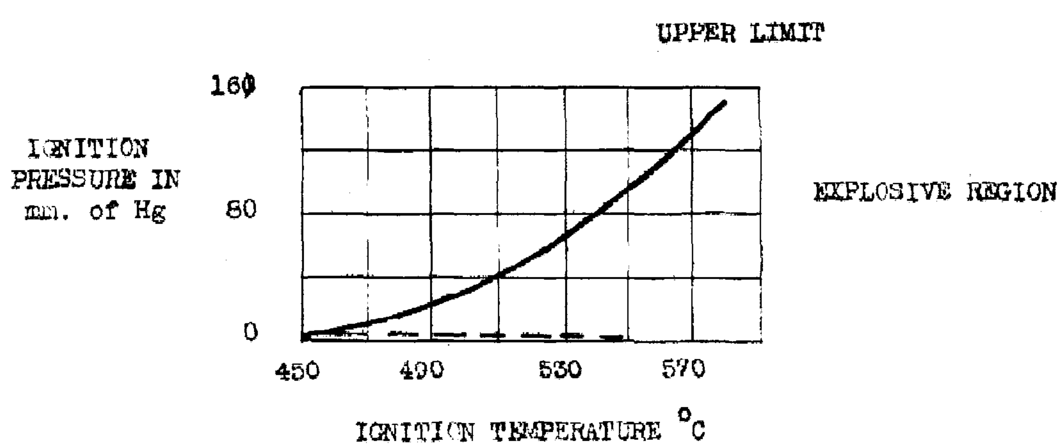

FIGURE 2a.

upon the energy in the discharge, ignition at various pressures were related not as the energy - but as the sparking voltage. This is the first indication that the sparking potential itself may be a factor without considering its relation to other quantities such as energy.

More recently Brewer and his associates have investigated the catalytic action of the glow discharge on various chemical processes[1]. Their results in the case of the synthesis of ammonia (38) are characteristic and worthy of mention. It was found that in a high voltage glow discharge, the chemical reaction of nitrogen and hydrogen to form ammonia proceeded very readily in the region of negative glow and to a more moderate extent in the positive glow, but seemingly in no other region of the discharge. The synthesis proceeds at a rate determined by the current and is independent of the pressure and temperature over a wide range. Explosive reactions could occur in the positive column - but in no case would they occur in the negative glow (39).

In tracing the several stages from the non propogating reaction to explosion in the positive column Brewer (in agreement with Finch) found a marked relationship between current, pressure and temperature (40). It was possible to choose values for the current, pressure and temperature such that for any explosible mixture, no explosion occurs. Above these critical values reaction

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[1]A total of fourteen papers has been published to date. The last two are mainly concerned with the problem of explosions.

occurred quite easily (41). It was concluded that initial reaction centers are created by ionization processes and that these centers[1] interact with energy rich molecules to bring about a chemical chain reaction. Temperature is looked upon as another means to create active centers by dissociation. The pressure coefficient has been explained by the effect it has on diffusion; and the current was taken to represent a measure of the initial centers of activity present.

1.6 OTHER INTERESTING WORK ON EXPLOSION PHENOMENA

R. S. Silvers (42) heated quartz spheres of different sizes and shot them into various explosible mixtures. He found that the larger the sphere, the lower its initial temperature had to be in order to cause explosion. In all cases however this temperature was never as low as the known explosibility temperature[2] for the given mixture. The strangeness of these results is based upon the fact that the smallest man made sphere will certainly seem like an infinite plane atomically. There are other indications that an extended surface will ignite a gas at a lower temperature than a local heat source will. This again brings up the matter of the creation of active centers by thermal means. Silvers (42) Paterson (43) and Landau (44) have attempted a mathematical treatment of this matter[3] with interesting results. However because the

[1]Positive molecules, atoms, radicals or ionic clusters.

[2]The explosibility temperature of a gas is not however one of its physical constants - this is sufficient evidence that even thermal explosions are not yet understood.

[3]The difficulties involved in such an approach are tremendous.

physical quantities involved in the expressions obtained are not yet determinable, the results cannot be applied.

1.7 THE INFLUENCE OF RADIATION ON EXPLOSIBILITY

It has long been known that light acts as a catalyst to many chemical reactions. To the chemist an explosion is merely an accelerated combustion. The essential difference between combustion and explosion appears to be that in the first case initial active centers cause the reaction - while in the second case, the sources of activity have the ability to regenerate other sources of activation by a process known as chain and branched chain reactions. As an interesting case in photo synthesis consider the reaction between hydrogen and chlorine gases[1].

In the dark, the ~~mixture~~ reaction of hydrogen and chlorine to yield:

$$H_2 + Cl_2 \rightarrow 2HCl$$

is inappreciable. In diffuse light the reaction occurs with a measureable speed - while in direct sunlight the combination is quite explosive. It is unnecessary to expose the entire mixture of hydrogen and chlorine to the light. If a small amount of chlorine is exposed to the light and then placed into the mixture of H_2 and CL_2 in the dark, the reaction will also proceed. (A similar effect is not noted for H_2) The accepted explanation of this phenomena is that chlorine molecules are dissociated by light:

$$CL_2 + \text{light} \rightarrow 2Cl \qquad (1)$$

Chlorine atoms then react with a hydrogen molecule

[1] See any college chemistry text.

$$Cl + H_2 \rightarrow HCl + H \qquad (2)$$

Hydrogen atoms are able to react with undissociated chlorine atoms to yield

$$H + Cl_2 \rightarrow HCl + Cl \qquad (3)$$

The resulting chlorine atom can now initiate a similar process. Thus the presence of a small amount of chlorine in the atomic state can cause the reaction between large amounts of hydrogen and chlorine in the molecular state. This is a chain reaction, and here it is said to be initiated by activated chlorine.

Chlorine and hydrogen will react in the dark at high temperatures too. This means that the chlorine molecule may be dissociated by heat also.

The entire reaction sketched above may be brought to a stop at any stage if a proper CHAIN BREAKING REACTION sets in. Thus if the hydrogen atom created in (2) were to combine with the chlorine atom in (3) to yield:

$$H + Cl \rightarrow HCl$$

the active atoms would be removed and the reaction halted. Foreign substances, certain surface phenomena, pressure, vessel factors, etc. may act as inhibitors or chain breakers, and in this way change the explosibility of otherwise dangerous mixtures.

Other effects of radiation on explosion are described by G. N. Hinshelwood and K. Clusius (47), J. D. Morgan (48) and B. Lewis[1] (49).

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[1]The Bibliography contains a short review of these papers.

1.8 EXPLOSIONS INITIATED AT CONSTANT TEMPERATURE

The purely thermal theory of explosion meets with difficulty in the attempt to explain certain reactions between hydrogen and oxygen[1]. One of these phenomena is illustrated by figure 2a on page 7A. This figure shows the explosive range for a stoichiometric mixture of hydrogen and oxygen (46). The reaction is as follows: If the required mixture is heated to say 510°C and admitted to the chamber care being taken to keep the pressure above 60 mm of Hg, then it is found that a slow reaction takes place between the constituents. If the pressure is slowly lowered by withdrawing some of the mixture the reaction rate decreases until a pressure of 60 mm is reached whereupon an explosion abruptly occurs. The upper limit shown is sharp and is not affected by vessel factors but the lower limit is not as well defined because of practical difficulties at such low pressures. Any explanation based on the thermal theory seems hopeless, but a branched chain of reactions as listed below will do so. We first suppose that by some means, thermal or otherwise, a hydrogen atom has formed. Then the following reaction can occur (50).

$$H + O_2 \rightarrow OH + O$$

$$O + H_2 \rightarrow OH + H$$

$$OH + H_2 \rightarrow H_2O + H$$

If the rate of increase of the H atoms is taken to be proportional

[1]The literature is so vast on this subject that the curious reader will do better to refer to the following books listed in the Bibliography. See first (6) Chapter 11. Then (45) (46).

to the concentration of H atoms present at any time, then $dH/dt = aH$. When the mixture does not explode it is assumed that a chain breaking reaction is decreasing the concentration of H atoms in the manner described by $-dH/dt = bH$. The criterion for explosion is then that *a* be greater than *b*. Taking *b* proportional to the pressure and *a* independent of it, as the pressure is lowered *a* will become equal to *b* and below that point explosion will occur. At very low pressures, H, O, and OH are destroyed at the vessel walls and this acts as a chain breaking process which explains the presence of a lower limit[1]. For further discussions of this nature reference should be made to the Bibliography. Before deciding on any one reaction the chemist is forced to consider reactions of all types that can possibily occur. The problem is a fascinating one and the methods used in its solution have been developed to a high degree.

1.9 CONCLUSION

An enormous literature exists on the subject of combustion and explosion. The illustrations above have been chosen with a view toward indicating the many directions in which research on these problems has thus far proceeded. A coordinated theory of the mechanisms involved must account for all of the results of the experiments described.

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[1]Hence the lower limit should depend upon size and shape of vessel. It is found to do so.

EXPLOSIONS BY MEANS OF ELECTRICAL SPARKS

2.1 INTRODUCTION TO THE PROBLEM

The work described in this thesis, was conceived by a desire to investigate the possibility that a correlation might exist between the ability of a spark to initiate an explosion, and certain of its electrical properties. The cathode ray oscilloscope being available, it was desired in particular to vary the character of the spark by a variation of circuit parameters and to observe the effects on its exploding power, as well as the wave shape of the current in the discharge.

All of the work has been done at atmospheric pressure and room temperature (20°C - 25°C). For this reason sparking potentials of the order of kilovolts were necessary.

2.2 INITIAL EXPERIMENTS WITH HOUSEHOLD GAS

Preliminary work was done using ordinary household gas as the combustible agent. The required electrical apparatus comprising a power supply, high voltage capacitor, and a sphere gap were readily assembled and testing begun as follows.

The spark gap was suspended directly above the opening of an ordinary bunsen burner, and sparks were passed thru the gas stream between the electrodes.

The capacitor, whose discharge provided the spark, was varied until combustion occurred. It was found that this method was not suitable. The results were highly statistical and in some cases contradictory.

In order to improve the physical arrangement a Meker (wide orifice) burner was substituted for the ordinary one, the gap and burner were completely surrounded by a metallic shield, and the flow of gas was made very mild. Still no consistent results could be obtained. Further modification was attempted. To be more certain that the gas-air ratio was known constant, required a method for measuring and controlling very small amounts of the combustible mixture. It was soon found that no meters existed for this purpose.[1] After some experimentation a convenient and simple manner for obtaining the required mixtures was developed[2]. It involved the use of five glass tubes arranged schematically as shown in the figure on the next page.

If the orifices at A, B, and C are properly chosen, it is possible to obtain an accurately controllable percentage of gas to air over a wide range of mixtures and gas velocities. The meters used are commercial gas meters. This achievement led to results of a more uniform nature, but it was not wholly satisfactory because of constant variations in gas line pressure. This source of annoyance could have been eliminated by using balloons as reservoirs, but it was found that the greatest difficulty lay

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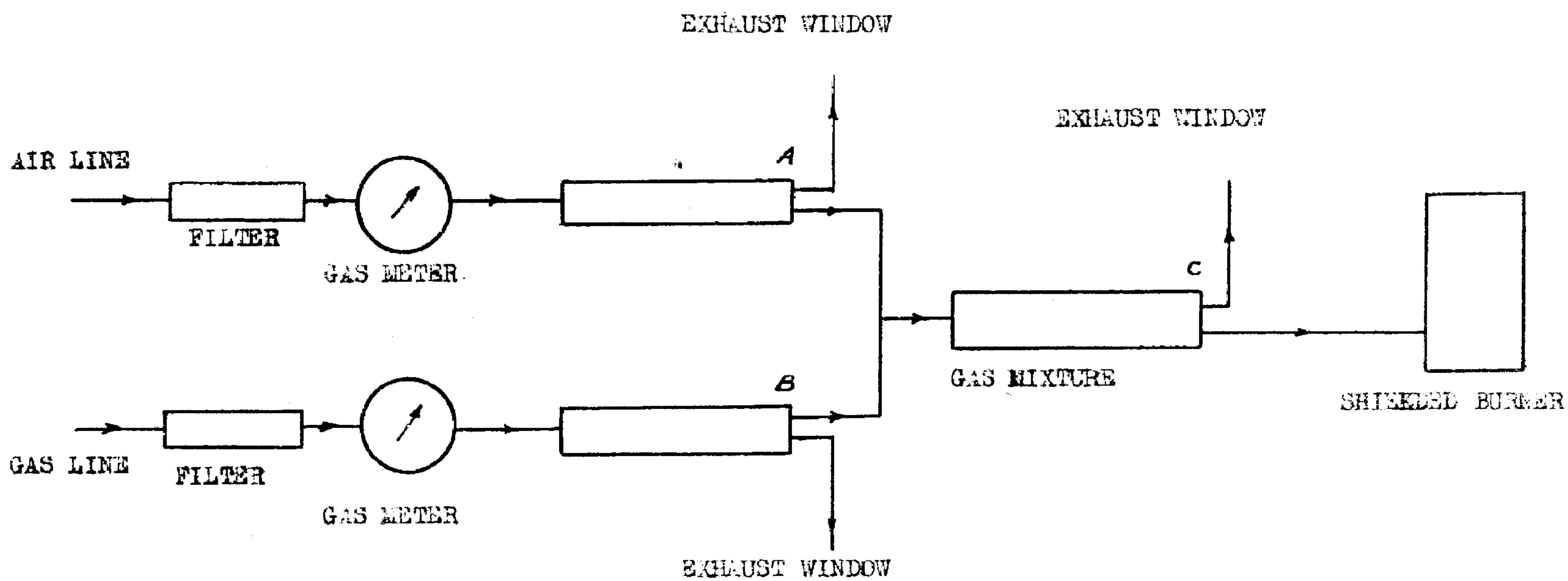
[1]The Southern California Gas Company laboratory analyses small quantities of gas by a method impractical for this research. The smallest commercial gas meters are much too large.

[2]Suggested by Dr. S. S. Mackeown



SCHEMATIC DIAGRAM OF AN ARRANGEMENT FOR OBTAINING VERY SMALL AMOUNTS OF A CONTROLLED MIXTURE OF HOUSEHOLD GAS IN AIR in the streaming of gas past the electrodes. The use of household gas was therefore abandoned.

Meanwhile however, certain valuable experience with the electrical circuit was obtained, and in the light of this a new arrangement of apparatus was made.

2.3 THE FINAL ELECTRICAL CIRCUIT

Figure 1 is a diagram of the final electrical circuit adopted. The diode rectifier (RCA 878) operates in series with a high resistance and the secondary of a transformer (Thordarson 110v - 25,000v 1KVA) to charge the capacitor at C. The sparking voltage is determined and controlled by adjusting the distance between the electrodes in the combustion chamber. The very high series resistance (about 180 megohms) serves to effectively isolate the discharge circuit from the main supply when sparking occurs.

Variable inductances and resistances were placed in the discharge circuit as shown. The character of the spark current could be seen with the aid of a pick up resistor, an oscilloscope and a sweep circuit[1].

THE COMBUSTIBLE GAS

It was decided to perform our tests with gas in a quiescent state. Rather than use gasoline, which has a very complex chemical make-up, a simple volatile hydrocarbon was sought. Ethyl Ether $(C_2H_5)_2O_2$ available in large quantities and offering the advantage of vaporizing readily at room temperatures, was finally chosen.

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[1]It is sufficient to indicate that the sweep circuit is an electronic device. Its operation is automatic - depending upon voltage induced in a pick up lead whenever a spark passes in the explosion chamber. Horizontal deflection for the electron beam is thus assured. Vertical deflection is produced by the voltage drop across the known resistance R_p.

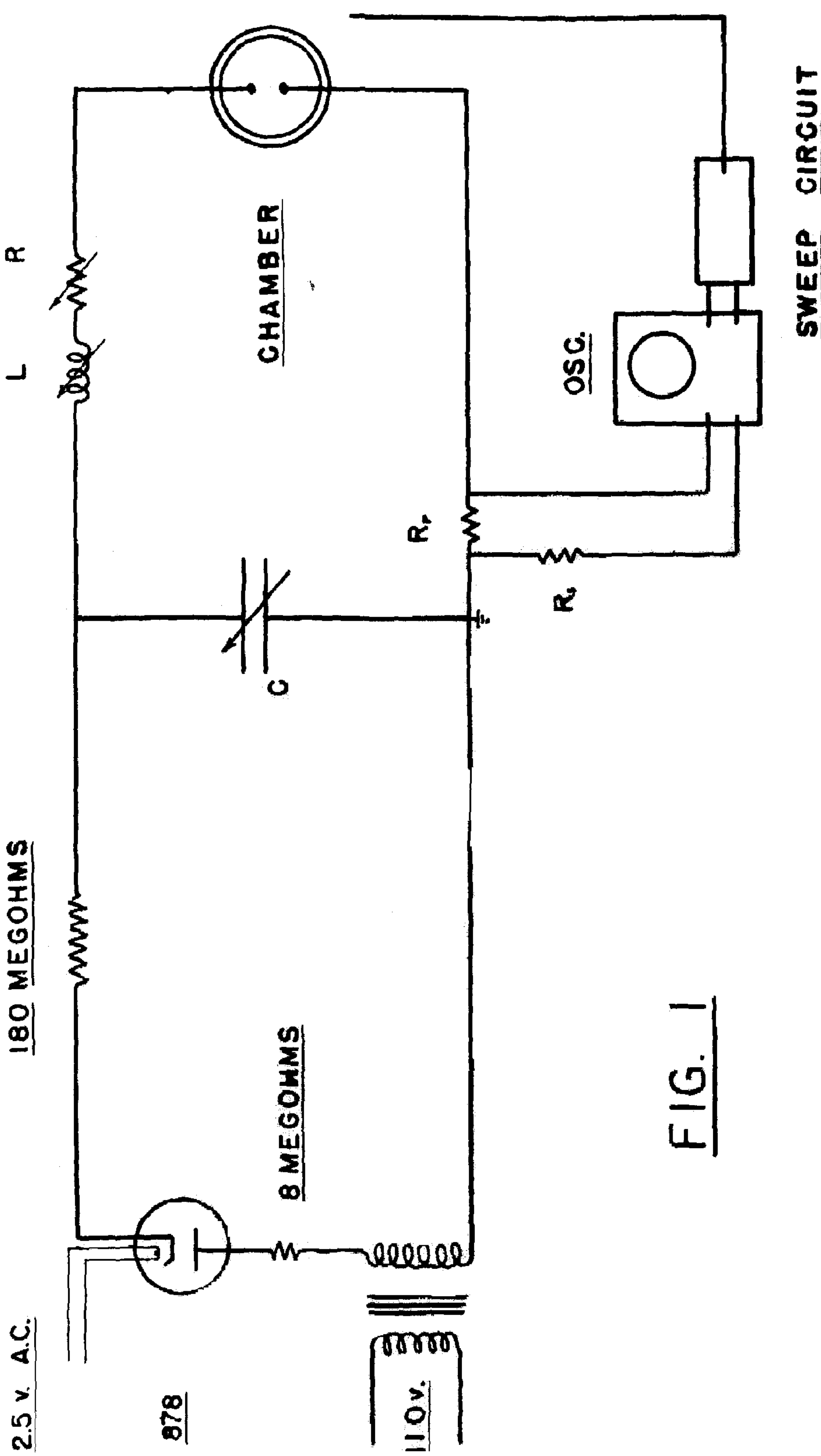
CHAMBER
L
R
C
R1
R2
OSC.
SWEEP CIRCUIT
180 MEGOHMS
8 MEGOHMS
2.5 v. A.C.
878
110v.

FIG. 1

2.4 THE EXPLOSION CHAMBER AND OTHER APPARATUS

The explosion chamber is shown in figure 2. A thick lucite cylinder was used because it presented several advantages.

(a) Visual inspection of the explosion, and of the electrodes surfaces.

(b) Lucite has good insulating properties.

(c) Lucite is easily machined so that the electrodes could be supported in the obvious fashion shown.

(d) Thick cylinders of lucite were easily obtainable.

The volume of the chamber was 345cc.

At different stages in the research, various electrodes were used. Most of the work was performed using aluminium or brass spheres 1/2 inch in diameter. The separation of the electrodes was always small compared to their diameter and hence many disturbing electrical effects were avoided[1].

Experience showed that a stirring device would be useful. The chamber was therefore mounted on an induction motor[2] fan in such a manner that the shaft extended thru the bottom. A small blade was attached as illustrated in figure 2.

A smooth tennis ball served to close the top and of the chamber. When explosion occurred, the ball acted very ef-

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[1]It is known that for such an arrangement of electrodes, time lag is less than 10^{-9} seconds.

[2]This type does not spark.

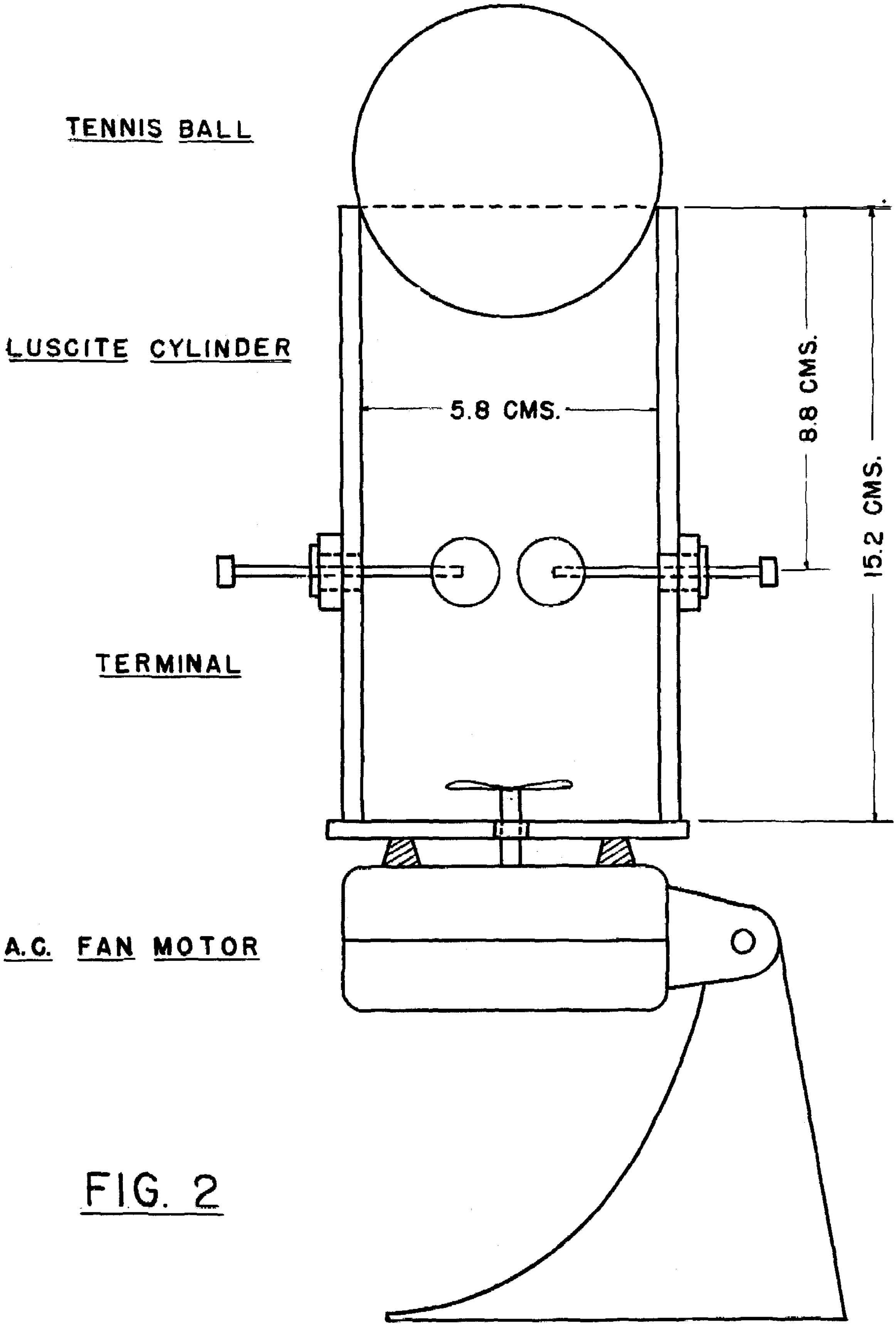

TENNIS BALL
LUSCITE CYLINDER
5.8 CMS.
8.8 CMS.
15.2 CMS.
TERMINAL
A.C. FAN MOTOR

FIG. 2

fectively as a pressure relief valve. In order to avoid difficulty after each explosion, a devise was built to catch this ball and retain it. The ball catcher may be seen in figure 3a. A circular hole was cut into a piece of wood. Hinged wooden pegs were mounted around the hole and kept horizontal by rubber bands in tension as shown. This assembly was nailed into an open cardboard box, a flap entry was cut in such a way that the ball could be easily retrieved, and the whole arrangement was firmly suspended over the explosion chamber.

The air used to flush the chamber between electrical discharges, was filtered by a gauze pad and dried by sending it thru calcium chloride. (see figure 3b)

The variable capacitor, C, of figure 1 was made up of an arrangement of capacitors as illustrated in figure 3c. Identical mica transmitting capacitors rated at 4,000 μμf and 12,500 volts were used. In some cases these were supplemented by Leyden jars. Capacities between the limits of 267 μμf and 25,000 μμf were possible.

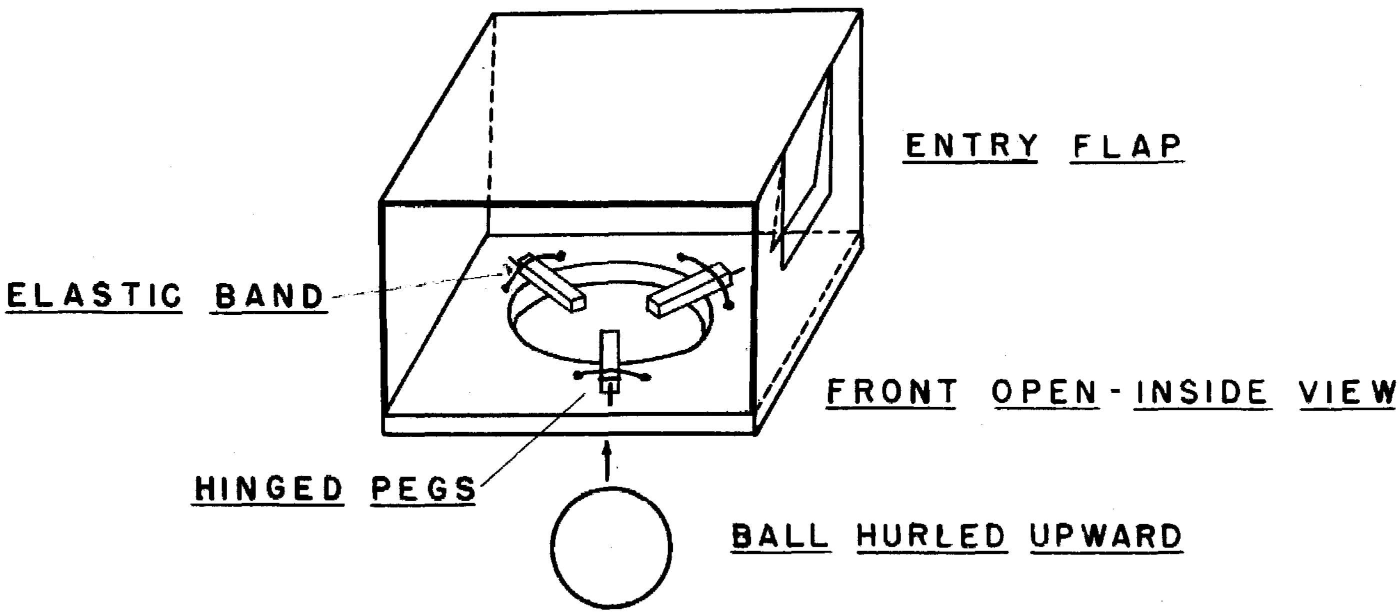
An electrostatic voltmeter was used for determining the sparking potential. Other apparatus used is discussed elsewhere.

NATURE OF THE DISCHARGE

Extensive oscillographic investigations of the current in the discharge were made. It was found that for general purposes of discussion, the spark could be considered as a non linear

A

BALL CATCHER

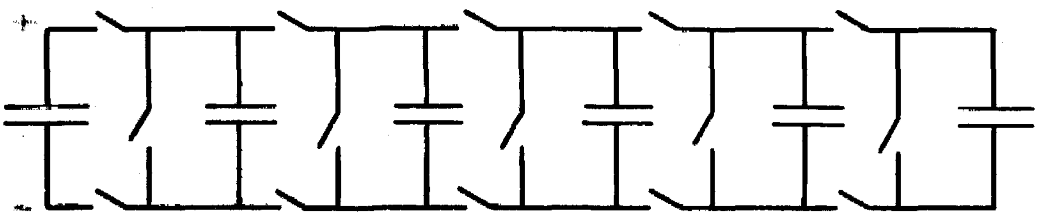


B

AIR CLEANER AND DRIER

C

ARRANGEMENT OF CAPACITORS



FIGS. 3

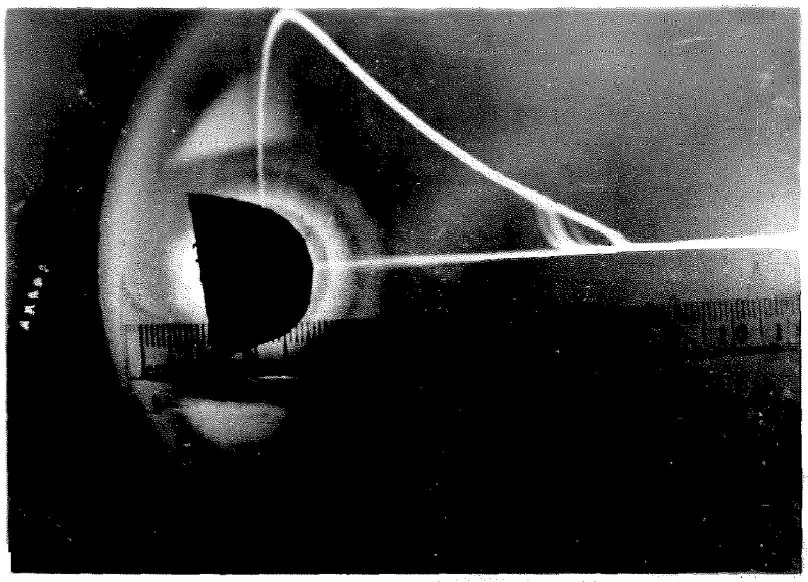
resistance. By suitably varying the parameters R, L, and C, the character of the circuit could be changed continuously from strongly "overdamped" to highly oscillatory. In the later case, calculations of the frequency of oscillation were simplified by neglecting the small series resistance involved, because oscillographic checking showed the error in doing so was trivial.

Calculated frequencies for some of the work - ranged as high as 10,000,000 cycles per second.

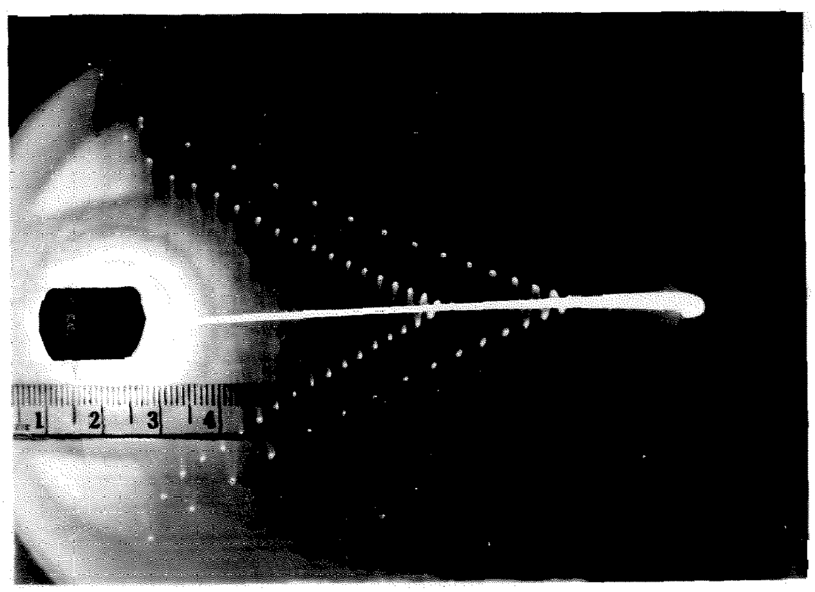
The photographs on the next page, show representative current wave forms encountered. To economize on the use of film involved, one negative was sometimes used to record the wave forms for two different conditions of the circuit. By means of calibrations explained in part 2 of this thesis, the scale seen in these photographs could be used to measure both the duration of the discharge and the current involved.

THE COMBUSTIBLE MIXTURE USED

In order to determine the best percentage mixture of ether air to be used it was necessary to investigate the range of explosible mixtures. For this purpose a high voltage, high current spark was employed. A charge of 0.065 milliliters of ether, corresponding to a four percent by volume ether air mixture, was found to be close to the center of the explosible region. The micropipette used to measure the ether charge was rated at 0.2 milliliter. It could be controlled easily to within



V = 3,900 volts
i_m = 0.035 amperes



(a) f = 88,300 cps. (b) f = 39,500 cps.

0.005 milliliter.

2.5 FIRST TEST RUN - PROCEDURE

A sparking potential is first chosen, say 2000 volts. The electrode spacing for this voltage is determined relatively accurately by sparking the gap in an atmosphere of ether air just rich enough so that explosion will not occur. This means must be resorted to because ether air mixtures break down electrically at lower voltages than air.

Having once set the gap, the series resistance and inductance are kept as low as possible, and a choice of capacity (usually 1000 μμf) is made. In order to bring about a condition of equilibrium the capacitor is then discharged a number of times by means of an auxiliary gap. This insures that each spark thereafter will involve the same amount of charge at the given potential[1]. The auxiliary gap serves to avoid unnecessary pitting of the main electrodes.

After carefully flushing the chamber with air, a charge of 0.065 milliliter of ether is run in, the tennis ball replaced, and the stirrer set going for five seconds. The gap is then sparked. If no explosion occurs, this procedure is repeated four times. Usually explosion will occur the first time or not at

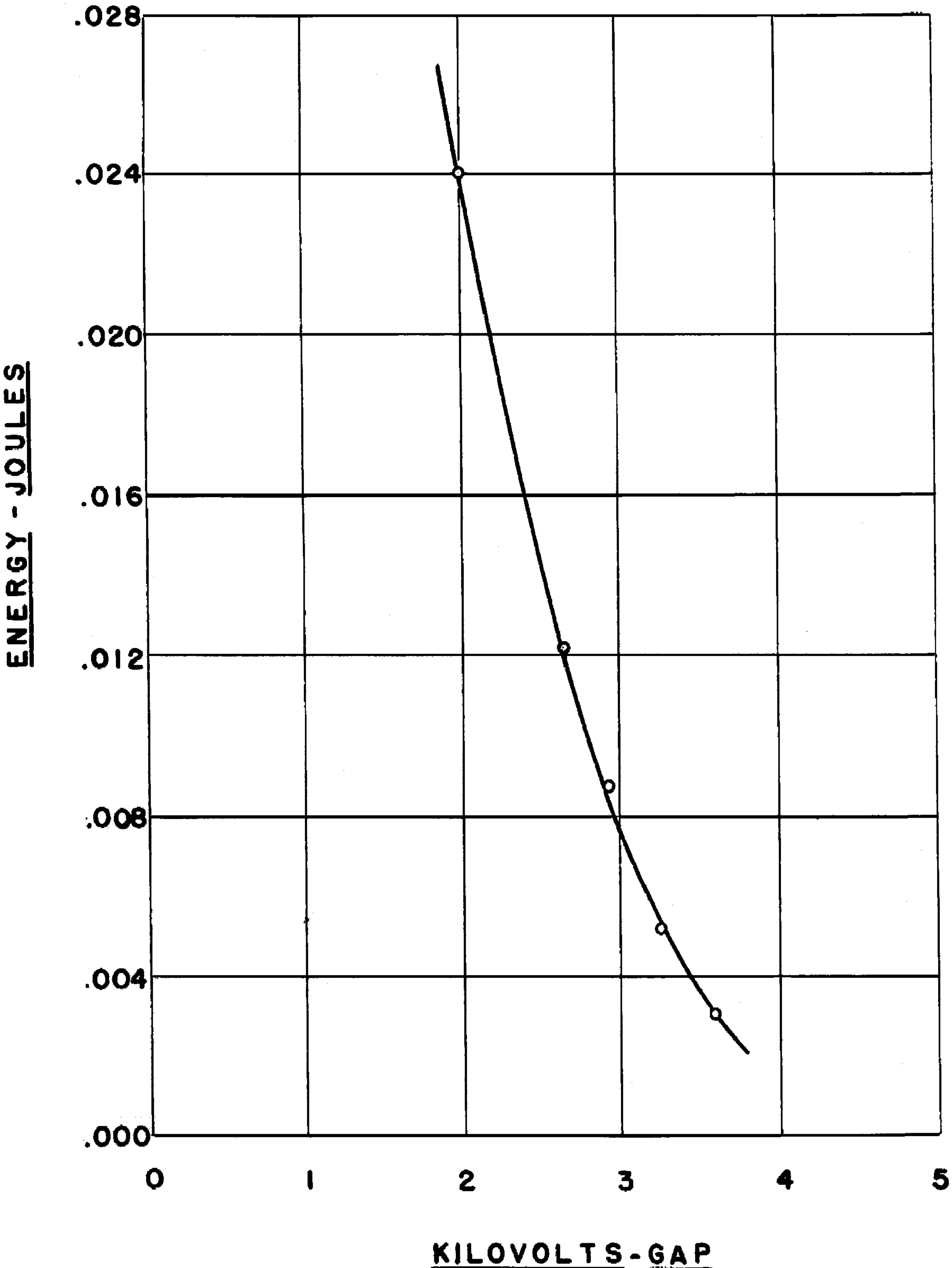
[1]That this was approximately the case can be seen from the first photograph on the preceeding page. The area under the current time curve is an indication of the charge passed. The only difference in this quantity for the ten or more current traces shown is the small amount due to the erratic manner in which sparks are extinguished. This represents less than 3% error.

all. In the latter case the capacitor is then suitably increased, and the process repeated. Ultimately a value of C will be obtained for which five explosions may be made successively. In cases where four explosions occur in five trials, five more attempts are made. Capacitors are recorded as causing explosion if either five explosions occur in succession, or eight occur in ten attempts.

FIRST TEST RUN - RESULTS and DISCUSSION

At a given sparking voltage, with all other circuit parameters fixed, it was found that a critical capacity was required in order to cause an explosion of the combustible mixture. The line separating the non explosive region from the explosive one was quite sharp. As the sparking potential was raised, the critical capacity required became smaller.

The total energy in the discharge most of which appears in the spark itself was taken to be $(1/2)CV^2$. The following curve taken from the data shows that the "energy required for explosion" is a variable quantity depending on the sparking voltage. These results check very well the work of previous investigators (20) (23) in this field. As far as could be determined no minimum energy to cause explosion existed - unless a voltage was also specified. In fact, from the results obtained there is reason to suspect that if the sparking potential were increased indefinitely, the "energy to cause explosion" would become trivially small.


.028
.024
.020
.016
.012
.008
.004
.000
ENERGY - JOULES
0
1
2
3
4
5
KILOVOLTS-GAP

Although it is true that a critical capacity is required for explosion at a given potential, it is felt that in the region investigated, it cannot be the product $(1/2)CV^2$ which is the determining factor. Other factors will have to be considered in order to explain the fact that at a sparking potential of 4000 volts one twenty fifth of the energy necessary at 2000 volts will cause explosion. To this end it is necessary to consider carefully a list of factors which vary when the capacitor is changed as described above.

(A) The electrode separation is proportional to the sparking potential used. All other factors remaining constant the current will also increase with the voltage. Hence the volume of the spark as well as the area it presents to the gas - both increase at increased voltages. However efforts to find a correlation between explosibility and these factors were unsuccessful.

(B) The resistance of the circuit is not constant when different capacitors are used because of change in the frequency of oscillation of the current.

(C) The spark current at a constant voltage is a function of the capacity used, and in fact may be varied within wide limits without varying either R or L. However in the range investigated the energy dissipated by the resistor was negligible.

(D) The possibility of a local oscillation between the electrodes themselves exists. Transient phenomena have been known to occur in such cases.

(E) The frequency of the discharge itself may produce some kind of electrical activation in the gas.

In an attempt to settle some of these matters, further investigations were made. It was for example found that for a constant voltage, the igniting ability of a spark could be suppressed by increasing the series resistance. The following technique was adopted to obtain data.

2.6 SECOND TEST RUN - PROCEDURE

At a sparking potential of 2000 volts, and with the series inductance and resistance as low as possible, the capacity necessary for explosion was determined by use of the same procedure outlined in obtaining data for the first test run. The series resistance was then increased until the explosibility fell below 2 out of 6 trials. This value of resistance was recorded. The capacity was increased until explosion once more became assured using the criterion previously explained. The resistance was again increased and so on. The counteracting effect of capacity on the explosibility was followed up to 25000 μμf - a limit imposed by the equipment on hand.

The voltage was then raised to 2650 volts without changing the resistance. The critical capacity to cause explosion was again determined and the entire procedure above repeated. Results were recorded for the following sparking potentials: 2000 volts, 2650 volts, 2950 volts, 3250 volts, 3600 volts, and

4000 volts. A complete run required a number of days. Between voltage runs the electrodes were polished carefully.

SECOND TEST RUN - RESULTS and DISCUSSION

The curves on the following plate summerize the effect obtained by varying the resistance and capacity in the manner described above. All of the regions of explosibility lie above the curves shown.

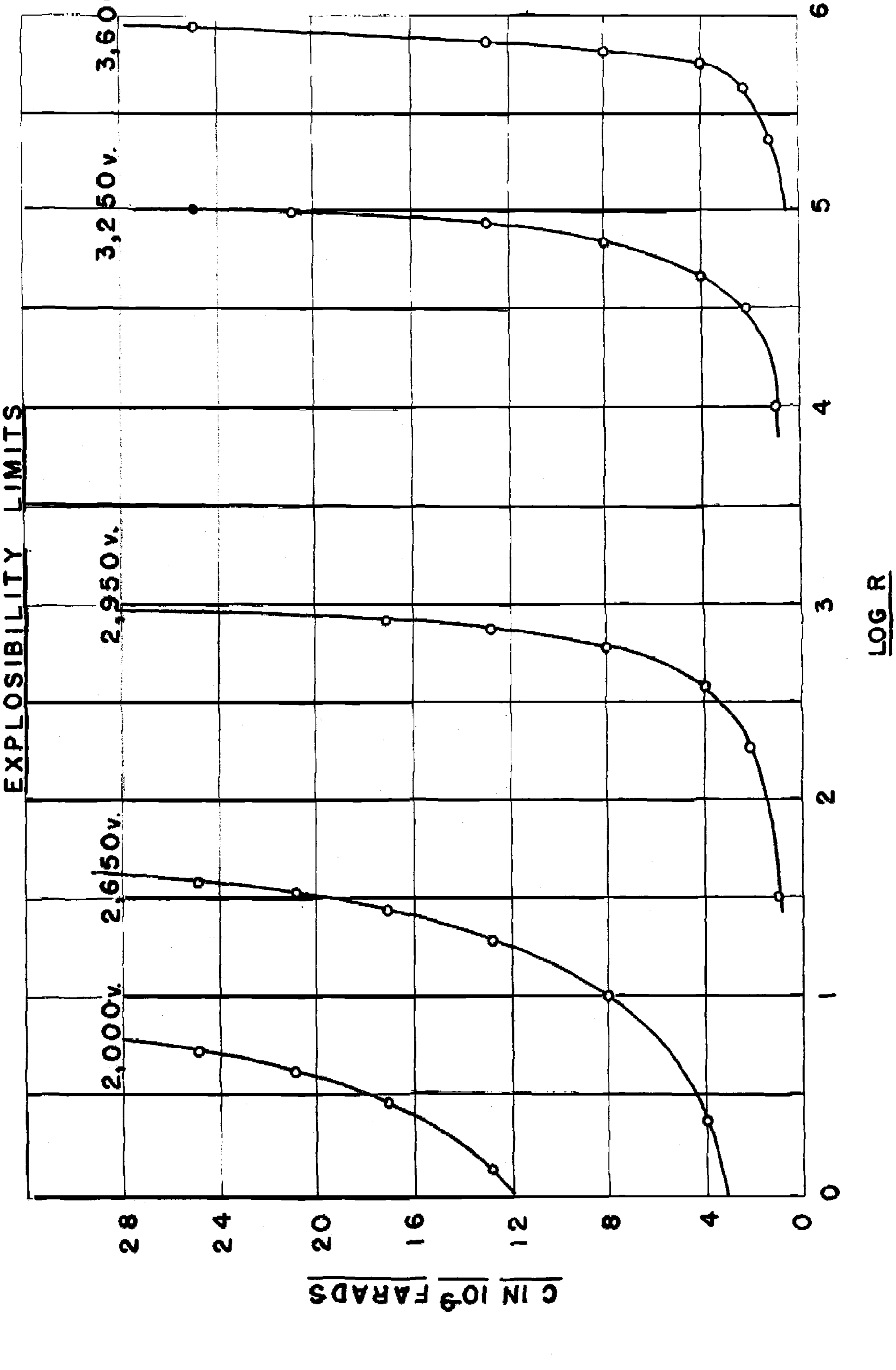
At a sparking potential of 2000 volts, it is noticed that a series resistance of ten ohms was sufficient to ~~unhilate~~ annihilate the explosibility of a spark from even a 25000 μμf capacitor. At 2650 volts however, a forty ohm resistance was required to destroy the igniting power of the same capacitor. Oscillographic analysis of the current showed the circuit to be oscillatory for the tests at both voltages.

In order to determine the cause of these effects we must consider the following.

(a) The sparking potential is unaffected by changes in R or C and hence the electrostatic field between electrodes just previous to sparking is unaffected also.

(b) The charge that can be delivered by a capacitor depends <u>entirely</u> upon its voltage. This eliminates charge as a factor.

(c) The rate at which charge is delivered ($dQ/dt = i$) depends upon the series resistance, the capacitor and the voltage.


EXPLOSIBILITY LIMITS
3,600v.
3,250v.
2,950v.
2,650v.
2,000v.
LOG R
0
1
2
3
4
5
6
C IN 10-9 FARADS
0
4
8
12
16
20
24
28

For this reason it is investigated more thoroughly later.

(d) The energy in the spark is given by

$$E = 1/2\ CV^2 - \int i^2\ R\ dt$$

Variation of R, C, or V are seen to produce the proper qualitative trends - but this relation can not provide the key to explosibility phenomena because of arguments put forth earlier and which still hold here.

(e) The rate at which energy is delivered, or wattage of the spark is effected by all three variables R, C, and V.

(f) The frequency of oscillation changes with C, and may change with R if the resistances used have some inductance. This is eliminated by other tests later.

(g) The current density in the spark may be changing in some fashion when the parameters are changed.

The results obtained at the higher sparking potentials may be used to advantage in discussing some of these factors.

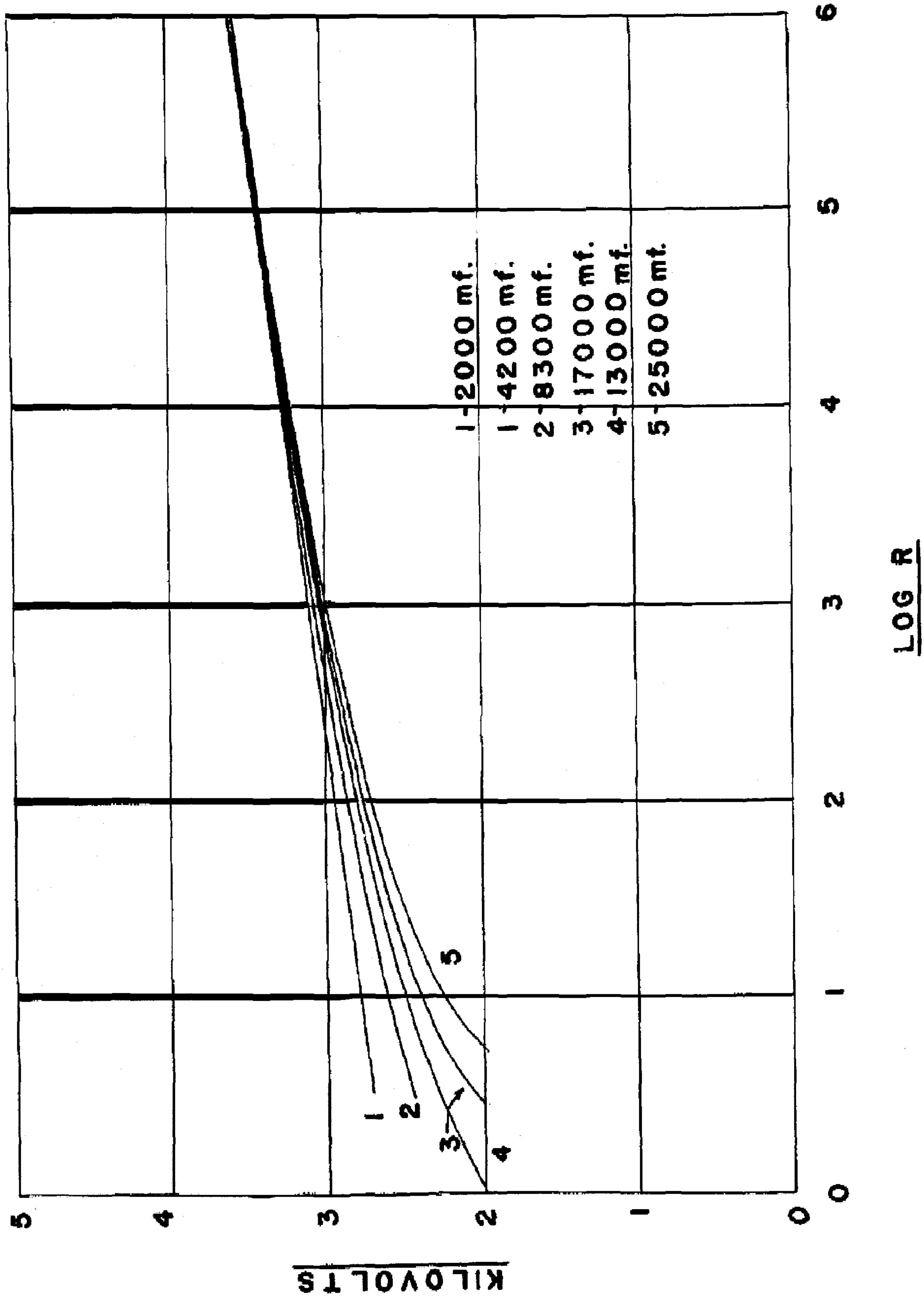
At the higher voltages (2950v and up) the series resistances necessary to quench the explosibility were so high that in all of these cases the circuit was overdamped. The results, however, as seen on Page (32) were much the same. This effectively eliminates the suggestion that a critical frequency may be determining explosibility, in this range.

That the total charge passed in the spark cannot be the determining factor is evident from a consideration of the product CV as a function of the sparking voltage. As the potential is increased, CV descends even more rapidly then the energy given by 1/2 CV^2 and illustrated on page 9a.

Another indication was obtained from results derived with the use of a pressure vane. A thin metallic strip was set into a "crystal pick-up" and carefully supported a fixed distance from the center of the spark gap. When the explosion occurred the effect of the pressure wave upon the strip was translated into a voltage by the crystal. Viewed on the oscilloscope screen simultaneously with the current in the discharge it was evident in many cases that the explosion occurred even before the current ceased to flow. It was unfortunately not possible to correlate the advent of pressure with the attainment of the maximum current.

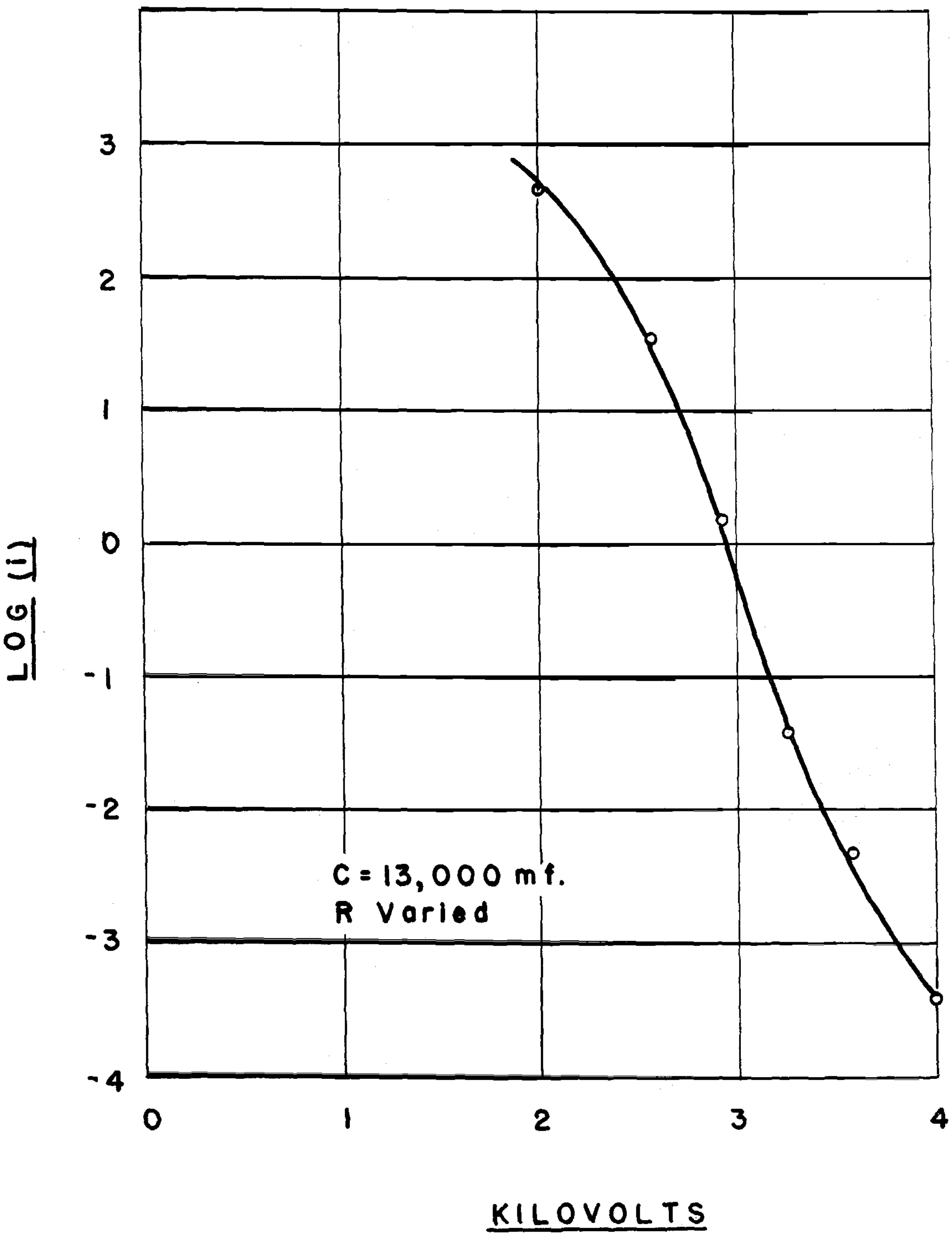
THE EFFECT OF SPARK POTENTIAL

Other information of a striking character was obtained. While the presence of ten ohms vitiated the explosive nature of a spark at 2,000 volts, at 4000 volts with a series resistance of a number of megohms, explosion could be obtained continually. Furthermore, the series resistance did not affect the violence of the explosion (as determined by the velocity with which the tennis ball was hurled from the top of the chamber). This is reasonable when considered from the point of view that whatever the initiating process, the explosion is a reaction of


1-2000 mf.
1-4200 mf.
2-8300 mf.
3-17000 mf.
4-13000 mf.
5-25000 mf.
LOG R
KILOVOLTS
0
1
2
3
4
5
6

the chemical constituents in the chamber. (57) (58)

From the curves of page 32 it was possible to obtain the curves given on page 35 which illustrate the series resistance necessary to limit explosibility - as a function of sparking potential. It is clear that the sparking voltage is an influential factor in the explosion of a cumbustible mixture. At elevated voltages, the capacitor is not nearly as important as it is at lower voltages. It appears, in fact, that below a series resistance of 500 ohms (circuit oscillatory) the capacitor as well as the sparking potential are important - but as the sparking voltage is increased - the latter predominates. It may well be that two initiating phenomena appearing simultaneously are operative - one dependent upon sparking potential and a second determined by the capacitor. Since both of these quantities act in the same way upon the current, it was suspected that the maximum current in the discharge might supply a criterion for explosion. This led to oscillographic measurements. A typical set of data, taken at different sparking potentials for a capacitor of 13000 μμf is given on page 37. It is seen that the maximum current "necessary" for explosion varies over a wide range. Further, although a spark with maximum current of the order of amperes would constantly refuse to ignite the mixture at 2000 volts, a 3600 volt spark with a maximum current a thousand times smaller would explode the mixture at every discharge. It does not seem reasonable therefore to suspect that the current is <u>itself</u> the controlling quantity in the initiation of the explosion.


3
2
1
0
-1
-2
-3
-4
LOG (i)
C = 13,000 mf.
R Varied
0
1
2
3
4
KILOVOLTS

2.7 TESTS WITH AN INDUCTANCE

Some experiments on the effect of inductance were performed. Special air core inductances were built for these tests. Four single layer coils using No. 12 B. and S. gauge wire were made. Micarta tubes of convenient dimensions were used. When completed, the forms were dipped in insulating varnish and baked until thoroughly dry. These precautions were necessary because of the impulsive character of the current. The resistance of the coils was less than 1 ohm.

Inductances serve to produce at least 2 important effects. The oscillatory character of the circuit can be changed and the maximum current can be decreased without changing the amount of energy dissipated in the spark. From spectroscopic work on electron stripping by sparks, (56) it is known that the presence of inductance in the discharge circuit hinders the stripping of valence electrons. In this connection it was interesting to note that the explosibility of a spark could be decreased by placing a series inductance in the discharge circuit. This seems quite reasonable from the excitation view of explosion. A decrease of the current does not affect the probability of generation of excited molecules, but it does decrease the amount of activation generated because so many less electrons are involved. G. I. Finch found however that lowering the frequency of the discharge could greatly increase the ignitibility of a spark. This matter is being more thoroughly investigated (34).

There is a possibility that the current density in a spark is a function of all of the variables employed thus far. It is known and commonly accepted that an electric arc is a constant current density affair (59) (60) - but no such definite information is available for the spark. Photographic attempts were made to obtain some data on this matter - but useful results have not yet been obtained. Other investigators have also made such attempts (51).

The fact that at reduced pressures the detonation of a combustible mixture appears to require a critical density of activation, led to an investigation of the explosibility of our ether air mixture when subjected to a corona discharge.

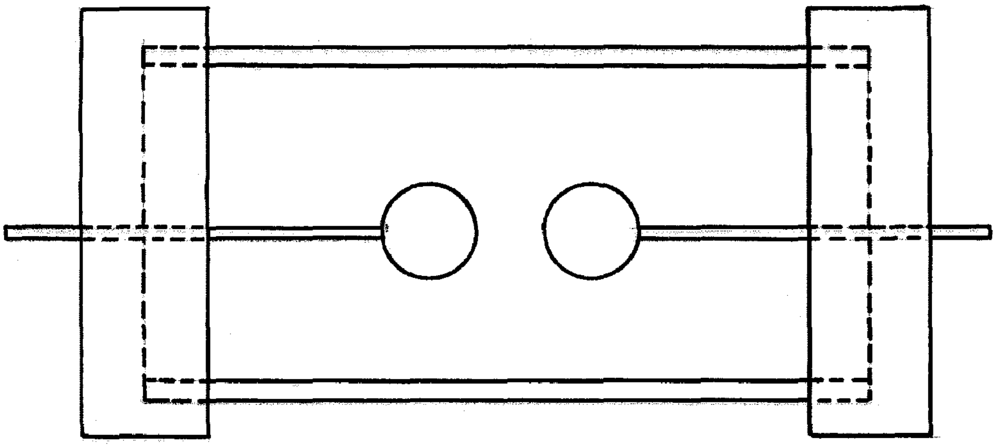
2.8 TESTS USING CORONA DISCHARGES AND SPARKS AT HIGHER VOLTAGES

At atmospheric pressure a convenient way to investigate the effects of current density is to use the corona discharge. Accordingly tests were made with the same explosion chamber at higher voltages then previously used.

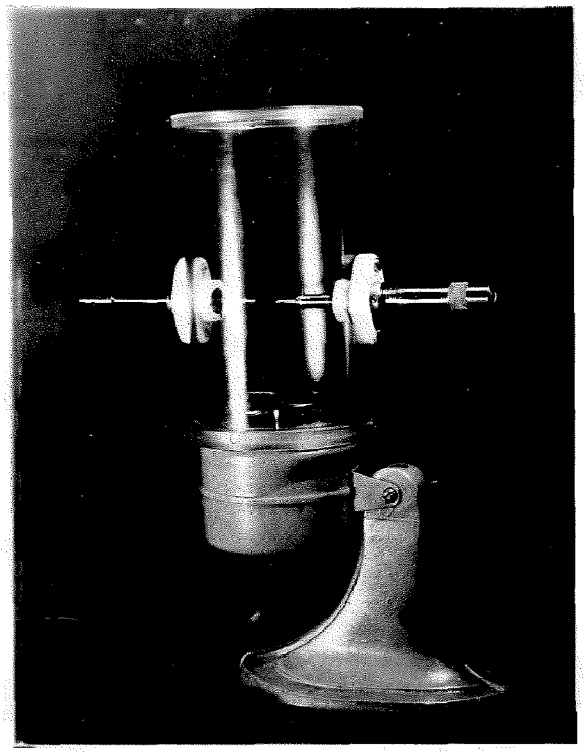
A Wimshurst machine was used as a high voltage source. The capacitance of the device being reduced as much as possible, the terminals were connected to the chamber electrodes and an electrostatic volt meter was connected in parallel to the gap. The oscilloscope was used as previously described.

In order to obtain these higher voltages the gap had to be made so wide that the back sides of the spheres were in contact with the lucite walls. It was soon found that surface leakage was prohibitive. To avoid these difficulties a new cylinder of larger dimensions was designed. Two definite improvements were made. The electrodes were supported by porcelain insulators set into the lucite, and a micrometer screw arrangement was adopted to control the electrode separation. During the period of construction of the new chamber, several tests were performed using a third cylinder of the same dimensions as the first. However, the electrodes were mounted axially in two blocks of paraffin which sealed the chamber. Illustrations appear on the following page.

No electric stirring devise was used. Instead, after the usual charge of ether had been placed inside, the cylinder was sealed and revolved a number of times before voltage was



Sketch of Chamber used for Corona Tests



The New Chamber for High Voltage Tests

applied. Explosion caused one of the paraffin blocks to be blown out of position but there was no danger involved because the amount of combustible used was so small.

RESULTS - DISCUSSION

Different types of electrodes were used and all of the tests were performed in a darkened room in order that the discharge might be seen. Employing aluminum spheres 1/2" in diameter the following results were obtained:

1. Sparking voltage approximately 4500 volts.
    a. Explosion occurred with every spark passed. Voltage too low for corona.
2. Gaps set for 10,000 volts.
    a. A continous "spray" discharge was maintained between electrodes and no explosion could be obtained. Occasional popping sounds could be heard superimposed on the general corona "wheeze." These sounds were readily correlated with the occurance of highly ionized paths which seemed a dull red in the dark. The oscilloscope proved invaluable in the study of this discharge. The wave form of the current is given by Cobine (56) page 262.
    b. By carefully controlling the speed of the Wimishurst machine a weak spark could be made to

pass between electrodes. In all such cases explosion occurred.

3. The electrode separation set for 19,000 volts. A continuous bright pink spray of charge could be maintained between electrodes without a spark passing. No explosion could be obtained.

4. Violent corona discharge was maintained up to 35,000 volts but no spark passed and no explosion occurred.

Using steel needles as electrodes it was found that:

1. Due to leakage of charge from the sharp points the potential could not be raised much above 4,000 volts.

    a. With the needles close together a small spark could be passed and in every case explosion occurred.

    b. At larger gap distances only corona could be obtained and no explosion was recorded.

When the aluminum sphere was made the positive electrode and a needle was used as the negative electrode, explosion occurred with every spark for voltages above 4,000 volts. With the polarity of the electrodes interchanged, the needle could be made to glow with discharge but no explosion occurred.

In many of the cases described above the continuous corona current which upon no occasion exploded the mixture was greater than the maximum current in a spark which did explode the mixture every time.

This suggests that before explosion can occur a definite current density or concentration of electric activation may be necessary. Such an assumption is in complete accord with the conclusions reached by investigators who have studied the problem of explosion by electric discharges at low pressures. However, this theory will not explain the results obtained from previous experiments at sparking potentials of 2,000 to 4,000 volts unless it can be shown that variations in the sparking voltage or of the circuit parameters, affect the current density in a spark.

2.9 SUMMARY OF RESULTS

The initial phase of investigation of the explosion of combustible mixtures of ether-air with electric sparks has been brought to a close. Several interesting results have been obtained.

(a) If the sparking potential, series resistance, and inductance are fixed, a critical value of capacitance exists below which explosion will not occur.

(b) If other parameters are kept constant, the value of capacitor required for explosion decreases with increased sparking potential.

(c) At a sparking potential of 2000 volts, addition of a small resistance has a marked adverse affect on the explosibility of a spark. At a sparking potential of 4000 v. series resistance has a mild affect.

(d) Explosions have been observed to occur before the spark current has ceased to flow.

(e) The total charge passed in a spark does not by itself control the igniting power of a spark.

(f) At 2000 volts the peak current of sparks causing explosion was of the order of amperes - while at 4,000 volts, sparks with a maximum current 1000 times smaller exploded the mixture continually.

(g) No correlation appears to exist between the maximum average or effect value of the spark current and the ability of a spark to initiate explosion.

(h) The sparking potential is of paramount importance in determining whether or not a spark will cause explosion. It was found that doubling the sparking potential from 2000 volts to 4000 volts decreased the "energy necessary for explosion" by more than 25 times.

(i) The energy dissipated in a spark is not by itself the determining factor in the initiation of explosion.

(j) No explosions could be obtained with a steady prolonged corona discharge at voltages ranging up to 35,000 volts. However at 4500 volts a spark with maximum current less than the corona current at 35,000 volts exploded the mixture continually.

ADDITIONAL COMMENTS AND SUGGESTIONS

In the early stages of experimentation it was hoped that a correlation might exist between the maximum spark current and the ability of a spark to cause explosion. However, later results showed that the process of initiating an explosion is very complex and depends upon many factors. The results obtained with corona discharges are very interesting and further experiments using higher corona currents are being conducted.

The indication that current density may be an important factor in determining "exploding power" of a spark is encouraging and seems more reasonable than a "critical current" criterion for ignition.

Attempts to obtain spark current densities by photographic means are being considered.

It may be desirable to use combustible mixtures which are chemically simpler than the ether-air mixtures used. Hydrogen and oxygen are recommended because of the ease with which these elements can be obtained electrolytically and the extensive literature which exists on such explosible mixtures.

The influence of different types and sizes of electrodes may reveal further important facts concerning the explosion process.

THE DYNAMIC RESISTANCE OF A SPARK

I.I INTRODUCTION

The problem of correlating the ignitibility of a spark and the wave form of the current makes it imperative to obtain oscillograms from which measurements can be made. The impulsive character of the current complicates the situation.

In due time it was possible to introduce, for engineering purposes, the term "spark resistance" and to calculate it by a simple method. Other interesting facts were brought to light and it became desirable to concentrate these matters in a separate section.

1.2 APPARATUS AND METHOD OF MAKING MEASUREMENTS

Theoretically, any varying quantity which can be "translated" into a voltage can be viewed on a cathode ray oscilloscope screen. Practically, a two-fold problem exists. First one must be sure the voltage measured is actually due to the quantity it is supposed to represent. Secondly, a knowledge of probable errors and limitations on the method of measurement, must be available.

The research was begun with use of a Dumont 5 inch Single Sweep Oscilloscope. This instrument has a post accelerating electrode - or Intensifier which proved quite useful for photographic purposes.

The probable values of the circuit parameters to be used in the main researches were known. It was a simple matter to determine that frequences in the range of a megacycle would occasionally be encountered. This eliminated the use of any ordinary amplifiers - such as those which occur in even the best laboratory oscilloscopes. For a convenient vertical deflection it was found that 50 volts or more had to be applied directly to the plates of the oscilloscope. Rather than design and build a proper video amplifier, it was decided to obtain the required voltage by placing a suitable pick up resistor into the discharge circuit as shown in figure 1 on page 19. Usually when the circuit frequency was high, a high current also flowed and so a small pick up resistor - in some cases less than 1/2 ohm could be used. The voltage drop across this resistor was led thru a 50,000 ohm resistance, to the vertical plates of the oscilloscope. The effect of this measuring circuit upon the main discharge circuit, was negligible.

The voltage drop across the pick up resistor is generally speaking

$$v = Ri + L \frac{di}{dt}$$

During the initial part of some of the transients investigated the value of di/dt was of the order of 10^7 amperes per second. For this reason pains were taken to make a non inductive resistance - or at least one for which Ri was at least 90% of the voltage drop across it. Nichrome wire was used. One of the resistors used had an inductance of 10^{-8} henry for resistances up to 15 ohms and served quite satisfactorily.

The vertical deflection sensitively of the oscilloscope was determined in the usual manner using a Hewlitt Packard Oscillator and A General Radio Vacuum Tube Voltmeter. Calibration was carried out at 5,000, 10,000, and 40,000 cycles per second. It was found that 1.9 volts would cause a deflection of 1 millimeter.

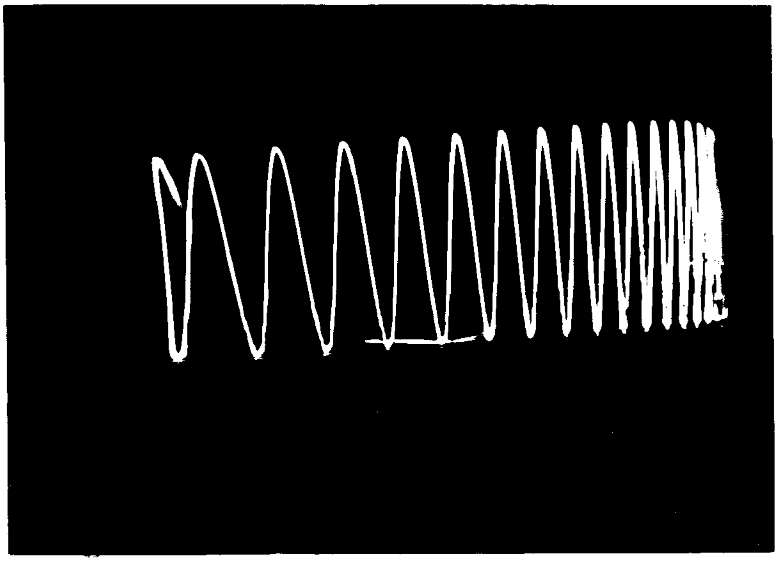
Faithful vertical deflection (proportional to the discharge current) being assured, it was desired to obtain a convenient horizontal sweep for the oscilloscope. The most useful sweep circuit can be defined as one that will keep the electron beam satationary under normal conditions of no current, and which will without lag initiate a horizontal deflection of the beam at the instant that spark current begins to flow. In order to really be able to study the spark current transient it is nice to be able to repeat it at will.

Fortunately it was possible to obtain an electronic device - orginally designed by Dr. W. H. Pickering - and which, it was found, could be made to satisfy the above requirements. The circuit diagram and principle of operation can be found in The Physical Review (61).

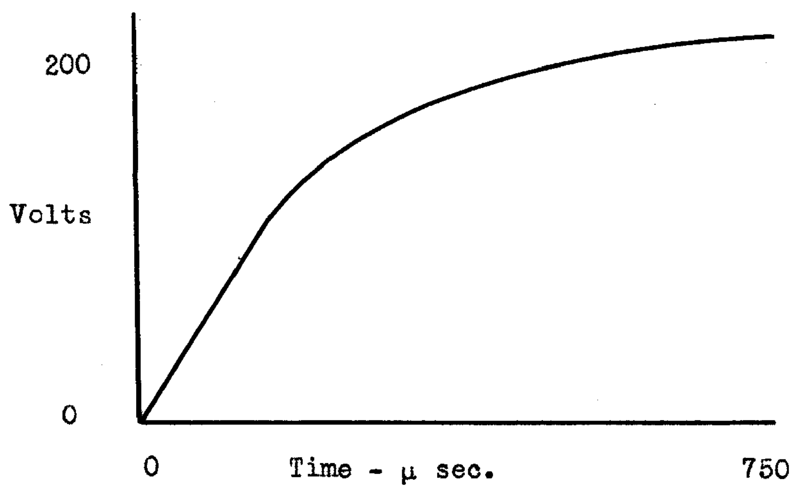
With a very small input voltage pulse, this device would put out a voltage pulse whose maximum could be adjusted up to nearly 250 volts. The time lag of the circuit was of the order of one microsecond. The wave form of the output wave could be varied between the limits of "nearly square" and "almost saw tooth," the duration being adjustable also. In addition it was found that the voltage induced in a pick up lead placed near the spark gap - was sufficient to initiate this sweep circuit. In actual operation, the horizontal sweep was made to be very rapid at the start of the transient - and slower toward the end.

To calibrate the sweep circuit, a sinusoidal wave of known frequency (usually 20,000 or 40,000 cycles per second) was placed on the vertical deflection plates of the oscilloscope while the sweep circuit was connected to the horizontal plates. A millimeter scale was attached to the oscilloscope screen. From the frequency of the applied sine wave, the time between peaks was known.

A photograph of the screen during a typical calibration using a 20,000 "cycle" sine wave is given on the next page.



Distance between peaks = 50 μ sec.



Voltage output of sweep circuit for calibration of Horizontal time axis.

1.3 RESISTANCE OF A SPARK

In investigating the "spark energy required for explosion," it became necessary to determine what portion of the total energy discharged by the capacitor, was dissipated in the spark. Information on this matter was obtained by examining the resistance of the spark. To check on the "negative character" of the spark resistance, the circuit parameters, R, L, and C were kept constant at values such that the urrent was mildly oscillatory and hence would be sensitive to changes in resistance. Different sparking potentials were used and photographs of the resultant wave forms were taken - on one film. The results obtained yielded simple and direct proof that a spark may be considered as a non linear circuit element - with a resistance which decreases as the current increases.

For higher sparking potentials and currents, the circuit became "more oscillatory." That is the degree of damping decreased. Since all other circuit parameters were kept constant, this could only come about if the resistance of the spark was a decreasing function of the current.

The photograph on the following page was used for these observations.

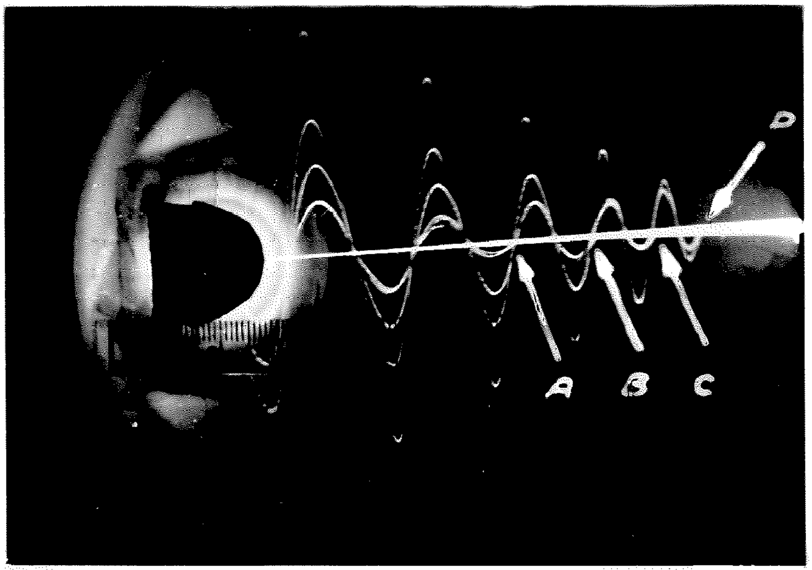
The ends of the current transients, for the different sparking voltages, are indicated by arrows.

A more detailed study to determine the magnitude of the spark resistance was based upon the following theory.

$L = 91{,}000\ \mu h$

$C = 13{,}000\ \mu\mu f$

$R_p = 40\ w.$



Sparking Potential	Cycles of Current
1300	2.5 ends at A
2000	3.5 " " B
2950	4.5 " " C
4450	5.5 " " D

1.4 THEORY OF THE METHOD EMPLOYED

When a capacitor discharges through a constant series inductance and resistance, the current will be over-damped if $R^2/4L^2 > 1/LC$; critically damped if $R^2/4L^2 = 1/LC$; and oscillatory if $R^2/4L^2 < 1/LC$. In the later case the analytical expression for the current is (62)

$$i = \frac{V}{\beta L} \varepsilon^{-\alpha t} \sin \beta t$$

$$\beta = \left(-\frac{R^2}{4L^2} + \frac{1}{LC}\right)^{1/2} \qquad \alpha = R/2L$$

The frequency is given by

$$f = \beta/2\pi$$

The "decrement" of the current is defined as the natural logarithm of the ratio of any two successive current peaks separated by a complete cycle. In the case of constant parameters:

$$\delta_n = \ln\left(\frac{i_n}{i_{n+1}}\right) = \ln\left(\frac{V_n}{V_{n+1}}\right) = \frac{R}{2Lf}$$

where V is the potential difference produced by the current.

If the circuit resistance and inductance are onstant, the damping is said to be logarithmic. If the resistance varies in such a way that successive current peaks differ from one another by a constant amount, the damping is linear. In general if the circuit resistance is considered variable we may write

$$\delta_n = \frac{R_n}{2Lf} = \frac{\pi R_n}{L\beta}$$

$$\text{or} \quad R_n = \frac{1}{\pi} \beta L \delta_n$$

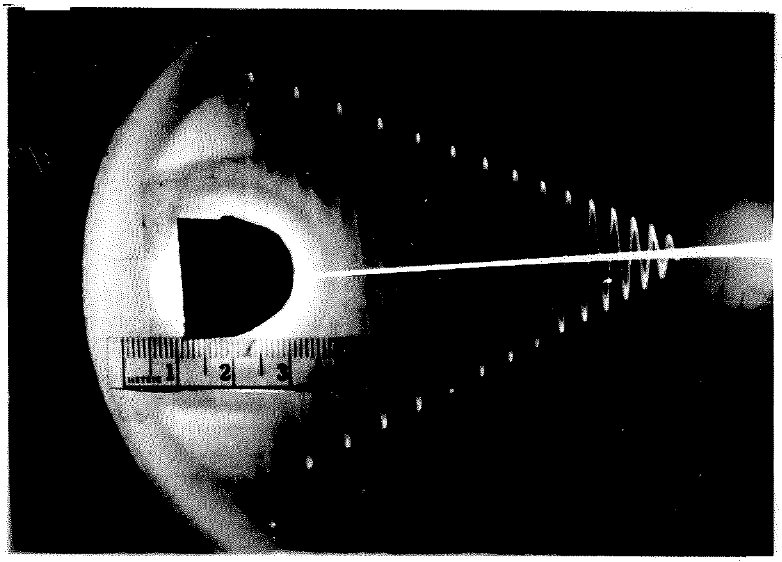
The total circuit resistance may then be obtained by a measurement of the "instantaneous decrement" δ_n and the other circuit parameters. When R_n^2 is small compared to $4L/C$, β is approximately given by $(1/LC)^{1/2}$ and

$$R_n = \frac{1}{\pi} \delta_n \sqrt{\frac{L}{C}}$$

Since the inductance, capacitance, and series resistance, are known and adjustable, we may obtain a value of resistance assignable to the spark itself.

$$(R_n)_{spark} = R_n - R_{series}$$

This matter was extensively investigated. In the next few pages are given a photograph of the current wave form for a particular condition of discharge, and a curve showing the variation in the resistance of the spark as a function of the current.



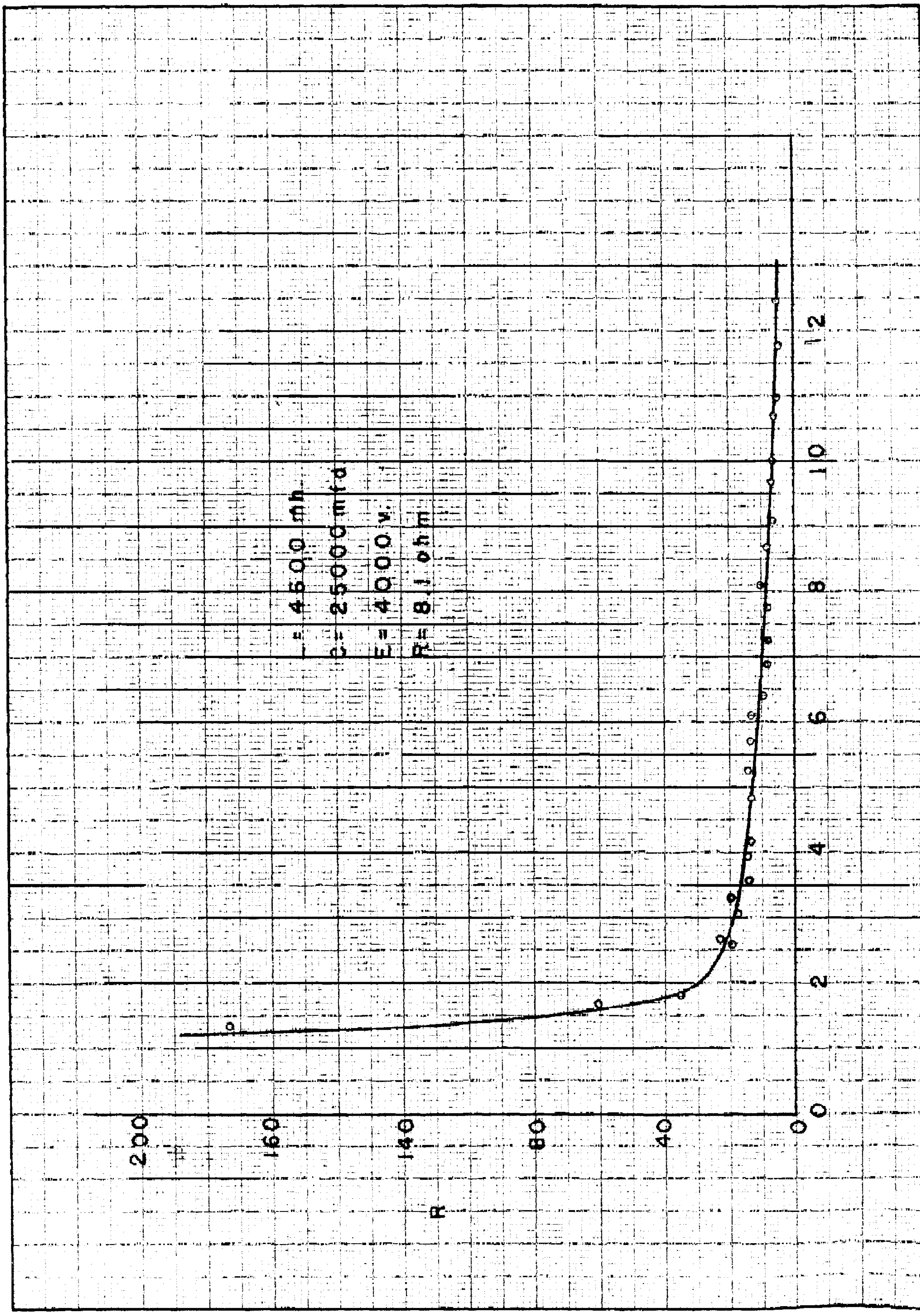
$L = 4{,}600\ \mu h$
$C = 25{,}000\ \mu\mu f$
$V = 4{,}000$ volts
$f = 14{,}800$ cps.

$R_p = 6$ ohms

$i_m = 15$ amperes

Total Series $R = 8.1$ ohms

Time of transient = 1050 μ sec.


L = 4500 mh
C = 2500 mfd
E = 4000 v.
R = 8.1 ohm
R
0
40
80
140
160
200
0
2
4
6
8
10
12

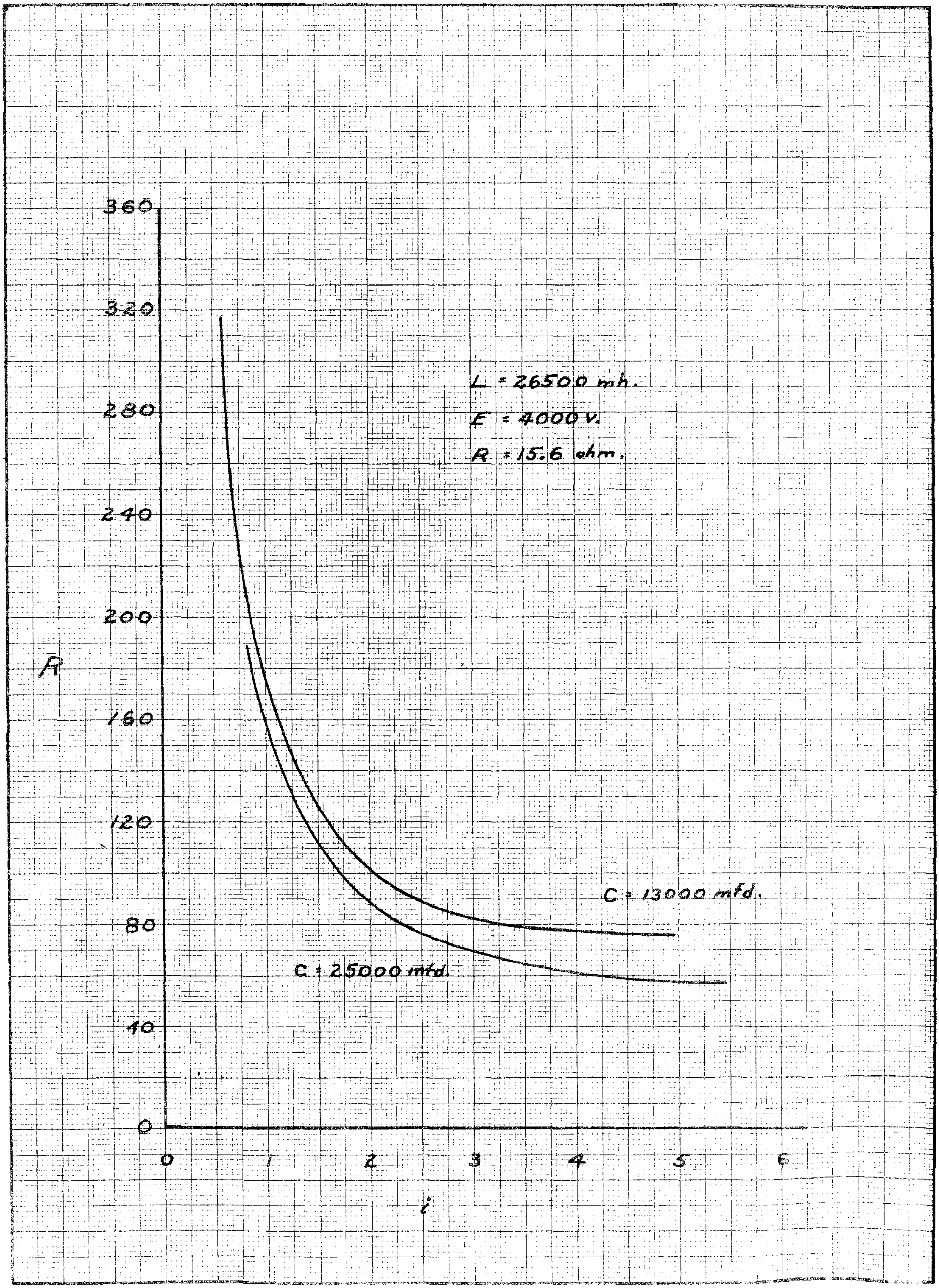
1.5 DISCUSSION

As may be seen from the preceeding curve, the resistance of the spark for the conditions given is "mainly" very low. Further consideration of the rapid manner in which the current is extinguished, leads to the conclusion that over most of its life, the resistance of the spark studied was of the order of 10 ohms. With higher current sparks the resistance is much lower. This is in accord with results previously obtained (63).

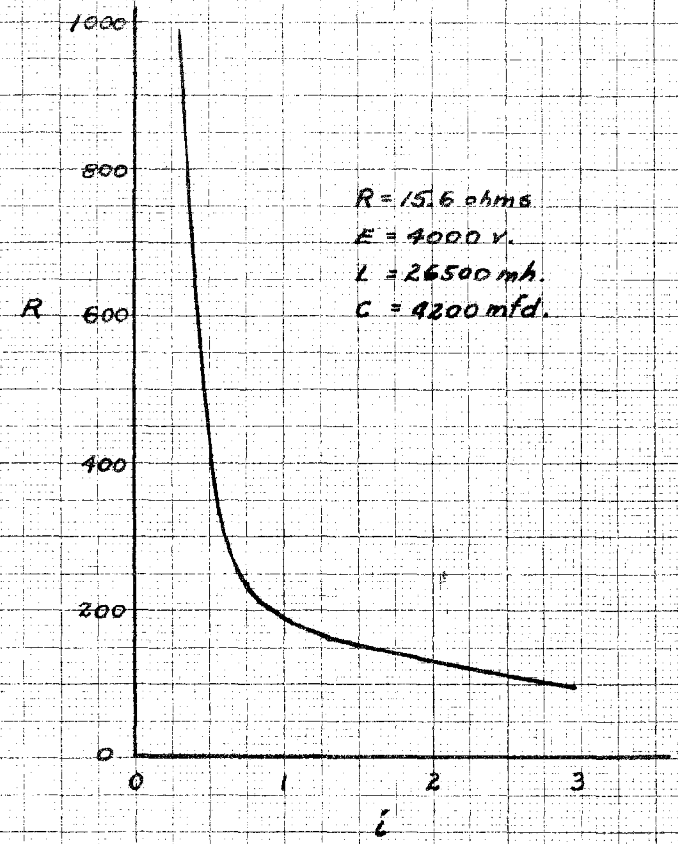
Any factor which will affect the magnitude of the current in the spark, will affect its resistance also. Thus with a constant sparking voltage, a change in the series resistor, inductor, or discharge capacitor will bring about corresponding changes in the spark resistance. Illustrations occur on the following pages.

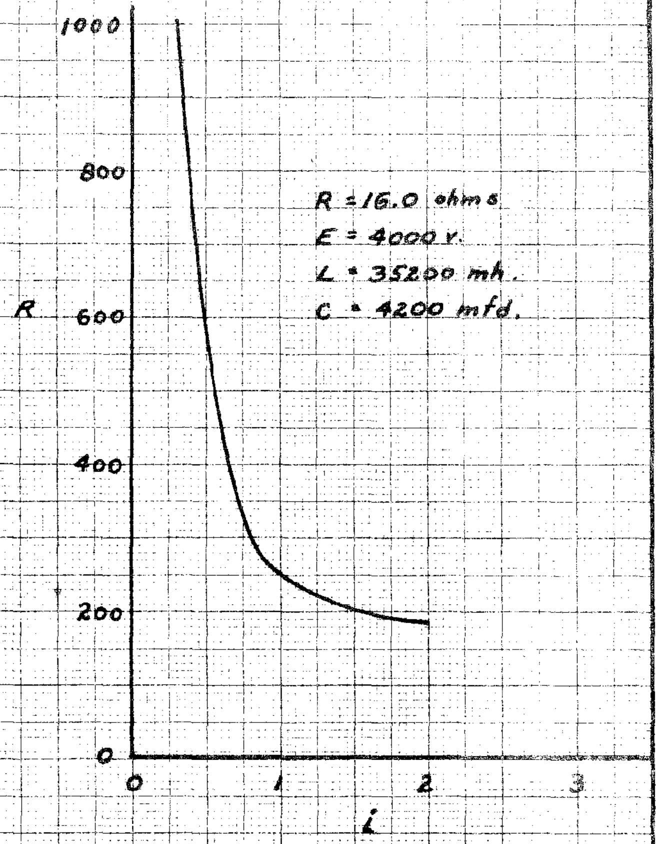
Attempts were made to obtain an expression for the resistance as a function of current. It was found that the non-linearity, could be described for a given set of circuit parameters by the empirical relation:

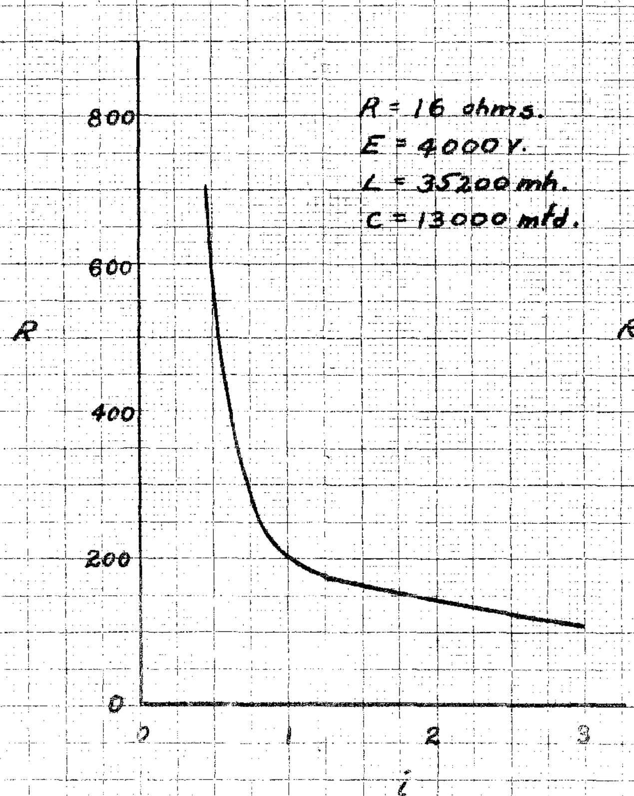
$$R = \frac{1 + ai}{bi}$$

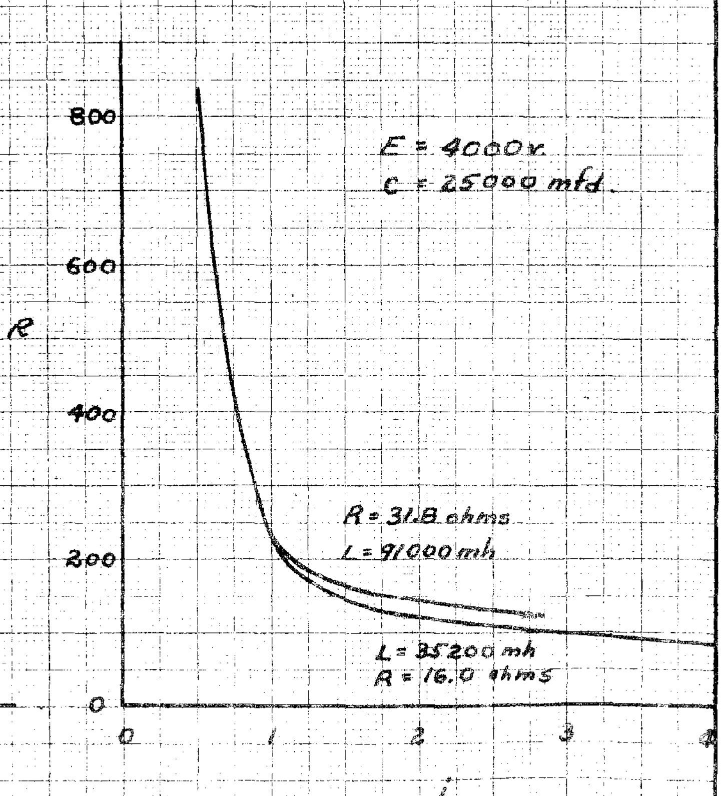


360
320
280
240
200
160
120
80
40
0
R
0
1
2
3
4
5
6
i
L = 26500 mh.
E = 4000 v.
R = 15.6 ohm.
C = 13000 mfd.
C = 25000 mfd.


R = 15.6 ohms
E = 4000 v.
L = 26500 mh.
C = 4200 mfd.
R
1000
800
600
400
200
0
0
1
2
3
i

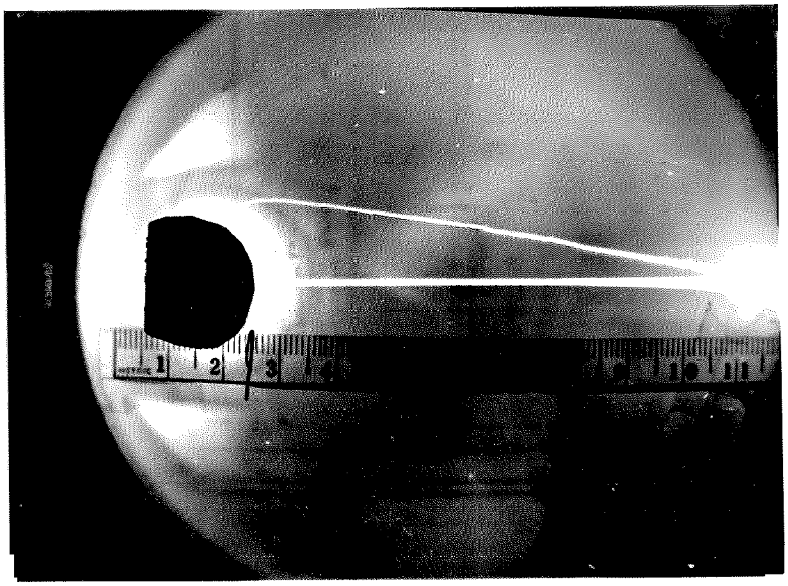

R = 16.0 ohms
E = 4000 v.
L = 35200 mh.
C = 4200 mfd.
R
1000
800
600
400
200
0
0
1
2
3
i


R = 16 ohms.
E = 4000 v.
L = 35200 mh.
C = 13000 mfd.
R
800
600
400
200
0
1
2
3
i

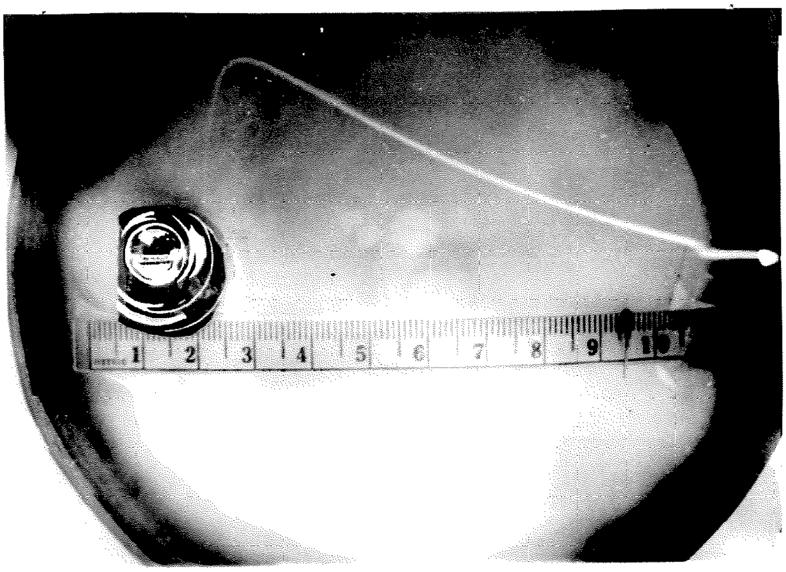

E = 4000 v.
C = 25000 mfd.
R = 31.8 ohms
L = 91000 mh
L = 35200 mh
R = 16.0 ohms
R
800
600
400
200
0
0
1
2
3
4
i

APPENDIX - A: PHOTOGRAPHS OF CURRENT TRANSIENTS

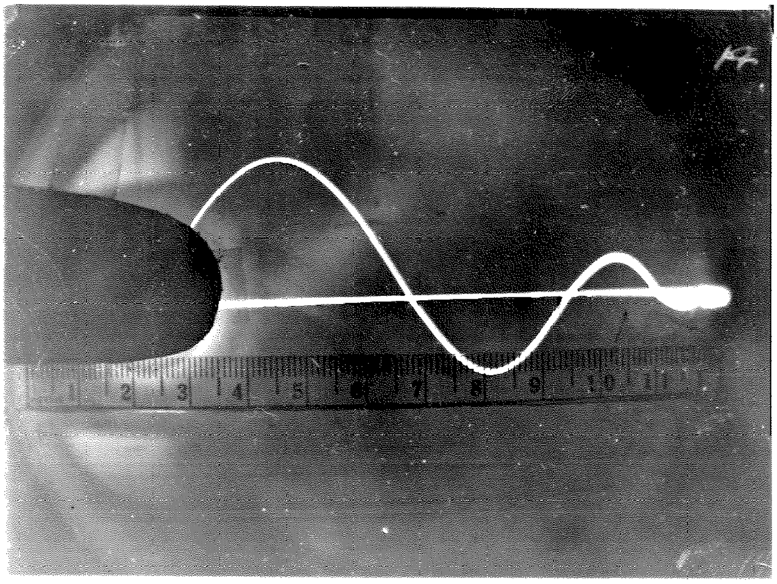
The photographs which follow are illustrative of the fine way in which the measuring circuit responded to repeated current ransients. Representative examples covering a wide range of operating conditions have been chosen. Each photograph represents a number of repeated traces. The statistical manner in which the spark is extinguished is due to the small variations in the charge stored in the capacitor previous to sparking. To conserve film, photographs for two circuit conditions were taken with the same film. Occasionally prints were made thru the back of the negative so that they seem reversed.



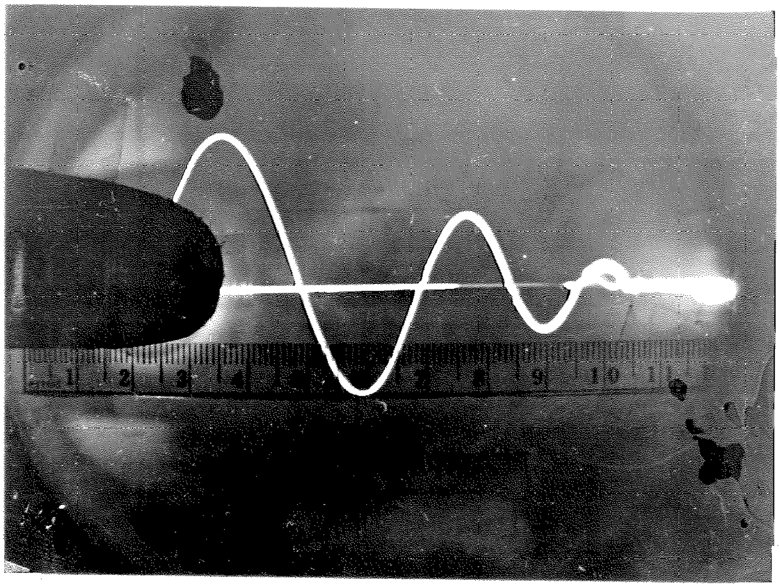
V = 4000 volts
Series R = 1,000,000 ohms
i_m = 0.004 amperes



V = 4250 volts
Series R = 307,000 ohms
i_m = 0.013 amperes

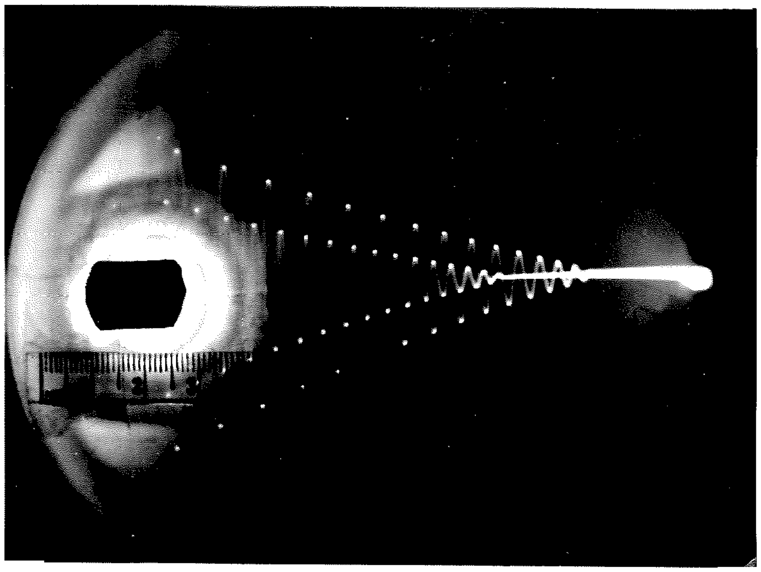


C = 8000 $\mu\mu f$
L = 0.237 h
V = 2750 volts
R_s = 1800 ohms

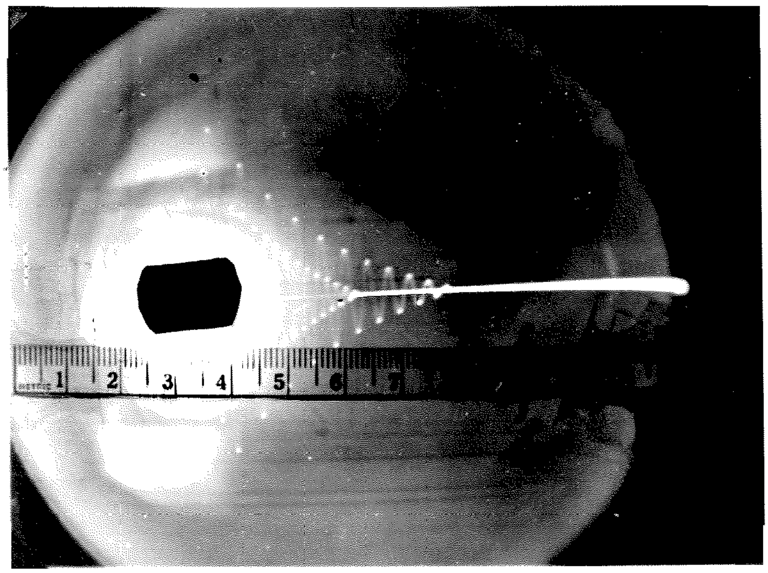


C = 2000 $\mu\mu f$
L = 0.237 h
V = 2750 v
R_s = 1650 ohms

Photograph of 12 superimposed current traces.



(a) f = 28,300 cps
(b) f = 45,000 cps



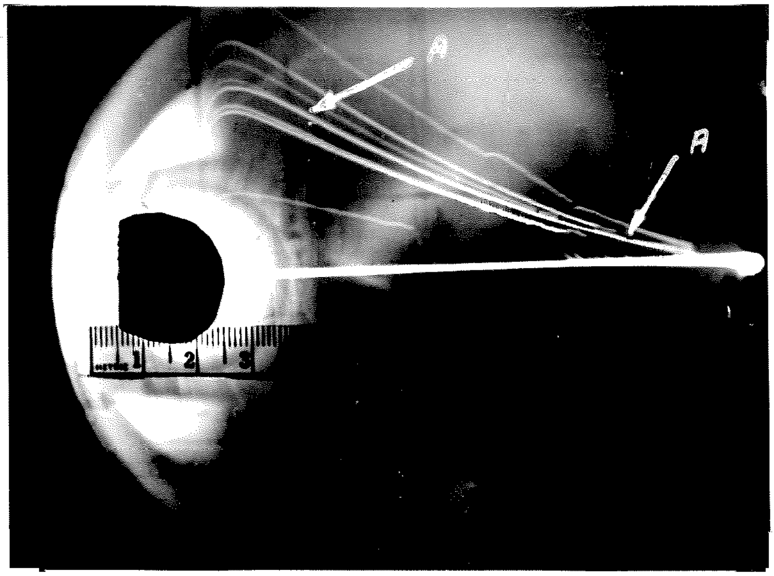
(a) f = 114,000 cps
(b) f = 271,000 cps

For both photographs on this page the shutter of the camera was kept open and 15 to 20 sparks passed. That the current traces fall on one another so carefully, is a tribute to the faithful operation of the horizontal sweep circuit.

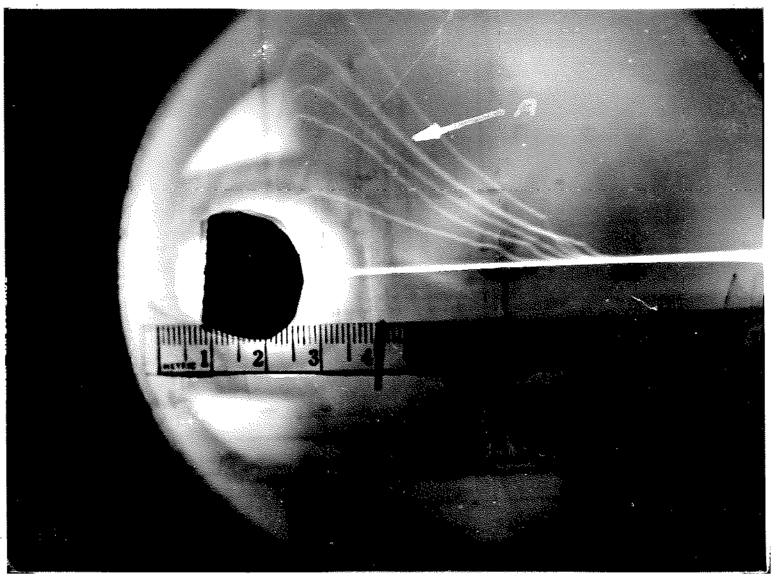
APPENDIX - B : GAP RESISTANCE IMMEDIATELY AFTER EXPLOSION

Information concerning what happens in the gap after an explosion of the ether-air mixture can be obtained from the following photographs. In each instance current A caused explosion. The consequent flame produces a high state of ionization in the gap and sparks will pass at lower potentials - in fact much before the capacitor is recharged to half of the initial sparking voltage.

As the ions are swept out of the path, higher potentials are necessary to spark the gap until finally the sparking potential is even greater than that for the same electrode spacing in air. A thorough sweeping of ions must therefore take place in the wake of the explosion.



V = 4000 volts



V = 4000 volts

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