AN INVESTIGATION OF A METHOD FOR ESTABLISHING

PREIONIZED CURRENT PATHS

IN TRIGGERING ARC-TYPE FACILITIES

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George Lee Maddrea, Jr.

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LIST OF SYMBOLS

AWG	American Wire Gage
C	capacitance in farads
C1	main capacitor energy storage bank
C2	trigger capacitor
I	current
I_p	peak current
K	constants
kV	kilovolts
L	inductance in henries
L_L	long electrode configuration inductance
L_s	short electrode configuration inductance
L*	arc length in centimeters
M	mutual inductance in microhenries
Q	charge in coulombs
Q_1	tabulated value
R	resistance
Reff	effective resistance
SW	switch
V	voltage
Vc	initial charge voltage on a capacitor
d	main electrode separation in feet
f	frequency
h	height in inches

i	instantaneous value of current
j	$\sqrt{-1}$
l	length in centimeters
psig	pounds per square inch gage
t	time
w	watts
$\Delta T^{o}C$	temperature rise in degrees centigrade
π	3.14 radians
Ω	ohms resistance
ω	radian frequency

CHAPTER I

INTRODUCTION

Shock tubes and shock tunnels over the last decade have proven to be valuable tools in the engineering development of the aerodynamic and thermodynamic problems of hypervelocity flight.[1] Needless to say, reentry physics has served us well through these years. However, orbital velocities (i.e., 26,000 ft/sec)[2] have become commonplace and research physicists have now turned their sights toward interplanetary flight with velocities ranging up to 75,000 ft/sec.[3]

The burden has thus been thrust upon the engineer to develop to its fullest the existing shock tubes or create new facilities such that fundamental research may be conducted for the flight environment of these supervelocities.

At this point a very brief description of how shock tubes simulate hypervelocity flight is helpful. A shock tube consists of two chambers - the driver chamber and the downstream or driven chamber. The driver chamber is separated from the driven chamber by a rupture

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[1] H. Hoshizaki and J. C. Andrews, "The Lockheed Missiles and Space Company 12-Inch Arc-Driven Shock Tube" (Palo Alto, California: Lockheed Research Laboratory, Lockheed Missiles and Space Company, 1964) p. 1 (Mimeographed).

[2] W. R. Warren, D. A. Rogers, and C. J. Harris, The Development of an Electrically Heated Shock Driven Test Facility (Space Sciences Laboratory, General Electric Company, Missile and Space Vehicle Department, 1962), p. 1.

[3] Hoshizaki and Andrews, loc. cit.

disk called a diaphragm. These diaphragms are precut to up to 40 per cent deep with two perpendicular lines intersecting in the center. The driver chamber is pressurized with a gas (usually helium or a stoichiometric mixture of hydrogen and oxygen diluted by helium) called the driver gas. The driven chamber is evacuated with a vacuum pump. This is all accomplished slowly with the diaphragm in place and intact. Then the driver gas is suddenly heated in our case by the arc discharge of an energy storage capacitor bank. This sudden application of heat with a fixed volumn of gas[4] causes a sudden pressure buildup in the driver which causes the diaphragm to rupture sending a very fast incident shock wave down the driven chamber which is generally a long tube, and across a model or specimen. A vast number of problems result encompasing all areas of study from contamination in the flow to shock wave reflections. This investigation concerns one technique of solving one of these problems. The subject problem can now be more clearly defined: to increase the strength of the resulting incident shock wave, such that flight environments of the superorbital velocities are simulated. More simply stated - to increase the shock Mach number.

Now that the principle of operation has been reviewed, we call upon shock tube theory to enlighten us as to the best approach to increase the shock Mach number.

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[4]The gas heat-up time is considered short compared to the opening time of the diaphragm, therefore, the diaphragm is assumed to remain intact during the energy discharge process.

Theory shows that this can best be achieved by increasing the pressure ratio across the rupture diaphragm.[5] That is to increase the sound speed ratio of the driver gas.

The sound speed of the driven gas (i.e., vacuum) is essentially fixed, therefore, only the sound speed of the driver gas is variable. Theory further shows that driver gas sound speed (Mach number) increases with the square root of the absolute temperature of the driver gas.[6]

Evans[7] describes a shock tube constructed with a driver section heated with commercially available (General Electric Calrod) heaters. The advantages listed are: (1) less hazardous operation, (2) good heating uniformity, and (3) simple control of driver energy. The disadvantage is inefficient energy utilization since most of the electrical energy goes into heating the driver wall.

Still another method is to heat the gas with the arc discharge of a capacitor bank. The big disadvantage being localized heating at only one end of the shock tube driver. Axial uniformity in the heated driver chamber is a strong requirement since any calculations assume a uniform steady flow and since experiments in uniform steady flow are desired.

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[5] John C. Camm and Peter H. Rose, "Electric Arc-Driven Shock Tube," _The Physics of Fluids_, Vol. 6, No. 5:664, May, 1963.

[6] Robert C. Evans, "_Operation and Performance of a Shock Tube With Heated Driver_," Memorandum No. 48 of the Guggenheim Aeronautical Laboratory at the California Institute of Technology, 1959, p. 1.

[7] Ibid., pp. 1-4.

Large efforts have been expended to achieve better heating uniformity, such as using parallel rail electrodes and allowing the electromagnetic field to blow the arc down the rails in much the same manner as an arcing horn or by stringing several trigger wires between parallel electrodes in an effort to produce several arcs simultaneously.[8]

One technique of interest to Langley Research Center scientists which had not been investigated prior to this author's interest is a high voltage triggering method currently being used by the Lockheed Missiles and Space Company in their shock tube at Palo Alto, California.[9]

The hypothesis is that an arc discharge from an energy storage capacitor bank can be drawn axially throughout the entire length of any given shock tube driver. The technique would be to put the two electrodes of the main energy storage bank at opposite ends of the driver chamber. Then string a trigger wire from one electrode to the vicinity of the other and by means of a separate high-voltage trigger capacitor ionize the trigger wire and thus provide a current path allowing the main capacitor bank to discharge. This axial arc discharge would thus produce subsequently higher driver gas temperatures uniformly in a shock tube driver.

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[8] L. Loukopoulos, "An Investigation of High Energy Arcs" (Mimeographed).

[9] H. Hoshizaki and J. C. Andrews, op. cit.

Just how long an arc can be drawn? How high a trigger voltage is required? How fast can the gas be heated? What type of trigger wire is best? And what is the arc resistance as a function of arc length? All these questions could only be answered through an experimental analysis. They constitute the purpose of this research and are herein answered.

The technique in itself is not new. Others have used variations of the technique in very short (up to 18 inches)[10] drivers. The present emphasis is to extend the technique applicability to long driver chambers with the immediate objective of 4 feet.

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[10] W. R. Warren, D. A. Rogers, and C. J. Harris, op. cit.

CHAPTER II

ELECTRICAL DESIGN

Figure 1 shows the basic electrical circuit used in the experimental study. The power supply shown is a Universal Voltronics Corporation model, number BAL 60-250-NSA, rated 0-60,000 volts dc at 250 milliamperes. The main energy storage capacitor bank C1 consists of 10 capacitors of 43 microfarads each. These capacitors were purchased in 1961 and rated at 12,000 volts for 1,000 hours electrification time or a minimum of 5,000 discharges at full voltage. These capacitors are of the extended paper-foil construction having one high-voltage terminal and one ground stud (case) each. Further design characteristics are a maximum discharge duty of 65 per cent voltage reversal and a frequency of 1,500 hertz.

At the time the capacitors were originally purchased, they were supplied from the manufacturer individually fused with discharge limiting expulsion type fuses. The purpose of the fuses being to isolate a faulty capacitor from the circuit in the event of a unit failure.

The fuses were removed and the capacitors connected directly with two parallel plates separated by 30 mils thickness of polyethylene insulation. With the capacitor bank modified as described and because of the bank's frequent use over the past 3 years, the bank's voltage rating was reevaluated and a new rating of 10,000 volts was determined safe.

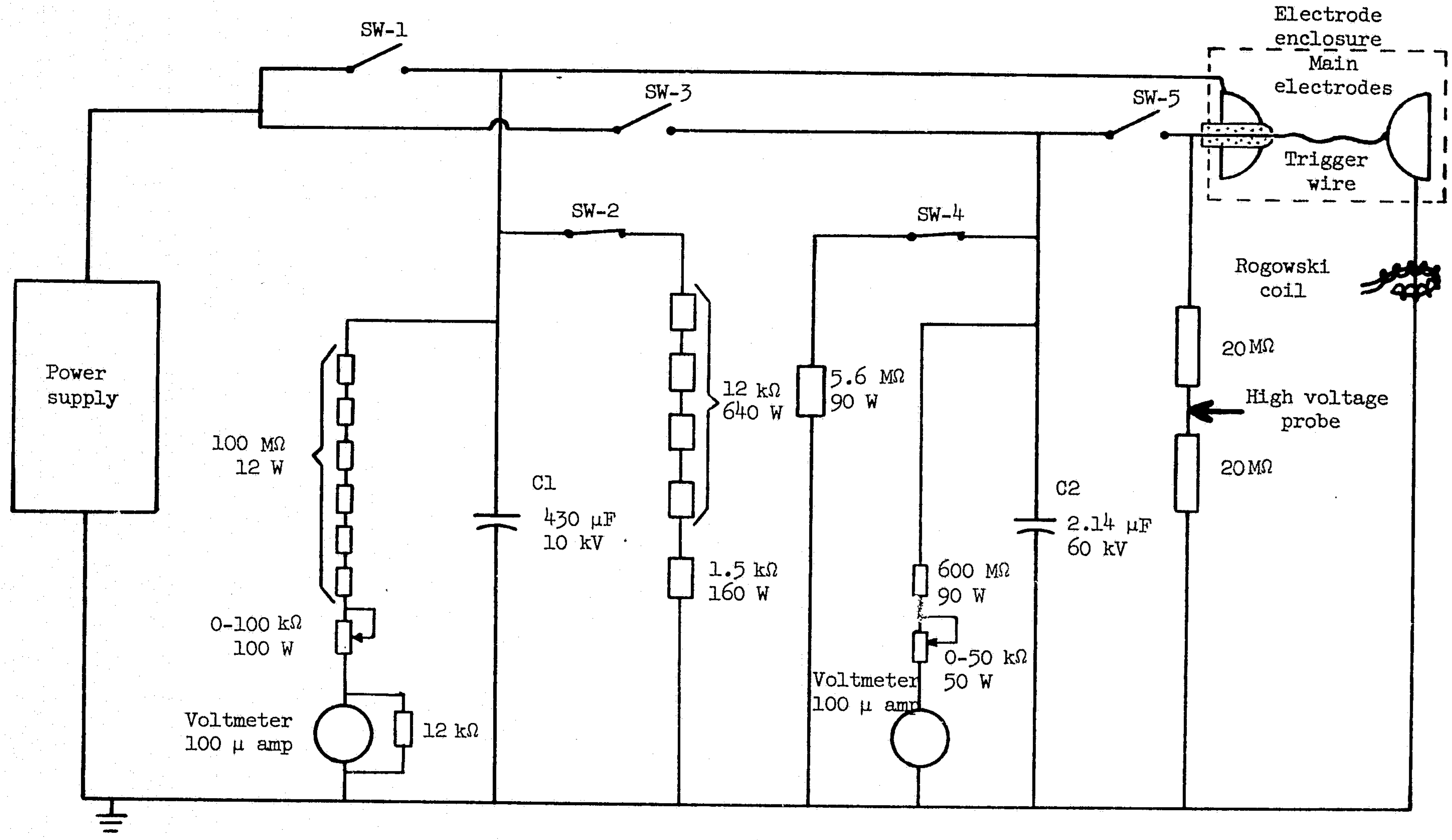

FIGURE 1

BASIC HIGH-VOLTAGE ELECTRIC CIRCUIT

The trigger capacitor C2 was selected from the list of commercially available low-inductance, high-voltage capacitors. The list of capacitors along with their respective characteristics is shown in Table I.

TABLE I

CAPACITORS CONSIDERED FOR C2

Unit	Capacitance in microfarads	Rated voltage (kilovolts)	Energy at rated voltage in joules	Inductance in nanohenries
A	0.8	100	4,000	80
B	.84	120	6,000	30
C	1.0	100	5,000	50
D	1.0	100	5,000	60
E	1.0	100	5,000	80
F	1.2	100	6,000	30
G	2.14	75	6,000	30

Unit G, a Tobe Deutschmann Laboratories Incorporated model, number ESC-250-B, 2.14 microfarads, rated for 6,000 joules at 75,000 volts dc and 90 per cent voltage reversal was selected for C2.

Unit G was more desirable since it had the highest energy storage capacity at 60,000 volts. It carried a built-in safety factor in that it was designed for a higher voltage than its intended use. The voltage rating was enough above the supply voltage to eliminate worry about flash-over or marginal capacitor design. In addition, its price was understandably lower since it had a lower voltage rating.[11]

Switches SW-1 and SW-3 are two Ross Engineering Corporation models, number E-120-N.O., rated for 60,000 continuous operating volts dc and 100 continuous amperes dc. Each has a 1-minute 60-cycle peak test voltage of 120,000 volts. These switches are normally open; energize to close. Each has a 115-volt ac solenoid actuator with gravity return.

Switch SW-2 is a Price Electric Corporation Model, number 6297-7, rated 25,000 volts dc.

Switch SW-4 is a Ross Engineering Corporation model, number E-120-N.C., rated for 60,000 continuous operating volts dc and 100 continuous amperes dc. It has a 1-minute 60-cycle peak test voltage of 120,000 volts. This switch is normally closed; energize to open. Its actuator is a 115-volt ac solenoid with gravity return.

Switches SW-1, SW-2, SW-3, and SW-4 are only functional devices and are not instrumentally involved in the discharge cycle. However, switch SW-5 must trigger the system and also carry the triggering pulse.

Two general types of switches are commercially available for use in this application - spark gap switches and mechanical action vacuum

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[11] E. L. Kemp, Considerations in the Design of Energy Storage Capacitor Banks, Los Alamos Scientific Laboratory of the University of California, (Washington: Office of Technical Services, 1961) p. 8.

switches. Spark gap switches have no moving parts and hence have no contact bounce. However, they operate over a voltage range of, at best, two to one which means that at least two and possibly three switches might be required interchangeably in the circuit depending on the magnitude of the trigger voltage. Further, since magnitude of the optimum trigger voltage is a quantity being sought rather than already known, spark gap switches seem clearly not to be preferred if the mechanical action vacuum switch will suffice.

The peak current requirement for switch SW-5 was calculated using worst case conditions. Circuit resistance was neglected altogether and circuit inductance assumed distributed one-third in the load and two-thirds in the connecting circuitry. The load inductance calculation is shown in Chapter III on mechanical design. The net effect of these assumptions was that an oscillatory discharge was presupposed. It has the highest peak current of the three modes of discharge and is, therefore, the worst case. Using the Equation (7) developed in Chapter IV an expected peak current was calculated.

$$
\begin{aligned}
I_p &= V \sqrt{\frac{C}{L}} \\
&= 60{,}000\sqrt{\frac{2.14 \times 10^{-6}}{2.51 \times 10^{-6}}} \\
&= 54{,}000 \text{ amperes}
\end{aligned}
$$

where

I_p = peak trigger current in amperes

V = trigger capacitor charge voltage in volts

C = capacitance of trigger capacitor in farads

L = inductance of trigger circuit in henries

Duration of the first positive pulse was calculated using the Equation (12) developed in Chapter IV.

$$\text{pulse duration} = \frac{1}{2}\ (\text{time of one period}) = \pi\sqrt{LC}$$

$$= 3.14\ \sqrt{(2.14)\ (2.51) \times 10^{-12}}$$

$$= 7.22 \text{ microseconds}$$

where period = the inverse of frequency

π = 3.14

L = trigger circuit inductance in henries

C = trigger circuit capacitance in farads

Knowing these requirements an International Telephone and Telegraph Corporation, Jennings Company, vacuum switch model, number RH7G4601F26B20, was installed as switch SW-5. This switch is rated for 70,000 continuous operating volts dc and 200 continuous amperes dc. It has a 100-volt dc solenoid allowing the switch to be closed within 18 to 34 milliseconds with 25 milliseconds being typical. Resistance of the closed switch contacts is 0.024 ohms maximum.

The circuit shown in Figure 1 was operated as follows. With the circuit secured (i.e., with switches SW-2 and SW-4 closed and switches SW-1, SW-3, and SW-5 open) a trigger wire was strung from the ground electrode to the trigger electrode. The power supply was then cut on and switches SW-2 and SW-4 opened and switches SW-1 and

SW-3 closed and both main and trigger capacitors charged simultaneously. When the main capacitor bank reached the desired voltage or a maximum of 10,000 volts, switch SW-1 was opened and the trigger capacitor continued to charge until it reached the desired voltage or a maximum of 60,000 volts at which time switch SW-3 was opened. The method of charging is described in detail later in the text. At this point both circuits were now armed. The system was fired by closing switch SW-5. When an abort was necessary, switches SW-2 and SW-4 were closed. After a fire or abort the circuit was again secured.

Method of Charging

Constant current charging was employed as the charging method. The principle being, a power supply whose output voltage is changing at a constant rate will deliver a constant current into a capacitor.

Analytically the argument[12] can be presented:

$$Q = CV = \int i dt$$

or

$$i = \frac{dQ}{dt} = C \frac{dV}{dt}$$

$$\text{if } \frac{dV}{dt} = \text{constant } K \quad (\text{i.e., } V = Kt)$$

$$\text{then } i = CK$$

$$\text{also } CV = Q = It$$

therefore, $\frac{V}{I} = \frac{C}{t} = R\ eff$ = some effective resistance.

This effective resistance starts at zero and increases linearly with voltage. As long as the voltage rises linearly, the effective

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[12] Ibid., p. 21.

resistance rises proportionally eliminating the need for a dissipative current-limiting charge resistor.

The constant $\frac{dV}{dt}$ characteristic can be achieved by providing a motor driven autotransformer in the primary of the power supply. However, in this instance the autotransformer was controlled manually.

Constant current charging offers the advantages of being more efficient in transferring power and has a shorter charging time since there is no RC time constant.

The power supply was protected by a fast breaker in the primary to protect against any premature discharge while charging.

Metering

One hundred microampere meters were used to indicate the trigger capacitor and the main bank voltages. These meters have 1.5 kilohms resistance and a 2 per cent accuracy.

The resistance necessary for each circuit, its wattage rating, and the resulting time constant for each circuit were calculated as follows:

$$R = \frac{V}{I} = \frac{60{,}000}{100 \times 10^{-6}} = 600 \text{ megohms}$$

$$\text{Power} = I^2R = (100 \times 10^{-6})^2 \, (600 \times 10^{6}) = 6 \text{ watts}$$

$$\text{time constant} = RC = (600 \times 10^{6}) \, (2.14 \times 10^{-6})$$

$$= 1284 \text{ seconds}$$

$$\approx 21 \text{ minutes}$$

where

R = resistance of trigger capacitor metering circuit in ohms

V = voltage of trigger capacitor metering circuit in volts

I = current of trigger capacitor metering circuit in amperes

$$R = \frac{V}{I} = \frac{10,000}{100 \times 10^{-6}} = 100 \text{ megohms}$$

$$\text{Power} = I^2R = (100 \times 10^{-6})^2 \, (100 \times 10^{6}) = 1. \text{ watt}$$

$$\text{time constant} = RC = (100 \times 10^{6}) \, (430 \times 10^{-6})$$

$$= 43,000 \text{ seconds}$$

$$\approx 11 \text{ hours}$$

The time constants were calculated only to obtain an idea of how fast 63 per cent of the voltage was decaying.

A more elaborate metering scheme was not used since the nature of the reading was not intended to be precise, but the area of interest was only in the relative voltage levels present before and after firing.

After installation each meter was calibrated against the power supply meter and the appropriate circuit adjustments made. Meter calibration data are presented as calibration curves in Appendix II.

CHAPTER III

MECHANICAL DESIGN

Electrode Design

It should be pointed out again that this investigation was intended as a preliminary effort and that valuable shock tube and tunnel time was not used. Only after this preliminary study and based on a favorable conclusion would such a request be considered. As a result a simulated load had to be designed and built.

This simulated load consisted of two main discharge electrodes. Each electrode was a 4-inch-diameter hemisphere constructed of S.A.E. No. 51416 stainless steel. The positive electrode as defined in Figure 1 was stationary. Through it, and insulated from it, was fed a 3/16-inch brass rod with a 3/8-inch screw-on cap and screw which served as the 60 kV trigger electrode. (See Figure 3.) The ground electrode was mounted on a sliding base which was long enough to allow the distance between the two main electrodes to be varied from touching to 4 feet. This ground electrode also served as the trigger ground.

The base upon which each electrode was mounted formed two parallel plates separated by 60 mils thickness of polyethylene insulation. These plates connected the 430-microfarad capacitor bank C1 shown in Figure 1.

Electrically, for the purposes of inductance calculations, this geometry represented two equal parallel current paths. The first was the trigger wire itself, then its ionized or exploded wire path and the base plate return. A typical cross section is shown as Figure 2.

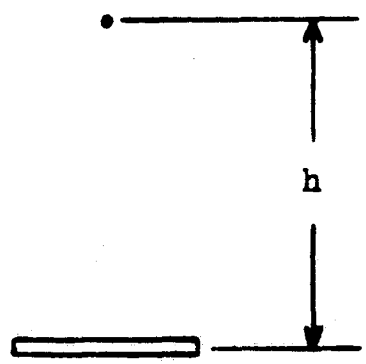

FIGURE 2

TYPICAL CROSS SECTION OF INDUCTIVE LOAD

The distance between center lines represented by h is 7 inches. The length running perpendicular to the paper, as previously described, varied from nothing to 4 feet, the latter being the desired arc length.

For purposes of calculating the inductance of this simulated load and because no known fixed value of diameter could be attributed to the exploding wire, both conductors were assumed to be filaments 6 feet long including electrode length, separated 7 inches. The inductance of the simulated load was then calculated according to Mr. Grover.[13]

$$M = 0.002\, l Q_1$$

[13] Frederick W. Grover, Inductance Calculations - Working Formulas and Tables, (New York: Dover Publications, Incorporated, 1962), p. 32.

$$M = 0.002\ (182.8)\ (2.297)$$

$$M = 0.838 \text{ microhenries}$$

where

l = filament length in centimeters

Q_1 = tabulated value

M = mutual inductance in microhenries

Mr. Grover's formulas assume the magnetic permeability to be one which is not the case for this particular stainless steel. And because no average value of permeability was known, a better estimate of load inductance could not be made. The load inductance was estimated by the author to constitute about one-third of the total trigger circuit inductance. This assumption yielded a trigger circuit inductance of 2.514 microhenries which was used in Chapter II to calculate the estimated peak current.

Electrode Enclosure

The entire electrode assembly was housed in a 12-inch-square by 7-foot-long enclosure constructed from 1/4-inch polystyrene. The top was hinged to permit changing electrode separation and stringing trigger wires.

One end remained open as in a gun barrel to relieve pressure buildup inside the enclosure. Suspicious that this opening was not large enough and too distant for the initial shock wave, eight holes, 4 inches in diameter equally spaced were cut in the top resulting in an additional 10 per cent relief evenly distributed.

In order to minimize any variation in data resulting from environmental effects, a standardized atmosphere was maintained by purging the electrode enclosure lengthwise, from the closed to the open end, with pressurized nitrogen. A very light sheet of polyethylene was placed over the holes in the top and end during the purge-fire cycle.

Electrode-Insulator Assembly

The basic mechanism which governs the success of this technique is the physical relation between the trigger wire and the main 10 kV electrode. The initial separation must be enough to prevent the main capacitor bank voltage from flashing over and likewise long enough to prevent the trigger capacitor voltage from discharging into the main capacitor bank and yet be small enough such that the ionized particles sufficiently provide a conductive path for the main capacitor bank to discharge.

To experimentally determine the proper positioning 1/4-inch-thick spacers were used to vary the relative position of the trigger electrode and the main electrode. A total of six spacers were used allowing seven positions which are shown in Figure 3. Actually the electrode was stationary and the insulator moved. However, for convenience, the converse is shown in Figure 3. Tests, as described later, were conducted to determine the optimum relative position numbered 1 through 7 in Figure 3.

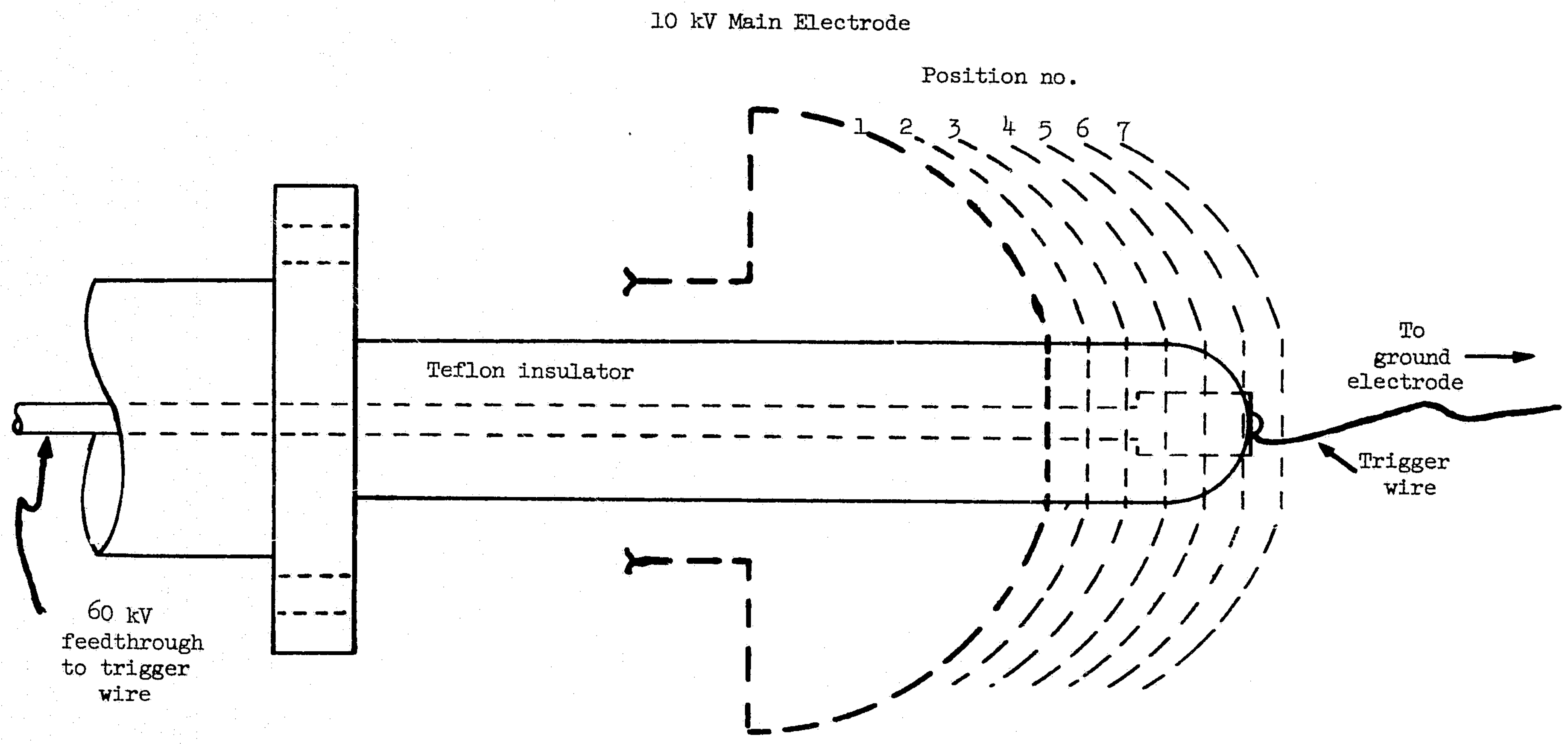

FIGURE 3

ELECTRODE - INSULATOR ASSEMBLY

CHAPTER IV

APPLICABLE MATHEMATICAL CIRCUIT THEORY

Capacitor arc-discharge phenomena take place in full compliance with the same basic laws of nature which govern all other electrical processes. While the mathematics of applying these laws can become complicated, there is nothing complicated about the process of discharging a capacitor. The chief complication arises from the fact that the arc is a nonlinear circuit element. Fortunately, however, the voltage drop across an arc is invariably low (after breakdown has occurred) and can be neglected in the mathematical analysis.[14]

The basic circuit is comprised of the series arrangement of the capacitor bank, the unavoidable circuit inductance, and the unavoidable circuit resistance.

Using Kirchhoff's Voltage Law, Equation (1) can be written as follows.[15]

$$\frac{1}{C}\int_0^t i\,dt + L\frac{di}{dt} + Ri = Vc \qquad (1)$$

where

Vc = initial voltage across the capacitor which is constant

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[14] M. W. Sims, "Capacitor Arc Discharge," Aero Digest, Volume 65, No. 1 (July 1952), pp. 40-46.

[15] Sylvan Fich, Transient Analysis in Electrical Engineering (Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1951), p. 68

By differentiating each term with respect to the independent variable, time (t) and manipulation Equation (1) can be rewritten as Equation (2) as

$$\frac{d^2i}{dt^2} + \frac{R}{L}\frac{di}{dt} + \frac{1}{LC} = 0 \tag{2}$$

which yields the solution, as taken from Skilling[16]

$$i = \frac{V}{L} \cdot \frac{e^{-\frac{R}{2L}t}}{\sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}} \left[\frac{e^{\sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} \cdot t} - e^{-\sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} \cdot t}}{2} \right] \tag{3}$$

At this point, based on experience, the resistance is assumed to be so low that

$$\frac{R^2}{4L^2} < < \frac{1}{LC}$$

therefore, the roots have an imaginary part which means that the resulting current is a damped sinusoid often referred to as an oscillatory response.

Assuming the resistance is so small that for practical purposes it can be assumed to be zero, then the current can be approximated by Equation (4) as

$$i = \frac{V}{jL\sqrt{\frac{1}{LC}}} \left[\frac{e^{j\sqrt{\frac{1}{LC}}\,t} - e^{-j\sqrt{\frac{1}{LC}}\,t}}{2} \right] \tag{4}$$

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[16]Hugh Hildreth Skilling, Electrical Engineering Circuits (New York: John Wiley and Sons, Inc., 1959) p. 473.

or

$$i = \frac{V}{jL\sqrt{\frac{1}{LC}}}\left(j \sin \sqrt{\frac{1}{LC}}\, t\right) \tag{5}$$

or

$$i = V\sqrt{\frac{C}{L}}\left(\sin \sqrt{\frac{1}{LC}}\, t\right) \tag{6}$$

The peak current occurs when $\sin \omega t = 1$ hence the peak current

$$Ip = V\sqrt{\frac{C}{L}} \tag{7}$$

For this case when the resistance is zero, it is thus seen from Equation (6) that the radian frequency

$$\omega = 2\pi f = \sqrt{\frac{1}{LC}} \tag{8}$$

and hence the undamped natural frequency of the oscillatory current is

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{9}$$

therefore, this means that the time for one period is equal to

$$\frac{1}{f} = 2\pi\sqrt{LC} \text{ seconds} \tag{10}$$

and the time to reach peak current is one-quarter of a period or

$$\frac{2\pi}{4}\sqrt{LC} \quad \text{or} \quad \frac{\pi}{2}\sqrt{LC} \tag{11}$$

The duration of the first positive pulse is then one-half a period or twice the time to reach peak current

$$\pi\sqrt{LC} \tag{12}$$

CHAPTER V

EXPERIMENTATION

Determination of Trigger Circuit Parameters and Description of Instrumentation

The first experimental shots were conducted in an effort to determine the trigger circuit inductance and discharge parameters. For these shots it was not desired to ionize or explode a trigger wire. The trigger wire was replaced with a heavy copper conductor capable of carrying the trigger capacitor discharge. The main electrodes were separated 4 feet and a size 10 AWG bare wire was strung from the trigger electrode to the ground electrode. The exact length of the wire was 47 inches - the 1-inch difference being in the extrusion of the trigger electrode and insulator assembly from the main bank electrode. During these shots the main energy storage bank was shorted out and was not charged. A bare copper wire was used so that if it burned open its failure could be detected. Since the charge voltage need only be some token amount, an arbitrary choice of 10,000 volts was made.

Oscillograph records of the discharge waveform were obtained from a Rogowski coil which encircled the return bus of the main electrode. The output of the coil was not calibrated since magnitude was not required. The output from the coil was connected into the vertical input of a model Type 535A Tektronix oscilloscope and the oscilloscope was equipped with a Polaroid camera.

The external trigger source was provided by a 1000:1 resistance divider high-voltage probe, Tektronix Model P6015, which was connected through a voltage divider circuit (see Figure 1) to the dead side of the trigger circuit "fire" switch.

The trigger sweep was adjusted to begin (at time $t = o$) 1 centimeter inside the left-hand margin in an effort to more clearly determine the first positive pulse.

The discharge waveform was found to be oscillatory, as expected. A typical 10,000-volt discharge waveform is shown in Figure 4.

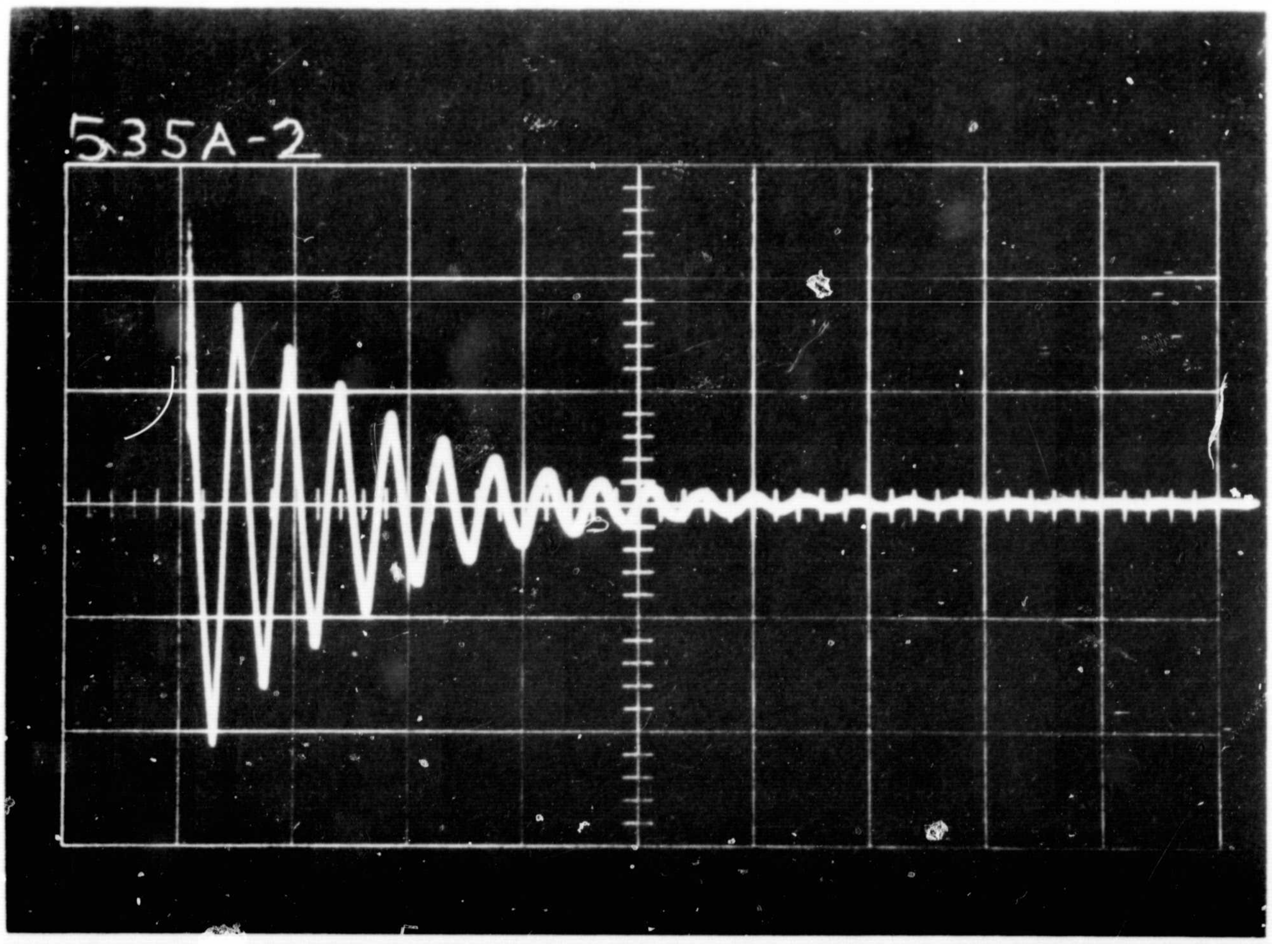

FIGURE 4

10,000 VOLT TRIGGER CIRCUIT DISCHARGE WAVEFORM - ELECTRODE SEPARATION 4 FEET, CONNECTED WITH SIZE 10 AWG COPPER WIRE - NO ARCING

In Figure 4 the time base was 50 microseconds per centimeter. Time starting at $t = 0$ begins one division from the left margin of the picture.

From the oscillograph and Equation (9) developed in Chapter IV the inductance was calculated:

$$f = \frac{1}{2\pi \sqrt{LC}}$$

$$f^2 = \frac{1}{4\pi^2 LC}$$

$$L = \frac{1}{4\pi^2 f^2 C}$$

a frequency of 9 cycles per 200 microseconds was determined from Figure 4

$$L = \frac{1}{4(3.14)^2 (0.045 \times 10^6)^2 (2.14 \times 10^{-6})}$$

$$L = 5.86 \times 10^{-6} \text{ henries}$$

$$L = 5.86 \text{ microhenries}$$

This compares favorably with the 2.51-microhenry estimate predicted in Chapter III.

Knowing the trigger circuit inductance and Equation (7) developed in Chapter IV, the amplitude of the trigger circuit peak current can be determined to be

$$I_p = V \sqrt{\frac{C}{L}}$$

$$I_p = 60{,}000 \sqrt{\frac{2.14 \times 10^{-6}}{5.86 \times 10^{-6}}}$$

$$I_p = 36{,}240 \text{ amperes}$$

The expected peak current calculated in Chapter II and based upon the early estimate of trigger circuit inductance was 54,000 amperes. This overestimate of peak current points out the need for accurate inductance calculations and the dependency of peak current on inductance.

The pulse duration instead of being 7.22 microseconds, as previously calculated, is more like 12 microseconds, as seen from Figure 4, and is 11 microseconds as calculated by Equation (12) in Chapter IV.

The trigger circuit short circuit accumulative resistance was found using Equation (15) developed in Appendix I. By applying the equation twice to two successive peaks in the oscillograph shown in Figure 4 the resistance was found as follows:

$$I_p = \frac{V\,e^{-\frac{R}{2L}t}}{\omega L} \sin \omega t$$

here we assume I peak occurs where $\sin \omega t = 1$, taking the first visible positive peak

$$1.78 \text{ divisions} = \frac{V\,e^{-\frac{R}{2L}(25 \times 10^{-6})}}{\omega L} \tag{13}$$

taking the second visible positive peak

$$1.42 \text{ divisions} = \frac{V e^{-\frac{R}{2L}(48 \times 10^{-6})}}{\omega L} \tag{14}$$

taking the ratio of Equation (13) to Equation (14)

$$\frac{1.78}{1.42} = e^{-\frac{R}{2L}(48 \times 10^{-6} - 25 \times 10^{-6})}$$

$$0.798 = e^{-\frac{R}{2L}(23 \times 10^{-6})}$$

therefore

$$\frac{R(23 \times 10^{-6})}{2L} = 0.2258$$

$L = 5.86 \times 10^{-6}$ henries as previously determined, therefore,

$$R = \frac{2(5.86 \times 10^{-6})\ (0.2258)}{23 \times 10^{-6}}$$

$$R = 0.115 \text{ ohms}$$

Determination of Load Inductance

The second experimental shots were made with the main electrodes separated 2 inches and all other factors unchanged. The 2-inch separation was to allow for the 1-inch extrusion of the trigger electrode insulator assembly and a 1-inch length of size 10 AWG bare wire to permit a hard line connection of the trigger electrode and the ground electrode.

A typical discharge waveform for this new configuration is shown in Figure 5.

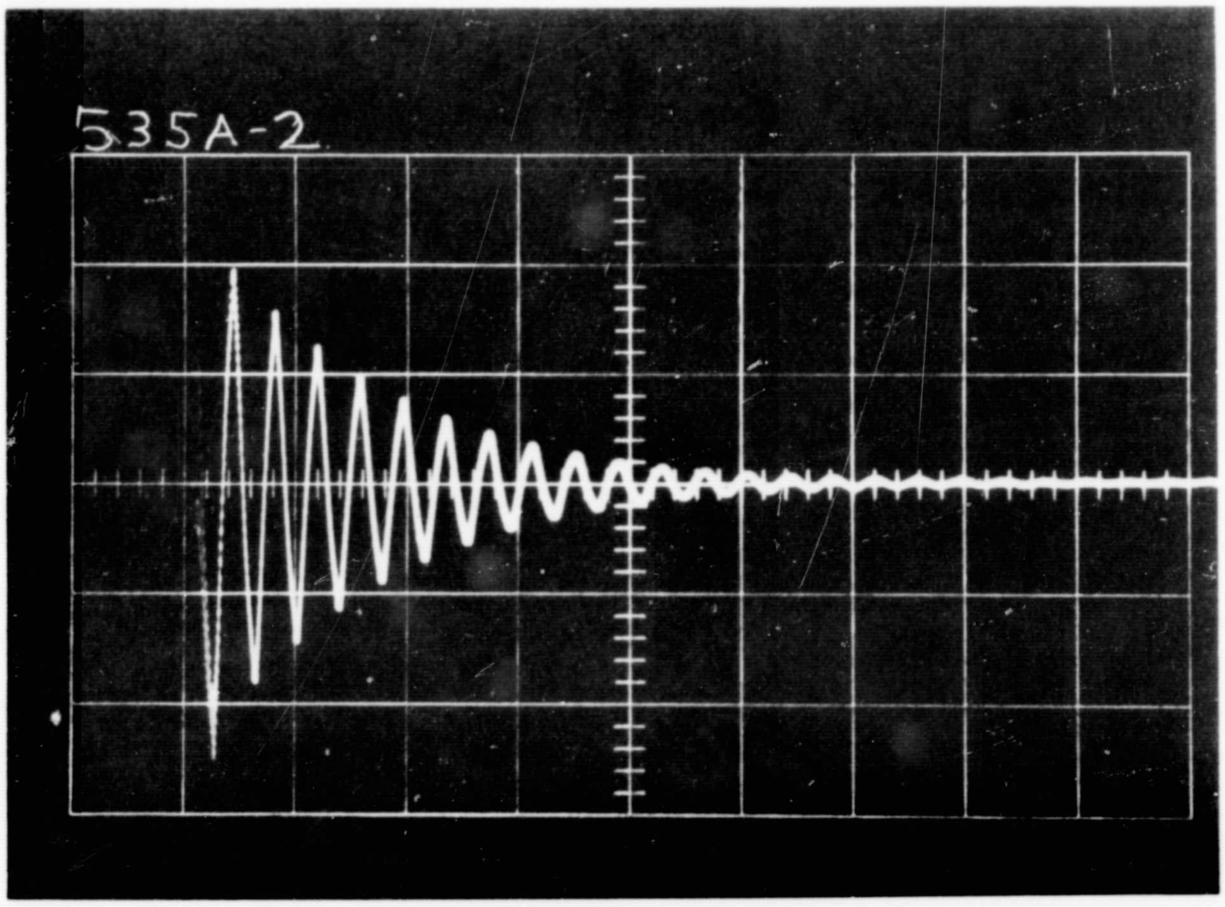

FIGURE 5

10,000 VOLT TRIGGER CIRCUIT DISCHARGE WAVEFORM - ELECTRODE SEPARATION 2 INCHES, CONNECTED WITH SIZE 10 AWG COPPER WIRE - NO ARCING

The time base was 50 microseconds per centimeter and time begins 1 centimeter from the left-hand margin. A frequency of 10.5 cycles per 200 microseconds was obtained and the new trigger circuit inductance was calculated as before

$$L = \frac{1}{4\pi^2 \; f^2 \; C}$$

$$L = \frac{1}{4(3.14)^2 \; (0.0525 \times 10^6)^2 \; (2.14 \times 10^{-6})}$$

L = 4.3 microhenries

By subtracting the short configuration inductance from the long configuration inductance a value for the inductance of the main electrode assembly is obtained

$$I_L - L_S = 5.86 - 4.3$$

$$= 1.56 \text{ microhenries}$$

This agrees with the calculated value of 0.838 microhenry calculated in Chapter III on the mechanical design.

This 1.56 microhenries represents the hard line bus conductor inductance of the electrode assembly and can only be assumed to be somewhat indicative of the inductance of a highly ionized current path between the same electrodes separated the same distance.

Estimate of Main Bank Peak Current

Knowing the load inductance and allowing for a possible 10 per cent increase in inductance due to the connecting bus work to the main capacitor bank the main discharge circuit inductance was estimated to be 1.71 microhenries.

Therefore, the main discharge peak current was calculated to be about

$$I_p = 10{,}000 \sqrt{\frac{430 \times 10^{-6}}{1.71 \times 10^{-6}}}$$

$$I_p = 158{,}500 \text{ amperes}$$

when discharged from a full 10,000-volt charge.

Exploding Wires

Since several types, sizes, and kinds of wires were desired to be tried in an effort to determine the most desirable, the third series of experimental shots were made with the main capacitor bank shorted - using only the trigger capacitor charged to different levels to explode various wires.

The first wire attempted was a size 40 AWG enamel coated copper magnet wire. The main electrodes were separated 4 feet and three spacers were used to establish the relative position of the trigger electrode. This represents position 4 in Figure 3.

The amount of energy required to melt the mass of a 4-foot-length of size 40 AWG copper wire was calculated according to Hudson[17] to be

$$\text{joules} = (\text{Mass})\ (4.18)\ (\text{specific heat})\ (\Delta T^{\circ}\ C)$$

where

Mass = grams

specific heat = 0.0928 gram calories per gram per degree C°

ΔT = temperature change (ambient to melting) in degrees centigrade.

$$\text{joules} = (5.44 \times 10^{-2})\ (4.18)\ (9.28 \times 10^{-2})\ (1083 - 20)$$
$$= 22.3 \text{ joules}$$

The wire was first subjected to a 5,000-volt discharge which represents 26.7 joules. The complete discharge of the capacitor was noted. The wire smoked along its entire length, burned apart at each end and

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[17] Ralph G. Hudson, The Engineers' Manual (New York: John Wiley and Sons, Incorporated, 1958) p. 156.

dropped to the bottom of the electrode enclosure. The wire remaining still had body and some strength although it was somewhat annealed. The enamel coating showed evidence of burning and could be wiped off.

An identical shot was made at 6,000 volts representing 38.5 joules. One kilovolt or less remained on the capacitor. The wire burned into in several spots leaving about an equal number of long (3 to 4 inches) and short (1 inch or less) pieces. Evidence of the enamel coating appeared as badly burned char on the remaining pieces of wire.

Likewise, a shot was made at 7,000 volts - 52.4 joules. The wire exploded leaving only varying lengths of tubular enamel coating with no evidence of copper. About 1 kV of charge still remained on the capacitor.

Another shot at 10,000 volts - 107 joules exploded the wire and left 5 kV on the capacitor. Only small pieces of enamel coating remained. Each shot was repeated several times with the reported results, though somewhat varying, generally consistent.

Some readily apparent findings resulted from this test. The actual energy required to vaporize a 4-foot length of size 40 AWG resin enamel coated magnet wire is higher than the theoretical estimate calculated. Possible reasons for this difference are: No allowance was made for the heat required to vaporize (heat of vaporization) the melted molten copper liquid. Such datum is not normally tabulated since copper exists as a solid, not a liquid, in its natural state.

And secondly, no allowance was made for heat absorbed by the enamel coating. Likewise it is questionable whether an allowance is justified since it was observed that the copper could be extracted from the enamel coating without burning the coating when higher energies were used.

The oscillographs showed that a definite delay existed between the time the trigger circuit fire switch closed and the time the trigger wire started conducting. This delay varied from 140 to 210 microseconds, depending on how the trigger was attached to the electrodes and charge voltage. However, the time to breakdown was definitely not proportional to charge voltage but seemed to be dependent upon inconsistencies in the enamel coating insulation thickness as one piece which held off completely a 6,000-volt potential when several hundred volts would have seemed sufficient for breakdown.

The minimum energy density required to explode and completely vaporize a 4-foot section of size 40 AWG enamel resin coated magnet wire was 52.4 joules - 7,000 volts.

As the charge voltage was increased, more and more energy was delivered to the exploding wire. However, the difference in the charge voltage and the voltage remaining after firing seemed to remain the same, always 5 to 6 kV. Two questions immediately arise: First, what happens to the excess energy input (that amount above the minimum required to vaporize the wire)? And second, why is the capacitor voltage differential before and after firing always the same? Answers to these questions have been deferred to the end of the exploding wires section.

The second type of wire tested was 4-foot sections of size 36 AWG bare copper wire. The energy required to melt this wire was again calculated according to Hudson[18] as

$$\text{joules} = (1.375 \times 10^{-1})\ (4.18)\ (9.28 \times 10^{-2})\ (1.063 \times 10^{3})$$
$$= 56.6 \text{ joules}$$

Sections of this wire were tried at the voltages listed in Table II. Tabulated beside each voltage is the energy represented by that respective charge voltage and the amount of voltage remaining on the trigger capacitor after each shot.

TABLE II

EXPERIMENTAL RESULTS USING SIZE 36 AWG BARE COPPER WIRE

Initial charge voltage (kilovolts)	Energy available (joules)	Remaining charge voltage (kilovolts)
5	26.7	0
6	38.5	0
7	52.4	0
8	68.4	1
9	86.6	1
10	107	1.5
12	154	3.5
14	209	5.5

[18] Ibid.

The experimental test revealed that when 9 kV was used, two or three small 1/2-inch pieces were left and no visible remains of the wire were left when 10 kV was used. The 9 kV (86.6 joules) seemed to be very close to the necessary vaporizing energy. However, slight traces of the wire remains were always present unless 10 kV was used. Therefore, the minimum energy density necessary for complete vaporization was determined to be 107 joules - 10 kV.

There was no delay between the trigger circuit closure and the time the trigger wire started conducting as had been experienced with the enamel coated wire.

The capacitor voltage differential before and after firing remained about constant at 8.5 kV, as can be seen from the data in Table II.

The third type wire tested was 4-foot sections of size 30 AWG soft drawn tinned copper. This bimetallic wire was found to completely vaporize at 25 kV - 668 joules. The delay previously mentioned was not present and the capacitor voltage differential before and after firing remained about constant at 20 kilovolts. One noticeable difference was that the tinned wire after exploding left a dense brown smoke presumably because of the introduction of the tin which was not present when the solid copper wires were used.

The fourth type wire tested was 1-mil-diameter Pyrofuse.[19] Pyrofuse is a bimetallic composition of an outer shell of palladium

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[19]Pyrofuse is a registered trademark of the Sigmund Cohn Corporation affiliate Pyrofuse Corporation, 121 South Columbus Avenue, Mount Vernon, New York.

surrounding an inner core of aluminum which is insensitive to shock, impact, or vibration but which will alloy violently and exothermically without the support of oxygen when heated to a specified operating temperature. The wire is not a pyrotechnic material and is sometimes used to trigger arc type facilities of this nature.

The 1-mil-diameter Pyrofuse wire was found to vaporize with 2 kV. The capacitor voltage differential before and after firing remained constant at 1 kilovolt. The amplitude of the signal supplied by the Rogowski coil was not within the range of the oscilloscope at the 1 kV firing level, so the presence of a delay could not be determined. However, some delay is expected since the initiating heat is time dependent.

The following conclusions were made as a result of the exploding wire tests.

The resin enamel coated wire, even when greatly overpowered, leaves solid particles of insulation which would be undesirable particles - projectiles in a shock tube.

The resin enamel coated wire introduces an unpredictable delay, caused by the resin insulation itself, between trigger circuit closure and trigger circuit conduction which may or may not suit a shock tube operator.

Bare soft drawn tinned copper wire offers no delay but introduces a dense brown smoke contamination which may or may not suit a particular shock tube study.

One-mil-diameter wire of any nature is hard to work with and equally hard to see which can and will introduce unforeseen misfires when loose ends are overlooked.

Energy Studies

The "exploding wire phenomenon" commonly denoted (EWP) was first reported on by Edward Nairne in 1774.[20] The mechanism of wire explosions is poorly understood; some parts of the process are without explanation and others have been explained by a number of theories.[21]

The fact, as explained by Chace[22], that when the exploding wire is replaced by a wire capable of carrying the discharge, the discharge is a damped sine wave has already been seen. This fact allowed the first and second experimental shots with the size 10 AWG conductor to be conducted yielding both Figures 4 and 5.

The two leading theories of the exploding wire mechanism, the unduloid theory of Kleen[23] and the colloidal theory of Chace[24], both

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[20] Frank B. A. Früngel, High Speed Pulse Technology (New York and London: Academic Press, 1965), Volume I, p. 390.

[21] William G. Chace and Howard K. Moore, Exploding Wires (New York: Plenum Press, Incorporated, 1959), Volume I, p. 9.

[22] Ibid.

[23] Von Werner Kleen, Ann. Physik, Vol. 5, No. 11, 1931, pp. 579-605.

[24] Chace, op. cit., pp. 1-16.

share the common similarity that there are two distinct regimes of exploding wire phenomena depending on capacitor voltage and hence energy input. Both agree that when higher capacitor voltage-energies are employed the "dark interval" or "dwell time" is essentially eliminated and restrike occurs immediately.

The question presented earlier as to what happens to the excess energy input (that amount above the minimum required to completely vaporize a given wire) will now be discussed in some detail.

The hypothesis is that this extra or excess energy input serves to better prepare the region between the main electrodes such that a more conductive path is offered to the main discharge.

The following analysis is applicable whether an experimenter is more inclined to accept the unduloid theory of Kleen or the colloidal theory of Chace.

Whether it be by adding sufficient energy to electrons moving between the electrodes such that they produce secondary ionization upon impact and therefore increase the number of charge carriers and/or increased thermal ionization when the wire material is superheated as would apply to the colloidal theory, or by increased vaporization of the unduloids through superheating resulting in a higher evaporation rate as applies to the unduloid theory. Whichever theory proves more acceptable, the contention here is merely that there is a distinct advantage gained by using higher than the minimum ionization energy for a given trigger wire.

The next experiment was conducted in an effort to prove this hypothesis.

Excess Energy Verification

The hypothesis could be stated for experimental analysis another way. Does increasing the trigger bank energy allow firing the main bank at a lower main bank voltage gradient?

The question was approached two ways: First, by decreasing the charge voltage and keeping the distance constant and, secondly, the gradient was lowered by increasing the distance and keeping the voltage constant.

In the first case the electrodes were separated and held constant at 4 feet and the main bank voltage was varied as various trigger bank voltages were tried.

Instrumentation was, as previously described, with an integrator circuit inserted between the Rogowski coil and the oscilloscope (see Appendix III). This permitted the line integral of the time varying magnetic field to be taken, allowing the oscilloscope to display the waveform of the discharge current. (Rigorous theoretical treatment by Patrick.[25]) In addition, the oscilloscope was operated as a dual beam oscilloscope and trigger bank voltage was monitored on the upper beam along with discharge current on the lower beam. Environmental

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[25] R. M. Patrick and A. M. Schneiderman, Axial Current Distribution in the Exhaust of the Magnetic Annular Arc, American Institute of Aeronautics and Astronautics, Paper No. 66-198 (New York, New York, 1966) pp. 2-3.

effects were minimized and a standard repeatable environment was provided by purging the electrode enclosure lengthwise with dry nitrogen gas.

The nitrogen was supplied from a 2,000-psig bottle through a single stage regulator with a delivery pressure of 6 psig which, according to manufacturer's literature, represents a flow rate of approximately 350 scfh. By purging the electrode enclosure for a period of 15 seconds prior to each test shot the 6-cubic-foot enclosure was purged with 1.45 cubic feet of nitrogen or 25 per cent by volume.

Tests were made using both the size 36 AWG bare copper wire and the 10-mil-diameter Pyrofuse. (These are the two wires which showed the most promise of the wires tested earlier.) After each test the procedure was to clean the exterior surfaces of the electrodes and insulator with denatured alcohol. The trigger voltage was then plotted against main bank voltage gradient in kilovolts per foot which was varied by selecting various main bank voltages, keeping the electrode separation constant at 4 feet. The results for the size 36 AWG bare copper wire and the 10-mil-diameter Pyrofuse are shown in Figures 6 and 7, respectively. Note that size 36 AWG wire has a diameter of 5 mils, exactly half the diameter of the Pyrofuse wire tested. Also shown in Figure 6 is a line at 10 kV trigger voltage denoting the minimum energy required to completely ionize the size 36 AWG copper wire, as determined in the exploding wire experiments.

Main arc length constant at 4 feet
Trigger wire - size 36 AWG bare copper
Three spacers - position 4
In nitrogen

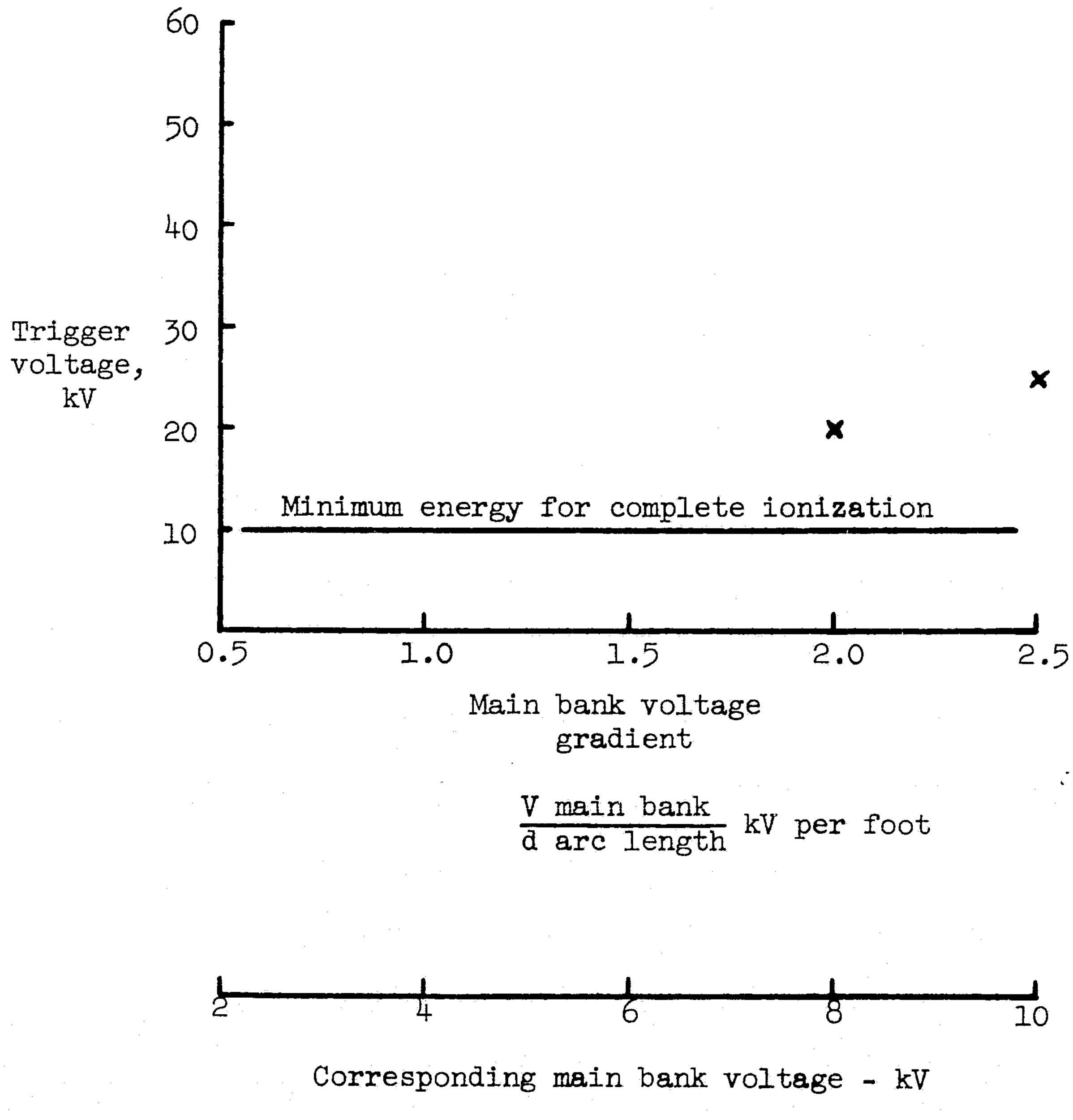

FIGURE 6

TRIGGER VOLTAGE VERSUS MAIN BANK VOLTAGE GRADIENT - ARC LENGTH CONSTANT, FOR SIZE 36 COPPER WIRE

Main arc length constant at 4 feet
Trigger wire - 10-mil-diameter pyrofuse
Three Spacers - position 4
In nitrogen

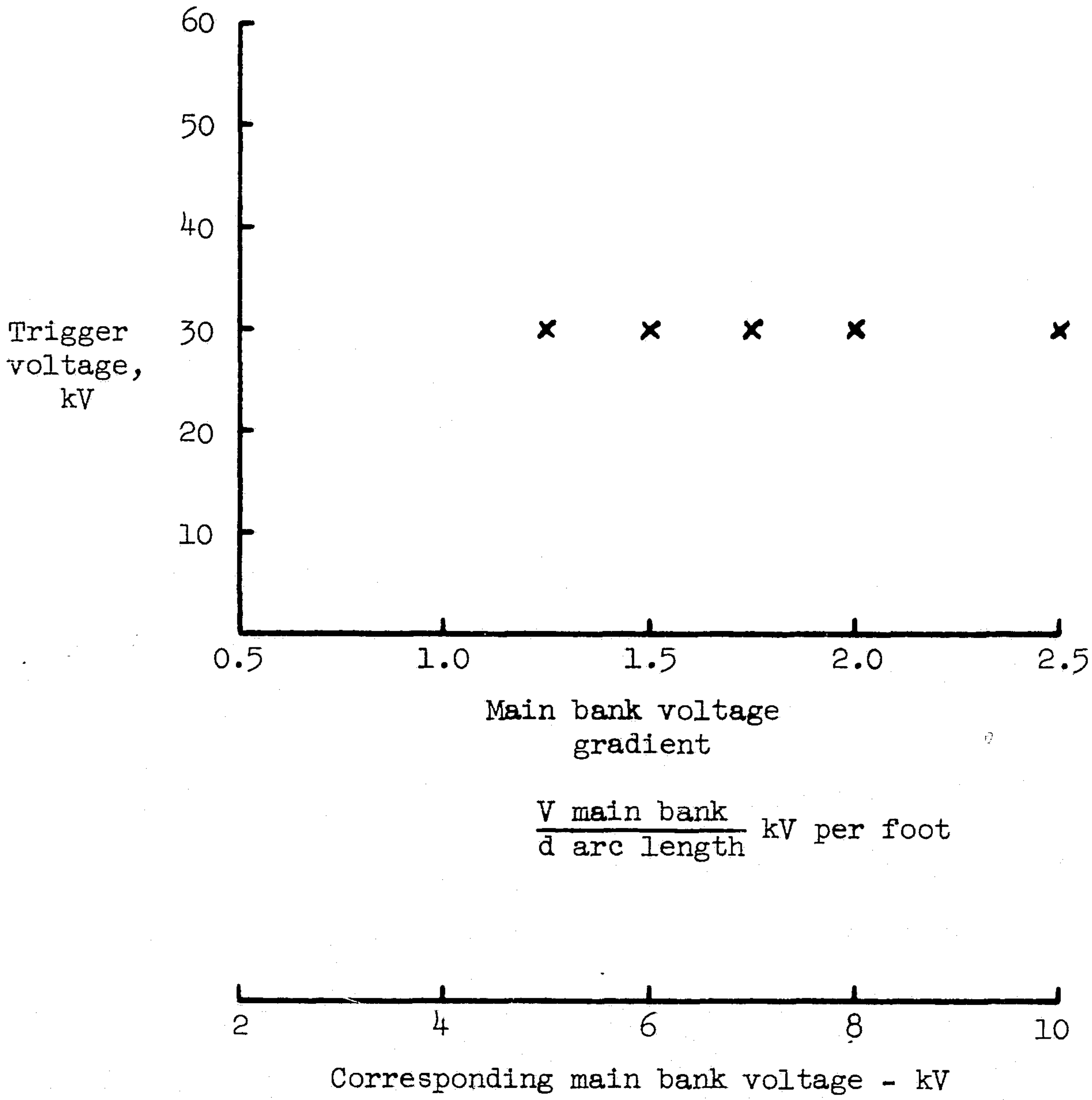

FIGURE 7

TRIGGER VOLTAGE VERSUS MAIN BANK VOLTAGE GRADIENT - ARC LENGTH CONSTANT, FOR 10-MIL-DIAMETER PYROFUSE WIRE

For either wire the test revealed, as was likewise reported by H. Hoshizaki[26], one of three things happened when triggering was attempted. One, the trigger capacitor would be discharged exploding the trigger wire, but the main bank would retain its full charge. Second, the trigger capacitor would discharge into the main bank equalizing the voltage on both trigger and main banks, exploding the trigger wire but not striking the main arc. Third, both trigger and main banks would discharge drawing the desired arc.

By monitoring the trigger bank voltage as well as discharge current, two distinct variations of the third process were noted. One in which the presence of the main bank voltage was realized immediately by the trigger bank, always occurring when the trigger bank voltage was 30 kV or more and yielding an earlier main bank discharge. And another in which the trigger wire exploded solely by the trigger bank energy (in which the dark time and restrike are clearly visible) and the ionized trigger wire some time later, about 100 microseconds, initiates the main bank discharge. This mode occurring for trigger voltages of 25 kV or less. Examples of each type for both wires are shown in Figures 8 and 9.

Considerable patience was required to obtain the working region shown in Figure 6 for the size 36 bare copper wire, and the

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[26] H. Hoshizaki and J. C. Andrews, "The Lockheed Missiles and Space Company 12-Inch Arc-Driven Shock Tube" (Palo Alto, California: Lockheed Research Laboratory, Lockheed Missiles and Space Company, 1964) p. 7 (Mimeographed).

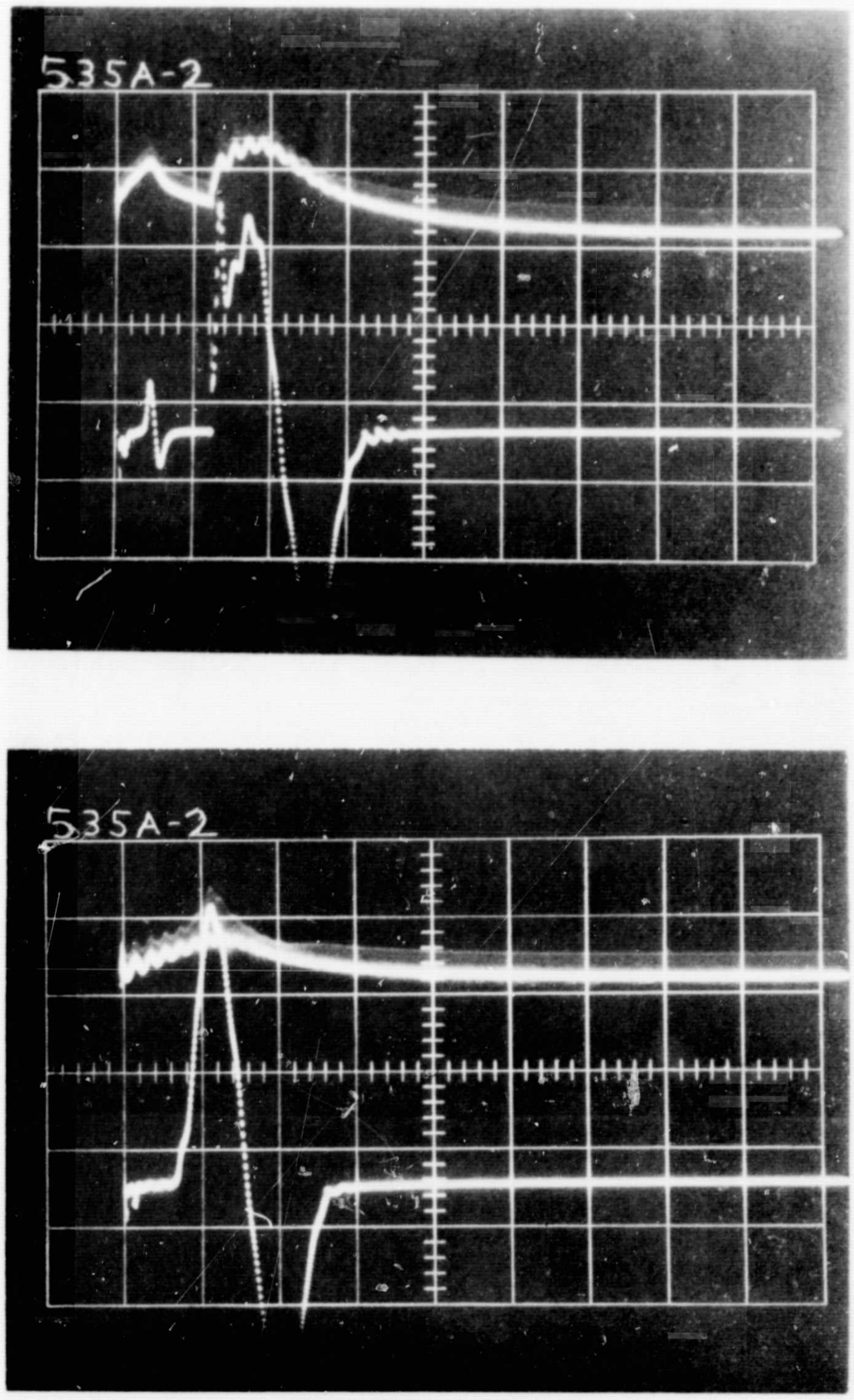
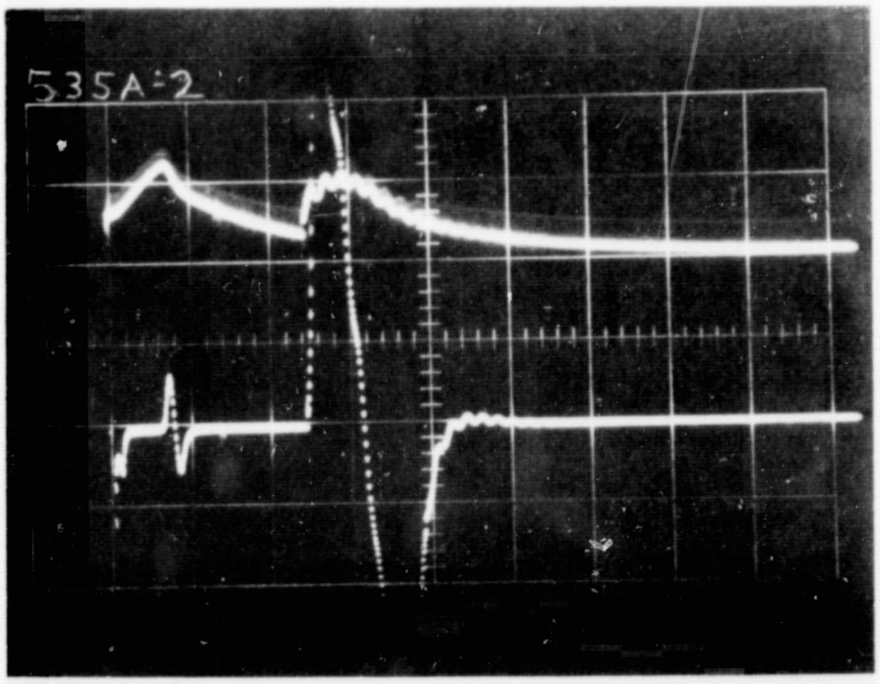


FIGURE 8

TWO TYPES OF DISCHARGE FOR SIZE 36 COPPER WIRE, TIME BASE FOR BOTH - 100 MICROSECONDS PER DIVISION. TOP TRACE IN EACH PICTURE IS TRIGGER BANK VOLTAGE. LOWER TRACE IN EACH PICTURE IS MAIN BANK DISCHARGE CURRENT



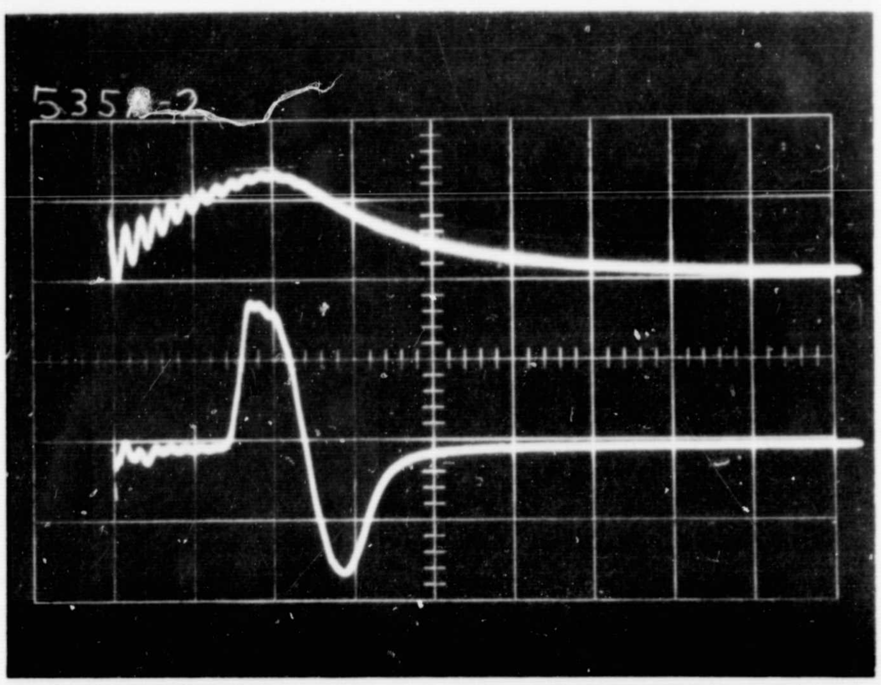


FIGURE 9

TWO TYPES OF DISCHARGE FOR 10 MIL-DIAMETER PYROFUSE, TIME BASE FOR BOTH - 100 MICROSECONDS PER DIVISION. TOP TRACE IN EACH PICTURE IS TRIGGER BANK VOLTAGE. LOWER TRACE IN EACH PICTURE IS MAIN BANK DISCHARGE CURRENT probability of repeating successfully a given shot is less than 50 per cent. However, the 10-mil-diameter Pyrofuse was found to be highly repeatable.

The main bank discharge always consisted of one complete cycle and occurred later for lower main bank voltages. Typical data for each wire is tabulated in Tables III and IV.

TABLE III

TYPICAL DATA USING SIZE 36 BARE COPPER TRIGGER WIRE

Main bank voltage (kilovolts)	Trigger voltage (kilovolts)	Time at start of main bank discharge (microseconds)	Amplitude of peak discharge current (normalized)
10	20	130	3 units
10	30	80	3.8 units

TABLE IV

TYPICAL DATA USING 10-MIL-DIAMETER PYROFUSE WIRE

Main bank voltage (kilovolts)	Trigger voltage (kilovolts)	Time at start of main bank discharge (microseconds)	Amplitude of peak discharge current (normalized)
10	35	75	8 units
10	30	200	9 units
8	35	115	4 units
8	30	170	4 units
7	35	190	2 units
7	30	600	5 units
6	35	700	3 units
6	30	900	3 units
5	35	2400	1 unit
5	30	3300	1.5 units

The main bank did not completely discharge when the main arc was drawn but would consistently end the cycle with about 200 volts charge remaining. This was deemed insufficient to restrike the remaining weakly ionized path. Likewise a negligible amount less than 0.5 kV usually remained on the trigger bank after firing.

The hypothesis was evaluated a second way by charging the main bank to the full 10 kV and varying the electrode separation to achieve different gradients as various trigger bank voltages were tried. Again, both the size 36 bare cooper wire and the 10-mil Pyrofuse were tested in the nitrogen environment. The results are shown in Figures 10 and 11, respectively. In both figures the trigger voltage is plotted against main bank voltage gradient in kilovolts per foot, which was varied by varying the electrode separation rather than the charge voltage.

Here, again, the copper wire was somewhat unpredictable but became more reliable as the distance shortened.

The decisive advantage of increasing trigger voltage is seen in Figure 11 for the 10-mil-diameter Pyrofuse.

Three interesting variations were noted as the arc length was reduced 1 foot at a time from the maximum of 4 feet. First the number of cycles in the main bank discharge increased from one to three. This variation was plotted in Figure 12 for both wires. An interesting point of speculation to the electrical engineer is: does the point exist wherein only the first half cycle might be obtained? The

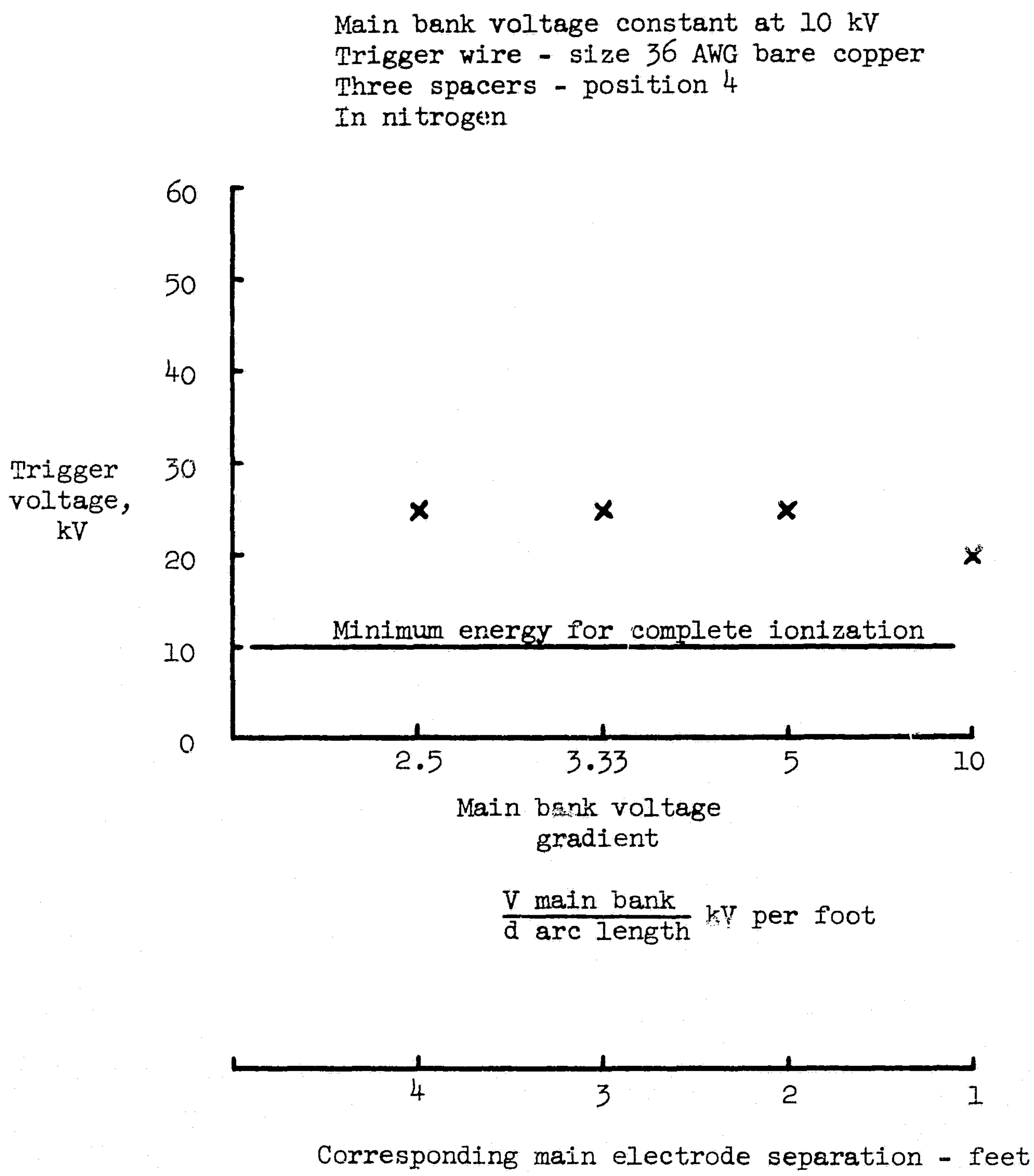


FIGURE 10

TRIGGER VOLTAGE VERSUS MAIN BANK VOLTAGE GRADIENT - MAIN BANK VOLTAGE CONSTANT AT 10 kV, FOR SIZE 36 BARE COPPER WIRE

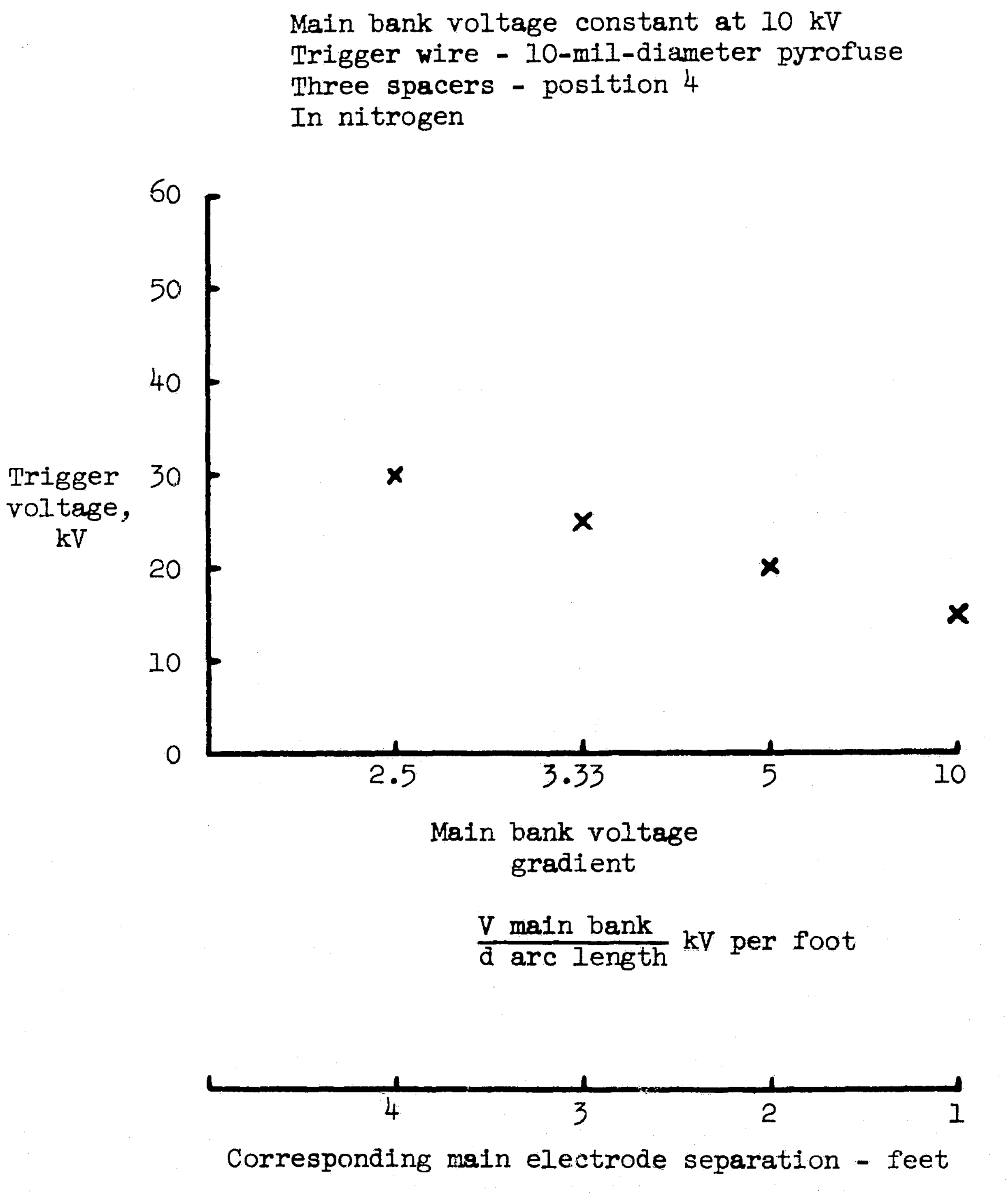


FIGURE 11

TRIGGER VOLTAGE VERSUS MAIN BANK VOLTAGE GRADIENT - MAIN BANK VOLTAGE CONSTANT AT 10 kV, FOR 10-MIL-DIAMETER PYROFUSE WIRE

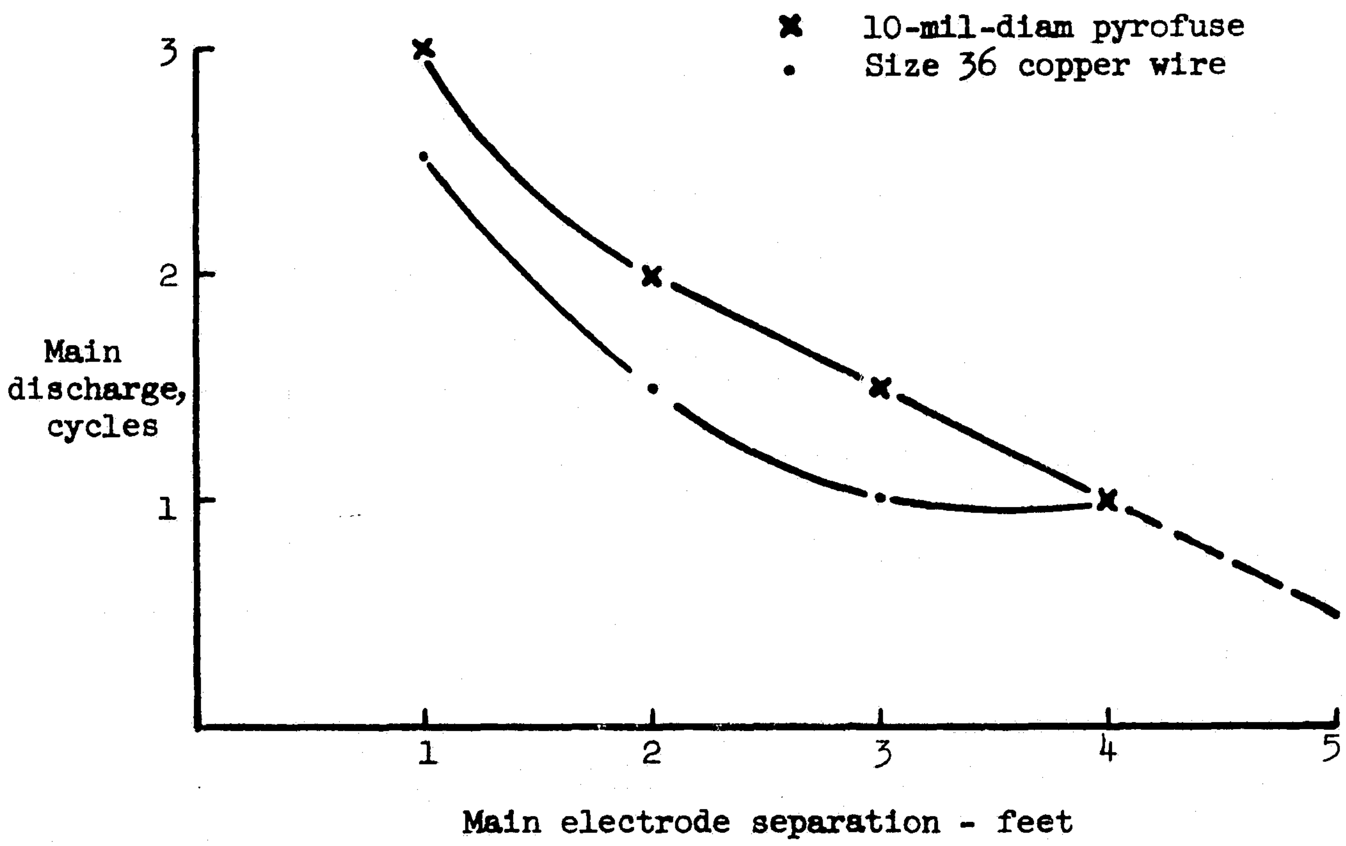


FIGURE 12

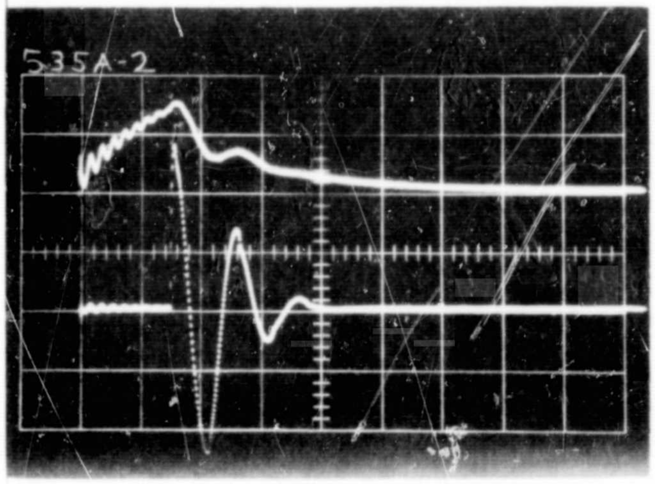
NUMBER OF CYCLES IN THE MAIN BANK DISCHARGE VERSUS MAIN ELECTRODE SEPARATION IN FEET extended fuse wire curve seems to indicate that possibly this point does exist, corresponding to an arc length of 5 feet. Physical dimensions limited the present system to the study of up to a 4-foot arc only, therefore, this point could not be checked. Also, an oscillograph showing three cycles is shown in Figure 13(a). Second, the main discharge frequency increased from 5,890 hertz at 4 feet to 12,500 hertz at 1 foot. And last of all, the peak amplitude of the discharge current increased by a factor of 10 times.

The above items were generally true without regard to type trigger wire used. In the case of Pyrofuse wire which has a measured resistance of 0.6 ohm per linear foot, a 4-foot length having 2.4 ohms, it was found that this initial resistance had no effect on the peak amplitude of the main bank discharge current.

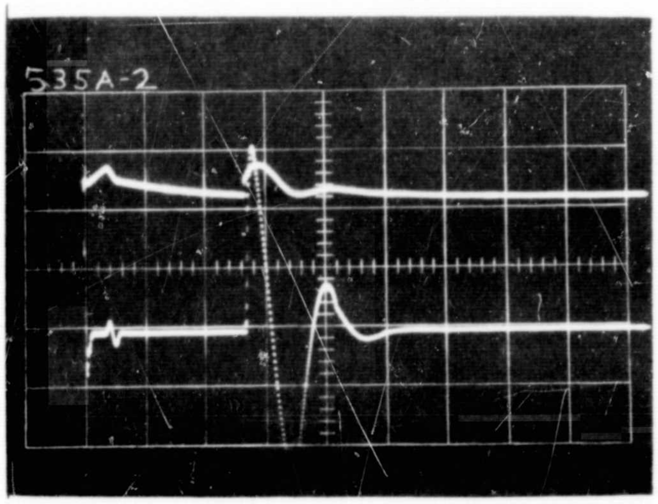
Figure 13 shows typical discharges for a 1-, 2-, and 3-foot arc.

Constant Delta - V

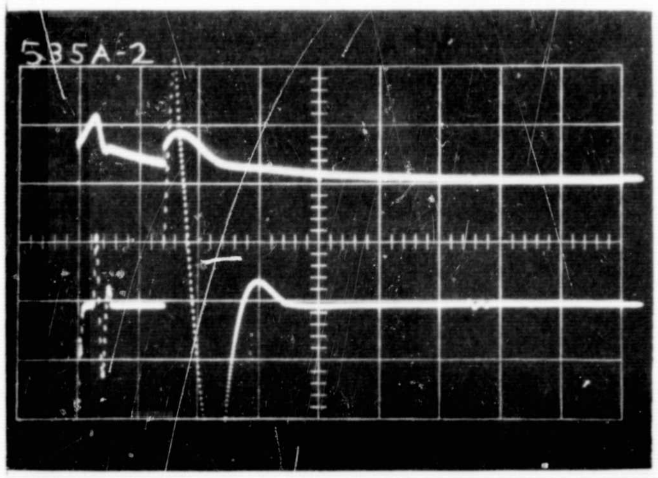
The second question presented earlier was, why is the capacitor voltage differential before and after exploding a given wire always the same? No decisive answers have been found to date. However, two things are certainly clear: (1) that the same amount of coulombs charge are consumed in exploding a given wire and therefore (2) the same number of electrons are traveling from the capacitor each time a certain wire is exploded.



(a) Typical discharge for a 1-foot arc length - size 36 copper wire



(b) Typical discharge for a 2-foot arc length - 10-mil-diameter fuse wire



(c) Typical discharge for a 3-foot arc length - 10-mil-diameter fuse wire

FIGURE 13

TYPICAL DISCHARGES FOR A 1-, 2-, and 3-FOOT ARC. FIGURES (a), (b), AND (c) HAVE A 100-MICROSECOND PER DIVISION TIME BASE AND 20, 10, AND 5 VOLTS PER DIVISION AMPLITUDE, RESPECTIVELY

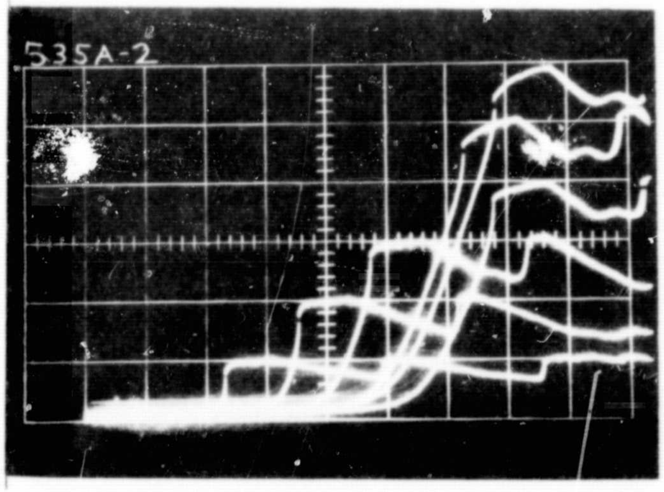
Firing Switch Characteristics

The trigger bank circuit firing switch was tested in the following way. With the switch installed as shown as SW-5 in Figure 1, but with the load side disconnected and the high-voltage probe fed from this dead side, the capacitor was charged and the switch closed and then the capacitor discharged. This sequence was repeated with the charge voltage being increased by 5 kV each time through 30 kV. The switch closure, voltage presence, and the switch bounce were recorded and superimposed on the same oscillograph picture for comparison. This picture is shown in Figure 14(a). The time base was 0.5 millisecond per division. The switch was unloaded and hence the voltages are out of step. The switch closed in 1 to 3.5 milliseconds.

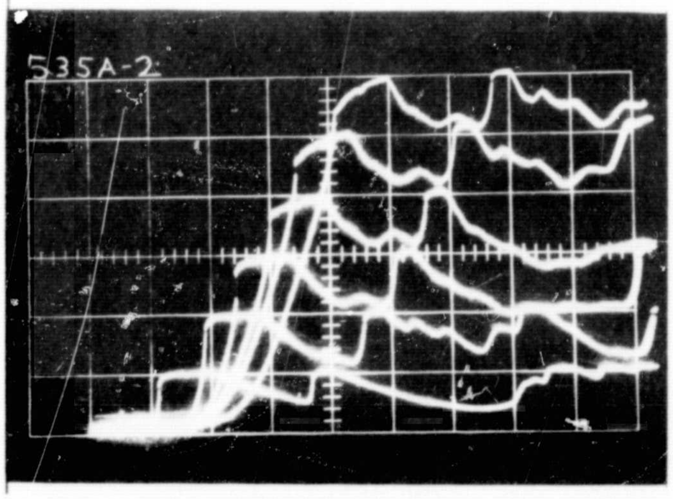
The voltage divider shown in Figure 1 was then added and the same test repeated. This time the successive voltages were noted (Figure 14(b)) to be in step and the voltage presence occurs much more quickly (0.5 to 2.0 milliseconds).

The main bank positive electrode was then added and the test repeated a third time. This time because of the proximity of the main electrode and the trigger electrode the 20 kV is seen to have arced across to the main electrode. (See Figure 14(c).)

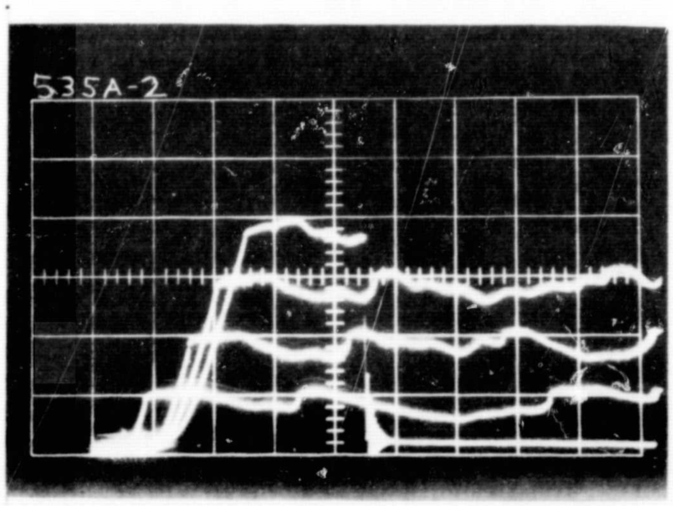
The above tests were made after approximately 200 shots of varying voltages and energies were made. Therefore, it may or may not represent the characteristics of a new switch.



(a) Fire switch - no load characteristics for 5, 10, 15, 20, 25 and 30 kV



(b) Fire switch characteristics loaded with voltage divider circuit for 5 through 30 kV



(c) Fire switch characteristics - loaded, showing trigger breakdown to main electrode

FIGURE 14

TRIGGER CIRCUIT - FIRE SWITCH CHARACTERISTICS. FIGURES (a), (b), AND (c) HAVE A 0.5-MILLISECOND PER DIVISION TIME BASE AND 5 VOLTS PER DIVISION AMPLITUDE

The interesting points are, first, that by increasing the current load the effective switching speed is greatly increased although its actual closing time remains the same. This is because the voltage jumps across the switch poles during their motion, but long before they close. This is witnessed by the fact that in the earlier test the trigger wire exploded and the main bank discharged within microseconds (300 microseconds being typical) whereas the actual switch electrical closure is 1 to 3.5 milliseconds. The second point is that because of the first point the earlier worry about contact bounce was premature and unpredicated.

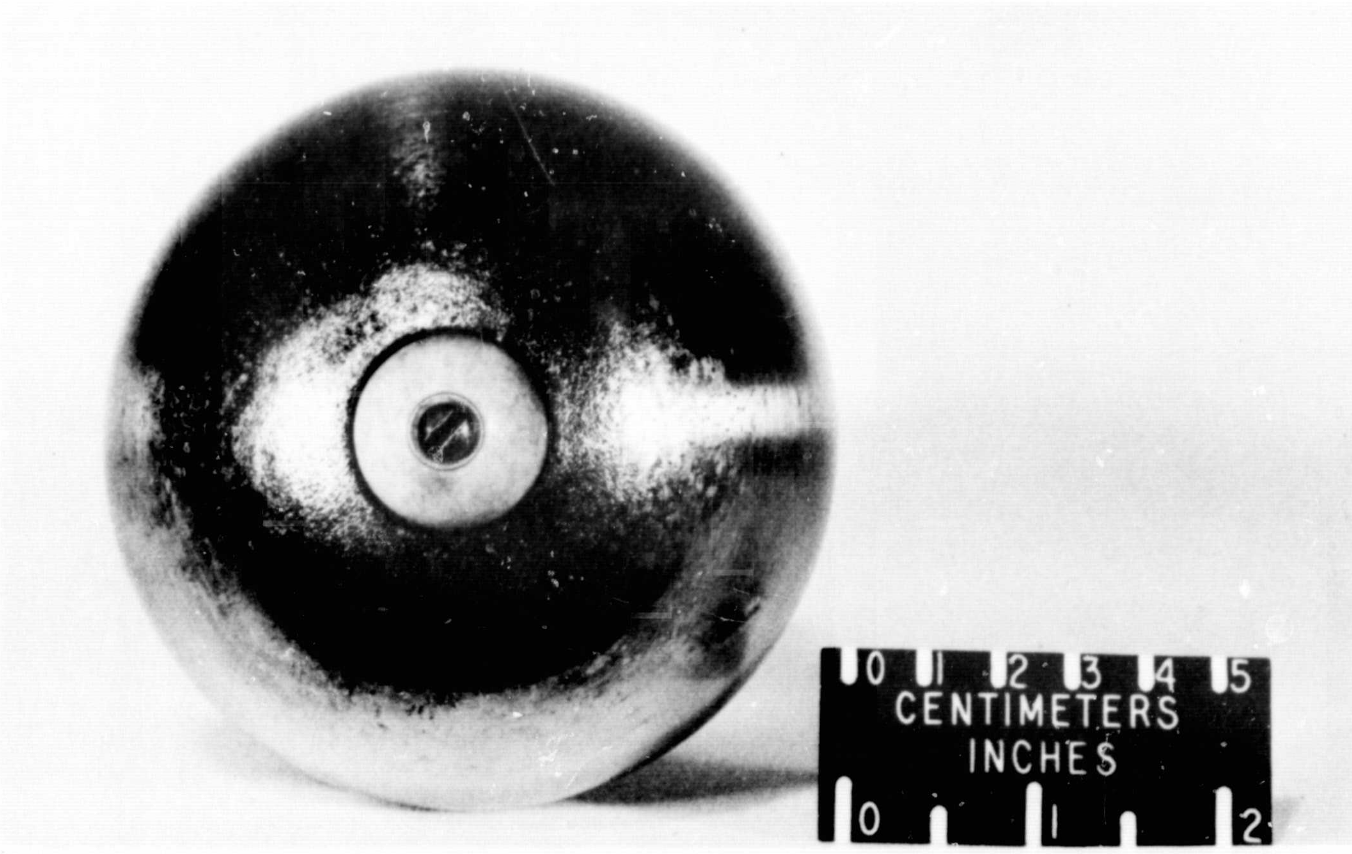
Insulator Positioning

Other positions of the trigger electrode with respect to the main electrode were tried by inserting more or less spacers. However, best results were obtained using three spacers corresponding to position 4 as shown in Figure 3.

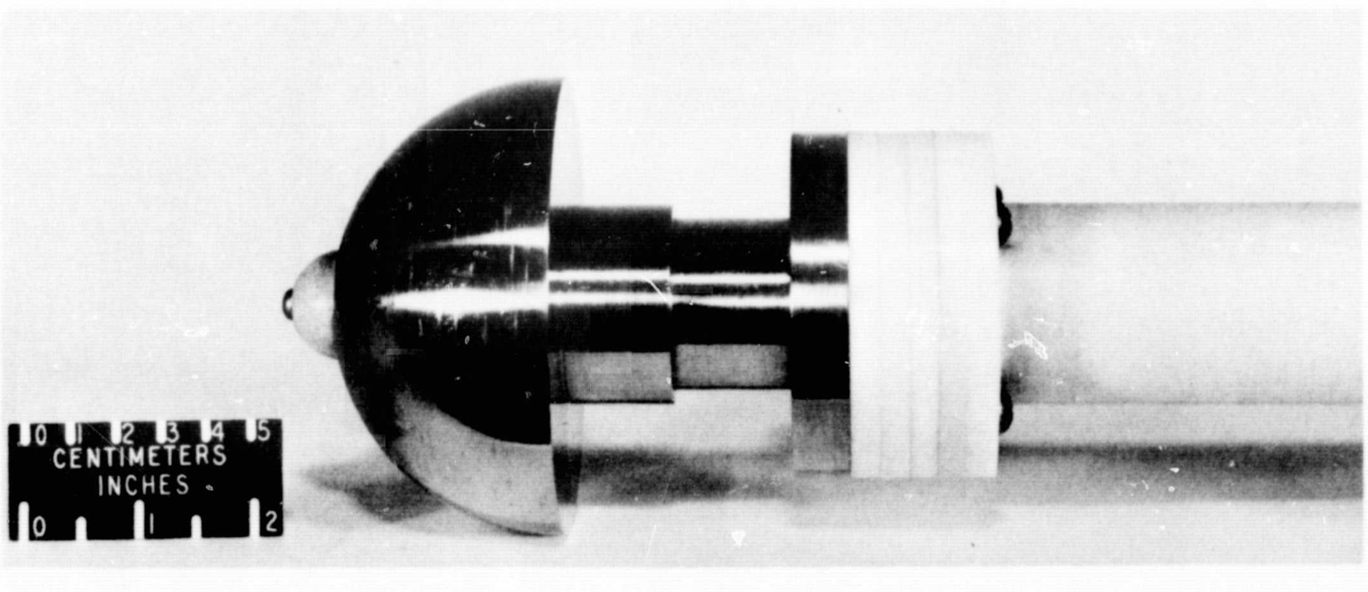
Figure 15 shows the actual high-voltage electrodes and Teflon insulator assembly used during the entire experiment. The Teflon insulator ended the experimental test with a glazed finish on the nose which was subjected to the hot arcs. But no other degradation was apparent.

Arc Resistance

Arc resistance as a function of arc length was not investigated as was originally intended. The original intent was to verify Toepler's Law for arc resistance as a function of arc length.



(a) Front view of actual high-voltage insulator and electrode assembly



(b) Side view of actual high-voltage insulator and electrode assembly

FIGURE 15

MAIN ELECTRODE, TRIGGER ELECTRODE, AND INSULATOR ASSEMBLY

According to Toepler[27] arc resistance is expressed as

$$R = \frac{K \times L^*}{Q}$$

where

K = constant

$K(\text{air}) = 0.8 \times 10^{-3}$

L^* = arc length in centimeters

Q = the number of ampere-seconds transmitted through the arc

The fact that the discharge current peak amplitude decreased by a factor of 10 when the arc length was increased from 1 to 4 feet is now realized to occur because of increased circuit inductance and not arc resistance.

Conclusions

The following paragraphs are written, though somewhat redundant, to construct a brief summary, to reiterate certain aspects of the experimental analysis, and to demonstrate that the objectives of the analysis were met.

The complete design details of the experimental model were given to help others who might follow this work. The various circuit and load parameters were determined. The basic theory of the technqiue worked as was witnessed by the fact that many 4-foot arcs were successfully drawn.

[27] Frank B. A. Früngel, High Speed Pulse Technology (New York and London: Academic Press, 1965), Volume I, p. 113.

Magnet wire, tinned copper wire, bare copper wire, and a bimetallic fuse wire were tested. A preferred wire, the fuse wire, was established mainly upon its most significant attribute - reliability.

A working region for two wires, bare copper and the bimetallic fuse wire, was established.

The best relative position of the trigger electrode was determined through a trial and error process of inserting and/or removing spacers until an optimum position, position 4, was found.

A hypothesis was presented and proved justifying an excess energy input into the trigger wire when it is exploded. The direct results being that a more conductive path is presented for the main bank discharge.

The discovery of a constant delta-V before and after exploding a given trigger wire was noted.

The resulting change in frequency resulting from a change in arc length is shown. Also observed was the total number of cycles of the main bank discharge resulting from the same arc length change.

An investigation into the mechanical action fire switch showed that the fire switch characteristics are not as critical as was generally believed and that the mechanical action type switch is suitably applicable.

It was established that the energy from the main bank could be delivered to a 4-foot-long arc within 300 microseconds. This time sequence for the complete process to occur lies well within the acceptable realm of shock tube and shock tunnel users and, therefore, deems the technique applicable.

And last, one theory and the resulting working formula for arc resistance as a function of arc length are briefly discussed.

As with all experimental endeavors, the knowledge gained is only a small portion of the whole story. But this investigation, as a first effort, bridges a large gap in knowledge over what was known at the outset.

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APPENDICES

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APPENDIX I

As developed in Chapter IV the expression for the current in a series RLC circuit is

$$i = \frac{Ve^{-\frac{R}{2L}t}}{L\sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}} \left[\frac{e^{+\sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}\,t} - e^{-\sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}\,t}}{2} \right]$$

this can be simplified accordingly as:

$$i = \frac{Ve^{-\frac{R}{2L}t}}{L\sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}} \left[\sinh\sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}\,t \right]$$

$$i = \frac{Ve^{-\frac{R}{2L}t}}{jL\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}} \left[\sinh j\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}\,t \right]$$

$$i = \frac{Ve^{-\frac{R}{2L}t}}{jL\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}} \left[j \sin\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}\,t \right]$$

$$i = \frac{Ve^{-\frac{R}{2L}t}}{L\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}} \left[\sin\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}\,t \right]$$

or

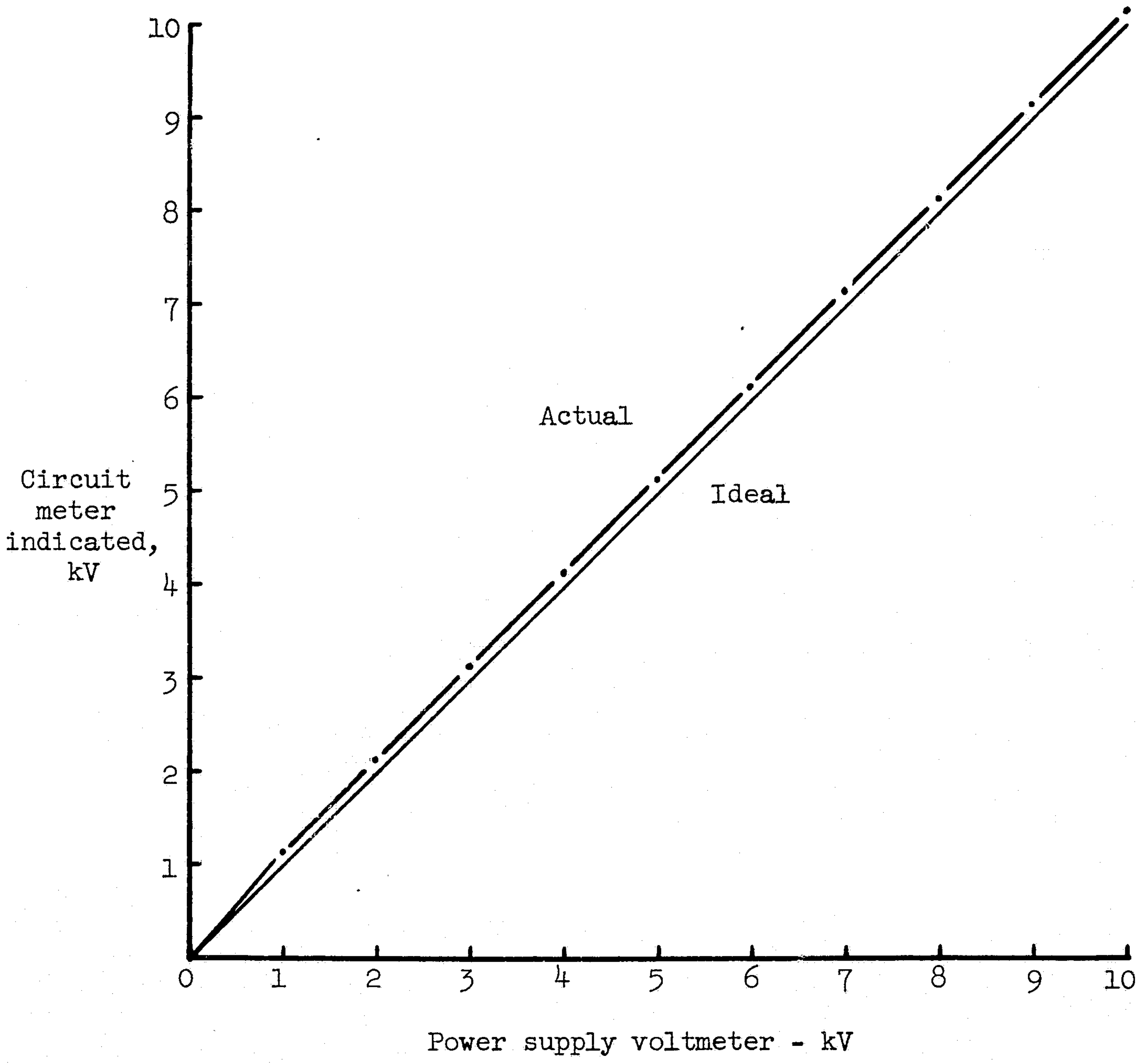
$$i = \frac{Ve^{-\frac{R}{2L}t}}{\omega t} \sin \omega t \tag{15}$$

where

$$\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

APPENDIX II (A)

METER CALIBRATION CURVE
MAIN BANK



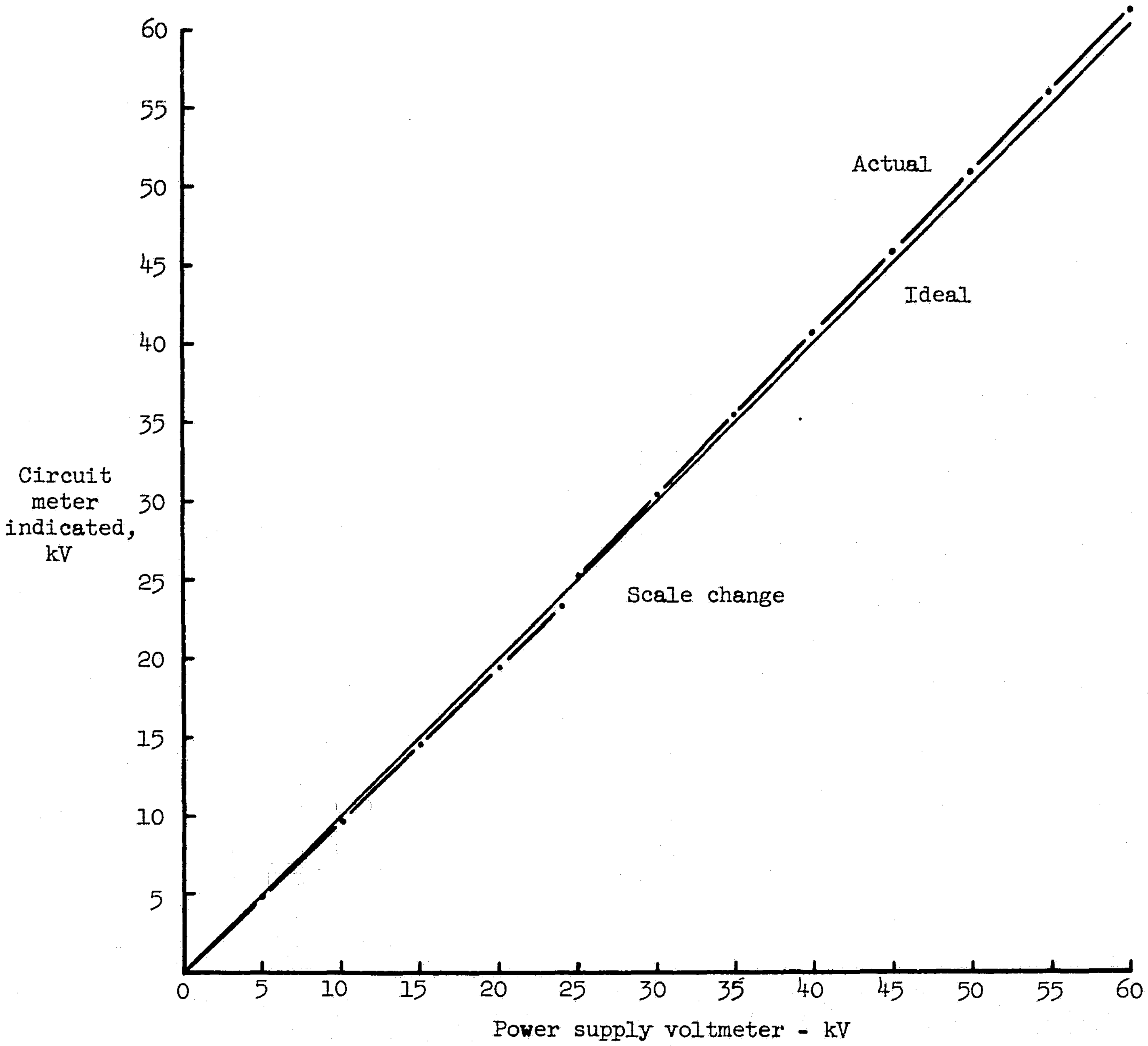
100 kΩ variable resistor all in and meter shunted with 12 kΩ resistor as shown in Figure 1

FIGURE 16

MAIN BANK VOLTAGE VERSUS POWER SUPPLY VOLTAGE

APPENDIX II(B)

METER CALIBRATION CURVE
TRIGGER BANK



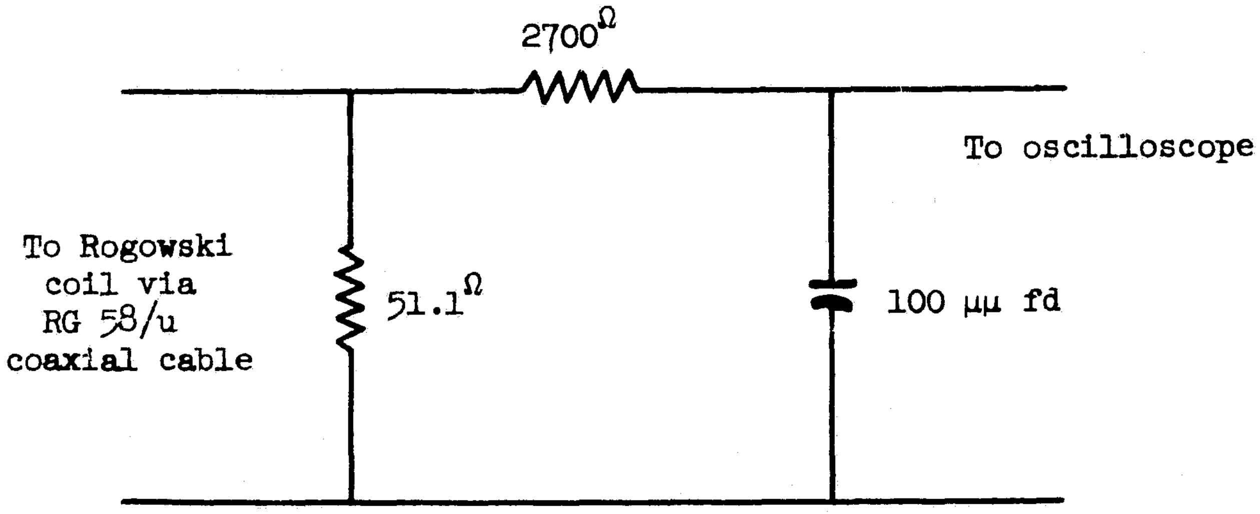
50 kΩ variable resistor in Figure 1 all out

FIGURE 17

TRIGGER BANK VOLTAGE VERSUS POWER SUPPLY VOLTAGE

APPENDIX III

SCHEMATIC REPRESENTATION OF TERMINATING RESISTOR AND INTEGRATOR



Design criteria

$$\frac{1}{2\pi fC} > 10 \text{ times } 2700^{\Omega}$$

where frequency was 52,500 hertz taken from Figure 5

$$C \leqq \frac{1}{(27 \times 10^3)\ (6.28)\ (52.5 \times 10^3)}$$

$$C \leqq 112.5\ \mu\mu F.$$

NOTE: Trigger bank frequency was used because the main bank frequency is much lower due to the large capacitance bank.

$$RC = (2.7 \times 10^3)\ (100 \times 10^{-12})$$

$$= 0.27 \text{ microseconds}$$