Note 12

NANOSECOND SWITCH DEVELOPMENT

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AIR FORCE WEAPONS LABORATORY
Research and Technology Division
Air Force Systems Command
Kirtland Air Force Base
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FOREWORD

This report was prepared by Space Sciences, Inc., 301 Bear Hill Road, Waltham, Massachusetts, under Contract AF 29(601)-6429. The research was performed under Project 3805, Subtask 380505, Program Element 6.24.05.03.4, from 1 June 1964 through 1 April 1965. The report was submitted in October 1965 by the Air Force Weapons Laboratory Project Engineer, Dr. Arthur H. Guenther (WLRE).

This technical report has been reviewed and is approved.

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ABSTRACT

A program to develop a switch or switch technique suitable for use in a stripline voltage multiplication circuit is reported. Switch requirements include rise time and jitter of less than 5 nsec, inductance in the low nanohenry range, as well as simplicity, reliability and ease of maintenance. Two major tasks have been the design and development of a high pressure gas switch aimed at meeting the above requirements and the obtaining of sufficient fundamental breakdown data in liquid and solid dielectrics to show their feasibility as a nanosecond switching medium. A comprehensive switch literature search and the bibliography included here show that no existing switches meet program requirements.

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1. INTRODUCTION

Requirements for high-power nanosecond pulse generation have led the Air Force Weapons Laboratory to sponsor a number of programs which depend upon very rapid, high-power, high-voltage switches. The performance requirements for such a switch are severe because the energy storage elements are used in Blumlein or similar circuits. The switch must have jitter and rise time in the nanosecond range, inductance in the nanohenry range, high-voltage holdoff capability in the 100 kilovolt range, as well as reliability and simplicity of construction and maintenance.

A program of one year duration to develop a switch or switching techniques suitable for strip line use in Blumlein or similar circuits is reported here.

2. SUMMARY

In order to evaluate and develop unique nanosecond, nanohenry, 100 kilovolt shorting switch techniques, the present program has encompassed a variety of tasks. These may be divided into four groups:

1. The compilation and evaluation of relevant published information on switch design, operational principles and basic data of value to advanced switch design.
2. The supplementing of published basic data by laboratory investigation where feasible and necessary.
3. The formulation of switch designs based on published and new experimental data.
4. The evaluation of developed switch designs in applied physics studies of performance characteristics.

This report is divided into sections reflecting the above divisions. A literature review summarizing and explaining the literature survey appears in Section 3. Sections 4 and 5 give new basic data on nanosecond breakdown in liquid and solid dielectrics. Section 6 develops quantitatively the strip line switch problem, the theoretical design of a high pressure air switch and the actual evaluation of the strip line switch in a strip line facility. The evaluation of one particular switching technique for use as a nanosecond switch is given in Section 7. The final section, Section 8, is a bibliography.

Section 3, the literature review, includes relevant journal articles on switching for the last twenty years, with particular emphasis on articles appearing in the last five years. All major scientific journals have been searched. No existing switches have been found which meet all the requirements of a Blumlein switch. Certain switches, however, meet a portion of the requirements in respect to jitter, rise time, or low inductance.

The largest background in switching techniques is associated with gas switches; both high and low pressure switches have been extensively used. The basic mechanisms of gas breakdown are thoroughly understood, although the actual breakdown action for a complicated switch geometry and field configuration may not be fully explicable. Solid dielectric switches have come into recent use although little is known of the exact nature of their operation. Although dc breakdown in solid dielectrics has received considerable attention, little is known of pulse breakdown characteristics for pulses in the nanosecond time scale. Additionally the geometry actually used in solid dielectric switches is complicated and could well mean that the switch breaks down because of gaseous and solid dielectric failure. Liquid dielectrics have only recently been used as a switching medium. Basic data on liquid breakdown is lacking. Along with this lack there is confusion as to the theoretical description of the breakdown process. Previous investigations of breakdown in liquid and solid dielectrics have been limited in the time resolution (0.1 μsec.) and in over voltage ratios (approximately 1.5 to 1). In order to supplement existing breakdown knowledge and supply some basic data applicable to the design of fast switches we have performed nanosecond measurements in both liquid and solid dielectrics.

Section 4 describes our liquid dielectric breakdown measurements. Because there exists a background of information on breakdown in liquid hydrocarbons of simple structure the initial liquid dielectric measuring effort was devoted to breakdown in n-Hexane. Based on the laboratory work three conclusions were reached.

(a) Both the dc hold-off fields and the breakdown lags in liquid dielectric gaps are very erratic and dependent on conditioning as noted by previous investigators.

(b) With sufficient pulse overvoltage (3 to 4 times static hold-off) the observed lag times and the spread in observed lag times may be reduced to less than 10^{-8} second.

(c) Small static bias (2-4% of impulse voltage) reduces the above lag and jitter time to the sub-nanosecond range.

Once nanosecond breakdown had been confirmed in a simple hydrocarbon liquid we attempted to show its existence in a wide variety of other fluid types. We therefore investigated the pulse breakdown of transformer oil, paraffin oil, Freon E-3, Dowclene W R, Dow Corning 704, Dow Corning 200, and distilled water, using simple averaging for obtaining lag times and taking data with and without the application of bias. Of the fluids tested only two (Freon E-3 and distilled water) showed no reduction of lag time due to the application of a bias field. Only one fluid tested (Freon E-3) failed to show nanosecond breakdown times with sufficient overvoltage. Some of the problems associated with using liquids as a switching medium were examined.

The major conclusion of the liquid dielectric measurements is that nanosecond breakdown is possible. Up to this time there has been no experimental evidence showing such breakdown, in fact, a number of investigators have thought it not possible. With the proven existence of nanosecond breakdown the possibility of liquid dielectric switching in the nanosecond time regime becomes possible. One of the major advantages of such a system is low inductance for high holdoff capability. However, because of the erratic nature of liquid dielectric holdoff voltages, the requirements for fluid purity and electrode conditioning, the high overvoltages involved and the lack of understanding of the fundamental processes in liquid dielectric breakdown, actual switch development will only come as the result of a realistic research and development program. Because of the great potential advantages of this switch in low-impedance, high-voltage strip line applications it is suggested that such a program be pursued.

A theory is proposed to explain why bias fields reduce the breakdown lag times in many liquid dielectrics. It is conjectured that polarized impurities in the liquid are "pumped," under the influence of the field gradients, to the center of the breakdown gap. There, they might form a channel of low dielectric strength particles which facilitate breakdown. Detailed experiments of the bias effect, amplitude, polarity and time constant do not as yet uniquely confirm the above explanation.

Section 5 is concerned with nanosecond breakdown measurements in dielectric films. Pulse breakdown measurements were performed on four different film dielectrics: Mylar, Teflon, polyethylene and cellophane. The most detailed measurements were performed on Mylar film. The film measurements show pulse breakdown for a 0.5 nsec rise time, 48 nsec long pulse. It is shown that the film breakdown behaviour for pulses of this length is similar to the dc characteristic, i.e.; the breakdown voltage in terms of volts/mil increases as the pulse length decreases. However, for Teflon, the pulse breakdown voltage was comparable to the dc breakdown voltage (32kv/mil). Polyethylene showed characteristics similar to Mylar in terms of thickness versus pulse breakdown strength. Cellophane showed the lowest pulse breakdown voltage (10 kv/mil).

In addition to the measurements mentioned above, observations of the film rupture caused by breakdown were made on all films tested. Observations of the risetime of the voltage pulse as the film dielectric breaks down indicated that the process is very fast, occurring in less than one nanosecond.

In Section 6, detailed performance specifications for a high pressure switch are worked out on the basis of the Blumlein system. These specifications indicate that a switch of 2 nhenrys inductance with less than 1 nsec jitter and risetime of less than 5 nsec would be satisfactory. Further, the interrelation between jitter, inductance and rise time is specified. A high pressure air switch suitable to strip line geometry has been designed on the basis of available fundamental data. This switch has been operated on a 5 ohm, 50 kv strip line facility built for testing purposes. This facility allows pulse charging of a 5 ohm line and supplies a trigger pulse of up to 24 kv in amplitude with a 1 to 2 nanosecond rise time at time of voltage maximum on the 5 ohm line. Present strip line switch operation has shown rise times of 4 to 5 nsec and jitter of 6 nsec. Because of the inherent flexibility of the switch design a number of options available for reduction of jitter and rise time remain to be tested.

Section 7 describes a brief investigation of surface switching. Since this technique is unique and no measurements of the time of switching have been made we investigated the suitability of surface switching for use in the nanosecond time scale. Because observed jitter (100 to 1000 nanoseconds) and rise time (17 nanoseconds) were all relatively long in spite of experimental efforts to reduce their duration, surface switching was not deemed a suitable nanosecond switch technique.

The report concludes (Section 8) with the bibliography of switch references and techniques. Abstracts of all articles as well as an author index and a tabular summary of switch characteristics are included.

3. LITERATURE REVIEW

In order to have a firm basis for our own research and to illuminate the state of the art in practical switch design, a systematic search of the literature was initiated during the first quarter and continued throughout the program. In this section, the search methods are described and the results of the search are summarized.

3.a. Search Methods

Primary emphasis was placed on the search for switch design and performance data for switches used in high energy and/or short time duration discharge applications. As an adjunct to this, information was also sought on pulsed dielectric breakdown in solids, liquids and gases. In the process of this search additional publications were obtained which deal with relevant nanosecond circuitry and pulse generation techniques.

The open literature was searched by means of Physics Abstracts and Electrical Engineering Abstracts over the period January 1940 through April 1965. In employing abstracts, the following categories were consulted: Breakdown Electric - gases, liquids, solids; Discharges Electric; Laboratory Apparatus and Techniques; Spark Electric.

Additionally, the yearly subject indices of the Review of Scientific Instruments and the British Journal of Scientific Instruments were searched over the period 1940 to the present. In the Review of Scientific Instruments the following subjects were searched: Circuits; Electrical Measurements; Gas Discharges; High Current Techniques; High Voltage Techniques; Millimicrosecond/Nanosecond Techniques; Plasmas. In the British Journal of Scientifis Instruments the search categories included: Current Pulses; Discharges, Gaps, pressurized; High Current; High Voltage; Millimicrosecond/Nanosecond Pulses; Spark Gap.

The search was extended to the American Institute of Electrical Engineers' "Bibliography on Gaseous Dielectric Phenomena " S97 and Supplements S97A and S97B. Additionally, a search was conducted through the facilities of the Defense Documentation Center of relevant unclassified literature. This search produced only references that were available through open literature. Finally the National Academy of Sciences/ National Research Council "Annual Digest of Literature on Dielectrics" has been used for the years 1955 through 1963. Of the many references in the Digest only a few of the more appropriate ones have been chosen for inclusion in this bibliography.

3.b. Selection and Grouping of the Bibliographic Material

Employing the results of the title search, relevant publications were reproduced and filed in the categories cited below. Switch design publications were retained on the basis of their contribution to an understanding of initiation mechanisms, high voltage technique , materials for electrodes and insulators, low inductance design, current or charge handling capacity or their representation of the state of the art for a particular class of switch. All data concerning the breakdown formative processes in dielectrics was retained while publications regarding high voltage pulse generation were catalogued if the techniques described possessed relevance to fast triggering or synchronization circuitry. The resulting bibliography is thereby quite broad as regards switch design and switching fundamentals and should be useful beyond the specific scope to this program.

The reference material totaling 131 articles has been grouped into eight categories as follows:

a. Gas Switches (37)
b. Low Pressure Switches (24)
c. Solid Dielectric Switches (7)
d. Liquid Dielectric Switches (0)

e. Breakdown Processes in Gases and Gas Switches (22)

f. Breakdown Processes in Solids (7)

g. Breakdown Processes in Liquids (12)

h. High Voltage Pulse Generation Techniques (22)

The number of referenced publications that were retrieved and evaluated in each group is indicated by the numbers in parenthesis. Switch design information placed in category a. includes that for gas switches operated at pressures from near one atmosphere to several hundred pounds per square inch. Low pressure switches included in b.are generally classified as switches. While no reference work was found on liquid dielectric switches, category d. had been defined in anticipation of future information in this area.

Abstracts for all evaluated material are arranged according to the above scheme in Section 8 of this report. Section 8.i contains a tabulation of switch performance characteristics and therefore embodies information in categories a. through d. An author index is furnished in Section 8.j. In most cases the abstracts are those of the original authors. When an abstract was not furnished or did not represent the switching content of the paper, a brief abstract was prepared by the authors of this report.

In the tabulation of switch performance parameters a brief statement is made to describe the switch type for each reference and six performance parameters are given. These include the operating potential, the peak current, the total charge that is switched, the trigger lag time, the jitter and the self-inductance. In many cases the published information was incomplete as will be seen in the tabulation. Table entries have been made only for parameters specified by the publication author or for quantities which could be estimated with some certainty from the design or performance characteristics that were published. We have, therefore, refrained from speculation as to the probable magnitudes of unspecified parameters and have not attempted to predict the limiting values which one might obtain with appropriate redesign.

3.c. General Summary of Findings

The literature review clearly indicates that most of the previous work in switching has been performed with high and low pressure gas switch techniques. This work has been supplemented by extensive research into the fundamental processes of high voltage breakdown in gaseous dielectrics. Switch design background in liquid and solid dielectrics consists largely of several recent developments in solid dielectric switches and some sparse information on formative lag time for liquids. Information in these latter categories as contained in the bibliography is not sufficiently complete to permit any firm conclusions regarding the suitability of liquid and solid dielectrics for use in the switch application of this program.

Among the key design parameters required for the switch development undertaken here are: high voltage hold-off (~100 kv), low inductance (~1 nh) and low jitter (~1 ns). None of the switch designs evaluated approached this set of characteristics very closely. However, the following table is indicative of the characteristics of presently developed gas, vacuum and solid dielectric switches with regard to these three parameters. The table cites the number of published switch designs in each category which: (1) were employed at potentials above 50 kv, (2) had a reported jitter less than 5 ns or (3) had a self-inductance less than 5 nh.

TABLE I

Summary of Published Switch Parameters Relative to Present Needs

Switch Type	Gas	Vacuum	Solid Dielectric
No. of References	37	24	7
$V > 50$ kv	15 (41%)	10 (42%)	1 (14%)
$\pi_j < 5$ ns	8 (22%)	0	0
$L < 5$ nh	2 (5%)	7 (9%)	4 (57%)

The table indicates that nearly one-half of the referenced work on high pressure and vacuum switches has been carried out for potentials above 50 kv. Only one evaluated publication on solid dielectric switches dealt with this potential range. Gas switches are reported which operate at potentials up to 10^6 volts.

To the extent that the literature has been evaluated, the high pressure gas switch is the only switch which has led to jitter time less than 5 ns. Of the eight authors reporting jitter less than 5 ns, five report 2 ns or less. The minimum reported jitter for vacuum switches was 10 ns (four publications), while the minimum jitter for solid dielectric devises was 20 ns as reported by one author.

All three switch types have been designed for low inductance (<5 nh), but only a small fraction of gas switches have been in this range. Low inductance is clearly an important characteristic of all solid dielectric switches. Of the four publications reporting a value of self-inductance for this switch type, inductance values ranged between 0.5 nh and 2 nh.

Only two switches were reported which simultaneously met two of the three parameter ranges indicated in the table. Two gas switches operated above 50 kv and had a jitter less than 5 ns. The self-inductance for these switches was reported as 10 nh in one case and 30 nh in the other.

A wide variety of triggering methods have been employed in the switch designs reviewed. In general, these are indicated in Section 8.i. for each switch listed in the tabulation. The following is a summary of the methods which have been employed.

TABLE II

Summary of Trigger Methods

Overvoltage	UV Radiation
Overvoltage plus Spark or UV Source	Mechanical
	X-Radiation
Exploding Wires	Gas Injection
Heated Wire	Magnetic Fields

Trigger Spark	Electron Beam
Plasma Injection	Control Grid
Explosive	Focused Laser Beam

Of all of the methods employed in high pressure gas switching, overvoltage in the presence of spark or UV illumination has been the fastest since the lag time is limited only by the formative time for breakdown. At high pressures formative times for moderate overvoltage can be achieved in the sub-nanosecond range. Recently intense laser beam switching has also been shown to be of utility in nanosecond switching. Many of the other methods cited simply bring about overvoltage conditions with charge carriers present, but do so by slower intermediate steps. High pressure also enhances the hold-off capability and makes possible low inductance design.

The jitter characteristics of all previously studied vacuum switches are poor compared to the requirements of the present program. The underlying reason is apparently due to the relatively slow development of breakdown in low pressure gaps. The characteristic time lags in vacuum gaps are generally dependent on secondary processes and are typically of the order of ion transit times across the gap space. Rise time, however, may be short for a vacuum switch. Reduction of jitter with increasing pressure is observed with a consequent reduction in the potential hold-off capability. In spite of the fact that low inductance and high voltage design can be achieved, the jitter and delay problem appears very severe in the present application for vacuum gaps.

Solid dielectric switch development has been largely confined to the period since 1960, and reported switch designs are few. The outstanding characteristics of such switches are high voltage hold-off at very low inductance with some sacrifice in convenience due to the necessity for replacing the ruptured dielectric after each discharge.

The mechanisms which control the speed of the breakdown mechanism and reduce jitter have not been fully treated and will require further investigation.

4. LIQUID DIELECTRIC MEASUREMENT

4.a. Introduction to Breakdown Lag Measurements in Liquids

The previously reported investigations of electrical breakdown time lags in liquids have been plagued by the lack of a suitable theory. As one effect of this lack, there is not even general agreement as to whether the measured lags are the formative or statistical lag components (c.f. References g.3 and g.6). Beyond this problem, the experimental results have another more serious shortcoming in relation to the needs of the present program for very short time data, i.e. in the nanosecond range. Crowe (Reference g.6), for example, employed voltage pulses with 0.25 microsecond rise time. With this limited time resolution overvoltage ratios were studied only up to values of about 1.5:1.

Our approach has been designed to determine the temporal breakdown characteristics for liquids with much improved time resolution. While the primary goal has been to obtain practical background information for fast switch design, we have effectively supplemented previous results and in experiments using bias fields have shed some light on the questions of formative versus statistical lag. The most detailed measurements have been performed with n-Hexane. This liquid was chosen as representative of the simple hydrocarbons which have been previously investigated and not because it is indicated as a suitable dielectric for switch applications. The techniques established in studying n-Hexane have been directly applied to the other liquids studies.

4.a.1. Apparatus and Techniques

The apparatus used in the breakdown studies is that which has previously been employed by this laboratory in gas breakdown work (Reference 1) with some modifications. The circuit, represented in Figure 1,

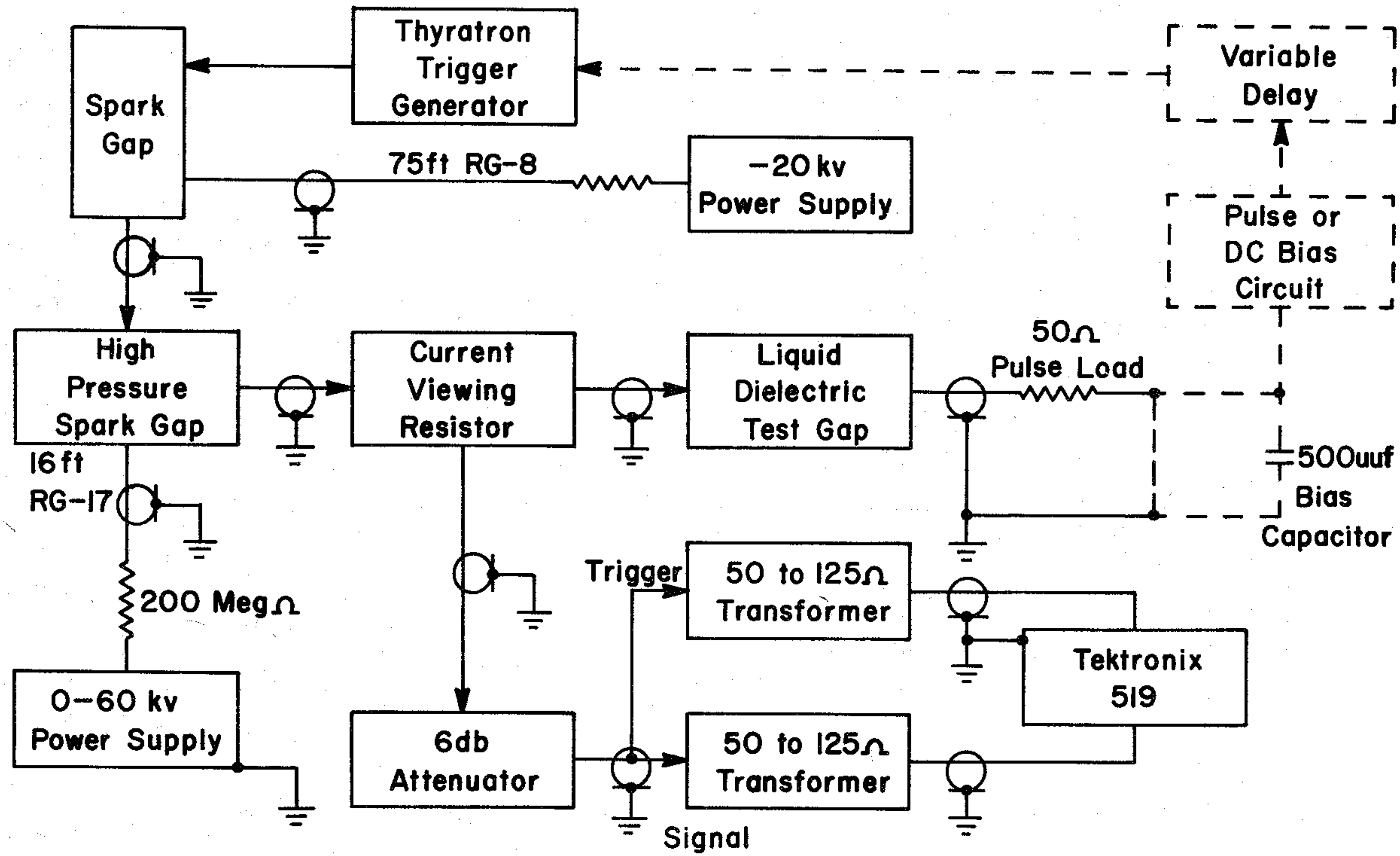


FIGURE 1.
SCHEMATIC DIGRAM OF LIQUID DIELECTRIC ELECTRICAL TESTING SYSTEM.

consists of a uniform impedance coaxial transmission line (RG-17) system for generating fast rise, high voltage pulses which are applied to a test gap containing the dielectric under study. In operation a 16 foot (48 nsec) length of line is charged to the desired pulse potential through a 200 megohm resistor. A high pressure (Nitrogen at 100-200 psi), three ball gap is triggered by means of a -20 kv line discharge with an air spark gap. The latter gap is triggered by a manually controlled thyratron pulse generator. With proper adjustment of the high pressure gap a square pulse is generated with rise time less than 1 nsec and typically 0.5 nsec. The pulse propagates through the current viewing resistor and is applied to the test gap. The resistor made by T & M Products, Albuquerque, New Mexico, is a coaxial resistor of 0.202 Ω with a band pass of dc to about 2 gc. When breakdown occurs in the test gap, the pulse is attenuated in a coaxial 50 ohm attenuator which terminates the line. The pulse reflected from the test gap cancels the forward propagating pulse at the current viewer until breakdown occurs, thereby providing a direct observation of breakdown lag time. The output from the current viewing resistor is passed through a 4 gc bandwidth pad of 6 db and thence through matching transformers to the oscilloscope trigger and vertical deflection inputs. A Tektronix 519 oscilloscope with a deflection sensitivity of 9.8 v/cm and rise time of 0.29 nsec is used to view the signals. The signal information is normally recorded on film with 2:1 image reduction at sweep speeds of 10 to 2 nsec/cm.

A simple test gap was constructed for the investigation of liquids as illustrated in cross-section in Figure 2. The gap consists of 1/8 inch stainless steel balls pressed into the center conductor of the coaxial line which makes up the system. The aluminum housing is bored to the diameter of the cable dielectric providing a press fit for liquid sealing. The cable braid is clamped (not indicated) in place at the ends of the aluminum housing. The gap geometry differs markedly

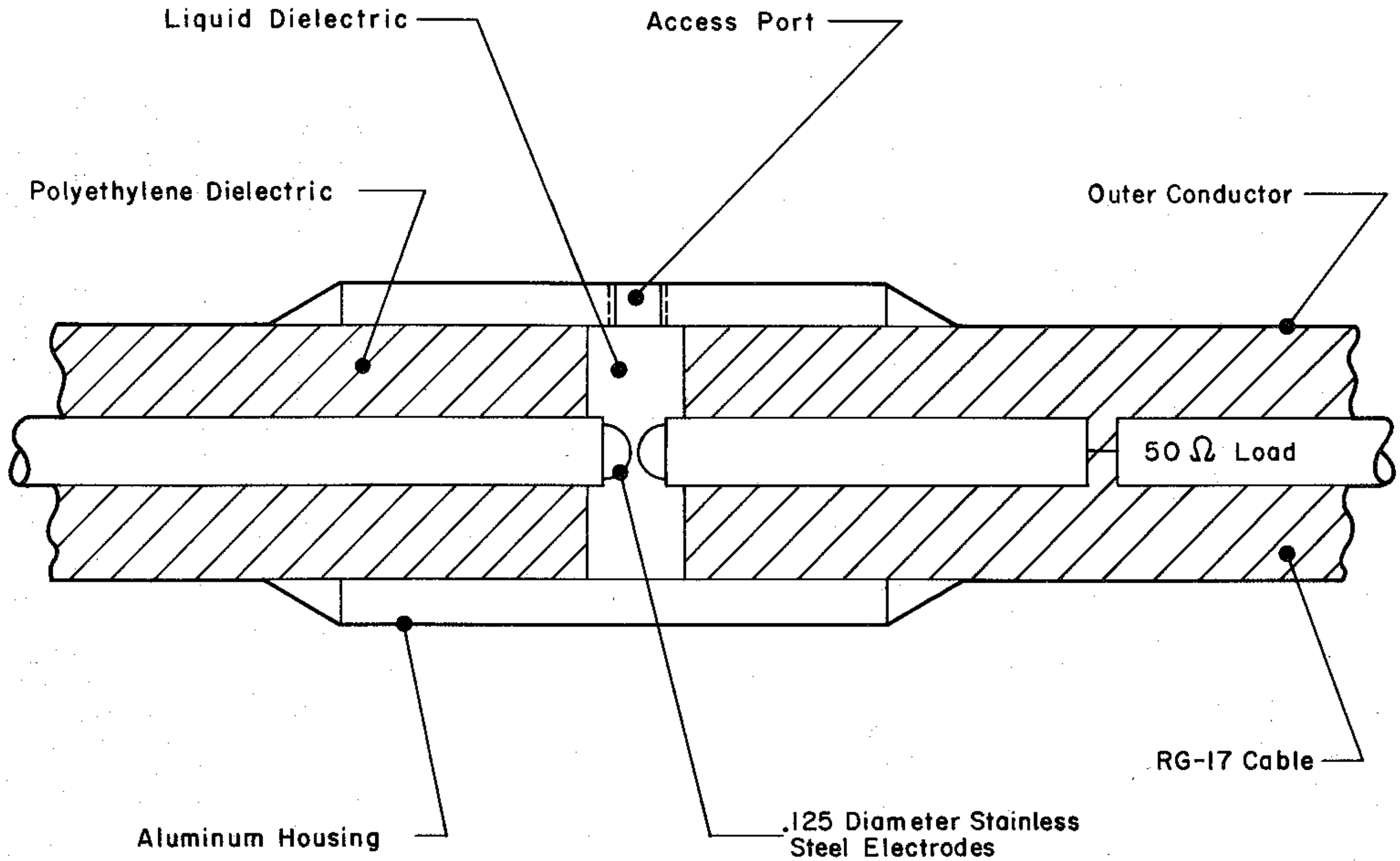


FIGURE 2.

LIQUID DIELECTRIC TEST GAP

from that employed in gas breakdown studies in two aspects. First, tapered dielectric and conductor transitions are obviated because of the short line length over which an impedance change is necessary and the partial matching of the dielectric constants of the cable and that of the liquid. Second, the electrode diameter is much reduced for liquids in order to reduce the capacitance of the gap at the very close spacing employed. A gap separation of 0.0024 inch was used throughout the tests. This was set by means of a stainless steel shim and subsequently checked visually after each test series by means of a shadowgraph.

Between various tests the gap was thoroughly cleaned with Dowclene W R and then blown free of remaining liquid with a hot high pressure air stream. The gap was always rinsed at least four times in the test fluid to reduce impurity concentrations. Procedures for fluid handling were adopted so that the original purity of the test fluid could be maintained. The breakdown electrodes were always measured with a stainless steel 0.0025 inch shim between tests. Examination with a 20 power binocular microscope showed that this was accurate for setting the gap distance and because it is a force fit, it is sufficient for removing any residues that remained on the electrode area.

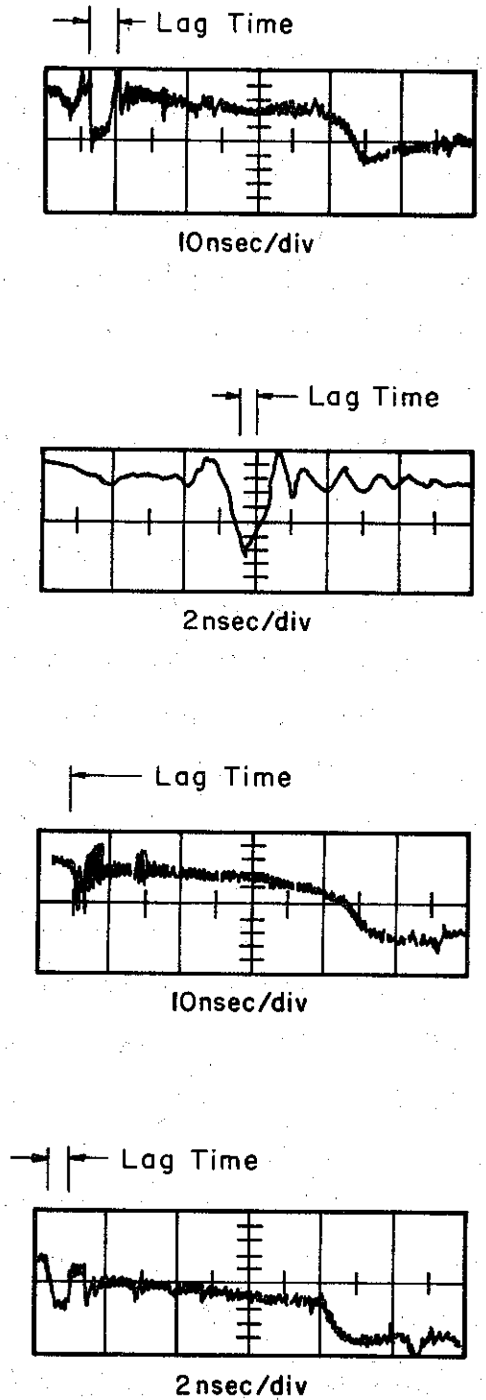
Eight different dielectric liquids were examined during the course of the present program. Because there exists a background of results from other investigations on n-Hexane, it was chosen as the fluid to test first. On the basis of the n-Hexane results an experimental method was developed which was used in obtaining results in the seven other fluids.

As will be seen below in the discussion of n-Hexane results there are no clear cut interpretations that may be made of either Laue plots or histograms of the breakdown data. Hence differentiation between formative and statistical lag time has not been possible. We have therefore used simple averaging of the data to determine the lag time for a particular liquid and applied pulse voltage. This method smooths out some of the large variation inherent in liquid breakdown. At least 72 data points were taken for each value of the applied field. Thirty-six of these points were taken with the bias field and thirty-six without the bias field. Each fluid was tested to see if there were any gross impurity effects. Applied voltages in the range of 8 to 26 kv were used. In general it was the aim of the experiment to cover the full range of delays available for measurement with the present experimental system (48 to less than 1 nsec). Bias voltage was applied with a separate bias supply in the circuit described below. Bias and pulse supply voltage were measured with an accuracy of 2.5%. Formative time accuracy was dependent on our ability to read the oscilloscope trace. An example of a liquid dielectric breakdown as seen on the oscilloscope traces is shown in Figure 3. These traces were obtained with the circuit of Figure 1. The upper set of traces was taken at 14 kv pulse voltage; the lower set was taken with 500 volts bias (82 kv/cm) and 10 kv applied pulse voltage. The liquid used for this test was Dowclene W R, one of the eight liquids tested. The pulse rings because of the impedance mismatch at the test gap, not because of poor pulse generation. The lag time is defined as the time between the moment the trace goes to the base line after the initial short pulse and the time it again rises to its full amplitude. The ringing after breakdown is caused by mismatch in the 50 ohm termination. The lower picture has a displaced baseline because of the effect of the charged 500 pf bias capacitor on the viewing circuit.

We will report the n-Hexane results first, followed by results in transformer oil (Esso Univolt 35), Paraffin Oil U.S.P., Freon E-3, Dowclene W R, Dow Corning 200, Dow Corning 704, and distilled water. Finally, we will give a qualitative interpretation of the results.

4.a.2. <u>Results in n-Hexane</u>

Spectroscopic grade n-Hexane was used in the experiments. While no attempt was made to enhance the purity of the liquid, the gap interior



Applied Voltage 14kv
Gap 0.0025 in.
Dowclene WR

Applied Voltage 10kv
Bias + 500 Volts
Gap 0.0025 in.
Dowclene WR

FIGURE 3.

LIQUID DIELECTRIC BREAKDOWN LAG TIME WAVEFORMS.

was washed in Dowclene W R and rinsed at least four times in n-Hexane before each test series. Static breakdown experiments were conducted to ensure that no gross contamination was present. Characteristically, the static breakdown conditions are very erratic, varying from breakdown to breakdown over a voltage range of as much as 10:1. With some conditioning a relatively stable breakdown rate of one per second was observed for the 0.0024 inch gap at 5 kv. This corresponds to about 8.2×10^5 volts/cm as compared to Crowe's value of 1.29×10^6 volts/cm for one microsecond pulse obtained in a gap of similar geometry (Reference g.6.). Because of the erratic nature of dc breakdown, no better value of static hold-off field was tenable.

Breakdown lag measurements were carried out at three pulse amplitudes: 12 kv, 15 kv and 20 kv. For each set of conditions approximately 50 individual observations were made to provide adequate statistical evaluation of results. Average values of lag time for three experiments are cited in Table 1.

TABLE 1

Experiment	12 kv (1.96×10^6 v/cm)	15kv (2.45×10^6 v/cm)	20 kv (3.28×10^6 v/cm)
#1	38.7 nsec	23.6 nsec	4.67 nsec
#2	26.0	11.6	6.74
#3	40.1	18.2	12.1

Experiment #1 was conducted with fresh electrodes and fresh liquid; Experiment #2 was performed with fresh liquid but with conditioned electrodes (from the previous experiment); Experiment #3 was carried out with no change of liquid or electrodes. The data for pulse amplitides of 20 kv are presented in Figure 4 for each of the three experiments. The vertical scale in the histograms shown in the figure represent the number of observed lag times within a given time interval. The distributions are seen to vary from one experiment to another while there

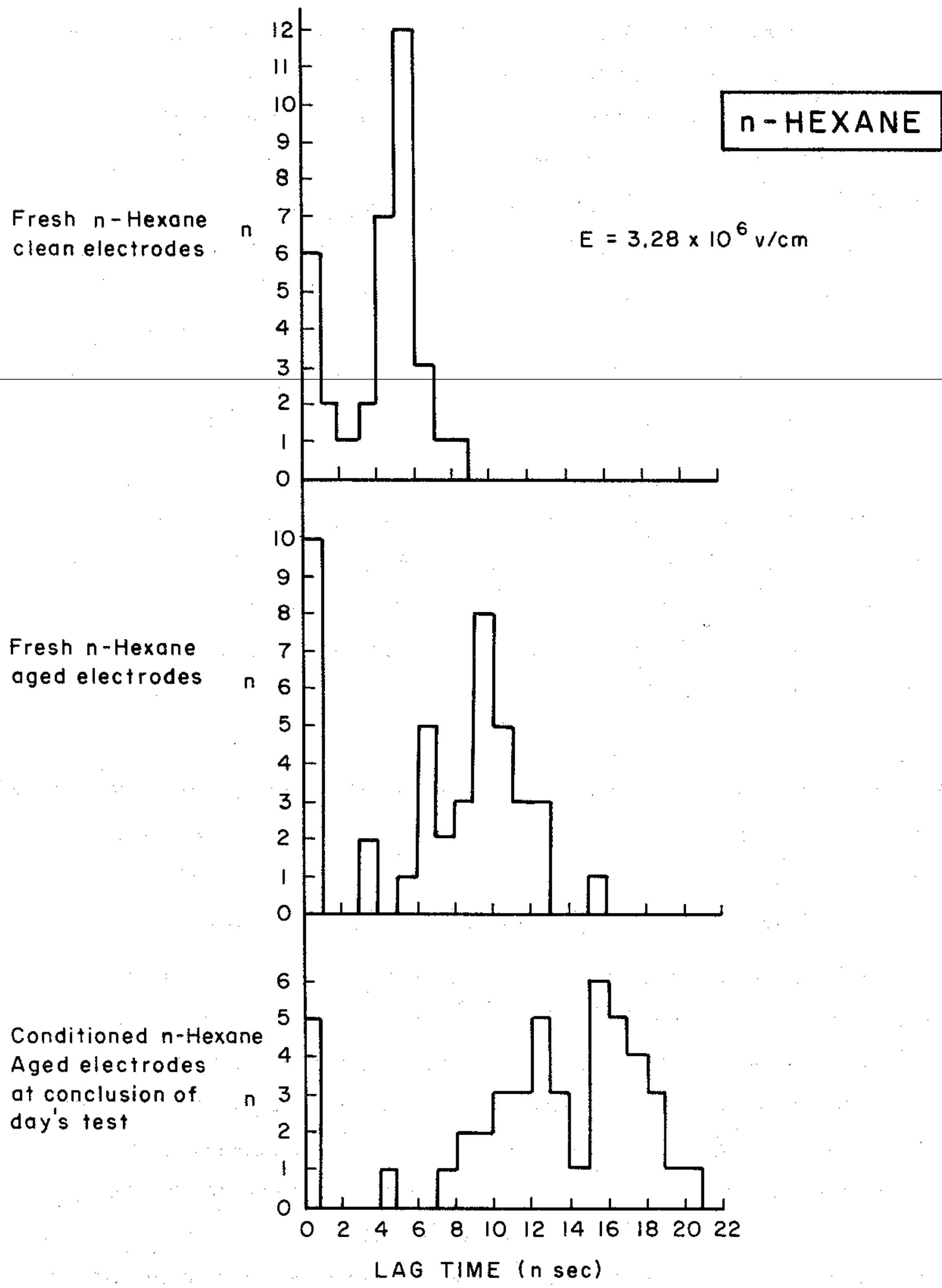


FIGURE 4.

HISTOGRAMS OF BREAKDOWN LAG DATA

is a tendency for the peak of the distribution to peak near the average values listed in Table 1.

A Laue plot (Reference 2) of the 12 kv data from experiment #2 is given in Figure 5. Normally a Laue plot of breakdown data is used to determine the electron emission rate in the gap. Under most circumstances the electron emission is exponentially distributed in time and hence the Laue plot is a straight line. The curvature indicated is characteristic of the several Laue plots which have been made and suggests unstable conditions for the production of initial electrons or for initiation of breakdown. Lewis and Ward (Reference g.3.) found that aging of the liquid-electrode interface led to increases in the lag time. We can only speculate that the wide distributions of lag time as seen in Figure 4, the curvature of the Laue plots as exemplified in Figure 5 and the aging effects are all related to the conditions in the liquid or at the liquid-electrode contact surface.

To explore the effects of aging of the dielectric and electrodes an additional experiment was conducted. Using a pulse height of 15 kv, a series of lag time measurements was obtained over a period of 400 minutes. The average value of each series of nine measurements is plotted in Figure 6. The gradual increase in lag time from about 10 nsec to about 35 nsec is in evidence over the time period in accord with the observations of Lewis and Ward (Reference g.3.).

A substantial difference in the results was obtained when a static potential was applied to the gap prior to the application of the impulse potential. To apply this bias voltage the termination end of the coaxial line system was charged to a potential of 500 volts and a coupling capacitor was introduced just ahead of the 50 ohm termination (see Figure 1). The potential across the test gap was a polarity which opposed the impulse potential which is positive. The value of 500 volts was chosen so as to cause little ambiguity (4% at most) in

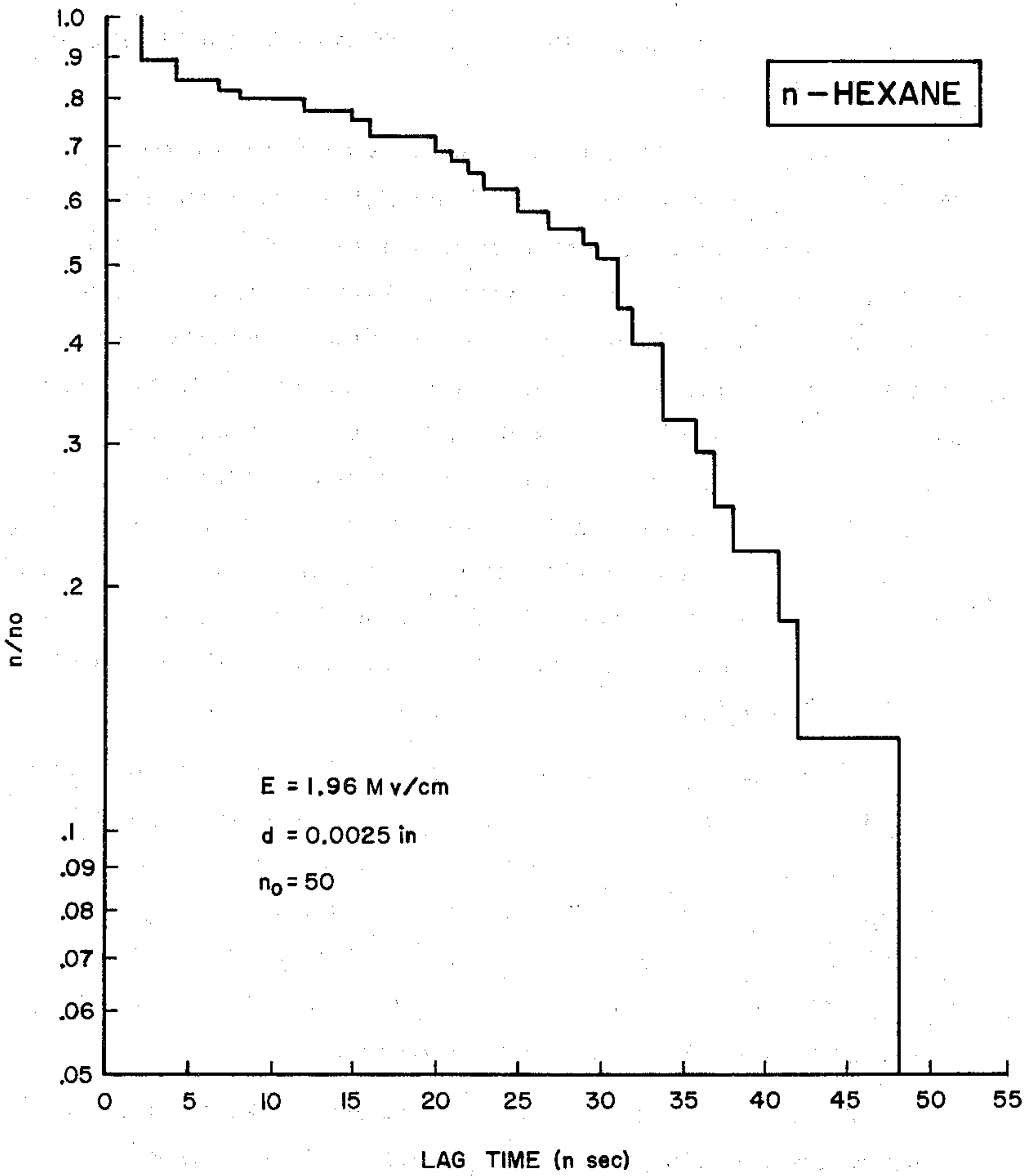


FIGURE 5.
LAUE PLOT OF DATA WITH NO BIAS FIELD.

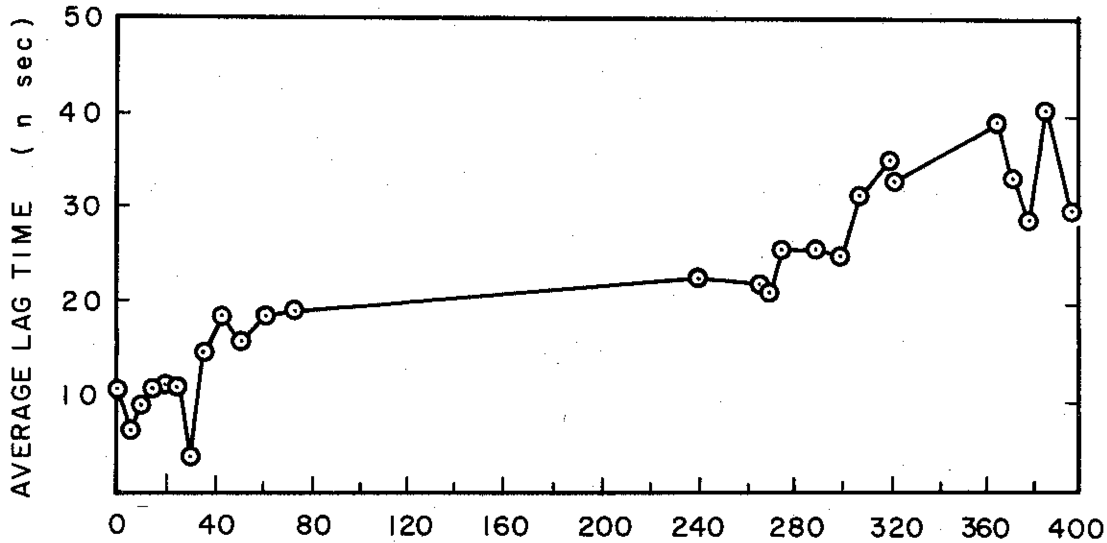


FIGURE 6.

LAG TIME AGING HISTORY WITHOUT BIAS FIELD the instantaneous value of the impulse field. Also, at this low value of bias field (8.2×10^4 volts / cm) premature breakdown was unlikely.

A typical Laue plot is shown in Figure 7. As compared with the similar plot obtained without bias field (Figure 5) the locus of steps is much more nearly straight. This suggests that the bias field has increased the stability of the sources of initial electrons which probably exist at the liquid-electrode interface.

The reduction of lag time and the elimination of aging effects with applied bias is illustrated in Figure 8. Two long-term experiments are represented for an impulse voltage of 15 kv. With a 500 volt bias continuously applied the observed lag times generally average less than 5 nsec and show no increase over a period of 320 minutes. Without bias much larger values are noted. (see Figure 8) During the short period in which a bias potential is applied, there is a substantial reduction of lag time, but the reduction seems to be reversibly dependent on bias as indicated in Figure 8 when bias is removed.

A summary of breakdown lag time data as obtained with and without 500 volt bias is presented in Figure 9 which also illustrates the data of Crowe (Reference g6) and the results obtained by Lewis and Ward (Reference g3). The data from our investigation clearly indicate that the lag times in liquids are, under conditions of large overvoltage, substantially shorter than would be suggested by the results reported by the above authors. Furthermore, the effects of a small bias field provides a substantial reduction of lag time. In the new data indicated in Figure 9, the spread in time is the spread in average lag time values from several experiments and is not directly a measure of jitter. However, Figure 10 is presented to show that this spread in average time is affected strongly by the application of bias. The latter results indicate that the combined use of bias and large impulse overvoltage (e.g.3:1) may make feasible the use of liquids as switch dielectrics in fast

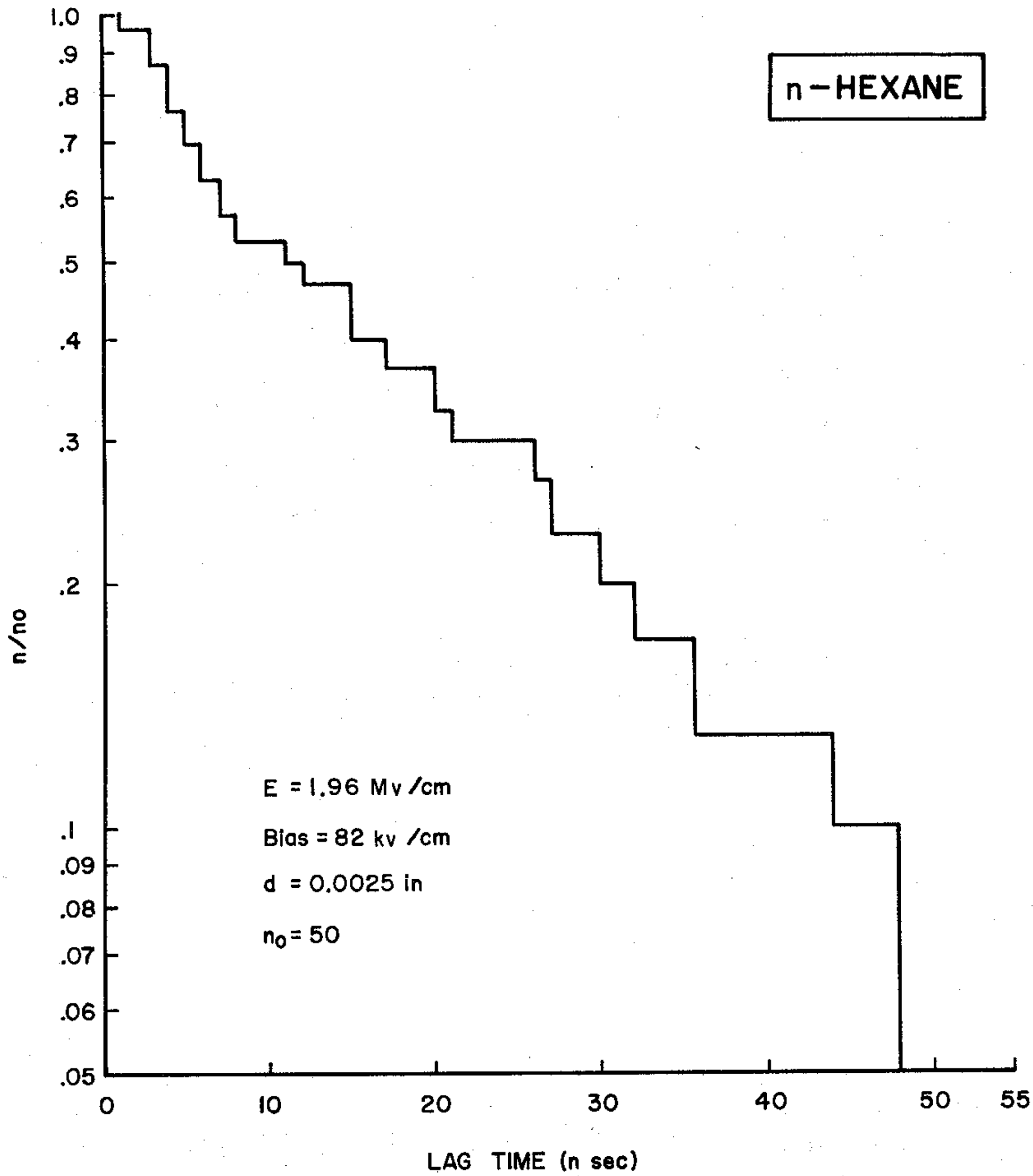


FIGURE 7.
LAUE PLOT OF DATA WITH BIAS FIELD.

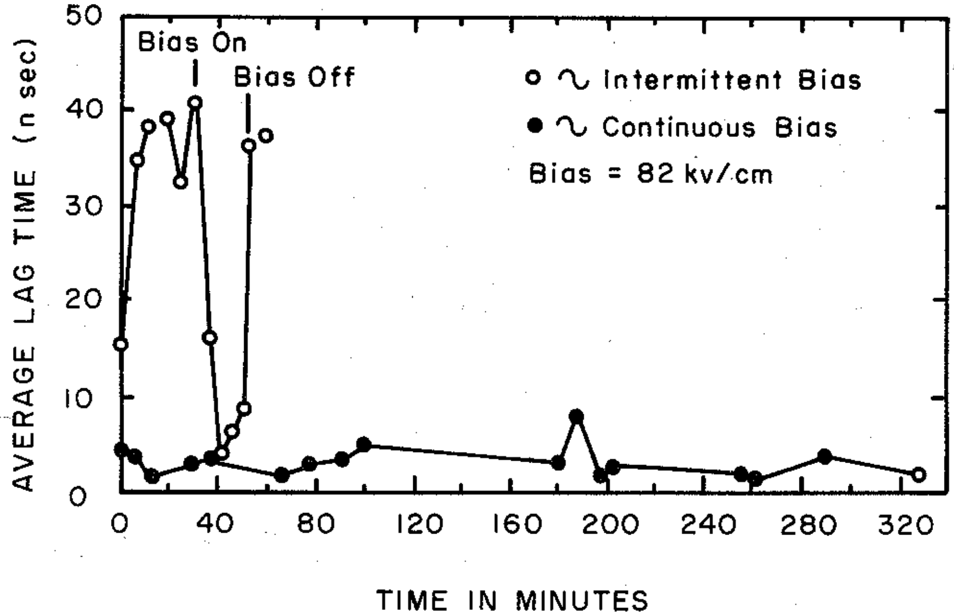


FIGURE 8.

AGING HISTORY SHOWING EFFECTS OF BIAS FIELD.

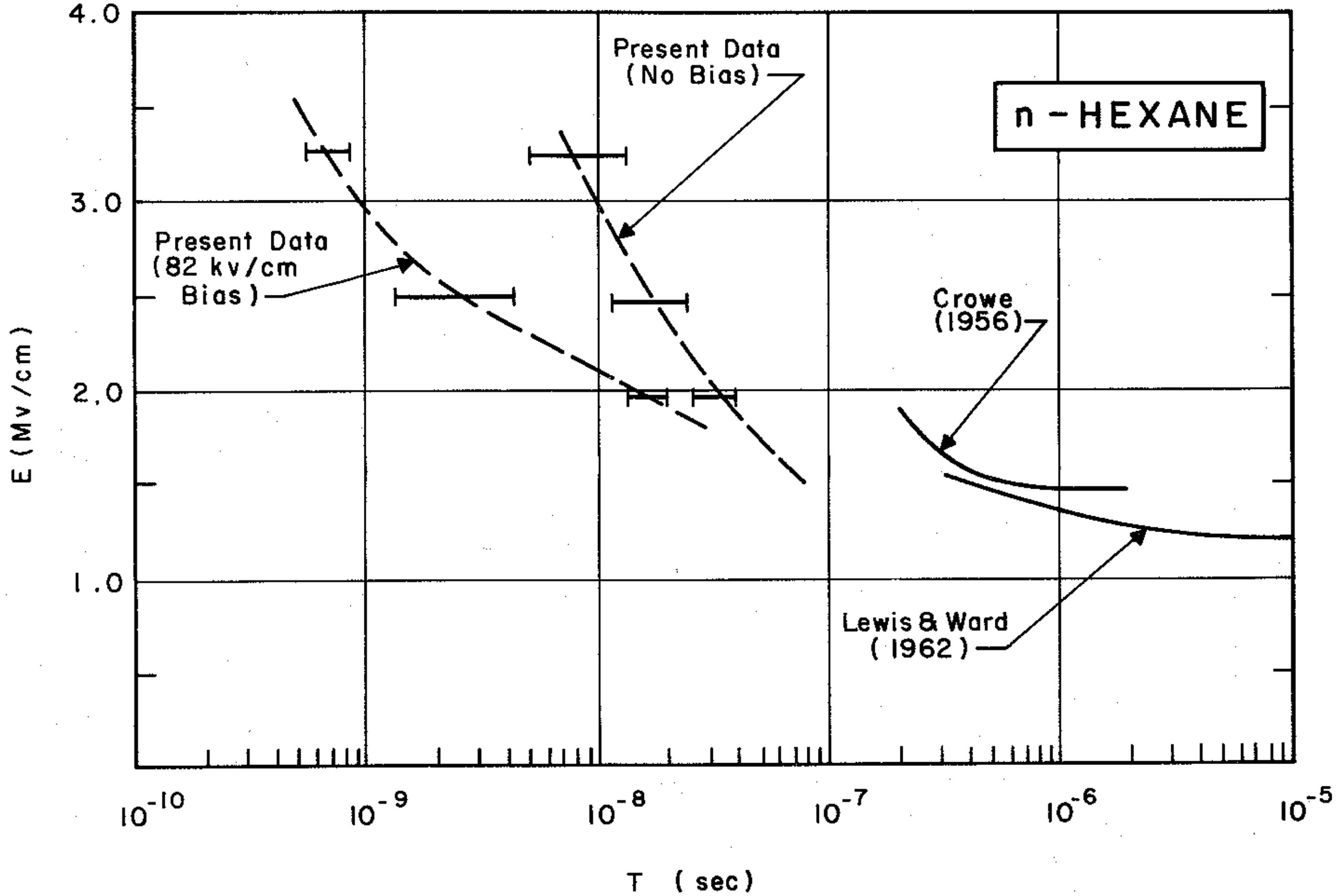


FIGURE 9.

BREAKDOWN LAG TIME IN n-HEXANE

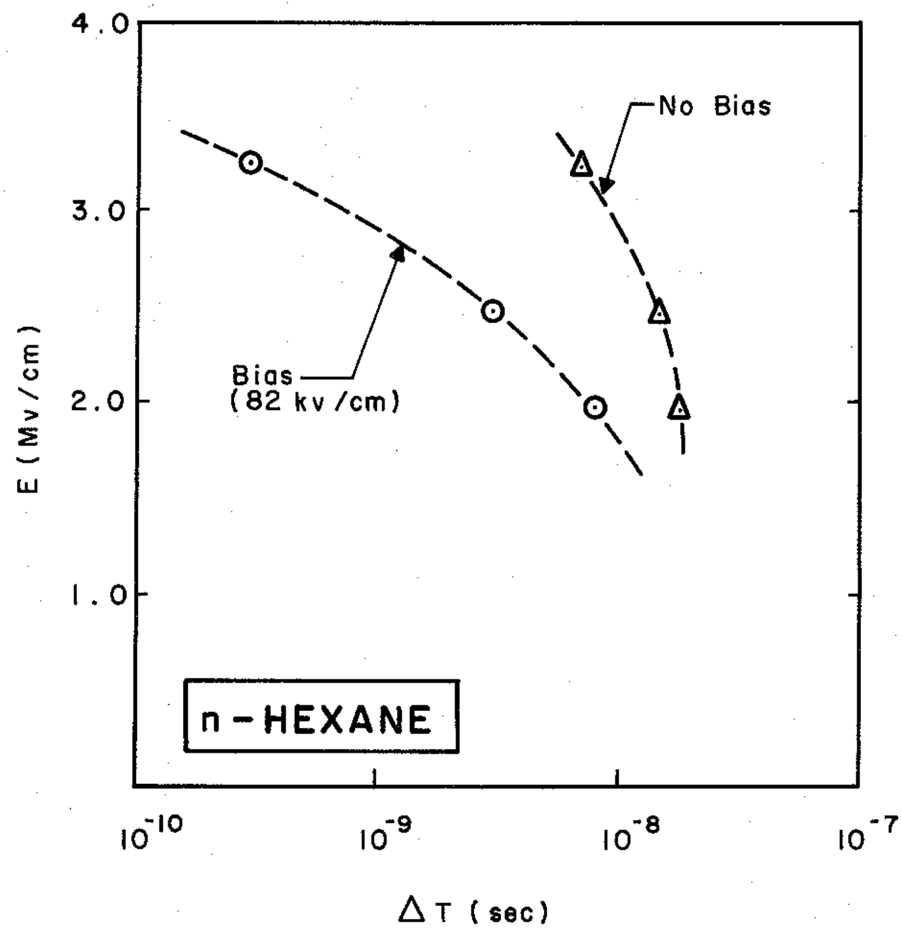


FIGURE 10.

VARIATION OF SPREAD IN BREAKDOWN LAG TIME switch applications. From the above results for n-Hexane it appears that the only drawback is the highly erratic nature of static hold-off conditons.

In order to further investigate the effects of the bias field, two diagnostic experiments were performed. The first of these experiments investigated changes of bias on the reduction of formative time. The second experiment was designed to shed light on the time dependence on the bias field reduction of breakdown lag times.

For the first experiment bias fields of +500; +100; -100 and -500 volts were applied to the normally grounded electrode (see Figure 1). No gross effects due to bias amplitude and slope were apparent (Figure 11). That is to say with one exception the slope and relative position of the bias to non bias results were the same for all four fields tested. The exception is that for the lower bias fields {+ 100 volts (+16.5 kv/cm) and -100 volts (-16.5 kv/cm)}. The bias and non bias results tend to join each other at the delay times in the 10^{-8} to 10^{-7} second range, while for the higher bias field the bias and no bias voltage versus delay time curves tend to be parallel.

One further result should be mentioned. At the highest fields applied (3.3 Mv/cm) the non bias data shows a tendency for an increased delay time compared to the delay obtained at the next lower field (2.9 Mv/cm). This should be looked at more closely to obtain assurance that the effect is real and not an artifact.

The second experiment was designed to determine the time it takes for the bias field to effect a reduction of the lag time. The special circuit used for this experiment is shown in Figure 12. The circuit makes possible the pulse charging of the termination side of the liquid test gap (see Figure 1) with a charging time of one microsecond. The nanosecond pulse apparatus is triggered through a variable delay of 10^{-7} to 10 seconds. However, the maximum possible time the bias

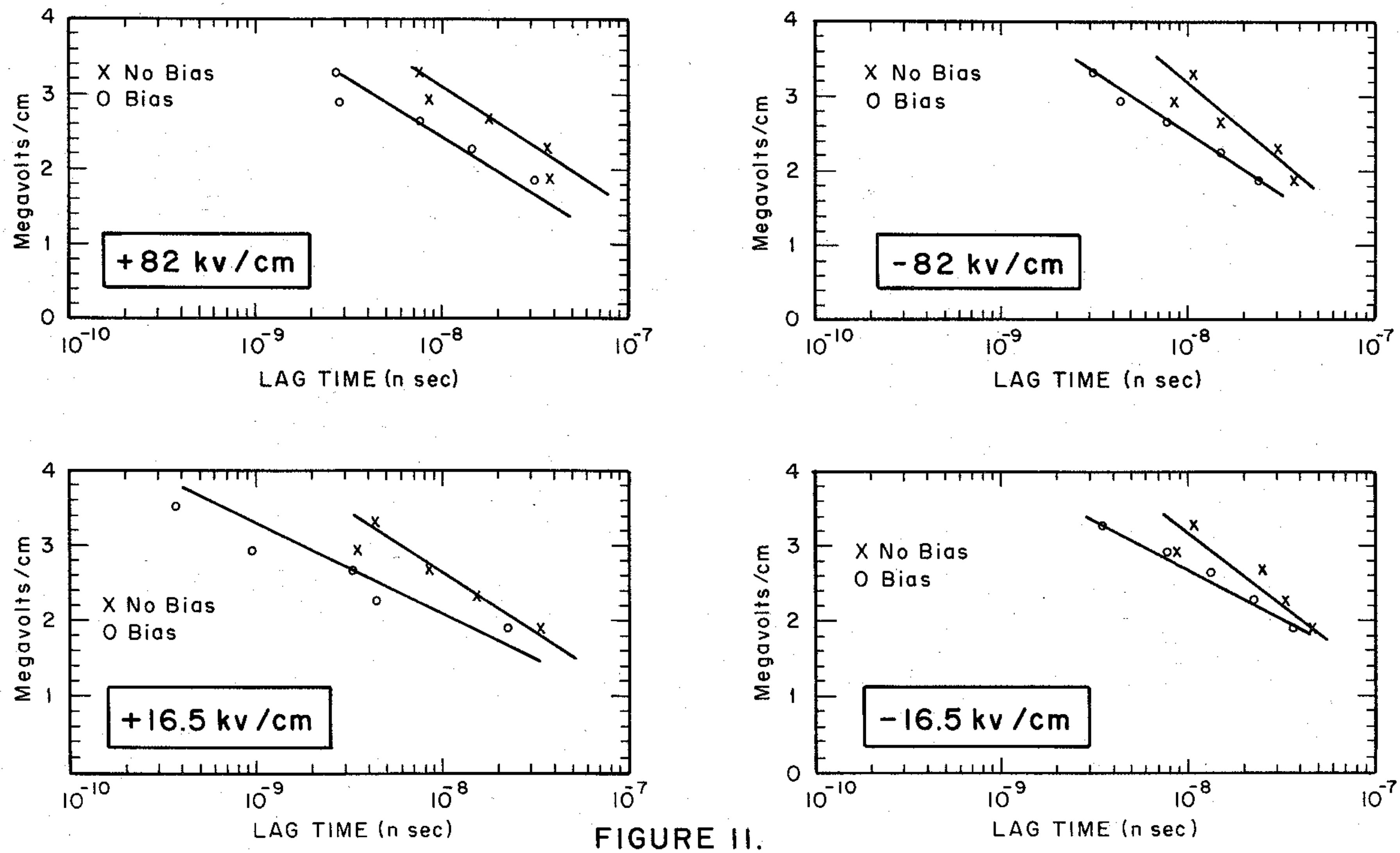


FIGURE II.
EFFECT OF BIAS POLARITY AND AMPLITUDE ON n-HEXANE LAG TIMES.

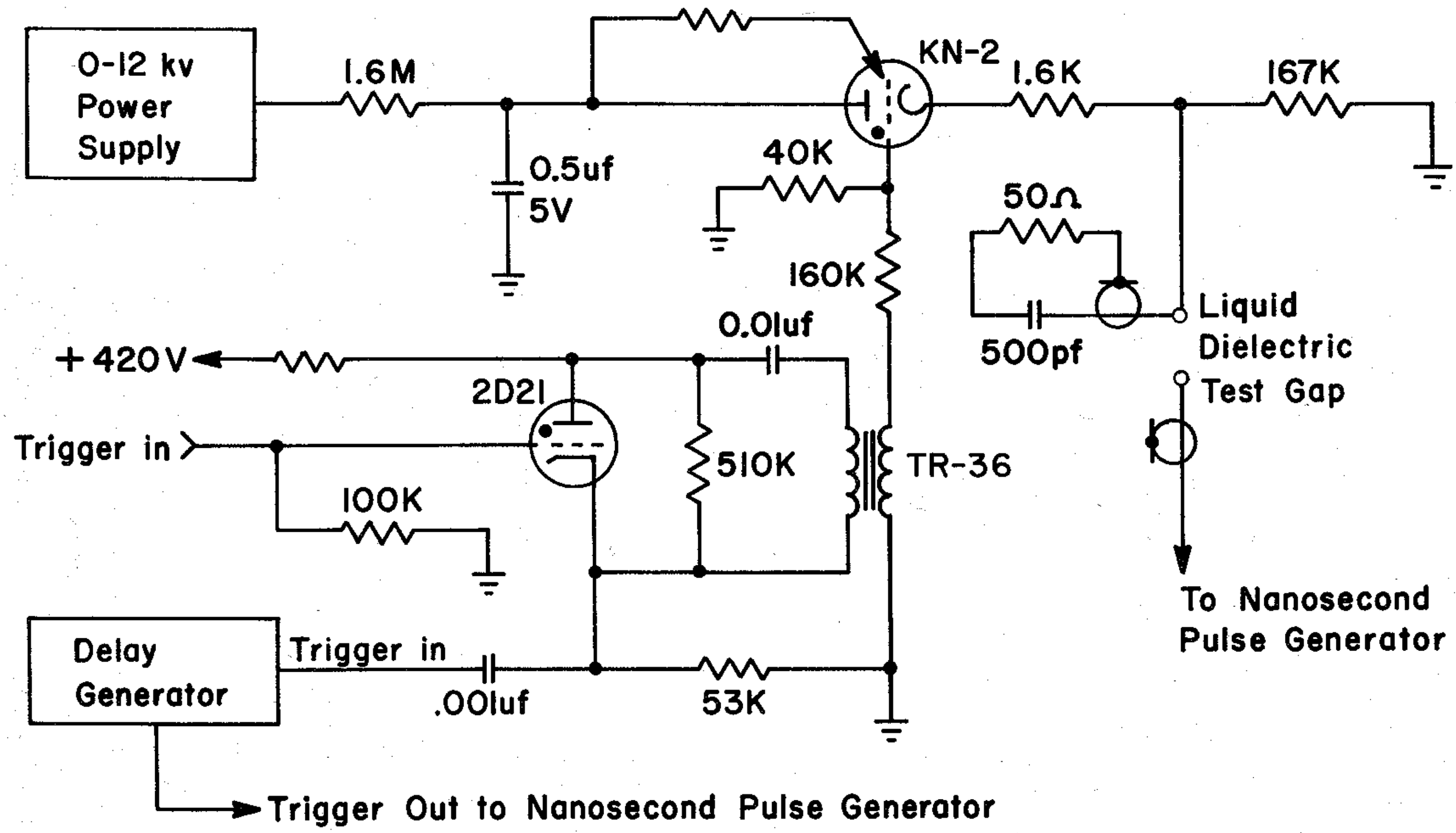


FIGURE 12.
CIRCUIT FOR PROVIDING DELAY BETWEEN APPLICATION OF BIAS VOLTAGE AND TRIGGERING OF HIGH VOLTAGE PULSE GENERATOR.

may be applied to the test gap by this circuit is 20 milliseconds due to the KN-2 (Krytron) turning off. Measurements of the bias time constant were made with the bias applied for 5 msec at an initial amplitude of 3 kv and final amplitude of 500 volts. No effect of this bias field could be seen on the measured lag times. A zero bias control experiment was run at the conclusion to show that electrode conditioning was not the determining effect. Table 2 shows the results of the experiment. Each value of delay represents a 36 point average.

TABLE 2

Results of Measuring Time Constant of Bias Effect in n-Hexane Breakdown

Time	Delay Time (nsec)
No Bias	33.0
+ 500 Volt Bias	10.0
Pulse Bias 5 milliseconds	
3 kv decaying to 500 V	43.8
No Bias	43.5
+ 500 Volt Bias	28.4

4.a.3. Results in Transformer Oil and Paraffin Oil

Due to its widespread use as a high voltage insulating medium, standard commercial transformer oil was investigated. Because mineral oil (paraffin oil) is the major ingredient of transformer oil the results of formative time measurements in the two liquids will be reported together. Esso Univolt 35 has a viscosity of 11 centistokes and a dielectric strength of 35 kv/0.1 inch. U.S.P. grade paraffin oil with a viscosity of 75 centistokes was used in the tests.

When the first few tests were made in paraffin oil it became apparent that the insulating quality of the oil was becoming degraded after a number of discharges. On examining the oil after it had undergone 100 discharges of 0.05 joule each, carbon particles in suspension were noted in the fluid. Hence, during subsequent tests, the fluid was changed after every nine breakdowns. The same was done for transformer oil. Results of breakdown measurements in the two oils are shown in Figures 13 and 14. In both figures the average deviation of the non-bias field are shown. In both oils the bias field drastically changed the formative times. An aging test in Univolt 35 showed the opposite sort of aging as that obtained in n-Hexane. As time increased the lag times decreased. Specifically lag time measurements showed a decrease from 25 to 5 nsec when the fluid was allowed to sit in the test gap over a 36 hour period. Lag time measurements were taken only at the beginning and end of the 36 hour period to obviate degradation of the fluid.

4.a.4. Results in Freon E-3

A new highly inert series of dielectric fluids is being introduced by DuPont. We have tested one of these fluids, Freon E-3. The material is a pure compound. It is a highly florinated polyether containing no chlorine or bromine. Its room temperature viscosity is 1.2 centistokes. Because of this low viscosity any bubbles formed at the electrodes will rise very quickly to the surface. The rated dc dielectric strength is 39.5 kv/0.1 inch. The boiling point is 306^{o}F and the dielectric constant at 1 gc is 2.76. The liquid is colorless and odorless and although complete tests have not been run, it is thought to be non-toxic. Figure 15 shows the results of lag time measurements at applied voltages of 18 to 24 kv. It may be seen that none of the breakdown measurements showed lag times less than 15 nsec. Further, there was no change in lag time with applied bias field of 500 volts. The fluid showed bubble formation at each breakdown. It was found that changing the liquid after every nine breakdowns or leaving it in the gap also didnot change the results. At voltages lower than 18 kv the liquid did not give any electrical breakdown.

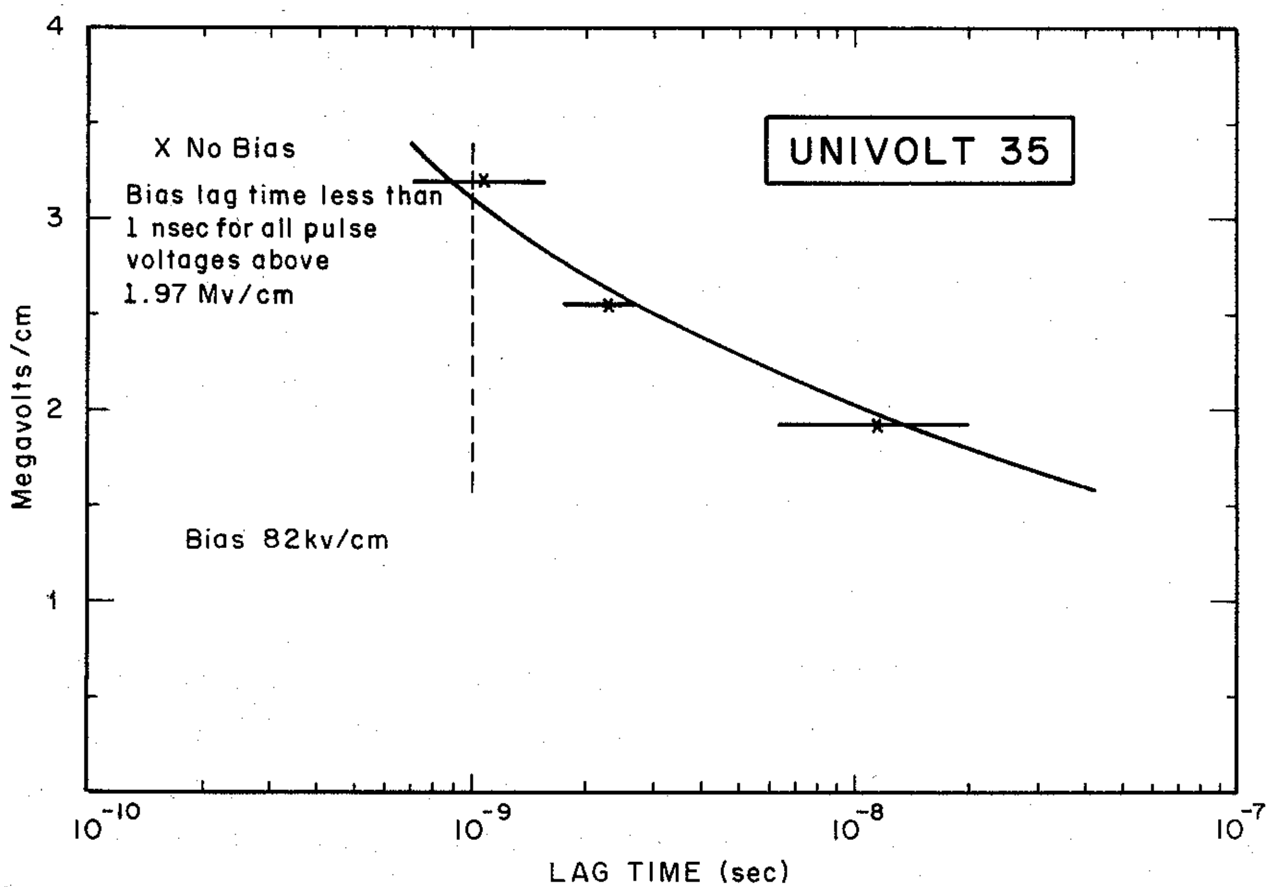


FIGURE 13.

BREAKDOWN LAG TIMES IN TRANSFORMER OIL
(ESSO UNIVOLT 35).

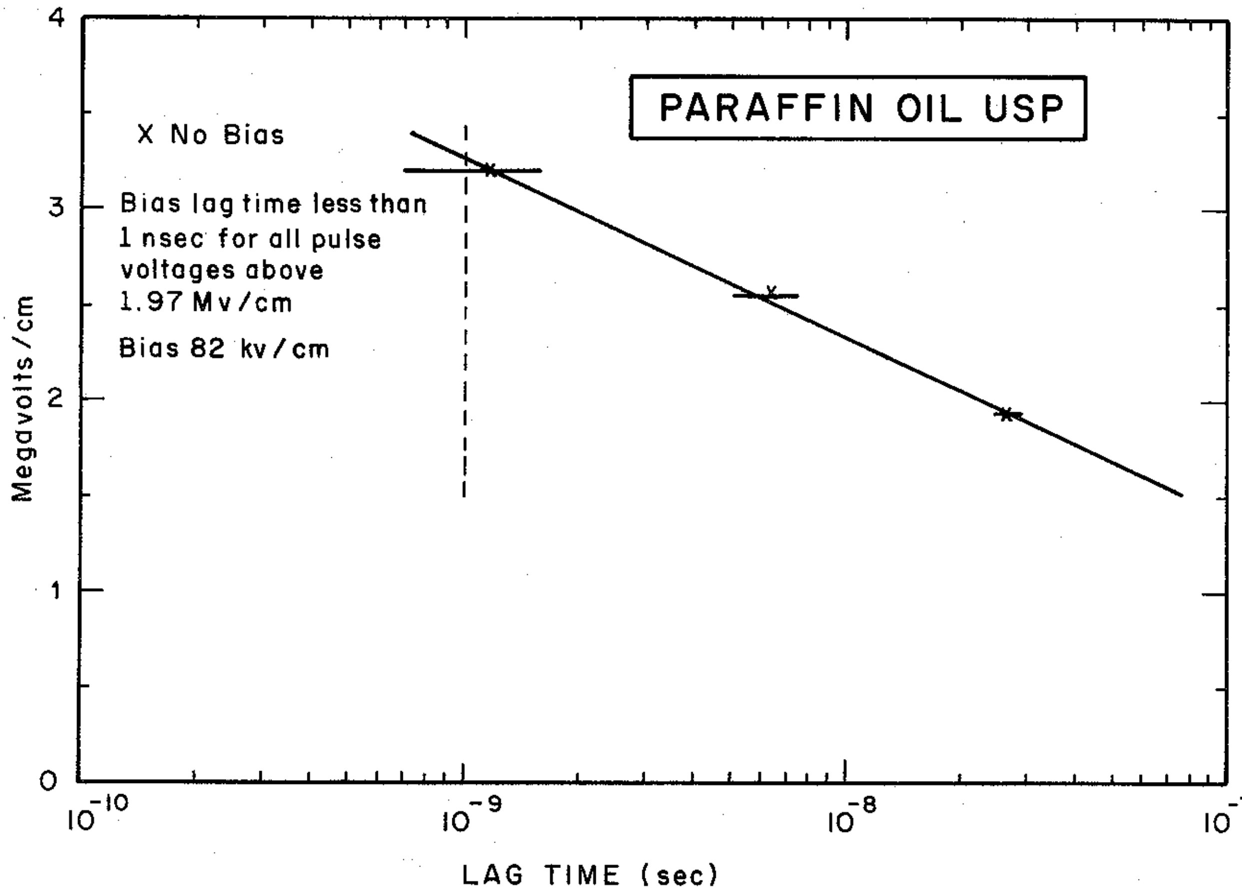


FIGURE 14.

BREAKDOWN LAG TIMES IN PARAFFIN OIL.

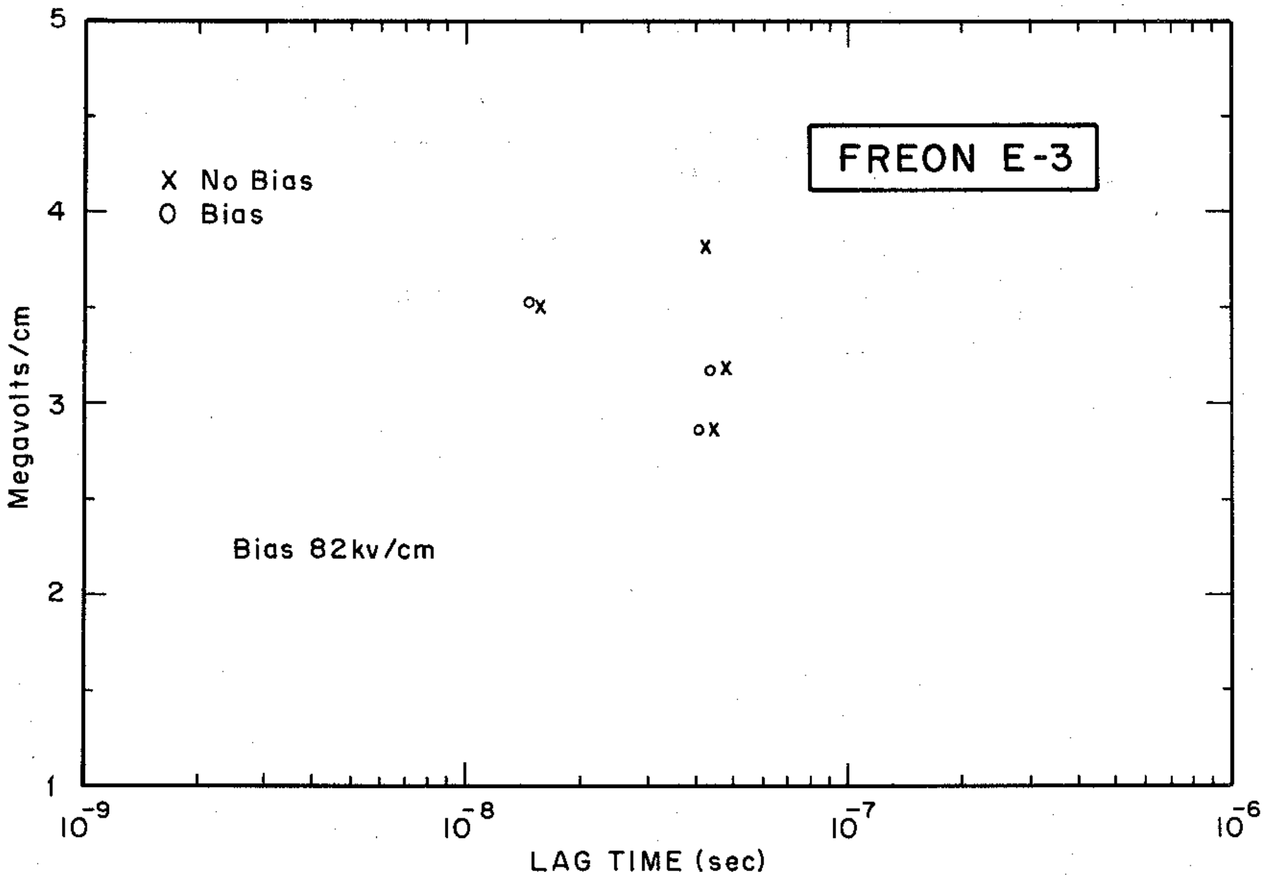


FIGURE 15.
BREAKDOWN LAG TIMES IN FREON E-3.

4.a.5. Results in Dowclene W R

Dowclene W R is purified 1,1,1 Tricloroethane of a purity and consistency suitable for use in "white rooms." It has a boiling range of 73.4 to 85.7°C, a dielectric constant at 100 kc of 6.9, a viscosity of 0.61 centistokes and dielectric strength of 31 kv/0.1 inch.

The results shown in Figure 16 indicate that there is a very strong bias effect. Further they indicate that the breakdown strength without bias is lower than that obtained for many other fluids. Tests were made to see if the breakdown delay was affected by changing the fluid in the test gap. Indications were that after 27 discharges the breakdown characteristics changed. The data were very uniform for a particular voltage and bias setting. As in other fluids, small bubbles appeared in the gap after a breakdown. These quickly surfaced because of the low fluid viscosity and hence did not affect test results which were taken at intervals of once every ten seconds.

4.a.6. Results in Silicone Fluids, D.C. 704 and D. C. 200

Two silicone fluids were chosen for testing. D. C. 704 is a highly stable fluid used commonly in diffusion pumps. It is highly purified and has a viscosity at room temperature of 39 centistokes. It was chosen as a test fluid because of its stability under conditions of high heat. Dow Corning 200 fluid is a very clear water-colored fluid, available in a variety of viscosities. Fluid with room temperature viscosity of 1.0 centistoke and boiling point of 211° F was used in the tests. This fluid has a rated dielectric strength of 32.5 kv/10.1 inch a dielectric constant of 2.29 at 1 mc and a volume resistivity of 1×10^{16} ohm-cm.

Results were first obtained in D. C. 704 fluid. Initial results were obtained using only a few seconds between test pulses. It was noticed, however, that the bubble formed between the electrodes did not rise in the time between pulses. The test was repeated with time

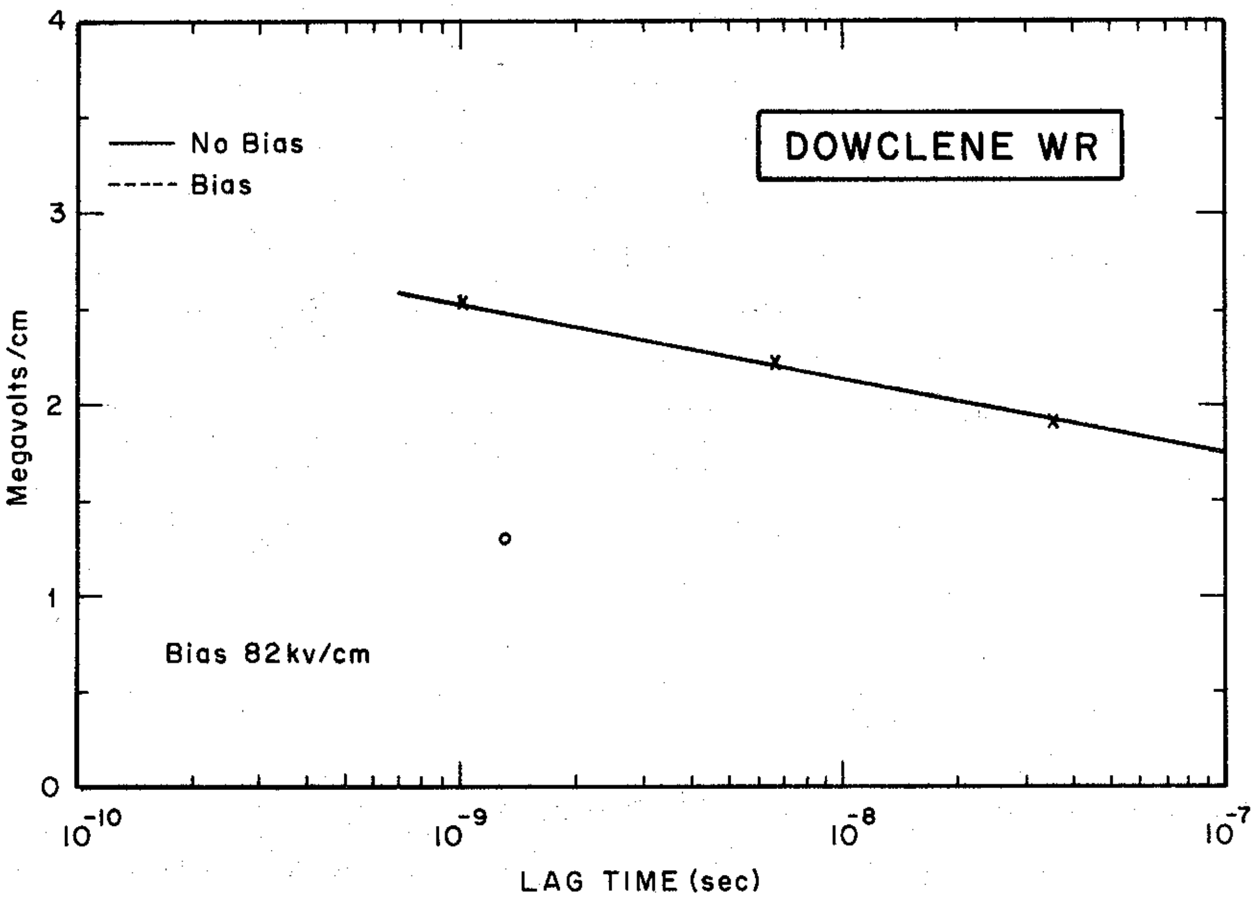


FIGURE 16.

BREAKDOWN LAG TIMES IN DOWCLENE WR.

allowed for the bubbles to float to the surface (~ 30 seconds between discharges). The results are illustrated in Figure 17. All delays were short, and the bias field had a very pronounced effect. Small particles were seen in the fluid as received from the manufacturer. Comparison of the fluid with a separate shipment of the same material received some months earlier showed the same particles, indicating that this source was indeed the manufacturer. It is thought that these particles may account for the inconsistencies in the non-bias results.

Results obtained in Dow Corning 200 fluid are shown in Figure 18. Because of its low viscosity the bubbles always surfaced between the test pulses and no delay was necessary in data taking. As may be seen, the results are not entirely consistent. However, the steep change in formative time for the small percentage change in applied voltage was repeatable.

4.a Results in Distilled Water

Triple-distilled demineralized water was used for testing. Its rated resistivity at the time of shipment is 18-20 x 10^6 ohm-cm. The results of the water tests are shown in Figure 19. The average deviation of the results is also shown. It will be noted that the bias field has some effect but certainly it does not drastically change the results. Given sufficient overvoltage, it is possible to obtain nanosecond formative times in water.

4.b Investigation of Electrode and Dielectric Effects

Some preliminary observations of electrode damage and conditioning were carried out using the test gap-capacitor arrangement shown in Fig. 20. The coaxial gap is mounted directly to a circular disc capacitor rated at 10 kv and 0.10 microfarad. The test gap itself consists of an adjustable stainless steel ball electrode of 0.125 diameter and a flat fixed electrode 0.5 by 0.5 inch on a side of the same material. Adjustment can be made to an accuracy of better than 0.005 inch and both electrodes are easily replaceable. The discharge of the capacitor in initiated by self-breakdown

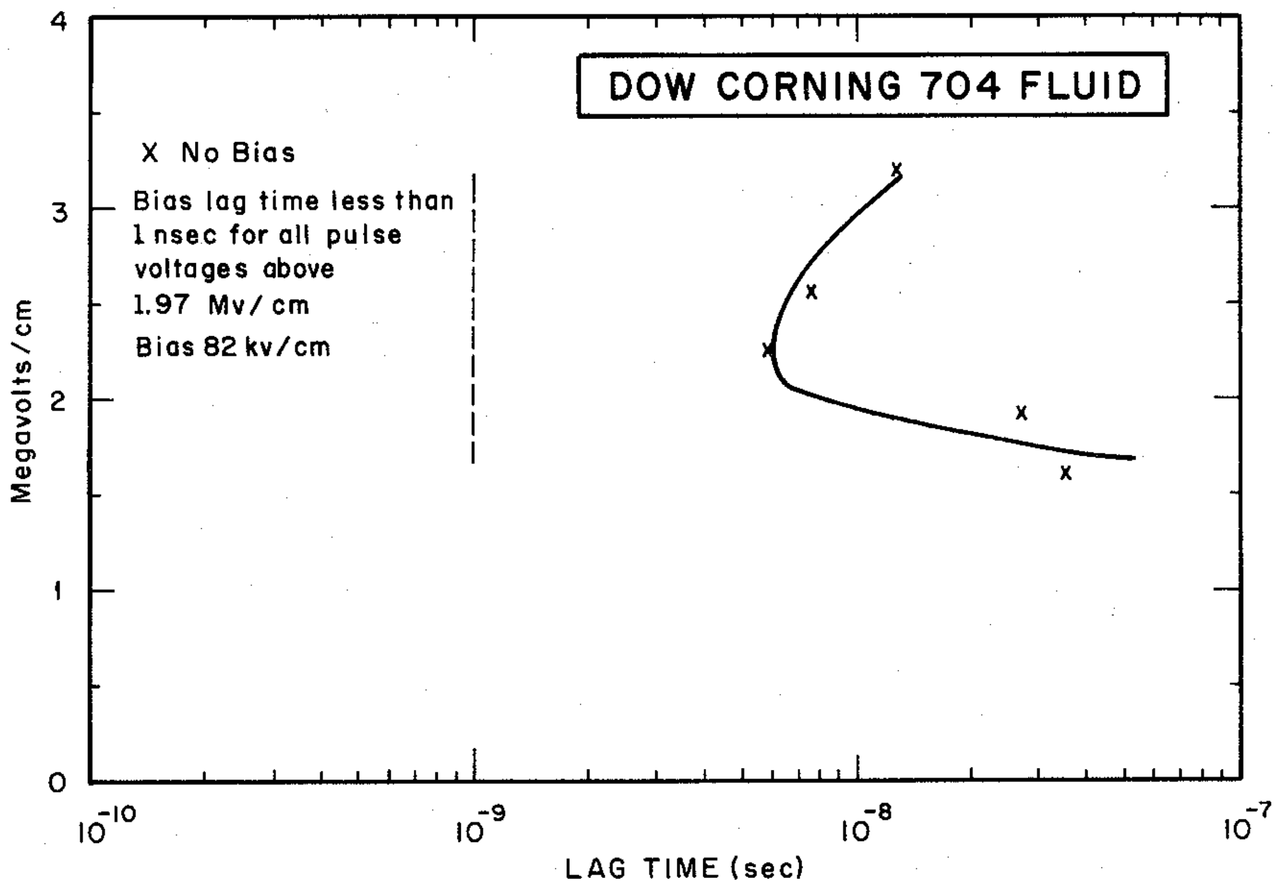


FIGURE 17.

BREAKDOWN LAG TIMES IN DOW CORNING 704 FLUID.

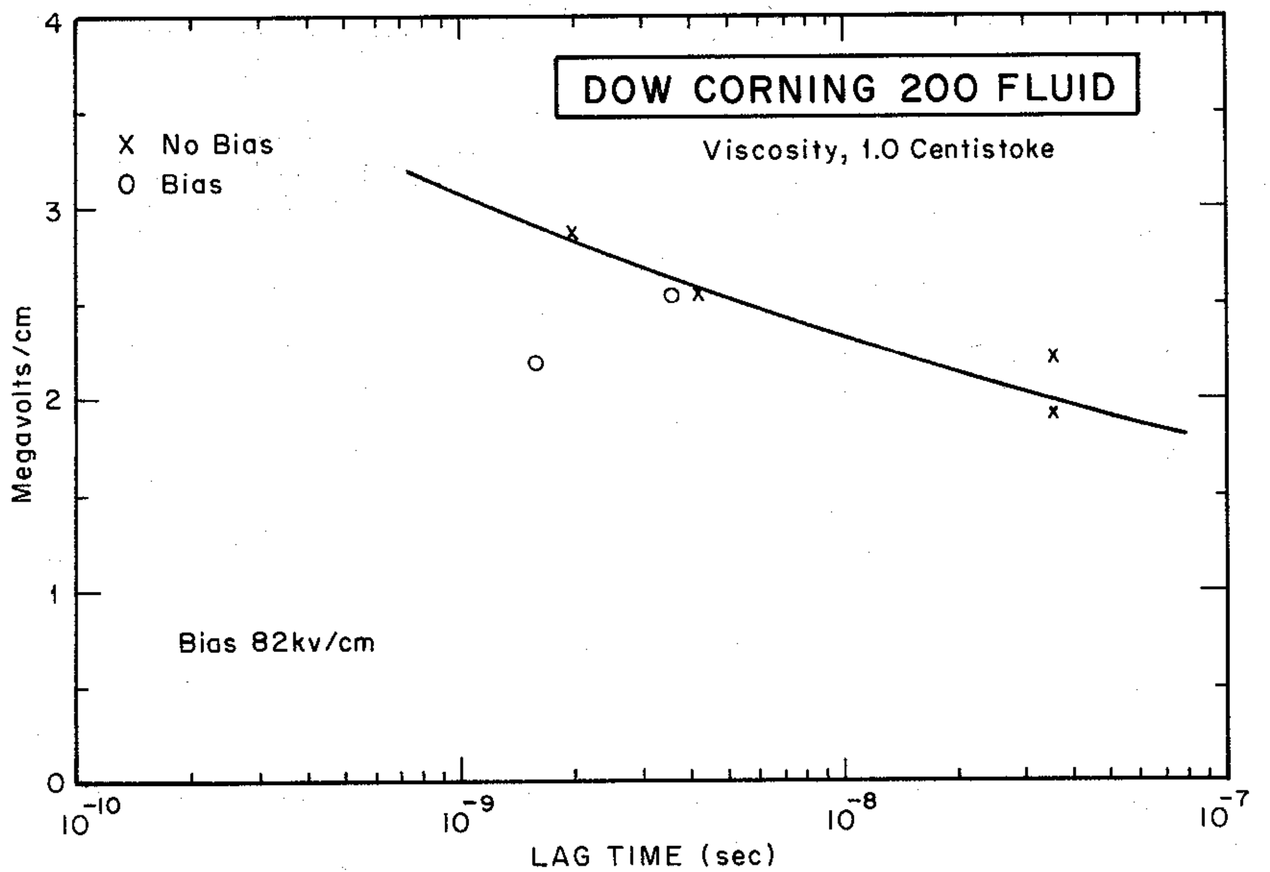


FIGURE 18.

BREAKDOWN LAG TIMES IN DOW CORNING 200 FLUID.

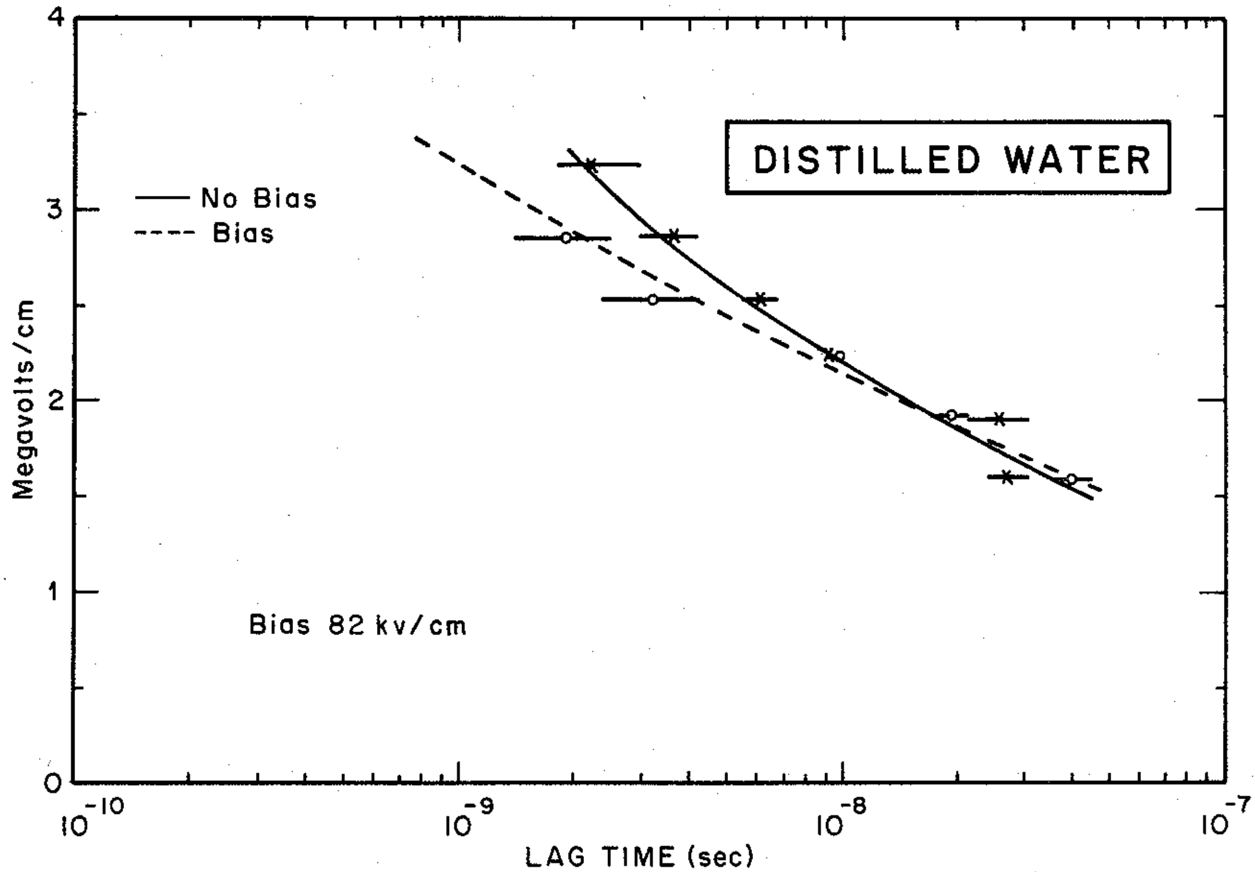


FIGURE 19.

BREAKDOWN LAG TIMES IN DISTILLED WATER.

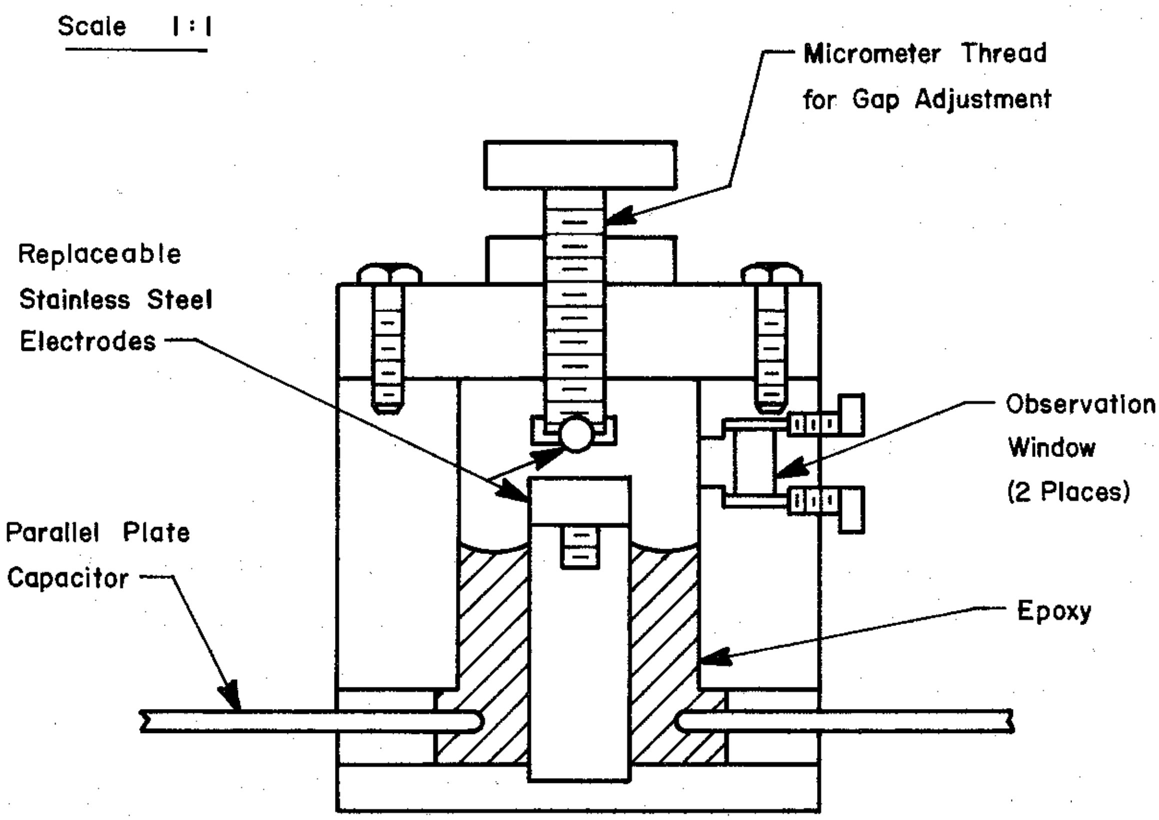


FIGURE 20.
TEST GAP FOR ELECTRODE AND DIELECTRIC EFFECTS EVALUATION.

of the gap. The ringing frequency is approximately 3.0 megacycles. The total charge passed through the gap is as large as 10^{-3} coulombs. Some qualitative results have been obtained in a number of liquids, namely: n-Hexane, D.C. 704, D C. 200, Dowclene W_R, and Freon E-3.

In n-Hexane, with a gap setting of 0.0035 inch self-breakdown potentials ranged from 500 to 5000 volts, with a tendency to stabilize toward the higher values after a number of discharges ($\sim$ 50). Visual inspection of the gap following this test series revealed that the wear region on both electrodes was over a diameter of about 0.040 inch and was made up of smaller pits whose depths were approximately 0.001 inch. A second test in which the flat electrode was sand-blasted prior to test led to more stable breakdown conditions but damage effects were similar to the first test series. Following each test a substantial quantity of black particles (presumed to be carbon) was observed in suspension in liquid.

Dow Corning 704 silicon fluid was tested at 0.010 inch gap spacing with 100 discharges at about 1 kv. At the conclusion of the test, not only was the fluid very dark with many carbon particles; but it was also very active, discharging gases even after removal from the test gap. Dow Corning 200 silicon fluid was tested at 4 kv and 0.010 inch gap spacing. At the conclusion of 100 discharges, the fluid showed carbon much the same as the Dow Corning 704 except that the carbon was more evenly mixed than in the more viscous D.C. 704 fluid. Dowclene W R was tested in a 0.005 gap for 100 discharges at 5 kv. Very fine carbon particles were seen evenly distributed in the gap at the conclusion of the test. Freon E-3 was also tested for 100 discharges. After the test no change in the fluid could be seen. This was the only organic fluid tested which did not show carbon particle deposits after operation in the test gap.

4.c. Interpretation of Breakdown Lag Measurements in Liquids

Table 3 is an aid to understanding the general features of our experimental results. It provides a basis for comparing some of the features of nanosecond liquid dielectric breakdown that we have described in greater detail in the preceding sections.

As has been stated, "Breakdown in liquids could readily become a compendium of unrelated observations" (Reference g.9.). There is no clear understanding of the phenomena of liquid dielectric breakdown. Reading of the references listed in the bibliography will only reinforce this conclusion. Therefore, only the most brief and tentative of interpretations will be made of the data given above.

First, and perhaps of primary interest for this program, is that formative times in the nanosecond time scale may be obtained between electrodes immersed in liquid dielectrics. It is, of course, not clear whether these lag times are characteristic of purely liquid behaviour or whether absorbed gases may play a role in the breakdown process.

Secondly, certain liquids showed a reduction of lag time with the application of a bias voltage. Detailed experiments in n-Hexane showed little effect for changed bias potential or amplitude. They did, however, show that in n-Hexane, the effect takes longer than 5 milliseconds to occur. Some liquids showed little or no bias effect, notably water and Freon E-3. It may be that the bias effect is due to the presence of small dielectric particles in the test fluids. These particles would be "pumped" under the influence of the nonuniform electric field, into the volume between the electrodes. There, they might well form some sort of a link which would aid in reducing formative time. Whether the particles are colloidal in nature or foreign contaminants is, of course, not presently known. Actually determining the bias effect time constant or the effect of fluid temperature would give a suggestion as to the particle size. For quantitative treatment of this effect in liquified gases see Reference g.9.

In all fluids studied, breakdown was accompanied by the presence of a small bubble which is thought to form between the electrodes. Nothing is known of the gas composition of this bubble nor of its time history. Complete knowledge of the source and formation of the bubble may well hold an important clue to the understanding of liquid dielectric breakdown.

Finally, many of the liquids showed irreversible aging effects due to the formation of carbon particles or other contaminants. If these contaminants are allowed to remain in the discharge system, they drastically change the breakdown characteristics. Hence any practical liquid switching system will probably have to include apparatus to purify the liquid and prevent either self-contamination or the intrusion of contaminants of foreign origin in the liquid.

TABLE 3

Summary of Some Liquid Dielectric Breakdown Characteristics

Liquid	Over voltage ratio at applied pulse voltage of 3 MV/cm[1]	Show aging (or decomposition) with nanosecond pulses	Shows effect of bias	Range of Applied Voltage MV/cm	Range of measured delays ns
n-Hexane	3.6	yes	yes	1.96 to 3.28	1 to 48
Transformer Oil	24.6	(yes)	yes	1.96 to 3.28	1 to 48
Paraffin Oil		(yes)	yes	1.96 to 3.28	1 to 48
Freon E-3	19.4	no	no	2.76 to 3.9	15 to 48
Dowclene W-R	24.6	yes	yes	1.96 to 2.5	1 to 48
Dow Corning 704		no	yes	1.96 to 3.28	6 to 48
Dow Corning 200	23.5	no	slight	1.96 to 3.28	1 to 48
Distilled Water		no	slight	1.96 to 3.28	1 to 48

(1) These ratios (except for n-Hexane) have been computed on the basis of the manufacturer's rated breakdown voltage. N-Hexane ratio is computed on the basis of our measured dc value of 8.2×10^5 v/cm.

5. DIELECTRIC FILM BREAKDOWN MEASUREMENTS

There exists extensive literature on the breakdown of solid dielectrics because of their wide use in industrial and military applications. Much of this literature is not of relevance to the problem of high voltage switching because little stress has been put on pulse breakdown, much less nanosecond pulse breakdown. In spite of this, the last few years has seen the development of fast, low inductance switches using solid dielectric films (see Section 8.c). Much unpublished knowledge of these switches has been accumulated, principally in government laboratories in England. However most of this knowledge has been concerned with polyethelyene as the switching medium.

In order to investigate the suitability of other materials our own program has obtained nanosecond pulse breakdown measurements in a variety of dielectric films. In addition, observations of dielectric damage have been made on all the films tested.

Breakdown measurements of dielectric films have been made on Mylar, Teflon, Tedlar, polyethylene, and cellophane. The experimental apparatus used for these measurements was the same as that used on the liquid dielectric lag time measurement. (Section 4.a.1.) Thin films of the dielectrics to be tested were held in a special clip and placed between the 0.125 inch diameter stainless steel sphere electrodes. The electrode spacing was 0.0025 inch for all tests. Difficulty was initially encountered with surface breakdown on the dielectric occurring at low voltages (less than 10kv). However, filling the test gap with distilled water was very effective in changing the breakdown behaviour so that true pulse breakdown measurements could be made. Hence all measurements of dielectric film breakdown were made with the test gap filled with distilled water.

Measurement procedure consisted in applying gradually increasing pulse voltages of 48 nsec duration to a fixed thickness of dielectric film. The current viewing resistor allowed photographing the incident and reflected waves appearing across the dielectric film. At the conclusion of a photograph (with, for example: traces at 12,14,16,18, and 20 kv) the sample was removed, the picture developed, and another test begun. The picture could then be read and the breakdown voltage and lag time determined.

The .0025 inch test gap was partially filled with water (dielectric constant 80) and partially filled with the dielectric film (dielectric constant 2-4). Further the bulk resistivity of the water is probably much lower than that of the film. When a fast rise pulse is applied to the gap it is not at all apparent how the voltage will divide because not only should one consider the linear circuit effects of capacity and resistance but non linear effects such as breakdown and current growth must also be considered. We have therefore presumed on the basis of our results (Fig.21) which show the expected linear relationship between pulse voltage and thickness, that the full pulse voltage appears across the film.

Because a greater range of thicknesses was available in Mylar than other films, we have the most complete data on Mylar. A type Mylar film was used in all tests. Assuming the entire pulse voltage appears across the film, Figure 21 shows the film thickness versus breakdown voltage and film thickness versus dielectric strength in volts/mil (1 mil=0.001 inch). Each data point represents 5 breakdown tests. These results should be compared with the following figure (Figure 22) which shows: (1) manufacturers data for dielectric strength versus thickness (E.I. du Pont de Nemours, and Company, Mylar bulletin M-4A) and (2) pulse length versus breakdown voltage for 0.001 inch thick Mylar as reported in ref. f.7. It may be observed that the dependence of the thickness versus breakdown voltage is the same. However, the absolute values of the breakdown voltage are somewhat higher for nanosecond pulses than microsecond pulses. It is

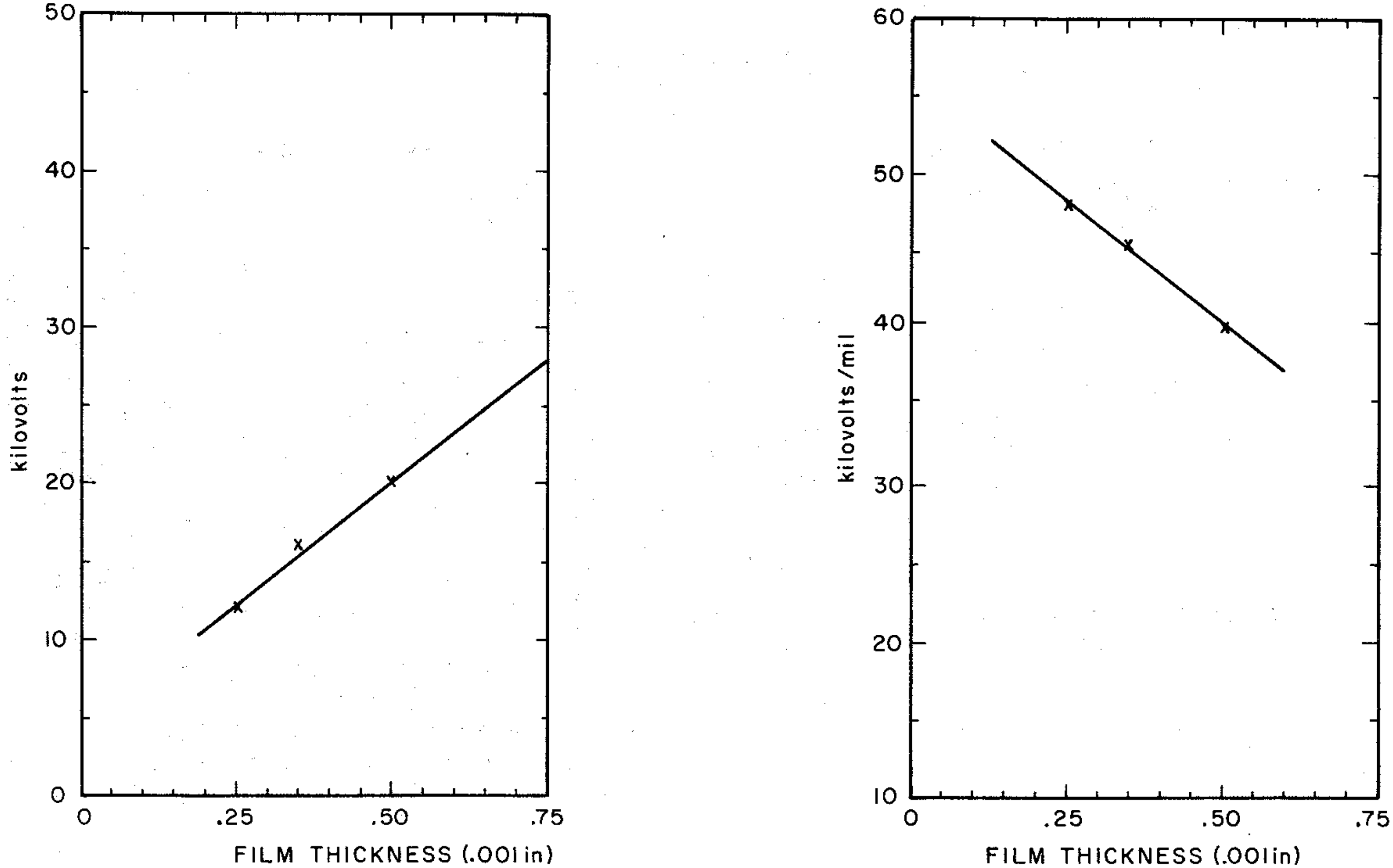


FIGURE 21.
48 NANOSECOND PULSE MYLAR BREAKDOWN.

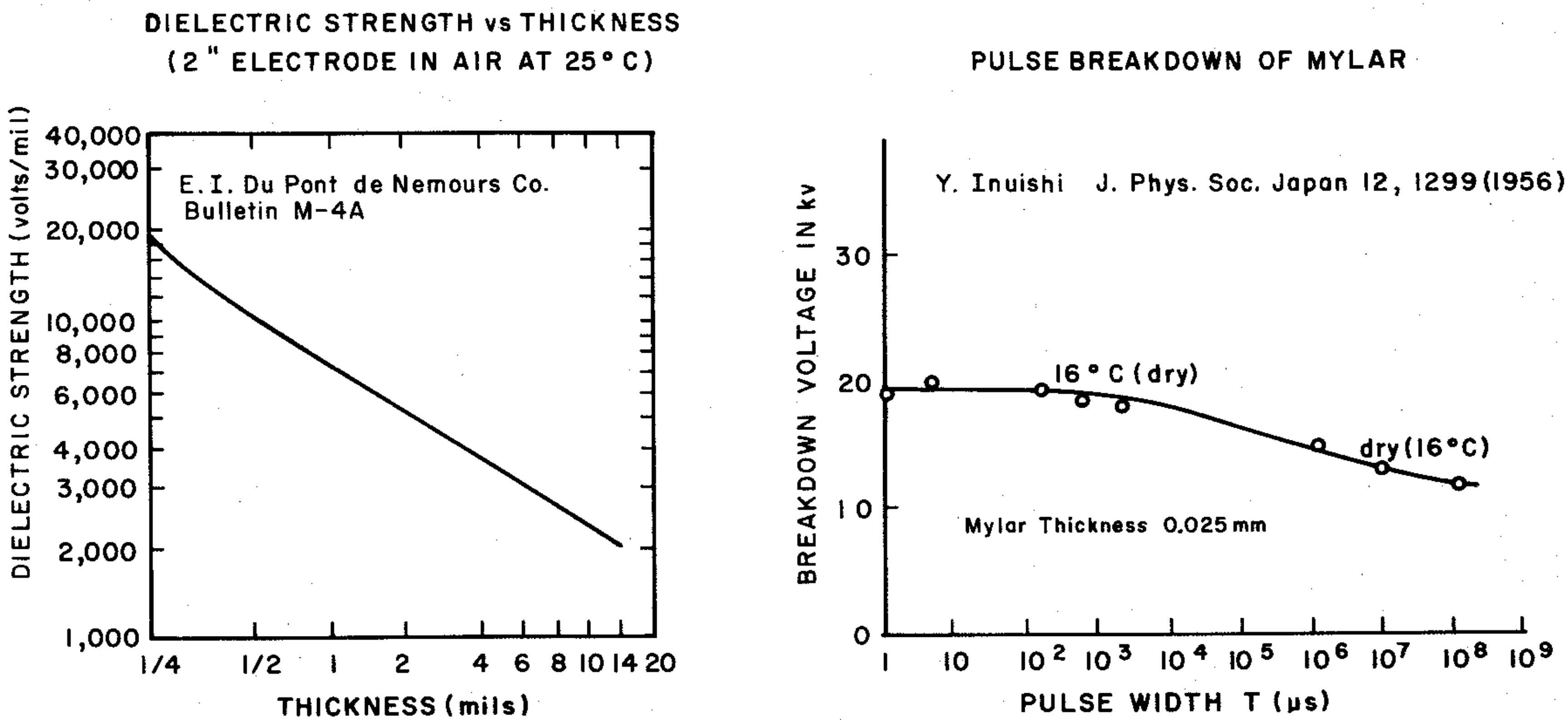


FIGURE 22.

PUBLISHED MYLAR BREAKDOWN DATA.

difficult to know whether this is an intrinsic difference or is due to differences in experimental technique. Breakdown of the film was accompanied by rupture of the film itself. The diameter of the rupture gradually decreased as the film thickness increased, going from 0.025 inch diameter for a 0.00025 inch thick film to 0.012 inch diameter for a 0.0005 inch thick film.

Although Teflon films of 0.0005, 0.001 and 0.002 inch were available, it was only possible to breakdown the thinnest film with the pulse voltages available. The 0.0005 inch film broke down at 16 kv as measured in 5 separate breakdown tests. The breakdown that caused rupture in the film had an average diameter of 0.010 inch. The manufacturer's information on breakdown strength taken with 0.25 inch electrodes at dc gives the same dielectric strength. Thus, for the one thickness for which nanosecond pulse data are available, no difference is seen between dc and pulse dielectric strength.

Tedlar film of 0.0005 and 0.001 inch was available for testing. This film is a new polyvinylflouride manufactured by E. I. du Pont de Nemours and Company. Its rated dielectric strength at 0.0005 inch thickness is 9 kv. However, we were unable to obtain breakdown using 48 nsec pulses of up to 26 kv in amplitude

Polyethylene of 0.0005 and 0.001 inch was tested. The 0.0005 inch material showed a dielectric strength of 20 kv/mil, the 0.001 inch material of 14 kv/mil. Ten data runs were used for each point because of sample thickness non-uniformity. No manufacturers data on thin film polyethylene breakdown are available to us. The diameter of the hole punched in the polyethylene varied from 0.005 to 0.015 inch.

Cellophane of 0.001 inch thickness was also tested. Its breakdown strength was 10 kv for the 48 nsec pulse. This was the lowest breakdown strength of any of the solid dielectrics tested.

At the breakdown voltage, all the solid dielectrics showed some breakdown delay. This ranged from 18 to about 23 nanoseconds with a jitter of a few nanoseconds. The delay is not a result of breakdown delays in the distilled water used in the gap, because the same delays were obtained with pulse voltages of 13 to 18 kilovolts using different dielectrics. The rise time at breakdown looks to be shorter than 1 nsec on a 10 nsec/cm trace for all the films tested.

A sample of 0.001 inch polyethylene was evaluated in the system described in Section 4.b. The gap was adjusted to hold the dielectric firmly in place without undue compression of the sample. Ten breakdowns were conducted through renewed sample material. Breakdown potential was 3.5 kv $\pm$ 10% in this series. The dielectric punctures were in the form of well defined holes of about 0.030 inch diameter. The electrode damage was not so well defined and indicated a melt region with little of the pitting observed for liquids.

It may be concluded that breakdown in times less than 48 nsec is possible with a number of different dielectric films. Pulsed dielectric film data reported in the literature or by the manufacturer has been extended to a new time regime. The question of suitability for switch devices depends not only on obtaining nanosecond rise times but on jitter, ability to trigger, availability of different thicknesses, etc. Our investigations have been confined to observations of nanosecond pulse hold off capability rise time observations and film damage.

6. STRIP LINE FACILITY AND STRIP LINE SWITCH

6.a. Introduction

The present program has been divided into two major portions, the development of a nanosecond switching techniques and the development of a high pressure air dielectric switch. This section deals with the latter switch development and application.

The severe requirements placed on the switch include low inductance, low energy loss, high voltage operation, low jitter, short rise time, long life, low prefire probability, adaptability to low inductance bus work, etc. In order to meet these requirements, a thorough quantitative analysis of strip line switching was made. This analysis was applied to the design of high pressure switches on strip lines and in particular to a single high pressure strip line switch. The strip line switch was built and tested on a strip line facility designed for this program. The switch design, strip line facility description and switch performance are given in detail below.

6.a.1. General Requirements

The design goals of this program are based on the switching requirements for a stacked Blumlein system made up of strip line elements. The nominal charging voltage is taken to be 100 kv. The characteristic impedance of individual line elements will be about 0.16 ohm. Discharge pulse lengths are to be about 30 nsec with a voltage rise time less than 5nsec.

A Blumlein circuit with 120 stages and 60 switched lines is planned. Since as many as ten switch elements may be required per line short, a total of several hundred switch elements will eventually be required. It is clear that minimum jitter is of the utmost importance, not only in the switch elements, but also in the initiating mechanisms and synchronization circuitry. Because of the large number of switch elements, problems of long operating life and ease of adjustment, replacement and maintenance are also of prime importance.

For the purpose of developing the initial physical design all but the most fundamental system considerations may be set aside. The central problem at the outset is to develop a shorting switch technique that has appropriate electrical properties for shorting a large, single strip line. The design presented here is addressed to providing this technique for a strip line with the approximate characteristics listed in the following table.

TABLE 4

Typical Elemental Strip Line Characteristics

Characteristic Impedance, z_o	0.16 ohm
Electrical Length (single transit), τ	15 nanoseconds
Dielectric Material	Polyethylene or similar material
Wave Velocity, v	2.0×10^{10} cm/sec
Dielectric Thickness, a	0.1 cm
Width, b	150 cm
Physical Length, ℓ	300 cm
Total Capacitance, C	9.2×10^{-8} farad
Charging Potential, V	100 kv
Total Charge, CV	9.2×10^{-3} coulombs
Peak Current	3.0×10^{5} amperes
Stored Energy, $1/2\ CV^2$	460 joules

If a line of this type is suddenly shorted at a single point, the traveling wave generated will possess a circular wave front. For long lines ($\ell >> b$) the effect is not serious. In the present case, however, where $\ell \gtrsim b$, it will be necessary to produce the short at several points across the width of the line. An effectively plane wave front will then be generated if

$$n \cdot \ell >> b$$

where n is the number of switch elements composing the short.

The rise time of the signal which arrives at the far end of the line will be governed by several factors including the high frequency losses of the dielectric, the jitter in the switch elements composing the short and the inherent rise time of the composite switch. If L is the self-inductance of each switch element, then the inherent (minimum) rise time of the switch (10 to 90%) is given approximately by

$$\tau_r \approx 2.0 \; L/nz_o$$

If the jitter of individual switch elements is comparable to the inherent rise time, the effective number of elements in the short is reduced and the actual rise time will be increased. The practical requirement to insure that the proper electric field conditions exist at the time each element is triggered is that the jitter be smaller than the transit time between elements. For the gas switch design presented here, the wave velocity between elements is the velocity of light. Therefore, the jitter requirement is that

$$\tau_j < b/nc$$

Taking the values of b, ℓ and z_o given in Table 3, the choice of n can be based on the following relations:

$$n >> 0.5$$

$$n \approx 12\ L/\tau_r$$

$$n < (5 \times 10^{-9})/\tau_j$$

Based on preliminary design of the high pressure gas switch, a switching jitter of less than 1.0 nsec and a self-inductance per element of less than 2 nhenry may be achieved. Since a pulse rise time of less than 5 nsec is desired, a value of n=r or greater is sufficient to satisfy the above relations. Smaller values of n will increase the distortion of the traveling wave front and will lengthen the rise time. Larger values require comparable reductions in switch element jitter below one nanosecond and increases in the quantity and complexity of the control circuitry.

Any variation in the uniformity of the transmission line will lead to variation of the characteristic line impedance. Near a switch element the effective impedance is altered due to the convergent current paths at the initiation points. In the gas switch, there is additionally an abrupt change in the line dielectric. In the strict sense it is virtually impossible to provide perfect impedance matching at the short. Fortunately, it is not necessary to match impedances exactly provided that the effective electrical length of the line occupied by the switch is very short compared to the rise time. Wave reflections and pulse distortion can be reduced by minimizing the impedance change and the electrical length of the switch.

6.a.2. Basic Gas Switch Design Considerations

The general electrical requirements for a fast, strip line shorting switch have been discussed in the previous section. The following considerations apply specifically to the design of a high pressure gas switch for this purpose.

Air and nitrogen are the two gases most commonly employed in gas switches, although air has been found, in most cases, to have superior properties. In addition to problems resulting from the formation of nitrides (e.g. Ref. a.9.), nitrogen has also been found inferior to air and oxygen in regard to inconsistencies in high voltage hold-off (Ref. a.22.). In our own experience (Refs.a.2 and e.4.) we have found that insulating gases such as SF_6 give rise to considerable fluctuation in the breakdown lag time and tend to degrade the electrode surfaces by chemical interaction. Since air is superior in these regards, since it is the most thoroughly investigated gas in gas breakdown technology and since it is readily available; compressed, dry air (dew point less than $50^{o}F$) is the design choice.

The choice of gas pressure is predicated on a variety of considerations including the spatial requirements for low inductance design and the lag time for the triggering method to be employed. The conclusion based on the consideration given below is that a pressure of approximately 600 psig (40 atm) will be necessary. Data on high pressure breakdown in air (Ref. 2) indicate that breakdown fields will approach 10^6 volts/cm. This is then comparable to the minimum fields that can be supported by solid dielectrics such as polyethylene.

The switch design considered here is, schematically, a three ball, potential divided gap. With the upper electrode at the charge voltage, V_1 (= 100 kv) and the lower electrode at ground potential, the center electrode is initially at some intermediate potential V_2. Breakdown is initiated when the center electrode potential is reversed thereby overvolting the upper gap space. As the center electrode potential then approaches V_1, the lower gap space is also overvolted, completing the breakdown path.

Following the analysis of Adlam (Ref.a.22.) it can be shown that the overvoltage ratios are equal when $V_1/V_2 = 2.4$. Under conditions such that there is a 20% safety factor against pre-breakdown, both gap spaces are then subjected to a similar overvoltage ratio, R = 2.0. If τ_1 is the formative lag time for the upper gap and τ_2 is the formative lag time for the lower gap, it is easy to show that the sum, $\tau_1 + \tau_2$, is a minimum when the overvoltage ratios are equal. It now remains to estimate the values of these lag times.

Data obtained on the formative lag time as reported in Ref.e.2. are directly applicable. While the referenced experimental work was carried out at pressures below one atmosphere, the theoretical framework permits the adaptation of the data to the present high pressure regime. For the present we assume that an overvoltage ratio of R = 2 can be attained in a 40 atm gap as outlined above. The predicted lag time in each gap space is then 0.13 nsec.

In dealing with the formative lag time to develop this estimate, the assumption has been made that initial electrons exist in the gap prior to triggering to eliminate the statistical lag component. With the high fields to be employed in the present switch design it is probable that a small pre-breakdown current will be induced by field emission or other field-induced processes so that auxiliary means for producing a copious supply of initial electrons may be unnecessary. Field emission might be enhanced, if necessary, by sand-blasting of all electrode surfaces. The conditions cited above for equal overvoltage ratios, hold-off safety factor and operating pressure lead to the following summary of breakdown for the schematic three electrode gap.

TABLE 5

Summary of Breakdown Parameters for Ideal Three-Electrode Gap

Gas Pressure (P)	600 psig	300 psig
Self-Breakdown Voltage/Charge Voltage (a)	1.2	1.2
Upper Electrode Potential (V_1)	100 kv	50 kv
Center Electrode Potential (V_2)	42 kv	21 kv
Upper Gap Space (d_1)	1.2 mm	1.2 mm
Lower Gap Space (d_2)	0.8 mm	0.8 mm
Equal Overvoltage Ratios (R)	2.0	2.0
Estimated Total Lag Time ($\tau_1 + \tau_2$)	0.26 nsec	0.6 nsec

To illustrate the inherent flexibility in a high pressure gap, two values of operating pressure are summarized. It is demonstrated theoretically that a relatively wide operating voltage range may be achieved with no geometric adjustments while still preserving sub-nanosecond lag times.

Further consideration of design is best discussed in connection with the physical layout of the conceptual design presented in the next section. In passing, however, it is important to make note of the fact that the very short lag times estimated above, and the consequent small jitter time for a switch element, can only be achieved by the application of a very fast rise field-reversing pulse to the center electrode. The generation of control pulses of this type and the simultaneous application of such pulses to a multi-element array is well within the state of the art (Reference Part h of the Bibliography). Pulse amplitudes of 30 kv amplitude and approximately 0.5 nsec rise time have been routinely generated in this laboratory for formative lag time measurements in gases (References e.2, e.4).

6.a.3. <u>Conceptual Strip Line and Switch Physical Arrangement</u>

The conceptual design is illustrated in Figures 23 and 24. A full scale cross-sectional view through a single switch element is shown in Figure 23 while a cut-away isometric sketch illustrating the physical layout is presented in Figure 24. The main electrodes of the gap are uniform in cross-section across the entire width of the switched end of the line. Because of the high pressure, the air gap between the upper and lower electrodes is about equal to the dielectric thickness employed in the body of the strip line. The line is switched at several points by means of adjustable ball electrodes whose potential (42 kv for 100 kv line potential) is reversed with a trigger pulse. The electrode potentials and spacings are as indicated in Table 5 above.

The contours of the facing portions of the main gap electrodes have been designed to meet a number of needs. The distance between the breakdown region at the trigger ball and the transition to the solid dielectric portion of the strip line has been kept as short as possible. The reason for this is to minimize the switch inductance and to maintain a minimum electrical length for the impedance mismatch portion of the switch assembly. This distance is made up of an offset gas space between the main electrodes which prevents direct exposure of the strip line insulator to the radiation and any debris from the discharge channel. The remainder of this distance consists of the combined gas and solid dielectric space as illustrated. The length of this region has been conservatively derived from known high voltage hold-off for plastics immersed in high pressure gas (Ref. 3).

The wedge-shaped switching surfaces of the main electrodes lead to the unique advantage that gap adjustments can be performed by translation (horizontally in Figure 23) of the trigger electrode. Furthermore, when electrode wear degrades the gap performance, a new trigger electrode may be installed at an unused portion of the main electrode

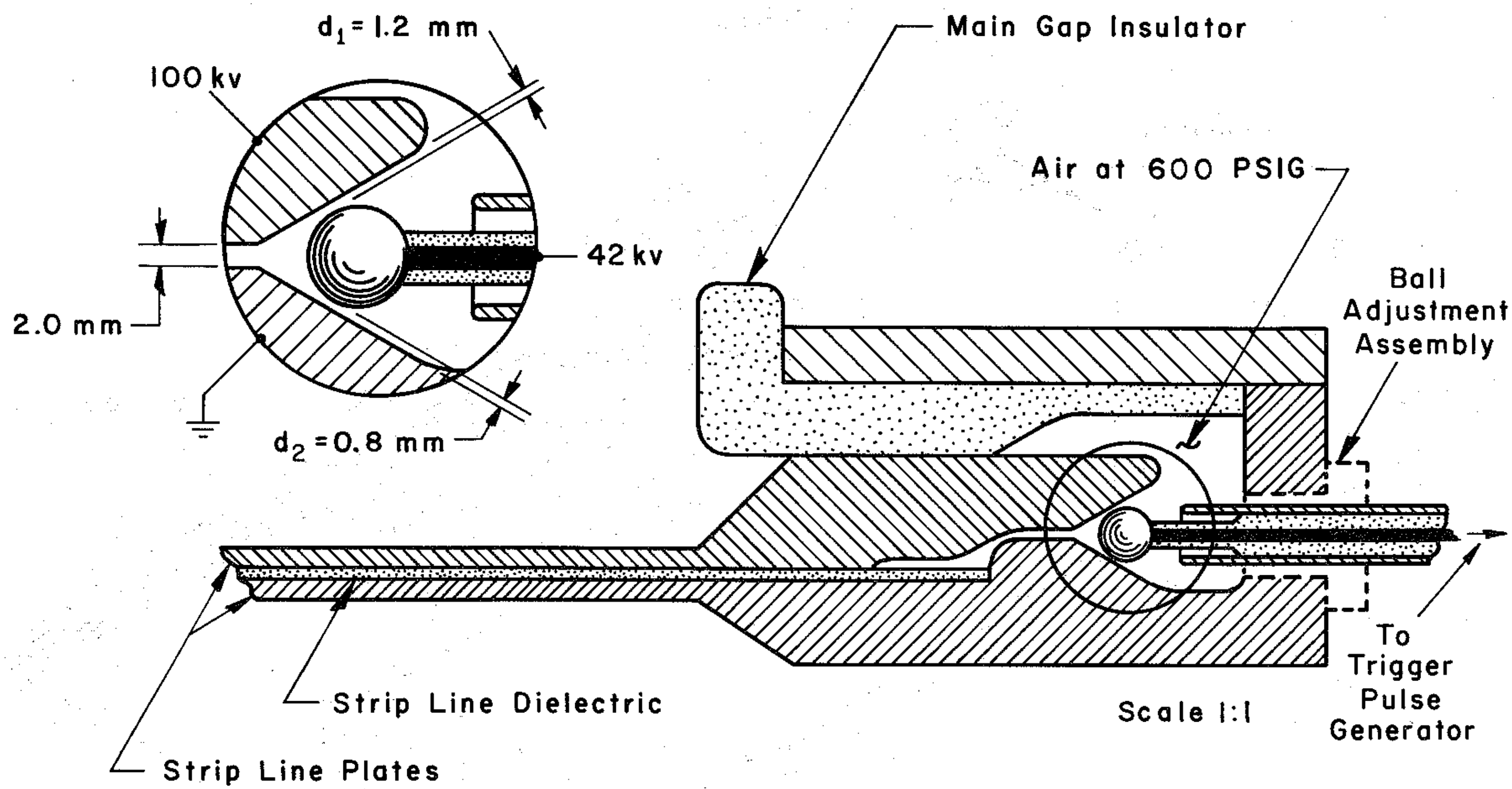


FIGURE 23.

CONCEPTUAL HIGH PRESSURE GAS SWITCH ELEMENT FOR STRIP LINE.

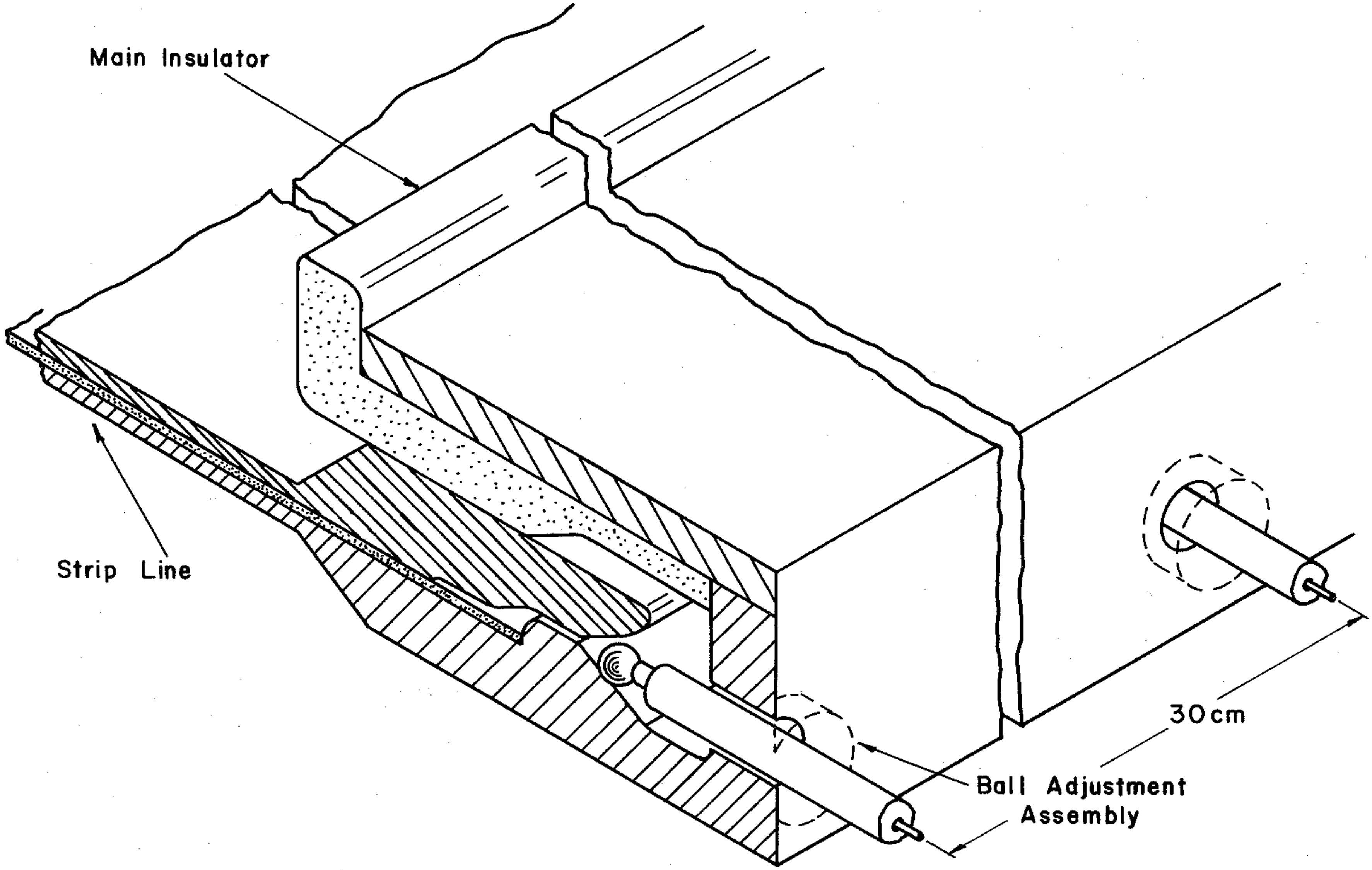


FIGURE 24.
PHYSICAL LAYOUT OF HIGH PRESSURE GAS SWITCH ELEMENTS.

face, thereby obviating the need for replacement of the entire main gap assembly. Based on the charge handling requirements summarized in Table 4, electrode wear should not be serious and the main electrode assembly can be considered as essentially permanent.

The lower electrode portion of the gap is shaped as shown to provide mechanical stability and to establish a ground potential reference at the connection of the trigger input line. The outer conductor of the open ended line is continued into the high pressure volume as shown to form a geometric shield for the coaxial insulator and to maintain approximately uniform tirgger line impedance.

The completion of the high pressure envelope, the high pressure gas sealing methods and the ball adjustment details are not fully represented in the design sketches given here. Consideration of these problems has been undertaken to the degree which establishes that a practical mechanical design for strip lines can be achieved.

The self-inductance of the switch has been estimated approximately from standard strip line formula. The current distribution has been taken as one which diverges uniformly from the spark channel diameter to a distance equal to the switch element separation (typical separation assumed = 30cm). Using this method of calculation the self-inductance for a switch element is expected to be between 1 and 2 nhenrys.

6.b. Strip Line Facility

In order to evaluate strip line switch designs a strip line facility was constructed. This facility presently allows operation of a pulse charged 5 ohm line at potentials up to 50 kv.

Figure 25 shows a diagramatic layout of the system. A strip line of 3 inch width, 0.00253 μf capacity is used as the storage element. This line consists of two copper plates, eight feet long, with 0.040 inch thick polyethylene insulator between the plates. The entire sandwich is clamped together with plexiglass and wood outer layers, and nylon

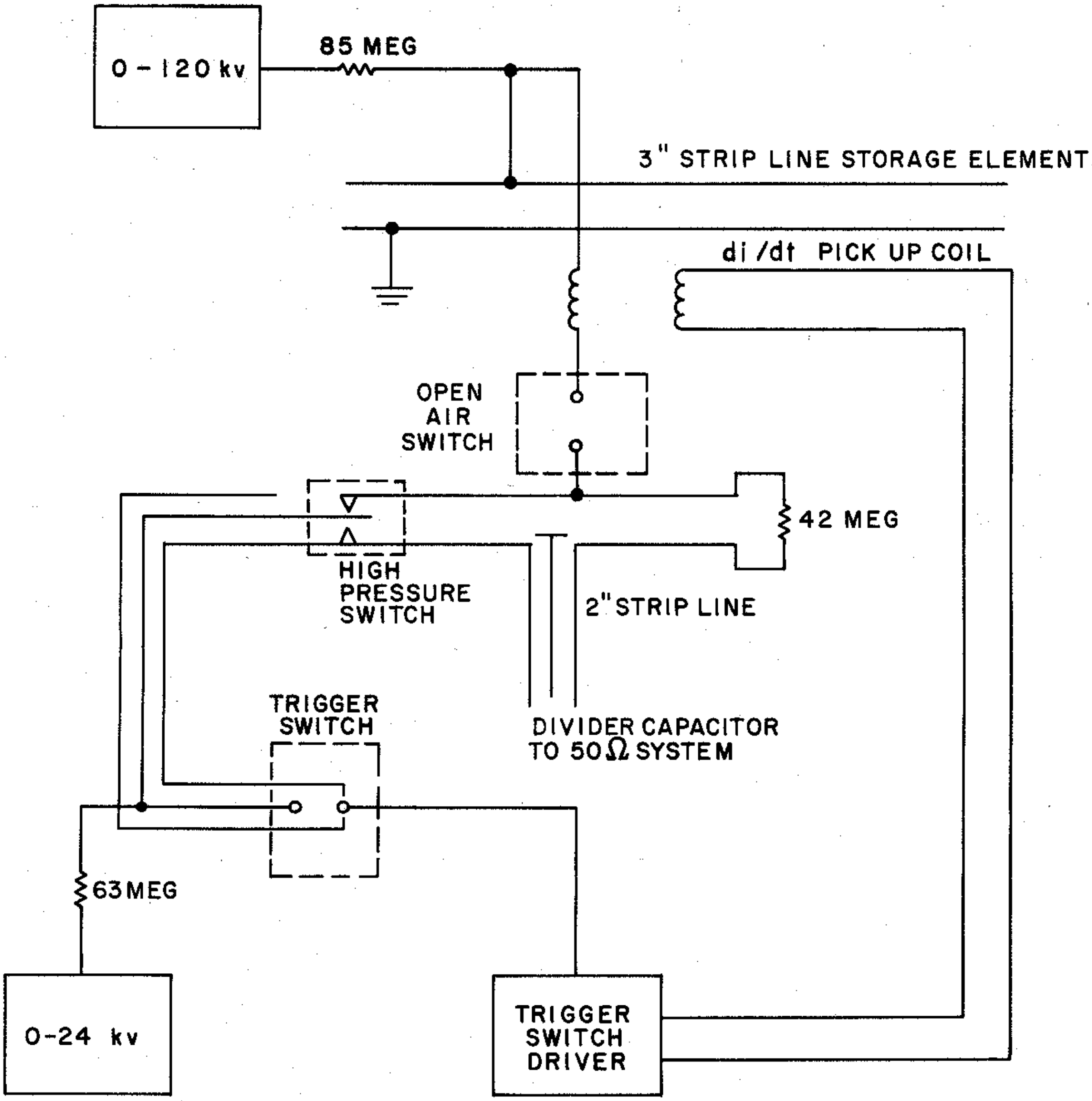


FIGURE 25.

STRIPLINE SWITCH SYSTEM.

tightening screws. The line pulse charges a second strip line of 2 inch width, through two air inductors of 280 μ henrys and two 2.5 inch diameter spheres. The air inductors serve to lower the pulse charging frequency (280 kc) to allow for 0.1 μ sec jitter in the trigger timing.

The 2 inch line of 0.0015 μf capacity 5 ohm impedance is also constructed of 8 foot long copper plates with an insulation of 0.040 inch thick polyethylene. A capacitor voltage divider is an integral portion of the ground section of the line (see Figure 25). The output of this divider is led to 50 ohm coaxial cable and a conventional 50 ohm coaxial attenuator. Because the voltage division ratio of the capacitor divider is 162:1 the voltage across the 50 ohm coaxial divider is low enough (about 300 volts) so that a conventional attenuator (such as the General Radio 874G20) may be used. With the 50 ohm system the RC decay time of the capacitor divider and cable impedence (approximately equivalent to the longest pulse that may be viewed) is 80 nsec. The rise time of the divider is only limited by the skin depth of its conductive coating (approximately equivalent to 1.5 gc for the present divider).

A schematic of the trigger switch driver chassis is shown in Figure 26. It provides both high voltage for the trigger switch and a pulse for the trigger pin. The pulse portion of the circuitry allows manual triggering by means of a relay and small hydrogen thyratron or automatic triggering when the 2 inch strip line is pulse charged. In this mode a pickup coil is positioned near one of the large balls. The voltage induced in the coil plus the bias voltage appears across a Shockley diode (Figure 26). The diode fires and in turn triggers an E.G. and G.KN-2. It is here that the major portion of the jitter (0.050 microsecond) and delay occur. The output of the KN-2 drives a TR-153 with a measured rise time of 0.3 μsec at full 35 kv output. Variation in timing of the automatic firing circuit may be obtained by bias adjustment of the Shockley diode or insertion of delay cables between the pick up coil and the driver chassis. Because low impedance shielded circuitry

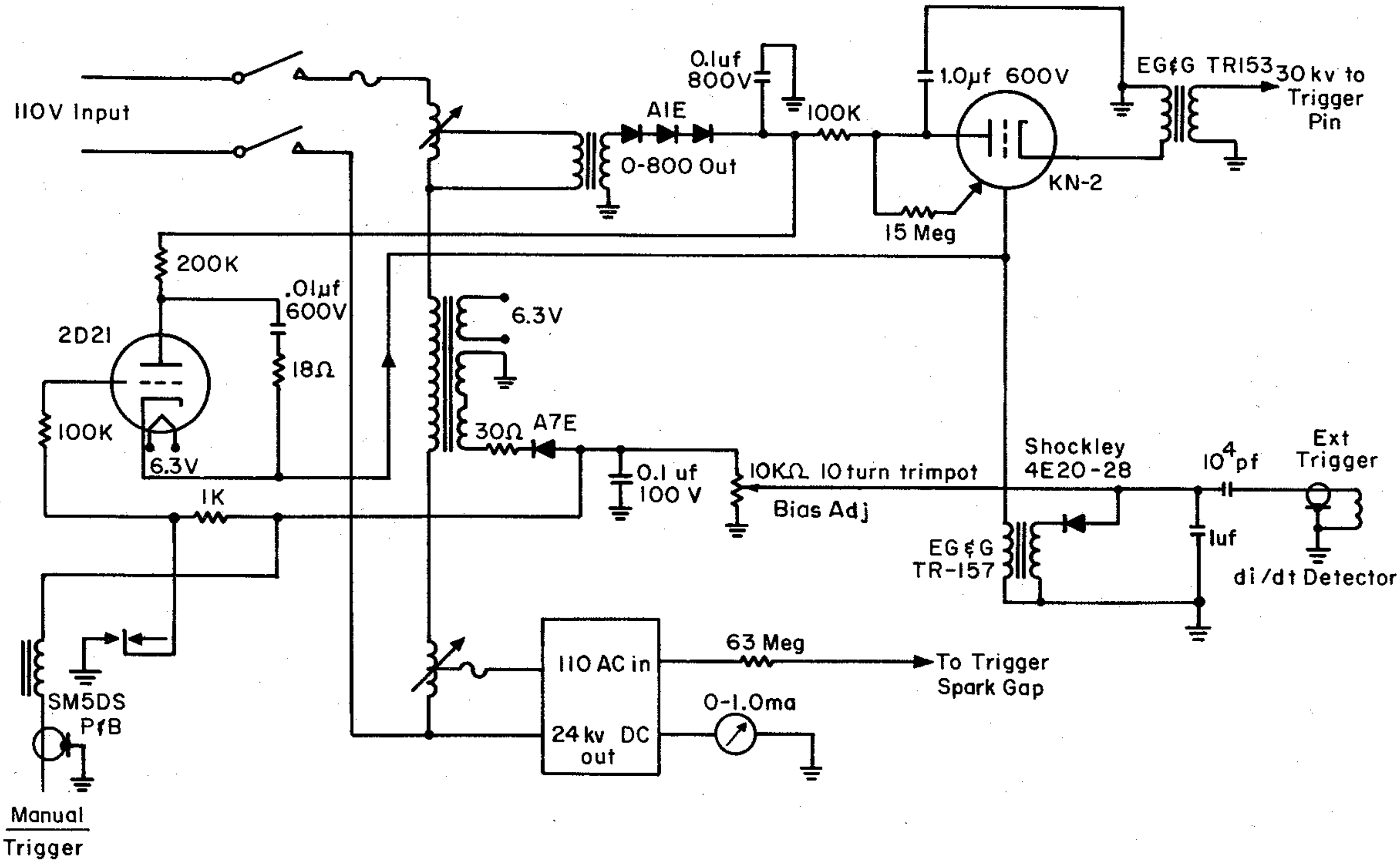


FIGURE 26.

TRIGGER SWITCH DRIVER

was used, no difficulties were encountered with pickup and premature firing.

The trigger switch is designed to provide a fast rise, high voltage pulse for triggering of the high pressure strip line switch. As shown in Figure 26 it is powered by the tirgger switch driver unit.

A cross section of the trigger switch is shown in Figure 27. It is of conventional trigatron design but uses an AL_2O_3 ceramic tube to insulate the trigger pin. Experiments were performed to optimize the rise time of this switch. Operation was explored in relation to a number of variables, specifically gas pressure, gap distance, shaping capacitors, etc. As a result, we have obtained switch operation with a 1 to 2 nsec rise time and a delay of 10 nsec. (See Figure 31.)

With the triggered electrode positive, operation with positive and negative trigger pulses was attempted. The trigger pulse is a 35 kv 1.1 μ sec pulse. It was found that negative trigger pin pulsing gave a much wider range of operation for a given gas pressure and gap spacing. Operation at various gap spacings and gap pressures was explored. It was found that, at a gap spacing equal to the trigger pin insulator thickness, lowest delay and fastest rise pulses were obtained. For optimum operation of this switch the gap spacing is about 0.062 inch and the gas pressure about 130 psig at 25 kv charge voltage. It was found that the output pulse rise time was adversely affected if the gas pressure was raised appreciably above the minimum pressure necessary for hold off. That is the gap was run at about 90% of self-breakdown voltage.

Single shot operation of the entire strip line system was obtained in a very simple manner. The voltage on the storage capacitor was varied by control of the charging power supply so that single charging pulses could be supplied to the 2 inch line.

For the most part the entire strip line system worked stably and reliably, however some problems were encountered. Three different

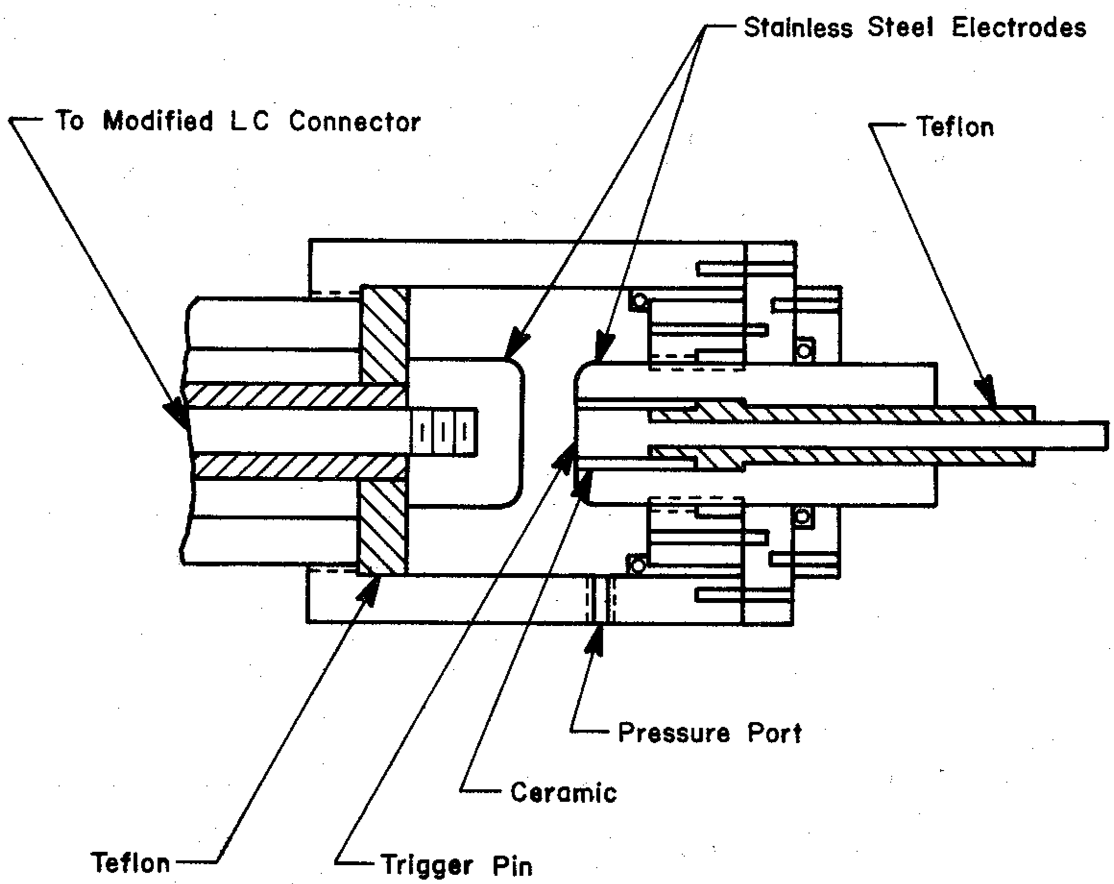


FIGURE 27.
CROSS–SECTION OF TRIGGERED SHORTING GAP FOR 50Ω LINE.

polyethylene sheets were used in the storage line until one was found sufficiently void free to take the stress (1250 volts/mil). Also some difficulty was originally encountered at operating voltages above 35 kilovolts. However, the replacement of wood and metal parts with plexiglass and nylon plus the liberal use of high voltage insulating grease reduced corona currents at the 50 kv level to less than 10μA and completely eliminated surface breakdown discharging of the capacitor.

6.c. Actual Strip Line Switch Design and Operation

6.c.1 Actual Switch Design

The final realization of this switch is shown by the full scale partial section Figure 28. The switch was designed to be used with a 5 ohm strip line. The geometry of electrodes G, H and T have been described above. The switch is enclosed in a stainless steel cylindrical envelope.

The ball H is electrically connected to the center conductor of a length of RG-17U cable by means of the special connector O. The ball is adjustable with two degrees of freedom to permit independent adjustment of the spacing between H and T and between H and G. The following is a tabulation of the various components noted in Figure 28.

TABLE 6

Components of the High Pressure Switch Shown in Figure 28

A - 50 kv Strip Line
B - Epoxy Insulator
C - Stainless Steel Retaining Ring
D - Housing, End Ring
E - Stainless Steel Envelope
F - Insulator
G - High Voltage Electrode
H - Ball Electrode (Trigger)

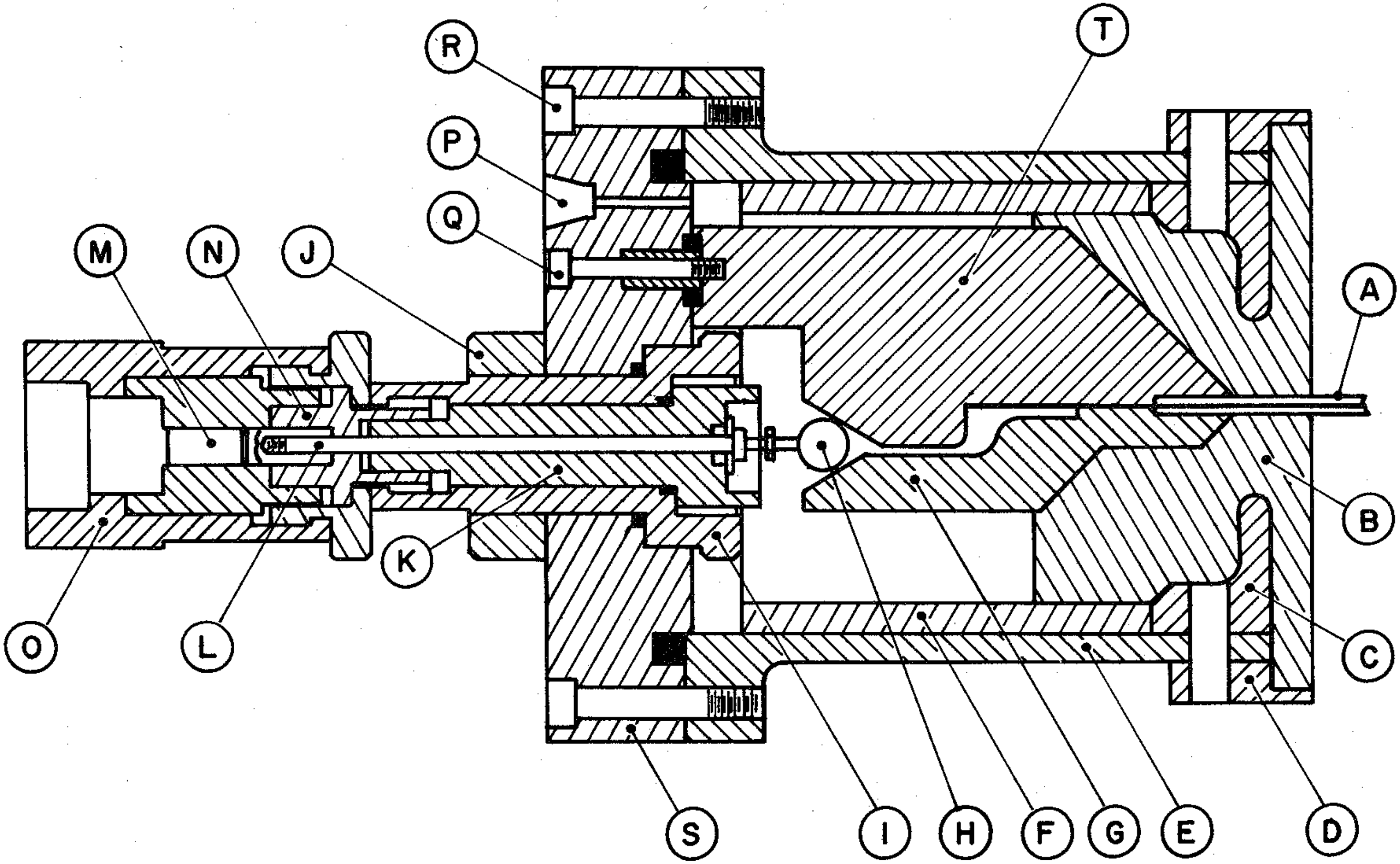


FIGURE 28.
SECTION OF HIGH PRESSURE AIR SWITCH.

I - Eccentric Shell of Trigger Body

J - Trigger Body Locking Clamp

K - Trigger Electrode Insulator

L - Trigger Electrode Connector

M - Modified LC Connector

N - Insulating Bushing

O - Modified Connector, TM-2415

P - Compressed Air Inlet

Q - Ground Connection Screw

R - Cover Bolts

S - Stainless Steel Cover

T - Ground Potential Electrode

6.c.2 Actual Switch Construction and Operation

Based on the mechanical design shown in Figure 28 a switch has been built and assembled. Originally it was planned to have the strip line insulation (0.040 polyethylene) extend into the high pressure gap and epoxy bonded to the electrodes. However, difficulty was encountered in obtaining an adequate polyethylene bond with an epoxy. Surface etching using Emerson and Cumming "Eccoprime PP" was performed; however, the resulting surface did not prove sufficiently bondable for use in the switch. Therefore, Rexolite 1422 of 0.080 inch thickness was used as the insulator within the gap. This was joined to the polyethylene insulation outside the switch by means of a lap joint and a generous quantity of high voltage grease. Operation to 50 kilovolts was obtained with no breakdown at the joint.

Obtaining the proper switch assembly and a stable epoxy casting was a time consuming task. The switch assembly procedure consists of two steps involving epoxy. First the upper and lower electrodes are cemented to the central strip line insulator. Secondly they are cast in place in the stainless steel shell. The shell is supported so that its axis is vertical and the epoxy poured into the gap. During this operation a dam is constructed on the outside of the gap so that the epoxy will pool properly within the gap volume. In all steps care must be taken to keep the epoxy off working electrode surfaces. Also for both operations the ground electrode must be fastened to the stainless steel shell so that the proper relative electrode position will be assured when the epoxy is poured. The gap was originally assembled using Emerson and Cumming "Eccomold L44." With room temperature cure the resultant clear epoxy developed some cracks. High voltage breakdown occurred between the high voltage electrode and the body. The crack and breakdown area were drilled out and new epoxy put in. The same process was repeated after a second breakdown; however, after the third breakdown the epoxy was removed and a new compound used. Thiokel Chemical Corp. Solithane resin 113 with catalyst C113-328 was used to obtain a flexible clear compound that showed no cracking with a room temperature cure and has successfully withstood the voltage and high pressure with no failure.

The trigger assembly requires no epoxy but a certain amount of high voltage insulating grease to prevent breakdown along the insulating plastic surfaces. Adjustment of the trigger ball is accomplished by removing the gap cover and then adjusting either the ball rod support or the locking nut and the trigger body. The latter moves the ball about an axis 0.030 inch eccentric to the axis of rotation of the trigger body.

Once the switch was assembled observations of its functional operation were made. These consisted largely in measurements of rise time and jitter under different conditions.

Initial difficulties in switch operation were caused by contamination of the air used as the switch dielectric. Because all pressure seals in the switch were well made, air circulation under conditions of high pressure was minimal. When the switch was operated with no circulation it was found that its performance changed considerably as a function of the number of discharges run in the switch. Under these circumstances when the air from the switch was released into the room a very strong odor of ozone was noted. Hence it was assumed that the composition of the air within the gap changed after each discharge. To overcome this instability an adjustable leak was added to the high pressure system. The leak was adjusted so that about one cubic foot per minute was released to the atmosphere. This was found sufficient to stabilize switch operation.

Electrode wear within the switch was not excessive. After approximately one thousand discharges the stainless steel electrodes were slightly pitted opposite the trigger ball. The trigger ball itself showed two circles of wear. The anode to trigger ball circle was 0.100 inch diameter with a surrounding circle of 0.118 inch diameter. The brass ball was roughened and silver colored in both areas. However, the roughness probably accounted for less than 0.002 inch change in ball dimension.

Electrical observation of the switch consisted in measurement of rise time and jitter. Rise times are measured on the traveling wave generated by switch closure. The wave form was viewed by means of the capacitor divider and the Tektronix 519 oscilloscope. Jitter measurements require a zero time so that jitter may be measured in relation to some time base. For the jitter measurements reported here the circuit of Figure 29 was used. This circuit provides triggering of the oscilloscope by means of the traveling wave used as a trigger for the main switch trigger wave. Sihce this wave has a rise time of 2-3 nsec the trigger amplitude control of the scope was set to trigger the scope during the steep portion of its rise.

Jitter measurements were taken as a function of overvoltage ratio. The ratio was changed by varying the gap pressure and the trigger voltage. The jitter measured was the total jitter of the two breakdowns, i.e. anode to trigger jitter plus trigger to cathode jitter. Histograms of jitter measurements for various overvoltage ratios of the two gaps are

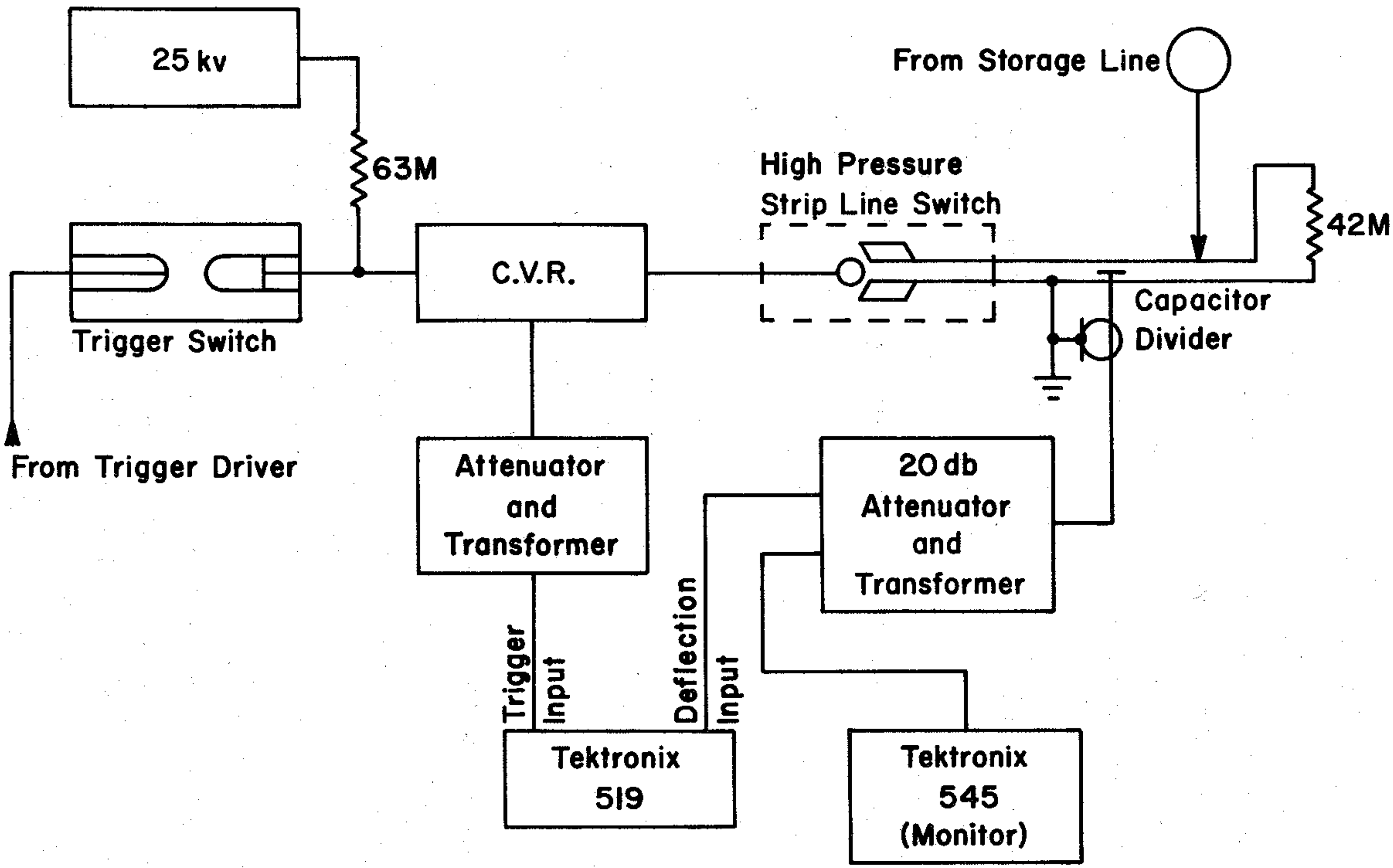


FIGURE 29.

SCHEMATIC OF SYSTEM USED FOR JITTER MEASUREMENT.

shown in Figure 30. The minimum overall jitter for both breakdowns was 6 nsec. Jitter measurements were found to be adversely affected by an increase in the number of breakdowns occurring in the high pressure gap per unit time. For this reason at least thirty seconds was allowed between each data point. This effect is thought to be due to build up of gaseous impurities within the switch.

Main gap rise time was in the 4 to 5 nsec range. Figure 31 shows the waveform for two different gap pressures. Variations of pressure and ball spacing were not effective in reducing this rise time although some changes in pulse shape were noted. (It is interesting to note that a switch of somewhat similar design used in a 2 ohm system (Ref. a.22.) had a rise time of 4 to 5 nsec and a jitter of 2.5 nsec.)

Because our high pressure switch comes close to meeting the requirements outlined in Section 6.a.l., it is worthwhile inquiring where the design or design calculations may have erred and what might be done to the switch to improve its performance.

In design of the switch gap predictions of formative times and by implication rise times were made on the basis of our past work. Although the fractional nanosecond formative lag times predicted may exist in switch operation, a statement of the formative lag time as such does not necessarily convey information about rise time. This is because formative lag time is defined as the time from the initiation of the breakdown process to the time when the breakdown begins to draw appreciable current in the breakdown gap. By definition during this time the voltage across the gap remains at close to the full value. Rise time, however, encompasses the time from the end of the formative time to the time that the voltage across the gap goes to zero. This time may be governed by physical processes which are not operative during formative times, namely sheath formation and cathode secondary processes. Additionally it is during the rise time that the breakdown channel makes the accommodation

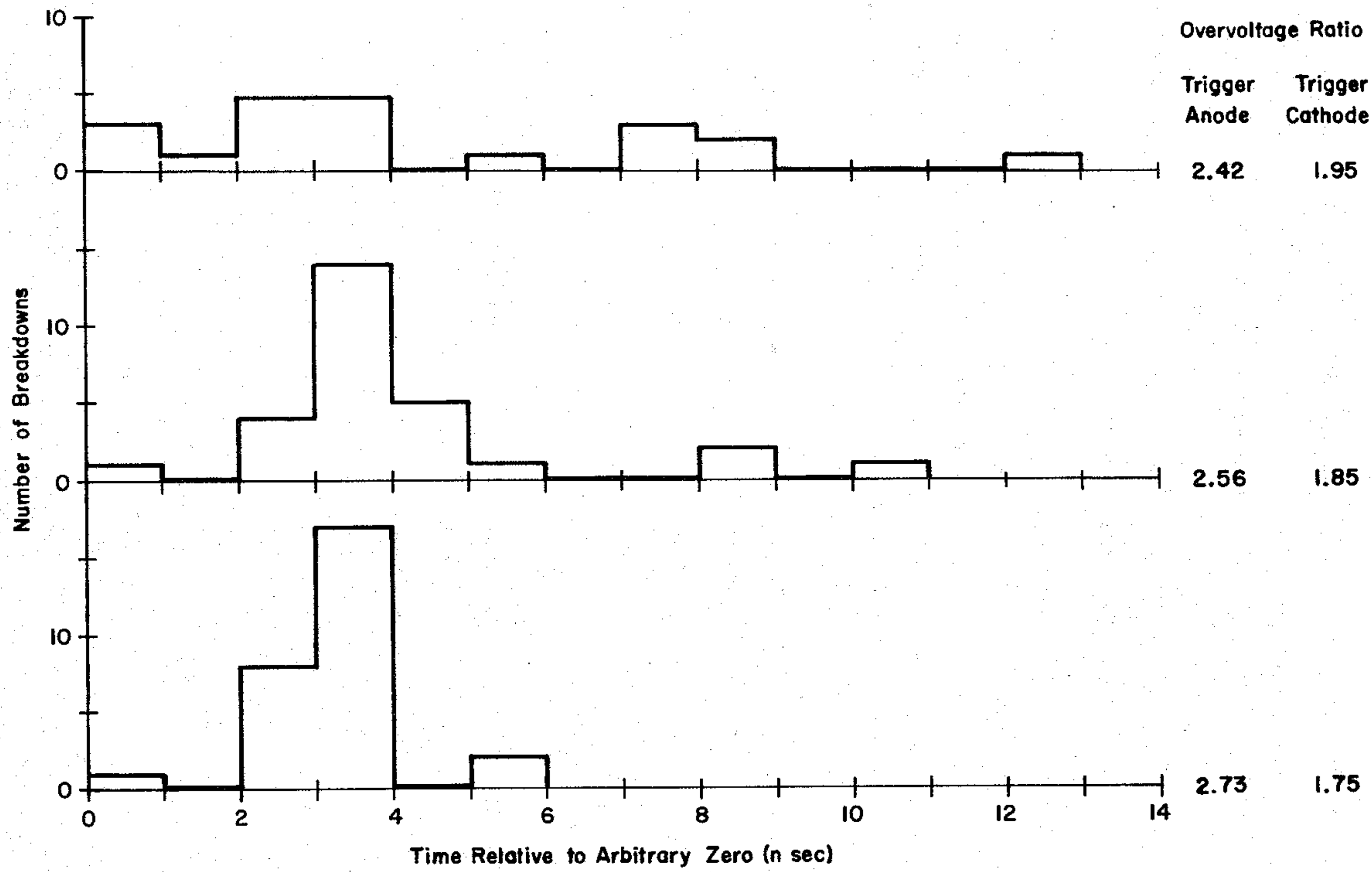
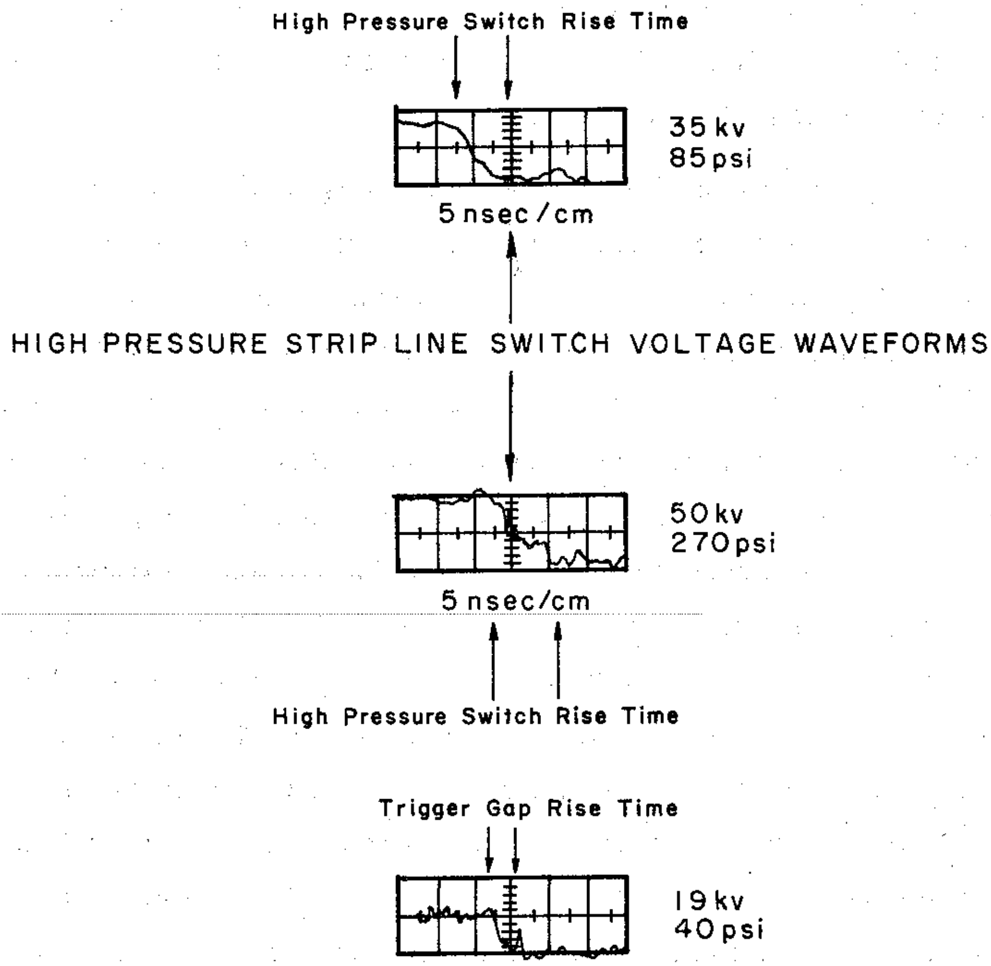


FIGURE 30.
HISTOGRAMS OF JITTER



TRIGGER GAP VOLTAGE WAVEFORM

FIGURE 31.

STRIP LINE SWITCHING SYSTEM WAVEFORMS.

for the particular line impedance involved.

Two phenomena may account for the large switch jitter measured (6 nsec). One possibility is excessively long rise times for the trigger voltage pulse. Actual times were in the 2 to 2.5 nsec range (see Figure 31), hence this cannot be responsible for the large jitter. The second possibility is that free electrons are not present in the gas and that the first breakdown does not illuminate the second breakdown. Both of these exist as possibilities although in view of the low total jitter the latter explanation seems far more reasonable.

In order to overcome the above difficulties a number of changes may be made to the present switch. Different operating gases could be used, specifically a nitrogen-carbon dioxide mixture which would have the advantage of greater stability. Present operation has been with the trigger ball centrally placed between the cathode and anode. There exists the possibility of displacing the ball towards the cathode as is done in the Fletcher gap. It may be that under these circumstances the trigger could be maintained at ground potential and the trigger pulse coupled in through a switch or capacitor. The present trigger ball has a form factor which is certainly not optimum if one considers irradiation of one breakdown channel by the other. Various shapes, some rotationally symmetric, some not, should be used to obtain more illumination of the breakdown channels. Finally, it may be that the switch should be made into a true potential switch, that is the trigger electrode impedance should be made more than an order of magnitude larger than the main gap. This could provide sufficient isolation so that the rise time would be materially reduced.

7. EVALUATION OF SURFACE BREAKDOWN SWITCH TECHNIQUE

Some preliminary measurements of switching by surface discharges (Reference a.21.) were performed. This type of discharge was investigated because it had a wide reported operating voltage range and because no time measurements have been performed on this. We sought to determine its possible utility in the present program by making initial measurements of the rise time and jitter associated with such a phenomenon.

The experimental setup was as shown in Figure 32. The switch electrodes (leading to the center conductor and braid of the RG-17) were #16 copper wire one turn of which went around the dielectric switch tube. Low inductance short leads were used between the RG-17 and the switch. In order to minimize jitter the surface of the dielectric was illuminated with ultraviolet just prior to the application of the trigger pulse. Timing for oscilloscope measurements was based on the output of a relatively fast (4nsec rise time) photodetector.

Two different dielectrics used in the experiments were borosilicate glass tubing and zirconium oxide tubing. The borosilicate glass was 0.118 inch-OD with a 0.019 inch wall thickness and a dielectric constant of about 4.8. The zirconium oxide was 0.100 inch -OD with a 0.012 inch wall thickness and a dielectric constant of 8.6. Rise times of the pulses were limited by switch inductance to L/Z in this case about 0.4 nsec. Observed rise times were 17 nsec switching 7 kv on the glass dielectric switch and 13 nsec switching 3 kv on the zirconium oxide dielectric. Although the gaps were brightly illuminated the jitter of both switches was considerable, varying from 100 to 1000 nsec. A Laue plot of the jitter distribution shows that it is not caused by a simple electron emission process. Additionally, the zirconium oxide which is naturally radioactive showed longer lags than the borosilicate glass. The gap distances between electrodes was much greater than that of the corresponding uniform

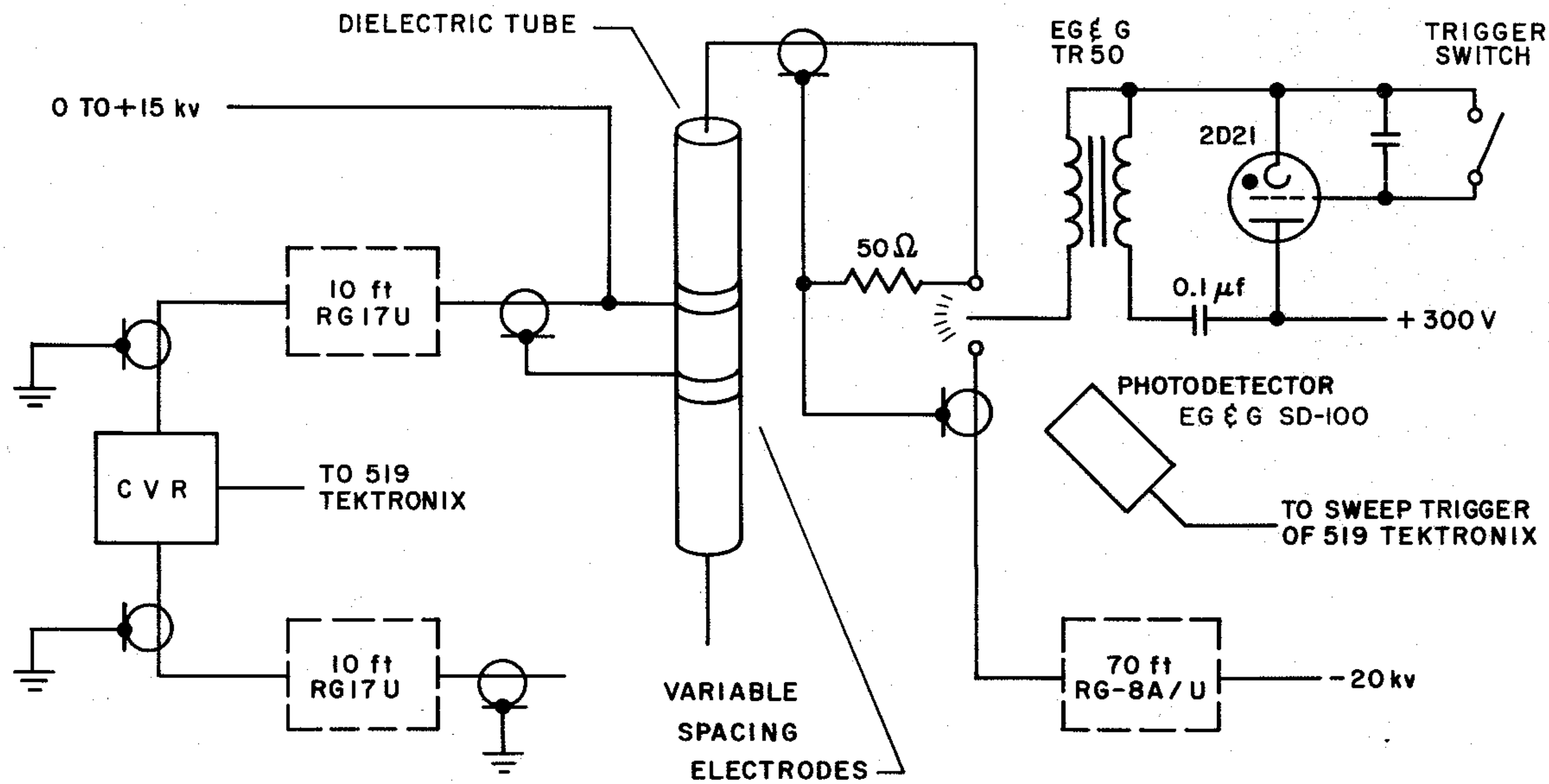


FIGURE 32.

SCHEMATIC TEST SET-UP FOR SURFACE DISCHARGE SWITCHING field gap (for instance at 0.177 inch breakdown occurred at 8 kv) indicating that the breakdown was indeed a surface phenomenon.

Although the original description of the switch operation (Reference a.21.) includes an unsatisfactory account of its operating principle we might put forward the following tentative explanation. The two electrodes although in physical contact with the dielectric tube do not everywhere make intimate physical contact with the electrodes. Hence there are air spaces between the electrodes and the dielectric surface. Now when the center electrode is pulsed the pulse voltage appears across the air spaces and the dielectric. Because of the field intensification across the air space on the edges of the electrodes it is possible that a surface discharge is initiated at each of the switch electrodes. This discharge would then grow across the gap between the electrodes further aided by the field intensification present because of the trigger voltage. The dielectric serves as a help in supporting and initiating the discharge. (One would therefore obtain higher field intensification with a tube of higher dielectric constant. It would be interesting to try the switch using a barium titanate tube.) On the basis of present results it may be concluded that dielectric surface discharges seem too slow to be applicable to the present program.

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A crowbar switch consisting of two highly reliable air spark gaps is described. Performance of the switch on a 600 kJ capacitor bank is given. Circuit details including trigger timing considerations are outlined.

a.5. F. H. Bohn, "A Simple Low Inductance Pressurized Spark Gap with Wide Operating Range," Paper SB2, Third Symposium on Engineering Problems in Thermonuclear Research, Munich (1964)

The planning and design of a capacitor bank for short current rise time and voltages up to 40 kV, variable in a large operating range (down to 18kV), required the development of a new type of pressurized spark gap.

Further requirements for the design were simplicity of construction, easy exchangeability of parts, and long lifetime. A current rise time of 0.6μsec for the given capacitor set-up can be reached only by means of an inductance below 15 nH for each spark gap.

The requirements mentioned were solved in the following ways:

1. by a coaxial system
2. by a shortening of creepage path by pressurizing
3. by a solid insulation of good mechanical and electrical stability
4. by an adapted dimensioning of trigger electrode diameter and trigger bore diameter, and selection of trigger electrode insulation.

Results obtained by a 10 nH inductance spark gap and an operating range of $U_{min}/U_{stat.} = 0.5$ will be reported.

a.6. F. L. Curzon and C. C. Daughney, "Simple Method of Overcoming the Effects of Noise Signals Produced by Spark Gap Switches," Rev. Sci. Instr. 34, 430 (1963)

A method of adjusting the trigger pin in a trigatron type spark gap is shown to yield much reduced noise pick up in auxiliary equipment.

a.7. R. C. Fletcher, "Production and Measurement of Ultra-High Speed Impulses," Rev. Sci. Instr. 20, 861 (1949)

The capabilities and limitations of several impulse generators and voltage dividers, and a micro-oscillograph sweep circuit for dealing with kilovolt impulses in the millimicrosecond range, are described. The most successful combination produces and measures an impulse of a rise time equal to 4×10^{-10} sec.

a.8. W. A. Cilliers and S. Leeman, "Switching and Clamping by Means of Plasma Jet Switches," J. Sci. Instr. 39, 528 (1962)

An air gap switch triggered by means of a plasma jet is described. This switch operates over a 1 to 10 kV range with 0.2μsec jitter.

a.9. L. M. Goldman, H. C. Pollock, J. A. Reynolds, and W. F. Westendorp, "Spark - Gap Switching of a 384 -kJ Low Inductance Capacitor Bank," Rev. Sci. Instr. 33, 1041 (1962)

A three-electrode spark gap which can handle high energy (96kJ) has been designed and used with a 384 -kJ capacitor bank having an operating range from 30 to 60 kV. The gap jitter time has been reduced to less than 25 nsec. During θ- pinch experiments involving 3000 discharges of the bank, there has been no significant deterioration of the gaps or variation of the electrical characteristics of the system.

a.10. A. E. Bishop, G. D. Edmonds, and J. Sheffield, " A 100 KV Switch for Rapid Discharge of High Energy Capacitors," J. Sci. Instr. 39, 566 (1962)

A pressurized, low inductance switch (250 nH) operating between 40 and 100 kV and up to 30 kA for discharging low inductance capacitors is described. The breakdown time of the switch is about 60 nsec, with a jitter of less than 20 nsec.

a.11. T. E. Broadbent and A.H.A. Shlash, "The Hot-Wire Triggered Spark Gap at Very High Voltages," Brit. J. Appl. Phys. 13, 596 (1962)

The performance of the hot-wire triggered spark gap at voltages up to 1 MV and gap spacings up to 80 cm is described. It is shown that the effect of the hot wire is to lower the breakdown voltage of the gap by as much as half. Optical phenomena which occur in the gap when positive voltage is applied are discussed.

a.12. W. F. Westendorp, "Switching of High Currents in Fast and Slow Plasma-Compression Systems," Engineering Aspects of Magnetohydrodynamics, Columbia U. Press (1962) ed. C. Mannal and N. W. Mather.

A low inductance 60 kV, 8.5×10^5 A switch is described. The switches are suitable for use in parallel switching of large capacitor bank units.

a.13. M. A. Levine, L. S. Combes, and C. C. Gallagher, "Crowbar Triggering Method for High Power Pulse Circuits, "Rev. Sci. Instr. 32, 1054 (1961)

A circuit involving a timing spark gap is used to accurately time the firing of a crowbar switch. The firing of the crowbar is thus adjustable with the characteristics of the timing gap.

a.14. S. I. Lobov and M. A. Kanunov, "Controlled Double-Trigger Spark Gap," Pribory i Tekh. Eksper. 6, 94 (1961)

The double - trigger principle in spark gaps operating on the right branch of Paschen's curve provides very fast action with a high safety factor. In instruments of this type at a working voltage of 1.5 kV the testing voltage is at least 3 kV, and the lag of the main discharge behind the trigger pulse does not exceed 0.05 sec. The spark gap is designed for a current up to 3 kA and electric pulses of several μ sec duration.

a.15. E. M. Goldfarb and H. G. Heard, "Full-Voltage Range Spark-Gap Crowbar," J. Appl. Phys. 32, 326 (1961)

A full voltage range spark gap or crowbar switch is described. The switch, suitable for use at very high voltages (100 to 1000 kV), has many unique properties because of its ability to operate in three different modes.

a.16. F. L. Curzon and P.R. Smy, "High-Voltage Trigger Pulse Generator," Rev. Sci. Instr. 32, 756 (1961)

A high voltage trigger pulse generator which provides for complete electrical isolation between input and output is described. The main component of the system is a pulsed UV light source used to trigger the generator spark gap.

a.17. G. V. Sklizkov, A. I. Pavlovskii and Y.A. Zysin, "Discharge Device for Precision Switching of High Power Pulses, "Pribory i Tekh. Eksper. 5, 89 (1961)

The construction of a five-electrode discharge device is described, which secures a synchronization accuracy of not worse than ± 0.02 μ sec, with operating voltages between half of the breakdown potential and the breakdown potential without any adjustment of the interelectrode distances. The device is designed for operation in the range of 5-70V. Dependence of the precision of the device in operation upon various factors is discussed.

a.18. S.A. Smirnov, L.A. Makhnenko and A.M. Shendrovich, "A Trigatron for Large Currents in High Voltage Apparatus," Pribory i Tekh. Eksper. 3, 89 (1961)

A trigatron is described which can handle currents up to 2.5 ka at voltages from 20 to 60 kv, for a pulse duration of 2.7 μsec and a repetition frequency of 50 cycles.

a.19. A. S. Husbands, J.B. Higham, "The Controlled Tripping of High-Voltage Inpulse Generators," J. Sci. Instr. 28, 242 (1951)

This paper summarizes the requirements of tripping circuits and spark gaps which enable a high-voltage impulse generator of one or more stages to be discharged in synchronism with the operation of such measuring equipment as a cathode-ray oscillograph or a rotating-mirror camera. A triggered spark-gap and the associated circuits which give accurate synchronism are described. A tripping pulse of only about 5kV is required, and this may be obtained from the time sweep circuit of a high-voltage oscillograph, or from a blocking oscillator. Tripping of a single-stage generator is obtainable within 0.1 μ sec of a pre-determined short delay time.

a.20. W.H. Lupton, "Fast Triggered Spark Switches for a Two megajoule Capacitor Bank, "Proc. of the Fifth Int. Conf. on Ionization Phenomena in Gases," Munich (1961)

Spark gap switches (or trigatrons) suitable for use with large capacitor banks, with many switches in parallel in the range of 3 to 30 kV have been developed. Tests on small capacitor banks run at 5 kJ per switch at 60 kc/s and 70% reversal have shown that one may expect the lifetime of the switch to be in excess of 4000 shots. This life is limited by erosion and this has been studied for various metals using an asymmetric arrangement where the magnetic fields blow the arc to a position where the erosion is not so critical. The relatively low inductance of about 2×10^{-8} makes such a switch suitable for use in fast energy storage systems. Four hundred of these switches are used on a 2 MJ, 20 kV bank; 70 on a 200 kJ, 6 kV slow bank; and 60 on a 5 F, 15 - 30 kV, preheater bank. The use of this large number of switches has made it necessary to study the factors affecting the breakdown (prefire) probability. The need to fire all of the switches on a bank simultaneously, and independently of the other banks of the system, has prompted a study of the factors affecting the switching time. The circuits used in the switching time measurements are described.

a.21. J. S. T. Looms, "Switching by Surface Discharges," J. Sci. Instr. 38, 380 (1961)

Switching along the surface of a dielectric is used to trigger a compact surge generator. Advantages include complete trigger isolation and large voltage operating range.

a.22. J. H. Adlam and L. S. Holmes, "Production of Millimicrosecond Current Pulses Using A Pressurized Spark Gap," J. Sci. Instr. 37, 385 (1960)

A pressurized spark gap has been designed to discharge a number of coaxial cables in parallel thus producing a current pulse of 10^4 A with a rise time of 4.5 mμ sec. It is intended to use a number of these spark gaps in parallel, and to test the feasibility of doing this, measurements have been made of the statistical variation of the time lag for breakdown after triggering.

a.23. P. I. Shkuropat, "Study of Operation of Controlled Spark Gaps in Air," Zh. Tekh. Fiz. 30, 954 (1960)

A study was made of the relation between the breakdown time lag of controlled spark gaps in air at atmospheric pressure and various trigger conditions. On the basis of the experimental data obtained a mechanism for the development of the discharge in triggered spark gaps is proposed. A recommended design for a controlled spark gap with a short time lag is given.

a.24 T. E. Broadbent, A. Fernandez, "Surge Diverters Using Trigatrons," J. Sci. Instr. 36, 452 (1959)

The work described shows that a single-stage trigatron surge diverter is a simple and effective method of removing the voltage from a specimen once the breakdown initiation process occurs. With solid specimens, the device is of value in enabling the breakdown tracks to be observed, whilst with gaseous specimens the diverter can conveniently be used in the study of the filamentary discharges which occur during the breakdown initiation process. The results of detailed experiments designed to investigate the performance of trigatron surge diverters at direct voltages up to 1000 kV are discussed.

a.25. H. B. McFarlane, "Spark Gaps for Fast High-Voltage Switching," Electronics - July 31, 72 (1959)

A method of triggering a large number of air spark gaps so that jitter is less than 10 nanoseconds is described. Voltage reversal and ultra violet light coupling between gaps is used to reduce jitter.

a.26. E. H. Cullington, W. G. Chace and R. L. Morgan, "Low-Voltage Trigger," Electronics - April 11, 86 (1958)

A simple inexpensive triggered gap switch is used to handle voltages of 1 to 10 kV with peak currents up to 5×10^5 A. Time jitter is about 0.1 μ sec between successive pulses.

a.27. H. P. Furth, M. A. Levine and R. W. Waniek, "Production and Use of High Transient Magnetic Fields, II," Rev. Sci. Instr. 28, 949 (1957)

The transient containment of high magnetic energy densities in coils of various geometries is discussed. Inherent mechanical and thermal limitation are shown to apply to coils relying solely on the strength of materials. The usefulness of inertial effects is demonstrated. Instrumentation is described for producing 10 μ sec range pulses of amplitude up to 1.6 megagauss in single-turn coils. Experimental observations document the appearance of "saw effect" and Kruskal-Schwarzschild instabilities at very high fields. The limitations characteristic of conventional coils can be overcome in force-free geometries. The appropriate mathematics is developed and illustrated with practical examples.

a.28. A. M. Sletten and T. J. Lewis, "Characteristics of the Trigatron Spark Gap," Proc. Instn. Elect. Engrs. 104c, 54 (1957)

The behaviour of a trigatron three-electrode spark-gap in air has been investigated and its characteristics obtained with particular reference to its use as a controlled high voltage switch. It is found that the voltage range over which it may be triggered satisfactorily depends not only on the polarities of the main gap and triggering voltages, but also on the energy of the discharge. The breakdown time-lag is also determined by these same voltage polarities and also by the time constant of the trigger discharge circuit.

From these characteristics and certain other relevant observations, a theory of the breakdown process in such a spark-gap is suggested, involving the propagation from the trigger of a low-density easily-ionized region.

Finally, a brief investigation of the successful use of a trigatron in a diverter circuit capable of diverting the discharge energy in a spark-gap subjected to direct and impulse voltages of 300 kV and in a circuit providing accurate "chopping" of impulse voltage waves, is reported.

a.29. T. E. Broadbent and J. K. Wood, "A Thermally Triggered Spark Gap," Brit. J. Appl.Phys. 6, 368 (1955)

A new heat effect is described in which the presence of a small source of heat at one electrode of a spark gap considerably reduces its breakdown voltage. The performance of the gap is investigated.

a.30. M. Chodorow, et al, "The Stanford Electron Accelerator Mark III," Rev. Sci. Instr. 26, 134 (1955)

An air spark gap is used as the switch element in pulsing a thyratron for operation in the Stanford Electron Accelerator Mark III. A six ball triggered switch operating at voltage levels up to 130 kv at 60 pps is described in detail.

a.31. J. D. Craggs, M. E. Haine and J. M. Meek, "The Development of Triggered Spark-Gaps for High-power Modulators," J. Instn. Elect. Engrs. 93, 963 (1946)

A description is given of the development of rotary spark - gaps and triggered spark - gaps, and their application in high-power modulation circuits. The characteristics of such gaps for different pulse energies and pulse recurrence rates are discussed for gaps in open air, in compressed air and in other gases. A detailed account is given of the influence of gas filling and electrode material on the performance of the sealed triggered spark-gap or trigatron, with particular reference to the results observed in high-pressure argon-oxygen mixtures.

a.32. T. Shimizu, and M. Hirata, "On Starting an Electric Spark by Intense Ionization of the Sparking Space," Sci, Paper Inst. Phys. Chem. Res. Tokyo 38, 317 (1941)

An x-ray triggered spark gap is described. The x-rays are produced by stopping of electrons on a thin metal foil window of a cathode ray tube.

a.33 V. G. Kalinin and L. V. Tarasova, "An Air Discharger with Thermal Priming, "Pribory i Tekh. Eksper. 4, 90 (1959)

This article describes the construction of an air discharger (thermotron) for the commutation of large currents at voltages of 3-10 kV, where a metallic wire heated by electric current is used for ignition. The characteristics of the discharger are investigated.

a.34. C. Calvelli et al "Spark Chamber System for High Energy γ Ray Detection, "Rev. Sci. Instr. 35, 1642 (1964)

Describes a 15 kv fast rise (less than 10 ns) low jitter (less than 2-3 ns) pressurized spark gap. Using nitrogen at 7 kg/cm^2 and stainless electrodes very little damage to the switch was seen after 5×10^5 pulses of 1.7 j each. The diameter of the trigger pin is correlated with gap delay. The basic switch geometry is of the trigatron type.

a.35. L. Lavoie, S. Parker, C. Rey and D. M. Schwartz "Spark Chamber Pulsing System" Rev. Sci. Instr., 35, 1567 (1964)

A trigatron type gap is described with barium titanate dielectric as the trigger pin insulator. Low voltage triggering is thus possible. Delays of 10 to 70 nsec corresponding to gap voltages of 2 to 16 kv have been attained. Pressurizing or cascading of gaps may be used to reduce the delay to below the 5 nsec level. Lifetimes of over 5×10^6 pulses at the 0.1 j level have been attained. Jitter is said to be less than 3 nsec.

a.36. G. Schrank, G. Henry, Q. A. Kerns and R. A. Swanson "Spark Gap Trigger System" Rev. Sci. Instr. 35, 1326 (1964)

Describes a 30 kv, 5000 A spark gap using a 3 electrode configuration with pulsed ultraviolet illumination of the electrodes. Delay and jitter of less than 5 ns were attained with clean electrodes. A horseshoe shape center electrode was found optimum. The gap was pressurized at 3.5 kg/cm^2 with a mixture of 90% N_2 10% CO_2. This mixture allowed repetition rates of 10 pulses per second.

a.37. S. Goldenbaum, E. Hintz "Pressurized Trigatrons with a 10 kv - 50 kv Low Jitter Operating Range" Proc. of the Fifth Int. Conf. on Ionization Phenomena in Gases, Paris (1963)

By using enclosed switches at higher pressures and smaller electrode spacing the breakdown characteristics of asymmetric trigatrons, described in detail by Lupton , have been further improved. The mechanical construction remains simple and voltages up to 50 kv can be switched. At electrode distances from 3 mm to 5 mm and pressures between 15 and 75 psi both statistical and formative time lags are below 20 nsec , even with the operating voltage as low as one third of the static breakdown voltage. The comparatively small breakdown voltage in the triggered case with the observed short delay times is caused by the increasing nonuniformity of the electric field when the trigger potential is raised, and by an intermittent corona between the trigger pin and the main electrode which starts during the charging period.

8.b. Low Pressure Switches

b.1. R. F. Hemmings, L. A. Green and V. C. Cloke, "Sceptre IV - A Megajoule Discharge System," Proc. Instr. Elect. Engrs. III, 589 (1964)

Equipment for the production of a ring discharge of the Zeta or Sceptre type is described. The primary current is switched by a specially developed ignitron circuit, which provides also a clamping connection to increase the current, while preventing reverse voltage on the capacitor bank.

b.2. M.P. Young, "20 KV Vacuum Switches for Crowbar Applications," Paper SB 4, 3rd Symposium on Engineering Problems in Thermonuclear Research, Munich, (1964)

An asymmetric trigatron with magnetic displacement of the arc operating at low pressure is shown to be an inexpensive reliable crowbar switch for 10 kJ per switch duty.

b.3. E. L. Kemp and W. E. Quinn, "The Power Crowbar Energy System for Scylla IV, "Paper No. SA 5, 3rd Symposium on Engineering Problems in Thermonuclear Research, Munich (1964)

The energy storage system of Scylla IV has four capacitor banks which are applied in the following order: a) The reverse bias bank - 10-kV, 280-kJ, with a rise time of 60 μsec. b) Preionization bank - 60-kV, 9-kJ. This bank rings at 300 kc. c) Primary bank - 50 kV, 540-kJ with a rise time of 3.6 μsec. d) Power crowbar bank - 20-kV, operation for over a year, their performance will be discussed. The main problem with the power crowbar bank is the switch. This switch must hold off the pulse voltages applied by the other three banks while also holding off the dc voltage of the power crowbar bank. This switch must also fire with low jitter when the voltage across it is near zero. Three types of switches were considered for this application, a 20-kV ignitron, a developmental 50-kV ignitron, and a vacuum spark gap. The characteristics of each switch will be discussed and the choice of the vacuum switch will be discussed in detail. The discussion will also include the various methods of triggering vacuum switches. A washer gun was chosen as the trigger for each gap. This gun will be shown and discussed. The 3-MJ Capacitor bank will be discussed as a system, including the capacitor protection scheme, the prefire protection circuit, and the complete firing system.

b.4. R. Hancox, "Low-Pressure Gas Discharge Switches for Use in Fusion Experiments," Proc. Instn. Elect. Engrs. 111 , 203 (1964)

Switches for fusion experiments are required to discharge energy-storage capacitor banks, charged to voltages up to 100 kV, and to pass currents of 50 kA to 2 MA. The characteristics of various types of switch are considered, and detailed descriptions are given of several switches in which the current is passed as a low-pressure gas discharge.

b.5. N.O.O. Eikel and H. M. Skarsgard, "Simple High-Voltage Plasma Switches," Rev. Sci. Instr. 34, 299 (1963)

Two vacuum switches are described which have unique properties. Specifically, they avoid the need for pressurized insulation found in earlier switches. The switches are triggered by a Bostick plasma gun and are suitable for use at 30 kV.

b.6 D. Harcombe, R. T. Plamer and C. F. Gozna, "A Magnetically Controlled Spark Gap," J. Sci. Instr. 40, 468 (1963)

A low inductance spark gap is described, utilizing the breakdown between coaxial cylinder electrodes with a transverse magnetic field at low pressure. The device can be triggered magnetically and it can be used as a "clamp switch."

b.7 R. G. Hahn, W. van Jaskowsky and A. J. Casini, "Gas-triggered Inverse Pinch Switch," Rev. Sci. Instr. 34 , 1439 (1963)

A low inductance (4nh) gas triggered inverse pinch switch is shown to have many desirable operating properties, including low noise and long life.

b.8. D. A. Swift, "A Compact Low-Pressure Trigatron," Proc. Instn. Elec. Engrs. 110, 1915 (1963)

The constructional details and operational characteristics of a 10 kA low-pressure switch, developed for use in research on rotating plasmas, are given. This switch, employing a single parallel-plate gap with a triggering pin built into the centre of one electrode, has a concentric cylindrical return path made integral with a current-measuring device. The switch is easily triggerable, operates over a very wide voltage range, has a low inductance, and is virtually silent, both audibly and electrically. From an investigation of the conditions affecting closing time and jitter, it is concluded that the device is feasible for synchronous switching, using several switches in parallel paths.

A brief account is given of the development, to date, of a higher-voltage switch suitable for application, in ten parallel paths, to a large capacitor bank.

The conducting channel of the switch has been observed by streak photography to spread radially from the trigger with a velocity of 1.2×10^6 cm/s. This value is consistent with that obtained in the measurement of the time variation of switch-gap inductance, for which a technique was developed to isolate the inductive from the non-inductive voltage drop. A theoretical basis of the triggering mechanism is presented.

b.9. R. Hancox, "Triggering Mechanism of Low-Pressure Spark Gaps," Rev. Sci. Instr. 33, 1239 (1962)

The triggering delay in two low-pressure spark-gap switches, operating in the pressure range 10^{-3} to 3×10^{-2} mm Hg, has been measured under a wide range of conditions. When the trigger pin is in the negative electrode, the delay is found to consist of two components. The first part depends on the construction of the trigger pin, the trigger voltage, and the impedance of the trigger circuit, while the second part depends on the nature and pressure of the gas in the gap, and the voltage and impedance of the circuit being switched. If the trigger pin is in the positive electrode a further delay is added which is approximately equal to the transit time of an ion across the gap. A mechanism for the breakdown is proposed which is consistent with the measurements and with previously reported results.

b.10. G. M. Bracewell, J. Maycock and G. R. Blackwell, "Switching Two Million Amps," Nuclear Power 4, 115 (1959)

A graded vacuum gap is described. Peak current in excess of 10^6 amperes are switched at 30 kV in the experimental design.

b.11. J. G. Bannenberg and F. G. Insinger, "Improved Vacuum Switch for Capacitor-Discharge Service,: Rev. Sci. Instr. 33,1106 (1962)

An improved design of the switch first described by Mather and Williams is given. The present switch is capable of handling higher currents for longer periods of time and is more ruggedly constructed than previous switches.

b.12. B. O. Baker and K. G. Cook, " A High Power Gas Discharge Switch," Brit. J. Appl Phys. 13, 603 (1962)

This paper describes a switch having a mercury pool cathode and a permanent gas filling. The switch has certain advantages over mercury pool devices of the ignitron type in reliability and accuracy of triggering, higher rate of increase of anode current and improved anode voltage performance.

b.13. G. D. Cormack and A. J. Barnard, "Low Inductance Low Pressure Spark Gap Switch," Rev. Sci. Instr. 33, 606 (1962)

A low pressure spark gap switch suitable for use as a main switch and as a "crowbar" switch on a capacitor bank is described. The switch has been operated over a voltage range of 0.5 to 24 kV, at energies up to 4 kJ and currents up to 500 kA. Under normal operating conditions the triggering time is 40 nsec. The inductance of the main switch is 4 mμH.

b.14. V. V. Sokol'skii, A. I. Nastyukha and E. A. Lobikov, "Vacuum Gap With Electron Triggering," Pribory i Tekh. Eksper. 2, 132 (1961)

A description is given of a vacuum gap designed for switching large pulse currents at a voltage from 0.3 to 12 kv. The maximum duration of a current pulse is 600 μsec. The gap is triggered by an electron beam extracted from a low-voltage pulse oscillation discharge. The characteristics of the gap are presented.

b.15. G. Boucher, "Thyratron a Champs Croises," Proc. Fifth Int Conf. on Ionization Phenomena in Gases, Munich (1961)

In this paper the possibilities of using cold cathode tubes as thyratrons are described. The tube is locked and the current is magnetically controlled. The length of the pulse is not limited and the modulator needs no pulse transformer or delay line.

b.16. R. B. Johansson and E. A. Smårs, " A Low-Pressure Spark-Gap Switch With Wide Voltage Range," Proc. Fifth Int. Conf. on Ionization Phenomena in gases, Munich (1961)

A triggered spark-gap switch operating at low gas pressure is described. Its working voltage range extends from a few hundred volts to at least 50 kV. At suitable pressure and polarity its delay time is less than 50 ns and its jitter time is less than 20 ns, both decreasing with decreasing gap voltage. At reversed polarity they are up to 10 times longer.

b.17. A. M. Rodin and V. V. Surenyants, "A High-Voltage Heavy-Current Vacuum Discharge Tube VIR-100," Pribory i Tekh. Eksper. 6, 62 (1960)

A description is given of a vacuum spark discharge tube which allows electrical circuits to be pulsed with currents of several thousand amperes at voltages up to 100 kV. The main circuit is completed through a vacuum discharge which is initiated by the discharge of an accessory ignition system. The vacuum in the discharge tube is maintained by a system of getters. The time delay between connecting the main circuit and the breakdown of the ignition system varies from a few hundredths of a second to 1 μsec according to the polarity of the electrodes, the value of the ignition voltage, and many other factors.

b.18. G. J. Brucker and K. C. Rogers, "A Kilovolt, Kilolampere Low Pressure Switch," Nuc. Instr. and Methods 8, 236 (1960)

A low pressure switch is described that is capable of passing kiloamperes at voltages up to 30 kV. The effect of pressure and gap voltage on the switch closing time is discussed.

b.19. S. I. Lobov, V. A. Tsukerman and L. S. Eig, "Controllable Low Pressure Discharger," Pribory i Tekh. Eksper. 1, 89 (1960)

A controllable low pressure discharger for switching currents up to 5 ka at voltages of 5 to 10 kv is described. The geometry of the main and starting discharge gaps is chosen so that for gas pressures of 0.1 to 0.7 mm Hg, the breakdown voltage of the main gap is determined by the left branch of the Paschen curve, and the breakdown voltage of the starting gap is near the minimum of the curve. The presence of a preliminary "guard" discharge in the starting gap eliminates the statistical delay in striking the discharge, and insures a stable firing voltage. The accuracy of control of the main breakdown depends on the working voltage and lies between 0.1 and 0.01 μ sec.

b.20. J. W. Mather and A.H. Williams, Some Properties of a Graded Vacuum Spark Gap, "Rev. Sci. Instr. 31, 297 (1960)

A high power, low inductance vacuum spark gap combination (crowbar and main switch) is described which is capable of dc operation over a wide voltage range. The electrical properties are discussed in regard to shorting and multiple switch operation. The principal difficulty of vacuum spark gaps, the coating of the inner surface of the insulator with evaporated and sputtered electrode material, is absent in this design after conditioning. A mechanism to account for this, based on the establishment of a large number of nucleation centers on the insulating walls, is shown to be consistent with observation.

b.21. D. C. Hagerman and A. H. Williams, " High-Power Vacuum Spark Gap," Rev. Sci. Instr. 30, 182 (1959)

The design and construction of a voltage graded vacuum spark gap is described. This gap is capable of switching currents as large as 10^6 amp at voltages up to 75 kv. The effect of the insulating walls of the gap is briefly discussed.

b.22. W. R. Baker, "High-Voltage, Low-Inductance Switch for Megampere Pulse Currents," Rev. Sci. Instr. 30, 700 (1959)

A switch is described that will handle pulse currents of several millions of amperes and stand off dc supply voltages of over thirty kilovolts. It is useful in powering fast pinch devices such as those used in thermonuclear research.

b.23. D. F. McDonald, C. J. Benning, and S. J. Brient "Subnanosecond Risetime Multikilovolt Pulse Generator" Rev. Sci. Instr. 36, 504 (1965)

A multikilovolt nanosecond pulse generator has been developed which uses a new approach to the design of an extremely fast gas-discharge switch. The design concept is based on the statistical time lag which precedes an electrical breakdown. The generator also employs large coaxial geometry so that extremely high operating voltages may be used. A description of instrumentation required to measure the fast risetime, high voltage pulses is included along with some typical oscilloscope traces.

b.24. R. G. Jahn, W. Van Jaskowsky and A. J. Casini "Gas Triggered Pinch Discharge Switch," Rev. Sci. Instr. 36, 101 (1965)

An inverse pinch switch used for a 15 μf, 10 kv bank is described. The switch has an inductance of 3×10^{-9} henrys and resistance of 5×10^{-3} ohms. The switch sustains several hundred discharges before requiring cleaning.

8.c. Solid Dielectric Switches

c.1. H. J. Huber, "Wide Voltage Range High Energy Solid Dielectric Switch," Rev. Sci. Instr. 35, 1067 (1964)

A solid dielectric, high energy, low inductance switch is described. The electrical and mechanical characteristics of the switch and the switch trigger are described. The switch is used at 15 kV and 1×10^6 A and is triggered by exploding bridge wires.

c.2. L. L. Alston, G. Barnes, G.A. G. Mosson and R. White, "A solid Dielectric Switch," Paper SB 8, 3rd Symposium on Engineering Problems in Thermonuclear Research, Munich (1964)

A solid dielectric switch suitable for series or crowbar operation with ratings of 40 kV , 100 kA and 10 coulombs is described. The development program leading to the design of this switch is outlined.

c.3. P. J. Rogers, "A Fast Mechanically Closed Switch," Paper No. SB 7, 3rd Symposium on Engineering Problems in Thermonuclear Research, Munich, (1964)

A mechanically closed clamp switch is being developed using a solid dielectric. Closing times as low as 30 μsec have been obtained in a switch suitable for 100 kv, and contact resistance as low as 3 μohms has been achieved.

c.4. F. J. Friedrich, "A Solid Dielectric Trigatron for Crowbar," Paper No. SB 9, 3rd Symposium on Engineering Problems in Thermonuclear Research, Munich (1964)

Development work on a solid dielectric trigatron is described. The results of tests on delay and jitter as function of switch parameters is given.

c.5. H. Huber, "Technical Specifications of an Exploding Wire Triggered Solid Dielectric Switch," Stevens Institute of Technology Report, SIT P-78 (1963)

A solid dielectric switch with unique properties is described. Advantages of the switch include extremely low inductance, low resistance , and ability to switch at low values of hold off voltage. Construction details of the switch are given.

c.6. A. H. Gabriel, V.T.S. Howell, E. Thornton, and R. J. Wilson, "Low Inductance Capacitor Banks and Linear Pinched Discharges, "J. Sci. Instr. 38, 136 (1961)

Details are given of low inductance capacitors and capacitor banks with energy storages in the 1 to 10 kJ range capable of giving maximum currents of 1.2 MA and rates of 6×10^{12} A/S. A solid dielectric switch is described which is triggered by means of a small explosive pellet.

c.7. E. Thornton, "Design and Performance of a Compact Surge Generator," Brit. J. Appl. Phys. 11, 265 (1960)

A compact surge generator for investigation of a fast, linear pinched discharge using only moderate energy storage is described. The techniques of construction using an explosive switch to obtain low inductance, and the method of measuring current are discussed. The behavior of the surge generator when short circuited is determined from the current waveform, and inductance and resistance values are deduced. The inductance and resistance of the switch are much less than those for the whole circuit, with a linear discharge in deuterium.

8.d. Liquid Dielectric Switches

Note: No published information has been located for evaluation to date. See Part G of the Abstracts for basic data on Breakdown in liquids.

8.e. <u>Breakdown Processes in Gases</u>

e.1. A. B. Shaw and D. Whittaker, "Effect of Gas Flow on Post-arc Gap Recovery," Proc. Instn. Electr. Engrs. <u>111</u>, 193 (1964)

Spark reignition voltage characteristics have been measured for gaps between stationary electrodes for various controlled speeds of gas flow following dc pulsed arc discharges. By varying the gap geometry, electrode material and duration of the initial arc, the influence of both the gas flow and the electrodes on the detailed shapes of the characteristics have been determined and qualitatively explained. A crude theoretical approach is described, in which the variation of spark reignition voltage is satisfactorily accounted for in terms of the average gap density as controlled by the initial electrode heating, the time constants of the conductive cooling of the gas and the electrodes, and the heat transport by the gas flow through the gap.

e.2. P. Felsenthal and J. M. Proud, "Nanosecond Pulse Breakdown in Gases," RADC-TRD-64-38 (1964)

It is shown analytically that under certain conditions pulsed dc and pulsed microwave breakdown are directly comparable. A pulsed dc experimental system to measure breakdown over a wide range of applied voltage, gas pressure and gap distance has been used to measure formative time in air, helium and nitrogen. The results when compared with the theoretical predictions of breakdown confirm the utility of the theory in describing breakdown within the imposed limits. The accuracy and extent of the present measurements materially extend the present range of pulsed microwave breakdown data.

e.3. D. T. A. Blair, F. M. Bruce and D. J. Tedford, "Analysis of Pre-Breakdown Current Pulses in Gas Discharge Gaps," Proc. Instn. Elect. Engrs. <u>110</u>, 2073 (1963)

The paper presents the theory relating the shape of the observed current pulses of individual electron avalanches to the physical processes involved, and indicates how measurements from the observed pulses can yield quantitative data on these processes. The theory is developed separately for gases which do not form negative ions and for those which do. The initial part of the paper is similar to previous work by K. J. Schmidt, with the differences that, in the present work, the case of avalanches initiated part-way across the gap is discussed and that it is not assumed here that the positive and negative ions have equal drift velocities. The final Section of the paper considers the effect of inductance in the circuit containing the discharge gap.

e.4. J. M. Proud and P. Felsenthal, "Nanosecond Breakdown in Gases," RADC-TDR-62-617 (1962)

A six-month program to investigate nanosecond breakdown in gases has demonstrated the utility and feasibility of a video pulse technique for obtaining data. It has been shown analytically that conditions exist for which the same theory of breakdown is applicable to both microwave and video pulse breakdown. Results of preliminary experiments conducted in air at pressures down to about 4 mm Hg are in general accord with theory. Data have been obtained for video pulses of 4.0 and 8.0 nanoseconds.

e.5. M. P. Vanyukov, V. I. Isaenko and G. N. Traveleev, "Dielectric Strength Recovery of a Spark Gap in a Repeating-Discharge Regime," Zh. Tekh. Fiz 32, 746 (1962)

The range of controllability of the breakdown voltage in a spark discharge and the behaviour of the dielectric strength recovery time in the discharge gap as a function of the discharge repetition rate is determined. It is shown that the upper limit of the discharge repetition rate is limited by the establishment of a stationary discharge in the case of xenon, and by irregularities in the breakdown in the case of air.

e.6. G. A. Farrall, "Cranberg Hypothesis of Vacuum Breakdown as Applied to Impulse Voltages, "J. Appl. Phys. 33, 96 (1962)

If the Cranberg hypothesis for breakdown in vacuum is valid, measurements made using impulse and dc voltages may yield different results depending in part upon the rate of rise of the impulse and the nature of the attachment of the "clumps" to the parent electrode. It is assumed that metallic clumps are instantaneously detached from an electrode surface at a voltage dependent upon gap length as described by Cranberg. Consideration of the rise in impulse voltage occurring during the transit time of the clump to the opposing electrode yields the following results. For an over-volting impulse of constant rise rate the breakdown voltage of a vacuum gap depends upon the 5/6 power of the gap length in the limiting case of large gap length and clump radii, and fast rise impulses. For the same limiting conditions, with an impulse of constant rise time, the breakdown voltage was found to be related to the 5/2 power of the gap length. A brief comparison of calculated results with experimental data in the literature indicates limited, although not conclusive, support for the Cranberg hypothesis in its application to impulse breakdown in vacuum.

e.7. H. Hamisch, "Surface Discharges Across Insulators in Vacuum," Electron Microscopy Conference, Philadelphia (1962) Ger.

Discusses an investigation of the pre-breakdown effects occurring at solid insulators in a vacuum gap. Insulators were bombarded with low-energy electrons at the cathode side of the insulator. Measurements were made of the resultant current density at various points on the anode due to the release of secondary electrons along the length of the insulator and of the charge density on the insulator as the angle of inclination with the cathode was varied. Suggested ways of improving the breakdown strength across insulators in vacuum include ensuring that increases in the field strength at the cathode are avoided and that the insulator surface does not become positively charged. The latter conditions can be satisfied by inclining the insulator at a suitable angle to the cathode.

e.8. R. F. Saxe, "The Breakdown of a Triggered Spark Gap," Proc. of the Fifth Intl. Conf. on Ionization Phenomena in Gases, Munich (1961)

The breakdown of a triggered, plane-parallel gap has been studied by a Schlieren technique. It has been established that, at least for low values of the applied voltage, breakdown is caused by the shock wave emitted by the trigger spark. The pre-breakdown channel in the main spark has been studied by the same technique and some of the implications of these measurements are discussed.

e.9. A. B. Boim and E. M. Reikhrudel, "Initial Stages of Low Pressure Pulse Disch," Zh. Tekh. Fiz. 31, 1127 (1961)

A study was made of the ignition of a pulse discharge in a tube containing a cold cathode with a trigger electrode, at initial pressures 10^{-4} - 10^{-6} mm Hg and initial voltages 30 - 60 kv. A study of the current and voltage variation with time by oscillography and simultaneous measurement of the integral intensity of the X-ray emission of the discharge showed that ignition of the pulse discharge passes through a stage of predischarge pulses prior to the stage of the gas-focused beam. The lifetime (τ_2) of the predischarge pulse stage with fixed initial conditions (capacitance and initial voltage of pulse generator, degree of outgassing of electrodes, pressure) depends on the emissive properties of the cold cathode; τ_2 can be prolonged from one microsecond to several milliseconds by variation of the resistance (R_t) in the trigger-gap circuit. The investigated prolongation of ignition can be used for control of the duration (τ) of the electron-optical stage, which includes the above-mentioned stages, of the pulse discharge.

e.10. T. E. Broadbent, "The Breakdown Mechanism of Certain Triggered Spark Gaps," Brit, J. Appl. Phys. 8, 37 (1957)

Experiments designed to investigate the breakdown mechanism of certain triggered spark gaps in air are described. Possible theories of the breakdown mechanism of the trigatron and the thermally triggered spark gap are put forward, based on experimental voltage and time lag to breakdown characteristics, corona measurements, and on optical studies using a photomultiplier. It is shown that the mechanism of breakdown for the two forms of triggered spark gap may be similar and depend, with positive charging polarities, on the movement of positive ions followed by a streamer process, and, in the case of negative charging polarities, on a streamer process only.

e.11. E. Z. Efendiev, "An Investigation of the Pulse Breakdown of Gases and the Rate of Development of Electron Avalanches," Zh, Tekh. Fiz. 27, 1010 (1957)

Measurements of the rate of avalanche formation for helium, air and SF_6 have been made using overvoltages as high as 60%. The results of the measurements in relation to the Meek-Loeb streamer theory are given.

e.12. R. F. Saxe and R. A. Chippendale, "Millimicrosecond Exposures by Image Tubes," Brit, J. Appl. Phys. 6, 336 (1955)

The technique whereby an image tube and a coaxial system may be used to obtain pictures with an exposure not exceeding 4 mμs is described. Pictures showing the growth of a streamer across a gap in approximately 4 mμs are given. The limitations of this technique are briefly discussed, and it is estimated that exposures of the order of 10^{-10}s should be possible.

e.13. R. C. Fletcher, "Impulse Breakdown in the 10^{-9}-Sec. Range of Air at Atmospheric Pressure," Phys. Rev. 76, 1501 (1949)

The formative lag of spark breakdown has been measured over the range from 0.5 to 50 x 10^{-9} sec. using transmission line circuits in conjunction with the micro-oscillograph. It is found to be a function only of the applied field (independent of gap-width) for the shorter times (high fields), but to increase for decreasing gap-widths for the longer times (low fields). A calculation of the formative lag is presented which is based on the assumption that it consists mainly of the time for a single electron avalanche to build up a space-charge field comparable with the applied field. This predicts the observed formative lags within the experimental accuracy of the measurement over the entire range used. The increasing times for decreasing gap-widths for the longer times is interpreted as the transition from a single avalanche to a multiple avalanche mechanism of breakdown. The critical field where this transition takes place for a given gap-width is computed and found to predict the observed critical fields within the experimental accuracy. The good agreement between theory and experiment enables a more reliable prediction than has previously been possible of the critical gap-width above which the threshold field is determined by a single avalanche mechanism.

A sharp drop in the rate of fall of the breakdown voltage is observed for the shorter times. It is suggested that this may be a change in the mechanism of electron release from the cathode.

e.14. A. B. Parker, "Some Factors Governing the Repeated Operation of High Current Generators," Paper No. SB 5, 3rd Symposium on Engineering Problems in Thermonuclear Research, Munich (1964)

An experimental investigation of the recovery of air pressure spark gaps is described. Shock wave and pulse techniques are used to investigate the gap recovery period. Results obtained in air, hydrogen and argon are presented.

e.15. T. F. Godlove, "Nanosecond Triggering of Air Gaps with Intense Ultraviolet Light," J. Appl. Phys. 32, 1589 (1961)

Measurements are presented of the breakdown time of a conventional two-electrode air gap. The applied voltage is maintained below the sparking threshold and breakdown is caused by the emission of a 6-nanosec burst of photoelectrons from the cathode, which produces space-charge distortion of the electric field. An auxiliary trigger spark provides the necessary light and results in cathode emission up to $\sim$ 10 ma/cm^2. The dominant wavelength region is found to be $\sim$ 1100A° because of the relatively low air absorption and high photoelectric yield in this region. For a fixed gap spacing and using the highest light intensity available, the time delay is typically found to decrease from $\sim$ 5t - to a minimum delay t - as the main gap voltage is increased from $\sim$ 8% below threshold up to threshold. The minimum delay ranges from 10 - 60 nanosec for the gap spacings studied and agrees with calculated values of gap spacing/electron drift velocity. The techniques developed have direct application to the triggering of conventional spark-gap switches and to pulsed light sources and may provide an additional tool for investigating some of the basic parameters of gaseous electronics.

e.16. T. E. Broadbent and A. H. A. Shlash, "The Development of the Discharge in the Trigatron Spark Gap at Very High Voltages," Brit, J. Appl. Phys. 14, 687 (1963)

The optical phenomena occurring during the initiation of breakdown in the trigatron spark gap in air have been investigated with voltages up to 2 MV and inter-electrode spacings up to 60 cm, using an image converter as an electro-optical shutter. Measurements of gap current flowing during the breakdown initiation process have also been made. The optical phenomena are similar in nature to those occurring in long untriggered gaps. One or more leader strokes occur, followed by a main stroke. Leader stroke velocities fall within the range 5×10^6 to

$3{\cdot}2 \times 10^8$ cm sec^{-1}, depending on experimental conditions. The average main-stroke velocity is about 10^8 to 10^9 cm sec^{-1}. Under certain conditions the path taken by the complete spark is partly governed by the production of a short leader stroke originating at one electrode. It is shown that this leader occurs only in the region of the gap where conditions laid down by Loeb and Meek and Raether as being suitable for streamer formation and propagation, are satisfied.

e.17. T. Ishikawa "Effect of the Plasma Jet in a Double Electrode Spark Gap" J. Phys. Soc. Japan 19, 367 (1964)

The mechanism of trigger action in a double electrode spark gap was investigated, clarifying the role of a plasma-jet measured under several different voltages. Form and growth of a plasma-jet were observed with a suitable arrangement of a lens and a photo cell.

The results show that the trigger mechanism may be assumed as follows: (1) A plasma-jet, ejected with a trigger spark, behaves itself like a protruding conductive stick. (2) Electric field strength in the gap is increased with growth of the jet. (3) A main spark is initiated in the space between the jet-front and the anti-electrode. (4) The critical distance between the jet-front and the anti-electrode is dependent on the voltage applied to the anti-electrode, and independent of gap length. Ions transported by the plasma-jet help to initiate the main spark.

From these assumptions, sparking voltage and time lag characteristics, fluctuation of time lags, and effect of various factors are explained.

e.18. J. D. Clarke, P. J. Hutton "Triggering of Undervolted Spark Gaps by a Microsecond Pulse of Fast Electrons" Proc. of the Sixth Int. Conf. on Ionization Phenomena in Gases. Paris (1963)

Triggering of undervolted spark gaps by an intense volume-ionizing pulse has been investigated experimentally and theoretically. Nitrogen-and hydrogen-filled gaps with static breakdown potentials of 1.2-13 kv were traversed by an 0.8 μ s pulse of relativistic electrons. The minimum triggering voltage fell with increase in pulse strength to as little as 20% of static.

A theory of the effect is based on the hypotheses that breakdown ensues, if field distortion by space charge is such that the Townsend criterion for static breakdown is fulfilled. Order of magnitude agreement with experiment is obtained with even a crude version of this theory; there is better agreement with less approximate numerical computations, if for the electron ionization coefficient in nitrogen, the values of Masch and Posin are used.

e.19 D.H.J. Goodall and R. Hancox "Formative Time Lags in a Pressurized Spark Gap" Proc. of the Sixth Int. Conf. On Ionization Phenomena in Gases", Paris (1963)

Measurements have been made of the formative time lag in air, oxygen, and nitrogen, in a uniform field gap. Gas pressures from 1 to 5 atmospheres (absolute) and electrode separation of 2 to 5 mm, were used. Time lags in the range 5 to 250 nsec were observed, using fields up to 220 kv/cm. The formative time lag was independent of the electrode separation at high overvoltage, and decreased with increasing pressure.

More accurate measurements in air at atmospheric pressure showed a step in the curve of time lag as a function of voltage, occurring at a time lag which was consistent with the time required for a single avalanche to cross the gap.

e.20. W. K. Pendleton, A. H. Guenther "Investigation of a Laser Triggered Spark Gap" submitted to Review of Scientific Instruments. (1965)

The influence of parameters affecting the laser triggering of a high-voltage electrical sphere-sphere gap has been experimentally investigated. Of primary interest was the delay time between arrival of the laser pulse and current flow across the gap. This delay was studied as a function of total laser beam power (0-80 megawatts); dielectric gas (SF_6, N_2, Air); gas pressure (100-1400 torr); electrode spacing (0.4-1.5 cm); gap electric field (10-;00 kv/cm) and focus point location between two 5-cm diameter stainless steel spheres. Delay times less than 10 nanoseconds were observed in SF_6 at atmospheric pressure with corresponding low jitter. For the cases studied, delay times varied inversely with the electric field, gas pressure, and focus point distance from the anode surface. Above a certain laser beam power the dalay time was not a significant function of laser power for the range studies. Applications of laser triggering are discussed with a description of current and future research areas.

e.21. A. B. Parker and D. E. Poole, "Cooling of High Current Spark Channels in Hydrogen and Argon" Brit. J. Appl. Phys. 15, 1011 (1964)

The considerable importance of gas temperature in the dielectric recovery of high current spark gaps using air as the dielectric has been demonstrated in previous papers. It was obvious however, that some other processes were effecting recovery with some electrode configuration. This paper describes similar experiments with both argon and hydrogen as the dielectric. It is confirmed that other processes might predominate even in the later stages of recovery, and possible effects are briefly discussed.

A simple model is used to calculate temperature decay, which gives fair agreement with measured values.

e.22. A. Goldman, M. Goldman, J. Reinhardt "On the Mechanism of Triggering in Trigatrons "Proc. of the Sixth Int. Conf. on Ionization Phenomena in Gases," Paris (1963)

In a trigatron the leader of the initiating spark has an important part in its mechanism of breakdown. When expanded it takes roughly conical shape and can be considered as a conductor which reduces the breakdown interval and modifies the sphere-sphere geometry into a point-sphere one.

8.f. Breakdown Processes in Solids

f.1. G. Ascarelli, "Low Field Breakdown in n Type Germanium, "Nuovo Cimento 22, 251 (1961)

Measurements of the time necessary to produce low field breakdown in n-type germanium have been made as a function of the applied electric field: this time interval is proportional to E^{-2}. The experimental results presented herein as well as the results obtained from dc measurements, can be explained on the basis of the avalanche multiplication model of breakdown.

f.2. M. N. Azam and H. Dickinson, "Time Lags in the Electrical Breakdown of Glass Immersed in Water," Brit. J. Appl. Phys. 12, 419 (1961)

When measuring the electric breakdown strength of cover glass immersed in deionized water, time lags to breakdown were observed. The mean statistical time lag was (12 ± 1) microseconds. The breakdown strength between spherical electrodes was found to be (11.4 ± 1) $\times 10^6$ v/cm.

f.3. R. Cooper and D. T. Grossart, "Time Lags in the Intrinsic Electric Breakdown of Solid Dielectrics," Proc. Phys. Soc. B69, 1351 (1956)

Time lag distributions for intrinsic breakdown in potassium chloride, potassium bromide and sodium chloride, were measured and found to be substantially the same. The distribution of time lags may be represented by $n = n_o \exp(-t/T)$ where T is the order of 1 microsecond for the above solids. Measurements on polystyrene and polythene could also be represented by the above equation with $T = 0.25$ microsecond.

f.4. S. I. Reynolds, "On the Behaviour of Natural and Artifical Voids in Insulation Under Internal Discharge," AIEE Transaction 77, III, 1604(1954)

Studies made on insulation containing natural voids which usually occur as prolete spheriods and on artifical voids in the form of cylindrical cavities, show that the discharge inception voltage is considerably different in the types of voids.

f.5. F. Forlani and N. Minnaja "Thickness Influence in Breakdown Phenomena of thin Dielectric Films" Phys. Status Solidi 4, 311 (1964)

The dependence on thickness of breakdown phenomena in thin dielectric films is considered, using the theory which attributes breakdown to electron ionization avalanche. On the basis of the electron-lattice scattering mechanism in dielectric materials and the electron behaviour in the conduction band of the dielectric, the ionization avalanche probability is derived and the current density evaluated by considering the tunnel-effect injection of electrons at the negative bias contact. It is assumed that breakdown occurs when the current density, at some point within the dielectric layer, reaches a particular value which depends upon the dielectric under consideration.

The correlation between breakdown field strengths and thickness agrees satisfactorily with published experimental results. The results derived are applicable to an estimate of the temperature of electrons injected by a tunnel cathode of the metal-dielectric-metal type.

f.6. L. Alston "Effects Due to Voltage Waveshape and Void Parameters" "Proc. Intern. Conf. On Gas Discharges and the Electricity Supply Industry" (1962)

A review of the effects of applied voltage waveshape on the electrical breakdown of solid insulation by discharges in voids is presented, together with data on effects due to void size and position. It is shown that the life of insulation subjected to voltage pulses may decrease if (1) the peak value, (2) the peak-to-peak value, (3) the rate of change of voltage, (4) the pulse duration, or (5) the interval between pulses is increased. Experiments are described where polythene samples containing artifical voids were subjected to unidirectional pulses of rectified 50 c/sec alternating voltage and 1/50 μ sec impulses. Results show that at high stresses with the void adjacent to the anode breakdown may occur in a shorter time than when the void is adjacent to the cathode. It is suggested that the present results indicate that intrinsic breakdown of the polythene occurred after relatively little erosion by discharges and, at high stresses where intrinsic breakdown may occur, voids adjacent to the anode are more deleterious, but at lower stresses where the mechanism of erosion predominates, voids at the anode are less harmful than at the cathode.

f.7. Y. Inuishi, "On the Pulse Breakdown of Plastic Films at Higher Temperatures" J. Proc. Phys. Soc, Japan 12, 1299 (1956)

Pulse breakdown measurements in the 1 to 10^9 microsecond range for films of polyethylene and mylar have been made. A temperature range of 5^o to 78^oC is covered. The dependence of pulse breakdown on pulse duration and temperature is shown.

8.g. Breakdown Processes in Liquids

g.1. J. A. Kok, J. W. Poll and C. E. Van Vroonhoven, "Electrical Breakdown of Hydrocarbon Oil and Liquified Gases", Dielectrics 1, 91 (1963)

A colloid-chemical theory of oil breakdown as a consequence of the formation of bridges consisting of conductive particles flowing towards a place of maximum stress is attempted. A relation is derived between the breakdown stress and the radius of the particles, coarser particles corresponding to lower breakdown strengths. Coarsening (flocculation) of the particles by attractive physical forces or chemical binding may be prevented by the presence or the addition of natural or synthetic inhibitors such as soaps and aromatic inhibitors having long aliphatic tails, which supply the impurities (carbon particles, minute cellulose fibres) with a cover (thickness > 20 Å) protecting them against further flocculation. The breakdown strength of liquid nitrogen shows other features; depending on the degree of purity, values of 93 kV/mm to 226 kV/mm have been published. The values of the breakdown strengths of liquid helium at 1.3 to 4.2°K agree with the sizes of the hypothetical polarized solid cage-like or bunch-like ionic helium structures of a size of 3 to 6 A° diameter, such as have been conceived for other reasons by Atkins and Careri.

g.2. D. W. Swan, "A Review of Recent Invesigations Into Electrical Conduction and Breakdown of Dielectric Liquids", Brit. J. Appl. Phys. 13, 208 (1962)

Recent work concerning electrical breakdown and conduction in dielectric liquids is reviewed. Particular emphasis is given to liquids of simple molecular structure although reference is made to some investigations using complex oils where the results obtained are also applicable to other liquids. Conduction measurements have been extended to fields up to 1.3 MV cm^{-1} using microsecond pulse techniques, and under these conditions very large currents are observed. The evidence concerning a collision ionization process is conflicting. Negative ion mobility measurements have been reported for fields of 600 kv cm^{-1} in n-Hexane, and both the positive and negative ion mobilities in superfluid liquid helium have been thoroughly investigated. Electrical breakdown of liquid argon has revealed pronounced electrode effects, and the influence of the anode is particularly emphasized. Dissolved oxygen is found to increase the strength of a liquid and to give rise to a number of effects which can be explained by assuming the formation of space charge layers at the electrodes. Recent measurements of formative and statistical time lags in n-Hexane have shown that previous interpretations were frequently incorrect.

g.3. T. J. Lewis and B. W. Ward, "A Statistical Interpretation of the Electrical Breakdown of Liquid Dielectrics," Proc. Roy. Soc. A269. 233 (1962)

Previous investigators, when measuring the electric strength of hydrocarbon liquids with short-duration rectangular pulses have assumed that the statistical component of the breakdown time was significant compared with the formative time. In the present investigation, however, the time to breakdown was measured directly by the use of step-function pulses, and clear evidence for a statistical time lag was found. The formative time was was 0.1 μsec, being less than that given by previous estimates. A statistical interpretation of short-pulse measurements is presented and this provides a consistent explanation of the results of other workers. Furthermore, by using an experimentally derived equation for the variation of the mean rate of breakdown f(E) with applied stress E, it has been shown that the form of the relationship between strength and pulse duration obtained by other workers agrees with that obtained by statistical analysis. Experiments on air-saturated n-Hexane with both short-duration and step-function pulses support the statistical ideas presented and indicate that electrode conditions are extremely important. It was found that strength and time to breakdown were affected by the number of breakdown measurements on a sample. Experiments with gas-free, n-Hexane and non-uniform fields have demonstrated the importance of air content when long duration pulses are used. It was found that, although the statistical time lag was insignificant, formative time lags as long as 10μ sec occurred with a point cathode-sphere anode configuration.

g.4. V. S. Komel'kov, "Development of Pulse Discharge in Liquids", Zh. Tekh. Fiz. 31, 948 (1961)

Shows experimentally that pulse discharges in polarized (distilled water) and nonpolarized (transformer oil) liquids are the result of a leader process. In a low-resistance discharge circuit the leader develops continuously. In a high-resistance discharge circuit a stepwise movement of the leader from electrode to electrode is noted. In oil a secondary discharge takes place after the completion of the leader stage. A qualitative analysis of the phenomena under study is presented.

g.5. Y. Murooka, S. Nagao and Y. Toriyama, "The Research of Spark Mechanism in Liquid With Bubble Chamber, "ETJ Japan 6, 56 (1961)

The paper describes the construction of two bubble chambers and discusses some of the experimental results obtained with these. If a heated liquid, under high pressure is suddently made overheated, by lowering the pressure, infinitesimal bubbles, already existing in the liquid, begin to grow. If any such bubbles have ions stuck to their surface they will grow much faster than those without ions. Therefore observation of such bubbles gives an indication of the place of emission and subsequent movement of any ions. In the experiments diethyl ether, at about 100° - $140^{\circ}C$, sphere, disk and needle electrodes, mm gaps and stresses in the MV/cm range were used. It was found that the rate of generation of bubbles was proportional to the surface area of the electrodes, in general bubbles started from both electrodes at right angles to the surface of the electrodes and tended to move along the lines of electric force, and that the bubble figures starting from the side of the positive electrode extended more than those from the negative side. It was concluded that ionic conduction, based on the electrical discharge of gases absorbed on the surface of the electrodes, was predominant in the conduction in the liquid under 0.3 MV/cm and that electronic conduction came into effect when the electric field was raised to about 1.0 MV/cm.

g.6. R. W. Crowe, "Formative Time Lags in the Electric Breakdown of Liquid Hydrocarbons", J. Appl. Phys. 27, 156 (1956)

Recent investigations of the time dependence of electrical breakdown in liquid hydrocarbons have led to a disagreement regarding the influence of molecular structure upon the formative time lag. This paper represents an attempt to resolve the discrepancy, and to determine if possible the significance of the time lag in the breakdown process. The experiments involve the application of rectangular pulses of voltage of variable duration and amplitude to the liquids between hemispherical electrodes.

The results of the investigation show definitely that the formative time lag is insensitive to changes in the molecular weight of the hydrocarbon liquid. Consequently, it cannot be associated with the time required for positive ions to cross the spark gap, as has been suggested by recent investigators. Its characteristic dependence upon the electrode separation, however, suggests that it may be mainly a measure of the transit time of an electron or an electron avalanche.

g.7. R. F. Saxe, T. J. Lewis, "Measurement of the Statistical Time Lag of Breakdown in Gases and Liquids," Brit, J. Appl. Phys. 6, 211 (1955)

It has been shown by earlier workers that the observation of the statistical distribution of time lags to breakdown of small spark gaps may provide information concerning the emission of electrons from the cathode. This paper discusses the restrictions imposed by this method of cathode emission. Since the measuring technique causes the surface being investigated to undergo a change, efficient spark quenching should be provided to reduce this change to a minimum. A circuit which provides efficient spark quenching is described, together with a novel circuit to record a set of time lags automatically. Preliminary experiments show that "conditioning" of the cathode surface in air is now more rapid than that obtained by previous workers, and the reasons for this are discussed. Further, application of the method to the breakdown of small gaps in n-hexane indicates that the behaviour is similar to that of a gap in air in that "conditioning" of the cathode surface and a statistical variation of time lags occur.

g.8. R. W. Crowe, J. K. Bragg and A. H. Sharbaugh, "On the Electric Strengths of Aliphatic Hydrocarbons", J. Appl. Phys. 25, 392 (1954)

Paschen's similarity law, which expresses a certain relationship between the breakdown voltage of a gas, the gas pressure, and the distance between electrodes, is known to fail at high pressures. This is owing, at least in part, to a change in the way in which electrons dissipate energy to the gas molecules. At high enough pressure, the electron transfers energy principally to molecular vibrations. In condensed phases this vibrational barrier is dominant, and one should expect a new kind of similarity law to hold under certain controlled conditions. The liquid aliphatic hydrocarbons provide an illustration of such a law. The electric strengths of nine hydrocarbons of various densities were measured and found to depend linearly upon density. It has also been found that the temperature dependence of the electric strength of a liquid aliphatic hydrocarbon can be accounted for by the change in density of the liquid due to thermal expansion.

g.9. J. A. Kok, J. W. Poll and C. E. G. M. M. Van Vroonhoven "Breakdown Tests Carried Out on Liquified Gases" Appl. Sci. Res. B 10, 257 (1963)

An explanation has been attempted of the mechanism of the breakdown strength of liquified gases such as A, N_2, O_2, and He.

It has been shown that these values may in part be explained by assuming the presence of minute contaminations such as P_2, O_5, Cr_2 O_3 or ice crystal unit cells. These polarized contaminants tend to align in a bridge at a high field strength and become the cause of a breakdown. For an explanation of the results of Blank et al. in helium the units of such a bridge are assumed to be polarized clusters or rigid cage-like structures. The positive ion is a solid cluster of He atoms polarized around a positive charge, which may change its site while still remaining inside the cluster. A negative charge is a cloud of electrons or a negative ion, self-trapped by a shell of say 50 polarized atoms. The experimentally determined sizes of these contaminants or calculated clusters or cage-like structures are in agreement with the values calculated in the theory given here.

g.10. M. E. Zein Eldine, A. A. Zaky, R. Haeley, M. C. Cullingford "Influence of Electrode Coatings on Space Charge Distributions in Transformer Oil" Nature 201, 1309 (1964)

Field plots are made for coated and uncoated electrodes immersed in transformer oil. The results are related to breakdown in liquids.

g.11. Y. Toriyama, T. Sato and H. Mitsui, "Dielectric Breakdown of Insulating Fluids" Brit. J. Appl. Phys. 15, 203 (1964)

Lichtenberg figures in insulating oil are employed in order to make clear the breakdown mechanism of a dielectric liquid.

The thin figure, which may be explained as the trace of the pure electronic process in the liquid, is not affected by the variation of atmospheric pressure above the oil surface; but the thick figure, which may show the discharge in the gas phase produced by the rupture of the bonding of the oil molecules by electron bombardment, is greatly broadened by reduction of pressure.

Even when an initial discharge takes place in the gas phase and breakdown occurs at lower field strength, the pure electronic process in liquid remains unchanged.

These results are in agreement with those of spectrographic observation of impulse corona in liquids.

g.12. A. M. Hug and H. Tropper "Conduction Current Pulses in Organic Insulating Liquids Under Electrical Stress" Brit. J. Appl. Phys. 15, 481 (1964)

The mean square values of conduction current fluctuations in organic insulating liquids under high direct electrical stresses were measured by customary noise measurement methods. The effect of dissolved air, oxygen and nitrogen was studied, as well as that of anthraquinone which is known to have an important effect on the gassing properties of transformer oil. Both uniform and non-uniform electrode configurations were used, and pulses in liquid paraffin, one of the main constituents of transformer oil, were also investigated. It was shown that the presence of limited quantities of air and especially oxygen had an important influence on the magnitude and the pattern of the conduction current pulses in insulating liquids. The role of the unsaturated organic constituents of transformer oil in improving its behaviour under electrical stress seemed also to be clearly indicated.

8.h. High Voltage Pulse Generation Techniques

h.1. A. I. Pavlovskii and G. V. Sklizkov, "Obtaining High-Voltage Square Pulses", Pribory i Tekh. Eksper. 2, 98 (1962)

The paper describes a new method for obtaining square pulses whose amplitude exceeds the charging voltage applied to the transmission line which forms the pulses by a factor of several times. The circuit and construction are cited for an oscillator which produces a square pulse with an amplitude of 160 KV and a current of 600 amp when it operates into a matched load of 250 ohm, and a pulse amplitude of up to 300 KV when it operates into a load of 200 ohm.

h.2. S. I. Andreev, M. P. Vanyukov and V. A. Serebryakov, "The Use of Ferrites for the Generation of Powerful High Voltage Pulses of Nanosecond Duration", Pribory i Tekh. Eksper. 3, 89 (1962)

When a conductor loaded with ferrite toroids is connected into the circuit of a high-current spark discharge it is observed that high-voltage nanosecond impulses arise across the loaded segment with powers of the order of 10^6 W. Data are presented concerning the influence of the discharge parameters on the amplitude, duration and repetition frequency of these impulses.

h.3. A. A. Vorob'ev, G. A. Vorob'ev, G. A. Mesyats and A. I. Golynskii, "A Generator Which Produces High-Voltage Pulses of Millimicrosecond Duration", Pribory i Tekh. Eksper. 1, 96 (1962)

The paper describes a generator which produces short high-voltage pulses; the generator output consists of signal pulses 15 kv in amplitude with a trailing edge duration of less than 1 millimicrosecond and a duration that can be controlled over the range 10 to 40 millimicroseconds. The generator consists of a shaping cable, a multielectrode commutating spark gap transmission lines, and devices for compensating the leading edge of the pulse and for shortening its duration. The compensating system includes a compensating capacitor and a peaking spark gap. The generator is simply constructed and easily adjustable in comparison with known units.

h.4. O. S. Kolotov, Y. N. Lobanov and Z. Shil'berskii, "A Source of Nanosecond Pulses of Continuously Variable Width," Pribory i Tekh. Eksper. 3, 87 (1961)

A description is given of a generator that produces square pulses of maximum amplitude 1.2 KV; the pulse length can be adjusted continuously between limits of 3 and 300 mμsec.

h.5. S. I. Andreev and M. P. Vanyukov, "Application of a Spark Discharge to Obtain Intense Light Flashes on Length 10^{-7} - 10^{-8} Sec.," Zh. Tekh. Fiz. 31, 961 (1961)

The methodology and results of an investigation of a spark discharge of short duration with very steep rise of current are presented. For this case, there is established a significant effect of the internal impedance of the spark channel on the value of the maximum steepness of the current rise. A check of the applicability of the theory of Weizel and Rompe, and also of the law of Tepler to the type of discharge under consideration was carried out.

h.6. T. J. Tucker, "Square-Wave Generator for the Study of Exploding Wires", Rev. Sci. Instr. 31, 165 (1960)

A 100 KV coaxial cable square-wave generator producing a 2000-amp 3μ sec duration, 6mμ sec rise time, current pulse has been constructed for the study of exploding wires. Unlike conventional capacitor current sources the circuit behaviour is described by algebraic rather than nonlinear differential equations, thus allowing easier and surer interpretation of results. Using coaxial-cable techniques for the entire system also provides mμsec resolution of current and voltage wave forms. The system features an output timing pulse, occurring 1.5 ± 0.005μ sec prior to the beginning of the wire explosion which provides triggering for oscilloscopes and for a 5-mμsec exposure time Kerr-cell camera. The electrical isolation of the output trigger pulse from the monitored signal also eliminates wave form distortion produced by trigger circuit loading and signal delay.

h.7. G. A. Theophanis, "Millimicrosecond Triggering of High Voltage Spark Gaps", Rev. Sci. Instr. 31, 427 (1960)

Pulse transformers often are employed in circuits which are used to trigger spark gaps. There are limitations in the use of this type of generator when a high degree of accuracy is desired. When operating light sources in conjunction with Kerr cell shutters, synchronization of the light source and shutter must be accomplished with a jitter of no more than a few millimicroseconds. Pulse requirements and spark gap conditions for millimicrosecond triggering are defined. Several transformerless trigger pulse generators are described. One of these has been used to trigger 50 -KV spark gaps with jitter times as low as 2 mμsec. A number of techniques for synchronizing the firing of spark gaps are discussed and some uses of these techniques are given. Several methods for pulsing Kerr cells using accurately triggered spark gaps also are described.

h.8. T. E. Broadbent, "New High-Voltage Multi-Stage Impulse Generator Circuit," J. Sci, Instr. 37, 231 (1960)

A new high-voltage multi-stage impulse generator circuit is described. The circuit is based on conventional multi-stage impulse generator circuits but trigatrons are used in each state in place of the sphere gaps used in conventional circuits. The triggering pulse necessary to fire each trigatron is derived from the breakdown of the previous stage. For all multi-stage impulse generators of this type (other than very small ones), the stray capacitance coupling between stages is sufficient to operate the trigatrons, and no extra coupling capacitance is required. With the new circuit, multi-stage generators operate over a much greater range of voltage for given gap spacings in the various stages than is the case with the conventional circuits. The need for the spark gaps in each stage to be critically set is thereby eliminated. The results of an experimental comparison between the new and conventional circuits are described.

h.9. G. Sahner, "Die Erzeugung kurzer Impulse hoher Leistung unter Verwendung von Schaltfunkstrecken," Nachrichten technik. 9, 36(1959)

A theoretical basis for determing the electrical characteristics of a spark channel versus time is derived. The theoretical results are then compared with experiment. Emphasis is placed on the early time history of the spark channel development and its application to pulse generators.

h.10. C.N. Winningstad, "Nanosecond Pulse Transformers," IRE Trans. on Nuc. Sci., March, 1959, 26.

The transmission-line approach to the design of transformers yields a unit with no first-order rise-time limit since this approach uses distributed rather than lumped constants. The total time delay through the transmission-line-type transformer may exceed the rise time by a large factor, unlike conventional transformers. The extra winding length can be employed to improve the low-frequency response of the unit.

Transformers can be made for impedance matching, pulse inverting, and dc isolation within the range of about 30 to 300 ohms with rise times of less than 0.5×10^{-9} seconds, and magnetizing time constants in excess of 5×10^{-7} seconds. Voltage-reflection coefficients of 0.05 or less, and voltage-transmission efficiencies of 0.95 or better can be achieved.

h.11. H. G. Heard, "20-Kilovolt Delta-Function Generator," Rev. Sci. Instr. 25, 454 (1954)

An electronically triggered impulse generator has been developed which produces 20 kilovolt pulses having rise times of less than 0.6 millimicrosecond. When used with a shorting stub, this instrument produces delta function pulses of less than 2.5 millimicrosecond total width at full amplitude. The functions of primary pulse generation and pulse sharpening are separated. A special 50-ohm coaxial switch was constructed of hydrogen thyratrons to produce 20 kilovolt primary pulses of arbitrary length and having rise times of less than 1.75 millimicroseconds. When triggered by a 2 -500 volt pulse of 5 millimicroseconds rise time, the over-all jitter of the system is of the order of 1 millimicrosecond.

h.12. J. Durnford and P. Reynolds, "Generation and Measurement of Oscillatory Current Impulses up to 470 kA," Proc. Instn. Elect. Engrs. 101, (Part IV, Monographs) No. 6, 1 (1954).

Investigations into the characteristics of spark discharges have been made for impulse currents of up to 100 kA peak. The generation of such currents is based on the techniques developed for surge-testing purposes to simulate lightning-stroke conditions. For oscillatory impulses the current is determined primarily by the discharge energy of the generator and the total effective inductance ($0.1\,\mu H$) and gives a peak current of 470 kA for a discharge energy of 18,000 joules at 25 KV. It is being used for studies of the spark channel under different conditions.

The measurement of impulse currents is normally made with the aid of a low-resistance shunt. A shunt of coaxial form, giving a small time-constant and freedom from unwanted coupling with the main current circuit, has been used with the above generator and is described.

h.13. D. H. Goodman, D. H. Sloan and E. Trau, "A High Voltage High Speed Square Wave Surge Generator", Rev. Sci, Instr. 23, 766 (1952)

A high speed surge generator design is given which reduces stray noise and provides a steeply rising (less than 10 n sec) voltage pulse of 80 KV and 1700 A°.

h.14. F. S. Edwards, A.S. Husbands and F. R. Perry, "The Development and Design of High-Voltage Impulse Generators", Proc. Instn. Elect. Engrs. 98, Part I, 155 (1951)

The paper explains the need for high-voltage impulse generators which will produce the standard voltage waveshapes specified for impulse testing. A theoretical analysis of the impulse generator and load circuit is given, and the development of the multi-stage generator for high voltages is described. The mechanism of operation of the multi-stage generator is analysed and is illustrated by oscillograms. Illustrations of two typical generators are shown, and some of the auxiliary equipment needed is briefly mentioned. The paper concludes with an example of impulse-testing technique.

h.15. H. Tigler, "Uber Impulse-Hochtastgerate fur Funkmess - Impulssender", Arch. Eleckt. Ubertragung 5, 47 (1951); 5, 91 (1951)

A review of pulse circuits used in modulator design is given. Hard tube, gas discharge and spark circuits are reviewed. Emphasis is placed on the generation of high voltage, high power short time pulse with particular examples of Marx type circuits.

h.16. R. L. Garwin, "A Pulse Generator for the Millimicrosecond Range", Rev. Sci. Instr. 21, 903 (1950)

A description is given of a laboratory pulse generator producing pulses with rise and decay times less than 2×10^{-10} sec at a repetition rate of 120/sec. Three simultaneous outputs are available, variable in amplitude from 100 microvolts to 100 volts and accurate to a few per cent.

h.17. E. L. White, "A Tripping Circuit for a Multi-Stage Surge Generator", J. Sci, Instr. 25, 307 (1948)

The sphere gap in the first stage of an existing multi-stage surge generator has been replaced by two equal gaps in series by introducing a third sphere. By applying an impulse to the centre sphere when the gaps are charged nearly to the breakdown voltage, breakdown can be initiated at a desired instant. This tripping impulse is generated by a thyratron becoming ionized when a low voltage impulse is applied to its grid, and simultaneously to the sweep circuit of the oscillograph. On account of the inherent time delay in the ionization of a thyratron, the sweep circuit is initiated before the surge generator. A delay cable in the measuring circuit is thus rendered unnecessary. Visual or automatic methods of controlling the output voltage of the generator can be used.

h.18. S. Darlington, "Impulse Generator", U.S. Patent No. 2, 420, 302 May 13, 1947

This patent describes impulse generating systems and more particularly circuits for generating impulses of controlled wave form and duration. Its principal objects are to facilitate the voltage transformation of an impulse while at the same time maintaining its wave form; to provide voltage multiplication without recourse to the use of electromagnetic transformers; and to increase the useful energy of generated impulses.

h.19. F. S. Goucher, J. R. Haynes, W. A. Depp and E. J. Ryder, "Spark Gap Switches for Radar", Bell System Tech. J. 25, 563 (1946)

A review of spark gap switching as applied to radar is presented. Detailed description of four spark gaps manufactured for use in radar sets during the Second World War are given.

h.20. K. J. R. Wilkinson, "Some Developments in High-Power Modulators for Radar", J. Instn. Elect. Engrs. 93, IIIA, 1090 (1946)

Modulators which depend upon the discharge of a pulse-shaping network, involve also the action of charging. These two component actions are inter-related but separate events, each with its set of characteristic problems. In dealing with these problems the paper first describes the principle of alternator charging, as it is applied to thyratron and to spark modulators, and compares this with a.c. rectifier charging.

It then discusses means, apart from the use of a pulse transformer, for generating higher pulse voltages than are possible by the discharge of a single pulse-shaping network. These include the Blumlein cable circuit, and the Marx connection of cables, with its auxiliary charging problem. Two forms of four-electrode air-blown triggered spark-gap are introduced, together with an account of the mechanisms of their triggering and of jitter. The paper outlines a theory for the series peaking transformer, which is an important component in triggering, and concludes with a description of modulators embodying these features, together with a reference to fault protection and to measures for the suppression of radar interference.

h.21. E. H. Beckner and R. H. Kotoski, "Ignitron-Switched 0.6 - to 90 KV Impulse Generator", Rev. Sci, Instr. 33, 914 (1962)

An ignitron-switched impulse generator has been developed, capable of providing a variable output voltage of from 0.6 to 90 KV with no circuit alterations. The generator consists of 6 capacitor stages, yielding a total energy of 5000 J at 90 KV, and is discharged with a single trigger pulse. The discharge time can be controlled to within 0.1μ sec.

h.22. E. Gygi and F. Schneider "A Nanosecond Pulse Generator of 200 KV Amplitude", Cern 64-46 November, 1964

The theory and realization of a fast Marx Generator are given. A 10 stage type has been developed with rise- and fall-times of 2 nsec. Depending on the load, a peak amplitude of about 200 KV was obtained. The delay between application of the trigger pulse and rise of the output pulse is about 10 nsec with a time jitter of 1 nsec maximum. Due to this small time jitter it is possible to connect several generators in parallel. It should be possible to apply the same construction principles to at least a 20-stage generator where one can expect about 400 KV, without increasing appreciably the rise- and fall-times.

8.i. Tabular Review Of Switch Characteristics

Part A - Gas Switch Parameters

Reference		V(kv)	I(ka)	Q(c)	τ_d(ns)	τ_j (ns)	L(nh)
a.1.	Exploding wire triggered air gap of wide voltage range	0.5-6	-	0.14	-	-	-
a.2	Wide range trigatron with hot filament, air gap	25-250	-	-	$\sim 10^3$	-	-
a.3.	Overvolted atmospheric to 5 psig, three electrode gap	25-45	250	0.09	$< 10^3$	$< 10^2$	35
a.4.	Triggered air gap for crowbar application	20	100	2.4	40	<5	35
a.5.	Trigatron of Simple construction at 2.7 atm air	7-50	200	1.2	5-20	2	10
a.6.	Air gap trigatron with low electrical noise	12	100	0.16	2×10^3	-	-
a.7.	High pressure switch for fractional nsec rise time	20	0.4	$\sim 10^{-5}$	-	-	~10
a.8.	Low inductance air gap triggered by plasma jet	1-10	-	0.4	-	2×10^2	4
a.9.	Three electrode, over-volted air gap	30-60	10^3	3	50	25	30

Reference		V(kv)	I(ka)	Q(c)	τ_d(ns)	τ_j (ns)	L(nh)
a.10.	High pressure (100 psig) gap with spark and over-voltage triggering	40-100	30	0.5	60	2-16	30
a.11.	Very high voltage gap triggered by hot wire	$(0.2-1) \times 10^3$	-	-	-	-	-
a.12	Three electrode, 200 psig overvolted gap	30-60	8.5×10^2	3	-	-	10
a.13.	Triga tron type air switch for crowbar application	5	-	-	5×10^3	200	-
a.14.	Fast, four electrode gap at 400 mm Hg	1.5-3	3	10^{-2}	10	-	-
a.15.	Wide voltage range air gap for crowbar	$10-10^3$	-	-	$<10^3$	-	-
a.16	UV triggered air gap	12	1	4×10^{-3}	-	8	-
a.17.	Three ball air gap with two trigger electrodes	5-70	100	~1	1	< 20	-
a.18.	Heavy duty trigatron with air gap	20-60	2.5	7×10^{-3}	-	100	-
a.19.	High voltage trigatron	100-200	-	-	-	100	-
a.20.	Air gap with magnetic blowing of arc	3-30	50	0.5	20	2	20
a.21.	Air gap with break-down along dielectric surface	9-14	-	-	-	-	-

Reference		V(kv)	I(ka)	Q(c)	τ_d(ns)	τ_j(ns)	L(nh)
a.22.	Fast, high pressure switch for Blumlein application	24	12	5×10^{-4}	4	2	<10
a.23.	High voltage trigatron in air	150	50	10^{-2}	300	50	-
a.24.	Air gap trigatron for high voltage diverter	$<10^3$	-	-	100	10	-
a.25.	Fast, three electrode air gap	30	30	3×10^{-3}	10	1	-
a.26.	Air gap trigatron	5-10	100	-	-	100	-
a.27.	High current switches with mechanical and spark triggers	4	2×10^3	12	-	-	1
a.28.	Air gap trigatron	~50	-	-	$\sim 10^3$	-	-
a.29.	Thermally triggered gap	200	-	-	5×10^4	-	-
a.30.	Six-ball air gap with overvolt trigger	130	20	5×10^{-2}	<50	-	-
a.31.	Various trigatron types and techniques	4-70	0.1	$\sim 10^{-4}$	-	-	-
a.32.	Air gap with X-ray triggering	5-20	-	-	-	100	-
a.33.	Thermotron, hot wire triggered gap	3-10	100	-	$\sim 10^5$	-	-
a.34.	Trigatron, needle trigger, 7 kg/cm nitrogen	15-25	-	6×10^{-4}	2-20	-	-

Reference	V(kv)	I(ka)	Q(c)	τ_d(ns)	τ_j (ns)	(L(nh)
a.35. Trigatron, low voltage trigger	3-9	-	$5x10^{-4}$	>5	0.5-3	-
a.36. Trigatron with U.V. illumination	30	5	$3.6x10^{-4}$	≤ 5	~ 3	
a.37 Pressurized trigatron 15-75 psi	10-50	-	-	< 20	-	30

Part B - Vacuum Switch Parameters

Reference		V(kv)	I(ka)	Q(c)	τ_d(ns)	τ_j(ns)	L(nh)
b.1.	BK 194 Ignitron	24	80	100	-	-	-
b.2.	Vacuum tee tube switch	20	125	~1	-	100	50
b.3.	Vacuum spark gap	50	10^3	-	-	<250	10
	High voltage ignitron ZG 7219-1	1-50	50	-	-	-	-
b.4.	Low pressure gas switch	30	$2x10^3$	-	-	-	3
	Low pressure gas switch	20	500	2.5	-	-	-
	Ignitron	25	100	18	$15x10^3$	-	40-100
	Hg vapor diode	80-100	50-150	15-90	10^3	-	60-100
b.5.	Plasma gun triggered low pressure switch	30	100	0.03	80-200	-	15
b.6.	Magnetic field triggered coaxial switch	50	-	-	-	-	-
b.7.	Gas triggered inverse pinch switch	10	-	0.15	-	-	4
b.8.	Low pressure trigatron	10	100	0.1	200	30	2-10
b.9.	Low pressure trigatron	4-100	0.05	-	$100-10^3$	-	-
b.9.	Parallel electrode pin triggered gap	2.5	-	-	$100-10^3$	-	-
b.10.	Graded vacuum switch	30-50	$2x10^3$	1.5	-	-	-
b.11.	Low pressure gas switch with spark plug	14	200	2.1	-	-	-
b.12.	Pyletron	40	50	50	100	-	-
b.13.	Low pressure gap with trigger pin	0.5-25	10-500	0.5	50-200	10	1-4

Reference	V(kv)	I(ka)	Q(c)	τ_d(ns)	τ_j(ns)	L(nh)
b.14 Electron Beam triggered vacuum gap	0.3-12	100	$\sim$10	$\sim 10^4$	$\sim 10^3$	-
b.15. Cold cathode thyratron	1.5	0.3	$\sim$0.1	3×10^3	-	-
b.16. Wide range low pressure spark gap	0.5-50	300	0.2	10-50	10-20	20
b.17. High power discharge tube VIR-100	100	$\sim$10	-	10^3-10^5	-	-
b.18. Plasma gun triggered switch	30	30	-	1.5×10^3	100	20
b.19. Low pressure tube with keep-alive discharge	5-10	5	-	20-100	10-100	
b.20. Graded vacuum spark gap	20	300	0.3	50	$<$20	5
b.21. High power graded spark gap	75	10^3	-	1.5×10^3	100	$<$30
b.22. The Baker switch	30	2×10^3	3	100	$<$100	2-4
b.23. Overvolted non-triggered statistical switch - 83 ohms	25-100		Statistical			
b.24. Pinch Switch gas triggered	10	300	.15	-	-	3

Part C - Solid Dielectric Switch Parameters

Reference		V(kv)	I(ka)	Q(c)	τ_d(ns)	τ_j (ns)	L(nh)
c.1.	Exploding wire triggered dielectric switch	10-20	10^3	-	100-300	50	~1
c.2.	Spark triggered dielectric switch	40	95	110	10^3	20-200	-
c.3.	Mechanically closed dielectric switch	100	100	$1-10^3$	$3x10^4$	10^3	-
c.4.	Solid dielectric trigatron	1-20	3-50	-	10^3	100	-
c.5.	Solid dielectric switch similar to c.1	10-20	100-200	0.12	300	-	2
c.6.	Solid dielectric triggered by explosive pellet	10	$\sim 10^3$	0.25-1	100	~100	0.5
c.7.	Explosive triggered dielectric switch	10	250	-	100	-	0.65

8.j. Author Index

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