A LOW-INDUCTANCE TRIGGERED MULTICHANNEL GAS SWITCH

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by

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ABSTRACT

Physics International has investigated the conditions necessary for obtaining consistent multiple-channel switching in a pressurized SF_6 spark gap of 5.5 nH effective inductance. The spark gap has been used to switch a 2.5-ohm line impedance Blumlein at voltages up to 400 kV with resultant pulse output risetimes of less than 5 nsec (10-90 percent).

FOREWORD

This report presents the results of a three-month program conducted to develop and demonstrate a triggered multichannel gas switch. Switches of this type should eventually supersede the replaceable stabbed-polyethylene switches which are now used on the Mylar-line pulse generators. The program was supported by IR&D contract No. 50-163.

CONTENTS

ILLUSTRATIONS

TABLES

LIST OF SYMBOLS

a	Length of Long Gap Spacing
b	Length of Short Gap Spacing
C_o	Marx Capacity
C_b	Blumlein Capacity
C_t	Trigger Electrode Capacity
L_o	Marx Inductance
L_1	Added Marx Inductance
N	Number of Spark Channels
P_{sb}	Self-Break Pressure
P_o	Operating Pressure
R_s	Trigger-Cable-Series Resistor
S_1	Master Switch
S_2	Multiple-Channel Main Switch
t	Blumlein Edge Thickness
t_{eff}	Full Time Width at 63 Percent of Peak
V	Pulse-Charge Voltage
V/n	Trigger Voltage
V_o	Operating Voltage
V_{sb}	Self-Breakdown Voltage
x	Grading Distance
Z_b	Blumlein Transmission Line Impedance
Z_t	Trigger-Cable Impedance

ρ_w	Water Resistivity
ΔT	Time During Which Useful Channels May Form
$\sigma(V)$	Standard Deviation of Self-Break Voltage
τ_b	Transit Time of Blumlein Transmission Line
τ_c	Transit Time of Trigger Cable
τ_L	Switch Inductive Risetime
τ_r	Switch Resistive Phase
τ_{tot}	Switch E-Folding Risetime
τ_{trans}	Switch Electrode Transit Time

SECTION 1

INTRODUCTION

The Mylar lines that have been constructed at Physics International generate at the switches a rate of change of current ranging from a few times 10^{13} to 10^{15} amperes per second. This rate of change of current has been made possible by the use of a number of solid dielectric switches, in which, in effect, many parallel spark channels are created on each shot. The large number of channels, each quite short, gives a very low inductance, and to date there has been no other method that achieves the same result.

The disadvantage of solid switches is that they must be replaced after each shot, slowing operation and consuming materials and labor. There are eight switches in the new high-voltage DASA line (SNARK). If this system is increased, as anticipated, to ten or more times its present size, the replacement of switches, though tractable and not unprecedented, will become very inconvenient. Therefore, it was desirable to demonstrate that Mylar lines could be gas-switched, to simplify the operation of a facility-type machine.

Multiple-channel pressurized SF_6 gaps offer the best approach to gas-switching. A number of channels similar to those achieved with solid switching is required. The simplest method is to use a single, multiple-channel rail gap for each line to be switched. An insulating pipe, which is laid along the edge of the dielectric stripline, provides a pressure vessel and contains two rail-like main electrodes and a third trigger electrode to which a fast-rising pulse is applied. The switch can operate repeatedly with only occasional maintenance and is variable over a large voltage range by pressure adjustment.

SECTION 2

THEORETICAL PRINCIPLES

Existing data suggest that, in a uniform-field switch with applied voltages rising in about 0.3 μsec, the breakdown strength of SF_6 is proportional to total pressure up to about 100 psi. At higher pressures the field rises less rapidly with pressure and does not exceed 1 MV/cm. The standard deviation, ρ(V), rises steadily from about 2 percent at 50 psi to about 7 to 8 percent at 300 psi.

Accordingly, SF_6 has a breakdown gradient virtually independent of the rate of application of voltage; i.e., when the risetime of the applied waveform is decreased from 300 nsec to 10 nsec, a 10 to 15 percent increase in breakdown voltage is observed.

However, in a point-plane or highly field-enhanced gap, the breakdown field of SF_6 is time-dependent and, at pressures above a few atomospheres absolute, increases only slowly with pressure.

Thus, to minimize the formative time and jitter, it is necessary not only to feed in a large, fast trigger pulse, but for the electrode to have a geometry designed to achieve an enormous field when the trigger pulse is applied. This means that a very sharp trigger electrode is required, the position and potential of which must be carefully controlled to avoid prefire. (A fairly stable corona sheath will temporarily relieve the high field on the trigger electrode.) This switching system was first carried out in high-pressure SF_6 by Physics International under a DASA contract, DASA 01-68-C-0175, "Trigitron Switching in Liquids," which was later modified to include other promising methods of switching.

The trigger pulse is applied to the sharp trigger electrode with a polarity which will break both sides of the gap simultaneously. Also, it is preferable that the trigger electrode be driven positive with respect to the main electrodes as the positive streamers travel faster.

In the normal "cascade mode" of triggered operation, the trigger pulse first breaks one side of the switch, which swings the full potential to the other side of the switch, which in turn breaks down. As shown in Figure 1, it would be normal to offset the trigger electrode and to provide a trigger pulse strong enough to break the larger gap first which in turn breaks the smaller gap.

In the case of the "simultaneous mode," after the application of the positive trigger pulse, the potential (V/n) of the trigger electrode will follow curve ABD. The trigger pulse breaks down both gap spacings before the trigger-electrode potential swings back to negative. The advantage of the simultaneous-breakdown mode of operation is that the time to breakdown and the jitter are minimized.

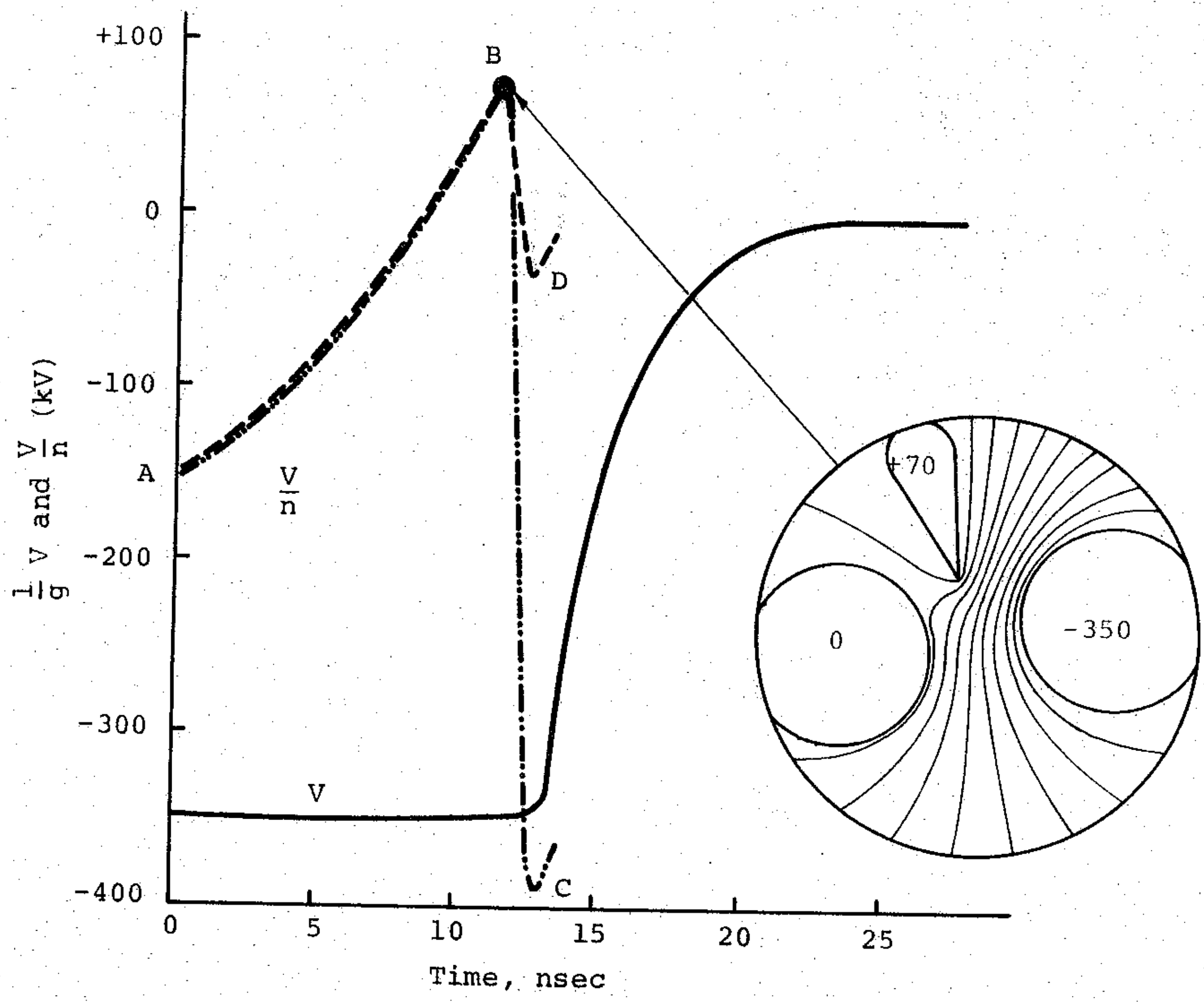

Figure 1 Typical main electrode voltage (V) and trigger-electrode-potential (V/n) curves after application of the trigger-voltage pulse.

Figure 1 gives a plot of the equipotentials in 10-percent steps as they exist at point B in the triggering cycle.

When the spark channel forms, the voltage across the gap falls more or less exponentially, serious deviations occurring only when the voltage has dropped to about 10 percent of its initial value. Most of the energy is delivered into the channel during the time that the channel impedance falls from a few times above the driving impedance to a few times below the driving impedance. This fall in impedance, or resistive phase, together with the channel and inherent electrode inductance, is the limiting factor upon the pulse risetime.

An estimate of the pulse risetime may be divided into two parts: (1) the resistive phase τ_r and (2) channel inductance plus switch-electrode inductance. The approximate resistive phase risetime is given by

$$\tau_r = \frac{5\ \rho^{1/2}}{Z^{1/3} N^{1/3} F^{4/3}} \text{nsec}$$

where ρ is the switching-medium density (gm/cc), Z is the driving impedance (Ω), F is the mean breakdown strength of the switch in (MV/cm), and N is the number of channels.

For the inductive contribution to the risetime, the channel is treated as a cylindrical conductor over a ground plane. Thus the inductance for N channels is

$$L_{channels} \sim \frac{2\ l}{N} \ \ln \frac{D}{S} \text{nH}$$

where l is the length of the channel (cm), D is approximately one third of the distance between channels (cm), and S is the channel diameter (cm), assuming an expansion velocity of the plasma channel to be approximately 10^6 cm/sec.

Then

$$\tau_L = \frac{2l}{NZ} \ln \frac{D}{S} + L_{switch\ electrode}/Z$$

and the total switch risetime (τ_{tot}) is given by

$$\tau_{tot} = \sqrt{(\tau_R)^2 + (\tau_L)^2} \quad \text{e-fold.}$$

SECTION 3

EXPERIMENTAL PROCEDURES

3.1 SWITCH ENVELOPE

The initial tests were directed toward fabricating a gas-containment vessel compatible to coupling into a parallel-plate Mylar dielectric transmission line. The following basic assumptions were made:

1. The electrodes of the rail switch should be about 12 inches long. (A greater length, though possible, would complicate fabrication.)

2. The switch may be coupled to a transmission line of as low an impedance as 0.6 ohm.

3. The operating field in the Mylar may be in the region of 1.3 MV/cm.

4. In order that these low-impedance transmission lines may operate at high voltages, the lines are immersed in water which is loaded with a copper-sulphate solution, the environment in which the switch envelope must function. This immersion reduces the fields at the edges of the conductors.

Dimensions not exceeding 2-1/2 by 2-1/2 inches seem necessary to ensure that, under these circumstances, the switch envelope does not contribute more than 12 nsec e-folding to the switch risetime. Conditions inside the envelope - with a working pressure of about 200 psi and a maximum field taking into account field enhancement, of about 750 kV/cm in the SF_6 - make it seem unlikely that an internal diameter of less than 1-1/4 inches should be considered. These inside dimensions imply that outside dimensions of about 2 by 2 inches are necessary to safely contain the 200 psi SF_6. Thus it was necessary to show that an insulating envelope with external dimensions of about 2 to 2-1/2 inches square would survive at voltages in excess of 500 kV in the environment indicated above.

A Marx generator was used to feed a 1 - cos ωt type waveform into various samples. The volts were taken off the sample by means of a solid dielectric switch parallel to the sample such that the t_{eff} of the applied waveform was typically 0.4 μsec.

Six-inch-wide electrodes 0.040-inch thick with a full radius on the edges, and 13 sheets of 0.010-inch Mylar as the main-line insulation were used to test a 1-1/2-inch-square cross section of a Lucite sample. The sample was tested by applying successively higher negative voltages to electrode A, Figure 2a. With the water resistivity, ρ_W, set at 8 kΩ-cm (a level higher than normal, thus emphasizing the grading problem) a track occurred between the electrodes across the Mylar-Lucite interface at 150 kV. The sample, when turned over and retested, broke in the same manner at a voltage of 180 kV.

The face of the Lucite sample adjacent to the Mylar was then fluted in order to provide resistive grading between the electrodes, thus reducing the field on electrode A, at the point where it bends

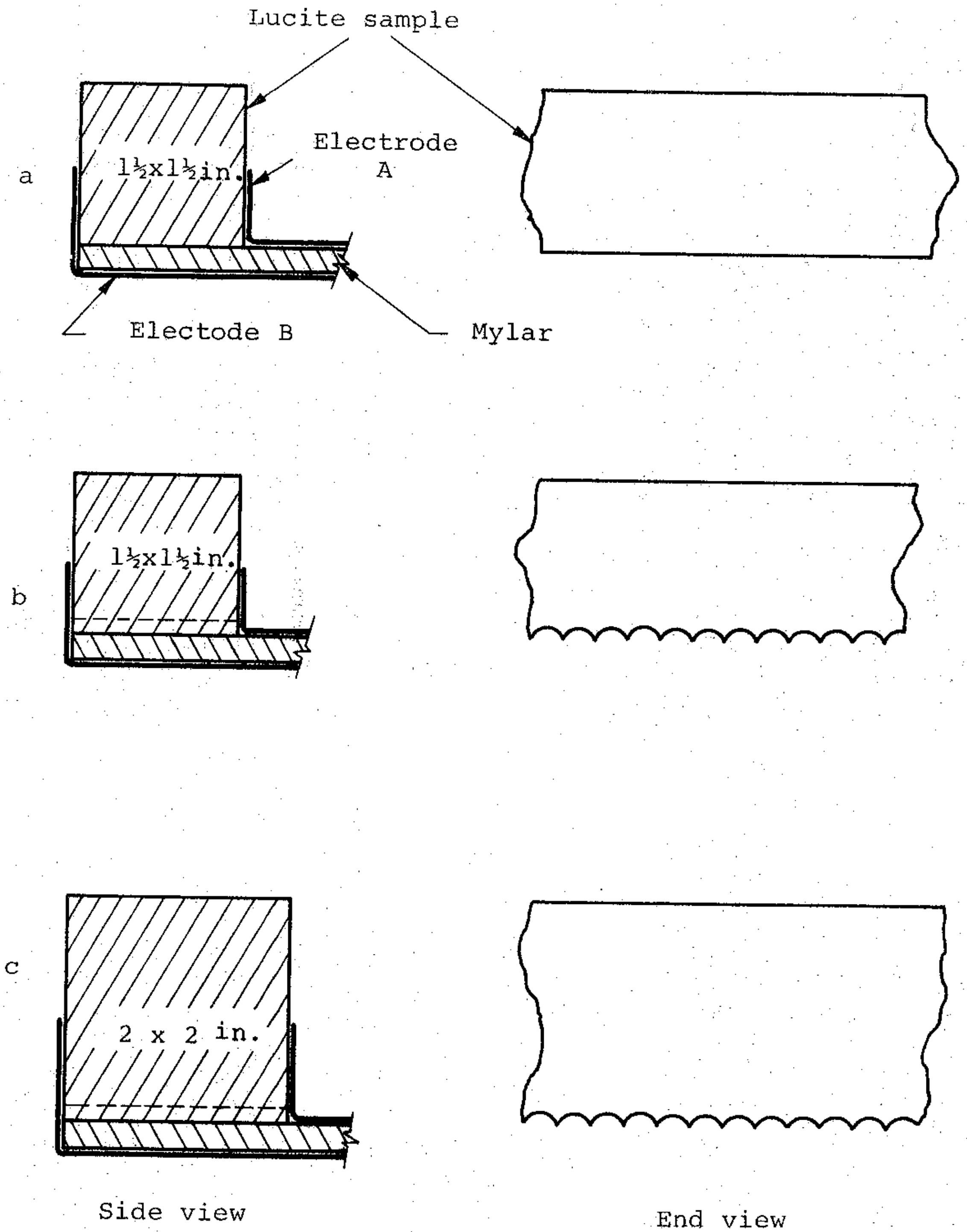

Figure 2 Envelope testing.

up the side of the Lucite envelope. The flutes were approximately 0.01 inch deep, full radius and 0.10 inch between peaks, Figure 2b. This sample was tested and failed as it had before being fluted, but this time at a voltage of 250 kV. The water resistivity was then lowered to 2 kΩ cm to improve the resistive grading and another 1-1/2-inch-square cross section of a fluted sample tested. This sample finally tracked along one of the flutes at 390 kV.

Next a 2-inch-square cross section fluted sample was tested with ρ_w = 4.5 kΩ cm. This sample tracked along the flutes at 528 kV. When the resistivity was lowered to 2.5 kΩ cm, a typical working level, the sample failed at 558 kV, but tracking did not occur. All thirteen sheets of Mylar were punctured at a point below the field-enchanced bend of electrode A. This corresponds to a mean field in the Mylar of 1.7 MV/cm. It was therefore concluded that the envelope and the means of its attachment to the transmission line were more than adequate for operation at 450 kV.

3.2 SWITCH SELF-BREAKDOWN CHARACTERISTICS

A switch (Figure 3) was fabricated initially without the trigger electrode in order to investigate the self-breakdown voltage (V_{sb}) versus pressure (P_{sb}). The switch was immersed in oil to eliminate external flashover problems. Because of the high shunt impedance represented by the switch, additional series inductance was added to the Marx generator, and the resultant t_{eff} of the applied waveform was typically 0.8 μsec. By this means the self-breakdown voltage was obtained in 20-psi steps using dried SF_6.

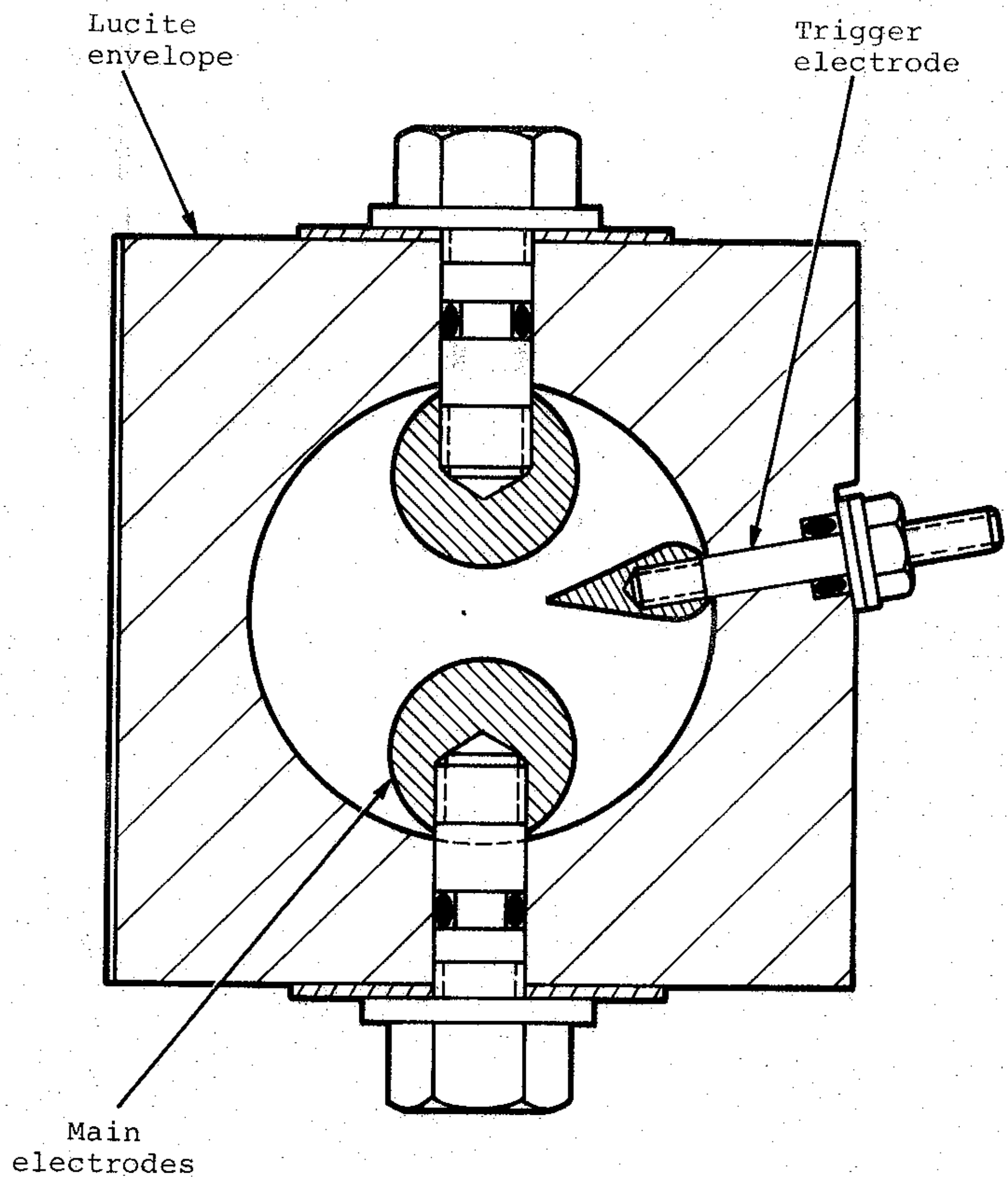

Figure 3 Gas-switch assembly.

At 95 psi absolute and at a voltage of 276 kV, the switch tracked from the ends of the main electrodes, via the end-plug O-ring, shattering the end of the Lucite envelope. The Lucite envelope was lengthened, so that the end plugs containing the O-rings were moved back from the ends of the main electrodes. With this new design a self-breakdown voltage-versus-pressure curve up to 95 psi absolute was established.

The trigger electrode was then positioned at a ratio of short-gap (b) and long-gap (a) spacing of 44 percent to 56 percent. The trigger was held in this ratio by means of copper-sulphate resistors. The self-breakdown voltage-versus-pressure curve was reestablished with the trigger electrode in position. In Table 1 the standard deviation (V) is indicated as a percentage of V_{sb} (kV).

TABLE 1

VOLTAGE VERSUS PRESSURE

SF_6 Pressure (psia)	Voltage (kV) Without Trigger Electrode	Voltage (kV) With Trigger Electrode
35	122 ± 1.5%	123 ± 2.3%
55	194 ± 3.5%	194 ± 2.9%
75	245 ± 1.9%	247 ± 2.8%
95	299 ± 4.3%	304 ± 2.5%

3.3 SWITCH TRIGGERED CHARACTERISTICS

The triggering of the rail switch is achieved by feeding the trigger pulse down a high-voltage coaxial cable which is connected to the trigger electrode via a series resistor (R_s), Figure 4. This resistor serves to reduce the amplitude of transients fed back down the cable when the rail switch fires. It has been demonstrated, for example, that without a series resistor RG 17 breaks due to switching transients at a line voltage of about 150 kV. With a series resistor twice the cable impedance, it does not break at a line voltage of 450 kV. Copper-sulphate solution is used to form the series resistor and is contained in a block of Lucite. This Lucite block prevents capacitive and resistive coupling, due to the presence of water both across the series resistor and between the trigger-electrode studs and ground. This is important not only in holding the trigger electrode at the correct potential during the charging phase, but in reducing the loading imposed upon the triggering pulse, which fires the rail switch.

A parallel-plate Blumlein circuit was fabricated using 12-inch-wide, 10-mil copper foil. The thickness of the copper is artifically increased at the edge by soldering a 50-mil-diameter wire around the edge of the copper. This increased thickness together with the 2 kΩ-cm water gives adequate resistive grading in the water to prevent edge breaks, during both the slow-speed charging phase and the high-speed transient phase. Each line of the Blumlein is composed of 13 sheets of 0.010-inch Mylar 2 feet wide. Since the resulting lines each have an impedance of 2.5 ohms, the Blumlein-output impedance is 5.0 ohms. The length of the active portion of the transmission line initially had a double-transit time of 23 nsec.

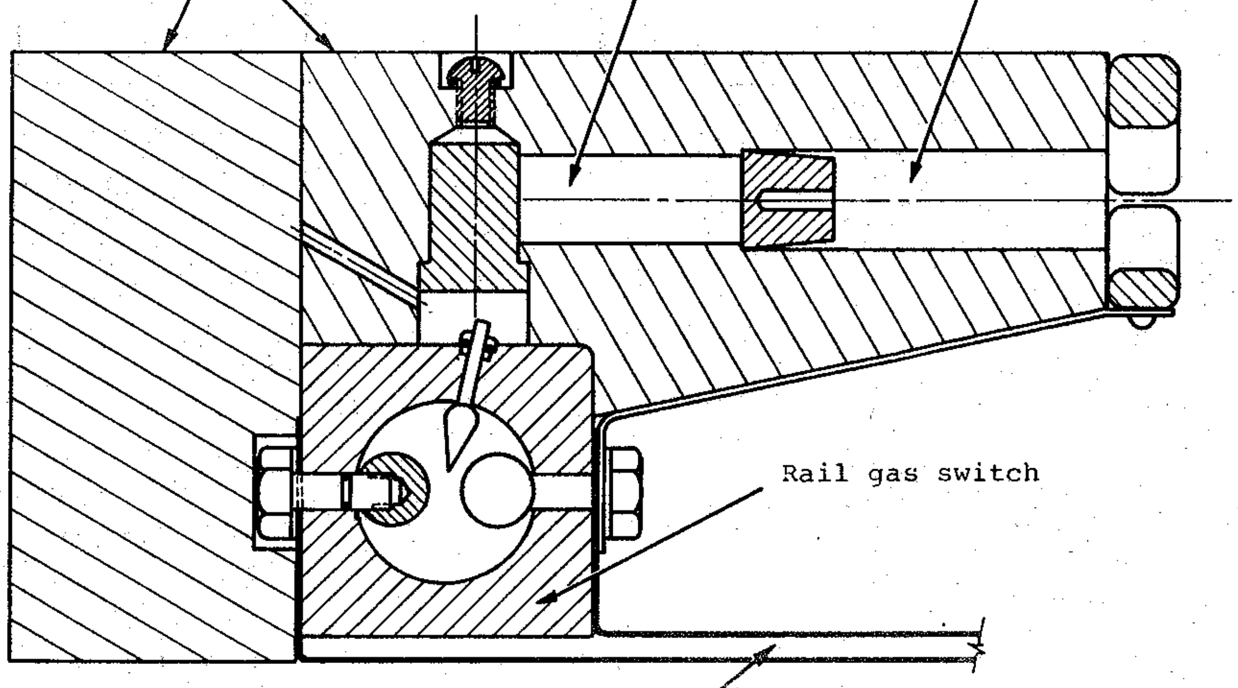

Figure 4 Gas switch with Lucite blocking and trigger feed.

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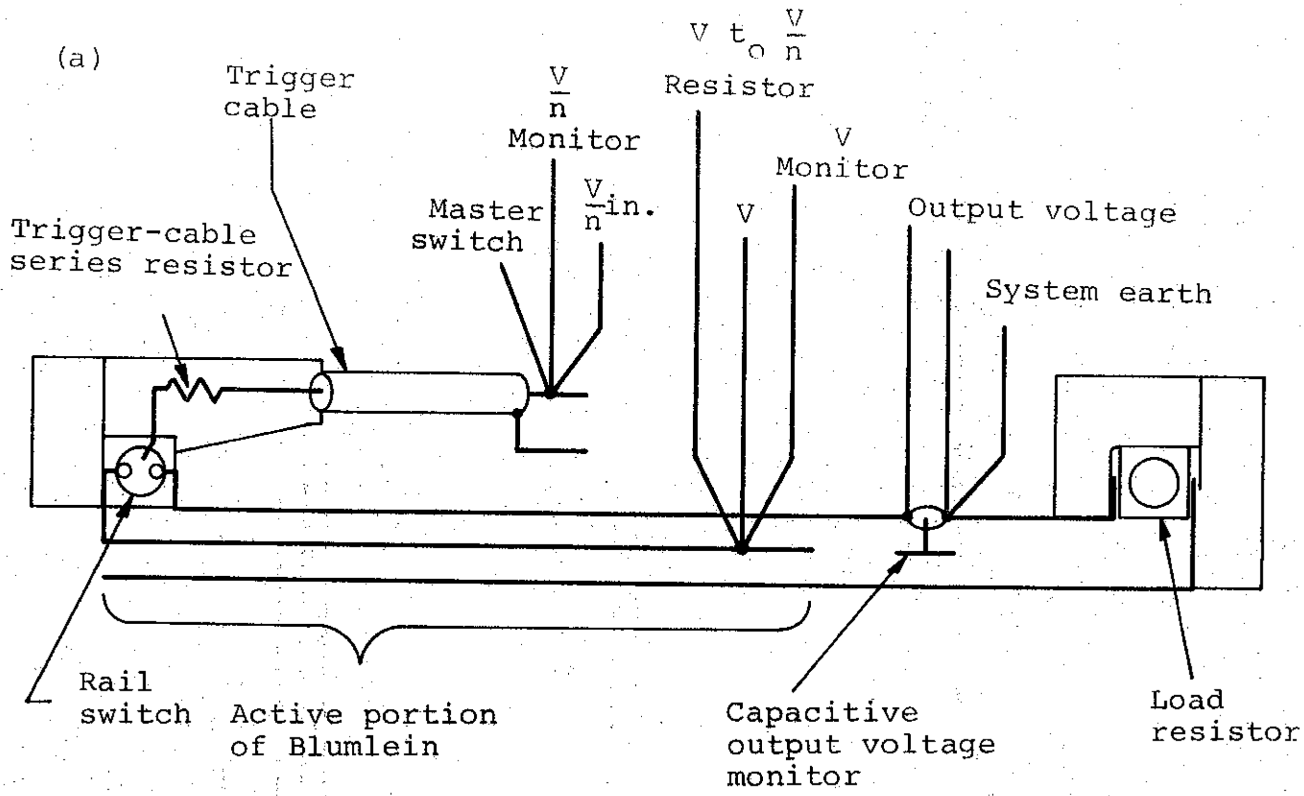
The Mylar forming each line and the outer copper sheets are continued beyond the active portion of the Blumlein. The Mylar and copper form a matched transmission line which is terminated by a matched copper-sulphate load. The reason for this length of matched transmission line is that the load, although designed to be low inductance, will not provide a perfect resistive termination. By positioning the capacitive-output monitor near the end of the active portion of the Blumlein, a "clear-space" is obtained, so that the pulse risetime may be recorded before mismatch transients return from the load (Figure 5).

The general arrangement of the Blumlein test assembly is shown in Figure 5a and 6. The equivalent circuit is given in Figure 5b. A Marx generator of effective capacity 0.25 μF (C_o) and inductance 10 μH (L_o) pulse charges the test Blumlein. (Series inductance o μH (L_1) was added to slow the time to peak on the charging waveform to approximately 3 μsec, the time to peak on a facility-type Mylar line.) A sample of the charging voltage (V) existing on the Blumlein is applied to a variable-geometry copper-sulphate resistor (V/n resistor). By means of a tap-off section in the V/n resistor, a fraction of the charging voltage is applied to the master switch. This switch connects, via the trigger cable and series resistor (R_s), to the trigger electrode of the rail switch. Thus the trigger electrode is held at the correct potential (0.44 V) by means of monitoring the V and V/n waveforms and tuning the V/n resistor.

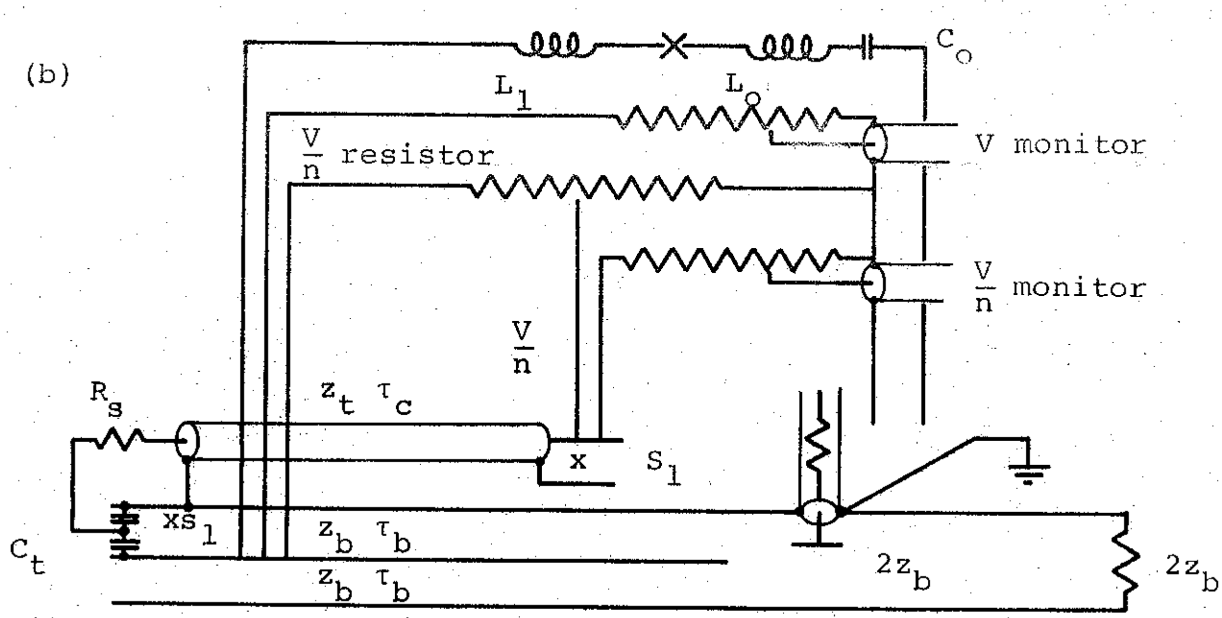
The master switch, S_1, consisted initially of a solid dielectric prestabbed-polyethylene switch and finally of a gas (SF_6) switch which was designed to operate at the same pressure

(a)



a. General arrangement

(b)



b. Equivalent circuit.

Figure 5 Blumlein-test assembly.

as in the rail switch, S_2. Both were arranged to fire at 85 percent of the peak of the charging waveform, and the rail switch was pressurized so that it received the triggering pulse when charged to 80 percent of self-break.

A capacitive monitor around the trigger cable and up against the rail switch (Figure 7) was used to look at the trigger waveform and for time-referencing the rail-switch closure. The e-folding decay time of this monitor was 370 nsec giving a droop time of only a few percent during the time of interest. The parallel-plate capacitive monitor, used to record the Blumlein output waveform, had a droop time of about 3 μsec.

Initially the impedance (Z_t) of the coaxial trigger cable was 50 ohm and that of the series resistor (R_s), 63 ohm. The system was fired at successively higher voltages up to about 300 kV; V and V/n waveforms together with a Blumlein-output waveforms are shown in Figure 8, and the multiple-channel breakdowns in the rail switch in Figures 9 and 10. All the photographs are of multiple-channel breakdowns occurring in the large gap (a); however photographs taken of the smaller gap (b) indicate a similar number of channels.

The capacity of the trigger electrode to the main electrodes was measured at 20 pF. In order to increase the rate of rise of the trigger pulse and at the risk of breaking the trigger cable, the series resistor (R_s) was shorted out by means of displacing the copper sulphate with Mercury. At 300 kV a similar number of channels were observed in the rail switch with no change in the output-pulse risetime.

With the series resistor (R_s) still shorted out, a trigger cable of 18-ohm impedance was used and records taken over a range of pulse-charge voltages.

At this time a break occurred in the Mylar that forms the dummy line of the Blumlein, where inadequate grading had been used. The Blumlein was rebuilt with the active portion somewhat shorter ($2\ \tau_b$ = 16 nsec) to give more "clear time" at the output end. Three 50-ohm trigger cables in parallel were used, each fed from a common master switch S_1 and each connecting to the rail-switch trigger electrode via a 60-ohm copper-sulphate resistor, Figures 6 and 7.

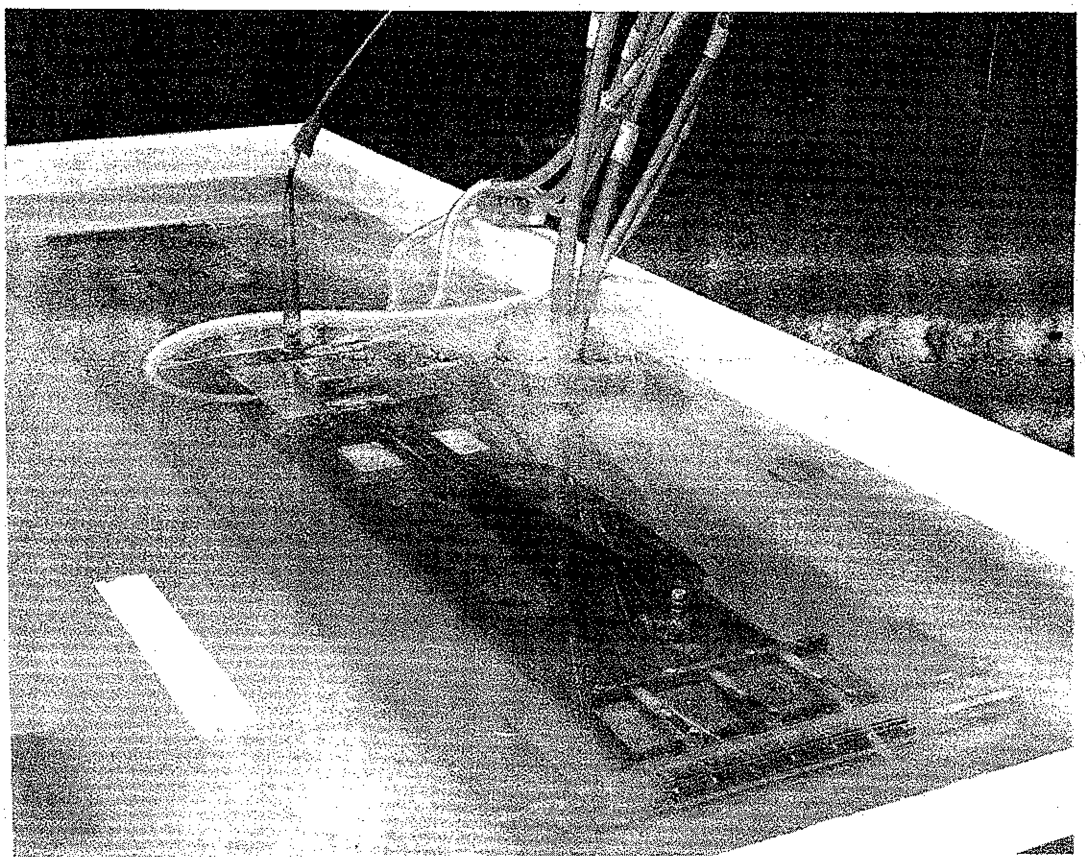


Figure 6 Blumlein-test assembly.

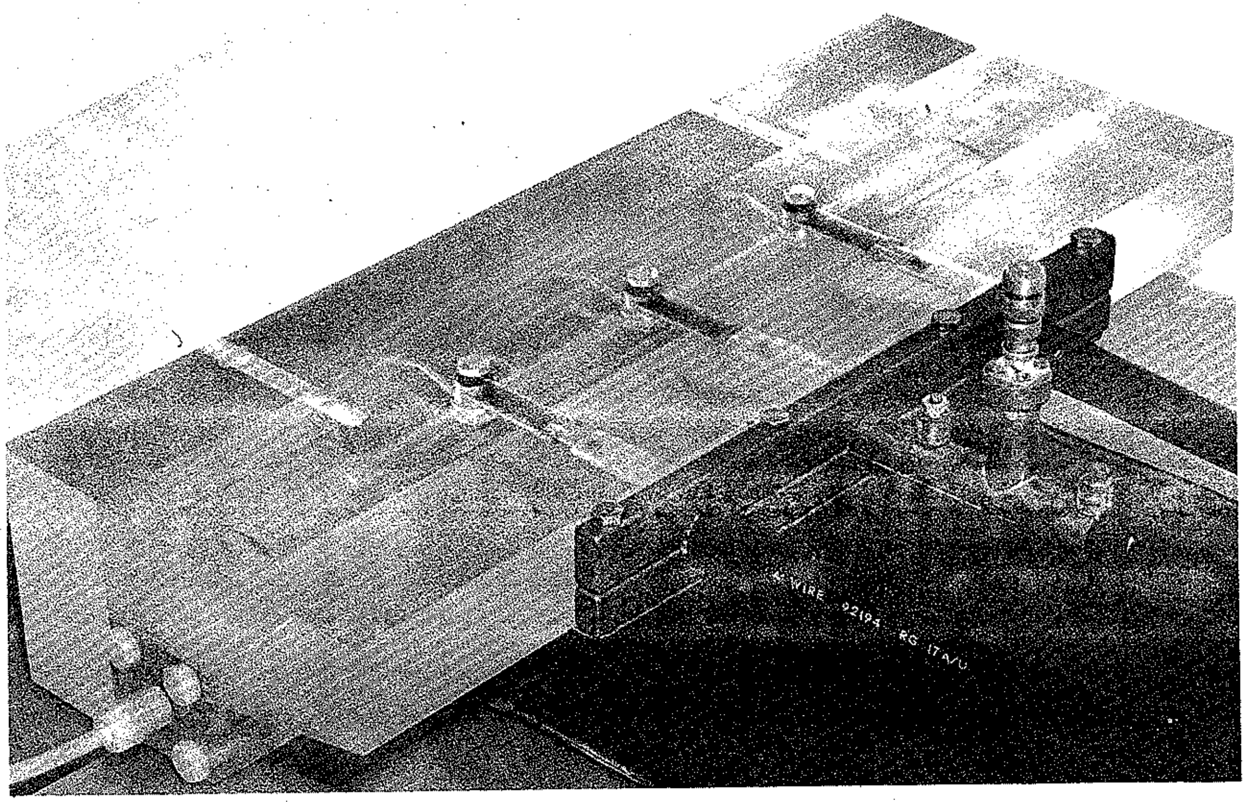
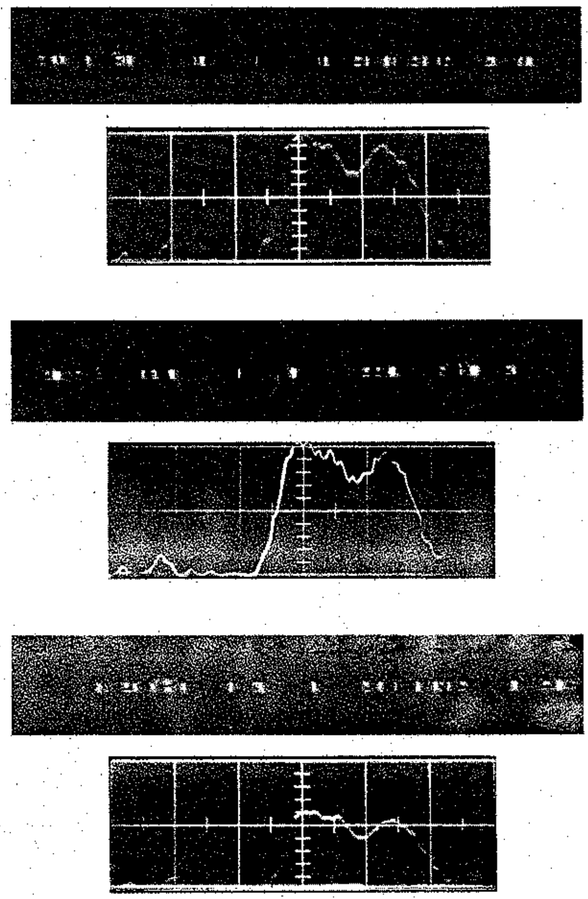


Figure 7 Gas switch with Lucite blocking and trigger feed.

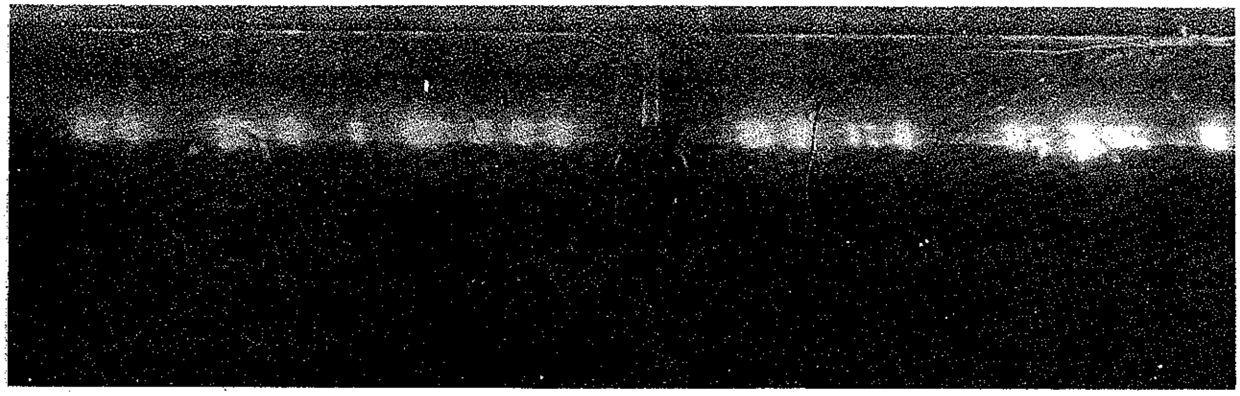


280 kV
10ns/division

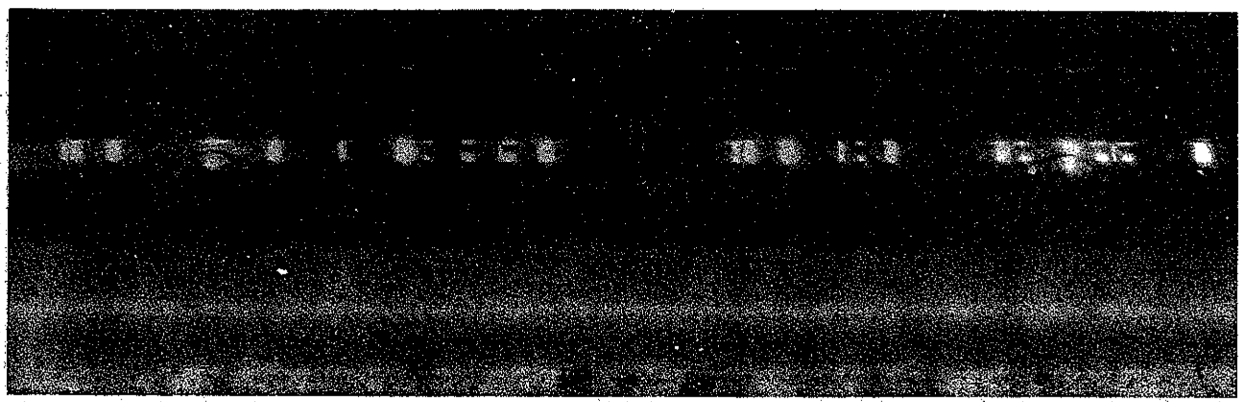
295 kV
10ns/division

320 kV
10ns/division

Figure 8 Blumlein-output waveforms. ($2\tau_b$ = 23 ns).



f 22 Neutral Density 1.0



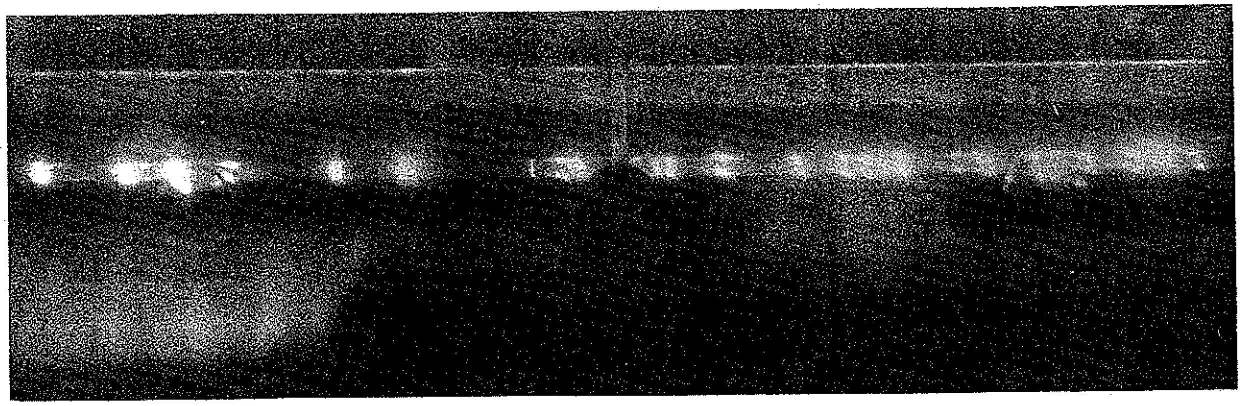
f 22 Neutral Density 1.6

113 psi SF_6, V_{sb} 375 kV

triggered at 313 kV

from 50-Ω cable via 62-Ω series resistor.

Figure 9 Multiple-channel photo.



f 22 Neutral Density 1.0

f 22 Neutral Density 1.6

113 psi SF_6 V_{sb} 375 kV

triggered at 320 kV

from 50-Ω cable via 62-Ω series resistor

Figure 10 Multiple-channel photo.

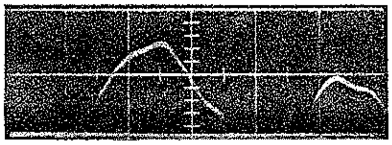
Records were again taken at voltage up to 350 kV, Figures 11 and 12. The self-break point at 205 psia was established and found to be 400 kV + 2.2 percent.

The following table gives the average number of breakdown channels for effective trigger impedances at various operating voltages. The change from a solid dielectric master switch to a gas master switch was not made until after the data for Table 2 were accumulated. However, a number of these shots were repeated with a gas master switch and showed identical results.

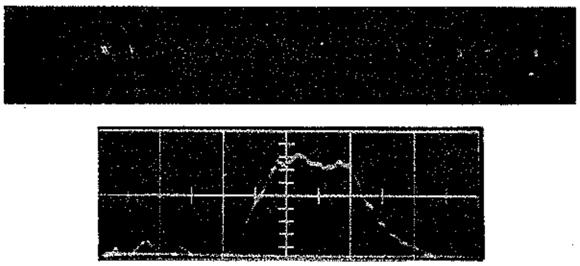
TABLE 2

NUMBER OF CHANNELS VERSUS INDUCTANCE

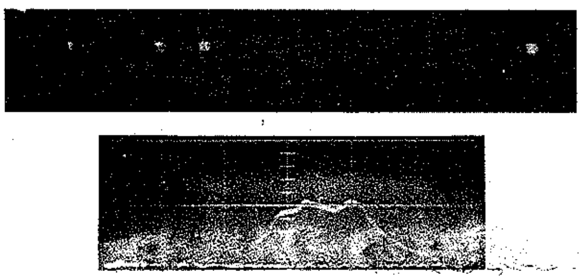
	Trigger Impedance Plus Series Resistance			
	18 + 0	3 x (50+60)	50 + 0	50 + 63
		Effective Trigger Impedance		
Line Voltage (kV)	18 Ω	37 Ω	50 Ω	113 Ω
100		5		
150	5	5-1/2		6
200	10	7-1/2		10
250	14	10		14
300	14	16	20	20
350		19		



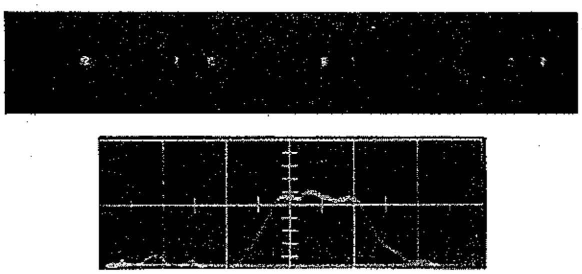
Trigger waveform
switch not firing
3 cables each
50 Ω + 60 Ω series
resistor.
10ns/division



113 kV
10ns/division



150 kV
10ns/division



160 kV
10ns/division

Figure 11 Blumlein-output waveforms (2 τ_b - 16ns).

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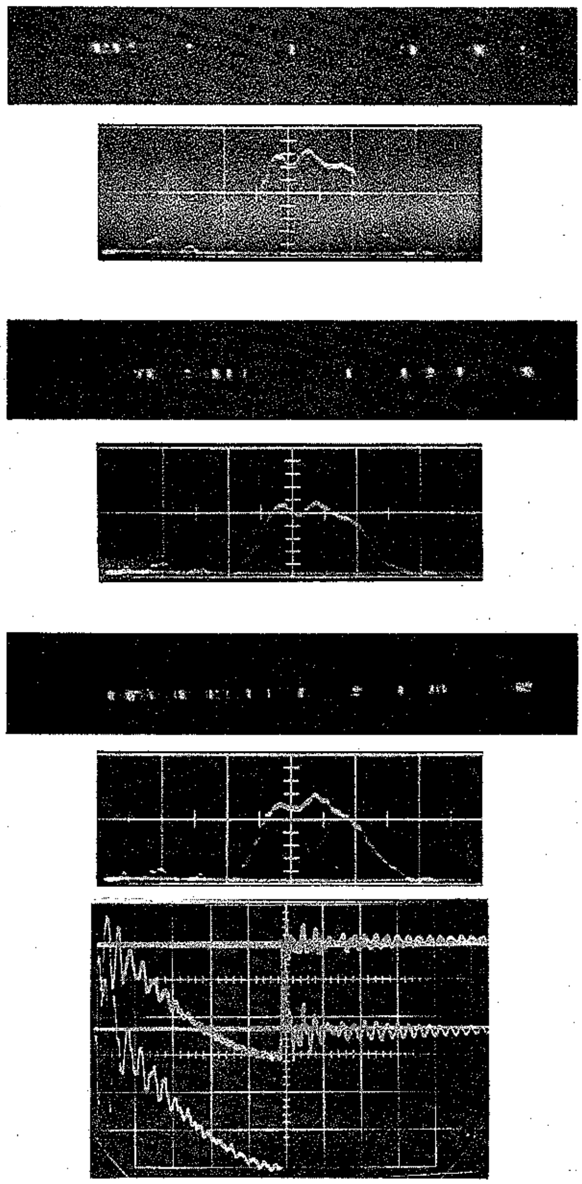

210 kV
10ns/division

267 kV
10ns/division

320 kV
10ns/division

Charging waveform

500ns/division

Trigger waveform

Figure 12 Blumlein-output waveforms ($2\tau_b$ = 16ns).

SECTION 4
DISCUSSION OF RESULTS

Due to the field limitation in the SF_6, switching voltages of 400 kV were not exceeded. As the pressure (and hence the operating voltage) is increased, the number of channels also increases; however, the gap inductance decreases by only 10 percent when the number of breakdown points increases from 6 to 20.

Over the range of pressures indicated, any change in time to breakdown or shot-to-shot jitter was not measurable by equipment on hand. This, with the roughly equal number of channels on each side of the trigger electrode and with the shape of the trigger waveforms, indicated that simultaneous triggering had been achieved instead of the more normal cascade mode.

Apparently, the number of breakdown channels is independent of the trigger impedance and of the number of points at which the trigger pulse is fed into the trigger electrode. This is somewhat surprising, since, for example, shorting out the series resistor should have injected a faster-rising pulse into the trigger electrode. When the switch is driving a lower-impedance transmission line, resulting in a longer resistive phase, a lower-impedance trigger circuit may then cause more channels to be formed.

It was expected that feeding the trigger pulse in at three points on the trigger electrode would result in more channels being formed, if only due to the reduced transit time of the trigger pulse along the electrode. Again, this did not occur. In the case of the single-cable feed, the trigger pulse may have transversed the transmission line formed between the trigger electrode and main electrodes, and doubled at the open circuit represented by both ends of the switch, offsetting the reduced transit time. Thus the delay of the trigger pulse in reaching the ends of the trigger electrode would have been compensated for by the trigger electrode excursing to a greater extent at the ends.

According to J. C. Martin the time, ΔT, during which useful channels may form is

$$\Delta T = f\tau_{tot}$$

where f is approximately 0.1. To this must be added an allowance for transit-time isolation. Thus,

$$\Delta T = 0.1\ \tau_{tot} + 0.8\ \tau_{trans}$$

A switch operating in the single-channel mode will have a breakdown voltage (V), the standard deviation $\sigma(V)$ of which may be measured. When a trigger pulse, rising at a rate dV/dt, is applied to the system, the standard deviation in voltage may be transformed into a deviation in time:

$$\sigma_{(t)} \cdot T \approx \sigma_{(V)} \cdot V(dV/dt)^{-1}$$

To a reasonable degree of accuracy, ΔT may be equated to $2\sigma_{(t)} \cdot T$. Thus,

$$2\sigma_{(V)}\ V(dV/dt)^{-1} \approx 0.1\ \tau_{tot} + 0.8\ \tau_{trans}.$$

Now

$$\tau_r = \frac{5\rho^{1/2}}{1.35\ N^{1/3}\ F^{4/3}} \text{ nsec.}$$

	150 kV	300 kV
$\rho^{1/2}$	0.148	0.225
$F^{4/3}$ =	0.148	0.37
τ_R =	$\frac{5}{1.35\ N^{1/3}}$	$\frac{5 \times 0.225}{1.35\ N^{1/3}\quad 0.37}$

Using the above relationship and the graph of number of channels versus inductance, it is possible to draw up Table 3, showing N versus ΔT, where

$$\Delta T = 2\sigma_{(V)}\ V(dV/dt)^{-1}$$

TABLE 3

N Versus ΔT

N	L	τ_L	τ_R 150 kV	τ_R 300 kV	τ_{tot} 150 kV	τ_{tot} 300 kV	τ_{trans}	ΔT 150 kV	ΔT 300 kV
1	14	5.6	3.7	2.25	9.3	7.85	1.0	1.73	1.59
2	9	3.6	2.94	1.78	6.54	5.38	0.5	1.05	0.94
4	6.8	2.72	2.34	1.33	5.06	4.05	0.25	0.71	0.61
8	6	2.4	1.85	1.12	4.25	3.52	0.125	0.53	0.45
16	5.7	2.28	1.47	0.83	3.75	3.11	0.06	0.43	0.36
32	5.5	2.2	1.04	0.59	3.24	2.79	0.03	0.25	0.30

In this case, $\sigma_{(V)}$ was measured to be 2.8 percent with a trigger pulse rising linearly through V in about 8 nsec.

Therefore: $\Delta T = 0.44$ nsec.

This value of ΔT, referred back to Table 3, predicts approximately 16 channels at 150 kV and 8 channels at 300 kV, instead of the observed numbers of 6 at 150 kV and 20 at 300 kV.

The breakdown of point-plane switches was initially investigated at Aldermaston, where switch-breakdown time once the trigger pulse has been applied was estimated from the equation

$$Ft^{1/n} d^{1/6} = K$$

leading to the result

$$t = (K/F)^{n} \cdot d^{-n/6}$$

If we assume that a smaller closure time would be obtained at higher pressures, where F would increase more than K, it may be argued that

$$t \alpha \ (1/p)^{x}$$

This argument can be applied to the data on the number of channels formed, using a factor of $(5.7/p)^{0.7}$ where p is the absolute pressure in atmospheres. This results in a reasonably consistent set of numbers that are in agreement with the observed data.

The validity of this assumption is somewhat in question, as data obtained with point-plane gaps at Physics International under SIEGE Phase II Study indicate strongly that $t \alpha\ p^{1/6}$.

The expressions listed in Section 2 may be used to compare calculated and observed switch risetimes.

Taking an operating voltage of 300 kV with 20 channels,

$$\rho = 0.006 \times 8.5 \text{ gm/cc } (SF_6 \text{ at } 8.5 \text{ atmos})$$

$$Z = 2.5\ \Omega$$

$$F = \frac{300}{0.63} = 0.475 \text{ MV/cm}$$

$$N = 20.$$

$$\tau_R = \frac{5 \times (0.051)^{1/2}}{(2.5)^{1/3} \times (0.0475)^{4/3} \times (20)^{1/3}}$$

$$\tau_R = \frac{5 \times 0.225}{1.35 \times 0.37 \times 2.7}$$

$$\tau_R = \underline{0.84 \text{ nsec}}$$

$$\tau_L = \frac{2 \times 0.63}{20 \times 2.5} \ln \frac{0.27}{10^{-2}} + \frac{5.2}{2.5}$$

$$\tau_L = 0.025 \times 3.3 + 2 \cdot 1$$

$$\tau_L = \underline{2.18 \text{ nsec}}$$

$$\tau_{tot} = \sqrt{(0.84)^2 + (2.18)^2}$$

$$\tau_{tot} = \underline{\underline{2.3 \text{ nsec.}}}$$

Taking an operating voltage of 150 kV with 6 channels,

$$\rho = 0.0006 \times 3.66 \text{ gm/cc} \quad (SF_6 \text{ at } 3.66 \text{ atmos})$$

$$Z = 2.5 \ \Omega$$

$$F = \frac{150}{0.63} = 0.238 \text{ MV/cm}$$

$$N = 6.$$

$$\tau_R = \frac{5 \times (0.022)^{1/2}}{(2.5)^{1/3} \times (0.238)^{4/3} \times (6)^{1/3}}$$

$$\tau_R = \frac{5 \times 0.148}{1.35 \times 0.148 \times 1.82}$$

$$\tau_R = \underline{2.03 \text{ nsec}}$$

$$\tau_L = \frac{2 \times 0.63}{6 \times 2.5} \ln \frac{2.5}{10^{-2}} + \frac{5.2}{2.5}$$

$$\tau_L = 0.84 \times 5.5 + 2.1$$

$$\tau_L = \underline{6.7 \text{ nsec}}$$

$$\tau_{tot} = \sqrt{(2.03)^2 + (6.7)^2}$$

$$\tau_{tot} = \underline{\underline{7 \text{ nsec}}}$$

Both examples are in reasonable agreement with the records in Figures 8, 11, and 12.

SECTION 5
CONCLUSIONS

The initiation of multiple-channel breakdown in the rail switch described has been consistently achieved. It has also been shown that when the rail switch is coupled into a low-impedance transmission line operating at voltages up to 400 kV and fields in excess of 1.5 MV/cm, the gap inductance is only 5.5 nH (Figure 13).

In order to demonstrate the switch in a lower-impedance line, two further rail switches and the associated Lucite blocking, etc., have been fabricated (Figure 14 and 15). At present they are being installed in a service-facility system. Each switch will feed a 1-ohm transmission line and the resultant two 2-ohm output-impedance Blumleins paralleled into a tube of 1-ohm matched impedance.

The switched-line voltage will be limited to a maximum of 350 kV until further experience has been gained. This maximum corresponds to a peak current in the switch of 350 kA as opposed to the original peak-test current of 160 kA. Triggering will be achieved by means of a single 50-ohm coaxial cable and a 50-ohm series resistor feeding each switch.

When the switch feeds a lower impedance line, the number of channels is expected to increase, due to the resistive phase increasing as the cube root of the drive impedance. A longer resistive phase allows the trigger to excurse more, thus initiating more breakdown sites along the trigger electode. As τ_{tot} predominantly determined by the inherent

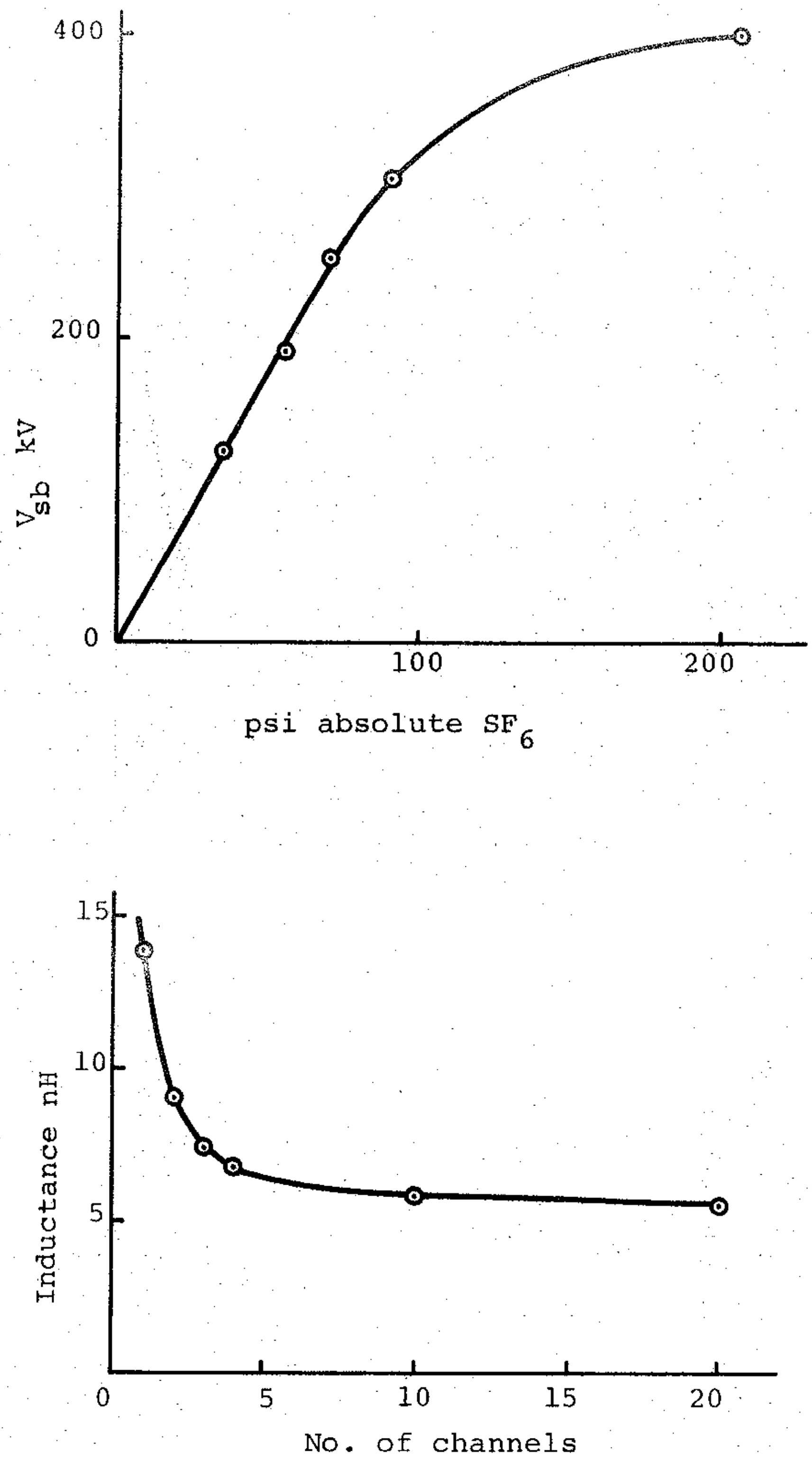

Figure 13 Pressure and inductance curves.

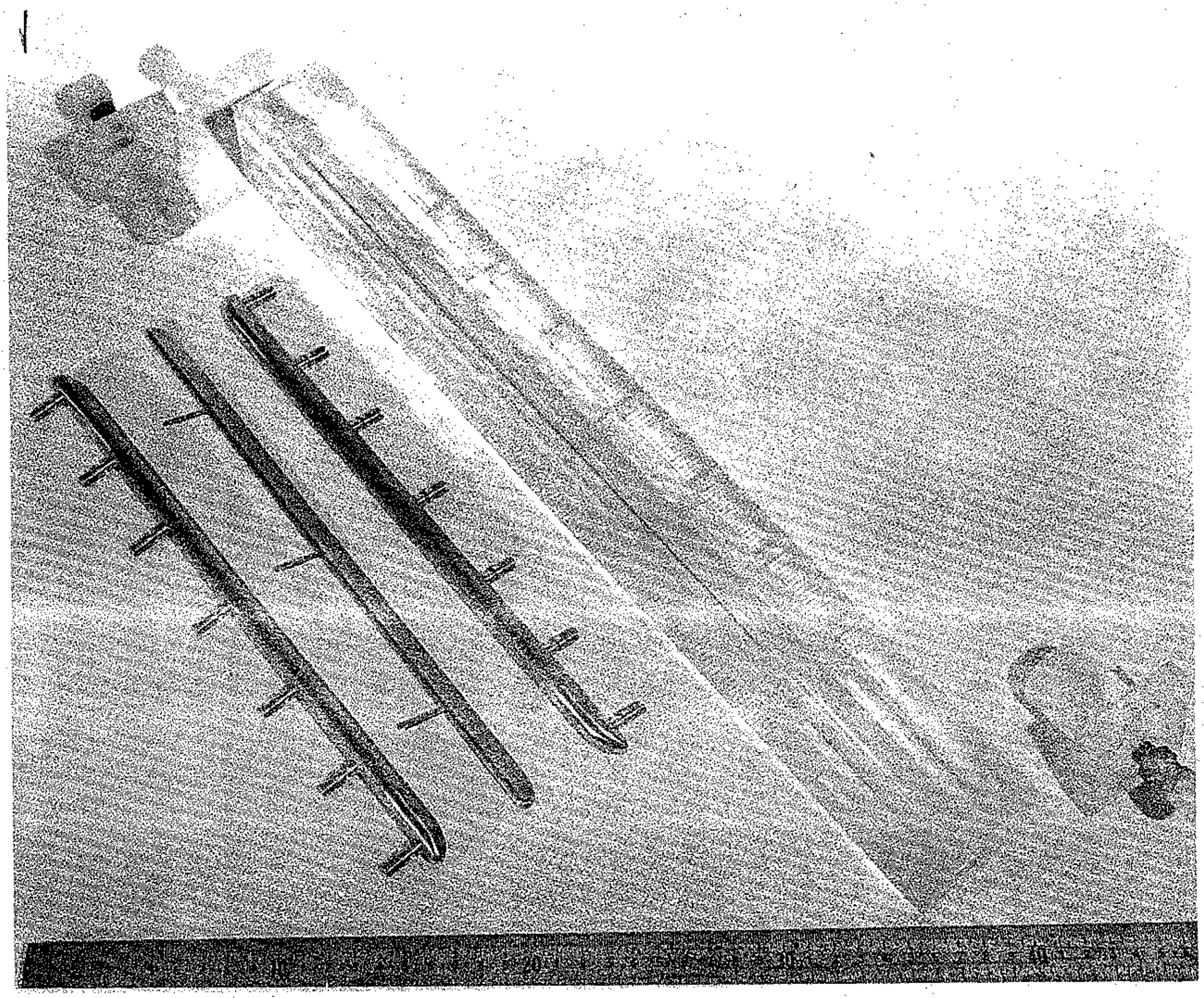

Figure 14 Gas switch disassembled.

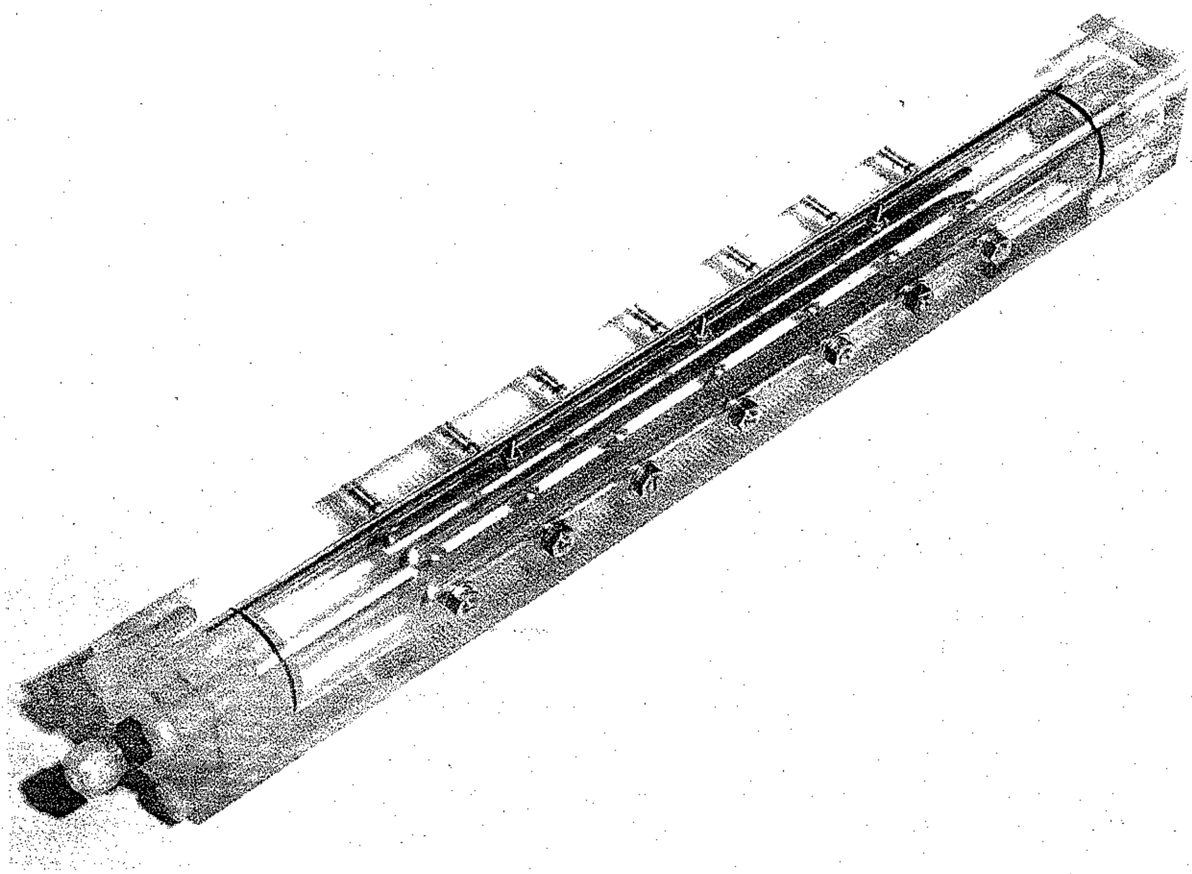

Figure 15 Gas switch assembled.

envelope inductance, more than six channels may seem an unnecessary luxury. However, with higher currents, electrode erosion may become a problem and the extra channels prove useful. Unfortunately the possibility of a single-channel self-break cannot be overlooked. During these tests the existing switch was subjected to single channel currents of 160 kA without any serious erosion occurring, but at very high currents (approximately 1 MA), electrode materials like heavy metal or molybdenum may have to be used.

Because of the electric-field limitation in the SF_6, it is impossible to raise the operating voltage from 400 kV to the desired level of 500 kV simply by increasing the pressure. Nor is it desirable to greatly increase the envelope size, due to risetime considerations. However, it may well be possible to make use of a polarity effect that has been observed in SF_6. With a ball-rod gap, field ratio 3:1, it was found that at 265 psia the enhanced field on the small electrode was the expected value when positive, and greater by 1.33 when negative. Thus it may be possible to reduce the diameter of the negative electrode so that the field on the negative electrode is as much as 33 percent higher. The gap would thereby be increased without the mean breakdown field being reduced. One fact that may complicate this approach is that in transformer oil, the polarity effect seems to increase with field enhancement; however, these data are confusing and sometimes contradictory. If this effect is present in SF_6, then optimization to achieve higher operating voltages may not be possible without a more careful investigation of this phenomenon.

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Uniform-field SF_6 switches have been used in many applications where fast risetime pulses are required since they were first suggested by Drs. Odian and Villa at Stanford Linear Accelerator Center, 1966. Much of the design data used in this program comes from work carried out over a number of years by a group under Mr. J. C. Martin, AWRE, Aldermaston, England.

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