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Explosively Actuated 100 kA Opening Switch for High Voltage Applications.

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The role of opening switches for high power energy sources such as those required in particle beam research is becoming more important as the prospects for use of inductive storage techniques widens. The technology associated with these switches is also applicable to protection of electric power transmission equipment where continually increasing voltage levels are being sought.

A single shot modular opening switch capable of carrying currents up to 100 kA indefinitely and opening in a time of approximately 20 μsec has been developed. Very low trigger jitter (Continues)

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characteristics as well as its simplicity allow the switch to be used both in series and in parallel operation. This switch operates on the principle of an explosively generated pressure which radially drives paraffin to produce multiple ruptures in a cylindrical conductor. Current probes and fast frame photography were used to determine its mechanical performance characteristics such as the reproducibility of the opening time and the simultaneity of the rupturing of the conductor. Current and voltage probes have shown, for example, that a 16-segment (25 cm long) switch develops 8 kV in 10 to 20 μsec in the process of interrupting 100 kA current when used as a safety interrupt device, or 110 kV at 40 kA when used with an integral exploding wire fuse for current transfer needed to extinguish the arc. Time dependent resistance of the arc and its restrike characteristics have been determined, showing that arc voltage is 500 to 800 V per gap, depending on the switch design.

High voltage tests with no current being carried by the switch were performed to determine the voltage hold-off capability of the switch. Application of high voltage across the 25 cm switch during its rupturing phase has shown that the gaps forming in the cylindrical conductor and the expanding gas core, as well as paraffin-gas interface can be stressed to more than 100 kV at times later than 70 μsec after the initiation of the explosive. Tests with 2-gap (5 cm) switch showed that up to 10 kV/cm can be maintained.

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CONTENTS

EXPLOSIVELY ACTUATED 100 kA OPENING SWITCH FOR HIGH VOLTAGE APPLICATIONS

I. INTRODUCTION

Interest in the development of current-interrupting technology has increased recently due to new requirements in the power transmission industry[1] and to realistic prospects of utilizing magnetic storage for production of high power pulses.[2] The power transmission at increased voltages and use of d.c. power lines has created a need for opening switches with increased voltage and current capabilities and reduced opening times. The large energy storage systems with high power needed in the electron beam fusion experiments, for driving flash lamps in laser fusion experiments and in magnetically confined plasma experiments have stimulated the development of inductive storage systems. The key element in the inductive storage system, as in the case of power transmission protection systems, is the opening switch.

The development of the opening switch technology is aimed at interrupting currents reliably and reproducibly with precise triggering in addition to operating at higher current and voltage levels. In inductive storage systems, the high voltage stress of the current interrupting element and its high resistance are important because of their impact on the efficiency of the storage system.[2] The development of these elements employs a wide variety of concepts and covers a broad set of operational parameters.[3] Mechanical disruption of conductors using explosives to interrupt a current flow offers an attractive method for extending the technology of opening switches into the regime of modern power transmission systems and for use in large, efficient, pulsers based on the magnetic storage principles.

An explosively actuated opening switch and its operation is described here. Because of the simplicity of construction and operation, the switch lends itself to multi-unit modular designs. The performance aspects associated with the use

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of modules, including formation of pulse trains, is also described. Additionally, in many applications where current commutation or power amplification is required, the explosively driven switch must be operated sequentially in parallel with other opening switches (i.e. "staged"). A two-stage switch consisting of an explosively actuated unit followed by an exploding conductor (fuse) was used to generate high voltage pulses[4].

The basic, 40 cm long, switch module interrupts 100 kA with 6 kV inductive voltage generated across the switch in about 20 μsec. Operated under conditions where arc current is extinguished by commutation through the conventional exploding fuse the switch interrupts 40 kA generating 110 kV inductive voltage, across the switch. The power associated with this switch operation is 4 GW. The rate of rise of recovery voltage (r.r.r.v.) approaches 10^{10} V/sec. This value of r.r.r.v. is in the range of that for the rotating arc vacuum interrupter, the device best suited for high recovery rates.[3] High voltage testing of basic gap opening design has shown that 10-20 kV/cm stress can be maintained across the switch. This is a significant stress in high voltage applications. The tests reported here extend the earlier work.[4,5] The tests do not represent the maximum performance capability of the switch. Rather, diverse data has been obtained to establish a baseline from which specific designs and improvements can evolve. Finally, the performance already achieved is equivalent to that of large air-blast circuit breaker with a commutating circuit.

II. SWITCH DESIGN AND PERFORMANCE

Mechanical disruption of current-carrying conductors using controlled separation of the electrodes, as in circuit breaking switch gear, is too slow for many applications. Therefore, more recently magnetic or explosive disruption of conductors has been employed to decrease the opening time from milliseconds to tens of microseconds. Magnetically driven pressure wave in oil has been used to interrupt 200 kA in 20 μsec at 9 kV across a single gap.[6] One disadvantage of magnetically operated interruptors is the need for a current source capable of operating at hundreds of kiloamperes. Use of explosives provides means of mechanically cutting a large series of gaps in tens of microseconds as first demonstrated by Glukhikh et al.[4] The explosive energy required for the switching function is approximately 10% of the stored electrical energy ($\leq$100kJ) used in the experiments described here. The use of a series of gaps to achieve high switching voltage, as well as the capability for the precise triggering for initiating the opening action provides a high degree of versatility in switch design.

The basic concept underlying the mechanical interruption of current is the formation of an arc across the separating electrodes and subsequent cooling of the arc by a contact with cold gases, liquids, or solids in its immediate vicinity, or by temporary reduction in arc current by use of external circuits. Alternately, arc resistance can be used to limit currents to prescribed values. Cooling of the arc leads to increased arc resistance and its eventual extinction. In addition, the separating electrodes and structural elements of the switch, as well as gases and debris generated in the process of disruption must often withstand the inductive voltage generated across the switch. This is an important requirement which is not easy to meet since, in general, the peak voltage appears during the time when the electrodes and the pressure transfer (pusher) medium are still in motion. These are, therefore, two aspects of the opening switch design, mechanical and electrical, that must be taken into consideration together.

To study the most important aspects of the explosively actuated opening switch, a basic multigap switch module was constructed to allow a variety of mechanical and electrical measurements and tests which have provided switch design data. The module, shown in Figure 1, is 40 cm long. Its active gap and electrode length is 25 cm. To complement the design data and to explore other options, derivative switch configurations and one substantially different design were also tested.

A. Mechanical Design

Figure 2 is a schematic illustration of two designs of the exploding switch and its functioning. Fig. 2A illustrates the cylindrical switch, detailed in the preceeding figure, before and after the interruption of current. This switch is constructed around the current carrying aluminum cylinder. The cylinder is filled with inert material with a 50 grain/foot PETN detonating cord in the center. The explosive is initiated by a EBW initiator at one end of the switch module. The first function of the inert pusher material is to transmit the pressure generated to burst the cylinder in those places where no externally mounted steel rings are emplaced. Every other ring is rounded as indicated in Figure 1. This facilitates bending of the aluminum cylinder section so that it lays flat against the ring surface maximizing the separation between rings. The second function of the inert medium is to cool the arc. One of the best choices to perform both of these functions is paraffin,[8] as discussed later in connection with the electrical performance. For pulsed operations, associated with inductive storage systems, water can also be used suggesting a method for simplifying switch replacement. Water provides a shorter delay time, about 50 rather than 70 μsec as when paraffin is used, in agreement with results of Ref 8.

Preliminary study of the second type of explosively interrrupted switching was initiated to investigate potential usefullness of other approaches. This design was selected since it lends itself to operations where shorter delay between the explosive initiation and current interruption is required as well as for being potentially more economical and more compact. The switch configuration before and after the operation is shown in Fig. 2.B. The time to rupture (Table I) of 40 μsec was observed. Because the arc, formed during the interrupting of the current, is acted upon directly by the high pressure gas generated during the explosion, it was speculated[9] that mechanisms, other than those operating in the switch shown in Fig. 2.B., determine the switch performance.

Figure 3 shows a 40 cm long exploding switch assembly. This assembly stays intact even when used for dissipation of energy of up to 80 kJ as may be the case in open circuit tests. Figure 4 is one of the series of steel rings with the aluminum cylinder section uniformly folded over it by the explosive pressure. To obtain proper metal forming[10] the aluminum cylinder must be scored axially on the outside surfaces at 20° (or smaller) intervals. In addition, gap length and aluminuim thickness are important parameters. Faulty forming results in curling of the folded metal, effectively reducing the gap. The simultaneity of rupturing was determined using a framing camera. Aluminum alloy 6064T6 cylinder (6.35 cm dia.) with 0.89 mm wall thickness ruptures producing 16 gaps (25 cm in length) within 20 μsec. This is consistent with the electrical measurements reported below. Thicker walls (1.65 mm) were also tested to provide data on switch design for higher current and/or longer pulse time operation. Burst simultaneity of gaps and electrical performance remained the same as for 0.89 mm wall cylinders. The 1.65 mm wall thickness can accommodate 100 kA current flow without substantial heating for significant periods. Larger, as well as smaller amounts of explosive were also tested to determine the effect of the amount of the explosive on the switch opening. To maintain good rupturing uniformity the location of the explosive initiator at one end of the switch module plays a key role. Premature venting of the explosive gas pressure also leads to slow or incomplete rupturing.

The time delay between the initiation signal and the cylinder rupturing is given in Table 1. This time decreases with charge weight. However, when charge weight exceeds 8 gm the steel rings begin to yield and tempered steel must be used. The delay of from 40 to 75 microseconds listed in Table I is the time required for the explosive to detonate, compress the paraffin, fill available voids, and rupture the aluminum tube at the appropriate ring dies. After the tube is ruptured it separates along axial scribe lines and folds around the bending dies as shown in Fig. 4, at a rate depending upon paraffin flow. For design purposes, the paraffin velocity may be calculated approximately from test parameters listed in Table II and from gas laws and the kinetic energy equation.

TABLE I. Time Delay Between Initiation and Switch Opening

	Weight of Explosive (gm)	Time to Rupture (μsec)
A. Cylindrical Design Wall thickness (*mm*):		
0.89	3.24	70 ± 5
0.89	5.67	50 ± 5
0.89	8.10	40 ± 5
1.65	5.67	140*
B. Flat Design		
	1.7	40 ± 5

* Minimum time to rupture has not been determined for switches using 1.65mm wall thickness.

TABLE II. Development Switch Module

Explosive charge $= 5.67$ gm

Explosive energy (PETN), $W \simeq 4200$ J/gm

Paraffin mass, $m = 0.82$ kg

Initial explosive volume, $V_1 = 9.5$ cm^3

Final explosive gas volume, $V_2 = 390$ cm^3

Gas efficiency,[11] η, defined as a ratio of gas energy at venting, E_F, to explosive potential energy, E_I, gives (using specific heat ratio, $\gamma = 1.2$):

$$\eta = \frac{E_F}{E_I} = \left(\frac{V_i}{V_f}\right)^{\gamma-1} \simeq 50\% \qquad (1)$$

The efficiency of transferring the internal energy of the gas to kinetic motion of a pusher is estimated to be be about 50% on the basis of results obtained in a test assembly[11] using similar explosive weight, gas volume and pusher weight. Thus, the overall efficiency, η_{TOT} of 25% suggests that the pusher velocity, v, given by

$$v = \sqrt{(2\eta_{TOT}\ W)/m} \qquad (2)$$

is 0.12 mm/μsec for the parameters in Table II. The estimated velocity agrees with measured values discussed below.

B. Electrical Properties

Mechanical design of the switch lends itself easily to a variety of switching functions. Stacking of many sections can be used to maintain large voltage across the switch; the conductor thickness or parallel use of switches is effective in carrying large current for indefinite time before interruption; the opening time is nearly independent of the conductor thickness in the range investigated, and can be decreased by loading the switch with increased amount of the explosive.

The triggering is quite precise, i.e., the triggering jitter is substantially shorter than the opening time. The EBW detonators can be initiated with submicrosecond accuracy.[12] The high detonation velocity (7000 m/sec) provides rapid pressure buildup resulting in a high degree of simultaneity of gap rupturing. These properties combine to give a low energy dissipation switch for high voltage, high current operation with command trigger capability for applications where very fast current interrupting times are required.

1. Breakdown Properties. The voltage that can be maintained across any given switch depends on the mechanical design of the switch and on its arc properties. The pusher medium, the paraffin, serves as an insulator to prevent discharges between the cutting and bending rings. In the process of rupturing the current-carrying cylinder, sharp jagged edges of the order of a fraction of one millimeter are formed (as seen in Figure 4). The ring thickness and its detailed surface shaping as well as the gap length between the rings were chosen to minimize the length occupied by the wrapped aluminum. Thus, the electric field averaged over the length of the switch, determined by the ring and gap lengths, can be high when the gaps are filled by the paraffin.

There are other possible breakdown paths that can be initiated by the voltage arising during current interruption. One of these can develop on the inner surface of the expanding paraffin cylinder by puncturing to the electrodes. Another breakdown path can develop on the outside surfaces of the switch. The high voltage tests with switch elements ranging in length from 4 to 25 cm, have shown that the weakest insulation is between the outside edges of cutting rings on the surface of the parafin moving against the confining cylinder shown in Figure 2A.

The high voltage tests were conducted by separating the mechanical functioning of the switch (the explosive disruption of the electrodes and paraffin flow) from the electrical function (the interruption of current and subsequent buildup of the voltage acorss the switch) by using an external test circuit, capable of applying up to 100kV in 10 μsec across the switch module being tested, as shown in Figure 5. By employing this external circuit, the potential could be applied at different times ranging from periods before switch rupture initiation to periods several minutes after explosion. In these tests no current was carried by the switch so that the separation of electrodes occurred without formation of an arc. As can be seen in Figure 5, the switch can hold the voltage indefinitely or for short periods (about 100 μsec), depending on the time of application of voltage relative to conductor rupturing and on the average electric stress associated with given switch length. Data points associated with short hold-off periods are denoted by asterisks. The applied voltage waveform is also shown in Figure 5.

The results of tests show that 25 cm long switch design, using 16 ring-gap sections, can be stressed at a minimum of 3.3 kV/cm. The breakdown level for this configuration has not been reached due to the limitation of the power supply. Since the degree of gap-opening simultaneity may effect the pre-breakdown stress level, shorter switches were also tested. These tests indicate that up to 10 kV/cm can be achieved for two-section switch with this design if a breakdown can be tolerated after some 20 μsec. By determining the breakdown path to be between the outer rims of the rings it was possible to redesign the insulation and electric field distribution as shown in Figure 6. This configuration has been tested under arc conditions described below.

In addition, the switch design shown in Figure 2 was also tested using voltage pulses with decay time exceeding 100 msec. These tests confirmed the results for 16-section switch as given in Figure 5, indicating that this data is valid in applications related to power transmission.

2. Arc Properties. The characteristics of the exploding switch during its interruption of current can be divided into several categories. Three most important ones are associated with its performance where (a) the switch is interrupting the current with a period much longer than the opening time (i.e., simulating the interruption of d.c. current); (b) the switch is interrupting an alternating current, so that the effect of arc extinction under current zero conditions can be determined; and, (c) the switch operates so that the current during the initial phase of interruption is commutated to an external circuit branch with an exploding wire (fuse) for generating higher voltage. In applications where more than one switch module is required small jitter in the delay between the initiation of the explosion and the current interruption is also an important characteristic.

Fig. 7 shows the typical behavior of the rise in arc resistance during the interruption of current in the 25 cm long exploding switch using different amounts of explosive. The change in arc resistance arises from the increase in the gap formed during the rupturing of the current-carrying cylinder. In these experiments the current in the switch was 20 kA. The rate of growth of the gap length, directly proportional to the rate of growth of the arc length, is calculated using a simple model shown schematically in Figure 7. This model represents the section of the aluminum cylinder as a straight flap hinged at one of the bending dies, moving with velocity determined from Eq. (2) for a given amount of the explosive.

The calculated velocity agrees with the measured values using a framing camera to observe the motion of the aluminum. Good agreement indicates that the perturbation of the flow by the rings is not significant.

The almost exact correlation of the two sets of curves in Figure 7, the gap length and the resistance of the arc, for a range of charges varying by a factor of 2.5, indicates that during this time the developed voltage and its rate of rise depend only upon the gap length and the rate of gap opening, respectively.

The current-voltage characteristics of the arc exhibit two types of behavior, as can be seen in Figures 8 and 9. Initially, the voltage is rising rapidly. The current in the switch, at the end of the voltage rise time is essentially unchanged as can be expected from the equation

$$V(t) = RI = L \frac{dI}{dt} \qquad (3)$$

for the circuit in Fig. 9. For an 80 μH inductor, the change in current is only 2-3 kA, i.e., some 10% of the initial current, at the time of peak arc voltage of about 10kV. This is very important for use in inductive storage systems, where the efficiency of energy transfer depends on the ratio $(I/I_0)^2$, where I_0 is the current interrupted by the exploded switch and I is the commutated current. The arc behavior after the peak voltage corresponds to the time when the paraffin is expanding between the rings. At this time the arc length becomes constant and its behavior follows Mayr's model[3] described by the balance between the input power, IV, and losses, W_0:

$$\frac{dQ}{dt} = IV - W_0 \qquad (4)$$

where Q is the energy stored in the arc. As the current from the source is cut off at about 270 μsec, the arc voltage vanishes. The time constant of the arc, $\tau = Q_0/W_0$, with Q_0 being a constant, depends on the loss rate W_0. It is calculated graphically (Fig. 8) for two different periods of arc life, following Reference 3. Initially, when the paraffin moves faster, τ is about 90 μsec, eventually increasing to about 170 μsec as measured by the slope of the curve given in Figure 8. This value is in the range of values for non-evaporating plates[3] with separation equal to that between the die rings shown in Figure 1, rather than with separation equaling total arc length.

The arc resistance rises to approximately constant value in time which depends on the amount of the explosive charge as shown in Figure 7. As the current being switched increases, the voltage developed across the arc does not change for a given amount of the explosive. This result is summarized in Figure 9 for the basic 25 cm module as well as for other configurations. For example, data for 2 modules connected in series shows that the voltage output is doubled relative to the single module. Increasing the module length to 60 cm also results in doubling of the output voltage. Such long modules, furthermore, retain the same opening speed so that rate [illegible] rise of voltage is also doubled. The performance of the flat switch eleme[illegible]wn in Figure 2B is also indicated in Figure 9 (circle). For this type of s[illegible]h the arc quenching mechanism and the restrike values as well as voltage recovery rates do not depend on the expanding paraffin wall but rather on the presence of the polyethylene insulator and on possible existence of the high pressure gas generated by the explosive.[9] Although no significant flat switch performance test data has yet been obtained beyond that given in Figure 9, it appears that such switch designs may be useful in low voltage operations without commutation.

Because the jitter in the time between the explosive initiation and the mechanical separation of the conducting cylinder (Fig. 2A) is much shorter ($\leq$ 10 μsec) in comparison with voltage buildup time (seen to about 40 μsec in Figure 8), the switch can be modularized into various configurations. Using, for example, a two-module switch, the arc voltage is very nearly twice that of the single module (Fig. 9). The power level in this test is over 600 MW, achieved in 40 μsec without use of commutation or of external circuits to generate current zero.

3. Restrike Properties. The application of the exploding switch in power transmission networks or in production of high power pulses based on inductive storage systems requires voltages as high as 1 MV across the switch. Therefore, in addition to proper insulation discussed earlier, the switch voltage recovery rate must be consistent with the system requirements. The recovery rate was tested during the first 50 μsec immediately after the rupturing of the cylinder, using a 60 kV, 20kHz pulser generating peak current of 20 kA through the switch before interruption. The voltage recovered about 40 μsec after current interruption was initiated, suggesting a recovery rate of more than 1 KV/μsec. This value is intermediate between the values attainable by commercial SF_6 breakers and vacuum interrupters[13] and agrees with that of the exploding switch described in Ref. 6. The voltage recovery tests were performed during the phase of the switch operation when the separation of the aluminum is not yet completed, i.e., within less than 40 to 50 μsec after the conductor rupturing.

4. Current Commutation. The high voltage capability of the exploding switch module demonstrated in the tests under conditions where no current was flowing and good r.r.r.v. values observed after current zero suggest that high current, high voltage operation can be obtained by commutating the current from the switch to external circuits.[6,8] This has been done, using fast-acting fuses

(copper wires or aluminum foils[14]) with resistance substantially higher than the 20μΩ resistance of the exploding switch, in the external circuits. The current commutated through the fuse was interrupted in a time shorter than exploding switch opening time and with higher final resistance, allowing much higher voltages to be generated at the switch-fuse output than those obtained using exploding switch alone (e.g., as summarized in Fig. 9). In generating high inductive voltages by staging of current flow through succeeding switches, final peak voltage, and energy dissipated in each stage, as well as the current available at the output, depend sensitively on the selection of the opening switches. The analysis and experimental results using a 80 kJ capacitor bank will be reported in detail elsewhere. These tests showed that 120 kV output is developed with small energy losses so that generator current remains at >80% (40 kA) of the initial current. The output pulse was generated 40 μsec after initiating the commutation. The r.r.r.v. in these experiments was 3 kV/μsec.

III. MULTIPLE MODULE TESTING

To satisfy a broad range of applications of opening switches, the exploding switch was tested in configurations utilizing two modules. These tests were performed to provide data on jitter in the opening time of each module and the effect of such jitter on the electrical performance of the switch arrays.

Two types of tests, shown on Figure 10, were performed. The circuit diagram in Figure 10A shows how two modules were operated to double the output voltage to a level of 60 kV. Initially, the current interrupted by the exploding switch is commutated to the exploding Cu wire denoted as the variable resistor. The wire parameters were selected to generate a 30 kV open circuit output. The output voltage is shown in Figure 2A. In addition, current in each fuse is included for determining the jitter time. The value of jitter time of about 10 μsec is typical for the 25 cm modules.

To provide a pulse train output, it was suggested[15] that two switch modules be connected in parallel with sequential interruption of current provided by appropriately delayed triggers, as shown in Figure 10B. The current of the first switch module was commutated through four copper wire fuses, each with 0.2 mm^2 cross-section area, to increase the output voltage and power. The second switch in addition to a sim[illegible] commutated into a smaller diameter fuse to generate 25 kV, demonstrating [illegible] versatility of this approach. This technique is limited to pulse trains with duration determined by the time during which the source current amplitude remains appreciably constant. The minimum separation between pulses in the train is controlled by the combined effect of the switch opening time (of less than 20 μsec) and the jitter time (10 μsec).

The simple design of the switch modules allows a relatively large number of them to be used in applications where pulsing rates are sufficiently low to allow for switch replacement time.

IV. CONCLUSION

Basic mechanical and electrical behavior of an explosively actuated multigap opening switch has been studied with special attention focused on the interdependence of mechanical and electrical functions. The main areas of application are the high power inductive storage systems and the protection of power transmission equipment. Broad range of applications at levels up to 10^{10} Watts is possible using single switch modules and at higher levels using multi-modular designs. The switch module is a reliable and versatile unit capable of extension to operating levels of hundereds of kiloamperes and hundreds of kilovolts.

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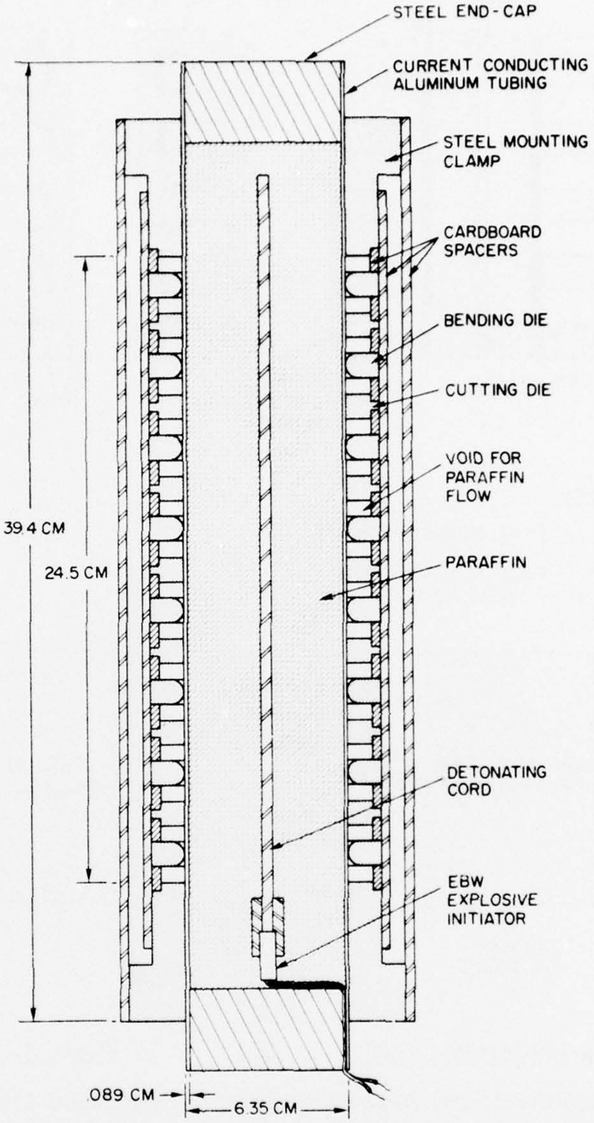


Fig. 1 — Explosively actuated switch module assembly diagram

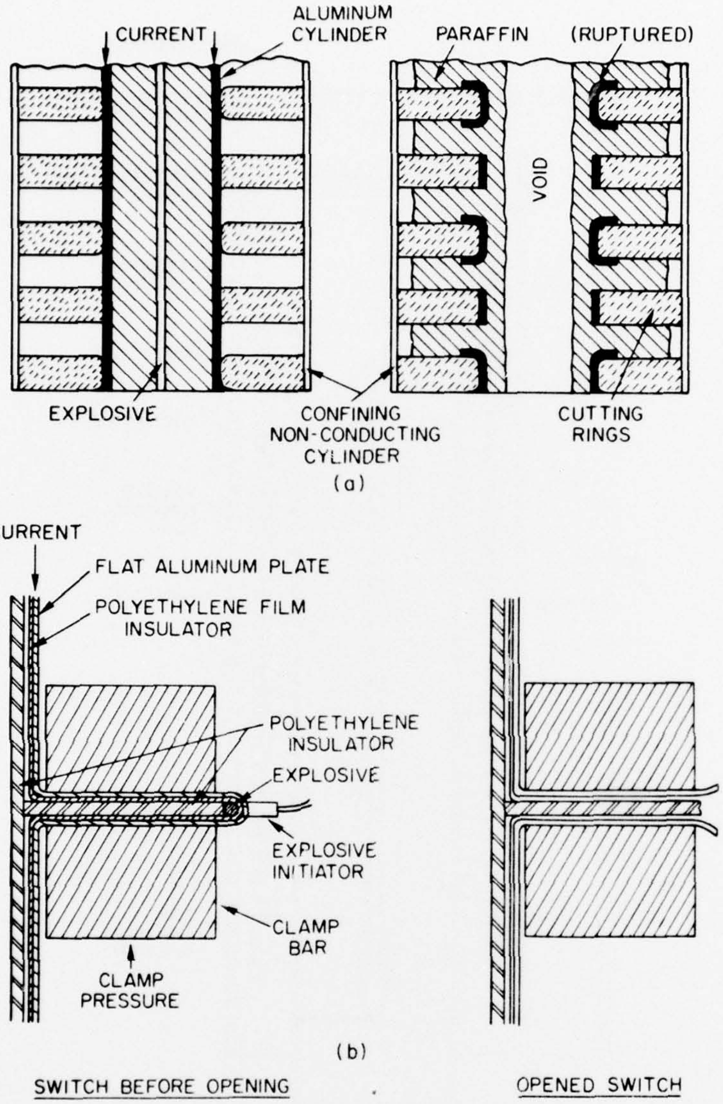


Fig. 2 — (a) Explosively actuated switch operation, cylindrical configuration, and (b) explosive actuated switch operation, flat configuration

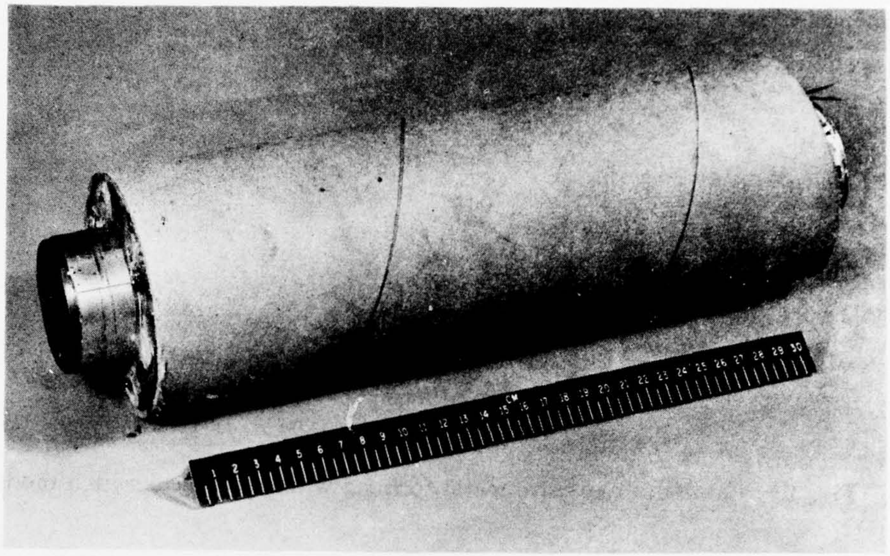


Fig. 3 — Typical switch module, fully assembled

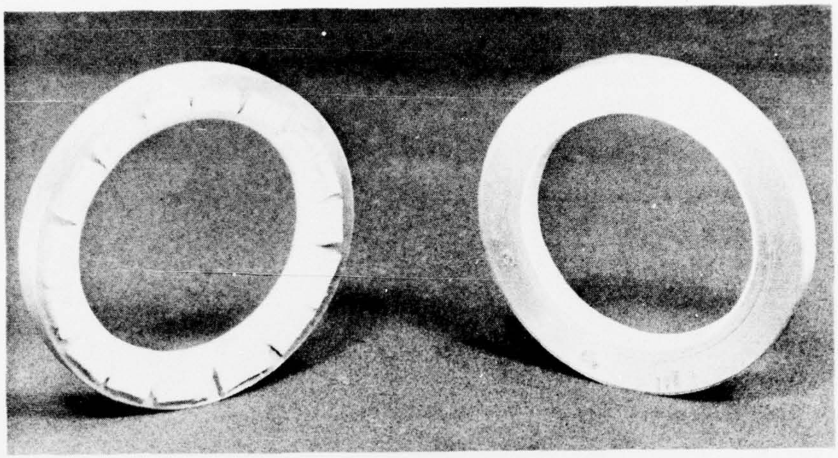
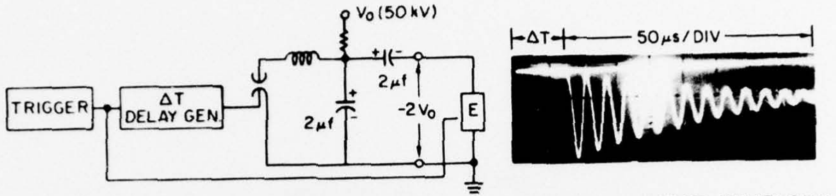


Fig. 4 — Results of explosive metal forming within a typical switch module



A. SWINGING MARX TEST CIRCUIT   B. TYPICAL VOLTAGE WAVEFORM

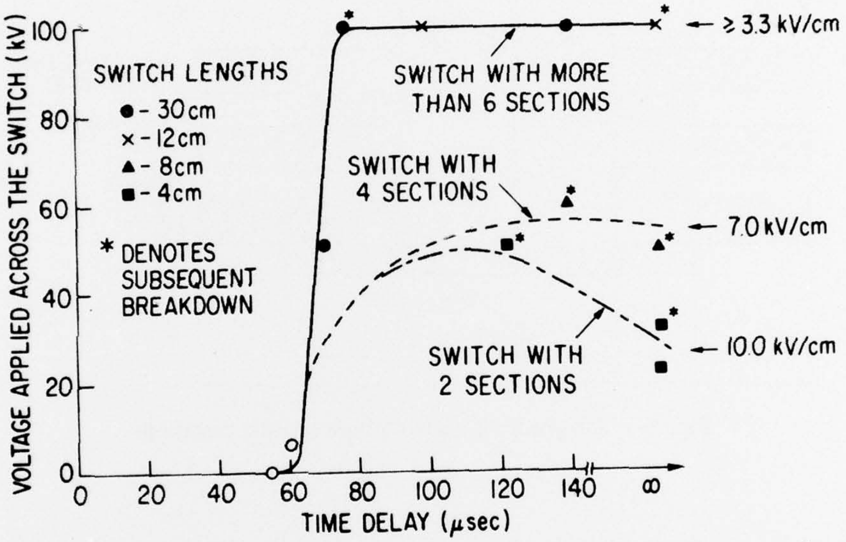


Fig. 5 — Explosively actuated opening switch voltage holdoff test results

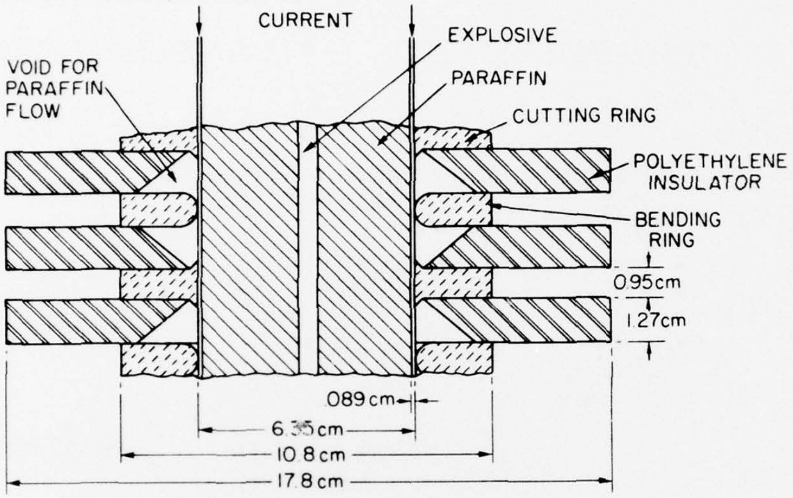


Fig. 6 — Diagram of high voltage switch assembly

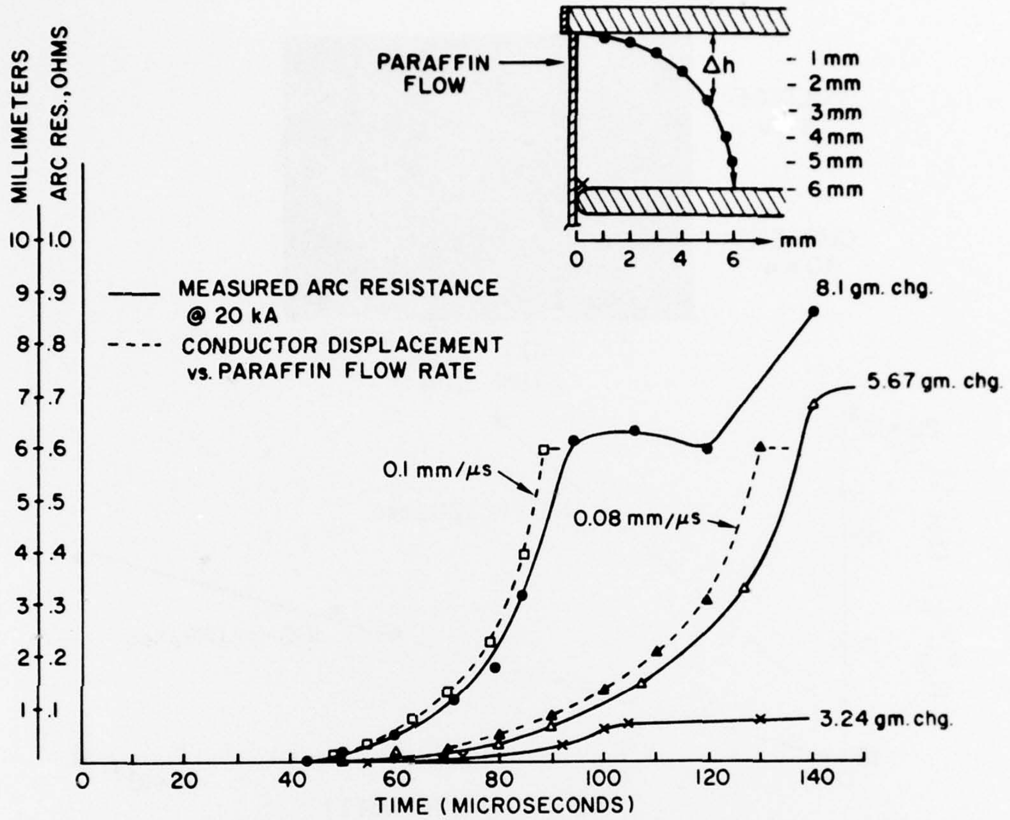


Fig. 7 — Explosive switch performance for various explosive charges

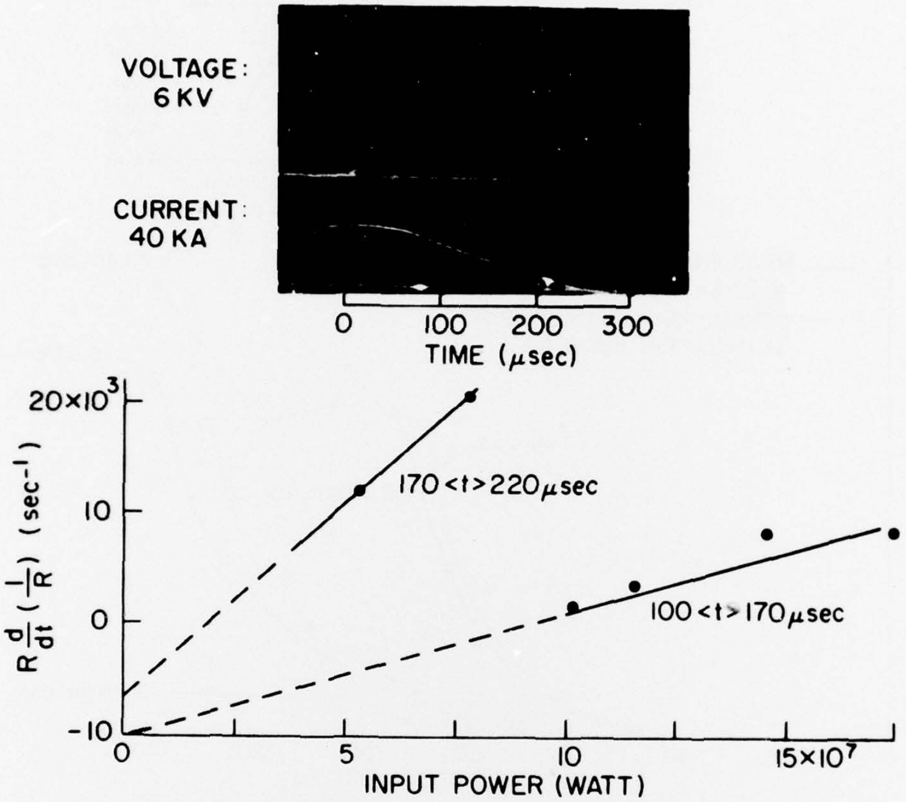
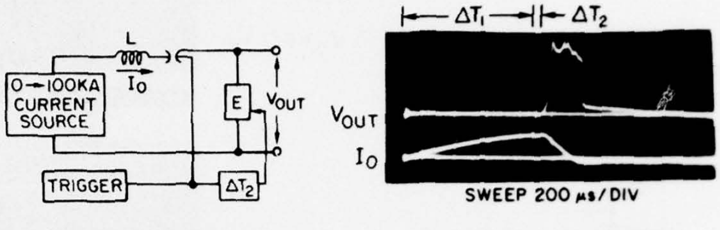
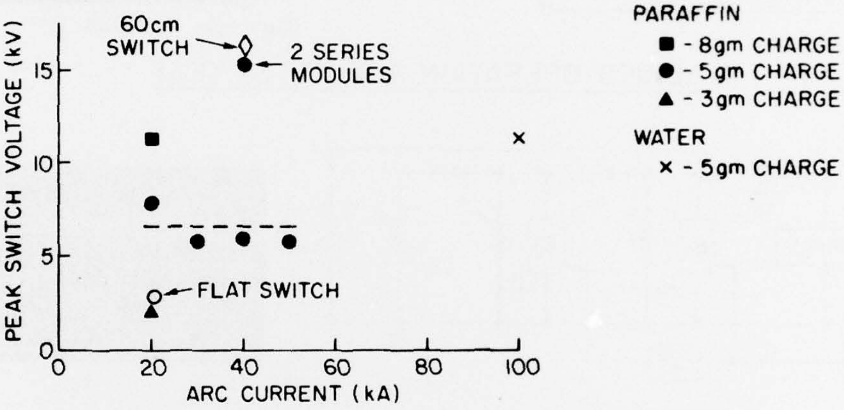


Fig. 8 — Arc resistance time constants



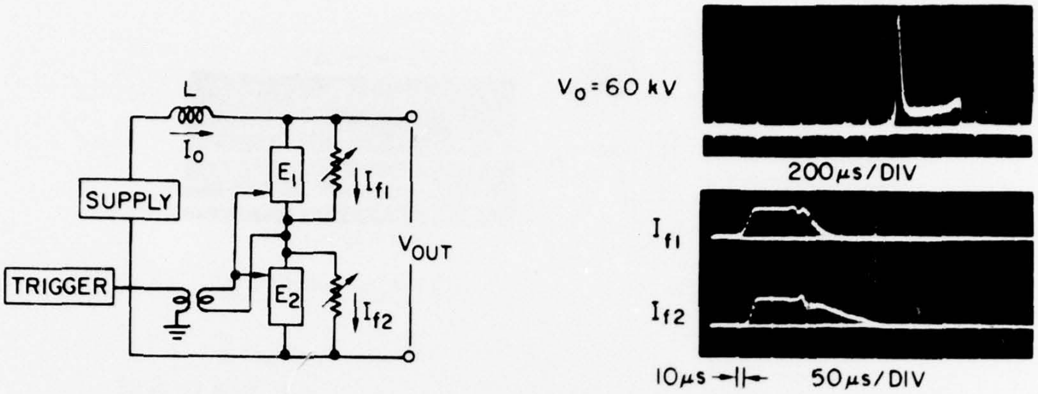
A. TEST CIRCUIT

B. TYPICAL WAVEFORM

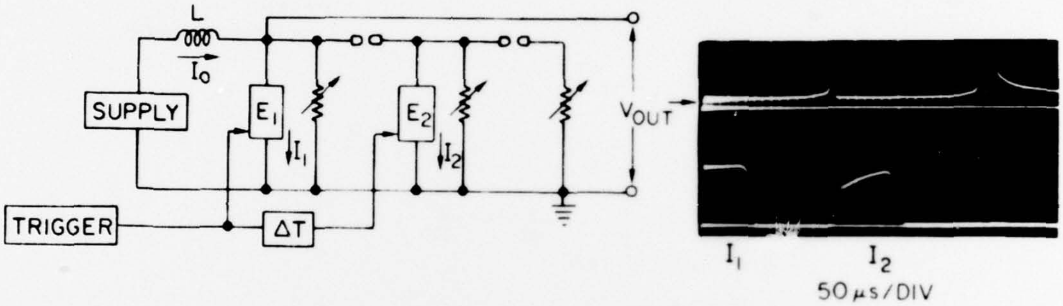


C. TEST RESULTS

Fig. 9 — Explosively actuated opening switch current test, no fuse



A. SERIES OPERATION AND JITTER TEST



B. SEQUENTIAL OPERATION

Fig. 10 — Dual module switch test results

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