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EXPLOSIVELY FORMED FUSE OPENING SWITCHES FOR USE IN FLUX-COMPRESSION GENERATOR CIRCUITS*

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INTRODUCTION

Explosive-driven magnetic flux compression generators (explosive generators) provide for the generation of large amounts of energy compactly stored in a magnetic field. Opening switches for use in explosive generator circuits allow the energy to be used for applications requiring higher power than can be developed by the generators themselves. We have developed a type of opening switch that we describe as an explosively formed fuse (EFF).[1-4] These switches are well suited to explosive generator circuits and provide a considerable enhancement of explosive pulsed-power capability.

Our first experiments with explosively formed fuses occurred while attempting to utilize the enhanced pressure developed in the high-pressure interaction between two detonation fronts. In these tests we attempted to use the interaction to sever conducting plates along lines perpendicular to current flow. The technique worked to some extent, and to ascertain how much advantage was gained from the high-pressure interaction, we substituted an areal detonation in place of the discrete lines required to produce lines of interaction. The result of this experiment was an outstanding opening switch effect that set the stage for all our subsequent work. We point out that the same effect could have been found by applying simultaneous detonation systems to the sweeping wave designs of Vitkovitsky[5] et al. and further, that Chernyshev et al.[6] have arrived at similar designs. The concept of the technique as an explosively formed fuse rather than as an explosive breaker came from comparing results of 2-D hydrodynamic code computations to experimental results. The calculations showed that the active conducting layer did not sever on the time scale of the opening, but was extruded into thin enough regions that Ohmic heating would be significant. A detailed accounting of the heating mechanisms has proved to be extremely difficult, but achieving significant resistance increases over a wide range of experimental parameters has been quite simple. We have brought explosively formed fuse opening switches to the present status by successive stages of experimentation and computation, driven by the needs of a high-current application. In the following material we describe much of our development effort, the state of the art, and the different manifestations of our technique.

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SWITCH CONCEPT

An explosively formed fuse consists of a relatively thick conducting sheet that is explosively driven into an insulating extrusion die. The die normally consists of a series of extrusion patterns and in all our applications, the extrusion occurs simultaneously throughout the die. Figures 1 and 2 illustrate the switching concept. Figure 1 shows 2-D hydrodynamic code (hydrocode) calculations of the hydrodynamic evolution at one die element. Figure 2 shows current and voltage records from an experiment utilizing four of these die elements in series. Arrows in Fig. 2 show the times of each frame in Fig. 1. Not only does the conducting element not sever in the frames shown, but calculations indicate that it does not during times of interest. The conclusion from these data and calculations is that the current interruption is due to heating of the conductor in the evolved thin regions. Recent results[4] indicate that the extrusion process may add approximately enough energy to melt the active region, but that the fusing action is relatively insensitive to the amount of heating thus produced.

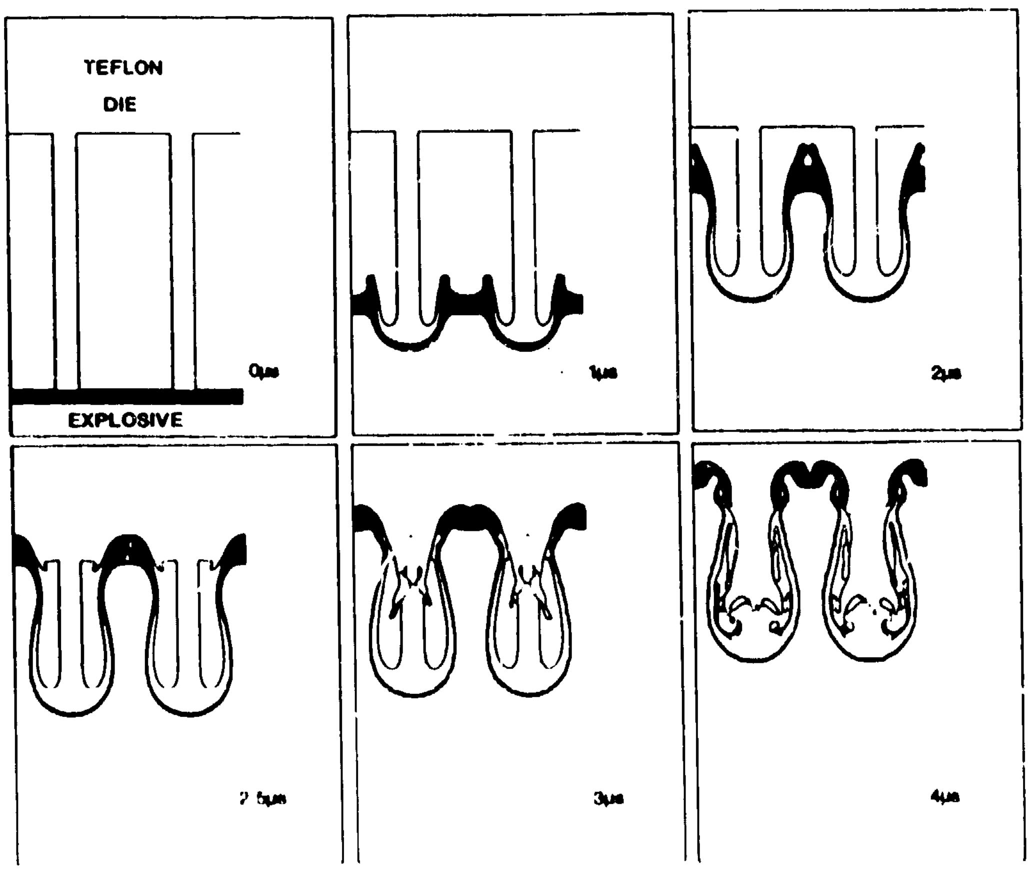


Fig. 1. Evolution of an explosively formed fuse. At time 0 (upper left) the cross-hatched aluminum conductor has just begun to be driven into the Teflon die. The calculation considers a die with one complete anvil-void-anvil pattern, and one half of a void on each side. The problem is bounded to right and left by reflective boundaries. In this calculation the voids are 6.5-mm wide and 13-mm deep. The Teflon anvils are 1.5-mm wide. Resistance becomes significant at ~2 μs.

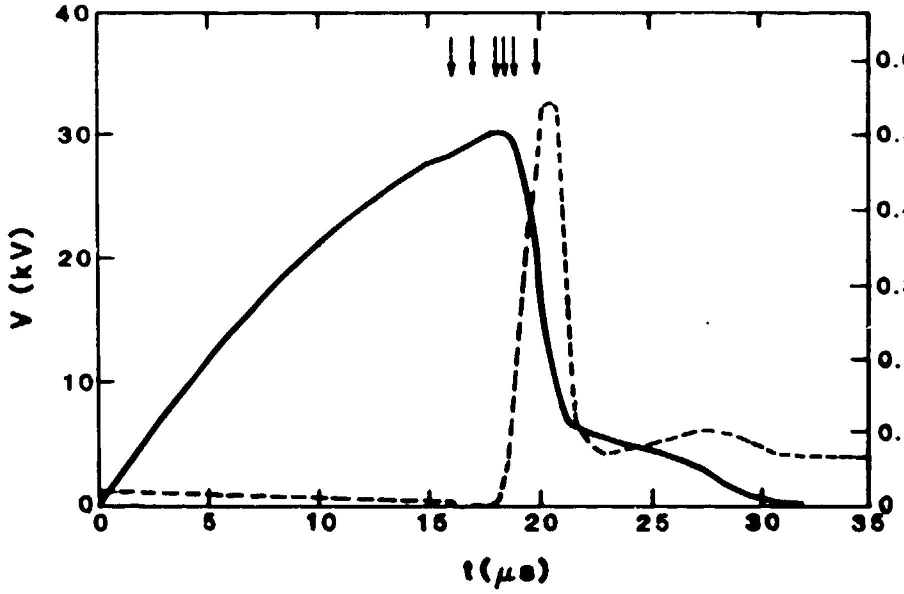


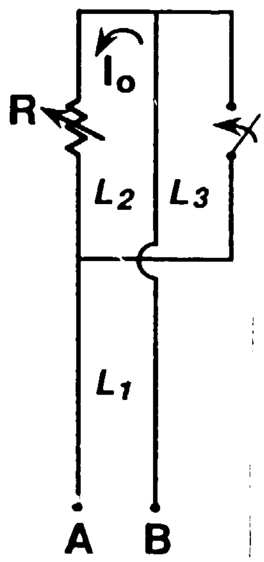
Fig. 2. Current and voltage waveforms from a small-scale test using four die patterns that correspond to the calculation in Fig. 1. Arrows indicate the times of the frames in Fig. 1. The circuit in the experiment consisted of a 1500-μF capacitor bank at up to 10 kV with a total inductance of ~200 μH.

SWITCH TOPOLOGY

We have operated explosively formed fuse opening switches in two different circuit topologies. Figures 3 and 4 illustrate these two switch versions that we will identify as Type 1 and Type 2, respectively. In a Type-1 switch, inductance associated with the opening switch must be represented as shown in the Fig. 3 schematic and flux in that inductance is lost during the current transfer process. A Type-2 switch has topology that is correctly represented schematically as shown in Fig. 4 without any wasted inductance. A Type-1 device is less efficient, but simpler and less expensive to operate. We have gained most of our experience with Type-1 devices, and a small scale test version of this device is shown in Fig. 5. Performance data obtained with such devices scale appropriately to devices such as that pictured in Fig. 6 which is the more efficient Type-2 version. As can be seen in Fig. 6, a Type-2 switch requires a few extra design, fabrication, and implementation considerations. The most expensive inclusion in this switch is a second explosive layer. In addition to expense, the thickness of the explosive (along with the insulation of this region) adds inductance to the load circuit. The switch will function if this explosive is omitted, but the resistance increases much more slowly in these cases. Operationally, the insulation in the load output section must withstand the shock wave from the explosive components, and still sustain the voltage required by the circuit parameters. Teflon has proven to be a good insulator for these purposes. In spite of the added complexities, Type-2 switches are the devices of choice if ultimate efficiency is required.

DESIGN AND APPLICATION CONSIDERATIONS

There are two essential parameters in explosively formed fuse design considerations. The resistance profile of the switch and the energy that it can dissipate. The rate of resistance increase is determined by two factors. First, there exists a limit on how fast high explosive (HE) will drive the active switch element and this controls the ultimate speed of the extrusion process. The extrusion can be slowed by adding more mass to the volume being driven into the die. In addition, since the opening depends on Joule heating, the current density in the switch can affect the speed also. In our experiments, however, this has not been an important factor.[4] A compensating mechanism occurs in explosively formed fuse operation that enhances the effective resistance rise. In practical designs, the extrusion die is inside the circuit loop and as the extrusion occurs the switch performs flux compression. The effect is to produce a forward voltage (counter to that of the eventual IR drop) that dominates until the resistance of the switch is equal to the magnitude of the negative dL/dt produced in the flux compression. The circuit current is amplified during this time, and the effects of early resistive phases are eliminated. This compensating feature is the fortunate coincidence of the fact that in high current density applications, the magnetic forces



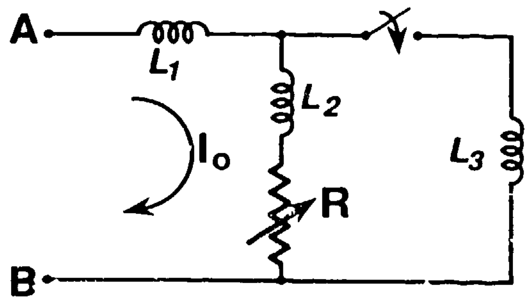
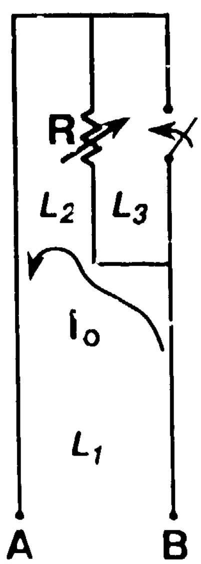


Fig. 3. Pictorial representation and schematic of a Type-1 EFF. The center line in the illustration indicates that the device is a figure of revolution of the lines shown. L_1, L_2, and L_3 relate the inductance in the schematic to a volume in the device, and R is the active opening switch element. A and B are the connection points to an explosive generator. Flux in L_1 is available to be transferred to the load, L_3, when the closing switch closes, but all flux ($L_2 I_0$) in the opening switch loop is lost.



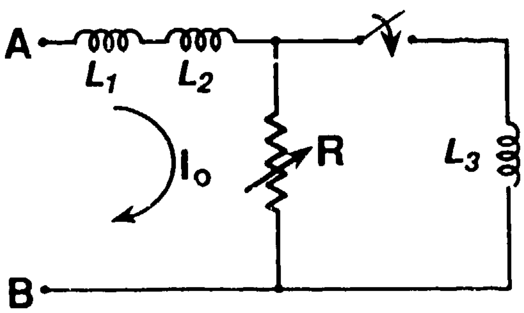


Fig. 4. The same two representations for a Type-2 EFF as presented for a Type-1 EFF in Fig. 1. L_1 and L_2 are kept separate to illustrate the point that some inductance is still associated with the EFF device, but L_1 and L_2 can be lumped together ($L_1 + L_2 = L_{STORE}$) for circuit analysis.

must be away from the extrusion die to prevent the premature extrusion of the switch by magnetic rather than explosive forces. The resistance of the switch initially is determined by the ratio of length, ℓ, to cross sectional area, A, in the active switch conductor. The hydrodynamic processes produce an extrusion in the die that changes the ratio ℓ/A, and the important length scaling parameter during the opening phase is the number of series patterns in the die, n. Since, in all applications to date, we have been able to use a conductor that is initially 0.8-mm thick, the dependence reduces to n/C where C is the circumference of the cylindrical switch. We base predictions of switch resistance in a new design on this ratio. Different die patterns yield different cross sections upon extrusion and each die pattern has its own scaling constant. The extrusion process adds heat to the switching region, but this is a constant per pattern and circumference and so does not affect the scaling. The magnitude of the scaling constant must be measured experimentally for each die, and the result can then be scaled for switches with differing physical dimensions. The details of the die design impact not only the resistance of the switch, but also the other important parameter, energy dissipation (ΔE). Figures 1 and 7 compare two different die designs. Figure 7 shows a die pattern that has wide anvils, while Fig. 1 shows very narrow anvils. Experimentally, we see that the resistance developed in the thinner regions produced by the wide anvils of Fig. 1 is larger per die pattern than that produced by the narrower anvils. The thin regions produced by the narrowed anvils, however, contain much more conductor mass and experimentally we see that the pattern of Fig. 1 will dissipate more energy per pattern. ΔE limits scale according to the product nC. The number of patterns per total switch length can be larger for the die with a narrower anvil, and this compensates somewhat for the reduced resistance per pattern while further enhancing ΔE. At linear current densities of 0.1 to 0.2 MA/cm the patterns

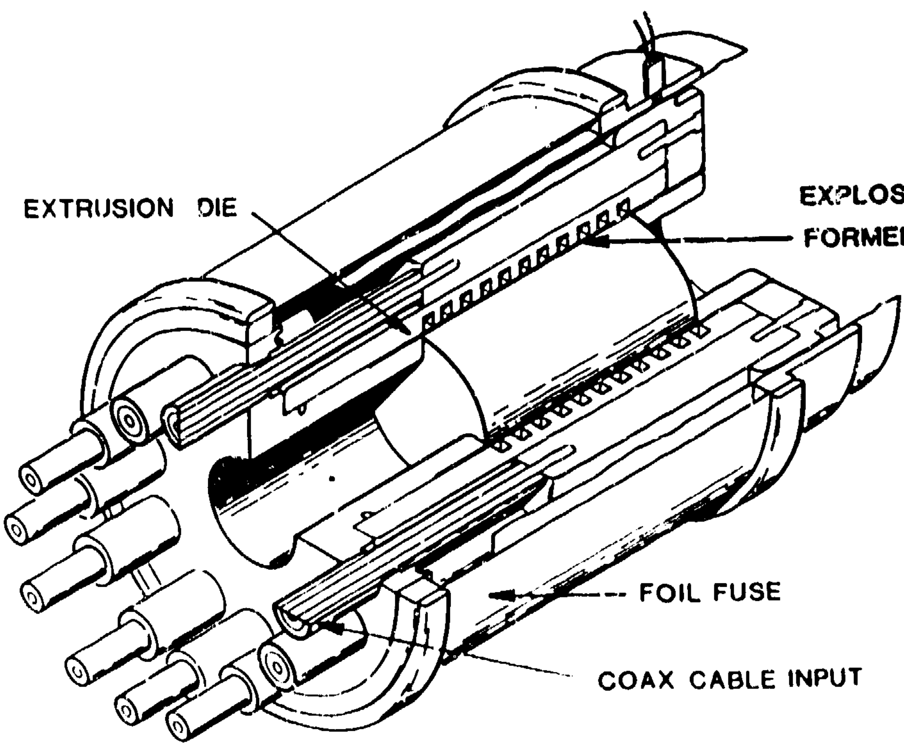


Fig. 5. Small-scale test version of a Type-1 EFF. The 15-cm-long cylindrical charge is detonated on axis driving the active conductor (labeled explosively formed fuse) into the extrusion die. Detonator-actuated closing switches allow current to be diverted to a foil fuse which can be a test dynamic load or a voltage pulse generator.

in Figs. 1 and 7, respectively, will develop a resistance at peak voltage of ~90 (mΩ-cm)/pattern and ~160 (mΩ-cm)/pattern. In addition, the two versions will dissipate ~0.78 kJ/(pattern-cm) and ~0.39 kJ/(pattern-cm). Figure 8 shows resistance curves from tests of both die patterns using the hardware in Fig. 5. We have discussed the amount of energy ΔE that an explosively formed fuse will dissipate. The interpretation of experimental data is that at some energy level, sufficient heating has occurred in sections of the explosively formed fuse that reconduction begins to occur in the same way as described by Lindemuth et al.[7] for conventional exploding foil fuses. This reconduction, however, does not produce a dramatic switch failure as might be seen in other devices, since there is a continuous range of cross sections in an explosively formed fuse, and some part of the switch continues to be cool enough to have high resistivity. Nevertheless, best results are obtained when none of the switch is overheated, and we say that the switch has reached its energy dissipation limit when we see a drop in total resistance occur as in Curve B off Fig. 8.

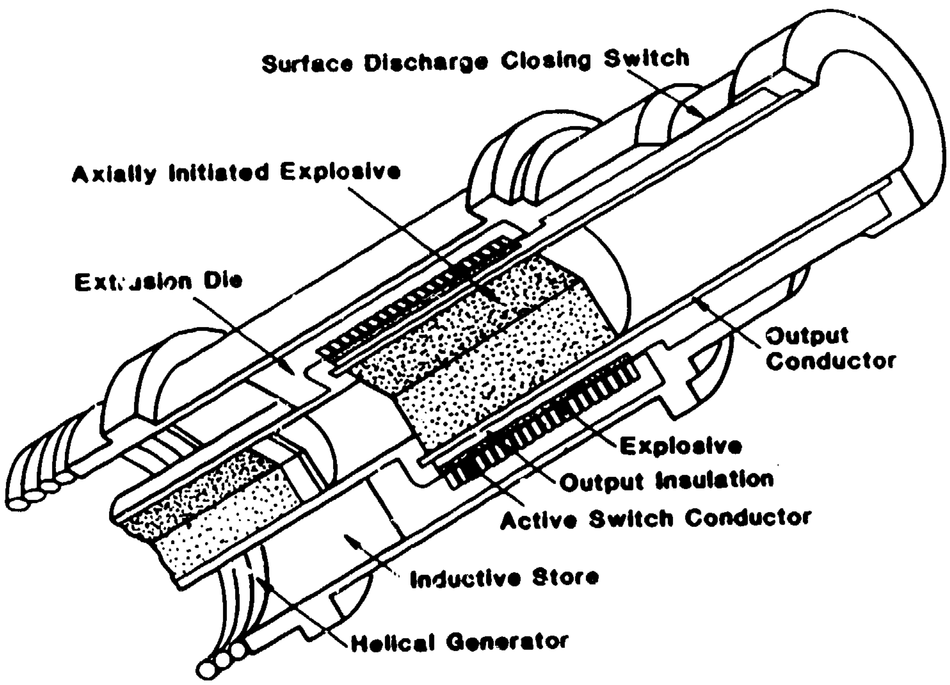


Fig. 6. Small-scale Type-2 EFF shown with a static inductance dummy load. The inner cylindrical charge is 15-cm long.

In choosing whether an explosively formed fuse is appropriate for a particular application, several things must be considered. The most obvious is that the switches typically make use of sizeable explosive charges. While not a factor for use with explosive generator circuits, considerable effort would be required to use the devices in close proximity to permanent pulsed power facilities. Further, there are the fundamental hydrodynamic limits on switching speed discussed earlier. Full resistance of explosively formed fuses require ~2 μs to develop. Conduction time, however, can be very long and as an example, in applications in which a large helical generator develops 11 MA in 350 μs, the pulse compression ratio into a 30-nH load is ~200. The low amplitude part of this current pulse can be almost arbitrarily long. Although hydrodynamics and current density determine the rate of resistance rise in an explosively formed fuse, we can delay closing the load isolation closing switch until the resistance is somewhat developed,[2] and ultimately, the current transfer rate is determined by the switch resistance and circuit inductances. In most of our applications, resistances in the 100-mΩ range have been sufficient. As an example of operational parameters, a switch that

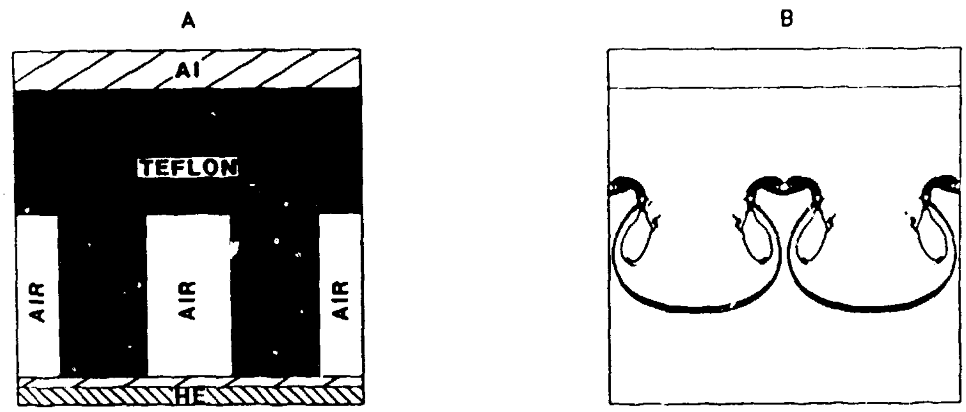


Fig. 7. Die pattern for comparison to Fig. 1. Frame B shows the evolution by 3 μs. Note that the sides of the extruded region are very thin but that the region where the Al is between the Teflon anvil and the HE remains relatively thick. More resistance per pattern develops, but less energy is dissipated. If the field across the HE in the narrow gap between anvils exceeds ~100 kV/cm, failure will occur.

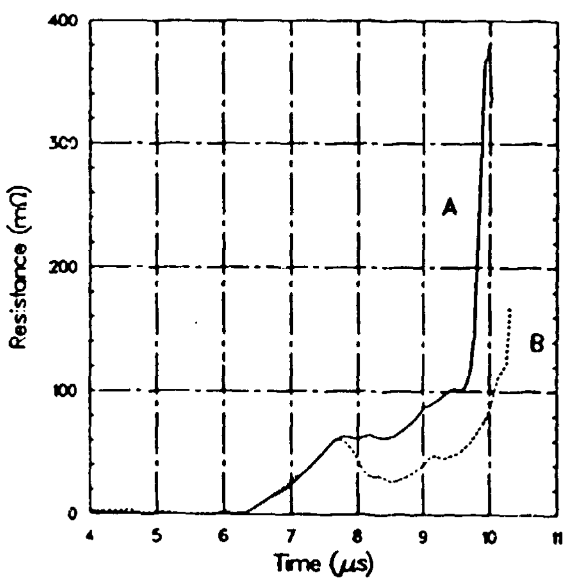


Fig. 8. Resistance curves produced by two different die patterns. Curve B used 20 of the die patterns in Fig. 1 and Curve A used 11 of the patterns in Fig. 7. ~125 kJ were dissipated in Test A while 450 kJ were dissipated in Test B.

conducts 11 MA and dissipates 2.5-MJ circuit energy develops ~100 mΩ, and scaling considerations indicate that it should perform that task at up to $\Delta E \simeq 7$ MJ. Based on these numbers and employing R and ΔE scaling relations, a switch developing well over 300 mΩ should be possible using available HE systems. To operate within the range of linear current densities in which we have typically worked, the switch would be limited to 6 to 7-MA peak current and $\Delta E = 2$ MJ. Since an experiment with this device would produce voltages of ~1 MV, other factors would have to be considered in addition to I and ΔE, however. IR voltage drops exceeding 9 kV/cm have been successfully sustained down the length of the switch, but transmission line designs must also be commensurate with the voltages generated. When nominal resistance values and energy dissipation limits are experimentally determined, other circuit parameter ranges are implied. If we perform a simple analysis on the circuit in Fig. 4, we see that for a constant resistance R carrying a current I_o when the load isolation switch is closed, current transferred is given by

$$I = \left(\frac{L_{\mathrm{STO}}}{L_{\mathrm{STO}} + L_{\mathrm{load}}}\right) I_o \left(1 - e^{-\alpha t}\right)$$

where

$$\alpha = \frac{R(L_{STO} + L_{load})}{L_{\mathrm{STO}} L_{\mathrm{load}}} \quad .$$

Further

$$\Delta E = \frac{1}{2} I_o^2 \left(\frac{L_{\mathrm{STO}} L_{\mathrm{load}}}{L_{\mathrm{STO}} + L_{\mathrm{load}}}\right) \quad .$$

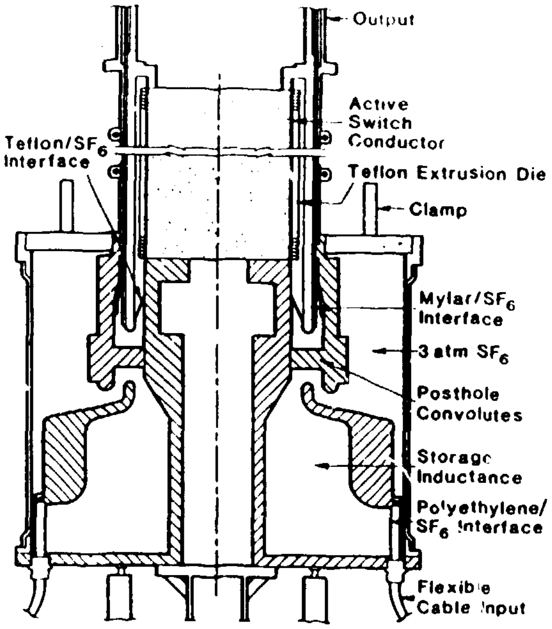


Fig. 9. Inductive store and current transfer section of a pulsed power system for driving plasma z-pinch experiment. The EFF seen in the top center of the assembly is a Type-1 device, and the post-hole convolutes (six total) provide the penetration necessary to connect the outer and inner return conductors. Flexible cables connect to a MK-IX helical generator. A surface discharge closing switch is located in the region omitted by the cut lines in the upper section.

We see that a maximum value for ΔE implies a maximum value for I_o for fixed store and load inductances. Although a realistic time-varying resistor and either a resistive load or time-varying load inductance change the implied circuit values, these simple relations can be used for determining the range of usefulness of an explosively formed fuse when ΔE and R have been experimentally determined. Finally, a question of synchronizing explosively formed fuse events with other experimental features must be considered. Although high precision firing circuits are available, the jitter in actuating the switch is the accumulation of several events. In addition, the explosively formed fuse turns off with different risetimes at different current densities. As a result, actuating the switch within a 100-ns window is reasonably simple, but improving that performance by a factor of two requires great care and precision. As an example, actuating an explosively formed fuse to coincide with the broad top of a sweeping wave helical generator waveform is trivial, but synchronizing the resulting voltage waveform that increases at the rate of $\geq$400 kV/μs with a detonator actuated closing switch is difficult. If each event occurs in a 100-ns window, the jitter in voltage at closing time is 80 kV.

APPLICATIONS

Although major applications of explosively formed fuse Switch Technology are the subject of other reports in this conference,[8,9] we will give a brief description here of some explosively formed fuse applications. Figure 9 is a cross section of an explosively formed fuse system that has the ultimate goal of driving 1-μs plasma z-pinch experiments. The explosively formed fuse in this system is a Type-1 device. Figure 10 summarizes data from a test of this device. We have not yet successfully sustained the entire voltage pulse produced by this inductive store-explosively formed fuse system. However, the failures have been due to dielectric interfaces and transmission lines rather than problems with the explosively formed fuse. We have sustained as much as 140 kV across a 15-cm-long explosively formed fuse,[4] and have every reason to believe that the 76-cm-long switch in this system will easily handle the 220 kV required for successful operation.

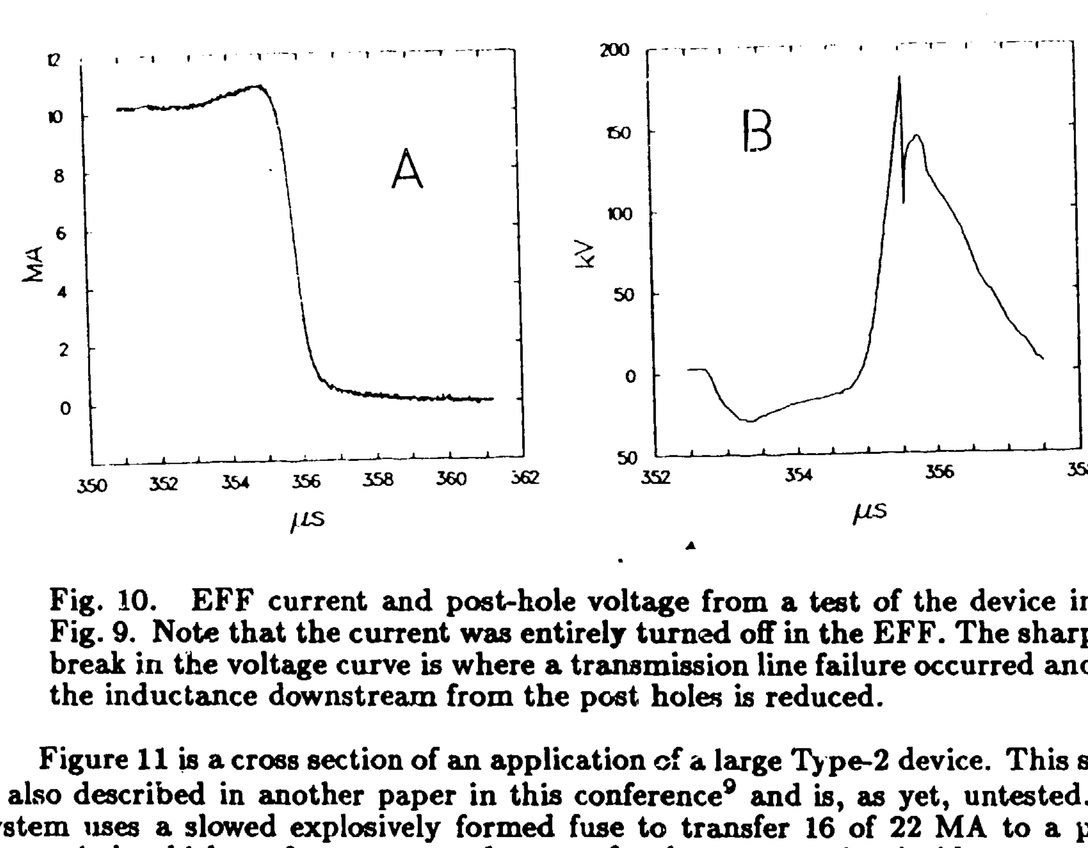


Fig. 10. EFF current and post-hole voltage from a test of the device in Fig. 9. Note that the current was entirely turned off in the EFF. The sharp break in the voltage curve is where a transmission line failure occurred and the inductance downstream from the post holes is reduced.

Figure 11 is a cross section of an application of a large Type-2 device. This system is also described in another paper in this conference[9] and is, as yet, untested. This system uses a slowed explosively formed fuse to transfer 16 of 22 MA to a plasma flow switch which performs a second stage of pulse compression inside an evacuated region. Ultimately, we will try to drive plasma z-pinches with the plasma flow switch. Figure 12 shows calculated performance of the system.

Figure 13 shows data obtained from a different use of a Type-1 device. In this test, the explosively formed fuse simply provides a complete circuit path to allow the delivery of initial flux to the generator and early flux compression to occur. Then, as the dL/dt of the generator becomes large, the EFF is actuated and the load is switched in. In this case, only a small amount of flux is lost in the switch and a Type-1 explosively formed fuse is fine. For applications where a generator will drive the load, but the early long time pulse is damaging to the load, this system is ideal.

A final application is suggested by initial small-scale Type-2 tests. These tests have been reported elsewhere,[4] and results are summarized in Fig. 14. When a high-voltage pulse is required for high-impedance loads, such a system could be built. As suggested earlier, a compact system that would develop 1 MV would be feasible if the voltage can otherwise be sustained.

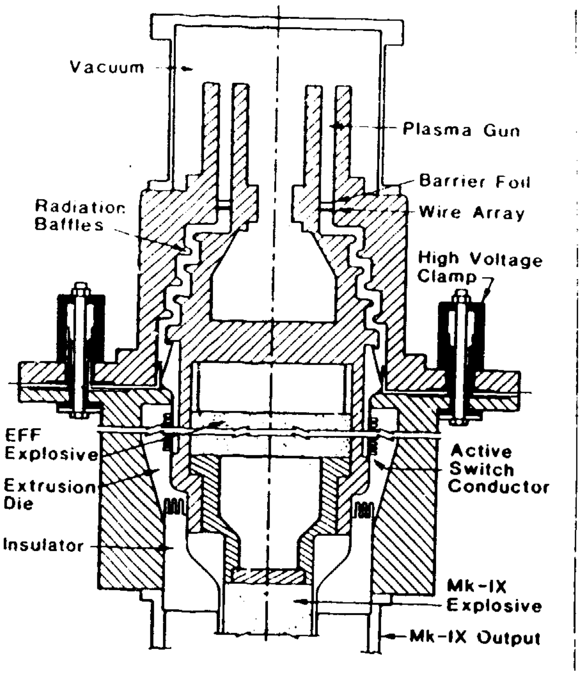


Fig. 11. System using a Type-2 EFF to drive a plasma flow switch experiment. This EFF is a slowed-down Type-2 device that does not have a second HE layer.

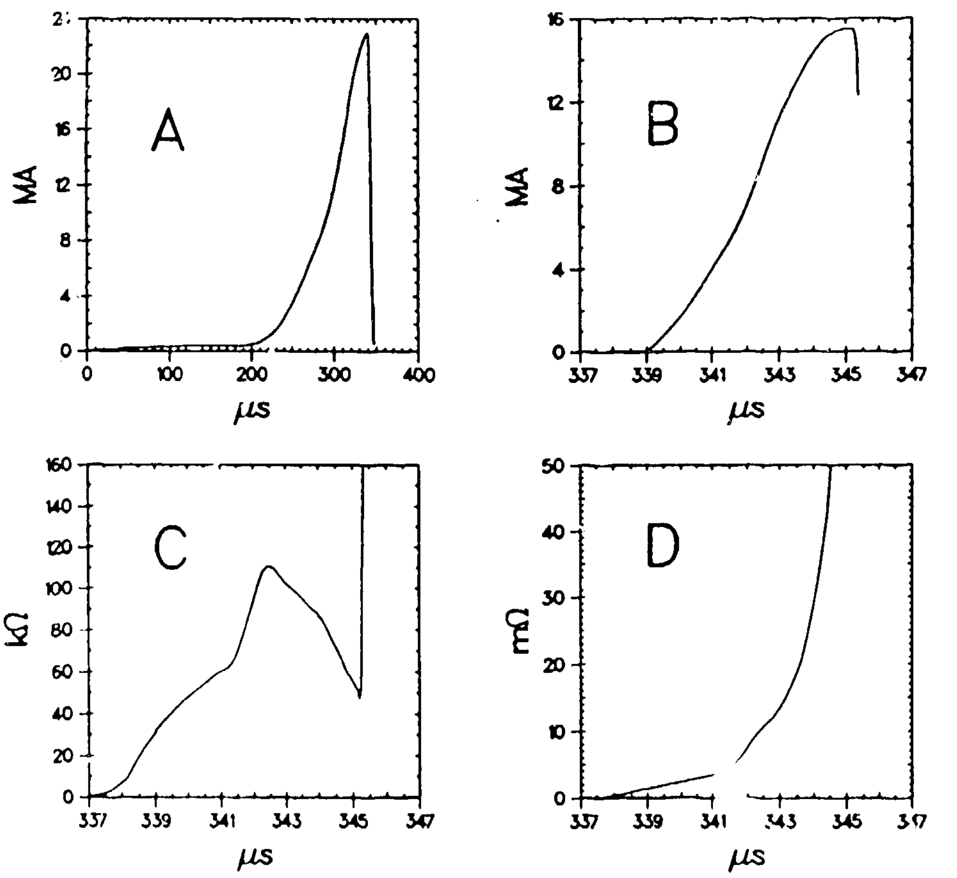


Fig. 12. Predicted performance for the system in Fig. 11. Frames A, B, C, and D show total system current, plasma gun current, the voltage at the gun input, and the EFF resistance, respectively. The R(t) curve in Frame D is an extrapolation from a test, with the device in Fig. 6, in which the second layer of HE was omitted.

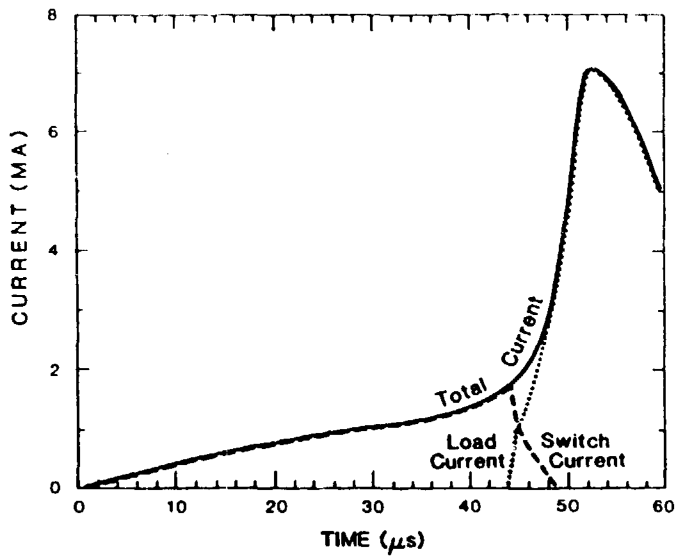


Fig. 13. EFF, load, and generator currents for a Type-1 EFF test driven with a plate generator.[10] Little flux is lost during switching in this test, as most flux still resides in the generator at switch time. Plate generators have a driving impedance of 20–30 mΩ, and this system is ideal when that is sufficient to drive the load.

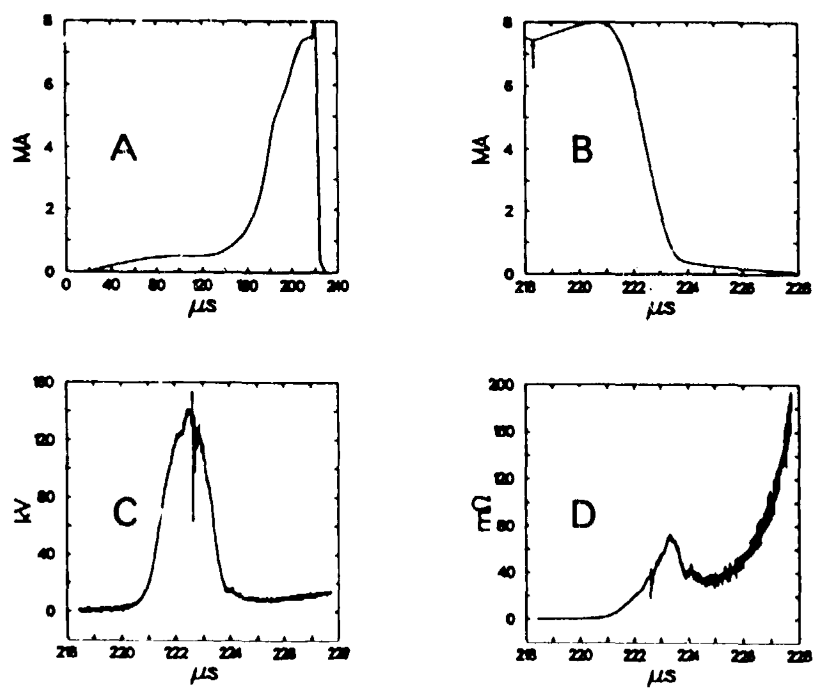


Fig. 14. Results of an open-circuit test (no dummy load attached) of the device pictured in Fig. 6. Frames A–D show total system current, EFF current at switch time, EFF voltage, and EFF resistance, respectively. The increase in resistance after ~225 μs should be regarded as uncertain due to the nature of dividing the two small signals in B and C to get the result. Peak power in this test is 0.56 TW.

CONCLUSIONS

We are just beginning to apply explosively formed fuses to a variety of systems, and to take full advantage of explosively formed fuse techniques, a great deal of work must still be done. Detailed understanding of the resistance rise, for instance, will allow the initial switch conductor and the die design to be tailored precisely to each application. In the meantime, we have developed a useful technique for on-going experiments and scaling relations for determining when explosively formed fuse switches may be useful in other systems.

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