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TITLE:

ADVANCES IN EXPLOSIVELY FORMED FUSE OPENING SWITCHES

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Abstract

We are pursuing the development of Explosively Formed Fuses along two separate lines. One design, which has previously been demonstrated to conduct a 9.5 MA 350 μs risetime pulse and interrupt it in 1.2 μs. This scaled up design should operate at up to 15 MA with 20 nH loads. A second design with enhanced performance characteristics is being examined and will be tested on a small scale. This design includes opening switch inductance as part of the inductive store and, as a result, should have shorter pulse transfer times and should be able to be scaled to handle currents up to ~25 MA with 20 nH loads.

Introduction

Useful classes of explosive-driven magnetic flux compression generators (explosive generators) will deliver many megamperes of current with characteristic pulse delivery times of tens or hundreds of microseconds. Many interesting applications require much shorter pulses, and opening switches can play a significant role in tailoring explosive generator wave forms to meet specific load requirements. We have been developing explosively formed fuses (EFF'S)[1,2] to satisfy the need for a first stage pulse compressor for explosive generator waveforms. In a typical application, an EFF is used to conduct for up to a few hundred microseconds at ~50 μΩ and then divert current to a separate branch of the circuit with a transfer time of 1- to 5-μs.

We have previously presented principles governing the operation of EFF's.[1,2] To summarize, a relatively thick conductor is explosively driven into a forming die that extrudes the conductor into a series of thin sections. Augmented by an undetermined amount of heating due to the extrusion process, Joule heating in the thin sections causes them to fuse and become resistive. Figure 1 illustrates the fuse-forming process for a particular die pattern. In the following material, we discuss experiments with small cylindrical devices at currents up to 5 MA and results of higher current tests of a device ultimately intended to conduct, then divert, currents of ~15 MA. Finally, we present a design that should ultimately enable currents up to ~25 MA to be conducted without increasing the size of the switch.

Small Cylindrical Switch

Our initial tests of EFF's in cylindrical geometry were conducted using a device having an active switch region ~15 cm long and ~29 cm in circumference. The power supply for these tests consisted of an explosive plate generator[3] with initial field fed directly into the generator by a capacitor bank. As described in Ref. 2, these tests demonstrated that the switch would conduct for up to 100 μs and would then divert current to low inductance loads in 1- to 2-μs, dissipating ~450-kJ electrical energy. Further, we showed that as the EFF resistance began to rise, a voltage of at least 80 kV could be withheld across the 15-cm switch prior to actuating the closing switch and diverting current to the load. This voltage leads to current transfer with a fast risetime.

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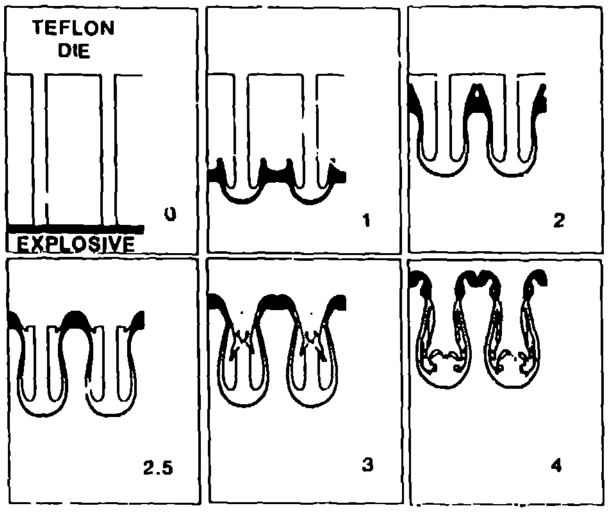

Figure 1. Two-dimensional hydrodynamics code simulation of the evolution of an explosively formed fuse. The simulation shows explosives driving an aluminum conduction (cross hatched) into a teflon die. The numbers in each frame are the time in microseconds from the initial motion of the aluminum. Fuse action begins to occur at ~2 μs.

Not shown in Ref. 2 are opening switch resistance data. Figure 2 shows resistance profiles from two of these tests. Two different die patterns were used for these tests, but compensating effects in the extrusion process produce very similar resistance profiles.

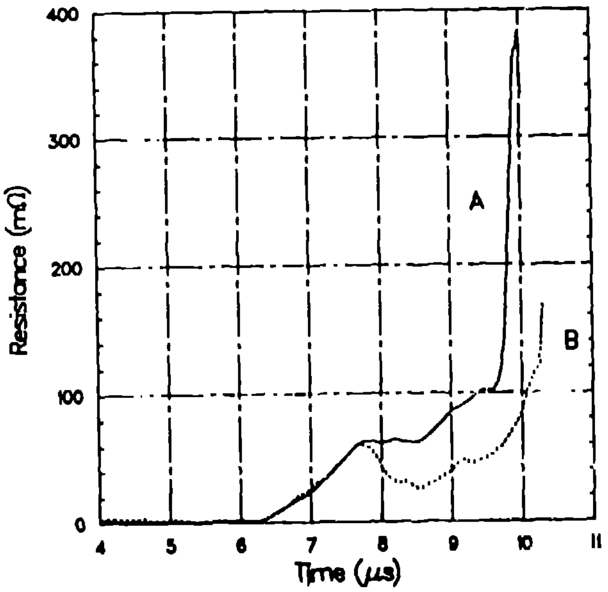

Figure 2. Resistance curves produced by two different die patterns operating at different energy dissipation limits. ~125 kJ were dissipated in test A while 450 kJ were dissipated in test B.

The important difference between the two curves is that curve B is produced by a die optimized for large energies and the EFF dissipated 450 kJ in this test. Curve A is for a switch that would only dissipate ~125 kJ. The dip in curve B is characteristic of a switch operating near its energy dissipation limit and indicates that the thinnest sections of the switch have overheated resulting in a decreased resistance. The die patterns in respective experiments A and B are

1.8 cm and 0.75 cm in length, and the long die patterns produce a very thin extrusion over a short distance, while the short pattern produces more than twice as many fuse sections that are thicker. The larger number of thicker fuse sections provides the extra energy dissipation capacity at the same resistance until the energy limit is exceeded.

For a final note on the small scale experiments, Fig. 3 shows data from a test in which a fuse was used to subject the switch to a high voltage pulse after current transfer was complete. This was the highest voltage we applied across our small switch. The small amount of reconduction shown from 64- to 65-μs is consistent with a resistance of >200 mΩ and demonstrates that no failure of the switch occurred even though a voltage >150 kV was applied to it.

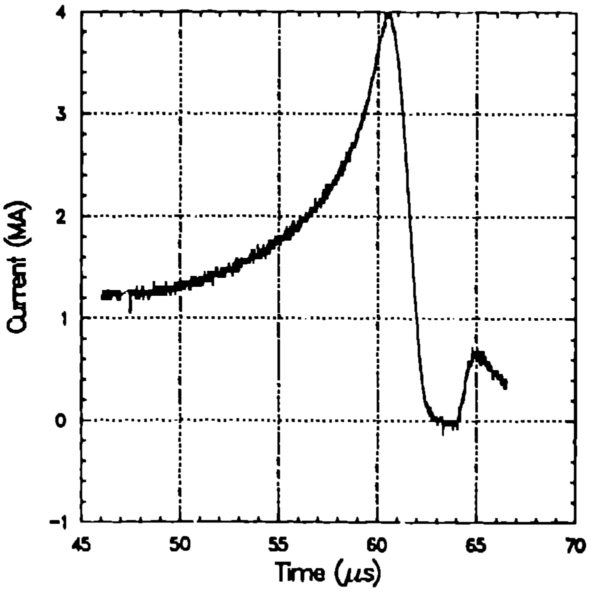

Figure 3- EFF current profile from fuse load test. The reconduction at 64- to 65-μs is due to a voltage >150 kV applied by the bursting fuse, and is consistent with an EFF resistance >200 mΩ. The current pulse begins at ~15 μs on this time scale.

Scaling

In order to design EFF's for higher current applications, some scaling assumptions must be made. Since the current interruption capacity of a switch is determined by the amount of energy it can dissipate, the first assumption addresses the way energy dissipation will scale with size. The amount of energy dissipated depends on the mass of material that fuses and therefore we consider how the active mass varies with switch dimensions. The switch conductor must initially have a large enough cross section to conduct the full pulse without appreciable heating. To allow our research to apply to a broad range of applications, we have kept the thickness of the switch conductor fixed at 0.08 cm. As a result, the thickness of the fuse sections per unit conductor width is also fixed and the fuse mass varies linearly with switch circumference, C, in cylindrical devices. Also, the switch dies consist of a series of fuse forming patterns and the fuse mass varies with length an the number of patterns in the die. For the same die pattern, this goes simply as the length, ℓ. These considerations lead to the conclusion that for a given die pattern, energy dissipation in the switch varies as the surface area of the switch conductor (ℓC).

The next scaling consideration addresses switch resistance, which is important in determining the characteristic current transfer time. Using the same physical model as above, we determine that resistance varies as ℓ/C.

A high explosive (HE) system is available for use in these systems that is 76-cm long and 96 cm in circumference. Using data from our 15-cm-long by 29-cm-circumference tests, we determine that a switch can be built using this HE system that will have a resistance R_L given by $R_L = R_{sm}(\ell_L C_{sm}/\ell_{sm} C_L) = 1.5\ R_{sm}$, where the subscripts L and sm refer to the large scale and small scale devices respectively. Similarly, the energy dissipation, ΔE, is given by $\Delta E_L = \Delta E_{sm}(\ell_L C_L/\ell_{sm} C_{sm}) = 16.7\ \Delta E_{sm}$. For $\Delta E_{sm} = 450$ kJ, as we have demonstrated, an energy dissipation of 7.5 MJ is indicated. We have built this switch and conducted preliminary tests as described below.

Preliminary Large Scale Tests

Our initial experiments with the 76-cm-long by 96-cm-circumference EFF are directed towards the needs of a plasma z-pinch experiment.[4,5] In most cases the best use for an EFF is as the first stage of pulse compression on a long duration waveform, but for this application it was deemed appropriate for the only stage of compression[4] and testing in this configuration was begun.[5] Reference 5 describes the current status of the overall system performance, and we focus this discussion on the performance of the switch. Figures 4-6 show the important waveforms from one test. Figure 4 shows the total current conducted by the EFF, and with the load pulse shown on the same scale, is a graphic representation of the degree of pulse compression.

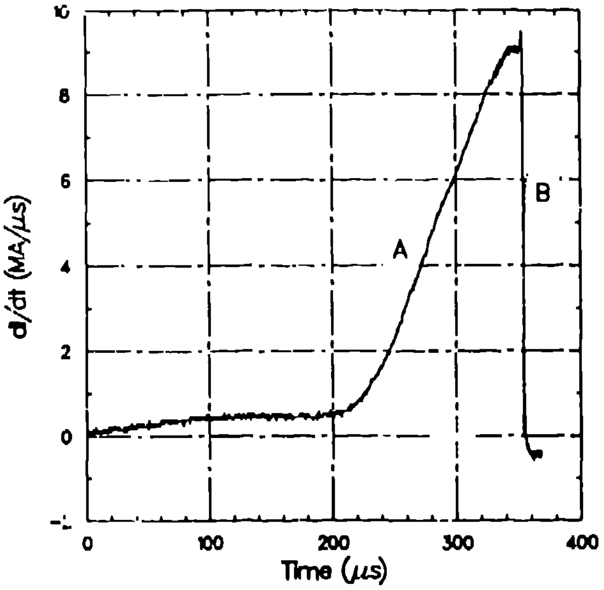

Figure 4. Large scale EFF test results. Curve A is the current pulse conducted (and interrupted) by the EFF. Curve B is the current transferred to a 10 nH load. On this scale, curve B, the load current, nearly disappears behind the decaying curve A.

Figure 5 shows the voltage generated at the 10-nH load input, the decaying switch current, and the load current pulse. Some load current was lost apparently at the input of the switch.

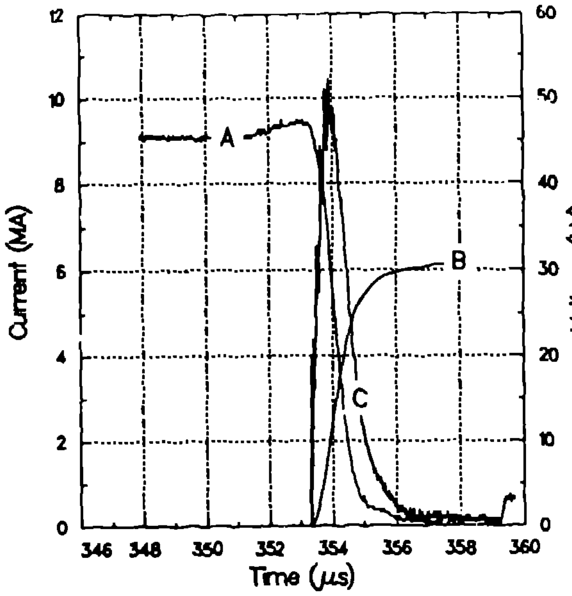

Figure 5. A) Decaying EFF current. B) Load current. C) Load $\dot{I}$ multiplied by the 10 nH load inductance. Since ~2 MA of storage inductor current are not accounted for in these curves we conclude that a transmission line failure occurred but had a higher impedance than the 10-nH load. The exact time of the failure cannot be determined from the data, but it occurred after the start of load current. The time scale is the same as Fig. 4.

Figure 6 shows the energy dissipated in the switch, the dissipation rate, and the switch resistance.

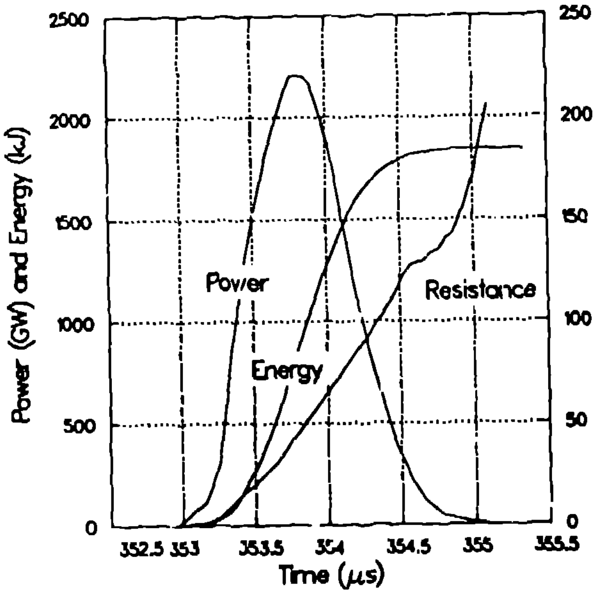

Figure 6. Resistance generated by the large scale EFF, the resulting power pulse and total I^2R energy dissipated. The time scale is the same as Fig. 4. The die pattern in this test is the same as that of curve B in Fig. 2, and the resistance profile compares favorably with 1.5 times the curves in Fig. 2.

In this test the load inductance was 10 μH and the switch inductance was 33 nH. The data are, therefore, representative of switch performance over some range of low inductance loads. Assuming a large storage inductor, the minimum energy dissipation is given by

$\Delta E = 1/2\ I_o^2(L_2 + L_3)$ and the pulse transfer time is characterized by $(L_2 + L_3)/R$. In these expressions, I_o is the EFF current when the closing switch to the load is actuated, the subscripts 2 and 3 have been chosen to be consistent with a figure and refer to the opening switch and load respectively, and R is a step resistance that approximates the actual EFF resistance form. From these expressions we see that a change from 10- to 20-nH for the load inductance does not have a dramatic effect on the experiment. The required energy dissipation changes from 1.9 MJ to 2.4 MJ and, assuming an average value for R of 70 mΩ during the transfer time, the e-folding time changes from 0.61- to 0.76-μs.

Tests of the EFF and a fuse load have been conducted but as described in Ref. 5, progress has been hampered by transmission line failures at ~100 kV and no high voltage pulses have yet been applied. We have interrupted currents of 10.5 MA in these tests, dissipating over 2 MJ, and to date, we have found no reason to doubt the projections that we made from small scale tests.

Advanced Design Concept

The EFF's discussed thus far can be represented by the circuit shown in Fig. 7, with R being a finite step resistance, L_1 a storage inductor, L_2 the EFF inductance, and L_3 a fixed load inductance. By a physical rearrangement of the components, however, an EFF can be designed that operates as shown in the circuit of Fig. 8. Here, the symbols represent the same quantities as in Fig. 7, but L_2, the switch inductance, is now included as part of the inductive store. This circuit offers some advantages. For the circuit in Fig. 7, the energy dissipation in the opening switch during a current transfer operation is given by

$$\Delta E = \frac{1}{2} I_o^2 \quad \frac{L_1L_2+L_1L_3+L_2L_3}{L_1+L_3}$$

and current is transferred to L_3 according to

$$I_3 = \frac{L_1}{L_1+L_3} \quad I_o \quad 1-e^{-\alpha(t-t_o)} \quad ,$$

$$\text{where } \alpha = \frac{R(L_1+L_3)}{(L_1L_2+L_1L_3+L_2L_3)} \quad .$$

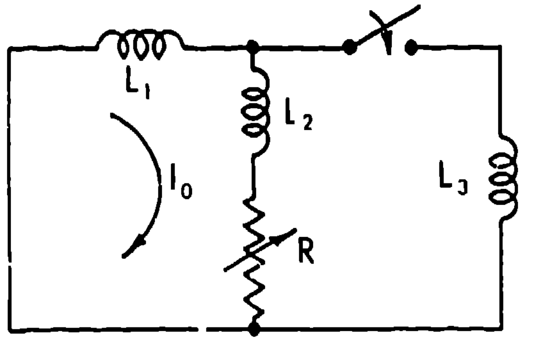

Figure 7. Circuit representing EFF devices tested to date. L_1 is a storage inductor, L_2 and R represent the EFF, and L_3 is the load. Magnetic flux in L_2 is lost from the circuit in this design when current transfer occurs.

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For the circuit in Fig. 8, however, we have

$$\Delta E' = \frac{1}{2} I_o^2 \frac{L_1 L_3}{L_1+L_3} \quad \text{and}$$

$$I_3' = \frac{L_1+L_2}{L_1+L_2+L_3} \quad I_o \quad 1-e^{-\alpha t}$$

where

$$\alpha = \frac{R(L_1+L_2+L_3)}{(L_1L_3+L_2L_3)} \quad .$$

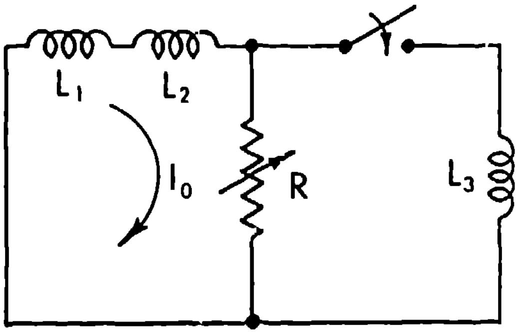

Figure 8. Circuit for advanced EFF design with same symbols as in Fig. 7. Magnetic flux in the EFF is not lost during current transfer in this design.

For a large storage inductor, the energy dissipation, ΔE, and time constant, $1/\alpha$, expressions reduce to

$$\Delta E = \frac{1}{2} I_o^2 (L_2+L_3) \quad , \quad \alpha = \frac{R}{(L_2+L_3)} \quad ,$$

$$\Delta E' = \frac{1}{2} I_o^2 L_3 \quad \text{and} \quad \alpha' = \frac{R}{L_3} \quad ,$$

and the advantages are readily apparent: both the energy dissipation in the switch and the load current risetime are reduced by a factor of $L_2/(L_2 + L_3)$. For large scale devices, L_2 is typically >35 nH and loads of interest are 20- to 150-nH which results in a savings of 20-64% in both energy and risetime. Figure 9 is an illustration of an EFF configured to operate as in Fig. 8.

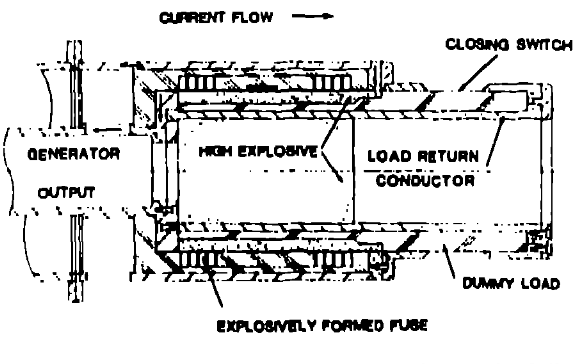

Figure 9. Side view of an advanced EFF design shown attached to a coaxial generator output and a coaxial dummy load. Arrows show initial conduction path. Surface discharge closing switch diverts current to load return conductor when EFF opens. Both a simultaneously initiated inner cylinder and an outer shell of explosives are required.

The primary difficulties with this design are that the outer layer of HE must be detonated by a shock passed through one of the output conductor cylinders and the output insulation without severing it. A plasma compression opening switch with this topology has been successfully demonstrated by Pavlovskii et al.,[6] however, and with appropriate care for hydrodynamic consideration we should be able to operate such a switch. We will perform tests with these systems on the same size scale (15-cm long) as our initial cylindrical EFF tests[2] in the near future, and plan to scale up to larger systems. With the 76-cm-long HE system, energy dissipation criteria would allow 25-MA currents to be considered with 20-nH loads, or 11 MA with 120-μH loads. Another advantage of this design is that no cables are required to couple this switch to either a helical generator at the switch input or a coaxial load. The extra efficiency and natural coaxial topology of this switch should make it a very useful opening switch for explosive pulsed power applications.

Acknowledgements

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