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High Voltage Applications of Explosively Formed Fuses*

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Abstract

At Los Alamos, we have primarily applied Explosively Formed Fuse (EFF) techniques to high current systems. In these systems, the EFF has interrupted currents from 19 to 25 MA, thus diverting the current to low inductance loads. The magnitude of transferred current is determined by the ratio of storage inductance to load inductance, and with dynamic loads, the current has ranged from 12 to 20 MA. In a system with 18 MJ stored energy, the switch operates at a power up to 6 TW. We are now investigating the use of the EFF technique to apply high voltages to high impedance loads in systems that are more compact. In these systems, we are exploring circuits with EFF lengths from 43 to 100 cm, which have storage inductances large enough to apply 300 to 500 kV across high impedance loads. Experimental results and design considerations are presented. Using cylindrical EFF switches of 10 cm diameter and 43 cm length, currents of approximately 3 MA were interrupted producing ~200 kV. This indicates the switch had an effective resistance of ~100 mΩ where 150-200 mΩ was expected. To understand the lower performance, several parameters were studied, including: electrical conduction through the explosive products; current density; explosive initiation; insulator type; conductor thickness; and on. The results show a number of interesting features, most notably that the primary mechanism of switch operation is mechanical and not electrical fusing of the conductor. Switches opening on a 1 to 10 μs time scale with resistances starting at 50 μΩ and increasing to perhaps 1 Ω now seem possible to construct, using explosive charges as small as a few pounds.

Introduction

Previous studies[1] suggested that electrical fusing, following mechanical deformation, performs a primary role in EFF operation. The parametric studies reported here show that electrical fusing performs a secondary role, and the mechanism of switch operation is hydrodynamic deformation of the conductor.

In the course of development of the switch for high voltage applications there was a noticeable and unexpected degradation in switch performance.

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Using cylindrical EFF switches of 10 cm diameter and 43 cm length, currents of approximately 3 MA were interrupted, producing ~200 kV. This indicates the switch had an effective resistance of ~100 mΩ where 150-250 mΩ was expected. To understand the lower performance, and to optimize the performance of the full-scale experiments, several parameters were studied in a series of small-scale experiments. Eventually it was learned that the switch performance in the 10 cm diameter EFF was limited by explosive initiation problems, peculiar to the 10 cm assembly, and these were corrected. However, this was not before the small-scale tests were performed.

Small-scale planar experiments

Planar, rather than cylindrical, assemblies were fired for simplicity, and economy. These experiments were designed to match the electrical and physical conditions of the full-scale switches. The anvil patterns were identical, and the current densities were matched to ~80 kA/cm, see Fig. 1. The effects of varying the following parameters were studied: the explosive; the aluminum thickness; the current density; the addition of Teflon between the explosive and the aluminum; the type of die plastic; the cavity-depth in the plastic die; the surface finish of the plastic; and the load inductance. Due to space limitations, only the more interesting effects are reported.

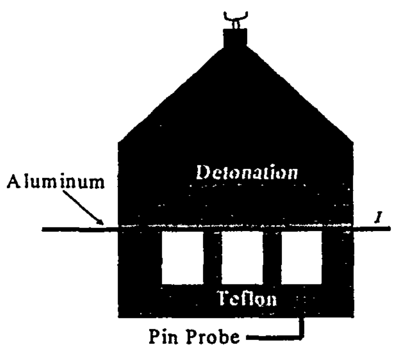

Figure 1. Schematic of small-scale assembly.

Baseline experiment.

In the baseline small-scale assembly, the 6061-T6 aluminum conductor was 812 μm thick, 63.5 mm wide, and 127 mm long. Typically the current in the conductor was between 550 kA and 600 kA. The PBX-9501 explosive had a thickness of 12.7 mm and was initiated by a P40, ~100 mm diameter plane wave lens. There was no insulation between the explosive and the aluminum. The Teflon switch die was 165.1 mm square, with nine1.50 mm-wide anvils and ten 6.00-mm spaces, making ten patterns; the cavity depths were 12.7 mm. A capacitor discharge circuit was used, with circuit parameters of 170 nH, 3 nF, and 2.9 mΩ. A typical current profile is shown in Fig. 2. In these experiments the switch was timed to interrupt current at peak current from the bank. At the beginning of switch operation the aluminum conductor was compressed into the Teflon cavities, and this reduces the switch inductance. Accordingly there is a compression of flux and the current increases, as shown in the inset of Fig. 2. The time of first flux compression (first motion) is a useful diagnostic, as it pinpoints the exact time that the explosive shock wave reaches the free surface of the aluminum conductor.

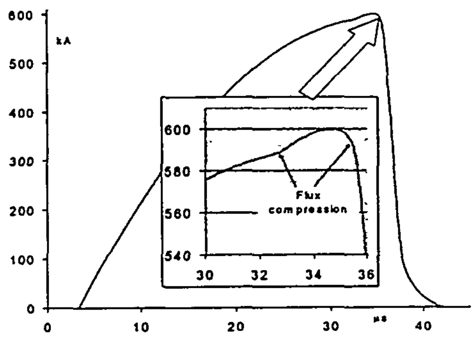

Figure 2. Switch current, showing flux compression and current termination.

Joule heating

To quantify the effects of electrical fusing in the aluminum, two experiments were fired in which the current density was reduced. In these the currents were 126 and 105 kA, and thus the Joule heating rate (being proportional to I^2) was reduced by factors of 19 and 27 from the standard experiment (~550 kA). If Joule heating contributed to the fuse action, then there will be a corresponding degradation in performance of the switch. In fact, switch performance was improved. The resistances were 540 mΩ and 580 mΩ respectively, compared to ~250 mΩ for the standard switch and current density. From these results we conclude that: switch action is primarily by mechanical deformation rather than electrical fusing; and because the resistance had increased, that switch performance is ultimately limited by breakdown in the explosive product gases. We did note that the rate of resistance rise was slower in these shots, which suggests that electrical fusing does perform a secondary role in switch action.

Effects of varying aluminum thickness

If the aluminum thickness is reduced below the standard 813 μm, calculations show that the initial velocity, when explosively-projected into the Teflon cavity, stays close to ~4.1 km/s because the PBX-9501 explosive to metal mass ratio is so high.[2] As the velocity is approximately constant, the predominant effect of thickness might be expected to be the increase in Joule heating as the current density increases. Experiments were performed using conductors of pure aluminum in thicknesses of 254 μm and 508 μm, and the resulting voltage data compared with the standard experiment (813 μm), Fig. 3. The data are plotted from the time of first motion. Two curves are plotted for the standard experiment: one at the full current (550 kA); and one at low current (105 kA) - multiplied by five to reveal the structure. The results show the peak voltages are roughly equal, yet there is a double-hump structure that varies with thickness. The delay to the first hump increases linearly with thickness. The 813-μm data show the delay is independent of the current density, so again, electrical fusing is not responsible for the structure, the effects are hydrodynamic. As shown by the pin data discussed below, impact with the

Teflon cavity floor occurs at 2.20 µs after first motion in the standard (813 µm) thickness, as indicated by the dashed line.

Hydrodynamic calculations of aluminum deformation confirmed that the initial velocities were identical, and that the times of impact with the cavity floor were similar; impact occurs at ~2.0 µs for the 254 µm thickness compared with 2.2 µs for the thickest sample. However, there was a significant thinning of the aluminum jet prior to impact. The calculations show maximum

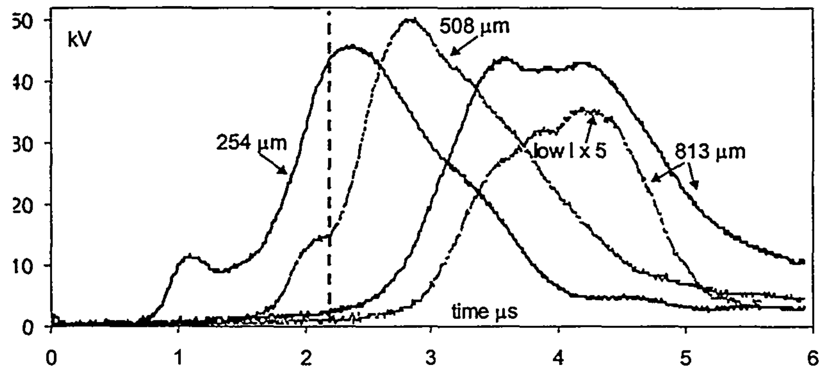

Figure 3. Results for three aluminum thicknesses.

thinning of the aluminum occurs at ~1 µs and ~2 µs after first motion for the 254 µm and 508 µm thicknesses, i.e., both before impact, but does not occur in the 813 µm thickness until after impact. These calculations agree with the data of Fig. 3. The calculations also show that for the two thinnest samples, the aluminum thickens again after impact as the aluminum piles up into the cavity floor. We conclude that mechanical fusing of the aluminum causes the first hump. The 813-µm thickness appears to be optimum to provide a broad, flat-topped structure.

Timing – Voltage Pin Diagnostics

To verify the calculations of switch performance published in ref. [1], a voltage pin probe was added to the test, as shown in Fig. 1. The probe was inserted so that the active element was flush with the floor of the switch cavity and insulated with a 125-µm Kapton layer. Consequently, no voltage appeared on the probe until impact of the aluminum jet with the cavity floor. The results of the small-scale experiment are shown in Fig. 4, plotted from time of first motion. Impact occurred at 2.20 µs, in good agreement with the predictions of ref. [1]. The switch acted as a voltage divider, thus reducing the pin data by a factor of 4.5. At impact, the switch voltage had risen to ~1 kV.

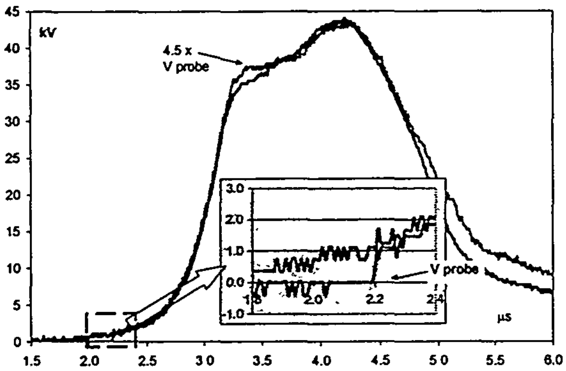

Figure 4. Voltage probe and pin data; inset shows impact on pin.

Inductance effects

The voltage across the switch, at the time of switch opening and peak current, is given by:

$$V = IR = -L\frac{dI}{dt}$$

So if R were constant, the output voltage would be independent of inductance, but if dI/dt were constant the voltage would be proportional to inductance. Also, as flux is conserved, and increases with inductance for a given current, the integral of voltage with time should increase with inductance. Fig. 5 shows the output voltages for inductances of 140 to 502 nH, for the same peak currents in the standard configuration. These are each plotted from the time of first motion. The waveforms are remarkably similar. The rising edges of the waveforms are almost identical, both in amplitude, slope and timing. Differences are only evident after the initial peak. This implies that the initial resistance of the switch is constant, and that dI/dt decreases as the inductance increases. Moreover, the fact that the voltage integral does not increase with inductance implies that breakdown is occurring after the initial peak.

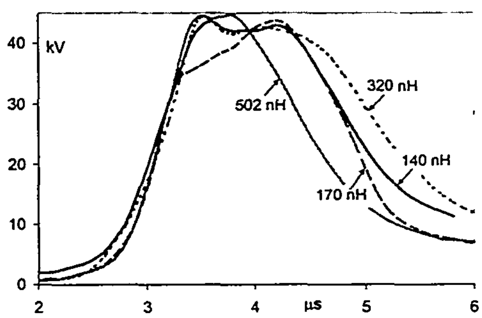

Figure 5. Load inductance effects.

Die Plastic

In one series of small-scale experiments the effects of substituting polyethylene for Teflon as the die plastic were studied. Polyethylene is known to be an inferior insulator to Teflon[3] at high pressures and was not expected to perform as well. In fact, the polyethylene exceeded the performance of Teflon, producing a voltage of 65 kV compared to ~45 kV for Teflon. However, there was no double-hump structure, as seen in the Teflon, which implies that aluminum thinning did not occur prior to cavity floor impact.

Mass-balanced, insulated experiment

To study the contribution of conduction in the explosive gas products, layers of 381-μm thick Teflon and 508-μm thick aluminum were substituted for the single layer of 813-μm thick aluminum. In this way the masses were matched between the combined layers and the single layer of aluminum, and consequently the velocity of the aluminum would be the same. The Teflon was placed between the explosive and the aluminum to insulate the aluminum from the gas products. The results showed a significant degradation in performance with a peak switch resistance of 129 mΩ, compared to ~250 mΩ for the standard experiment, and there were signs of breakdown in the dI/dt record. We speculate that this breakdown occurred along the surface of the Teflon between adjacent anvils.

Summary and Conclusions

From the results of an extensive series of experiments, and hydrodynamic calculations, we conclude that EFF switch action is primarily by mechanical deformation rather than electrical fusing of the aluminum; and that switch performance is ultimately limited by breakdown in the explosive product gases and along plastic surfaces. The hydrodynamic calculations were tested by experimental measurement of the time of cavity floor impact, with good agreement. The time and magnitude of the initial voltage rise was found to depend on aluminum thickness, and that the 813 μm aluminum thickness is optimum for a flat top. The initial voltage rise is independent of load inductance. Preliminary tests show that polyethylene may perform better than Teflon, but more work is needed to optimize its performance.

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