DESIGN AND TEST RESULTS OF A THERMALLY FUSED EXPLOSIVE SWITCH

K. Luu, D. Chang, T. Coradeschi
Electric Armaments Division
US Army Armament Research, Development and Engineering Center
Picatinny Arsenal, New Jersey 07806-5000

D. Hildenbrand, J. Rapka
Parker Kinetic Designs, INC.
EML Lab Support Group
Picatinny Arsenal, New Jersey 07806-5000

Abstract

The need to reduce solid armature and launch package start-up acceleration for an inductively driven railgun necessitates an increase in the storage inductor to gun commutation time. For this purpose, a "fused," high current, explosively actuated opening switch has been designed and tested at the Electric Armaments Division, ARDEC, Picatinny Arsenal, New Jersey. The switch has been operated in the 600 kA to 1300 kA current range and has repeatedly demonstrated opening times from 720 µs at 600 kA to 840 µs at 1000 kA. Armature jerk for an 615 gram solid armature has been reduced from 350 Megagees (MG)/sec to 38 MG/sec at the 600 kA operating point. The design premise for the thermal fusing section, operating experience and test results are presented.

Introduction

Explosive switches have been used widely in inductively driven railguns due to their reliability, fast opening times, high current capabilities and high voltage standoff characteristics. The opening time of an explosive switch can easily be in the order of tens of microseconds. Experimental data from 20 mm railgun firings using the ARDEC HPG/Inductor power supply show typical commutation times of 80 µs, for example. For this short opening time, current will rapidly commutate into the rail to drive the armature to a high velocity. However, the drawback to this fast opening is the high jerk (time rate of acceleration). The jerk directly relates to the stresses developed in the armature structure.[1] We may derive the jerk from the expression which defines the Lorenz force:

$$F = ma = \frac{1}{2} L' I^2 \qquad (1)$$

where m = projectile mass
L'= railgun barrel inductance gradient
I = breech current

So

$$a = \frac{1}{2m} L' I^2 \qquad (2)$$

By differentiating the acceleration with respect to time, we find the jerk:

$$jerk = \left(I \frac{dI}{dt}\right) \frac{L'}{m} \qquad (3)$$

Note that the jerk is directly proportional to the product of the current and the dI/dt. Since reduction of the current is undesirable, we have worked to reduce the dI/dt. The goal chosen for this program was to obtain jerk below 200 MG/sec, with peak acceleration below 100 kG. Explosive switch elements currently in use were modified to this end, in order to allow the mounting and containment structures to remain unmodified.

Design

Switch

There were several areas of concern in designing the switch, the most critical issue being its current rating. The overall switch current rating is driven by the cross sectional area of the current path in the explosive gap section, or "web", during the inductor charge cycle. This is a result of two factors; first, the limited switch width available in the existing mounting structure, and second the need to minimize the quantity of explosives used. The first requirement sets and absolute limit on one dimension of the web area, while the other constrains us to minimize the thickness of the web. The switch cross sectional area at a given operating current may be determined through use of the action integral (4). The required switch cross sectional area is found by dividing the switch action by the specific action of the material (5).

We find the switch action using

$$g_1 A^2 = \int_0^{t_{charge}} I^2 \, dt \qquad (4)$$

The minimum area necessary to avoid melting is then described by

$$A = \frac{[Switch\ Action\ ]^{1/2}}{g_1^{1/2}} \qquad (5)$$

Using as specific action for aluminum at melting 25,300 A^2-s/mm^4 [2] and a 120 ms inductor charge time

$$A = \frac{[\int_0^{1.20(10^{-1})} I^2 \, dt]^{1/2}}{[25300]^{1/2}} \qquad (6)$$

From the value found above, the web thickness may be defined for a given current and given length of the explosively actuated gap.

Thermal Fuse

To determine the dimension of the fuse, the fuse action is first defined in the same fashion as for the overall switch. Gaps 1 and 2 (As shown in Figure 1) are triggered at peak current. It takes approximately 30 µs for the explosive to remove the material adjacent to the fuse. In this interval, current is commutated info the fuse. Therefore the fuse action is as below.

$$g_1 A^2 = \int_0^{t_{explosive}} I^2 \, dt \qquad (7)$$

Fuse cross section area,

$$A = \frac{[\int_0^{3(10^{-5})} I^2 \, dt]^{1/2}}{[25300]^{1/2}} \qquad (8)$$

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14. ABSTRACT
The need to reduce solid armature and launch package start-up acceleration for an inductively driven railgun necessitates an increase in the storage inductor to gun commutation time. For this purpose, a "fused," high current, explosively actuated opening switch has been designed and tested at the Electric Armaments Division, ARDEC, Picatinny Arsenal, New Jersey. The switch has been operated in the 600 kA to 1300 kA current range and has repeatedly demonstrated opening times from 720 llS at 600 kA to 840 llS at 1000 kA. Armature jerk for an 615 gram solid armature has been reduced from 350 Megagees (MG)/sec to 38 MG/sec at the 600 kA operating point. The design premise for the thermal fusing section, operating experience and test results are presented.

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Based on above design study, the switch is made out of 1100-H14 aluminum as shown in Figure 1. There are 3 holes for inserting 50 grain/ft PETN explosives. Gaps 1 and 2 each are 4" long. Gap 3 is the full 9" width of the switch and was added during railgun tests as described later. The thermal fuse is in the middle of gaps 1 and 2. The switch is grooved to define the opening fracture of the gap, with the cross section shown in Figure 2.

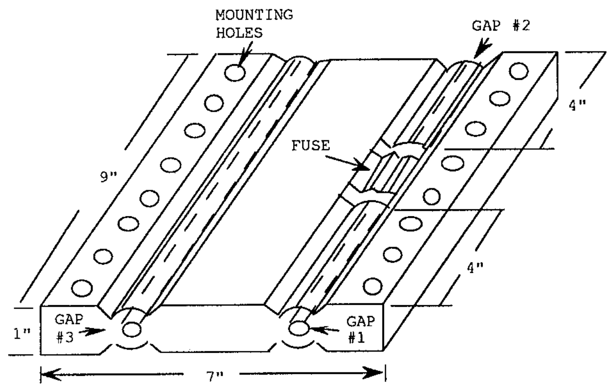

Figure 1. Fused explosive switch

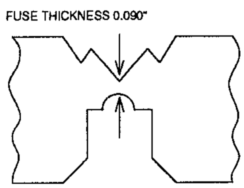

Figure 2. Fuse section

<u>Fragment Catch Block and Fuse Containment</u>

During operation, the switch fragments from the explosive opening section are stopped and caught with a set of high density polyethylene (HDPE) catcher blocks. (Fig. 3) The shape of the catcher block allows the switch fragment to enter the catcher block, then traps it atop the opening of the catch block. This design has worked successfully during the rail gun tests to prevent the switch fragment from reclosing the switch.

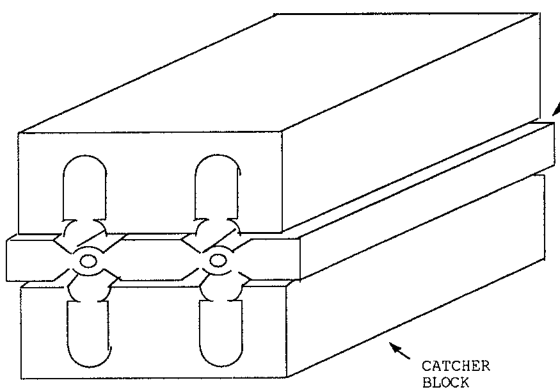

Figure 3. Catcher block

In early tests, it was found that the addition of the fuse had minimal effect on the opening time of the switch. An analysis of the current paths through the switch and mounting structure yielded the realization that magnetic pressure was ejecting molten material from the gap. This was exacerbated by the high current densities in the fuse (approximately 800 kA/in. The addition of a containment structure around the fuse area allows to contain the plasma within the set volume and to prevent the influence of the explosive blast on the fuse area. A G-10 insulator is used to confine the fuse (Fig. 4).

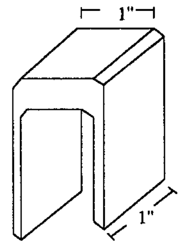

Figure 4. Fuse containment

<u>Test Set Up and Results</u>

<u>Tests Into a Short Circuit</u>

The circuit in Figure 5 was used to test the thermal switch. The switch opens into a short circuit at 600 kA. When the inductor is charged to a peak current, gaps 1 and 2 are triggered to open simultaneously. While the gaps "unzip" to open, current is commutated into the fuse. The fuse melts, turns into a plasma and then extinguishes. Table 1 shows test data and indicates that the switch opening time has been increased from 100 μsec to average of 440 μsec at 600 kA operation. The difference in magnitude between the switch and load currents is representative of the energy dissipated in the switching process.

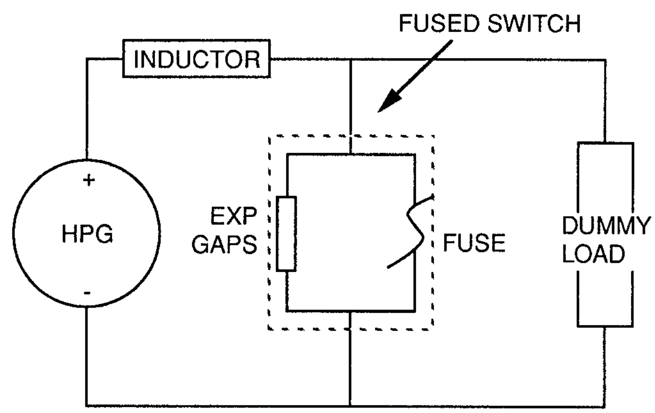

Figure 5. Test circuit

Test#	Sw Current (kA)	Sw Voltage (V)	Sw Opening Time (μs)
26	604	411	407
27	629	631	466
28	626	300	436

Table 1. Short circuit test data summary

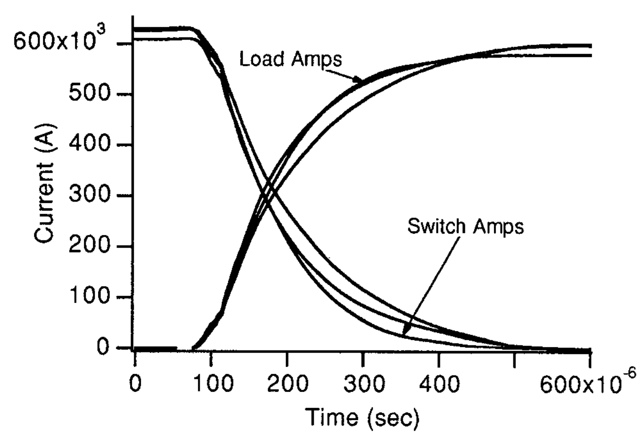

Figure 6. Switch and load current in short circuit tests

Explosive Thermal Switch Performance in Railgun Shots

Tests from 600 to 1,300 kA have been conducted in a 50 mm round-bore rail gun. During early testing, reclosure of the switch was evident in the switch and breech current traces. A third, purely explosive gap was incorporated (noted as Gap 3 in Figure 1) and delayed 700 μs from gaps 1 and 2. The third gap opens completely and adds more voltage standoff to the already opened switch, preventing a voltage breakdown which causes the switch reclosure. In the 600, 1,000 and 1,300 kA shots (Table 2), the switch opened at 720, 840 and 895 μs respectively. Using (3), the jerk is calculated to be 38 MG/s for 600 kA, 60 MG/s for 1,000 kA and 170 MG/s for 1,300 kA. The current and jerk profiles during commutation are shown in Figure 7 for a 1,300 kA gun shot.

HPG Current (MA)	Sw Opening Time (μs)	Armature Mass (g)	Armature Jerk (MG/s)	Exit Velocity (m/s)
0.6	720	615	38	508
1.0	840	754	60	828
1.3	895	240	170	1850

Table 2. Railgun shot data

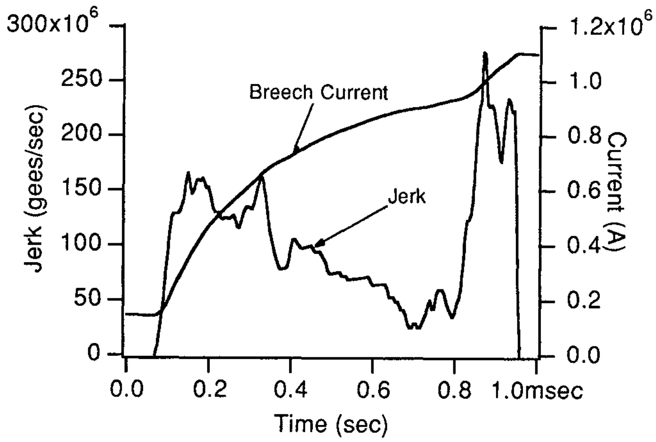

Figure 7. Jerk and gun current at 1,300 kA gun shot

Theoretical Explosive Opening Switch Resistance Model

Theoretical models to characterize the explosive opening switch resistance profiles were developed from the 0.090" fuse thickness performance data. These models are used in the ARDEC Railgun Modular Simulator (ARMS) to allow for accurate prediction of gun performance and diagnostics setup. The resistance profiles were obtained by relating switch voltage to current for the experimental data. The resulting resistance profiles (Figures 8 and 9), show that the resistance rises exponentially as the switch opens. A curve fit of the form $F(t) = e^{(\beta t)}$ was used, where ß is the exponential damping factor.

Figure 9 illustrates how the magnitude of ß determines the rate of resistance rise. It is evident that the switch opens more quickly for the short circuit load while the railgun load extends the commutation time. A value of ß=9898 was determined to be most suitable for the railgun load and is used in ARMS.

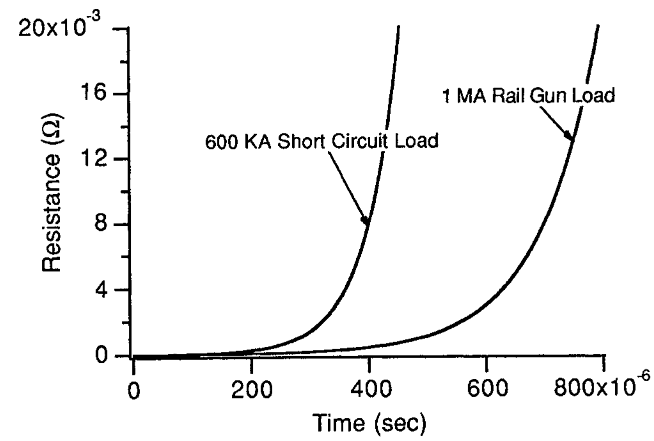

Figure 8. Short Circuit and Railgun Load Switch Resistance Profiles

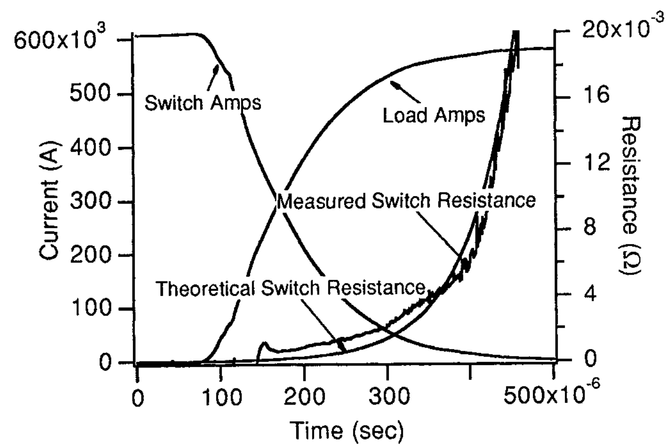

Figure 9. Curve Fit of Explosive opening Switch Resistance

Conclusion

The test results show that the added thermal feature has in increased the switch opening time compared to an explosive switch alone. The addition of a series explosive gap is sufficient to provide voltage standoff and prevent reclosure. The next series of experiments will be to study the geometry of the thermal fuse section to attempt to control the switch opening time more precisely.

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[1] R.C. Zowarka & J.P. Kajs, "Electromagnetic Force, Jerk, and Electric Gun Projectiles" IEEE Transactions on Magnetics, Volume 29, Number 1, January 1993.

[2] CRC Handbook of Chemistry and Physics