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ANALYSIS OF AN MCG/FUSE/PFS EXPERIMENT

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1. INTRODUCTION

The Los Alamos PROCYON high-explosive pulsed power (HEPP) implosion system is intended to produce 1 MJ of soft X-radiation for fusion and material studies [1]. The system uses the MK-IX magnetic flux compression generator [2] to drive a "slow" opening switch which, upon operation, connects the output of the MK-IX generator to a plasma flow switch [3], which, in turn, delivers current to a rapidly imploding load. An electrical schematic of the PROCYON system is shown in Fig. 1. The closing switch isolates the plasma flow switch (PFS) and load from any precursor current which might arise due to the finite impedance of the opening switch during its closed phase.

Two candidates for the opening switch/closing switch combination have been tested. The most extensively tested has been an explosively formed fuse (EFF) combined with detonator-activated closing switches [4]. The EFF uses high-explosive to extrude a solid conductor which would otherwise conduct current for a relatively long time; upon extrusion, the cross-section of the conductor is reduced sufficiently that very fast, "conventional" electrically exploded fuse operation occurs, leading to a rapid increase in resistance [5]. The EFF is a "command" switch in that its time of opening is related to the time of detonation of the high-explosive. The detonator-activated closing switches used in conjunction with the EFF are also "command" type switches, and proper timing between the closing switches and the EFF requires taking into account the different delays between explosive initiation and actual switch operation.

A second candidate for the opening switch/closing switch combination is an electrically exploded foil, i.e., a fuse, and a surface tracking switch (STS). In contrast to the command nature of the EFF/detonator switch combination, the fuse/STS combination is "passive." The operation of the fuse depends upon the current action integral, and the operation of the STS depends upon the voltage waveform generated by the fuse.

At the Megagauss-V conference, we reported our first test which used a MK-IX generator to drive a fuse/STS combination [6]. In that experiment, the MK-IX generated approximately 16 MA and 8.2 MJ, and approximately 9.8 MA and 1.15 MJ were delivered to a fixed inductive load (schematic same as Fig. 1 with the PFS and imploding load replaced by a constant inductance) in 8-10 microseconds. Computations performed after the experiment, taking into account experimental variables which could not be accurately predicted prior to the experiment, were in satisfactory agreement with all experimental observations, including a double-peaked dI/dt signal which indicated a particular trajectory of the copper fuse material through density-temperature space [5].

Prompted by our success with a fixed load, a second experiment was performed using the MK-IX/fuse/STS combination to drive a plasma flow switch. The objectives of the experiment were to observe the ability of the fuse/STS combination to drive a plasma flow switch and to evaluate our ability to predict system performance. The details of the experiment, the measurements taken, and the data reduction process have previously been reported [7,8]. The MK-IX produced approximately 22 MA, and approximately 10 MA was delivered to the PFS, which moved down the coaxial barrel of the assembly in an intact manner in about 8 microseconds. In this paper, we present the results of our computational analysis of the experiment.

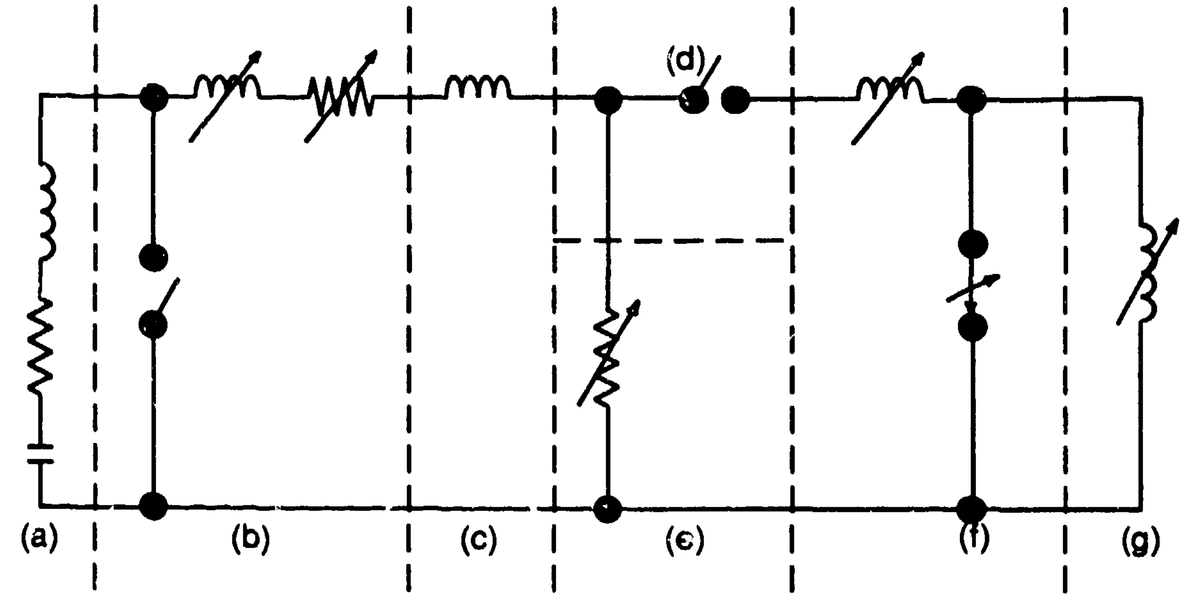

Fig. 1. The PROCYON system: (a) capacitor bank; (b) MK-IX flux compression generator; (c) storage inductor; (d) closing switch; (e) "slow" opening switch; (f) transmission inductance and plasma flow switch; (g) imploding load.

2. ANALYSIS

The experimental results could not be directly compared with experimental design computations performed prior to the experiment because of four factors. First, because of variability in the capacitor bank (Fig. 1) used to charge the MK-IX, the initial seed current was 455 kA rather than the expected 410 kA. This was taken into account by decreasing the capacitor bank resistance (Fig. 1) from the 17.5 mΩ used originally to 2.5 mΩ.

A second variation which could not be taken into account in design calculations was modification of the MK-IX generator. Fabrication errors were corrected by additional machining which led to a lighter armature with a larger internal diameter, leading subsequently to some additional explosive within the armature. Our computations represent the MK-IX as a time-dependent inductance in series with a time-dependent resistance, using values determined during characterization tests [2]. An analysis of armature time-of-flight taking into account the different armature and explosive mass and the armature-to-stator distance (but ignoring end effects) suggests that the inductance history of the modified generator should lead the standard inductance history by approximately 2 μs, so the computations reported here use the standard inductance and resistance histories started 2 μs ahead of the nominal start time (133 μs instead of 135 μs).

Because a new type of STS was used in the experiment [7], the voltage drop across the switch was not predictable. Design calculations assumed a constant voltage drop of 5.5

kV. For our subsequent computations, we represent the STS as a time-dependent resistance using values inferred from the experimental data [7].

A fourth uncertainty in our design computations was fuse performance as represented by the concept of "effective tamping." The computational model [9] considers only a simple foil/tamper geometry. In the experiment, however, individual layers of the cylindrically wrapped fuse can interact, so that tamping in the experiment is an ill-defined quantity in the context of the simple model. The tamping is presumably known to within a range of values based upon previous experiments, and our design calculations examined the effect of a range of tamping. However, the appropriate tamping value must be determined for each class of experiment, and one goal for this experiment was to establish the effective tamping value at higher fuse currents than in our previous experiment [6].

In our analysis, we vary the tamping to match the peak current. This procedure does not guarantee agreement with any other observables, such as timing of fuse operation, voltage generated, or features in the measured waveforms. For the present experiment, we find that the best value for effective tamping is 2500 kg/m2, approximately one-half the value appropriate to our first experiment [6].

In addition to treating the capacitor bank resistance, the generator inductance and resistance, the STS resistance, and the effective tamping as discussed above, other values required in our computations are as follows: the capacitor bank capacitance is 1.5 mF with a charge voltage of 34.2 KV; the capacitor bank inductance is 120 nH; the storage inductance is 55 nH; the copper fuse cross-sectional area is 2.8 cm^2 and the length is 30 cm; the load transmission inductance is 17.5 nH; the plasma flow switch mass is 150 mg, the inner diameter of the flow switch coax is 6 inches and the outer diameter is 8 inches, and the length of the coax is 12.4 cm.

3. GENERATOR PERFORMANCE

With the 2 μs lead as discussed above, the computed generator current waveform agrees reasonably with the observed waveform, indicating that the generator performance was nominal. Shown in Fig. 2a are the computed and measured waveforms. For times less than 310 μs and currents less than 15 MA, the two waveforms are essentially indistinguishble. At approximately 311.5 μs, the two curves begin to differ slightly, due either to inaccuracies in the fuse model or to losses greater than expected in the generator. The latter is quite possible because the initial generator current was comparable to that used in a high-performance characterization shot [2], where increased losses were observed.

4. FUSE PERFORMANCE

Fig. 2b compares the computed generator current for the experiment with the value which would be predicted in the absence of a fuse. Whereas the fuse cross-sectional area was chosen to give fuse operation at approximately generator burn-out, Fig. 2b indicates that the fuse operated prior to peak current because of the unexpectedly high generator initial current. An optimally sized fuse for the 455 KA seed current actually observed would have had a somewhat larger cross-section. The high initial current also indicates higher than expected magnetic flux within the generator circuit, thereby indicating that the length of an optimal fuse would have been longer than actually fielded. In fact, even for the expected current of 410 kA, the length chosen was approximately 15% less than optimal for fabrication reasons.

Fig. 3 compares the computed and observed current delivered to the plasma flow switch. The choice of tamping, 2500 kg/m^2, gives not only the correct peak current but also the correct time of STS operation and a dI/dt waveform very similar to the observed waveform. The accuracy of the timing is an indication of the accuracy of our model, because timing is very sensitive to the computational parameters, e.g., a 4% increase in the initial voltage on the capacitor bank reduces the time at which the STS closes by 3.6 μs. As in the previous experiment [6], the dI/dt waveform shows features which are indicative of the trajectory of the fuse material through density-temperature space.

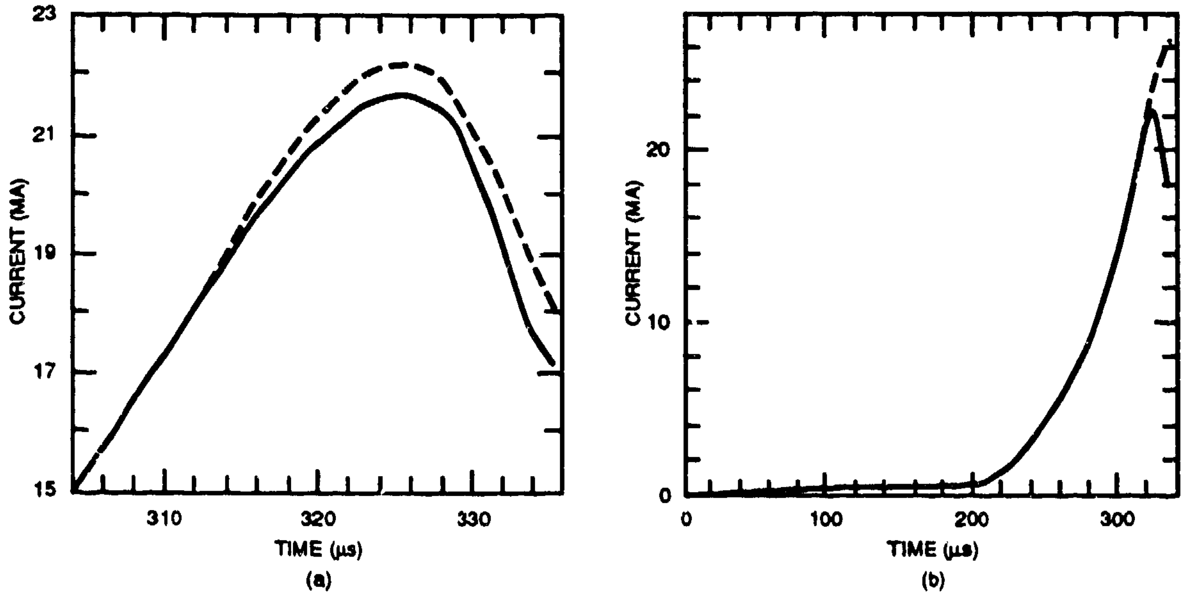

Fig. 2. Generator current: (a) measured (solid) and computed (dashed); (b) computed with fuse (solid) and computed without fuse (dashed). Note the suppressed zeros of the vertical and horizontal scales of (a).

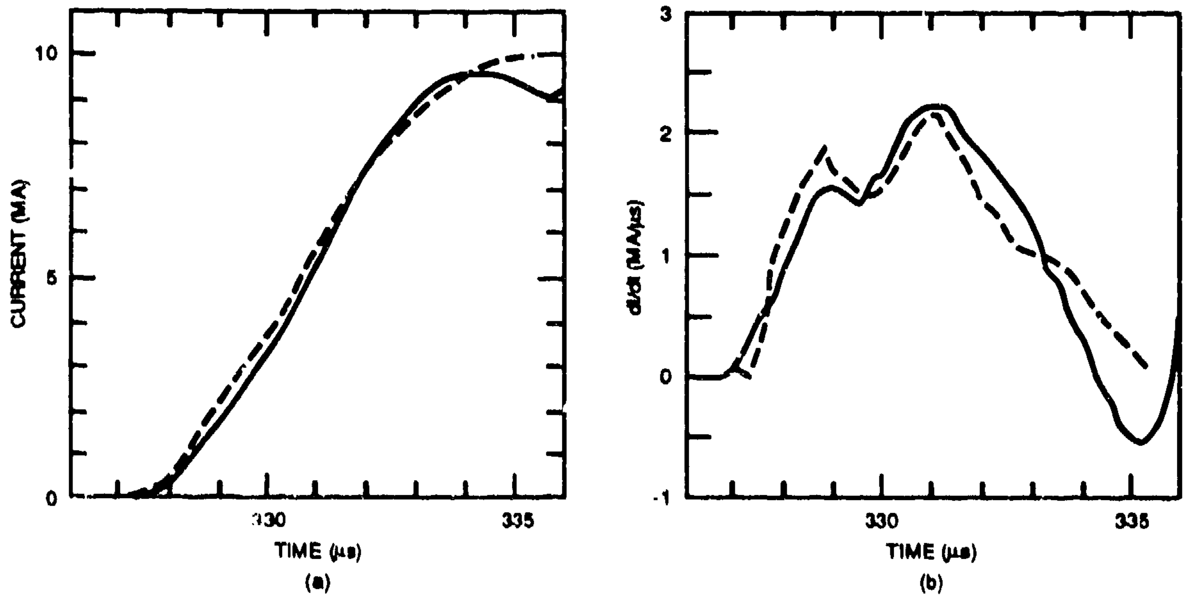

Fig. 3. Measured (solid) and computed (dashed) waveforms: (a) PFS current; (b) PFS dI/dt.

The computed load voltage is in agreement with the filtered signal of a capacitive voltage probe, as shown in Fig. 4. The computations do not include resistive effects of the plasma flow switch.

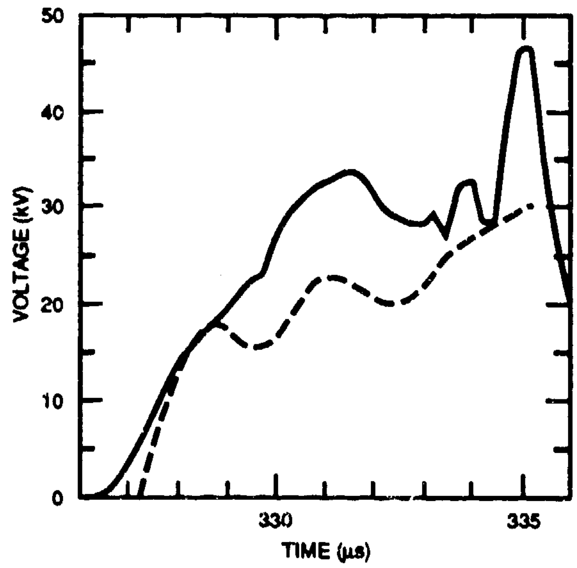

Fig. 4. Measured (solid) and computed (dotted) plasma flow switch voltage. This measurement includes the plasma flow switch and 10 nH of transmission inductance.

5. PLASMA FLOW SWITCH PERFORMANCE

The principle goal of the experiment was to determine how well the fuse/STS combination could drive a plasma flow switch. The location of the switch plasma is determined experimentally by dB/dt probes and by Faraday rotation probes located at various positions along the coax of the switch [7,8]. The probe signals can be affected by plasma, intense radiation, and mechanical stresses.

In most of our computations, we represent the PFS as a simple point mass, i.e., we use a "slug " model, and only the center-of-mass of the plasma is computed. The computed switch position is compared in Fig. 5 with information obtained from the dB/dt and Faraday rotation probes. The points associated with the dB/dt probes indicate the time at which the probe signal increases rapidly, presumably indicating time of arrival of the plasma. The points associated with the Faraday rotation measurements give the time at which the current indicated by the probes reaches 5 MA, approximately one-half of the maximum; assuming a symmetrical current profile, the points indicate the position of the center-of-mass. The computed position is in agreement with the Faraday points, indicating that the plasma moved down the coax in an intact manner, with all of the switch mass participating. The dB/dt signals lead the computation and Faraday signals, indicating spreading of the plasma. Furthermore, some forward tilting of the plasma is suggested because dB/dt signals at the outer electrode lead those at the inner electrode. The dB/dt probes in the ends of the "load" region show plasma arrival just as the computation and Faraday probes suggest arrival at the center of the load region.

The data and the computations of Fig. 5 give a final velocity of about 6 cm/μs and a velocity of about 3.7 cm/μs half-way down the coax. The approximately one-half microsecond lead of the Faraday rotation measurements by the dB/dt probes of the inner electrode (where the Faraday probes are located) suggests that the plasma is approximately 6 cm wide at the time the plasma reaches the load region.

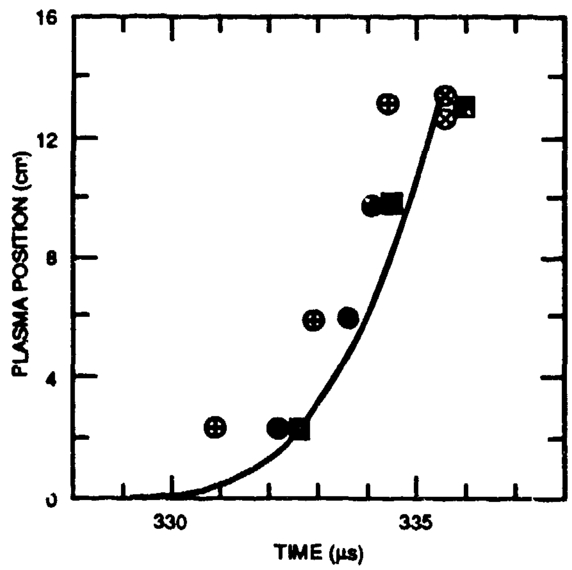

Fig. 5. Computed plasma position (solid); plasma arrival times, as determined from dB/dt probes, at inner electrode (solid dots), outer electrode (+), and load region (x); plasma center of mass as determined from Faraday rotation probes (solid squares).

Although two-dimensional computations using the parameters of the experiment as actually fielded have not yet been performed, two-dimensional computations using the initial design parameters were performed on a computer code which has been used primarily to study the behavior of cryogenic, solid fiber deuterium z-pinches [10]. The two-dimensional computations use one-dimensional computations to estimate the width of the switch plasma just after explosion of the wire array from which the plasma is formed and the computations treat the entire plasma as aluminum, although a significant fraction of the plasma comes from the barrier foil.

Shown in Fig. 6 are the results of two two-dimensional computations, one (Fig. 6a) using a $1/r^2$ mass distribution and one (Fig. 6b) using the same distribution with superimposed 2% random perturbations. The unperturbed computation (fig. 6a) shows a reasonably intact, 5-cm-wide plasma with some electrode effects which are not as pronounced as observed in other computations using another computer code [11]. On the other hand, the perturbed computation (Fig. 6b) shows a very non-uniform, significantly wider plasma.

Because the low density plasma at the edges of the switch in the computations of Fig. 6 carry very little current, even the perturbed computations give dB/dt signals which rise faster than experimentally observed. One possible interpretation is that a plasma layer surrounds the dB/dt probes, causing a signal which does not accurately reflect the actual magnetic field in the vicinity of the probe. A second possible interpretation is that the switch plasma is wider than in the computations.

6. AN IMPLOSION DRIVER?

One way we evaluate the performance of the system is to compute the kinetic energy which could have been coupled to an implosion load, assuming the plasma flow switch acts as an ideal opening switch and representing the implosion load with a "slug" model (l=2 cm, r_0=5 cm, r_0/r_f=10). Our computations suggest that the experiment as fielded could have coupled 360 kJ of kinetic energy to such an ideal load. The computations further indicate that an more optimum fuse (l=75 cm, A=3 cm^2), with no other changes in system parameters, could have coupled 633 kJ. Changes in other system parameters (e.g., reduced inductances, more massive PFS) can increase the predicted kinetic energy.

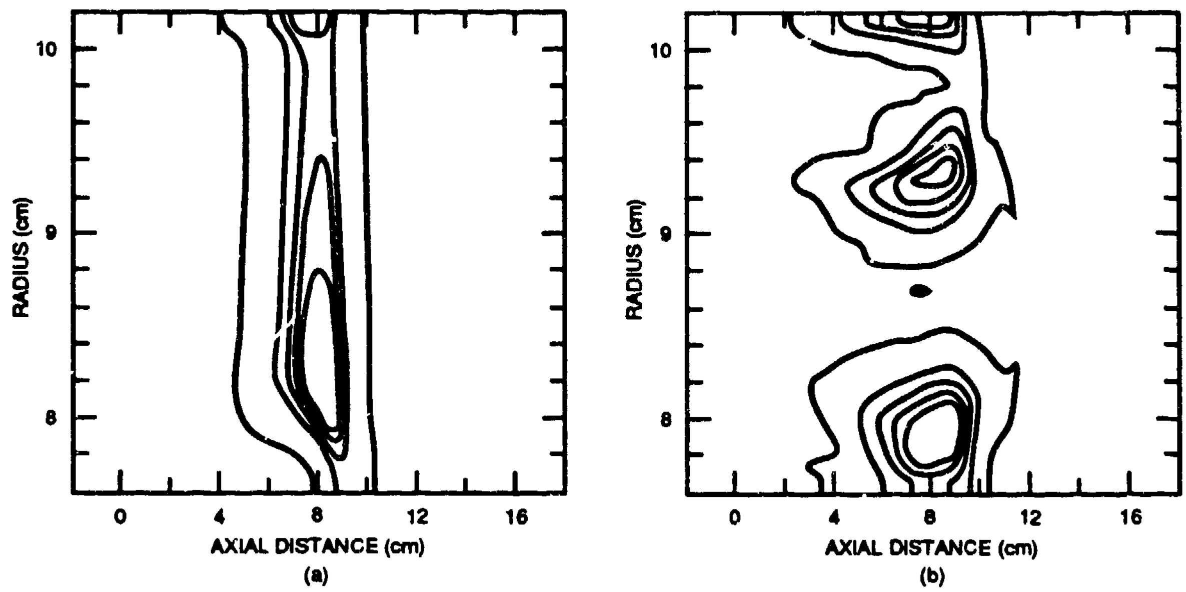

Fig. 6. Mass density contours in the r-z plane for unperturbed initial conditions (a) and 2% random mass density initial perturbations. Approximately 20% of the total PFS mass is enclosed within each pair of contours. Contour values (kg/m^3): (a) 0.01, 0.21, 0.33, 0.39, 0.46; (b) 0.01, 0.19, 0.36, 0.52, 0.65.

7. CONCLUDING REMARKS

Only two attempts have been made to couple a MK-IX generator to a fuse/STS switch combination. As previously reported [5,6], and as reported here, both experiments have been successful. Based upon computations which take into account experimental variables not well characterizable prior to the experiment, we conclude that the MK-IX generator performance was nominal, the fuse and STS performed as expected, and, in our second experiment, the flow switch plasma moved in an intact and predictable fashion. Our second experiment has demonstrated that a fuse/STS package can drive a plasma flow switch and has demonstrated that even a PFS which conducts for as long as 8 μs is a reasonable candidate for driving an implosion load. The previous experiment and the one discussed in this paper suggest than an optimized implosion experiment using a fuse/PFS combination would also be successful.

The experimental determination of the switch plasma width, coupled with two dimensional computations (Fig. 6), indicate that the possibility of magnetically driven Rayleigh-Taylor instabilities must be taken into account in the design of a successful plasma flow switch. In fact, such instabilities may preclude satisfactory application of the PFS.

Our two experiments at high currents and high energies have demonstrated adequate performance, in terms of the electric field generated across the fuse. Higher performance has been demonstrated in a similar context [12]. That experiment, and our experiments, confirm the obvious simplicity of fuses as an opening switch and demonstrate their reliability. Because fuses appear to have straightforward scalability to higher currents and energies, a fuse/STS combination appears to be an attractive choice for advanced systems where explosively operated opening switches may be "hypertrophical" [13].

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