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A FEASIBILITY STUDY FOR A FRAGMENT-PRODUCING CHEMICAL-ELECTRICAL LAUNCHER *

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Abstract

The Fragment-Producing Chemical-Electrical Launcher (FP-CEL) project investigated the use of explosively driven magnetic loading techniques to launch controlled fragments in a predictable manner. A conventional fragmenting warhead uses high-explosive detonation products to throw fragments directly for various applications; however, greater control is desired to enhance kinetic-energy lethality mechanisms, and to lower collateral effects associated with storage and usage. To establish the feasibility of such an FP-CEL system, we conducted small-scale experiments using a capacitor-driven ramp-wave generator to accelerate flyers and fragments to velocities of 2 to 3 km/s, and analyzed the data with a multi-dimensional magneto-hydrodynamic computer code.

An FP-CEL uses an explosive first stage, that is a flux-compression generator (or FCG), that would have similar electrical output to the capacitor-based approach. Such a two-stage system would have a significantly reduced total efficiency, therefore, in addition to overall feasibility, the present effort examined issues of system efficiency, as well as how to scale to operational capabilities. The work emphasized the study of the basic physics of the launching phenomena, while considering existing FCG technology as a prime power source.

I. PROJECT DESCRIPTION

The Institute for Shock Physics (ISP), in collaboration with Sandia National Laboratories (SNL), is conducting a feasibility study to evaluate the Fragment-Producing Chemical-Electrical Launcher (FP-CEL) concept for launching high-velocity fragments. The objective of the project is to evaluate the feasibility of using explosively driven magnetic loading techniques to launch controlled fragments to high velocities in a predictable manner. An important part of this concept uses Flux Compression Generators (FCGs) to provide the requisite driving currents. Of course FCGs add an additional stage to the proposed concept. This technology has been under development for many years, so reliance is placed on the extensive body of literature that already exists, and on available experts in the field. The specific requirements for explosive generators for FP-CEL applications may be somewhat different from more traditional FCG applications, and these differences will need to be understood for any operational applications for these types of systems.

The present study emphasizes the understanding of the physics and phenomenology that govern the controlled and predictable launching of the fragments. Small-scale testing and numerical analysis establish the overall feasibility of the physical processes, as well as the validity of the modeling techniques that are used in the analysis. These results lead to recommendations for extending the experiments to large-scale dimensions and to furnish preliminary estimates of operational-scale system parameters.

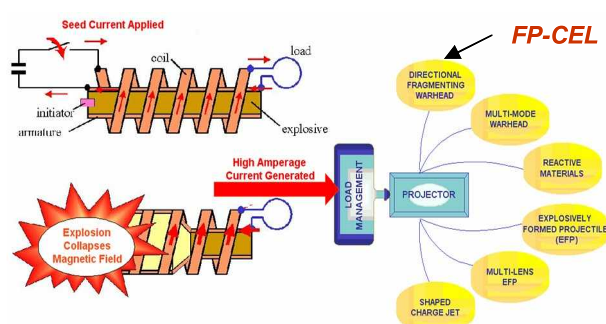

Figure 1. The FP-CEL concept compared to other similar systems. (adapted from Ref. [1]).

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II. EXPERIMENTAL STUDY

Small-scale experiments were conducted on the newly-installed magnetic pulser facility at Washington State University (see Figures 2 and 3) and addressed the geometric and electrical conditions necessary to magnetically launch flyers to reasonable velocities. Once the basic procedures were established, single and multi-layer flyers were launched, where only the “pusher” layer was a metallic conductor. This established the capability for launching a wide variety of useful materials.

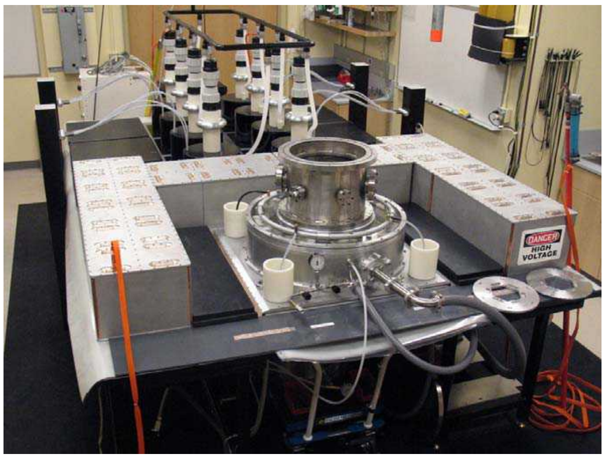

Figure 2. The WSU pulser located at the Institute for Shock Physics. The main capacitors are in the background, and the peaking capacitors surround the cylindrical load region in the foreground.

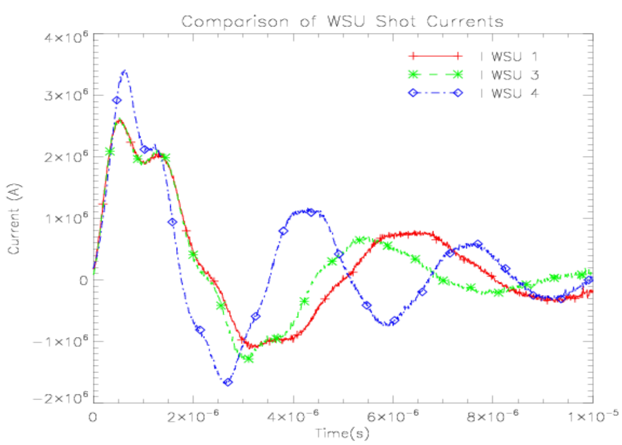

Figure 3. Plots of the measured pulser current profiles for shots 1, 3, and 4 are time-shifted to align the 10-90% rise time. Only the first half-cycle is usable for launching flyers.

Velocity measurements of the back or free-surface side of the flyers were made using VISAR interferometry. Typical velocity histories are shown in Figures 5 and 6. Single layer aluminum flyers ranged between 0.77 and 1.0 mm thick and attained velocity of 1.7 to 2.0 km/s. Composite flyers consisted of aluminum/lexan layers between 0.77/1.53 mm to 0.92/0.94 mm thick. Spall pull-back signals from the lexan data were measured; they are related to the separation or “spall” of the two layers of the composite flyer. This will be discussed further in the Computation Study section below.

A subsequent series of shots investigated the effects of aluminum flyers on witness plates. These helped to provide early estimates of the mechanisms for controlled flyer fragmentation, the divergence of these fragmented projectiles, and the effects of these projectiles (*e.g.*, cratering) on witness plates spaced some distance from the launch panels.

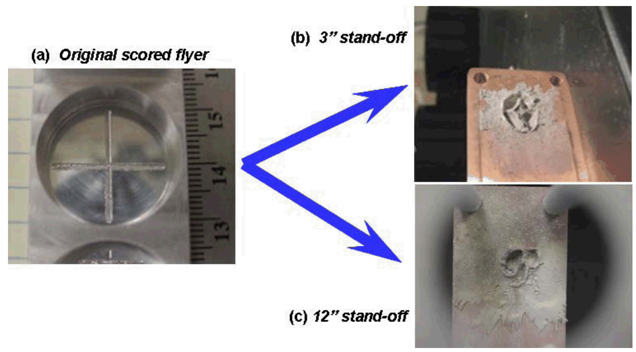

Figure 4. Photographs showing the small divergence of controlled flyer fragments. Copper witness plates at two stand-off distances show similar dimensions of the crater patterns.

III. COMPUTATIONAL STUDY

The 3-D and 1-D numerical modeling analyses essentially paralleled the experimental efforts. The first modeling tasks established the capability of the ALEGRA code to investigate the fully coupled magneto-hydrodynamic response for the small-scale FP-CEL experimental program. The uniformity of the current and magnetic fields was studied; how they are influenced by the shape of the magnetic launcher panels was also examined. Velocity histories of early flyer configurations were predicted and used to validate the numerical modeling. A typical comparison of experimental and computed histories are shown in Figures 5 and 6. The 1-D simulations used the magnetic boundary condition:

$$B = f\frac{\mu_0 I}{w}, \qquad (1)$$

where I is the total current and w is the width of the panel. f is current scaling factor used to account for edge effects and other factors., not otherwise accounted for in this idealized representation of the magnetic field in the gap between panels. This scaling factor typically has a value between 0.75 and 0.80. No such factor is necessary in the 3D simulations, although 3-D simulations indicate that the factor is not constant, but drops linearly from an initial value of 0.95 to 0.40 in 2.0 μs.

The lexan data shows a decrease or pullback in the velocity profile. This implies that a fracture or spall is occurring and that either a fracture or P_{min} model should be used in conjunction with the equation of state. Spall pull-back signals for the multilayer flyer assemblies are calculated according to the formula:

$$P_{spall} = -0.5 \cdot \rho_0 \cdot C_l \cdot \Delta v \ , \qquad (2)$$

where ρ_0 is solid density of lexan (1.196 g/cm^3), C_l is the linear elastic wave speed (2.18 km/s), and Δv is the change in velocity from the pullback. This results in a spall pressure of P_{spall} = -0.235 GPa. This value was used with both a P_{min} model and a spall model. While the peak velocity and the amount of pullback is captured by the simulations, the subsequent simulated velocity does not quite match the experimental data, as is seen in Figure 6.

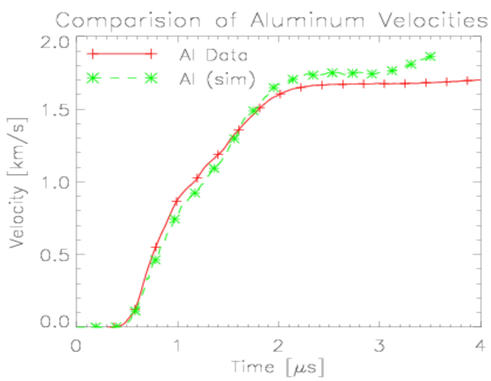

Figure 5. Comparison of experimental and simulated velocity profiles for a 0.919 mm thick Al flyer plate from WSU pulser shot 3.

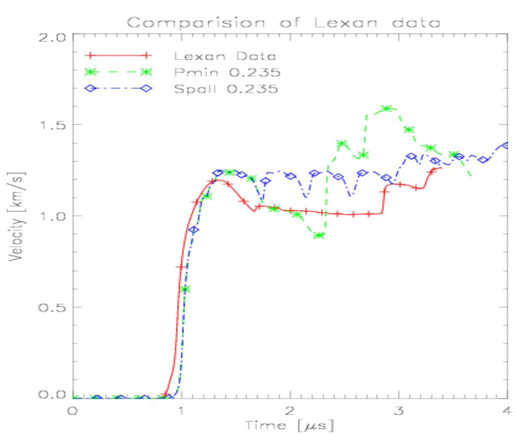

Figure 6. Comparison of experimental and simulated velocity profiles for a layered flyer from WSU pulser shot 3. The flyer had a 0.923 mm Al layer backed by a 0.944 mm lexan layer.

Analytic modeling also contributed to the analysis of some of the impact phenomena. In particular, simple scaling laws can suggest the effects of the various projectiles on the witness plates that represent targets for potential operational FP-CEL devices.

Pulser experiments at WSU were conducted at the 2.5 to 3.5 MA level with about a 2 μs half-period for the driving current. In order to apply the results of the WSU pulser experiments to full-scale systems, we formulated a scaling law that allows extrapolation of the present experimental results to 90 MA. This level of current was chosen because it represents the output of off-the-shelf FCGs, such as the RANCHERO device. Using the magnetic field relation in Eq. (1), Newton's second law, and averaging over a half-period of a sinusoidal current pulse, the scaled flyer velocity is:

$$V_{scaled} = \frac{1}{4} f^2 \frac{\mu_0 I^2}{w^2} \frac{\tau}{\rho d} \ , \qquad (3)$$

where I is the total current, w is the flyer width, τ is the half-period of the current profile, ρ is the flyer density, and d is the flyer thickness. This scaling law was tested against the velocity from 1-D simulations. As long as the flyer acceleration is quasi-isentropic, the scaling law is found to hold as is seen in Figure 7.

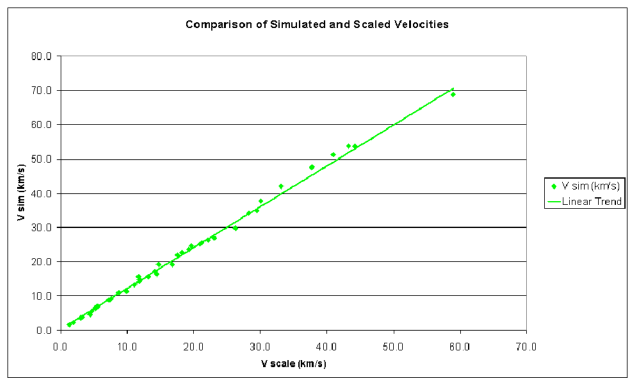

Figure 7. Scaling study to 90 MA. The scaled and simulated velocities are proportional, indicating the scaling formula in Eq. (3) is valid for the range of parameters chosen.

IV. EFFICIENCY STUDY

An important issue for FP-CEL systems is the overall energy conversion efficiencies with which they can operate. This is one of the better ways to compare the many and diverse methods that are used for launching, accelerating, and throwing projectiles. An analysis of this type was accomplished recently [2] by a study that put an extremely wide range of projectile launchers on a common ground in terms of overall system efficiency. That survey included devices from small arms, to cannons, to railguns, and was based only on observed experimental data. To study this large database with a common metric, the data were given in terms of "muzzle" velocity as a function of "equivalent propellant" charge-to-mass ratios. Using our small-scale experimental results and the experience from previous studies of FCG devices, the FP-CEL system was incorporated into this same framework. We found that although estimated FPCEL efficiencies tend to be lower than many other conventional systems, they are comparable to many novel launch technologies currently being investigated elsewhere. Also, other factors may compensate for this lower efficiency. For example, there is no inherent fragment velocity limit as there is with direct-drive high-explosive systems. In addition to a detailed understanding of the overall efficiency of potential FP-CEL systems, a further issue of importance relates to difficulties that might be encountered in enlarging the small-scale experimental configurations to operational scales. These will need to be addressed with more applied designs and large-scale testing.

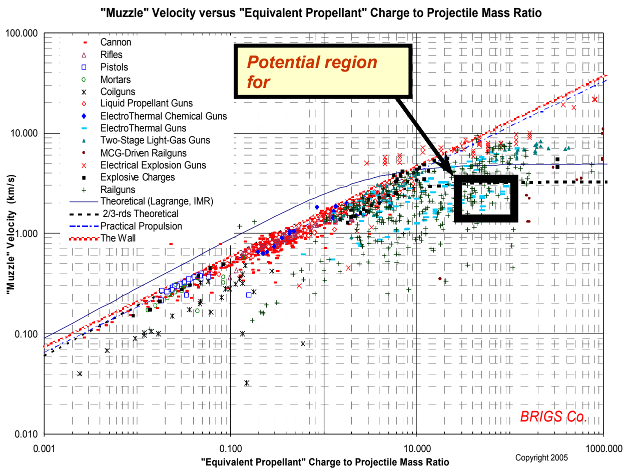

Figure 8. Efficiency of projectile launching systems and concepts. "Muzzle" velocity is plotted as a function of "equivalent charge-to-mass ratio." All the points are actual experimental data and the curves represent various theoretical limiting cases. Overall estimates of system efficiencies do not preclude an operational FP-CEL.

V. RESULTS AND CONCLUSIONS

The basic conclusions that have been drawn from this study suggest that FP-CEL systems are certainly feasible from the perspective of the physical phenomena that are involved. In particular the controlled and predictable magnetic launching of projectiles, flyers, and fragments, using ramp-wave generators is achievable.

The experimental work has shown that the magnetic launching of plates and controlled fragments really is feasible. The initial laboratory-scale experiments, which were conducted on the new magnetic pulser facility at Washington State University, successfully addressed the geometric and electrical conditions necessary to launch flyers or projectiles magnetically to reasonable velocities. Areas examined included the uniformity of the current profile that was necessary to launch the flyers in a quasi-isentropic planar fashion. Once the basic procedures were established, multi-layer flyers were launched, where only the "pusher" layer was a metallic conductor. This established the capability for launching a wide variety of useful materials such as energetic compounds. Fracture or spall pull-back signals from these shots were measured; they are related to the separation or "spall" of the two layers of the composite flyer. A subsequent series of shots investigated the effects of these flyers on witness plates. We measured the depths and volumes of these craters and were able to use simple scaling laws to correlate the results with simple flyer parameters such as size and velocity. Pre-scoring of the flyer plates produced flyer fragments reliably according to the desired pattern. Because of the uniformity of the loading, even with a very short "barrel length," the divergence of these fragments was very low.

Single and multi-dimensional modeling using the MHD code ALEGRA was also successful. One-dimensional simulations were compared to different pulser experiments. The simulations demonstrated the validity and utility of performing 1-D analyses, as well as the validity of using a single efficiency factor for a variety of panel widths, flyer diameters, and flyer thicknesses. These simulations are pointing the way to conducting more detailed scaling studies that will identify the trends that can be used to predict the performance of larger and possibly operational FP-CEL configurations. These initial analyses have also provided estimates of how a laboratory-scale FP-CEL system might scale up to a full-scale prototype configuration. It is important to note that these results suggest that the FP-CEL concept does *not* have an upper limit on projectile velocity, as do high-explosive-driven systems. Thus if there are real needs for much higher velocity launchers, the FP-CEL will be an excellent candidate for meeting these requirements.

Our recommendations for follow-on work related to FP-CEL systems include the design and testing of larger scale systems, which will incorporate driver stages using actual FCGs. We feel that such a testing effort will need the guidance of experts, especially in the area FCG design and operation. This collaboration activity would involve configuration and experiment design, test planning, and analysis and interpretation of the measured results.

A further recommendation involves the more accurate analysis of the efficiency of possible FP-CEL systems. Credible analyses of this type will be important for decisions on future FP-CEL development efforts. Initial stages of this work can be accomplished using the theoretical and modeling tools already in place, in particular the multi-dimensional magneto-hydrodynamic computer code ALEGRA.

VI. REFERENCES

[1] US Navy, Chemical-Electrical Warhead Technology Feasibility Study, Appendix D from draft white paper (~2005).

[2] Backofen, J. E., Practical Propulsion by Directed Energetic Processes, BRIGS Report 05-1, BRIGS Co., Oak Hill, VA (2005).