OPERATING EXPERIENCE WITH THE 90 MM RAILGUN AT CEM-UT

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ABSTRACT: **The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has operated its 90 mm x 10 m long railgun with great success and several recently added improvements. The testing has involved various types of projectile packages, including split armature designs for mid-body drive projectiles as well as base-push packages. CEM-UT has performed an 8.1 MJ experiment as well as many lower energy tests as part of the ongoing armature/projectile development program. One of the most important features added to the system was the development of thermal opening switches for smoother commutation into the gun and reduced acceleration loads on delicate projectile packages. Other new features include a copper vapor laser for enhanced high speed film data and a target x-ray system for capturing projectile data just before and after impacting the target. Both the copper vapor laser and the target-rays add to the excellent data collection and shot evaluation system in place at CEM-UT. This paper presents test results to date, a discussion on improvements to the system, and comments on future plans and capabilities of the large bore railgun program.**

SYSTEM OVERVIEW

The 90 mm railgun program at CEM-UT [1] is powered by the 60 MJ Balcones Homopolar Generator (HPG) power supply: a bank of six, 10-MJ machines each rated for 1.5 MA peak current. These six generators are linked to the gun by their own individual storage inductors for power conditioning. The system is actuated by large explosively driven opening switches which are used to commutate the energy from the inductor to the railgun load. High power, explosively driven closing switches are used to shape the current pulse by isolating HPG/inductor pairs and then staging these pairs at later time intervals. A large laminated aluminum bus is used to transfer the current to the railgun facility, ~11 m away.

The electromagnetic (EM) launcher associated with this program is a 90 mm x 10 m long round bore railgun. The rail and insulator package is placed inside a column of ceramic disks housed in a thin steel tube. This assembly is then placed inside a 10 m long, thick wall pressure vessel with pressure sealing end caps and the assembly is pressurized to approximately 33 ksi. This hydraulically prestresses the ceramic disks and rail/insulator package in a state of compression; thus counterbalancing the large bore pressures associated with multi-megamp railgun launch. This novel concept for railgun design limits bore deflection to amounts comparable to conventional large bore powder guns [2], approximately 0.254 mm (0.010 in.). The rails for this gun are full length 90° sections of extruded ETP 110 copper. The 10 m long insulator sections were cut from a wound composite tube of room temperature amine cure epoxy and E-glass fiber. The individual rails and insulators are epoxied together and then machined for installation into the hydraulic gun structure.

The large EM gun is located in a 50 m deep x 4.3 m diameter vertical gun range. There are a total of nine levels in the range with a large target chamber at the bottom. The breech of the gun is located at ground level and it extends down to level two. The muzzle of the gun is joined to the target chamber by a 1.0 m diameter flight tube which has a 47 mm wall for protecting hardware in the range. Each floor is equipped with four windows in the flight tube for in-flight diagnostics. Available diagnostics include orthogonal flash x-rays at the muzzle, orthogonal high speed film on any level, and both above and below target x-rays in the target chamber. A 15 ton bridge crane is available over the range for loading large targets into the target chamber and a small elevator is installed for personnel mobility within the range.

SHOT SUMMARY

Since last being reported on by Hayes [3], the 90 mm railgun program at CEM-UT has made significant advances in large bore railgun technology. Just prior to the last EML conference, CEM-UT successfully launched an aluminum armature with a muzzle energy of 8.1 MJ, the world record for solid armature EM launch. At this time the efforts were redirected by the sponsors to focus more on lower energy shots in support of the projectile development programs. CEM had demonstrated the capability for high energy tests with its 8.1 MJ test. A total of 51 railgun tests have been performed to date with 30 of these tests occurring since the last reporting. It should be noted that all 51 shots have been done on the same rail/insulator package. Other work has included a continued program for advancing solid armature technology. Both base push armature/projectile packages as well as mid-body drive projectile packages have successfully been tested in the CEM-UT facility. A complete shot summary for the 90-mm railgun is too large to include in this paper, but a small sample of significant shots is presented in Table 1.

TABLE 1. BRIEF SHOT SUMMARY

Shot #	Date	Peak Current (MA)	Projectile Mass (kg)	Velocity (m/s)	Energy (MJ)	Type of Projectile
20	2/22/90	3.04	2.44	2,577	8.1	C-shaped aluminum
31	1/8/91	3.12	2.3	2,033	4.7	Reduced mass CEM-UT C-shaped more compliant, aluminum armature
34	2/22/91	2.99	3.14	1,609	4.1	Base push armature with strain buffer, aluminum sabot, and Kaman Dart with steel rod
45	8/15/91	2.30	2.87	1,320	2.5	CEM mid body drive split aluminum armature with steel dart
51	20/25/91	2.73	4.49	1,325	3.9	Kaman SLEKE mid body drive tandem aluminum armature with titanium tungsten rod

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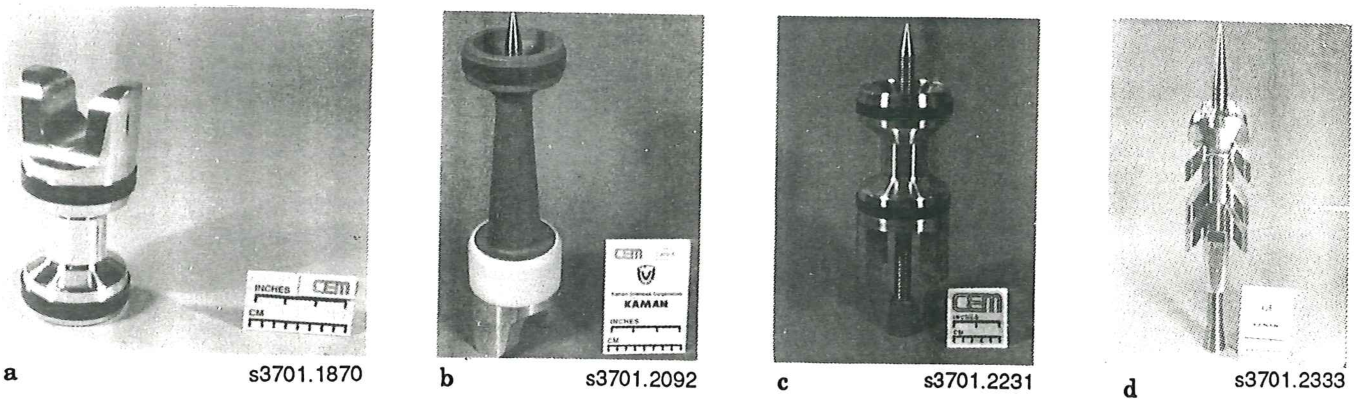
Shot #20 was the highest energy shot to date in the CEM-UT EM gun facility as well as a world record for solid armature drive EM launch. A 2.44 kg solid aluminum armature (Fig. 1a) with integral aluminum payload was accelerated to a peak velocity of 2,577 m/s. The projectile velocity was confirmed by both in-bore B-dot probes as well as high speed film data. This was a very important test because it was the first time the Balcones power supply had been used at full energy for an actual experiment. This was a major step in proving that large heavy projectiles can be accelerated using solid armatures to several kilometers a second. Shot #31 was a test of a new reduced mass, more compliant solid armature design. The package had a total mass of 2.3 kg, 900 g in the armature and 1,400 g in the integral payload, which was a 25% reduction in armature mass from the previous armature design. The package was accelerated to a peak velocity of 2,033 m/s. This was an important step in providing a lighter mass armature for base-push projectile packages. Shot #34 was a test of a CEM-UT aluminum solid armature pushing a Kaman Sciences four piece aluminum sabot with a steel tipped penetrator (Fig. 1b) as part of the ultrahigh velocity projectile (UHVP) program. Past tests of Kaman Sciences base-push packages had displayed a tendency for the tungsten penetrator tip to fracture in-bore. One proposed theory for these failures was a moment coupled from the solid armature to the sabot/projectile package. This test successfully demonstrated the use of a polypropylene strain buffer between the solid armature and the launch package to prevent mechanical moments from being transferred to the projectile. The 3.15 kg package was accelerated to a peak velocity of 1,609 m/s. Shot #45 was a very successful test of a 2.9 kg package consisting of a two-piece CEM-UT aluminum armature/payload supporting a threaded rod penetrator (Fig. 1c). The armature/payload package was split along the centerline of the rail contacts to act as a mid-body drive armature/sabot assembly. This was the first successful launch of a rod using a mid-body drive armature in UT's large bore EM gun. The package was accelerated to a velocity of 1,040 m/s and muzzle x-ray data showed the package left the gun intact. Muzzle voltage data showed the armature drop was less than 200 V until the armature exited the gun. Shot #51 was a very successful test of a Kaman Sciences SLEKE projectile package. The two-piece tandem aluminum armature with a tungsten/titanium threaded rod (Fig. 1d) had a mass of 4.5 kg and was accelerated to a velocity of 1,325 m/s. The rod fully penetrated a 6 in. thick roll hardened armor (RHA) target.

On shots #37 and 38 in the 90 mm gun, a Vought LTV/IAP SLEKE armature and projectile package was tested (Fig. 2). The data from these shots is proprietary to the contractor and further details may be obtained from LTV or IAP. A paper pertaining to this work [4] is also presented at this conference.

90 MM RAILGUN BORE DATA

To provide sufficient data for projectile contractors, the bore deflection in the 90 mm railgun was measured under current load. Measuring the bore deflection for the projectile designers was an excellent opportunity to confirm the computer analysis of the gun structure done at the outset of the tactical gun program at CEM-UT. Because the stiff gun structure deflects approximately the same amount as a 120 mm conventional smooth bore powder gun at peak bore pressure, it was necessary to have precise methods of measuring the deflections. The deflection tests involved loading a standard CEM-UT C-shaped aluminum armature approximately 48 in. into the gun. The homopolar generator (HPG) power supply was then used to apply a current pulse to the gun. Because this armature had a high loading force (approximately 41,000 lb), a peak current of about 1 MA could be applied before the armature would move. The deflection measurements were taken in the 48 in. behind the armature. The Vought LTV SLEKE group took part in the deflection measurements and used a laser interferometry setup to measure the deflections. CEM-UT included a fiber optic displacement measuring device as a backup and confirmation for the laser setup. As a precaution to prevent the armature from moving during the tests, a peak current of only 750 kA was applied to the armature. Because the rail loading scales with the current squared, this was only about one-eighteenth of the peak load seen at a full current of 3.2 MA. Discharging from this reduced current meant that deflections of only several tenths of a mil were expected. The tests confirmed the computer analysis of the gun structure as seen in Table 2. In the future, the optic sensors will be part of the data collected for each railgun shot. Using the optic sensors during peak current tests will provide data with a much better signal-to-noise ratio. Providing projectile designers with bore deflection data on each shot may help evaluate hardware performance as well as refine projectile assembly designs.



a s3701.1870 b s3701.2092 c s3701.2231 d s3701.2333

Fig. 1. Previously fired projectile packages

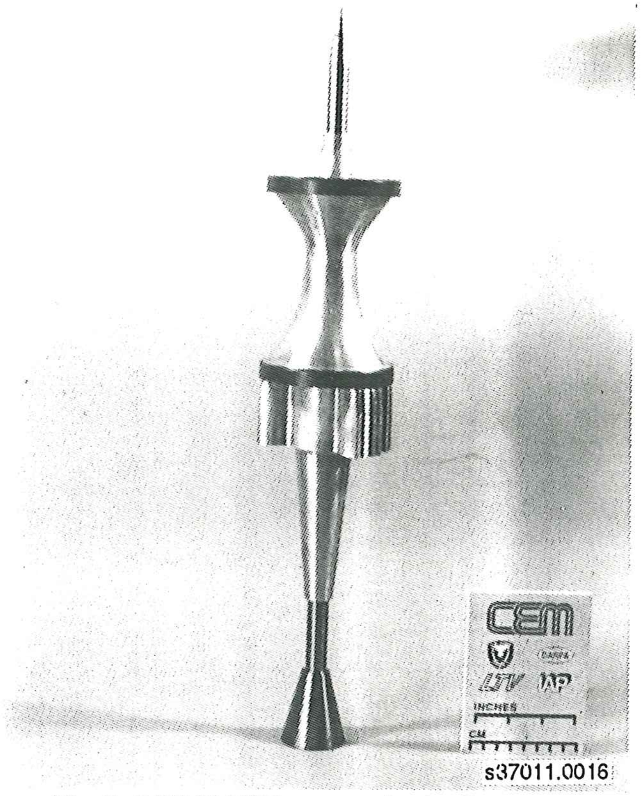


Fig. 2. LTV SLEKE armature/projectile package

TABLE 2. TYPICAL BORE DEFLECTIONS

	120 mm Conventional Powder Gun	CEM 90 mm Railgun
Peak Pressure (ksi)	69.8	54.1
Deflection (in.)	0.009	0.011 (calculated)
Measured at 750 kA (in.)	--	629 x 10 -6 (laser) 270 x 10-6 (optic)
Extrapolated to 3.2 MA (in.)	--	0.005 (optic) 0.012 (laser)

CEM-UT has also measured the straightness of the 90 mm x 10 m long railgun. This data has been requested for balloting side-load calculations on fragile projectile packages. The measurements have been done using a Taylor-Hobson optical alignment scope and a target sled pulled through the gun. The measurements have also been done by an outside group from Aberdeen Labs. They also used an optical alignment scope, but a different target sled to get their data.

The in-house measurements were resolved in terms of an "x" and "y" direction from a bore centerline. The measurements were taken every 12 in. down the bore and several sets of readings were taken and averaged to eliminate large error potential. The peak variation from centerline was approximately 0.665 mm (0.026 in.) in the "x" direction and 0.358 mm (0.014 in.) in the "y" direction. This means a larger variation was measured in the sidewall insulators, as one might expect.

The data from the Aberdeen Lab measurements were presented in terms of a rail and sidewall variation from the centerline. The peak sidewall variation was measured at 1.11 mm (0.044 in.) and the peak rail variation was found to be 0.381 mm (0.015 in.). This peak rail variation number is very close to the number obtained from the in-house data, but the sidewall insulator value is significantly larger.

There is a possible explanation for the discrepancy in the sidewall data. The target sled used for the CEM-UT measurements was an aluminum slug with two plastic boreriders to keep the assembly centered in the bore. This is very similar to a projectile package with boreriders travelling down the bore. The target sled used by the Aberdeen group used a sled with three spring loaded rollers to keep the assembly centered in the bore. Because the sidewalls have received much more damage than the rails, it is very possible a roller travelled through a pit or void in the sidewall and gave a higher value. The boreriders on the CEM-UT slug were more likely to travel over any voids without affecting the measurements.

The conclusion from both sets of measurements are that the 90 mm railgun is straight and within conventional 120 mm gun tube guidelines. Although balloting is a concern in launching long rod penetrators from large bore EM guns, this data shows the UT gun is an excellent test bed for transferring existing projectile designs from conventional guns to large electrical guns.

ARMATURE DEVELOPMENT AT CEM

Over the past two years a number of solid armature tests have been conducted in the 9 MJ vertical gun range. These have included a variety of base push and mid-body drive armature designs provided by CEM-UT and outside contractors. The following section will briefly discuss the evolution of CEM-UT C-shaped armature. For more detailed information on the tests of the C-shaped armature design and Kaman's UHVP program, see reference [5]. For information on LTV's SLEKE armature program see reference [4]. For results of Kaman's SLEKE armature testing see reference [6].

Early in the 9 MJ single shot gun test program CEM-UT elected to use a solid aluminum armature with C-shaped contacts. This design was chosen for a number of reasons including its adaptability to a variety of different configurations. The initial testing of the 9 MJ gun required a stable, robust package that could be used to test the entire system at full energy. The C-shaped armature design seen in Fig. 1a provided such a package and was fired at 8.1 MJ on shot #20 of the 90 mm gun. The C-shaped design in its "snub nosed" version also provided a mechanism for launching the four piece aluminum sabots and tungsten tipped penetrators designed by Kaman for the UHVP program and shown in Fig. 1b.

Once the system had been proven at full energy the requirements on the armature were modified. The mass of the armature needed to be reduced and the armature would eventually be required to carry penetrator with a high L/D ratio. Still the armature had to serve as a dependable test load for the 9 MJ single shot gun system when required. To provide a package that met these characteristics an evolutionary approach to the design was taken.

Over a series of several shots the mass of the armature was reduced from 1,200 to 900 g. The reduced mass armature (Fig. 3) was eventually tested at 2,033 m/s on shot

Fig. 3. Comparison of reduced mass C-shaped armature and original design

#31. A 19 mm diameter hole 75 mm into the rear of the armature was added to the package on that shot. The addition of that hole served as the starting point for the modifications that would be required for the armature to carry a penetrator. With shot #31 proving that a penetration in between the two contacts did not adversely affect armature performance, a steel rod was threaded through the package for the next reduced mass test, shot #39.

On shot #39 the armature served primarily as a load for a low energy test of the power supply but it also proved that the steel rod protruding from the front and rear of the armature package did not reduce armature performance. The biggest step in the armature development program came on shot #40 when the C-shaped armature was fired as a two piece design carrying a mid-body driven threaded rod. While the package was not allowed to separate due to the thick boreriders, it was the first test of the two piece armature and also the first time the "integral payload", used for the entire 9 MJ single shot gun test program, was configured as a separating sabot.

The most recent test of the reduced mass C-shaped armature was on shot #45 when the two piece armature/sabot shown in Fig. 1c was fired at 1,320 m/s. During the shot the armature/sabot performed well in bore and separated cleanly prior to impacting the sabot stripper. X-rays taken in the target chamber just a half meter above the target confirmed that the 597 g steel projectile was intact and flying straight prior to impact. This test allowed CEM-UT to confirm the proper operation of all the systems necessary for documenting a successful launch of a SLEKE package.

In addition to serving as a confirmation test for the 9 MJ single shot gun system the process involved in designing and building the armature/sabot and projectile package helped CEM-UT identify issues that may be critical to outside contractors designing packages for CEM-UT's 90 mm railgun. The C-shaped armature design will continue to be used to address those issues deemed relevant by the test community. At the present time the C-shaped armature is available in a base push design and as a separating armature/sabot for projectile designers wishing to test at CEM-UT without proceeding through the initial armature design phase. Future tests of the C-shaped armature will concentrate on increasing the package energy and decreasing the parasitic mass.

THERMAL OPENING SWITCHES

The basic principles by which the CEM-UT gun program is powered has lead to a unique and innovative development in opening switch technology. Powering the 90 mm railgun with only six HPG modules limits the ability to shape the current pulse into a uniform flat-top pulse. Normal operation when all six HPGs are used involves discharging several of the generators at time zero and then staging the remaining generators at varied time intervals later. Peak current is achieved in approximately 100 µs; with each staged generator rapidly bringing the current back to peak value. (Fig. 4). Powering the railgun with the opening switch commutated storage inductors means that with each HPG/inductor discharge, the circuit di/dt rapidly increases until peak current is reached around 3.2 MA.

As the effort advanced and more delicate projectile packages were fired from the gun, the need to reduce the acceleration (or jerk) on these packages was recognized. The standard equation for the force seen by the projectile package is given as

$$F = \frac{1}{2} L' I^2 \tag{1}$$

where L' is the inductance gradient of the gun and I is the instantaneous current in the circuit. The acceleration acting on the package may be described by the equation

$$A = \frac{L' I^2}{2m} \tag{2}$$

where m is the mass of the projectile. To determine the jerk or the rate of change of acceleration on the package, the derivative of the acceleration is required. This leads to the equation

$$Jerk = \frac{L' I \frac{dI}{dt}}{m} \tag{3}$$

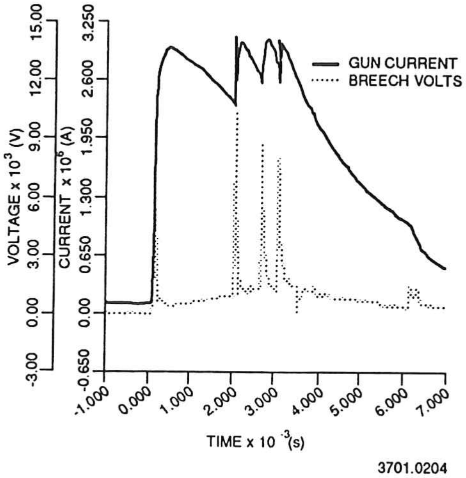


Fig. 4. Typical data for six-generator discharge

Because most of the parameters in this equation are constants, the most obvious approach for lowering the jerk was to reduce the dI/dt seen during the high power switching events.

The explosively driven opening switch used on the Balcones power supply [7] is a parallel plate design which incorporates multiple gaps in series to increase voltage hold-off capability. These gaps are machined with a dovetail design stress concentration. The gaps are loaded with 50 gr/ft detonating cord and upon actuation, the explosives rapidly remove the material from the 6061 aluminum switch element. The excellent performance of the switch is enhanced by magnetic assistance in blowing out the arc and magnetic insulation to improve voltage hold-off. These seven gap switches have experimentally opened, on a consistent basis, a peak current of 1.0 to 1.2 MA with a typical opening time around 100 μs and a voltage hold-off around 1,000 to 1,500 V/gap.

The unique approach for reducing the jerk came within the opening switch element itself. Because the detonating cord burns so rapidly (~7 km/s) and the cord is detonated from both ends of the 24 in. wide element, the material is removed from the gap very rapidly, causing a fast opening and a high dI/dt. A new thermal opening switch design [8] was adopted by leaving a 2 in. section at the center of each gap to act as a small fuse element. The center of the gap is milled with a "v" groove cutter leaving only 0.020 to 0.030 in. of material (Fig. 5). The "v" grooves were stop-drilled at each end to vent the pressure as the detonating cord approached. As the switch detonates and the current is pinched into the reduced cross-section, the thermal gaps rapidly turn to aluminum plasma. Magnetic loading on the switch element expels the plasma from the gaps into an expanding cloud. As this cloud expands, its impedance increases until the voltage across the switch can no longer sustain the arc. At this point the arc goes out and the switch is open. This occurs in approximately 200 to 300 μs as compared to the original switches which opened in approximately 100 μs. This slower opening time has been very important in reducing the jerk on the projectile packages from approximately 500 Mgees/s to only 200 to 300 Mgees/s.

Another definite advantage to using these thermal opening switches is a lack of effect on the switching efficiency. As seen by the equation for the energy absorbed and switch efficiency,

$$E_{abs} = \int_{o}^{opening\,time} vi\,dt \qquad (4)$$

$$Efficiency = 1 - \frac{E_{abs}}{0.5LI^2} \qquad (5)$$

where v and i are the instantaneous voltage and current across the switch, L is the storage inductor inductance and I is the original inductor current. The two parameters that will determine switching efficiency are the generated voltage and the opening duration. Experimental results to date show these switches generate 500 to 1,000 V/gap. The reduced voltage counterbalances the longer opening time to provide no net affect on switch performance (Fig. 6). The conclusion is that the thermal switches are an effective way to lower jerk on the projectile package while maintaining the excellent efficiency of a standard fully blown switch, approximately 90 to 95%.

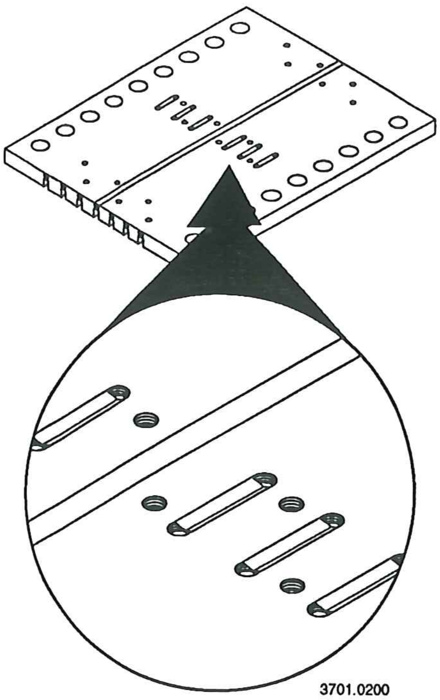


Fig. 5. Thermal opening switch element

Down Range Diagnostics

As projectile development has advanced and the present technology has reached the ability to deliver meaningful penetrators on-target, the need for improved target diagnostics was realized. Projectile designers are extremely interested in the angle at which their penetrators impact a target. It goes without saying that this angle strongly affects penetration depths, therefore some type of data was requested to verify the impact angle. The projectile contractors specifically requested an orthogonal x-ray station within 1 m of the target surface and a single x-ray view within 1 m below the bottom of the target to document debris patterns from a full penetration test.

Due to the layout of the vertical gun range, this required taking the x-rays inside the target chamber, where the environment may be quite harsh on x-ray equipment during a shot. CEM-UT has designed, installed, and is presently operating such a system. Two 300 kV Scandiflash x-ray heads were placed inside protective steel enclosures inside the target chamber to provide the above-target orthogonal view. Two large film holders were designed to accommodate film sizes up to 17 in. x 61 in. with a series of Kevlar™, high density polyethylene, and Lexan™ shields used to protect the film from the impact blast and debris. This system can take an x-ray of a projectile up to 28 in. long within 1 m of the target surface. The below-target x-ray has not yet been installed, but it will use one 300 kV head aimed just below the target bottom surface. A make-screen circuit will trigger the x-ray should any debris or projectile pieces exit the

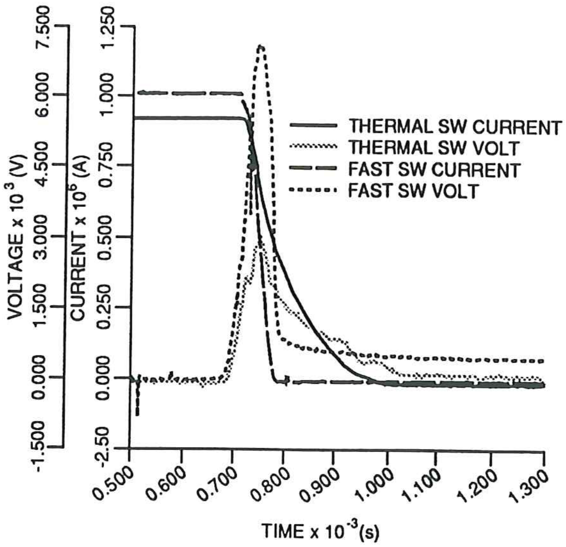


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Fig. 6. Data comparison for thermal switch vs. fast switch

bottom of the target. The target x-ray system has performed very well and it has provided very valuable data for the projectile contractors [9].

A unique and very useful diagnostic tool is in-house and available for use. CEM-UT purchased a gold vapor laser as part of its original contract to build the vertical gun range. On several occasions early in the test program, an attempt was made to use the gold vapor laser as a light source for the high speed cameras. These attempts were unsuccessful and the laser was left idle for a long period of time. Because of the cost of this equipment and the potential for excellent film data collection, the idea of using the laser as a high speed film light source has been reconsidered. After consultation with the laser manufacturers, it was determined the laser would be much easier to operate and maintain as a copper vapor laser. The equipment was modified and ready for use. CEM-UT has since then gone through an extensive test program to understand the use of the laser with the high speed Photonic framing cameras. The test program addressed issues such as camera/laser synchronization, light intensity, film speeds, laser power output, and fiber optic laser light transmission. At the end of the test program, CEM-UT had successfully taken high speed film footage of a stationary object with good image detail. Due to the tight budget of the 90 mm railgun program, there were not sufficient funds to install the laser and fiber optic transition lines in the gun range. This very useful tool is at UT should funds become available, the system will be installed and used as part of the downrange diagnostic setup [10].

CONCLUSIONS

The work done at CEM-UT's large bore gun range over the past two years has moved EM launch technology even closer to the reality of becoming a future weapons option. This program has demonstrated its high energy capability as well as providing projectile designers with a reliable and efficient method of testing their hardware. CEM has provided gun bore data such as bore deflection and bore straightness to aid in projectile design. The problem of excess jerk has been addressed with the development of thermal opening switches. Improved down range diagnostics such as the target x-rays and the metal vapor laser significantly enhance the in-flight projectile data. The advances in both base-push and mid-body drive projectile designs has proven that lethal kinetic energy penetrators can be delivered on target from an EM gun. Future work will slowly continue increasing the muzzle energy of packages while studying the basic aspects of EM launch.

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