RAPID FIRE RAILGUN FOR THE CANNON CALIBER ELECTROMAGNETIC GUN SYSTEM

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Abstract

A rapid fire railgun launcher has been designed and fabricated and a single-shot prototype has been tested for the Cannon Caliber Electromagnetic Gun (CCEMG) System. Three, five round salvos of 185 g launch packages are to be accelerated to 1,850 m/s at a rate of 5 Hz. The 2.25 m launcher has a 30 mm round bore equivalent, rectangular geometry and is water-glycol cooled. Rapid fire operation is achieved by driving the launcher with multiple 835 kA pulses provided by the CCEMG compulsator. The launcher is a series augmented railgun and has demonstrated breech efficiencies over 50%.

A high CCEMG system efficiency is in part attributable to the use of a solid armature and is enhanced by having a structurally stiff railgun. Historically, a railgun's stiffness was proportional to its weight. Laboratory based railguns that have respectable mechanical properties have required massive structures that are nowhere near meeting the requirements of future vehicle integration and weaponization. The Cannon Caliber railgun design incorporates a directional preloading mechanism, ceramic sidewalls and a composite overwrap which together give it a structural stiffness dominated by high modulus ceramic with an overall mass of only 273 kg. These characteristics make the Cannon Caliber launcher one of the most "fieldable" railguns built to date.

Introduction

The Cannon Caliber Electromagnetic Gun System (CCEMG) design represents the culmination of two decades of electromagnetic launcher research in the areas of pulsed alternator, railgun and integrated launch package (ILP) development. Although this paper focuses on the design and initial testing of the CCEMG railgun, the power supply[1] and ILP design must be acknowledged for their contribution to the gun's final configuration. Early in the design process, an optimization code called EXCALIBER was utilized to identify the ideal system parameters and launcher geometric and electrical configuration[2]. The resulting railgun design parameters are listed in table I. The railgun is 2.25 m long with an augmented turn in series with the main rails. Only the first 1.85 m of the gun is augmented and the gun has an muzzle switch "tap" located at 1.9 m. The railgun bore geometry is rectangular; 1.75 cm x 3.94 cm (fig. 1).

Table I. Cannon caliber railgun design parameters

Performance	
Launch package mass	185 g
Muzzle velocity	1,850 m/s
Muzzle energy	315 kJ
Launcher energy density	1.16 J/g
Inductance gradient	1.1 μH/m
Peak current	835 kA
Number of salvos	3
Rounds/salvo	5
Firing rate	5 Hz
Time between salvos	2.5 s
Physical	
Railgun type	Series augmented
Bore dimensions	Rectangular 17.5 x 39.4 mm
Overall length	2.25 m
Augmented length	1.85 m
Stiffness at peak current	0.2% deflection
Coolant	Water-ethylene glycol
Weight	273 kg

The CCEMG railgun incorporates several unique features: ceramic sidewalls, directional preloading and liquid cooling. A developmental mentality was adopted by the program to evaluate the gun's structural design while studying the performance of several ILP concepts. As a result, two single-shot guns were built (referred to as launchers IIA and IIB) in addition to a water-glycol cooled, rapid-fire gun (launcher III). This paper presents test summaries and general performance observations for launcher IIA performed at both the Center for Electromechanics at The University of Texas at Austin (CEM-UT) and U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground, MD.

Design

In addition to railgun structural and electrical design requirements, the Cannon Caliber gun design considerations include thermal management, bore wear and weight. For the

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14. ABSTRACT
A rapid fire railgun launcher has been designed and fabricated and a single-shot prototype has been tested for the Cannon Caliber Electromagnetic Gun (CCEMG) System. Three, five round salvos of 185 g launch packages are to be accelerated to 1,850 m/s at a rate of 5 Hz. The 2.25 m launcher has a 30 mm round bore equivalent, rectangular geometry and is water-glycol cooled. Rapid fire operation is achieved by driving the launcher with multiple 835 kA pulses provided by the CCEMG compulsator. The launcher is a series augmented railgun and has demonstrated breech efficiencies over 50%. A high CCEMG system efficiency is in part attributable to the use of a solid armature and is enhanced by having a· structurally stiff rail gun. Historically, a railgun’s stiffness was proportional to its weight. Laboratory based railguns that have respectable mechanical properties have required massive structures that are nowhere near meeting the requirements of future vehicle integration and weaponization. The Cannon Caliber railgun design incorporates a directional preloading mechanism, ceramic sidewalls and a composite overwrap which together give it a structural stiffness dominated by high modulus ceramic with an overall mass of only 273 kg. These characteristics make the Cannon Caliber launcher one of the most "fieldable" railguns built to date.

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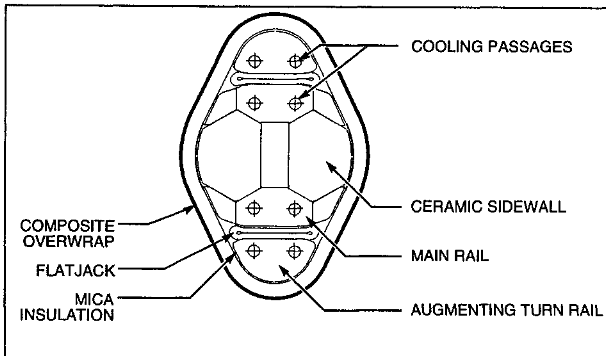

Figure 1. CCEMG launcher cross section

interested reader, reference [3] presents specific details of the electromagnetic (EM) and thermal design as well as the launcher component development. Launchers IIA and IIB are identical to the multishot launcher with the exception of coolant passages and deceleration guide required for autoloading. A peak gun current of approximately 830 kA for 15 rounds requires active cooling between salvos by coolant passages located in both main and augmenting rail sets.

Directional preloading mechanisms called "flatjacks" located between the main and augmenting rails (fig. 1) are utilized to counter electromagnetic loading and maintain a compressive state in alumina ceramic sidewalls. This results in an extremely stiff design. Preload is reacted against a filament wound composite overwrap composed of 82%, 90° graphite fibers and 18%, 0° fiberglass. The overwrap reacts the preload plus a fraction of the EM loading and provides stiffness to the launcher in the axial direction. These features give the launcher a peak bore growth of 0.2% at full electromagnetic loading and an overall weight of 273 kg.

The success of the launcher design depends heavily on the flatjacks ability to apply a pressure to the main rails so that the ceramic sidewalls (AD-96 alumina) remain in compression throughout the discharge. The flatjacks have received much attention during fabrication and initial testing. Launcher IIA experienced a flatjack failure due to an electrical arc and a flatjack in launcher IIB failed during its initial pressurization. Both setbacks, however unfortunate have proved beneficial in identifying weak areas of the launcher design. Nevertheless, both launchers are still fully functional, each operating on a single flatjack. Failure of the flatjack in launcher IIA and repair is discussed in more detail in the CEM-UT testing section. Launcher IIB was repaired, boxed, and is awaiting testing at ARL. Design improvements are being incorporated into launcher III.

The flatjacks are formed by a series of cold drawing operations on a seamless Inconel 718 tube. Manifolds and fill tubes are welded to the ends. The flatjacks are pressurized to 138 MPa for a full current shot and must endure a displacement of approximately 1.3 mm. Inconel 718 in the annealed condition fulfills the strength, ductility, and nonmagnetic requirements of this application.

Chromium copper (C18200) was chosen as the rail material because of its strength (310 MPa yield), conductivity (82% IACS), relatively low cost and its dimensional stability. The rails of launcher IIA have to date experienced a total of 45 shots. Coolant passages in launcher III are formed from 8 mm holes (two parallel) drilled the length of the main and augmenting rail forgings. To attain the launcher's high breech efficiency, the main rails are slit (1.6 mm wide on 3.2 mm centers) transverse to the gun's axis to the mid-point of the ceramic sidewall. This region of the main rail is required for structural purposes but is detrimental to performance and therefore is slit to minimize its current-carrying ability.

CEM-UT Testing

Testing of single-shot launcher IIA has been performed both at CEM-UT and ARL. A total of 11 shots were performed at CEM-UT and as of the writing of this paper ARL has shot 34 times. Testing at CEM-UT was successful in verifying the predicted mechanical and electrical performance of the launcher. Launcher IIA was powered with the 1 MJ/pulse, iron core compulsator (ICC) (fig. 2). A schematic of the ICC/launcher IIA circuit is shown in figure 3.

A total of 11 shots were performed with a gradual increase in system energy. Table II lists the system parameters and projectile performance for selected CEM-UT and ARL tests. Prior to electrical testing, bore straightness was measured before and after flatjack pressurization to determine the flatjacks effect on straightness. Very little change in the bore straightness was observed, indicating that a uniform amount of axial strain was being applied to the structure, or the flatjack axial strains have little effect on the structure. The peak deviation from a straight line for either the sidewall or rail direction was 0.2 mm. Honing of the bore was performed between shots to remove armature deposits with no attempt to remove rail material; the bore dimensions remained consistent throughout testing. The bore straightness was checked after CEM-UT shot #11 and again there was no significant changes in bore straightness as compared to the initial measurements. CEM-UT range diagnostics consisted a single set of orthogonal muzzle x-rays, velocity screens and a single yaw card located at 6.4 m. Launcher instrumentation included b-dots, a flux

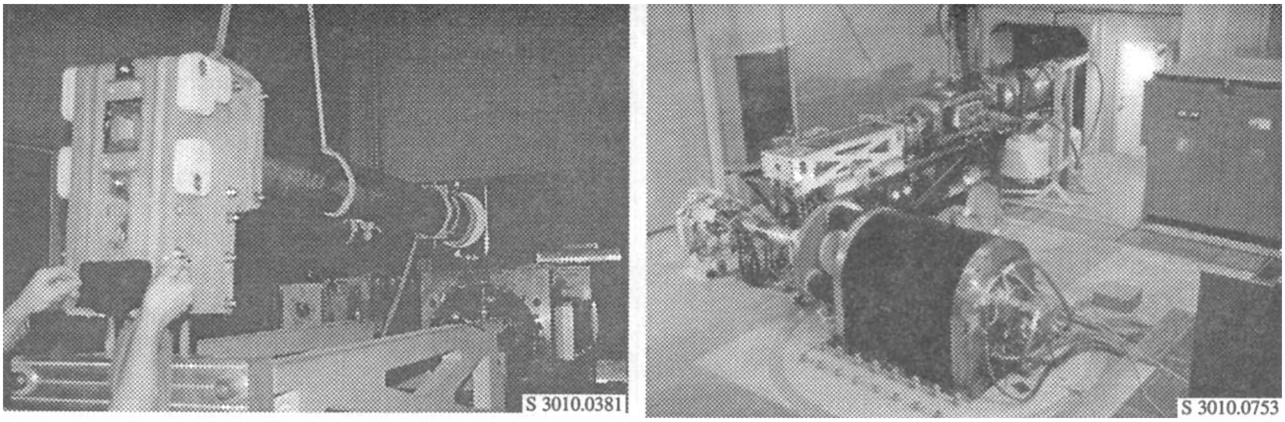

Figure 2. CEM-UT testing: CCEMG launcher IIA and the iron core compulsator

ruler and voltage and current measurements. Several unsuccessful attempts were made at measuring flatjack pressure transients with a PCB pressure transducer.

Highest performance occurred on UT-CEM shot #7 which has a peak current of 552 kA. Voltage limitations of the ICC combined with the inductance of the augmented launcher prevented testing to higher current levels. Although the structural limits of the gun could not be fully characterized, its electrical insulation was tested by the multiple open circuit cycles of the ICC after a shot. During this testing, an insulation flaw was identified within launcher IIA.

During shot #11, failure occurred in three of the system components. Immediately after launch, the muzzle insulation of the gun broke down resulting in approximately 60 restrikes with an average current level of 50 kA. This event eroded about 7.6 cm of the muzzle conductor and apparently melted the surface of the ceramic sidewalls up to 5.1 cm away from the muzzle. No structural cracks were observed in the sidewalls. A voltage breakdown between the top flatjack and its adjacent augmenting rail burned a hole in the top jack and thus ignited the high pressure (103 MPa) glycerin. Further post-mortem examination of the launcher revealed that the voltage standoff between other gun components was weak.

In order for the gun events just described to occur, two components had to fail. The SCR closing switch shorted inside the SCR trigger box, resulting in a single SCR to fail in the closed state. Secondly, the ICC emergency

Table II. Launcher IIA selected shot summary

Shot #	CEM 7	CEM 8	CEM 9	CEM 10	CEM 11	ARL 7	ARL 14	ARL 16	ARL 34
Date	3/1/94	3/4/94	3/8/94	3/11/94	3/14/94	8/31/94	9/28/94	10/21/94	6/1/95
Pulsed Power Supply Parameters									
CPA Speed (rpm)	3774	3493	3333	3456	3837	N/A	N/A	N/A	N/A
Field Excitation (A)	1489	1085	787	996	1500	N/A	N/A	N/A	N/A
Peak Voltage (V)	1638	1334	1095	1290	1612	8500	8400	9200	7400
CPA Volts @ trig (V)	110	90.5	142	177	220	N/A	N/A	N/A	N/A
Firing Angle (°)	5.84	5.09	9.3	10.26	5.00	N/A	N/A	N/A	N/A
Peak Current (kA)	552	479	403	458	462	609	586	667*	639
Pulse Width (ms)	4.15	4.525	4.367	4.43	4.10	1.9	2.2	1.9*	2.6
Time to peak (ms)	1.893	2.157	2.34	2.065	1.975	0.38	0.38	0.38*	0.47
Launcher/ILP Parameters									
Velocity (m/s)	1339	1034	1042	1061	1350	1886	1369	1492	1350
ILP Mass (kg)	0.186	0.185	0.136	0.172	0.182	0.098	0.174	0.178	0.180
Breech Efficiency (%)	51	44	42	46	30	37	42	42*	37
Armature Insertion Force (kN)	11.6	9.96	8.07	6.18	5.98	2.79	5.89	7.57	5.58
Armature Current @ exit (kA)	123	28.15	4.02	9.79	94	294	263	300*	132
Action @ exit (MA^2s)	514.8	417.1	308.5	380.5	355.9	367	436	511	468

* estimated

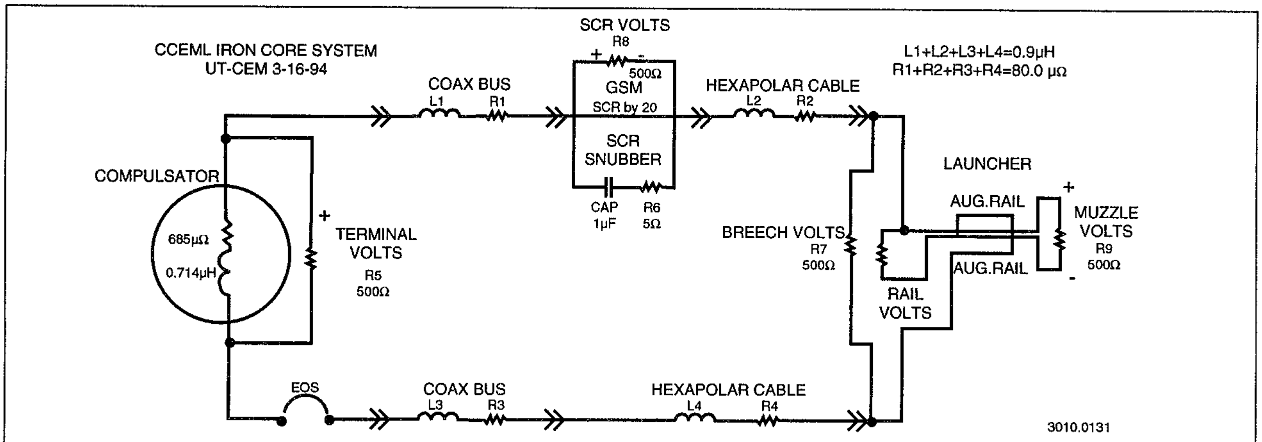

Figure 3. ICC/launcher IIA circuit schematic

opening switch (EOS) attempted to open the circuit upon detecting multiple pulses however it continued to restrike to a nearby conductor.

Launcher IIA was repaired by pumping the upper failed flatjack with a filled epoxy while the lower flatjack was depressurized to allow the epoxy in the top jack to cure at maximum displacement thus limiting displacement of the lower jack. Once the epoxy had cured, the remaining flatjack was repressurized to 103 MPa. The electrical resistance between rails was deemed adequate for performing single-shot tests using capacitor banks and launcher IIA was shipped to ARL.

A number of modifications were made to the electrical insulation design of launchers IIB and III. These include: thickening the mica insulation, adding a composite insulating barrier between the flatjack manifold region and the augmenting rails, applying Limitrak insulating enamel to both sets of rails, and adding an additional fiberglass layer to the bore of the composite overwrap. In addition, several intermediate dc and transient hi-pot tests were added to the assembly procedure.

ARL Testing

Test Objectives

The test objective was to experimentally verify launcher and ILP performance in a single-shot mode of operation. The launcher's ability to convert electrical energy to kinetic energy is a strong function of attaining its rated peak performance. Testing was planned such that an abundance of relevant data could be obtained early in the program without placing the hardware at unnecessary risk. To date 34 rounds have been shot from launcher IIA at ARL. Tests can be grouped into component characterization (shots 1-9), armature development (shots 10-16), launch dynamics (shots 17-27), pseudo multishot (shots 28-32), and peak performance (shots 32-34). We are presently increasing the peak current levels and thereby subjecting components to their design values.

Range Facility and Power Supply

Testing took place at the EM Facility, Transonic Range, Aberdeen Proving Ground (APG) MD. The Facility consists of a (upgraded after shot 27) 1.55 MJ capacitor-based pulsed power supply (PPS) with a 222 m free-flight range[4]. The PPS is comprised of eight banks, each with the flexibility to be charged to different initial voltages as well as to be triggered independently in time. Maxwell Laboratories and General Electric capacitors are used throughout the PPS. Each bank is nominally 200 kJ at a rated maximum charge voltage of 10 kV. Each bank is connected to a common bus through a D-size ignitron (NL-2888A) and a nominal 10 μH inductor. Stacks of diodes are connected across each bank output to prevent voltage reversal across the capacitors. Four banks use 12 PowerEx RA204420 diodes each while the remaining banks use International Rectifier semiconductors. The PPS, under short-circuit load conditions, can provide a current pulse with a 375 μs rise time with a transfer admittance of 120 kA/kV. The current decays with a time constant of nearly 8 ms. With launcher IIA as the electrical load, peak current is estimated to be 875 kA, occurring at 450 μs and a time constant of 3 ms. Launcher IIA installed in the EM Facility is shown in figure 4.

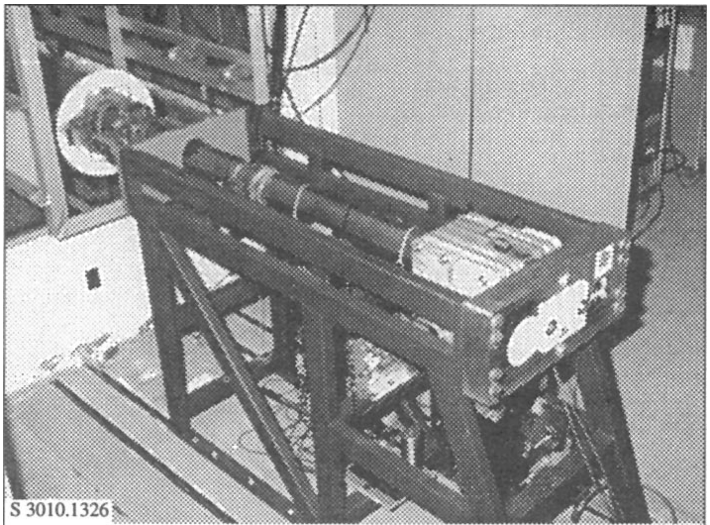

Figure 4. ARL testing: CCEMG launcher IIA at test range

Instrumentation to monitor and assess ILP performance consists of bore-sighted yaw cards, multi-station orthogonal flash x-ray with fiducial cable, radar, smear and high-speed camera, and realistic armor targets located 222 m downrange from the launcher. Instrumentation to assess launcher performance includes b-dots, flux rulers, and current and voltage measurements.

Attaining system performance is first and foremost dependent on ILP structural integrity, and subsequently, subprojectile accuracy. One factor affecting both is the deviation of the bore centerline. The "straightness" measurement is made routinely on conventional guns and this data is often used to assess the quality of the gun. Often, launchers exhibiting large deviations from centerline are not used for projectile range testing. Railguns offer two distinct planes for centerline: one for the rail plane and the other for the insulator plane. The “straightness” for launcher IIA in both the rail and insulator planes, has been routinely measured by the Aberdeen Test Center, ATC (formerly Combat Systems Test Activity, a tenant activity at APG, MD) throughout the duration of all testing. On average the straightness for launcher IIA is the same for a similar caliber conventional gun. However, its deviations along the direction of projectile travel are smoother than those exhibited in launcher IIAs. The deviation at the muzzle of launcher IIA is upwards in the rail plane and towards the left in the insulator plane (looking downrange). For nearly all of the shots the ILPs have had trajectories biased towards the left side of launcher line of fire. On the other hand nearly all the rounds have exited the launcher with the nose of the projectile oriented downwards. Phenomena at the rail/armature interface near exit may overwhelm the dynamics offered by bore straightness in the rail plane for these velocities.

Prior to all the shots the launcher bore has been cleaned by pushing a lapping tool through the bore (i.e. honed). Mineral spirits is used as a cleaner and lubricant with the tool. The lapping tool consists of opposing steel wedges with diamond faces and locked to a preset width. The width has been set to only remove any aluminum deposited on the rail surfaces. Consequently, very little copper rail material has been removed. After the launcher is honed the bore is wiped with paper towels soaked in alcohol. In the pseudo multishot tests (shots 28-32) the bore was not maintained between the 5 shots. No unusual launcher or projectile behavior was observed.

The flatjack pressure is nominally at 97 MPa for the primary jack and 41 MPa for the secondary jacks. The pressure is measured with a standard pressure gage having increments of 0.7 MPa. Typically, immediately after a shot the pressure gage reads an increase of roughly one-half an increment and subsequently settles down to its original reading. It is uncertain as to the significance of this observation since the pressure increase is only one-half an increment.

Armature performance is partially dependent on mechanical preload placed on the armature contacts. The preload is provided by a tapered interference fit between the armature and the bore rail surface. Optimum preload is difficult to calculate but has been estimated to be 13.34 kN for this armature[2]. Clearly, no preload will result in an immediately arcing contact and too much preload will result in immediate structural failure. Armature interference is obtained from knowledge of the rail to rail dimension. For all the shots this has been estimated by measuring the rail to rail dimension set by the hone. This technique has a measurement error on the order of 0.13 mm. An indication of the preload placed on the armature contacts can be assessed by measuring the amount of force it takes to insert the ILP in the bore. The insertion force is measured by converting the pressure gage reading in a hydraulic cylinder as the round is inserted into the breech, roughly 30 cm from the rear face of the launcher. Lowest and highest recorded values for insertion force throughout the testing are 2.24 kN and 7.97 kN respectively. No anomalous armature behavior has been noted for these shots. In fact, the CCEMG design velocity was exceeded using a 100 g tandem contact slug with an insertion force of 2.79 kN (Shot 7, 1886 m/s). Afterwards, the bore rail surfaces were video taped and no visual evidence of gouging on the rail surface was observed.

After shot 32, the rail to rail dimension was accurately measured as a function of launcher length by ATC. The nominal rail to rail dimension is 3.73 cm with a +0.03 mm variation. No trend in the variation was noted as a function of launcher length.

Launcher Performance

The highest launcher current to date is 667 kA and occurred on Shot 16. Also on this shot the muzzle current was also the highest at roughly 300 kA. Afterwards it was found that the G-10 plate at the muzzle that supports the secondary flatjack plumbing had separated axially from the carbon fiber overwrap. Since this launcher was not designed to sustain such large forces at the muzzle it is not surprising that this structural deformation occurred. The G-10 plate was subsequently epoxied and thru-bolted to help support the EM and blast loads. In order for full launcher and ILP performance to be realized the most recent testing incorporates an explosively activated closing switch connected at the muzzle "tap"[5]. To date, two shots have employed the switch. On the last reported shot (shot 34) a peak armature current of roughly 360 kA was successfully commutated into the muzzle switch. The launcher current just before exit was 311 kA while the current flowing in the armature was reduced to 132 kA. No structural deformation at the muzzle was observed and moreover, light and sound signatures associated with a large exit current were significantly reduced. The average time for full commutation to occur is 500 μs.

The largest amount of rail wear occurs at the muzzle, primarily due to the large currents flowing through the launcher when the ILP exits the launcher. The wear at the muzzle end of the launcher has been monitored and found to be on average 0.79 mm per rail occurring over the last 10 cm of rail length. This erosion accrued during the five pseudo-multishots with ILP exit velocities of 1,100 m/s. The erosion of the rail at 13 cm from the muzzle was only 0.10 mm per rail.

It is found that the conversion of energy supplied to the breech to kinetic energy at the muzzle increases as peak current is increased. The highest recorded efficiency was obtained for shot 14 with a value of 33% and a launch velocity of 1,370 m/s (the current trace for shot 16 was not recorded). This value also includes the magnetic energy remaining in the circuit since current is not zero when the ILP leaves the barrel. The magnetic energy is transferred into additional ohmic heating in the resultant arc and conductors. If this energy could be converted into a charge on the capacitor banks (much like the compulsator rotor would spin up at projectile exit) the net efficiency would increase to 42%. The efficiency of converting the stored capacitive energy to kinetic energy is 21%. For a constant launch velocity all the efficiencies are found to decrease by a few percent for the shots that used a 100 g launch mass. For all 45 shots, the launcher inductance gradient has been computed from the measured current and velocity and found to be 1 μH/m.

Conclusion

An overview of the CCEMG launcher design has been presented and testing performed at CEM-UT and ARL has been described. The design incorporates directional preloading (flatjacks) and ceramic sidewalls which give the launcher its extremely high stiffness and low weight. A total of eleven shots have been performed at CEM-UT using the iron core compulsator and 34 shots at ARL using a capacitor power supply. The initial tests have demonstrated breech efficiencies over 50%. In addition, these tests have demonstrated the durability of the launcher's structural design in the presence of high and multiple muzzle currents and operation with a single flatjack.

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