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Abstract

In December 1993, the Center of Electromechanics at The University of Texas at Austin (CEM-UT) completed construction of an high L' railgun for the 9 MJ Range Gun System Program. The 90 mm bore railgun utilizes dispersion strengthened copper rails and incorporates a laminated stainless steel containment structure and filament wound fiber epoxy composite overwrap. In January 1994, the railgun was installed at The Electric Armaments Research Center (EARC) at Picatinny Arsenal, New Jersey for testing on the 52 MJ capacitor bank power supply.

The test program at EARC was designed to allow full 2.8 MA current testing of the railgun, breech connection, and flexible hexapolar cable bus system during completion of the 9 MJ Range Gun System compulsator. The EARC test program allows evaluation of the launcher and flexible bus components prior to the range test program at the Yuma Proving Ground electric gun test facility, and provides empirical data for concurrent design of other railguns incorporating laminated containment structures.

This paper will describe installation of the railgun into the EARC facility and discuss performance of the railgun and flexible hexapolar cable bus system during testing. The hexapolar cables have been tested to 34 kV and are rated for a nominal current of 200 kA per cable, and the flexible bus system and breech connection have repeatedly performed successfully at gigawatt power levels. The paper will also present the results of the railgun test program firing two variations of the sabot launched electric gun kinetic energy (SLEKE) projectiles along with an evaluation of the performance of the dispersion strengthened copper rails with transitioning solid armatures. This effort is being funded by the U.S. Army Armament Research Development and Engineering Center under contract number DAAA21-86-C-0281.

Background

The 9 MJ Range Gun system is a stand alone, field portable electromagnetic launch system designed to accelerate projectiles to a muzzle energy of 9 MJ at velocities from 2.5 to 4.0 km/s^[1]. The system includes a gas turbine prime mover, an air core compulsator, auxiliary and control systems, and a lightweight electromagnetic launcher. In order to meet the stringent size and weight requirements for a field portable system, all components of the system were designed to minimize weight and volume.

The design goal for the 9 MJ Range Gun System launcher was to provide a lightweight railgun with performance comparable to the 9 MJ Single Shot Laboratory gun at a fraction of the weight and volume. Table I is a comparison of the design parameters of the single shot and field portable launchers.

The 90 mm bore laminated railgun was designed for multiple shaped compulsator current pulses with a peak current of 3.2 MA and a total action of 3×10^{10} A²-s per shot. The lightweight barrel has a 7.2 meter active length (7.7 meters overall) with a nominal 32.5 cm. outside diameter, and weighs approximately 3,200 kg. This design represents an order of magnitude decrease in weight and a factor of 6 reduction in launcher volume, while maintaining comparable launcher stiffness and performance. Figure 1 shows an isometric section of the lightweight laminated barrel with the major components identified. The 75° rails are fabricated from single piece full length extrusions of Glidcop™ AL-60 dispersion strengthened copper. The 105° bore insulators are single piece full length pultrusions of fiberglass epoxy composite including both axial roving and bi-directional fiberglass cloth reinforcement. The primary electrical insulation consists of a single layer of 0.025 in. thick FEP Teflon™ sleeve supported with a mica filled epoxy. Primary radial structural support is provided by 0.048 in. thick, 301 half-hard stainless steel laminations bonded with a polyester/epoxy sheet adhesive. Barrel longitudinal stiffness is provided by a fiberglass/epoxy composite overwrap.

Table I. Design parameters of the single shot and field portable launchers

	Active Length [m]	Peak Design Current [MA]	Diametral Bore Deflection [mm]	Total Mass [kg]
9 MJ Range Gun	7.5	3.2	0.27	3,295
Single Shot Gun	10	3.4	0.08	32,300

Figure 1. Range gun structure

condition the material offers an ultimate tensile strength of 150 ksi [21.75 MPa], a tensile yield strength of 110 ksi [15.95 MPa] and 18% elongation.

Structural performance of the rail/insulator package, insulation layers, and laminated support structure was evaluated using a detailed 2-D structural finite element analysis. The rail separation force of 96.1 kips/in. at 3.2 MA peak current calculated by the electromagnetic finite element model was used as the input to the structural model. Use of a laminated material allowed the conductive stainless steel support structure to be located immediately adjacent to the rails, greatly improving the stiffness of the support structure. The 2-D finite element model was also used to evaluate techniques for radially preloading the rail/insulator package to prevent gaps from developing between the rails and insulators. Several preloading techniques were evaluated before selecting the pressurized cure technique. This method was originally developed to provide radial preload for composite rings the 9 MJ Range Gun system compulsator rotor. A mica reinforced epoxy is pumped into the gap between the FEP insulating sleeve and the bore of the laminated support structure. After being pressurized with an external pump, the epoxy is allowed to cure, locking the rail/insulator package and laminations into their preloaded positions.

The finite element model predicted a rail to rail deflection of 28 mils at a load of 96.1 kips/in. for a stiffness of 3.43×10^6 lb/in. This closely matches the measured stiffness of 3.33×10^6 lb/in. determined using a static hydraulic bore deflection gauge.

Component Fabrication

Rails and Insulators

The 75° rails were drawn to near-net shape as a single piece bar of Glidcop™ AL-60 dispersion strengthened copper by SCM Metals. The bore profile and coolant tube support slots were machined into the rail by SCM immediately after the drawing process. In the as built condition, this material provides a tensile yield strength of 72 ksi with an electrical conductivity of 78% IACS. After the drawing process, two full length 0.375 in. diameter brass coolant tubes were soldered into the support slots at the back of each rail.

The 105° bore insulators were fabricated as full length pultrusions of glass reinforced epoxy composite with both axial roving and bi-directional fiberglass cloth reinforcement. This configuration provides good axial strength and bending stiffness as well as resistance to abrasion and fiber "roll-up"

Laminations and Composite Overwrap

The 301 stainless steel support laminations were fabricated from half-hard sheet material. The initial profile was stamped into the sheets using an NC controlled punch press prior to the surface preparation and adhesive bonding operations. The stamped sheets were then bonded and cured as 2 in. thick assemblies and the rough profiles were cut from the sheets using a high pressure abrasive waterjet cutter. After rough cutting, the laminations assemblies were final machined and then assembled onto a full length internal mandrel for final bonding.

After final assembly onto the internal mandrel, the laminated support structure was mounted in a horizontal filament winding machine for fabrication of the composite overwrap. The low longitudinal bending stiffness and non-uniform cross section of the laminations assembly required an initial manual build-up of axial roving before the filament winding procedure could be completed.

EM Design and Analysis

In order to maximize the performance of the gun, several rail geometries and support concepts were evaluated using 2-D electromagnetic finite element analysis to predict structural and electromagnetic performance. The reduced rail angle (compared to the single shot barrel) and laminated support structure of the lightweight launcher contribute to a demonstrated inductance gradient of 0.49 $\mu\text{H/m}$. The inductance gradient and bore deflection figures have both been verified by direct measurement during laboratory testing of the launcher. This compares with an inductance gradient of 0.37 $\mu\text{H/m}$ for the Task B single shot launcher, which is reduced by the conductive boundary of the support structure[2].

Mechanical Design and Analysis

The laminated support structure is constructed of 0.048 in. (1.22 mm) thick 301 stainless steel sheet in the half-hard condition. In addition to the high elastic modulus of steels, in this

Breech Connection

The breech connection for the 90 mm laminated railgun is based on the design of the 90 mm single shot (Task B) railgun installed at CEM. The breech assembly consists of eight OFHC copper breech plates of alternating polarity separated by .25 in. thick Delrin insulators. Two additional copper plates provide the interface with 24 flexible hexapolar bus cables. The breech connection structural interface to the barrel is through a 2 in. thick stainless steel breech backing plate and collet type clamp to the outside diameter of the barrel.

Mount Structure and Recoil System

The barrel and breech connection are supported on a steel box tubing framework with a set of 11 linear bearings to allow for barrel motion against a set of two recoil buffers. Electromagnetic recoil forces appearing on the breech connection plates are reacted through two extensions from the stainless steel breech backing plate to a stationary I-beam recoil frame.

Because of space constraints in the EARC gun room, approximately 2 m of the barrel extends into the flight tube between the gun room and target chamber.

Hexapolar Cables

The breech connection was designed to accept 24 hexapolar cable assemblies from the solid state gun switch modules. Each hexapolar cable assembly consists of six transposed 83 MCM primary conductors, three of each polarity, with a central fiberglass core. Each primary conductor is insulated with a 0.070 in. thick layer of silicone rubber and the 7 cable bundle is wrapped in Mylar™ and support with a Kevlar™ overbraid. The entire cable assembly is overwrapped with a protective polychloroprene sheath. For the compulsator power supply, each cable is nominally rated for 140 kA, with each cable connecting two of the 48 gun switch modules to the gun breech.

In the EARC facility, current is carried from the capacitor bank modules to the breech connection through 16 independent hexapolar cables. This installation results a nominal current of in 175 kA for a non-staged 2.8 MA discharge. Higher energy shots, however, require time staging of the capacitor bank modules, resulting in much higher current per cable and significantly greater forces on the cable and connectors.

Railgun Assembly Procedures

Installation into the EARC Facility

The Electric Armaments Research Center (EARC) test facility is housed in building 717 at Picatinny Arsenal and was specifically designed to allow high energy testing of both EM and ETC launchers. The layout of the EARC facility is shown in figure 2[3].

The facility power supply consists of a 52 MJ capacitor bank designed for operation at 24 kV. The capacitor bank is divided into 16 modules, each rated at 3.25 MJ and capable of being independently triggered to provide current pulse shaping. Test instrumentation data acquisition and power supply control are performed from the RF/EM shielded "screen room". The gun room, flight tube and target chamber are designed to contain a 45 psi overpressure. The gun room and target chamber covers are removable to provide access for installation and removal of the test launcher and target plates. A launcher tie-down structure is mounted into the floor of the gun room, allowing reaction of the launcher recoil loads to ground. The flight tube is a 6 foot diameter steel cylinder with a 0.5 in. wall thickness. Orthogonal flash x-ray heads can be located at two stations down the length of the flight tube, with corresponding internal film supports and break wire triggers.

Figure 2. EARC facility layout

To allow inclusion of a coaxially mounted honing system into the gun chamber, the railgun was mounted with approximately 2 m of the barrel extending into the flight tube. Figure 3 is a photo of the railgun and support stand mounted in the EARC facility gun room

Bore Straightness

After the initial installation, the bore centerline straightness was measured by the Combat Systems Testing Activity (CSTA), using an optical telescope and backlighted bore target. Because of the horizontal arrangement and the cantilevered installation, the barrel exhibited significant deflections in the vertical plane. The vertical plane bore deflections were aggravated by the fact that the barrel orientation had been rotated 90° from the original design. The

Figure 3. Railgun installed at EARC

barrel low, the initial test projectiles were "slug" types with no payloads, overlapped with a fiberglass/epoxy composite winding to prevent separation of the armature during and after launch. Figure 4 is a picture of one of the overlapped test projectiles.

The first five shots of the test matrix were designed with currents increasing up to the peak rated current of 2.8 MA using overlapped projectiles and without time staging of the capacitor bank modules. In the second set of five tests, truncated tungsten rod payloads will be incorporated into the launch package. For the first two payload tests, the fiberglass overwrap will be included in the launch package; the filament wound overwrap would then be deleted from the balance of the projectiles.

Table II lists the parameters monitored during each test to evaluate the performance of the barrel and power supply. Audio and video records were also kept for each test. In addition to examination of the data collected during the tests, a complete visual and dimensional inspection of the bore was performed after each test to evaluate the condition of the dispersion strengthened copper rails and composite insulators and monitor the need for honing of the bore surfaces.

To date, six successful railgun tests have been performed, at peak currents up to 2.8 MA and muzzle energies of 3.0 MJ. Figure 5 is a summary of the current and velocity data traces collected during the test program. The railgun structure has been tested to a peak current of 2.8 MA, full rated current for a 9 MJ compulsator launch, demonstrating full performance bore pressure of approximately 54 ksi.

The gun has performed extremely well during the tests conducted so far, exhibiting no significant damage to the rails or insulators. After each discharge, the bore is cleaned with Scotchbrite™ pads to remove loose debris and a detailed video inspection of the bore is performed to evaluate the performance of the dispersion strengthened copper rails and fiberglass composite insulators. No honing operations have been required on the bore surfaces during the tests conducted to date.

non-uniform cross section of the composite overwrap leads to a higher longitudinal bending stiffness with the rails oriented in the 3:00 and the 9:00 positions. With this orientation and a horizontal honing system, such as the one in building 717, the weight of the honing head would be supported by the relatively soft insulator material. To prevent non-uniform material removal during honing, the barrel was oriented with the rails in the 12:00 and 6:00 positions.

To improve the barrel centerline profile, an additional muzzle support was installed in the flight tube and adjusted to limit the total bore centerline deflection to approximately 100 mils in the vertical plane. Testing and schedule constraints prevented further straightening efforts and repetition of the CSTA bore measurements after installation of the muzzle support.

Test Program

The original goal of the EARC railgun test program was to verify performance of the barrel to full rated current of 2.8 MA while the 9 MJ Range Gun System was completed. The EARC test program was to be conducted with minimum risk to the barrel to prevent delays to the field testing program at the Yuma Proving Grounds. The tests would also allow verification of the performance of the recoil management system, breech connection, and hexapolar cable bus system to be used in field tests of the 9 MJ Range Gun System.

Projectiles for the EARC test program are modifications of the SLEKE integrated launch package design used in the CEM-UT single shot (Task B) laboratory test program^[3]. To keep risks to the

Figure 4. Overwrapped "slug" projectile

Table II. Measured test parameters

Measured Quantity	Expected Peak	Time
Module Currents (16) (A)	1.80×10^5	16 ms
Breech Voltage (V)	3.50×10^3	16 ms
Breech Voltage (V) (high resolution)	2.00×10^3	16 ms
Muzzle Voltage (V)	9.00×10^2	16 ms
Muzzle Voltage (V) (high resolution)	1.00×10^2	16 ms
Gun Idot	9.00×10^9	16 ms
Gun Idot (high resolution)	6.00×10^9	16 ms
B-dots (13)	0.50	16 ms
Blast Pressure (4) (psi)	1.00×10^2	20 ms

Problems have been experienced during the test program. A hexapolar cable connector failure was experienced during EARC # 28, resulting in damage to two other connectors. There was no damage to the gun breech connection. Peak module (cable) current during the test was approximately 170 kA as measured by a capacitor bank module Rogowski coil. Interaction of currents in the hexapolar cable connectors with summed currents in the outer breech connection plates and between adjacent connectors resulted in significant lateral and axial forces on the transition conductors in the cable connectors.

In order to determine the cause of the failure, a detailed finite filament model of the cable connector and breech plates was constructed. The analysis revealed significant axial and lateral forces on conductors in the transition

Figure 5. Current and velocity profiles

region of the connector, primarily due to the large summation currents in the outer breech connection plates. Axial forces on the transition conductors tend to separate the strain relief boot and connector housing, resulting in failure of the threads in the glass filled nylon housing at the thread insert. Cracks extended from this region, propagated by the separation forces between polarities, and the twisting forces due to interaction with the large breech connection currents.

In order to complete repairs quickly and minimize delays to the test program, an external G-10 composite support structure was installed around the connectors at the breech connection. Figure 6 shows the cable connectors and support structure installed on the gun breech.

Figure 6. Gun breech and cable connectors

One of the goals of the EARC test program was to verify the performance of the gun and bus system components, identifying and correcting any problems to prevent unnecessary delays to the range test program at Yuma. Discovery of the problems with the cable connectors during the lab testing allows redesign of the connector geometry and materials to prevent delays and problems with future tests.

During EARC #31, a breakdown in the breech insulation system was experienced, resulting in minor arc damage to the rails and breech support structure. There was also secondary arc damage to the gun recoil management system components.

Figure 7. Simulated current profiles

Table III. Proposed test plan

Shot	$I_{\max}^{\dagger}$ (kA)	Mass (kg)	Charge Voltage (V)	Vel †† (m/s)	Action ($A^2 \cdot s \times 10^{10}$)	KE (MJ)	Exit (ms)	I_{exit} (kA)
7	1.6	3.2	12,000	784	1.17	0.785	12.4	180
8	1.8	4.1	14,000	841	1.57	1.45	11.8	253
9	2.2	4.1	16,000	1,065	1.95	2.32	9.9	367
10	2.6	4.1	20,000	1,488	2.68	4.54	7.7	594
11	2.9	4.1	24,000	1,927	3.44	7.6	6.4	978
12	3.0	2.8	24,000	2,466	3.0	8.5	5.4	1,250

† velocity dependent armature voltage model used:

0 to 1000 m/s: $V = 40 + L \cdot \dot{I} + I \cdot R$ 1000 to 1500 m/s: 400 V ramp 1500 and up: $V = 400$

†† includes friction: $F_f = F_{\text{nd}}$ $\mu_d = \mu_s V^{-0.4}$ $\mu_s = 0.3$

CEM-UT personnel traveled to Picatinny to evaluate the test data and procedures and perform the initial disassembly and inspection of the breech connection. After disassembly was complete and the extent of the damage evident, the barrel and breech connection were returned to Austin for repair.

Examination of the rail/breech interface and breech connection support structure indicated that the insulation around the rail coolant tubes had been compromised by plasma jetting from the rail/breech plate interface during EARC #30. A breakdown in the preshot checklist procedures at EARC allowed the next test to be performed without a pre-shot hi-pot test of the gun and breech connection. On the subsequent test, conductive plasma spitting from the rail/breech interface seeded an arc breakdown between the coolant tube (rail voltage) and breech backing plate (ground). After the initial arc, the conductive plasma cloud seeded several secondary arcs between polarities and to ground potential structures, resulting in minor damage to surrounding structures.

A detailed finite element model of the rail/breech interface was performed to evaluate the performance of the interface pre-loading wedges. Repairs to the insulation system are underway, including modifications to the rail/breech plate preloading wedges, removal of the rail coolant tubes, repair of the FEP sleeve insulator, and an additional insulating coating on the breech plates.

Current Status and Test Schedule

The railgun is currently in Austin for repairs to the breech insulation systems. After repairs are completed in June 1995 the barrel will be returned to the EARC facility for continued testing. The test program will continue through August 1995, starting with low level "check-out" shots before completion of the remaining shots of the test program. If schedule and budget constraints allow, a final test to 8+ MJ is planned. The test plan is summarized in table III. Predicted current waveforms are shown in figure 7.

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