INSTALLATION AND COMMISSIONING OF A HIGH L' LAMINATED RAILGUN

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Installation and Commissioning of the 9 MJ Range Gun System 90 mm High L' Laminated Railgun

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Abstract—In December 1993, The University of Texas at Austin Center of Electromechanics (UT-CEM) 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 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 initial 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.

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 of 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 1 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 compulsator current pulses with a peak current of 3.2 MA and a total action of $3 \times 10^{10} \text{ A}^2\text{-s}$ per shot. The lightweight barrel has a 7.2 m active length (7.7 m overall) with a nominal 32.5 cm outside diameter, and weighs approximately 3,300 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. Fig. 1 shows an isometric section of the lightweight laminated barrel with the major components identified.

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	0.28	3,295
Single Shot Gun	10	3.4	0.08	32,300

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Fig. 1. Range gun structure

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.

EM DESIGN AND ANALYSIS

In order to maximize the performance of the gun, several rail geometries and support concepts were evaluated using an ABAQUS® 2-D finite element model 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 $\mu\text{H}/\text{m}$. 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 $\mu\text{H}/\text{m}$ 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 its high elastic modulus, in this 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 analyzed in ABAQUS® using a detailed 2-D structural finite element model. The rail separation force of 96.1 kips/in. at 3.2 MA peak current calculated by the ABAQUS® electromagnetic finite element model was used as the input to the structural analysis 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 in 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.

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 UT-CEM. The breech assembly consists of eight OFHC copper breech plates of alternating polarity separated by 0.25 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 seven 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.

This installation results in a nominal current of 175 kA for a non-staged 2.8 MA discharge. Higher energy shots,

Fig. 2. EARC facility layout

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.

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 Fig. 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. In the EARC facility, current is carried from each of the 16 capacitor bank modules to transition blocks via conventional coaxial cables. Due to non-uniform current distributions seen during initial testing, the transition blocks were linked to form a common voltage node. Current then flows from the common voltage node to the railgun breech connection through 16 hexapolar cables.

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 ft 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.

To allow inclusion of a coaxially mounted honing system into the gun chamber, the railgun was mounted with approxi-

Fig. 3. Railgun installed at EARC

mately 2 m of the barrel extending into the flight tube. Fig. 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 non-uniform cross section of the composite overwrap leads to a higher longitudinal bending stiffness with the rails oriented in horizontal plane. 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 a vertical plane.

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. This measurement was made with a Taylor-Hobson optical alignment telescope by CEM personnel. Testing and schedule constraints prevented further straightening efforts and repetition of the CSTA bore measurements after installation of the muzzle support.

Fig. 4. Overwrapped "slug" projectile

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 barrel low, the initial test projectiles were "slug" types with no payloads, overwrapped with a fiberglass/epoxy composite winding to prevent separation of the armature halves during and after launch. Fig. 4 is a picture of one of the overwrapped 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 overwrapped projectiles and without time staging of the capacitor bank modules. The original test plan was modified to incorporate truncated tungsten rod payloads into the launch package. For the first two payload tests, the fiberglass overwrap was included in the launch package; the filament-wound overwrap would then be deleted from the balance of the projectiles.

Table II. EARC monitored parameters

Measured Quantity	Expected	Peak
Module currents (16) (A)	1.80×10^5	16 ms
Breech voltage (V)	3.50×10^3	16 ms
Breech voltage (V) (high resolution)	$20. \times 10^3$	16 ms
Muzzle voltage (V)	9.00×10^2	16 ms
Muzzle voltage (V) (high resolution)	1.00×10^2	16 ms
Gun I-dot	9.00×10^9	16 ms
Gun I-dot (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

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.

Fig. 5 is a summary of the current and velocity data traces collected during EARC shots 27 through 30. Current and velocity traces collected during the test program closely match the predicted performance of the railgun and power supply using ARMS, the Army Railgun Modular Simulator [4]. To date, the railgun structure has been tested to a peak current of 2.8 MA, full rated current for a 9 MJ compulsator launcher, 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.

Problems have been experienced during the test program. A hexapolar cable connector failure was experienced during EARC #27, 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 region of the connector, primarily due to the large summation currents in the

Fig. 5. Current and velocity profiles

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Fig. 6. Gun breech and cable connectors

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. Fig. 6 shows the cable connectors and support structure installed on the gun breech.

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 allowed 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.

UT-CEM 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 structures indicated that the insulation around the rail coolant tubes may have been compromised by plasma jetting from the rail/breech plate interface. During the 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 plate interface was constructed in ABAQUS® to evaluate the performance of the wedges responsible for preloading of the rail/breech interface. The analysis revealed a non-uniform pressure distribution across the rail/breech plate interface which may have contributed to the plasma spitting during the fault. The rail profile was modified to improve the interface pressure distribution.

Repairs to the breech connection have been completed, 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

All repairs to the railgun breech connection have been completed and the launcher was reinstalled in the EARC facility at Picatinny Arsenal, New Jersey during July 1995.

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