EM MORTAR TECHNOLOGY DEVELOPMENT FOR INDIRECT FIRE

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ABSTRACT

The DARPA Electromagnetic (EM) Mortar Laboratory Demonstration Program is a focused development and demonstration effort for an EM gun system for vehicle-based, non-line-of-sight, artillery applications. EM launch is a transformational technology, which, when applied to gun-launched munitions, will have a revolutionary impact on warfighter capabilities and logistics burden. EM gun capability includes: elimination of propellant, improved precision, increased muzzle velocity, extended range, and enhanced lethality. These key goals toward EM gun development for military applications are being addressed by the EM Mortar project: to demonstrate the ability to launch conventional munitions (M-934, 120-mm mortar) with minimal impact to lethality, manufacturability, and logistics support; to demonstrate launch velocity of 420 m/s; to provide enhanced range for the M-934. Range improvement of 30% (from 7 km to 9 km) is predicted. Two of the major types of EM launch technology are being developed in this program, a railgun and a coilgun. Both railgun and coilgun EM Mortar variants have been designed and are in fabrication. With these development goals for the specific next-generation Future Combat System (FCS) Manned Ground Vehicle (MGV) Non Line-of-Sight (NLOS-M) application, the program can establish early systems solutions for next phase implementation and integration onto prototype platform demonstrations. Modified M-934 mortar rounds have been designed and fabricated for both coilgun and railgun designs. Using the integrated launch package as the starting point, complete EM gun launcher designs have been completed, and both guns are in fabrication. Initial testing will begin in late 2006. This paper will report on the design, fabrication, and testing for the railgun, coilgun, and mortar rounds.

1. INTRODUCTION

EM launch technology holds the promise of high-velocity, high-precision, electric-powered (no propellant hazard) guns for future military capability. EM launch technology has been in development for over two decades, and significant advances have been made in barrels, power sources, controls, and lifetime and reliability. The EM Mortar application is an important early step toward broad application of EM weaponry. The EM Mortar addresses an important improvement in a widely used family of weaponry and can be achieved by a near-term technology spiral. Taking advantage of these improvements, our program is aimed at a demonstration of EM gun capability that could be quickly matured into a prototype integrated platform. Two EM gun types have been designed in this project: a four-rail isolated railgun design and a coilgun design. The augmented railgun has a simplified pulsed-power requirement, with a nominal current level of about 1.8 MA through a four-rail augmented configuration. The coilgun is an inductively coupled gun (with about 75 KA in each coil stage) with sequentially pulsed stages. Armatures for each of these guns have been designed for

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integrated launch packages, with M-934 mortar training rounds for laboratory demonstrations.

This program has spawned an effort to generate preliminary integrated platform concepts. The combination of an EM Mortar weapon module on a hybrid-electric platform has several synergistic features. First, the hybrid electric propulsion power system would offer an on-board power unit for load management of 500 KW for dual use between propulsion and the weapon module. Second, the elimination of on-board propellant and elimination of unused propellant cartridge stowage introduces a significant operational safety feature. Third, the EM Mortar lends itself well to a fully automated loader, with potential for crew-size reduction. Technical challenges are maintaining capability within weight, volume, and power restrictions. A number of design innovations have been made to meet these challenges. Thus, the EM Mortar, particularly designed toward implementation for the FCS NLOS M mission, is a worthy development path to explore the potential and challenges for EM gun introduction to the warfighter.

2. BENEFITS TO THE WARFIGHTER

Many operational and logistics advances are anticipated for the EM Mortar. Improved lethality is derived from enhanced precision that in turn comes from enhanced velocity control. Velocity error is predicted to be less than 0.1% from the EM gun. The small velocity error is due to feedback control of the power input to the launcher and elimination of propellant variability. Infinite zoning/range adjustment comes from precise velocity control. Improvement in velocity control and zoning flexibility allows a three-fold improvement in stowed kill capability and a commensurate increase in the number of rounds available for the Multi-Round, Simultaneous Impact (MRSI) fire missions. Improved survivability derives from the low-signature nature of the EM launch. Since there is no propellant, the thermal signature and acoustic signatures are greatly reduced. Added to the first-round kill capability of the EM Mortar, total surprise fire missions are possible. Range extension for indirect artillery fire comes from the higher muzzle velocity available from EM launchers. Range extension and larger battlefield coverage leads to increased lethality. Soft-launch capability (tailored acceleration profile) from the EM gun is also important for indirect fire, extended-range, guided projectiles. Eliminating on-board propellant and the need for stowing unused propellant cartridges introduces a significant operational safety feature. Also, the EM Mortar approach enables the ammunition handling system to be fully automated. Elimination of propellant reduces the logistics volume for hazardous materials for shipment, handling, and waste management. This also leads to the added advantage of eliminating the propellant manufacturing process for mortar propellant, a significant Life Cycle Cost reduction over current and planned systems.

3. EM MORTAR LABORATORY DEMONSTRATIONS

3.1 Demonstration Program

The DARPA EM Mortar Laboratory Demonstration Program is a focused development and demonstration effort to address the following key goals toward EM gun development for military applications:

a. Demonstrate the ability to launch conventional munitions with minimal impact to lethality, manufacturability, and logistics support. The M-934, 120-mm mortar, is the test round of choice. The U.S. Army Armament Research, Development, and Engineering Center (ARDEC) at Picatinny Arsenal leads the munitions adaptation effort.
b. Demonstrate launch velocity to provide enhanced range for the M-934. Range improvement of 30% (from 7 km to 9 km) is expected with muzzle velocity of 420 m/s.
c. Design and fabricate EM guns to launch the M-934 round to 420 m/s. Both railgun and coilgun variants have been designed and are in fabrication. Railgun design, fabrication, and testing are the responsibility of the Institute for Advanced Technology at the University of Texas, Austin. Coilgun design, fabrication, and testing are the responsibility of Sandia National Laboratories.
d. The railgun and coilgun test plans include demonstration of 420-m/s muzzle velocity, velocity control goal within 0.1%, extended shot lifetime, and conducting 100 shot test series to evaluate reliability and accuracy parameters.

The program is now in the gun fabrication phase, with full-scale laboratory testing to start in the fall of 2006. Coilgun mortar testing will be conducted at Sandia National Laboratories, and railgun testing will be conducted at the Institute for Advanced Technology. Both guns will use specially designed M-934 mortar training rounds. Testing with the full-scale EM mortar rounds will be conducted to the maximum velocity of 420 m/s. The railgun and coilgun barrels are designed for an elevating gun mount, so that these barrels can be readily adapted from the laboratory to the range test conditions.

3.2 EM Mortar Round Adaptation

The design effort for the mortar round integration was led by the Future Munitions Branch, Armament Research, Development and Engineering Center at Picatinny Arsenal. Figure 1 shows the concept for the EM Mortar integrated launch package. The mortar concept of operations requires organic fire support for infantry; thus, the mortar would be firing near and embedded with friendly forces. Due to overhead safety requirements, the armature is designed to be non-separating and is thus an integral part of the round. To this end, the design of the integrated launch package is the starting point for the design for both the railgun and coilgun mortars. The 120-mm M-934 mortar round is taken as the baseline munition. Armature designs for each EM gun were developed with the gun teams, and the resultant integrated designs were required to meet aerodynamic drag, aerodynamic stability, mass, mass balance, and operational handling requirements. Wind-tunnel testing verified the drag and stability performance predictions, and electronic fuze pulsing tests verified fuze functionality. The armature and tail fin are attached to the munition as an EM-adapted tail kit which is fully compatible with present off-the-shelf M-934 muntions. The integration process has been examined to minimize logistics impact. A simple screw-off removal of the M-934 tailboom and screw-on of the “EM kit” transforms the conventional munition into an electromagnetic-launched munition. EM-934 test rounds are now being fabricated for both railgun and coilgun testing.

Fig. 1. Mortar round is adapted to the EM launch environment with a conformal armature tail kit.

3.3 Coilgun-Based EM Mortar Design

Coilgun technology has been developed over a number of years at Sandia National Laboratories and elsewhere for applications such as long-range guns and mass launchers. The coilgun consists of short, solenoidal electromagnets that are stacked end to end to form a barrel as shown in Figure 2. The coils are energized sequentially to create a wave of magnetic energy moving from breech to muzzle. This transient wave generates an induced current in a movable armature coil attached to the launched projectile. The induced current and barrel coil’s magnetic field generates Lorentz forces that accelerate and compress the armature. Likewise, the windings of the barrel coil sustain a large radial and reaction axial force.

Each of the coils shown in Figure 2 is energized by its own capacitor bank. This is shown schematically in Figure 3 for three coils. To create the traveling magnetic wave in the barrel that is synchronous with the location of the armature, a real-time detector locates the projectile; the gun firing system generates the trigger to the main closing switches of the individual banks. Since each bank’s stored energy is adjustable, the launch acceleration can be tailored to the needs of the projectile. A uniform acceleration profile, near the projectile’s maximum permitted level, yields the desired muzzle velocity with the shortest length gun. The coilgun projectile has no electrical contact with the barrel, since energy is coupled inductively to the moving armature. The forces within the coil are such that the armature tends to be self-centered within the launch barrel. Since there is minimum surface contact between the barrel and armature/projectile, barrel wear is minimized.

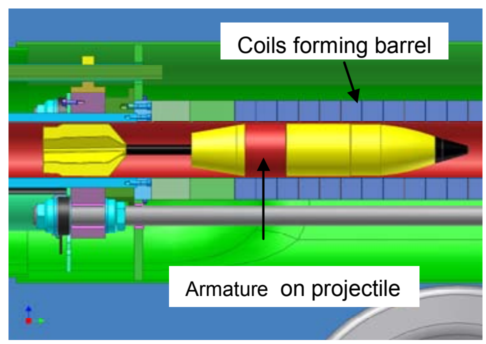


Fig. 2. Short coils stacked end-to-end around a boretube that contains the projectile. Currents induced in the armature on the projectile from the sequentially fired coils generate thrust.

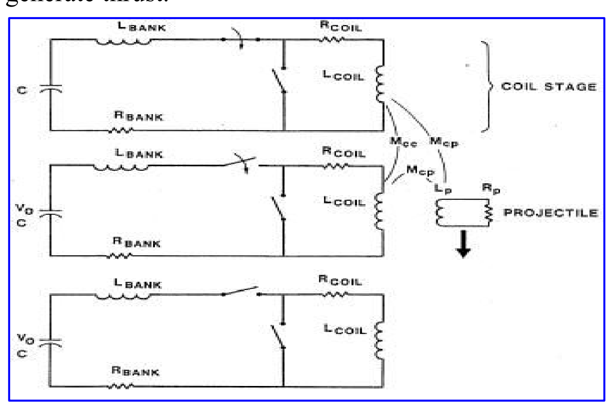


Fig. 3. Illustration of the coilgun pulsed-power circuit, showing triggered capacitor modules connected to drive coils. Inductive coupling from the drive coils to the armature provides the propulsion force.

High launch pressure (equivalent to 1000 atmospheres in a conventional propellant gun) can be maintained uniformly over the entire length of the gun barrel, and the resulting uniform acceleration allows high velocities to be achieved with a short barrel. In a coilgun, this pressure is withstood by copper windings embedded in high-strength composite structure in the coils.

Precision fire-control is achieved via an active controller with input from projectile position sensors and command-triggered switches in the capacitor bank module. Projectile position information is processed in real time to determine the optimum time to fire each successive module. A number of options are available for the position-sensing diagnostics, including light-beam breaks, proximity sensors in the barrel, and optical or radio-frequency (RF) rangers. The present mortar design uses a 94 GHz radar system for velocity and position measurement integrated into a real-time, fire-control system.

Simulation of gun performance has been done with our lumped-parameter circuit code, Slingshot, based on the circuit representation shown in Figure 3, using the detailed geometry of the coil and projectile. The code self-consistently solves for currents in coils and the armature through a system of mesh equations with parameters that are position and temperature dependent. Forces are based on mutual inductance gradients, and temperature-dependent resistances are self-consistent with Ohmic heating and material properties (Marder, 2001). Performance simulation of a 45-stage coilgun is shown in Figure 4 launching a 18-kg, 120-mm projectile to 424 m/s. The 1.6 MJ kinetic energy at the muzzle is 22% of the initial stored electrical energy, and the launch time is 14 ms in the 2.1 m acceleration length.

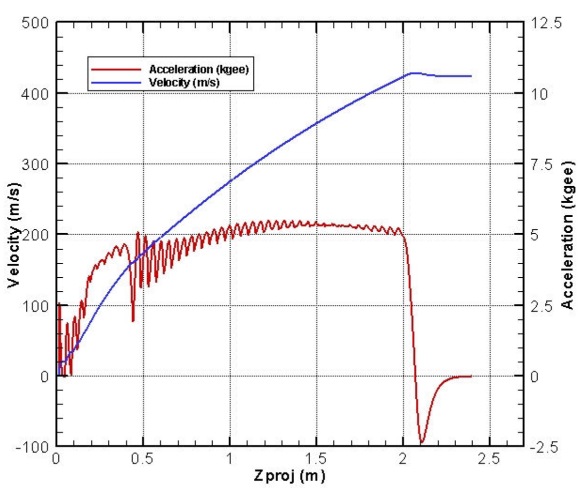


Fig. 4. Velocity and acceleration calculations for launch of 18-kg, 120-mm projectile from the 45-stage coilgun.

Each coil of the gun has 15 turns (42 uH, 10 mOhm) and is energized sequentially from its own capacitor bank. The stored energy of each stage is on the order of 160 kJ. This energy is larger than would be needed in a gun on a vehicle, since the banks in this laboratory test are up to 100 feet from the gun due to limited floor space. As all coils in this gun are identical, the capacitance and voltage of the capacitor banks are adjusted [8.5 mF at stage 1 (breech) to 0.8 mF at stage 45] such that the current risetime is consistent with the transit time of the armature through a given coil. That capacitance with the required stored energy results in bank voltages ranging from 6 kV at the breech to 20 kV at the muzzle, and the banks deliver current pulses ranging from 65 to 95 kA to the coils.

3.4 Status of Coilgun Laboratory Demonstration

Major components of the EM Mortar coilgun for laboratory demonstration are shown in Figure 5. The M-934 round has been configured with a conducting armature and support structure and is currently in fabrication. Simple low-cost, mass-equivalent slugs have also been designed for initial testing. Both type rounds will be fired at close range into a steel catchbox where they will be fragmented. Camera diagnostics will verify the integrity of the rounds during this short flight.

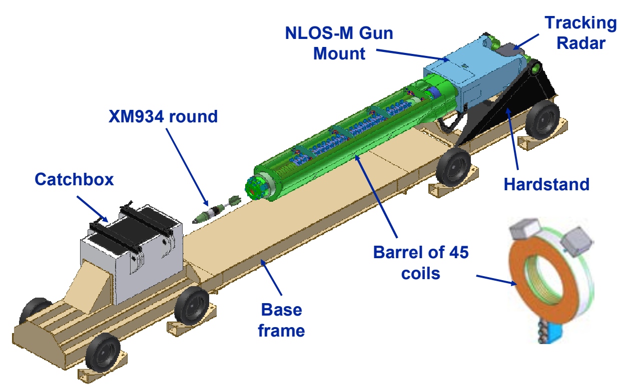


Fig. 5. Coilgun mounted on an FCS-type gun mount, with bullet catch-tank for the laboratory test.

The coilgun barrel is a space-frame that aligns and axially compresses the individual coils over a thin-wall fiberglass boretube. This barrel frame is coupled into the gun mount that is the same size as used in the Future Combat System (FCS) NLOS-M vehicle. The mount contains the recoil system and is capable of elevating the gun for future field demonstrations of projectile range capability. Also located in the mount is the 94 GHz Doppler radar that senses the projectile during launch for controlled firing of the individual coils. The hardstand and baseframe are coupled to conserve the momentum of gun's and catcher's recoil.

All gun components are in procurement or fabrication at this time. Coils for the gun are being tested in a separate fixture with a static projectile at operational stress levels. The projectile-sensing radar has demonstrated excellent signal return from the projectile in the 120-mm boretube and is currently being tested with the fire control system on a 50-mm, four-stage coilgun. Gun mount, hardstand, baseframe, and catcher are complete. Capacitor bank assembly is in progress, concurrent with testing of the prototype modules with the gun's power supply and control system. Gun testing will follow assembly of the pre-tested coils in the gun structure.

3.5 Railgun-based EM Mortar Design

Railguns are perhaps the simplest form of EM launcher. In the simplest form, current is conducted down a fixed conductor (rail), through a moveable projectile (armature), and returns through another fixed conductor. The interaction between the current flowing through the armature and the magnetic field generated by the current in the rails results in a Lorentz force that acts on the armature and accelerates along the rails. A sketch of this interaction is shown in Figure 6.

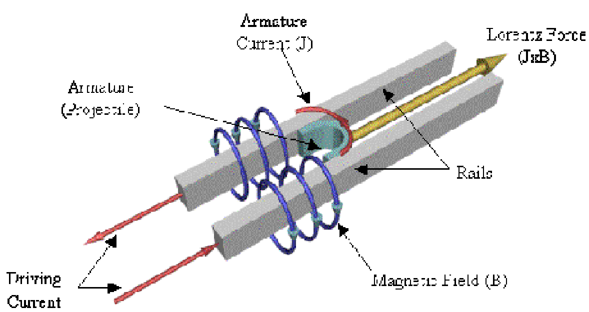


Fig. 6. Sketch of basic railgun operation.

Research on railguns has been actively pursued in the United States since the late 1970s. Early efforts focused on launching small projectiles to very high velocities (5-15 km/s) for strategic defense applications. In the mid 1990s, the bulk of the research efforts switched to developing high-velocity (2-3 km/s), moderate-mass (1-3 kg) launchers that would provide an improved capability in the direct line-of-sight applications. This research continues to be the primary goal of current U.S. Army programs. The U.S. Navy has recently initiated a program to develop high-velocity (2-3 km/s), heavy-projectile (15-20 kg) launchers for very long-range, non-line-of-sight applications.

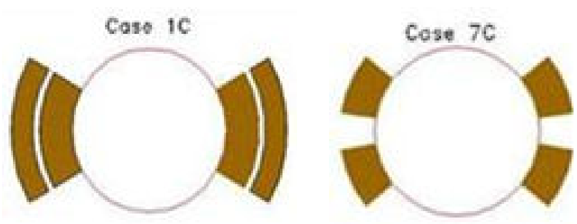
The Institute for Advanced Technologies (IAT), an Army University Affiliated Research Center (UARC), is a key U.S. institute for basic and applied research into high-velocity EM launch. IAT's experimental Electromagnetic Launch Facility (ELF) houses an 18-MJ pulsed-power supply and three separate gun lines that are capable of testing railgun configurations that can generate 1-3 MJ of kinetic energy in the projectile. The ELF has been in operation since 1995 and has performed over 1,000 railgun launches for a wide variety of military and government sponsors. Figure 7 shows the ELF with several of the pulsed-power supply modules in the background and two of the three gun lines in the foreground.

Figure 7. The IAT's Electromagnetic Launch Facility.

During the initial trade-study phase of this program, a wide variety of railgun configurations were evaluated against criteria that would ensure that a laboratory demonstration of the system could be achieved within the project timeframe and resources. The study's most stringent requirements were based on the requirement to utilize the existing pulsed-power system already in existence at the ELF.

At the end of the trade study, two basic configurations were considered. The first was a series-connected, two-turn augmented configuration as shown in Figure 8a. In this geometry, the inner rails are the connection to the armature while the outer (augmenting) rails form a separate loop extending to the end of the launcher. These loops are connected in series by a crossover at the breech. In this fashion, the magnetic field in the bore is increased by adding the augmenting current. In the trade-study analysis, this configuration met all of the operational requirements; but, 3D EM analysis indicated that the projectile body would be exposed to very high magnetic fields (~ 7T) due to the augmenting fields. This option was therefore removed from consideration.

The second was a series-connected two-turn isolated configuration as shown in Figure 8b. In the isolated configuration, the top and bottom rail pairs are each a separate, two-rail railgun. A crossover at the breech connects the pair in series. Again, this geometry met all of the operational requirements but had low magnetic fields in the region of projectile fuze. However, the nature of the geometry requires voltage isolation between the top and bottom rails, as well as the top and bottom armatures. During the preliminary design review, it was determined that the potential issues associated with the high magnetic fields at the fuze location were not likely to be feasible in a tactical system; therefore, the two-turn isolated configuration became the baseline geometry.



a. Series connected two-turn augmented configuration.

b. Series connected two-turn isolated configuration.

Figure 8. Two basic configurations considered for railgun design.

The project was divided into three operational phases. First, a subscale set of experiments were performed to demonstrate the feasibility of the isolated configuration and the integration of the isolated armatures onto the rear taper of the mortar body. Second, a full-scale laboratory system has been designed and installed in the ELF to demonstrate full-scale operational performance. Third, a gun structure capable of being cantilevered and elevated is being fabricated to demonstrate the launcher performance in configuration that more closely matches tactical operation.

Subscale testing of a two-turn, isolated configuration in a 40-mm square bore geometry has demonstrated high-inductance gradient operation at velocities and accelerations of interest. Isolated two-armature projectiles have been demonstrated in simple 54-mm round bore railgun configurations. These two demonstrations provide significant confidence in the design and modeling tools used for the full-scale 120-mm design.

The full-scale laboratory system consists of a breech system that is capable of handling a peak current of 3 MA, as well as the nearly 400,000 pounds of accelerating loads generated during acceleration of the full-scale projectile. A launcher containment system that is easy to disassemble and rests on an I-beam structure has been fabricated and will be utilized to evaluate the performance of the chosen bore geometry and materials, as well as the full-scale projectile.

The cantilevered railgun containment, typically referred to as the range barrel, is designed to act as a lightweight replacement of the laboratory containment. The exact same railgun core can be used for both demonstrations in the laboratory configuration and within the range barrel. This will minimize the new variables that are introduced during testing of the cantilevered assembly. The range barrel will be fabricated from metallic components in such a manner that the core components can be removed and replaced, if necessary. Even though the range containment is designed for cantilevered and elevated operation, it will be tested in this program in the horizontal position mounted in the laboratory breech. Figure 9 shows a model of the range barrel and railgun core components in the laboratory breech.

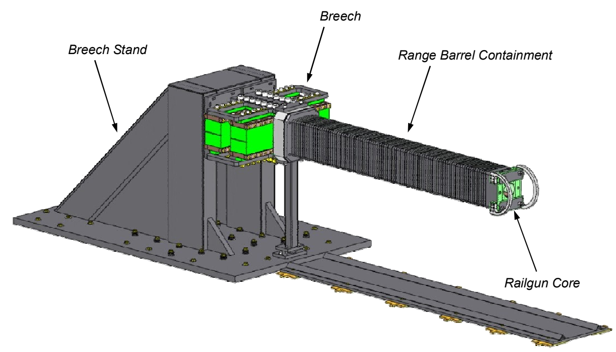


Figure 9. Model of railgun EM Mortar range containment in laboratory breech.

Performance simulations of the full-scale system utilizing validated models of the ELF pulsed-power system and railgun models based on extensive transient 3D simulations of the railgun geometry have been performed. The required demonstration parameters of an exit velocity of 420 m/s are achieved in an acceleration time of around 7 ms and an acceleration length of just over 2 meters. The basic kinematic variables for the anticipated launch are shown in Figure 10.

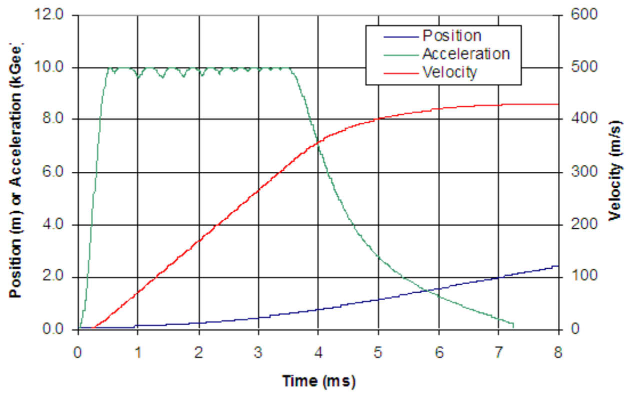


Figure 10. Performance parameters from simulations.

4. FUTURE STEPS FOR TECHNOLOGY MATURATION AND SYSTEM DEVELOPMENT

The focus of this demonstration has been the achievable near-term goals listed above. Additional steps for follow-on development and demonstrations are required.

The present laboratory EM guns (railgun and coilgun) under construction are designed with an elevating gun mount, thus allowing the gun to be elevated for down-range ballistic testing. Both guns are transportable and can be integrated into a field test environment. Future steps include advanced development to gain field experience with the prototype guns in a range test environment, such as the Yuma Proving Ground. Such range testing would meet the following objectives: gain realistic environmental test conditions for EM non-line-of-sight artillery; test the guns under real-world conditions; evaluate muzzle separation effects, such as tip-off, barrel braking, and muzzle flash, in live-fire conditions; gain troop experience with EM gun operations; measure projectile ballistic characteristics, trajectory dispersion, and range zoning; demonstrate a second-generation power system based on high-energy density power source, using advanced capacitor technology, which is also under development.

Further steps would be to design a weapon system prototype and integrate it into a vehicle demonstrator. Also, range extension beyond 10 km can be achieved with muzzle velocity around 460 m/s. Prototype demonstration of the weapon system would function on a hybrid-electric platform, powered by the platform prime power, with thermal management integral to the platform. The weapon system would include an automated loading system, a man-in-the-loop automated fire control system, and electromagnetic interference (EMI) qualification.

5. SUMMARY

The EM Mortar demonstration program has completed the design phase for the EM-934 round, the coilgun, and the railgun launchers. Subscale testing has been successfully completed, which validated key design decisions and studied scaling challenges. Launchers and test rounds are in fabrication, and launcher assembly is starting in August, 2006. The analyses thus far indicate that the EM Mortar concept is feasible, can be integrated onto a hybrid-electric platform, and can provide enhanced capability for the warfighter. Testing will commence in October and the project milestones for launching conventional munitions with EM guns will be completed in early 2007.

ACKNOWLEDGEMENT

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