Recent Activities in Electro-Thermal Chemical Launcher Technologies at BAE Systems

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Abstract— The three-year Line of Sight/Beyond Line of Sight (LOS/BLOS) electro-thermal chemical (ETC) launcher program, funded by US Army ARDEC, Picatinny Arsenal, is a comprehensive effort to advance ETC launcher technologies. The program includes development of ETC plasma injectors for 120 mm M829A2s, build of a 100 kJ pulsed power supply small and robust enough to be realistically integrated into a combat vehicle, improvement of power connections to the gun to allow electromagnetic field containment and automated connection to the round, and tests of the completed ETC system with various chemical propellants and electrical energy levels.

As part of the LOS/BLOS program, a new, coaxial version of BAE Systems' Basepad plasma injector has been developed and tested successfully in XM36, XM291, and M256 cannons. The Basepad's coaxial design effectively insulates the gun breech, thus preventing any part of the gun from being part of the high voltage discharge circuit. A compact electro-thermal ignition pulsed power supply (ETIPPS) has been designed, built, and tested. Including its own high-voltage charger, actuation circuitry, safety systems, and peripherals, ETIPPS' low weight and volume make it easily small enough for vehicle integration, as was demonstrated in a concurrent effort that included ETC firings from a combat vehicle.

Test firings, currently ongoing, have validated the system architecture and performance and continue to supply data on performance at different temperatures, electrical energy levels, propellant loading, and propellant type. These tests demonstrate many of the benefits of ETC launchers, including: improved accuracy from precision ignition; maximum performance

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potential across all temperatures ranges (temperature compensation); and reliable ignition of new, high-energy, high-density, and in some cases low-vulnerability propellants. The system-wide approach of the LOS/BLOS electro-thermal launcher program has advanced ETC technology significantly towards field readiness.

I. INTRODUCTION

The goal of the LOS/BLOS contract is to further the maturation of ETC propulsion through advancements in pulsed power supply design, plasma injector design, tests at reduced energy level, and incorporation of reduced-size components. This section provides an introduction to ETC propulsion and its benefits in large-caliber cannons.

Electro-Thermal Chemical Propulsion

ETC propulsion is an alternative to conventional methods of firing large-caliber cannon ammunition. In conventional ignition, a relatively low-powered electrical discharge sets off a primer cap that burns a small powder charge within an ignition cartridge, in turn triggering the combustion of surrounding chemical propellant in the round. This sequence of cascaded chemical reactions can take as long as 30 milliseconds to effect projectile motion, with a significant variation in launch times. Consequently, accuracy, particularly when the gun barrel is vibrating due to vehicle motion, is detrimentally affected.

In ETC ignition, the conventional ignition components are replaced with a plasma injector as shown in Fig. 1. The plasma injector houses a bridge wire attached between two electrodes. When a high-current, high-voltage pulse is applied, the bridge wire initiates a high-temperature plasma discharge that vents into the surrounding chemical propellant. The electrically conductive plasma transfers energy into the propellant, initiating its combustion much more quickly and repeatably than does conventional ignition.

(a)

(b)

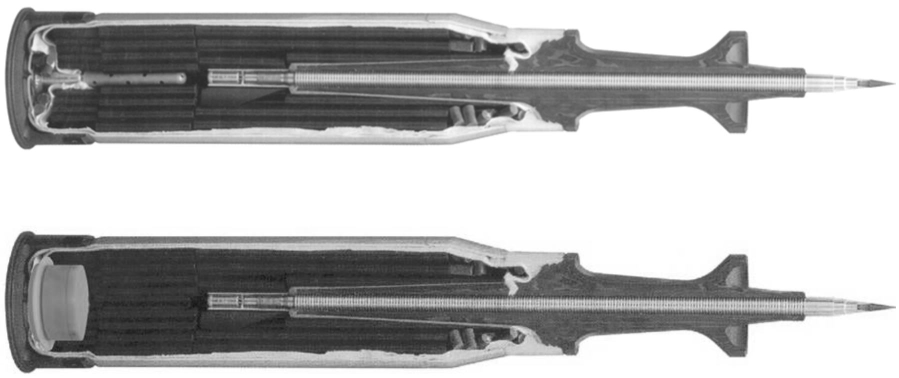

Fig. 1. Conventional 120 mm M829A2 round: (a) with M129 primer; (b) with coaxial plasma injector.

Benefits of ETC

ETC presents several benefits over the performance achieved with conventional primers, the most significant of which is precision ignition/improved accuracy. Fig. 2 presents chamber pressure vs. time data (which corresponds to initiation of projectile motion within the gun barrel) for 11 conventional 120 mm gun firings compared with 10 ETC 120 mm firings. The pressure initiation in the conventional shots, at the right hand side of Fig. 2, spread randomly between 21 and 30 milliseconds. The ETC shots, at the left hand side of the graph, overlay one another and all begin at the 2 millisecond mark. The electrical energy transferred from the pulsed power supply in the ETC firings was 85 kJ [1].

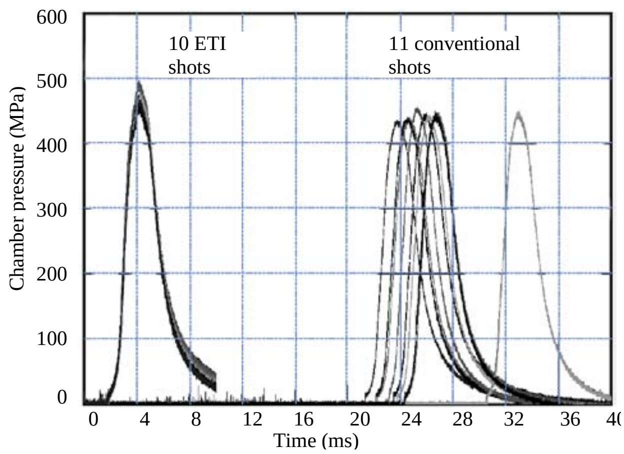

Fig. 2. 11 conventional gunshot pressure traces (at right) and 10 ETC pressure traces (at left), demonstrating the repeatability of ETC versus the relatively random initiation obtained with conventional ignition.

The precision ignition provided by ETC, when coupled with additional technologies such as a dynamic muzzle positioning system, can lead to remarkable improvements in weapon accuracy and effectiveness.

The performance (represented by velocity) of conventional ammunition degrades as a function of decreasing temperature. ETC propulsion provides compensation for this loss in performance by increasing the electrical energy delivered to the round at decreasing temperatures. Fig. 3 illustrates ETC temperature compensation in which "hot" (best) velocities were achieved with ETC even at low temperatures, while the velocity with conventional ignition decreases with decreased temperature.

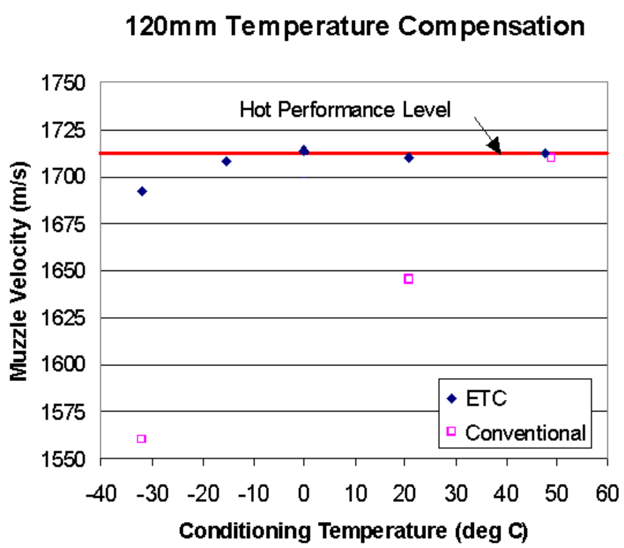

Fig. 3. ETC provides "hot round" velocity across a broad range of temperatures, while conventional round velocity decreases with decreased temperature.

The term electro-thermal ignition (ETI) is sometimes used to refer to ETC at energy levels of less than 100 kJ. ETI provides the same benefits as higher energy ETC, with the exception of thermal compensation for certain propellants, for which levels of 300 kJ or more are required. However, ETI offers precision ignition in a smaller and lighter package, suitable for vehicle integration.

II. ETIPPS I

In the past few years, ETC/ETI research has shown that precision ignition of 120 mm rounds can be achieved with energy levels of less than 100 kJ. This reduced energy level, coupled with advances in high-energy capacitors and other high-voltage components, has made possible the design and build of an ETI pulsed power supply small enough to be integrated onto a combat vehicle [2],[3].

System Overview

Electro-Thermal Ignition Pulsed Power Supply I (ETIPPS I) is a capacitor-based pulsed power supply consisting of the major subsystems shown in Fig. 4, and with properties summarized in Table I. A high voltage charger accepts 600 Vdc from a battery bank or battery-to-bus converter and converts it to a charging voltage up to 6.5 kVdc. The capacitor then stores up to 116 kJ of electrical energy until the thyristor is triggered, releasing the energy through a pulse-shaping inductor and into a high voltage output cable. Embedded control circuitry and auxiliary circuits provide for charging, triggering, disarming without firing (“safe-dumping”), monitoring of capacitor voltage, and collection and fiber optic transmission of output voltage and current data.

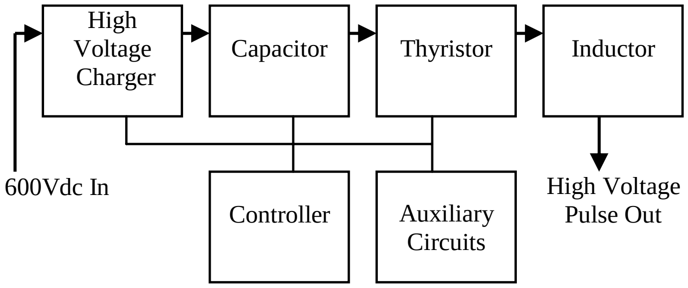

Fig. 4. Block diagram of major ETIPPS subsystems.

Table I. ETIPPS Characteristics

Description	Value	Unit
Mass	219.5	kg
Length	1099	mm
Width	414	mm
Height	440	mm
Volume	0.2	m^3
Energy storage at max voltage	116	kJ
Max voltage	6.5	kV
Max current output	47	kA
Output pulse duration	1.5	ms

For operation, the only external interfaces required by ETIPPS are a 600 Vdc source, a 26.5 Vdc source, and a fiber optic Ethernet connection to a remote control panel (allowing an operator to select mission parameters such as desired voltage, number of consecutive shots, and means of triggering). ETIPPS can then be charged and fired through the remote control panel or through connection to an existing combat vehicle fire control system.

Fig. 5 illustrates major ETIPPS components. The high-powered output section of the system, including the thyristor and inductor, is on one side of the capacitor, while the charger and low-voltage control section is on the opposite side.

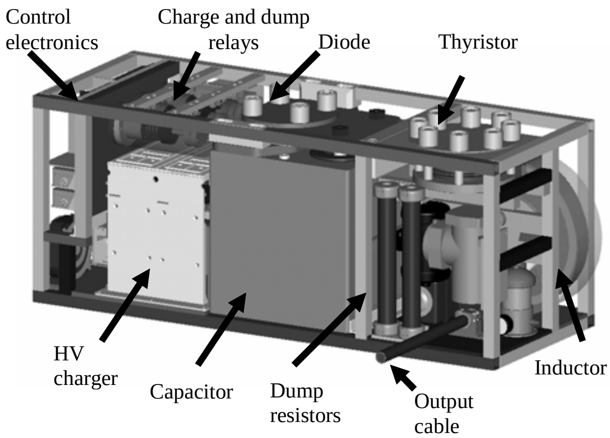

Fig. 5. 3-D model of the ETIPPS I system, with major components indicated.

High-Energy-Density Capacitor

A key component in meeting the 0.2 m^3 volume goal for the ETIPPS system is the capacitor, developed by General Atomics, under subcontract to BAE Systems. BAE Systems' most recent pulsed power supplies, prior to ETIPPS, used capacitors with an energy density of 1 J/cm^3. The metallized polypropylene capacitor in ETIPPS has an energy density exceeding 2.2 J/cm^3, and a charge/discharge lifetime exceeding 1000 full-energy cycles [4]. The General Atomics capacitor can be seen in Fig. 6 in relation to the other ETIPPS components. Since the capacitor accounts for roughly 24% of the ETIPPS volume, and 27% of its weight, the influence of capacitor energy density on the system volume is clearly significant.

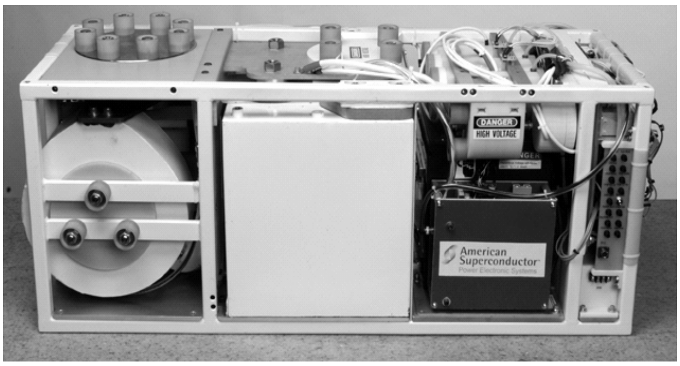

Fig. 6. Photo of ETIPPS I, showing the General Atomics high energy density capacitor (white module in center of system).

High-Voltage Charger

Another goal for ETIPPS was the ability to fire an ETI shot every 5 seconds, corresponding roughly with achievable reload times for an autoloader system. This requires a high-voltage charger that can deliver peak powers around 60 kW, yet is still compact enough to fit into the ETIPPS envelope. American Superconductor was subcontracted to deliver a high-voltage charger to meet these goals, and their solution is based on an existing standard American Superconductor building block, called “PowerModule,1000”[5]. The charger incorporates the required high voltage transformer and rectifier into the PowerModule structure (see Fig. 7) and provides an embedded microcontroller that accepts external commands such as “start charge” and “target voltage”, and returns feedback regarding input power status and capacitor bank voltage. The flexibility of the charger enables it to adapt to input bus variations from 350 Vdc to 800 Vdc.

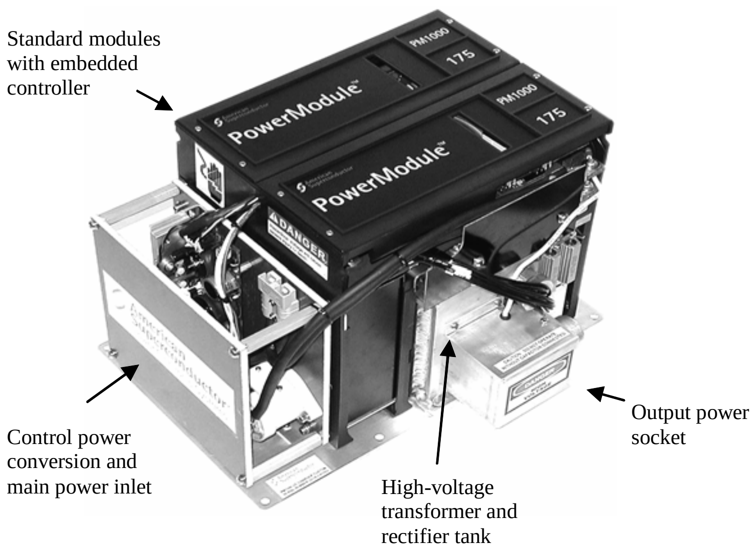

Fig. 7. High voltage charger

Other Challenges in Compact Design

In addition to the volume restrictions on the capacitor and high voltage charger, the compact design of ETIPPS I introduced packaging challenges for virtually all subsystems. The high-powered output section of ETIPPS brings the thyristor, capacitor, and inductor into close proximity to one another. To ensure that magnetic fields (requiring structural strength to withstand forces) and electric fields (requiring use of low-volume insulating materials) were manageable, detailed finite element analyses of the proposed layouts of ETIPPS were performed and iterated with design changes until an arrangement that would be both compact and reliable was achieved. Control and auxiliary electronics occupy a vertical panel on the opposite end of ETIPPS from the high voltage output. Several of the auxiliary circuits are electrically isolated from the others to allow them to “float” electrically when the system is charged and pulsed, since some circuits are linked to the output side of the thyristor, some to the input side, and others to the supply voltage and earth ground. In some cases, high voltage isolation was required among regions of a single printed circuit board. A custom DC-DC converter was designed and built to accept 26.5 Vdc as input, chop it to AC, pass it through a transformer with three separate secondary windings, and rectify it to three dc outputs (two at 15 Vdc and one at 26.5 Vdc) that are isolated from one another and from the primary up to 12 kV.

Performance of ETIPPS I

ETIPPS I was used successfully to fire 11 M829A2 ETI rounds from a 120 mm M256 gun in August 2004, and 10 M829A2 ETI rounds in December 2004 from the lightweight 120 mm XM-36 cannon as part of the ARDEC LOS/BLOS contract. In addition, ETIPPS I fired four conventional M829A2 rounds using its internal conventional firing circuit, to illustrate easy switching from ETI to conventional rounds. Further ETIPPS I testing in December 2005 was geared toward finding the minimum energy necessary to maintain precision ignition with ETI. Preliminary analysis indicates the lower energy boundary is less than 20 kJ for JA2 propellant.

III. COAXIAL INJECTOR

In previous BAE Systems pulsed power supplies for ETC applications, the output cable from the power supply to the gun has always been coaxial. However, the connection from the cable to the plasma injector itself has not. Typically the center conductor of the cable has been connected to an insulated anode in the base of the round’s case base (sometimes called a stubcase), and the return path of the output pulse has been through the metal case base to the breech block (as in a conventional round). The outer conductor of the output cable contacted the breech block to complete the circuit. This non-coaxial approach is not suitable for integration onto a combat vehicle, as the connection to the breech block brings the entire gun, and thus the vehicle chassis, into the high voltage circuit. A recent BAE Systems internal research and development effort resulted in the design of a new, fully coaxial plasma injector, of which several dozen were produced and demonstrated under the LOS/BLOS contract (see Fig. 8 and Fig. 9). In the coaxial design, the anode that accepts the center conductor of the output cable’s firing pin is surrounded by a concentric cathode, both of which are electrically insulated from each other and from the metallic case base. The fully coaxial plasma injector, case base, and firing pin design keep the breechblock, gun, and surrounding chassis out of the high voltage circuit, and provide good containment of magnetic field.

Despite the concentric return conductor around the center conductor, the coaxial firing pin that mates with the new coaxial plasma injector and case base design is still compatible with conventional 120 mm rounds. When firing a conventional round, the firing pin is simply inserted less deeply through the breech block such that the center conductor is pressed against the conventional round’s primer, leaving the cathode disconnected. The return path for the 24 V pulse is then through the breech block as is the case with all conventionally fired guns of that type. For conventional firings, a pair of high-voltage, low-current relays within ETIPPS closes to connect its integrated conventional firing circuit to the center conductor of the coaxial cable and through a return lead wire to the breech block.

Fig. 8. Coaxial Basepad injector and case base

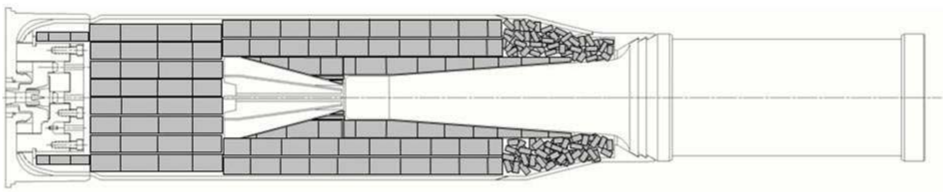

Fig. 9. Coaxial Basepad injector in M829A2 slug round

IV. ETIPPS II

Following design of ETIPPS I under the LOS/BLOS contract with ARDEC, ETIPPS II was designed and built as part of an internal research effort at BAE Systems, to demonstrate that a compact pulsed power unit could be integrated onto a vehicle and used to fire ETI rounds. ETIPPS II is a slight variation of ETIPPS I, the only significant difference being that ETIPPS II is split into two parts, whereas ETIPPS I is a single module. ETIPPS II is split between the high voltage charger and the capacitor to allow for the empty case eject cylinder of the Lightning Bolt vehicle (see Fig. 10).

Integration of ETIPPS II onto Lightning Bolt

The 18-ton Lightning Bolt is a modified M8 (Armored Gun System) combat vehicle. The original 105 mm gun has been replaced with a 120 mm XM291 gun, and its diesel engine has been replaced by a hybrid electric drive, making a 600 Vdc bus available for integration with systems such as ETIPPS II. ETIPPS II was integrated onto the bustle of the Lightning Bolt turret, as shown in Fig. 10. A rigid frame was bolted onto the turret to contain ETIPPS II, but within the frame, the high voltage output section of the system (to the right of the empty case eject in Fig. 10) was electrically insulated from the frame, and thus from the vehicle chassis. Only a 10 kΩ drain resistance connects ETIPPS II's high-voltage ground to vehicle ground. ETIPPS II was first demonstrated in August, 2004 when 7 ETI rounds, plus 7 conventional rounds, were fired from Lightning Bolt (Fig. 11). While these rounds were fired under remote control due to gun range safety requirements, on other occasions ETIPPS II was charged and test fired into an inert round by an operator in the turret, demonstrating safety of the system. Data taken during charging and firing of ETIPPS II indicate good containment of the magnetic fields within the system's coaxial connections, and no discernable effect of ETIPPS on the vehicle's electronics and controls were observed.

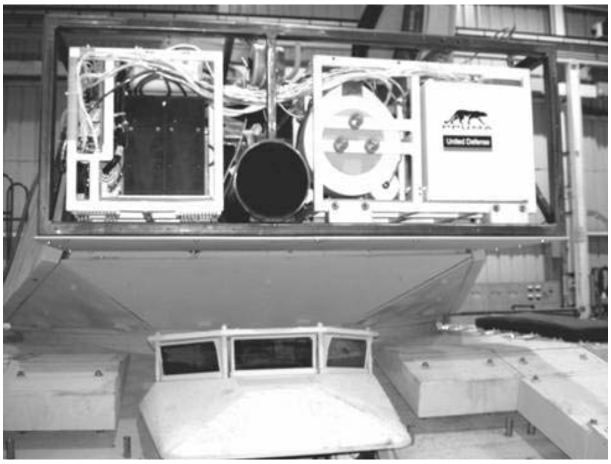

Fig. 10. ETIPPS II mounted on back of Lightning Bolt vehicle. In this view, the turret is traversed 180° with respect to the vehicle chassis, and the driver's hatch is visible below.

Fig. 11. Lightning Bolt firing ETC modified M829A2 with ETIPPS II mounted on back of turret.

Reliability Testing of ETIPPS II

As part of the LOS/BLOS contract, ETIPPS II was recently put through a reliability test series in which the system was charged and fired one thousand consecutive times into a dummy load with a resistance similar to that seen in an ETC firing. In this shot series, there was no degradation in performance of the ETIPPS system. The ETIPPS capacitors were rated for a 1000-shot lifetime (defined as number of full-energy shots before 5% loss of capacitance), but the capacitor used in the reliability test series has still not shown a loss in capacitance to date.

V. CONCLUSION

Advancements made under the LOS/BLOS contract, including development of a coaxial plasma injector, construction of a compact pulsed power supply, and integration of the power supply onto a combat vehicle, represent significant progress toward fieldability of electro-thermal chemical propulsion technology.

References

[1] G. Katulka, J. Dyvik, “Experimental Results of Electrical Plasma Ignition in 120-mm Solid Propellant Tank Fun Firings,” Proceedings of the 33rd JANNAF Combustion Subcommittee Meeting, November 4-8, 1996.

[2] J. Herbig, R. Appleton, “A Compact Electro-Thermal Ignition Pulsed Power Supply,” presented at the IEEE Pulsed Power Conference.

[3] J. Herbig, R. Appleton, “Compact Electro-Thermal Ignition Pulsed Power Supply,” presented at the 21st Meeting of the Electric Launcher Association, Oct. 2004. Available: http://www.electriclauncher.org.

[4] J. Ennis, X.H. Yang, F. MacDougall, K. Seal, and J. Herbig, “High Energy Density Capacitor Characterization,” in Conference Record of the 26th Int’l. Power Modulator Symposium and 2004 High-Voltage Workshop, 2004 IEEE International Power Modulator Conference, May 2004, p. 68-71.

[5] P. Schugart, “ETIPPS High Voltage Charger,” presented at the 21st Meeting of the Electric Launcher Association, October 11-13 2004. Available: http://www.electriclauncher.org.