

Green Farm Electric Gun Research and Development Facility: The Final Chapter

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Abstract—The Green Farm Electric Gun R&D Facility has been operated by Maxwell Technologies Inc. (MTI) for the Defense Threat Reduction Agency (DTRA) since its inception in 1986. MTI continued to operate this workhorse facility for thirteen years under the technical oversight of DTRA until its closure in 1999. The facility supported a wide variety of both Electromagnetic (EM) and Electrothermal Chemical (ETC) weapons concepts research and component development for the Department of Defense.

In the paper to follow, DTRA and MTI shall present their successes, achieved milestones, lessons learned, and recommendations for re-establishing the gun facility and its 32 MJ pulsed power system. Topics shall include the design of the facility, the analysis and engineering behind the 90 mm Single Shot Gun (SSG), shown in Fig. 1, and the 32 MJ power supply, system performance characteristics, diagnostic and instrumentation.

I. GREEN FARM GENESIS

IN 1985, based upon the success of the CHECMATE program, the Defense Science Board recommended the development of technologies with increased lethality to combat future tank armor. In response, the Defense Advanced Research Project Agency (DARPA) initiated the EM Gun Weapons System program which included Task B—a Single Shot EM Gun (SSG). The Defense Nuclear Agency (now DTRA) awarded Maxwell Laboratories Inc. (now MTI) a contract to build and test the capacitively powered Task B gun system. This required the design, construction and demonstration of a 90 mm bore, 8 meter long EM gun powered by a 32 MJ capacitor based pulse power system and the construction of a new facility at DNA's Green Farm Test Site to house system [1]. The program objectives were to provide a reliable tool for testing components and projectiles that could be used in a future rep-rated EM gun, and to support the development of hypervelocity and guided projectiles.

The system and facility design started in late 1986, construction started in January 1987 and the facility was operational by November 1987. In 1989 the facility was expanded to include two ETC gun emplacements, with containment and target areas, and a system was installed to extend the pulsed power buswork to feed the two external gun bays. In 1999 a 1 MJ - 22 kV ETC capacitor bank was designed and installed to support the DTRA Advanced Cartridge and Direct Fire Programs. The final facility

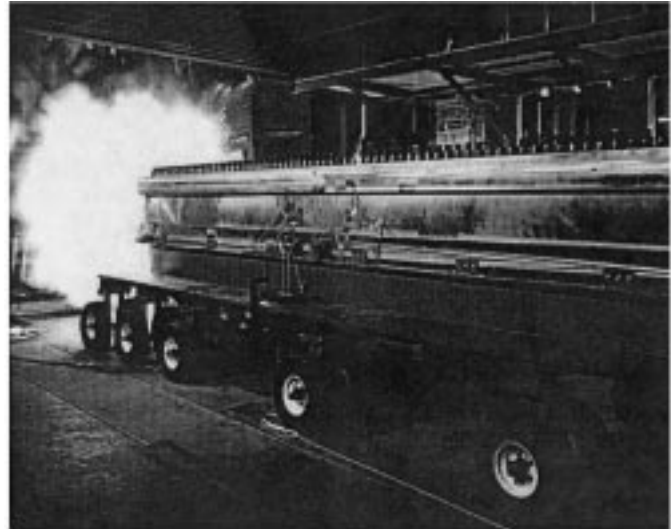


Fig. 1. The world famous SSG 90 mm electromagnetic gun.



Fig. 2. Green Farm facility.

configuration is shown in Fig. 2 and has been used as basis for the design of the 52 MJ facility at ARDEC [2] and the 32 MJ facility at Kirkcudbright, Scotland [3].

A. Facility Description

Initially, the Green Farm Facility was intended for use exclusively for EM Gun and EM Projectile development. The 32 MJ capacitor based pulsed power system was used to drive the 90 mm diameter, 8 meter long, SSG Railgun. The SSG was designed to deliver 9 MJ of projectile kinetic energy at the muzzle, to operate over a velocity range from 2.5 to 4.0 km/s and to provide an average of two shots per week. The final facility range was functional to only 50 meters. One of the key deficiencies of the facility was the Navy imposed range flight limitation. Although designs and plans were developed

Manuscript received December 17, 1999. This work was supported by the Defense Threat Reduction Agency.

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Publisher Item Identifier S 0018-9464(01)00233-3.

for a 1 km range, the NAS Miramar hosts would not allow the installation to be constructed. The ability to fire at a range of 2 to 3 km is one key element for projectile development and lethality studies, which needs to be integrated into the next generation Electric Gun Facility.

In 1989 the facility was rapidly modified to provide two additional gun positions for the Army 120 mm ETC Electrical Enhancement Factor (EEF) Experiments. New reinforced gun containment structures and target areas were constructed. The gun housings were designed to fully contain a catastrophic breech failure from a 155 mm cannon. Connections to the new gun positions were provided from the existing pulsed power system.

The command and control systems were located in a concrete safety bunker away from the gun firing positions. All signals between the Main Gun Building and the safety bunker were fiber optically coupled.

The personnel expertise, flexibility of the facility, and the ability to conduct both EM and ETC experiments from three independent gun positions allowed the facility users to successfully conduct over 250 EM and 300 ETC experiments during the thirteen year firing history of the Green Farm Facility.

B. Pulse Power Systems

The heart of the Green Farm pulsed power system is the 32 MJ, 11 kV, highly modular MTI capacitor bank. The bank system is divided into eight 4 MJ modules and is connected by buswork to the various gun loads. The eight modules can be fired simultaneously or sequentially into a common load. Flexibility of this system gives the ability to quickly configure the bank based upon load requirements from one capacitor to the full complement of 640 capacitors. Freewheeling diodes were a unique aspect of the bank, a passive device turning on at current zero.

The bank output is delivered to the load through interleaved, laminated aluminum buswork. These bus conductors connect directly to the SSG rail gun breech terminals. For other guns and test installations such as the 5", 120 mm, and 60 mm ETC guns, as well as open air, and visualization test fixtures, a tri-plate junction block configuration provides a transition to coaxial cables for connection to the gun breech. For added pulse shaping in support of DTRA programs an intermediate inductor stand was designed and built consisting of nine inductor slots and supporting buswork. These inductors could be connected in series and or parallel as required to provide the desired pulse shape.

The capacitor bank was charged using a Hipotronics three-phase full wave bridge rectifier rated for 120 amps at 11 kV. The original device was supplied using a variable core reactor for current control, however this was highly maintenance intensive and replaced with a capacitive reactance limiting system.

In 1999 a 1 MJ - 22 kV bank was designed and fabricated in support of a new test sequence for the ETC Advanced Cartridge Program for DTRA. Twenty-two kilovolt capacitors were installed and the local buswork was modified to connect directly to the intermediary inductor stand before feeding the 120 mm gun breech through a set of coaxial cables.

C. Diagnostics and Data

The diagnostic system at the Green Farm Electric Gun R&D Facility employs a wide variety of data gathering and recording instrumentation to characterize the operation of electric guns and the capacitor bank.

The original diagnostic system provided 40 channels of recorded data using 20 separate two-channel Tektronix oscilloscopes model 2430. These oscilloscopes were controlled with a Tektronix model 4041 DDAS computer. Also installed were 48 channels of 1 MHz CAMAC style digitizers manufactured by DSP Technologies. Eighty-eight channels of fiber optically isolated data links were provided between the digitizers in the control building and the gun diagnostics cabinet. These fiber optic links were model 5413AR and 5413AT manufactured by Lecroy.

While the fiber optic links were fast at 300 MHz, they lacked the needed accuracy at this frequency and were inadequate for the gun diagnostic signals. As solution a 10-foot by 10-foot screen room was installed in the gun building and all 20 oscilloscopes were moved to that location and controlled from the control bunker through the optically isolated GPIB interface.

In 1991 the Tektronix 4041 DDAS computer was replaced with an IBM compatible computer using LAB WINDOWS software. The 48 channels of DSP Technology digitizers became operational and we added a two channel Tektronix 710A digitizer for collecting data from a Weibel radar interferometer.

The EM launcher diagnostics consisted of the breech current, breech voltage, muzzle voltage, eight rail B-dot probes, and eight arc B-dot probes. Beginning in 1991 the B-dot locations were doubled along with the addition of four serpentine B-dot sensors. The B-dots and serpentines were embedded in the insulating side rails. The range diagnostics consisted of an orthogonal Hewlett Packard X-ray system located at the muzzle, three high speed framing cameras (Red Lake Hycam II), velocity breakwire stand, and a Weibel series 520 radar interferometer. After 1995 a separate X-ray system was installed at the target area, a new synchro-ballistic camera, and YAW cards were added to the range diagnostics. Also at this time orthogonal cameras views were obtained on the same films using plate mirrors that were slanted at 45 degrees.

The ETC diagnostics consisted of a breech current rogowski, breech voltage, PCB model P118A03 pressure probes, velocity breakwires, three high speed framing cameras (Red Lake Hycam II), and a Weibel series 520 radar interferometer. Math associates model 1000 A series analog fiber optic links were used originally for electrically isolating the pressure signals between the guns and the screen room. Beginning in 1996 these analog isolation links were replaced with Dymec 6700 series frequency modulated isolation links reducing the calibration and maintenance demands. In 1997 a new synchro-ballistic camera was also purchased and used on the ETC range. One of the high speed film cameras was modified into a split-frame which doubled the frame speed to 20 000 frames per second. On some of the igniter visualization tests all three high-speed framing cameras were used, which not only increased the views but also effectively increased the framing speed due to the inherent nonsynchronization of the cameras.

TABLE I
SSG BASELINE DESIGN PARAMETERS

Parameter	Specification
Projectile velocity	2.5 to 4.0 km/s
Projectile kinetic energy	9 MJ
Energy store	32 MJ
Prime power	SDG&E
Power	1 MVA
Energy per capacitor	50 kJ
Voltage	11 kV
On switch	RAG switch
Total charge transfer	6 kC
Action	$1.1 \times 10^{10} \text{ A}^2\text{s}$
Crowbar switch	Solid state diode
Total charge transfer	3.4 kC
Action	$0.6 \times 10^{10} \text{ A}^2\text{s}$
EMG Bore diameter	90 mm
EM barrel length	8 m
Injector (when used)	He gas
Projectile injection velocity	440 to 680 m/s
Rail separation pressure	345 Mpa
Projectile base pressure	414 Mpa
Current	3.6 MA
Thermal deposition/shot	5 MJ

D. Gun and Test Fixtures

During the firing history of the Green Farm Electric Gun R&D Facility several EM and ETC Guns were commissioned and used for testing. The SSG, an 8 meter long, 90 mm diameter bore, laboratory testbed provided a robust, prestressed, high current capability for firing full-scale launch packages. Bolted construction of the SSG provided easy disassembly, replacement rails and insulators can be installed within a 1 to 2 week time frame. The baseline design parameters for the SSG are shown in Table I.

Several guns and test fixtures were used for the ETC programs. The Army EEF ETC program incorporated the use of two 120 mm, M256 guns for the M1A2 tank. For Maxcart ETC testing the 5"/54 caliber Navy gun was used. SAIC's ETC program tests were performed at 60 mm and 120 mm scale. Additionally, numerous test fixtures were used to test propellant ignition systems prior to integration into gun cartridges.

The Open-Air test fixture was designed and fabricated to provide a test base for SAIC's ETC cartridge plasma generator. The original tests were performed in open air with results not matching predictions. To prove the hypothesis that current was being shunted through the external plasma a free-standing diagnostic assembly was built consisting of a 915 mm by 1220 mm piece of G10 with four large holes and one small hole in it. Each of the five holes were encircled by a rogowski to measure the plasma current. This structure verified the plasma current theory and provided useful information regarding the overall symmetry of the plasma generator. Based upon these tests, the fixture was modified to enclose the plasma generator with a clear polycarbonate tube filled with small plastic beads to simulate a propellant bed. To verify plasma symmetry in this configuration another diagnostic fixture was built. This fixture consisted of a polycarbonate disk inside the tube with two kidney shaped holes for plasma return. Once again rogowski coils encompassed these holes. This test device was instrumental in early plasma generator design changes for

TABLE II
GREEN FARM 90 mm EM SHOT HISTORY

Calendar Year	ARDEC	DSWA	UK/ DERA	Ford	Kaman	LTV	Sparta	USAF	Total	Test and Calibration
1987		20							20	100
1988		21		6	5			1	33	20
1989		9		1	3			3	16	15
1990		12		1	6	1	1	5	26	30
1991		6			22	3	12	3	46	34
1992	1	2			14	5		13	35	25
1993	9	10			8				27	10
1994	2	8	2		5				17	19
1995	2	2	7						11	17
1996			6						6	14
1997			10						10	16
1998			6	1					7	12
Total	14	90	31	9	63	9	13	25	254	312

optimum symmetry. In addition to the current diagnostics the plasma generator was routinely captured on high speed framing cameras positioned around the test fixture.

MTI designed and fabricated the Visualization Test Fixture to be used to view the ignition propagation into a live or simulated propellant bed. The fixture configuration consisted of two large diameter, 355 mm, steel containment blocks mounted on a 50 mm thick plate. The blocks were designed with 3 pressure ports each and were machined to accept a 140 mm outside diameter clear acrylic tube 915 mm long, simulating the 120 mm cartridge. This tube was designed to burst during the tests. At the base of the cartridge an electrical connection was provided and at the cartridge front, a short barrel section allowed for early shot start information as well as pressure measurements. The event would be filmed using high-speed cameras with a framing rate of 10 000 or 20 000 frames/s.

E. EM Projectile Firing History

During the Green Farm history 266 total EM Gun Firings were accomplished. Early firings were conducted primarily to qualify the SSG and the 32 MJ Pulsed Power System although some hypervelocity firings were conducted for the USAF and projectiles designed to defeat reactive armor were fired for the Ballistics Research Laboratory (BRL). From 1987 to 1994 the emphasis was to support EM Programs such as the Sabot Launched Electric Gun Kinetic Energy Projectile Program (SLEKE). During the period from 1994 through 1998 the emphasis was directed to be more on ETC Programs. Table II shows the Green Farm EM firing history over its 12 years of launcher operations.

F. DNA/DSWA Projectile Firings

During a nine-year period from 1987–1995, the MTI operated Green Farm Facility performed 122 EM Gun firings for DNA/DSWA, which now is DTRA. Most of the firings were conducted as gun and systems qualification tests using plasma armature, polycarbonate slugs as projectiles. However, it should be noted that several notable shots were undertaken.

- Highest muzzle energy 8.65 MJ with a 1.6 kg projectile fired at 3.3 km/s.
- Highest velocity 90 mm firing >4.3 km/s with a 640 gm projectile, 5.95 MJ energy.
- Qualification firing 7.0 MJ with a 1.13 kg projectile fired at 3.5 km/s.

G. Army SLEKE Projectile Firings

The SLEKE Projectile Program used the Green Farm Facility for 86 projectile tests, 45 for Kaman, 32 for ARDEC and 9 for LTV Missiles. The most successful firings were for Kaman under the SLEKE I & II programs. In August 1988 the first launch of a lethal projectile of tactical mass and flight configuration was successfully fired for the Kaman SLEKE Team from the SSG at Green Farm. This was the first of many successes for the program. Also during this program some launch packages failed when attempts were made to increase energy levels to >7.0 MJ. Barrel straightness and stiffness issues were studied as probable causes for the high energy level failures [4]. Notable firings for the successful Kaman SLEKE Projectile Program [5] are as follows.

- SLEKE I—Rodman cone—base push—solid armature—7.2 MJ, 3.88 kg, 1.92 km/s
- SLEKE I—Rodman cone—base push—plasma arm.—6.35 MJ, 2.68 kg, 2.18 km/s
- SLEKE II—Long rod—mid-riding—solid armature—6.02 MJ, 4.08 kg, 1.73 km/s.

H. Defense Evaluation & Research Agency (DERA) Projectile Program

The DERA group used the Green Farm Facility for the majority of their high energy firings under a government to government MOU between the UK and the Army along with DSWA. The quality of the available barrels in the UK limited the energy level in which the DERA group could fire their launch packages. The SSG proved to be the ideal candidate, providing world record performances for tactical launch packages. The DERA family of launch packages are shown in Fig. 3 and data from the launches are listed below. All of the launch packages are base push, solid armature, tactical sabot, KE type rounds.

- U4 Projectile—3.555 kg, 6.86 MJ at 1.965 km/s
- U4 Projectile—3.555 kg, 7.54 MJ at 2.060 km/s
- U4 Projectile—3.555 kg, 7.62 MJ at 2.070 km/s
- U7 Projectile—2.31 kg, 4.64 MJ at 2.004 km/s
- U9 Projectile—2.886 kg, 3.28 MJ at 1.514 km/s
- U9 Projectile—2.886 kg, 6.01 MJ, at 2.040 km/s.

Additional tactical rounds have been launched at the Green Farm Electric Gun R&D Facility in excess of 2 km/s, but will not be reported here.

I. Sparta Barrel Tests

In 1990–1991 testing of the Army’s 90 mm Advanced Composite Barrel (ACB) and the USAF HERID 25 mm sub-scale barrel was conducted at the Green Farm Facility for Sparta. A series of 13 shots were performed on the ACB prior to the containment structure failure at <6.0 MJ muzzle energy. The HERID gun failed in similar fashion after only 15 tests.

J. ETC Firing History

MTI’s Green Farm crew performed 339 ETC gun and fixture tests for DTRA over an 11-year period starting in 1989. The ETC firing history for the Green Farm Facility is tabulated in Table III.



Fig. 3. DERA launch packages.

TABLE III
GREEN FARM ETC SHOT HISTORY

Calendar Year	EEF Program		DTRA Programs				Test Fixtures	Total	Test and Calibration
	FMC 120 mm	GDLS 120 mm	MLI 5 inch	SAIC 120 mm	DSWA 60 mm				
1989	4	44					48	10	
1990	23	19					42	10	
1991			1				1	23	
1992			74				74	15	
1993			42				42	12	
1994			1			9	10		
1995			1		7	14	22	20	
1996					3	22	25	40	
1997				6		30	36	38	
1998				13		10	23	21	
1999				15		1	16	48	
Total	27	63	119	34	10	86	339	237	

K. General Dynamics Land Systems Division

In 1989 General Dynamics Land Systems Division (GDLS) in conjunction with GT Devices came to Green Farm to conduct the first 36–120 mm ETC firings at the facility using internal R&D funding. GDLS used plasma generators to ignite various slurry mixtures in a standard 120 mm cartridge. The performance reached near the 9 MJ muzzle energy level. The success of this 120 mm, M256 ETC program prompted the Army to initiate the Electrical Enhancement Factor (EEF) ETC program later that year.

L. Electrical Enhancement Factor (EEF) ETC Program

The US Army funded Electrical Enhancement Factor (EEF) ETC Program started at Green Farm in 1989. This series of

ETC firings was a competitive shoot off between GDLS and FMC. Two new gun containment structures and target areas were installed for the contractors to use during the competition. Electrical connections were extended to each gun position from the existing pulse forming network. Each contractor was allotted the same number of shots during the program. Unfortunately it is this authors opinion that the 27 shots allowed for each contractor was only enough firings to scratch the surface of the technology and that the technology never received the opportunity to mature properly during the program.

M. Maxwell - 5" Navy - MAXCART Program

MTI developed the MAXCART propellant ignition concept under the DNA sponsored ETC Advanced Cartridge Program. During 1992–1994 a total of 119 - 5" gun tests were performed at Green Farm in support of the program. MAXCART took advantage of the manner in which pulsed power can ignite tapered fuses in a water-aluminum power mixture. This technique showed that control of the ignition can be affected by the physical profile of the fuse and the pulse shape applied to it. This concept had a great influence on the SAIC ETC ignition concept. The MAXCART concept successfully increased the 5" Navy Gun performance from a standard 11 MJ muzzle energy to firing at over 22 MJ in final tests. The draw back to the technology is that the water-aluminum mixture burns very hot and degrades the life of the barrel.

N. DTRA/SAIC Advanced Cartridge ETI Program

During the Advanced Cartridge Program the Science Applications International Corp. (SAIC) used plasma generators to ignite advanced propellant systems. The additional heat provided by the plasma generators allows higher density propellants to be packed into a standard cartridge and to be fully ignited. The data from this program has become classified and will not be presented here.

O. Lessons Learned

There are some general areas in which the community needs to continue improvement. Smoother current pulses will impart

less jerk upon the launch package. With a capacitor based system it just requires more trigger generators for more stages. The future EM launchers must improve both the barrel straightness and stiffness. While most present X-ray system triggers near the gun provide adequate results during successful shots, the not so successful shots are frequently missed and must be improved. EM launcher bore materials must be improved. Plasma armatures are light but very demanding upon insulating materials and solid armatures are heavier and demanding upon conducting materials. The launch package parasitic mass must be lowered and large scale testing must begin on some of the more novel penetrators.

P. Conclusion

We believe the need to relocate the Green Farm Facility and create a National Electric Gun Facility to carry on this work is obvious, especially with respect to the future combat systems. This facility must have certain criteria: first it must be capable of firing at least 2 km on a regular basis, the site must have stability through a long term lease or equivalent, and the funding must be committed long term. The site should have the capability to support both EM and ETC testing. The Green Farm 32 MJ power supply and associated equipment has been shipped to Aberdeen Proving Grounds, which is an ideal candidate for resurrection of the new facility. Increasing the amount of stored energy from 32 MJ to 84 MJ could be accomplished by joining the Green Farm and ARDEC power systems.

REFERENCES

- [1] I. McNab and F. LeVine, "Experiments with the Green Farm Electric Gun facility," *IEEE Trans. Magn.*, vol. 31, p. 338, January 1995.
- [2] D. Chang *et al.*, "Performance of the 52 MJ power supply at the electric armaments research center," *IEEE Trans. Magn.*, vol. 31, p. 22, January 1995.
- [3] D. Haugh *et al.*, "The Kirkcudbright electromagnetic launch facility," *IEEE Trans. Magn.*, vol. 29, p. 975, January 1993.
- [4] L. Burton *et al.*, "Structural design issues for electromagnetic projectiles," *IEEE Trans. Magn.*, vol. 27, p. 465, January 1991.
- [5] T. Hayden *et al.*, "Mid-push plasma armatures for long-rod electromagnetic gun projectiles," *IEEE Trans. Magn.*, vol. 29, p. 792, January 1993.