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A Survey and Projected Performance of Pulsed Power Supplies at Aberdeen Proving Ground, MD

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Abstract

Electric guns require energy produced by a pulsed electrical discharge to accelerate the launch package. A number of research projects that utilize pulsed high-power sources are on-going at the U.S. Army Research Laboratory, Aberdeen Proving Ground (APG), MD. Demonstrations of electric gun technology thus far utilized rotating machinery or capacitor-based pulsed power supplies (PPS's). A survey of PPS's at APG was conducted. While a majority of the PPS's is not directly compatible with a railgun load, they can be modified and combined into a multiple, trailer-based PPS. In order to obtain 20 MJ of muzzle kinetic energy, a railgun launcher with greater than 50% system efficiency will require a 40-MJ PPS. However, a substantial investment in technology, as opposed to hardware, results in better utilization of a lower energy, site-based PPS. More modest muzzle energy requirements (8–11 MJ) can be satisfied with either a site- or trailer-based 32-MJ PPS and a launcher efficiency of 56%. Additionally, the site- or trailer-based PPS can easily supply a few Megajoules to an electrothermal-chemical (ETC) capillary as well.

Acknowledgments

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1. Introduction

Electric guns require energy produced by a pulsed electrical discharge to accelerate the launch package. Some electric guns use chemicals as the primary form of energy and therefore require a relatively small amount of electrical energy. Electromagnetic launchers, specifically railguns, use electrical power exclusively. Consequently, they require a more substantial supply. All electric guns utilize a tailored discharge current waveform. Therefore, the design of the pulse-forming network (PFN), is crucial in obtaining the desired performance.

A number of research projects that utilize pulsed high-power sources are ongoing at the U.S. Army Research Laboratory (ARL), Aberdeen Proving Ground (APG), MD. They include railguns [1, 2], electrothermal-chemical guns [3–5], coilguns [6], semiconductors [7], and electromagnetic armor [8, 9]. Each research team conducts small- and large-scale research with separate, individual pulsed power supplies (PPS's). Additionally, the Aberdeen Test Center (ATC), also located at APG, has a research facility for conducting pulsed power experiments [10]. A survey was conducted to estimate the total amount of stored capacitive energy at APG. Only those PPS's with greater than 0.4 MJ are considered.

This technical note addresses the extent to which the individual PPS's are useable when integrated together. Also discussed are the shortfalls and remedies to obtain 20 MJ of total kinetic energy from an electromagnetic railgun. Finally, a strategy is presented by which 20 MJ of muzzle energy and more modest performance (8 and 11 MJ) can be assessed relative to the available PPS's.

2. Pulsed Power Supply Survey

A total of 11 capacitor-based PPS's were identified at APG, of which 2 are specifically designed to provide current to a railgun. The remaining PPS's are deficient. In some cases, components may even be missing from the PPS. For example, a coilgun and armor load do not typically utilize a discrete inductor incorporated into the PFN. In the case of a coilgun, the propulsive device (i.e., an inductor) provides for sufficient pulse shaping. In the case of an armor load, a large current with a very short rise time limits the amount of inductance that can be tolerated in the PFN. Still, for some armor loads, electrical discharge switches may even be omitted, due to the interaction of the penetrator (either a shaped charge jet or heavy metal alloy) and armor plates. Moreover, a railgun PPS by design does not meet the rise time requirements for an armor load, regardless of the amount of energy stored in the PPS. Crowbar diodes used to prevent voltage reversal across the capacitors are equally important to provide for a near constant current to the railgun, but they are not entirely necessary for electrothermal-chemical (ETC), coilgun, and armor loads. In a few PPS's, they are not incorporated. The disparity between load current waveforms, for different applications and therefore PPS design specifications, is illustrated in Figure 1.

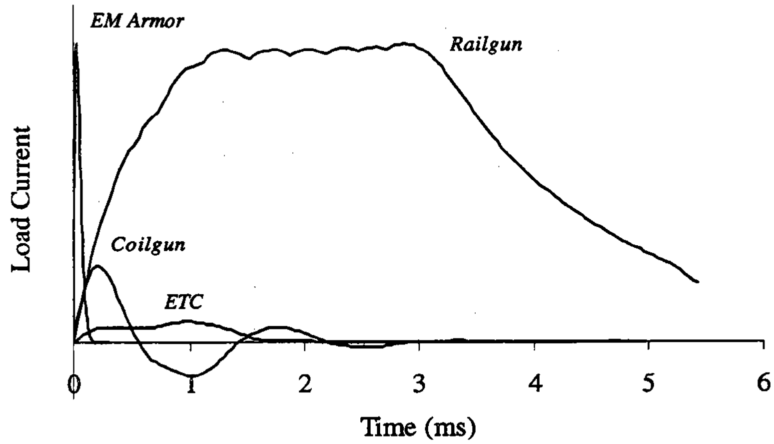

Figure 1. Illustration of Typical PPS Load Current Waveforms.

Generally, a PPS for railgun operation can be used, albeit not at the highest efficiency, with all other load types. The converse is not true since railguns require high currents and they usually complicate the design of the PFN components (e.g., the number of diodes required, stresses on conductors, etc.).

Essentially, the only common component in the survey is the capacitor. While this component is certainly vital for a PPS, it is by no means the only component. Considerable effort is involved in converting the nonrailgun PPS's to function with a railgun load. These include upgrading (or adding) PFN inductors that are capable of conducting the increased currents, upgrading (or adding) semiconductor diodes to deliver the proper pulse-shape, upgrading (or adding) fuses on the capacitors, and upgrading (or adding) discharge switches. A majority of the PPS's, nearly one-half the total available energy, are not immediately compatible with a railgun load.

Additionally, a PPS operational prior to 1999 will require, at a minimum, some maintenance to reestablish routine operation. Resources will be proportional to the amount of time that the PPS has not been operated. Nearly one-half the number of facilities surveyed will require resources to reestablish routine operation. Collectively, these facilities also represent the majority of the energy storage capacity in this survey. A summary of the relevant characteristics from the PPS survey is listed in Table 1.

Table 1. Summary of Capacitor-Based PPS's at APG, MD

Facility Descriptor	POC	Location	Maximum Stored Energy (MJ)	Primary Load	Capacitor Voltage Rating (kV)	Recent Operation
Green Farm[a]	T. Wolfe (MLI[b])	San Diego, CA	32.0	Railgun	11	1999
CCEMG	A. Zielinski	B 740-I	1.6	Railgun	11	1997
Closed Bomb	M. DelGuercio	B 390	0.4	ETC	11	1999
GDLS	A. Zielinski	B 740-G	4.5	ETC	11	1995
ETC Trailer	G. Katulka	R-18	4.0	ETC	22	1994
Static Tester	C. Hummer	B 120	0.4	Armor	22	1999
PI Trailer	M. Keele	1100-F	1.6	Armor	22	1999
SAIC Trailer	M. Keele	1100-F	4.0	Armor	22	2000[c]
General Research Support	L. Francis (ATC)	Briar Point B 933E2	10.0	Armor	22	1993
Switch Tester	D. Singh	B 120	0.72	Switch	20	1999
Plate Launcher	P. Berning	B 120	0.77	Coilgun	13.5	1999

[a] Presently under consideration for installation and operation at APG.
[b] Maxwell Laboratories Inc., San Diego, CA.
[c] Presently under construction; expected operation is 2000 [9].

3. Projected Performance

Two types of accelerators are considered: ETC and railgun. For an ETC load, the General Dynamics Land Systems (GDLS) and ETC trailer PPS's can each easily deliver 1 MJ to the capillary. The situation is quite different for a railgun. Numerical simulation codes are available to estimate the performance of a PPS with a railgun load. However, in this case, a more practical approach is to utilize the demonstrated performance at the Green Farm Facility in San Diego, CA, and, using analytical engineering expressions, estimate the performance at increased energy levels.

A drawback to this approach is that the magnitude of the perturbation around the demonstrated performance is limited. For reference, the tests conducted at the Green Farm Facility used a 90-mm round bore railgun, 8 m in length. Table 2 lists a brief summary of some of the more impressive results obtained at the Green Farm Facility.

Table 2. High-Performance Railgun Tests at the Green Farm Facility [1]

Launch Parameters	Large Muzzle Energy		High Velocity
	Plasma Armature	Solid Armature	Plasma Armature
Mass (kg)	1.58	2.35	0.65
Velocity (km/s)	3.3	2.6	4.3
Stored Energy (MJ)	31.5	28.7	24
Muzzle Energy (MJ)	8.6	7.9	6.0
System Efficiency (%)	27.3	27.6	25.0

Using an average system efficiency of 26% and assuming the railgun has an electrical efficiency of 40% (typical for a large-caliber, solid armature laboratory railgun [11]) yields a PPS efficiency from equation 1,

$$E_{ke} = E_s \eta_{PPS} \eta_{gun} , \qquad (1)$$

of ~65%. This efficiency takes into account sequentially discharging the modules to obtain a near constant current to the railgun.

Four PPS scenarios are considered for integrating the PPS's listed in Table 1: (1) the 32-MJ Green Farm PPS, (2) only capacitors with a rating of 11 kV incorporated into the existing Green Farm PPS, (3) all the capacitors located at APG and charged to a maximum voltage of 11 kV (i.e., the voltage for the 32-MJ supply), and (4) all the capacitors incorporated into one PPS (with their respective charge voltages). The muzzle energy can be calculated from equation 1, assuming that all PPS's possess an electrical efficiency similar to the well-designed Green Farm PPS (65%). Using that muzzle energy and projectile goals consistent with the Army's Electric Gun Program (e.g., useful payload of 50%, rod diameter of 20 mm, and launch velocity of 2.5 km/s) a total launch mass and subprojectile length to diameter ratio (*l/d*) can be estimated. Finally, the electrical efficiency of the railgun that is needed to produce 20 MJ of muzzle kinetic energy can be calculated. These results are summarized in Table 3. The only solutions for 20 MJ of kinetic energy that present reasonable gun efficiencies (i.e., <70% [11]) involve using all the capacitors surveyed at APG. More modest muzzle energy goals (8 and 11 MJ) can be satisfied using stored energies of 32 and 44 MJ, respectively, for reasonable launcher efficiencies.

Table 3. Summary of Projected Performance

Scenario	Stored Energy (MJ)	Kinetic Energy (MJ)	Mass (kg)	Length to Diameter (*l/d*)	Gun Efficiency for 20 MJ (%)
Green Farm Facility	32	8	2.7	12	92
11 kV rated capacitors	39	10	3.2	15	76
Capacitors charged to 11 kV	44	11	3.7	17	66
Capacitors (various voltages)	60	16	5.0	23	49

4. Packaging and Operation

4.1 Performance. The amount of stored energy required to achieve 20 MJ of total kinetic energy is nearly equal to the energy at the U.S. Army Armament Research, Development, and Engineering Center (ARDEC) Facility, Electric Armaments Research Center (EARC), Picatinny Arsenal, NJ [12]. The floor space for this PPS is 60 ft × 40 ft and 18 ft high. Packaging 60 MJ into trailers (8 ft × 48 ft) requires an assumption about the amount of energy that can be integrated into a trailer. Four power supplies are available for data (three previous and one recent). They are the U.S. Army, 9-MJ Pulse Power Module (PPM) [13], the United Defense Limited Partnership 11-MJ PPS [14, 15], the 4-MJ PPS for ETC investigations [3, 16], and the incomplete 4-MJ Armor PPS [9]. While each effort is different, each provides an estimate of the amount of stored capacitive energy that can be integrated into a trailer. For example, the PPM stores 9 MJ; however, there was considerable custom hardware and significant integration in this effort. The 4-MJ ETC PPS used commercial off-the-shelf (COTS) components; however, some custom integration was necessary to utilize one trailer for the PPS. A second trailer was necessary to contain the high-voltage charging power supply (HVCPS) and prime power. Still, the armor PPS is the most recent effort and is able to take advantage of prior efforts as well as available ARL hardware.

For a multiple, trailer-based PPS, a few assumptions are necessary to evaluate the technical merits. It is assumed that the trailers are arranged behind the breech of a railgun and that the four closest trailers (symmetrically arranged) have a PPS with an efficiency of 65%. The efficiency of each subsequent trailer is then reduced by 4% to account for the increase in cable lengths to reach the railgun breech. Certainly, the number of cables can be increased to compensate for the losses; however, the large number of trailers and spacing makes the cabling untenable at the breech connection.

Shown in Figure 2 is the total muzzle kinetic energy as a function of the stored energy per trailer. The effect of increased losses is clearly evident for large numbers of trailers (i.e., low energy per trailer). Also indicated are curves for various values for launcher efficiency. For

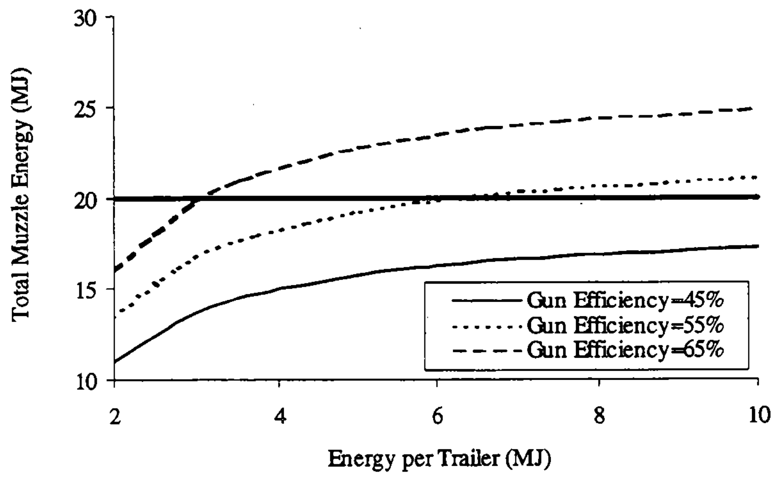

Figure 2. 60-MJ PPS Solutions.

launchers with an efficiency of 55%, greater than 6 MJ per trailer will meet the 20-MJ requirement. Less energy per trailer can be tolerated if higher efficiency launchers are developed (>60%).

More modest muzzle energy requirements (i.e., 8 MJ) can easily be met with only 32 MJ integrated into trailers. Using current launcher technology (η_{gun} = 40%), 8 MJ of muzzle energy can be achieved with as little as 4 MJ per trailer (and certainly from a fixed site facility as indicated in Table 2). Achieving 11 MJ of muzzle energy is possible with 4 MJ per trailer, with a launcher efficiency of 56%.

4.2 Costs. Costs for the four previously described trailer-based PPS's are evaluated in order to provide a cost estimate for 10 trailers, each with an independently charged 6-MJ PPS. Certainly, the total cost associated with each effort will not be accurate because of the caveats previously mentioned. However, the engineering, HVCPS, assembly, fabrication, and integration cost for each on a per-stored energy basis was extracted. The 1999 cost is on the order of 50¢/J. For the present scenario, $30M is estimated to construct the 60-MJ, multiple trailer-based PPS. Selecting less efficient packaging, namely 1 MJ per trailer, can reduce costs. The total cost for the required 60 trailers in the second scenario, is then $22M and will launch an

$l/d \sim 9$ subprojectile, less then the performance for the site-based 32-MJ Green Farm Facility (see Table 3). Roughly one-half of the total cost is expended in hardware, of which roughly 20% is devoted to the cost of the capacitors. Costs would increase accordingly if the surveyed capacitors were not integrated into the mobile, trailer-based PPS. Of the one-half of the total cost expended in labor, roughly 25% is allocated to the design of the PPS, with the balance for fabrication and assembly.

Costs not accounted for and over the long-term may exceed the amount to construct the trailer-based PPS, including the costs of not conducting competing high-energy experiments (i.e., scheduling conflicts) and experiments that would otherwise occur had the capacitors not been integrated into the trailer-based PPS. Trailers with an integrated HVCPS help eliminate competing, smaller energy experiments. The time to set up and disconnect the PPS will also increase for each experiment, since the equipment will need to be thoroughly checked for loose connections caused by trailer movement. Costs associated with training and operating the PPS are also not included.

Costs for integrating less stored energy (e.g., 32 MJ) into either a site- or trailer-based PPS, as outlined previously, will be similar to the 60-MJ PPS, albeit less. For example, a 32-MJ PPS is estimated to cost \$12–16M. If all hardware were provided, assembly, trailers, and some fabrication are expected to cost no more than \$5M.

4.3 Investment Strategy. For this scale in resources, it is instructive to look at investing in technology rather than in hardware. The Green Farm Facility provides a basis for comparison, since it is the largest operational PPS used in railgun experiments. Technology is correlated with gun and useful payload efficiencies. Gun efficiency will increase by extending solid armature operation to 2.5 km/s, recovering the barrel magnetic energy and using transposed rail conductors [11]. Integrating composites in sabots will increase useful payload efficiency [17]. A portion of these increases in efficiency will naturally occur as a result of various ongoing development programs and is accounted for.

In Figure 3, *l/d* is plotted as a function of facility configuration for various increases in the technology. For the 32-MJ Green Farm PPS, the increase in launcher efficiency (η_{gun}) is shown first, followed by the additional increase in useful payload efficiency (η_p). The following definitions are used:

- 60-MJ Trailers – All resources expended into the multiple, trailer-based PPS arrangement (6 MJ each)—50% useful payload efficiency and 50% launcher efficiency.
- Green Farm Trailer – A portion of the resources are allocated into trailers (3.75 MJ each) and the balance into technology (60% useful payload efficiency and 60% launcher efficiency).
- Green Farm Site – All resources are concentrated in technology development (70% useful payload efficiency and 70% launcher efficiency)—assumes ATC partnership to minimize facility and set up costs.

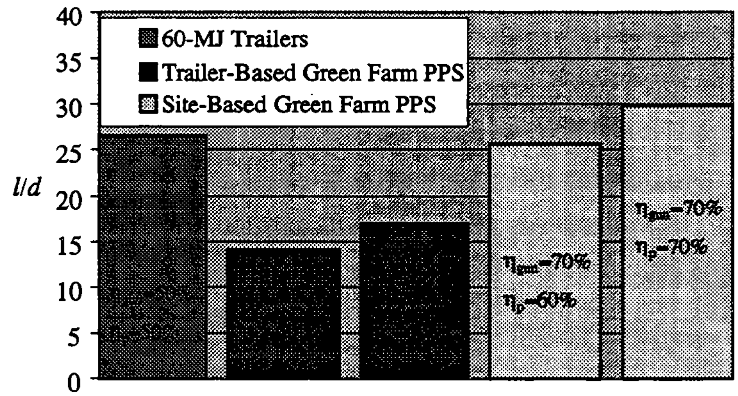

Figure 3. Investment Strategy.

The analysis indicates that the integration of all the capacitors at APG into a multiple, trailer-based PPS can achieve substantial performance with a heavy-metal payload. Simply integrating the Green Farm PPS into trailers with a modest increase in technology does not seem most productive, as the configuration only yields 12 MJ of muzzle energy. Given the Green Farm site at APG, however, a more substantial investment in technologies combined with a partnership with ATC can provide for capabilities greater than the 60-MJ trailer option. The 32 MJ fixed-site facility also preserves the integrity of the other PPS's. A detailed cost-benefit analysis is beyond the scope of this effort.

The Green Farm Facility, with 32 MJ of energy storage capability, was designed, constructed, and operational within one year [1]. A 60-MJ, trailer-based PPS, based on existing data [3, 5, 9, 13, 14] with available hardware and resources, should certainly be operational within a three-year period of time.

5. Summary and Conclusions

A survey was conducted of capacitor-based PPS's at APG, MD. While a majority of the PPS's are not directly compatible with a railgun load, they can be modified and combined into a multiple, trailer-based PPS. The majority of the PPS's have not been operated recently and they will, in any event, require resources to support routine operation.

In order to obtain 20 MJ of muzzle kinetic energy, a railgun launcher with greater than 50% efficiency is required, as well as 44 MJ of stored electrical energy. However, a substantial investment in technology, as opposed to hardware, results in better utilization of the lower energy, site-based, 32-MJ Green Farm PPS. No increase in launcher efficiency is required to achieve more modest muzzle energy requirements (i.e., 8 MJ) from either the site- or trailer-based configurations. Slightly larger muzzle energy (11 MJ) requires a launcher efficiency of 56%. Additionally, the 32-MJ Green Farm Facility can easily supply a few MJs to an ETC capillary.

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