Army Research Laboratory

Incident, Action, Recovery, and Recommissioning for the 4.5-MJ Pulsed Power Supply Located at the Electromagnetic Gun Facility, Barricade C, Aberdeen Proving Ground, MD

by Alex Zielinski, Miguel Del Güercio, Alex Michlin, Steve Niles, Anthony Canami, and Robert Glassman

ARL-TR-4088 **April 2007**

NOTICES

Disclaimers

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ARL-TR-4088 **April 2007**

Incident, Action, Recovery, and Recommissioning for the 4.5-MJ Pulsed Power Supply Located at the Electromagnetic Gun Facility, Barricade C, Aberdeen Proving Ground, MD

Alex Zielinski, Miguel Del Güercio, Alex Michlin,
Steve Niles, and Anthony Canami
Weapons and Materials Research Directorate, ARL

Robert Glassman
Dynamic Science, Inc.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
April 2007	Final	February 2006–December 2006

4. TITLE AND SUBTITLE
Incident, Action, Recovery, and Recommissioning for the 4.5-MJ Pulsed Power Supply Located at the Electromagnetic Gun Facility, Barricade C, Aberdeen Proving Ground, MD

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Alex Zielinski, Miguel Del Güercio, Alex Michlin, Steve Niles, Anthony Canami, and Robert Glassman*

5d. PROJECT NUMBER
AH80

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-WM-BD
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-4088

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
*Dynamic Science Inc., 1003 Old Philadelphia Road, Ste. 210, Aberdeen, MD 21001

14. ABSTRACT
A 4.5-MJ capacitor-based pulsed power system (PPS), previously owned and operated by General Dynamics Land Systems in the early 1990s, was acquired by the U.S. Army Research Laboratory. The system was placed in storage in the late 1990s. It was recently modified and, in 2001, was placed back in operation at barricade C to operate with an electromagnetic (EM) railgun load. On 9 February 2006, a capacitor in module 4 developed an internal short while charged to 7.2 kV. Further inspection revealed arc damage at the center post terminal on 20 capacitors in nearby modules and some amount of rust on every capacitor case. After the incident, all modules were charged individually to 3.2 kV and discharged into a short. The data indicates that the damaged center posts likely occurred quite some time ago. New hardware was required to restore relevant capability to barricade C. The capacitors form the primary and essential basis for the system. The PPS must be capable of reliably delivering higher energy pulses. New capacitors using modern manufacturing techniques and improved dielectrics were purchased. New center posts were designed and replaced concomitant with the installation of new capacitors. Lastly, the bus work that connects the pulse-forming inductor to the pulse-forming-network output cable was replaced in order to decrease the number of bolted joints and increase reliability at high-energy operation. Upon completing the upgrade in hardware, each module was discharged into a short at the breech of the railgun at initial charge voltages of 3, 5, and 7 kV. Additionally, all 18 modules were sequentially discharged into the shorted breech. Lastly, firings using a railgun were completed without incident. All simulation models were updated as necessary throughout the commissioning process. The stored energy at the maximum charge voltage of 11 kV is now 5.2 MJ.

15. SUBJECT TERMS
pulsed power, capacitor, railgun, armature, incident

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Alexander Zielinski
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (*Include area code*)
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	30	410-278-3889

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

List of Tables

1. Pulsed Power Supply System Background

1.1 Introduction

A 4.5-MJ capacitor-based pulsed power system (PPS) (previously owned and operated by General Dynamics Land Systems (GDLS), Huntington, WV in the early 1990s and used in electrothermal-chemical research [*1*, *2*]) was acquired by the U.S. Army Research Laboratory Weapons and Materials Research Directorate (ARL-WMRD). The system was placed in storage in the late 1990s. It was recently modified and, in 2001, was placed back in operation at barricade C to operate with an electromagnetic railgun load.

The PPS consists of 18 250-kJ independently triggered modules. Pairs of these modules (shown in figure 1) are symmetrically placed in nine racks (3 ft 7 in wide × 13 ft long × 4 ft high).

Figure 1. PPS racks.

A circuit schematic for one module is shown in figure 2. Capacitors (C) are charged via fuses (F_{cp} and F_{ch}) to an initial voltage. When the discharge is initiated, the output switch (SG) closes, and the current is shaped by the series inductor (L, R). Additional shaping is provided by diodes (D_{cp}) placed essentially parallel with the capacitors. The resulting shape of the current in the load has a sinusoidal rise time and an exponential decay. This type of waveform, when used in conjunction with additional similar waveforms, has been found to be advantageous for railgun operation.

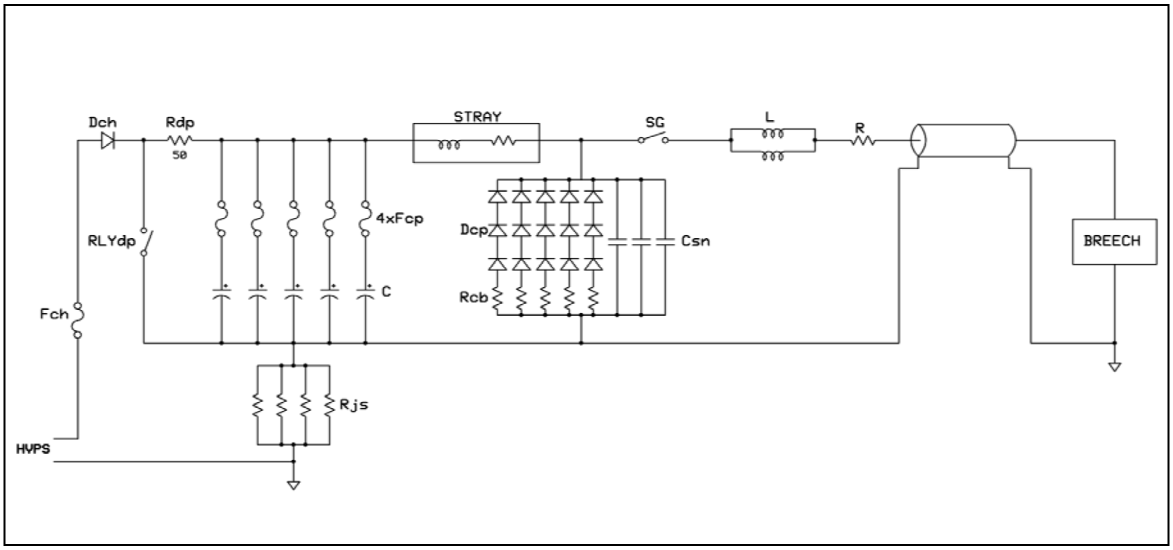

Figure 2. Module schematic.

An illustration of the component layout in each rack is shown in figure 3.

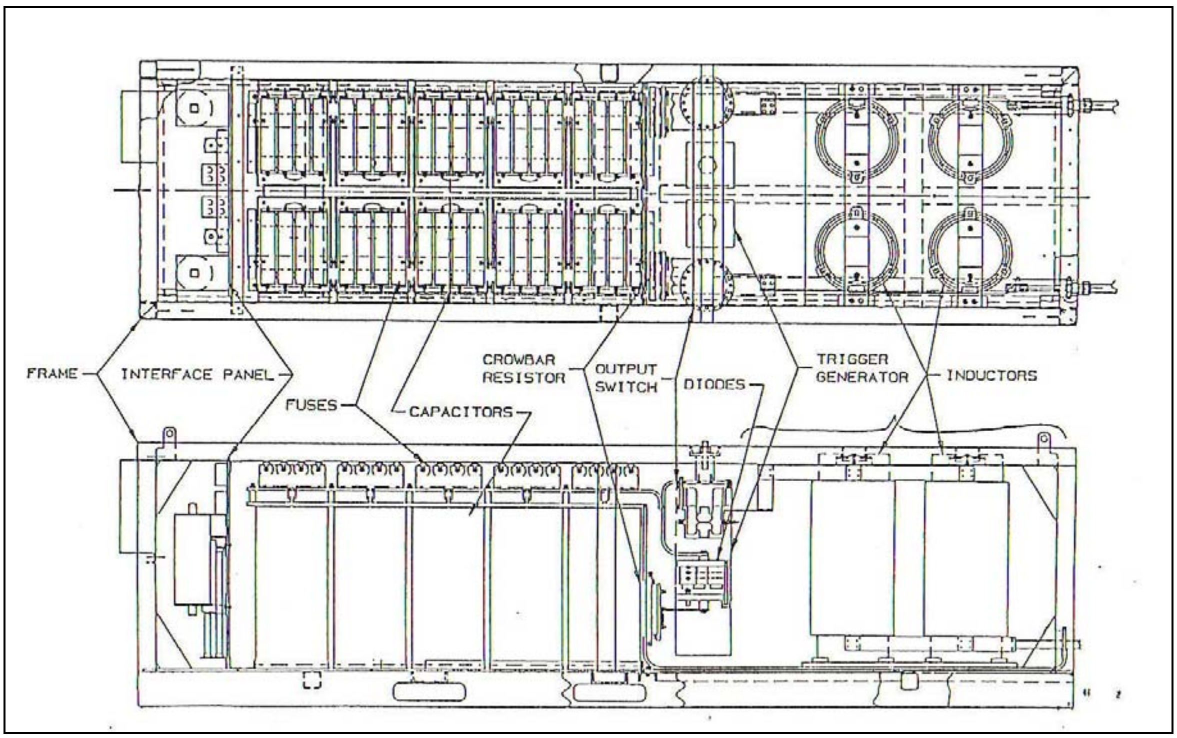

Figure 3. Component layout for one rack (2 × 250 kJ).

1.2 Hardware

The PPS is comprised of many subsystems and components. The following subsections address the parameters, physical characteristics, and operating characteristics for a few of the most important components.

1.2.1 Capacitors

The capacitor is the primary and essential component for energy storage in the system. Each module of the 18 250-kJ modules originally contained five 11-kV/50-kJ 830-μF capacitors Aerovox. These capacitors were designed and fabricated in the mid-1980s.

1.2.2 Inductors

Inductors are one of the primary components for shaping the output current pulse for each module. The pulse forming inductance was decreased on the original modules 1–9 in an effort to be more compatible with an electromagnetic railgun load. Nine of the 18 modules retained their two original 116-μH inductors connected in parallel, thereby forming 58 μH of pulse forming inductance. Nine 30-μH inductors replaced each one of the 116-μH inductors on the remaining nine modules. The final inductance for each of these modified modules was 24 μH. Modules 1–9 contain the lower value inductors.

1.2.3 Crowbar Diodes

Crowbar diodes are the second most important component in the pulse forming network. Fifteen Brown Boveri avalanche diodes (DSA 908-44 AG), arranged in five parallel stacks with three diodes in series in each one, form a crowbar diode set that protects the capacitors of each module from damaging voltage reversals and provides pulse-forming relevant for railgun operation. Each diode is rated at 4.4 kV and 50 kA for 1-ms half-sinusoid surge currents. Each crowbar diode set is clamped together and evenly distributed between two identical 1-in-thick circular aluminum plates (see figure 4).

There are three 0.01-μF capacitors connected in parallel and placed across the plates that provide protection for the diodes during large transients. Each of the five crowbar diode stacks is connected in series with a 15-mΩ resistor, providing 3 mΩ of total crowbar resistance per module. Since these diodes become susceptible to failure when switching at large charge voltages, the resistors limit the peak current and moderate the action through the diodes.

1.2.4 Capacitor Fuses

Four fuses (Maxwell Laboratories, model no. 94029) are connected in parallel and placed in series with the output of each capacitor to enable handling large currents while providing isolation in the event of a capacitor short circuit at high voltages. Each of the four fuses (see figure 5) is rated at 6 kA and 22 kV, providing a combined maximum rating of 24 kA per capacitor.

1.2.5 Discharge Switch

The discharge of each module is initiated by a high-voltage trigger generator (Physics International, model PI-TG-75S) and a spark gap (Physics International, model ST-300) output switch (see figure 5).

Figure 4. Crowbar diodes (lower image) and output switch, ST-300 (upper image).

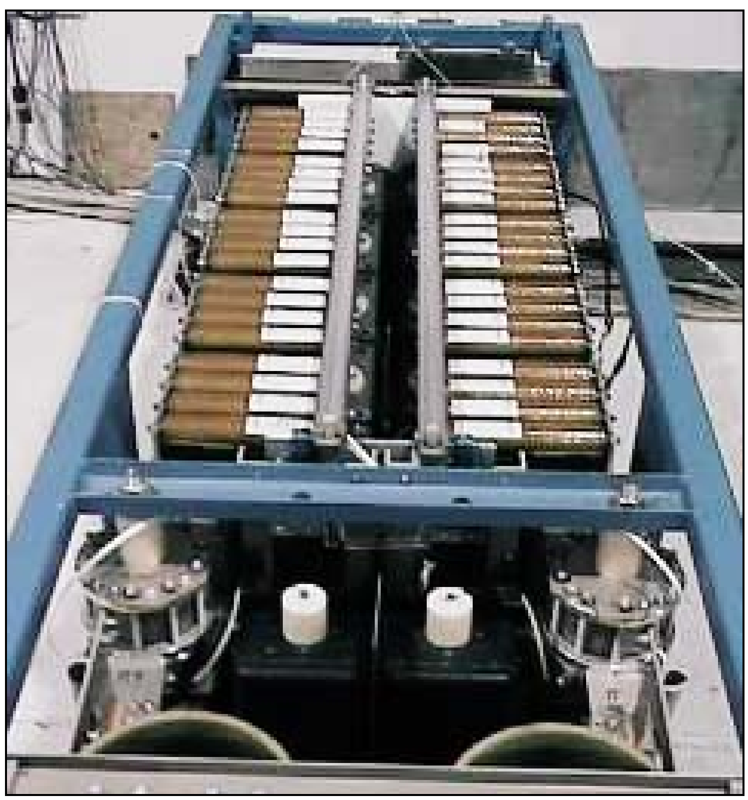

Figure 5. Capacitor fuses (left and right) and trigger generators (foreground).

The trigger generator for each module is located in the rack between ST-300 spark gap switches (see figure 5). The trigger generators use dry air to prevent electrical breakdown and produce over 80 kV into a high impedance load. The signal-to-discharge is sent via fiber optic cables and has a propagation delay of less than 600 ns. The ST-300 spark gaps (see figure 4) are rated at 500 kA with a breakdown voltage of 22 kV at zero pressure. A pressure of 5 psig is used to ensure reliable triggering with the 80-kV pulse from the trigger generator.

1.2.6 High-Voltage Charging Power Supply (HVCPS)

The HVCPS (Hipotronics Inc., Brewster NY, model no. 811-15A) shown in figure 6 is rated for 11 kV and 15 A DC. It is located in the same room as the 18 modules. The charging time for the PPS to reach full voltage (11 kV) can be as short as 60 s, with a maximum current of 15 A. Lower currents are used when charging to lower voltages and/or fewer than 18 modules. The capacitors are charged through a 50-Ω resistor (R_{dp}) located in each module (see figure 2).

Figure 6. HVCPS.

1.2.7 Module Output Cables

The output of each module is conducted through a single 10.7-m-long coaxial cable with a 6-mΩ resistance value (560 μΩ/m) and a 2.02-μH inductance (189 nH/m). Each of the 18 coaxial cables connects at the breech of the railgun.

1.2.8 Controls

The control system (shown in figure 7) is located in the data building adjacent to barricade C. Control is via fiber optic cables. The local controller for the HVCPS (shown in figure 8) is located in barricade C. The local controller is also linked with fiber optic cables and provides

Figure 7. Control console.

Figure 8. HVCPS local controller.

communication between the HVCPS and the consol control via the interface J-box (figure 9). All communications to and from the control console, to the interface J-box, and to the control boxes at each module are via fiber optics.

Recently added to the control system are detectors that measure the peak output current for each module (*3*). This system was added to the control system to provide a means of assessing the performance of the 4.5-MJ PPS without investing in 18 channels of high-speed digitizers. The operator can easily view the peak current and capacitor voltage of each module after a discharge.

Figure 9. Dry gas bottle and its distribution panel, interlock box, and interface J-box (left to right).

1.2.9 Shorting System

A pneumatically actuated shorting mechanism was added to each of the 18 modules. Each mechanism consists of an aluminum channel and two air cylinders positioned at opposite ends of the rack. In the shorted position, the channel makes contact on an array of copper “finger” contacts (see figure 10) secured to each of the five mounting brackets on each capacitor's output terminal. A control lever, centrally located behind a concrete barrier, allows all of the capacitors to be shorted.

Figure 10. Shorting system.

1.3 Charge and Discharge Operations

Operations begin by securing and setting equipment located in the barricade according to the standard operating procedures (SOP) and checklists. The charging current is set on the local controller. The pneumatic shorting system is raised, and the door to the barricade is locked. The desired charge voltage is set on the control console, and all modules are charged (and upon an abort are discharged) safely through a heavy-duty 50-Ω resistor (R_{dp}) (Allen-Bradley model AB67303M235).

When the desired charge voltage is reached per the setting on the control console, the HVCPS reaches a nearly constant voltage mode to maintain the voltage setpoint. When the fire button is pressed, the HVCPS is automatically disconnected and the delay generators which control the firing times of the individual modules, trigger the ST-300s. However, if the fire button is not pressed within 4 min of arming the system, an excess-time fault will occur and cause an automatic abort—the relays will connect the heavy-duty 50-Ω resistors across each module, depleting the energy stored in the capacitors.

2. Incident

An incident occurred on 9 February 2006. The intended charge voltage was 7.2 kV, which is not unusually high for this system or the highest while the system was in operation at barricade C. In fact, in weeks prior to the incident, the average charge voltage for 19 experiments was ~7.6 kV—a necessity in order to meet ARL 6.2 program objectives for FY06.

2.1 Statement of Events

Normal experiment procedures, SOP, and checklists were followed for the final test on Thursday, 6 February 2006. A bang was heard just about when the setpoint was reached (7.2 kV). A discharge was indicated via the peak detectors for modules 5 and 6. Additionally, their charge voltage read zero, further indicating that modules 5 and 6 had indeed produced an output current. When a discharge occurs prematurely (ST-300 pretrigger is typical), the fuses in the charging line typically open, and it is necessary to abort the test, short the system, and replace the affected charging fuse(s). When the incident occurred, the charging cycle was aborted. All charge voltages for the modules then read zero.

The door to the barricade was unlocked and the system was shorted using the pneumatically actuated shorting system. The HVCPS, local controller, and interface J-box systems were turned off.

A hissing sound could be heard emanating from the racks farthest from the barricade entrance. As each capacitor was shorted with the safety grounding stick, it was noticed on module 4 that the aluminum angle, which connects to the center post of one capacitor terminal and the capacitor fuses, was disconnected. The air line to the pneumatic shorting system on module 4 was severed. Upon closer inspection, the rearward facing side of the capacitor was bulged (see figure 11). A clip lead was attached from the remaining center post to the ground bus to complete the grounding operation.

Figure 11. Bulged capacitor in module 4.

While inspecting the remaining modules and subsequent grounding, it was observed that several of the capacitors had discernable arc marks at the center post connection on the capacitor (see figure 12). The center posts on those capacitors were not making a secure connection.

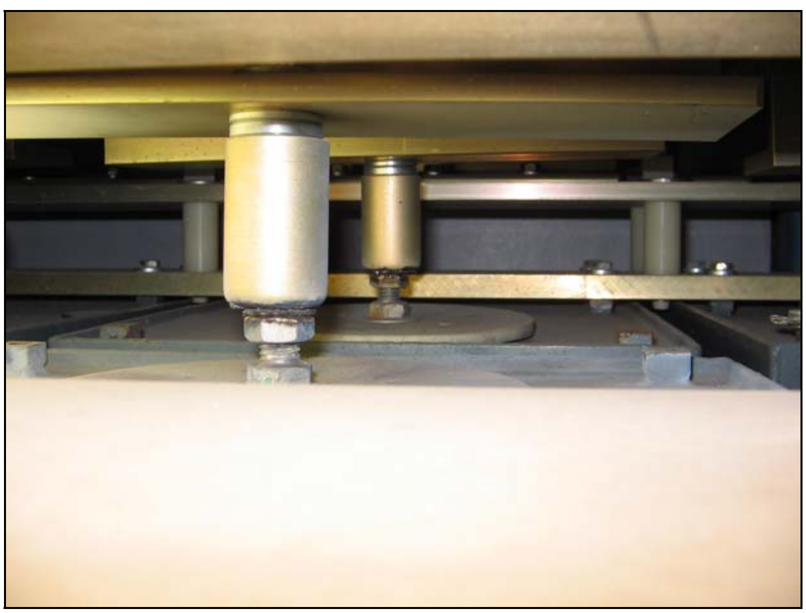

Figure 12. Arc damage at the center post terminals of capacitors.

All capacitor fuses were checked in place and, except for those connected to the single bulged capacitor in module 4, were found to be intact. Additionally, all charging fuses were checked and were also found to be intact. The PPS (and all related subsystems) were rendered completely safe.

2.2 Assessment of Events

Figure 13 shows an illustration of the affected capacitors. It is clear that the damaged capacitor in module 4 was a result of the incident. Recent tests have shown that the arc damage at the center post terminal (see figure 12) was most likely a preexisting condition. The current generated by the fault was not sufficient to open the fuses protecting the other capacitors. As expected, the current from capacitors charged in module 4 that were discharged into the single faulty capacitor opened the fuses.

Currents from modules 5 and 6 were discharged into the gun and armature, as evidenced by the peak detectors and a small displacement of the projectile loaded in the railgun. Pretriggering of the ST-300 has been observed under a variety of situations. The electronics in the trigger generators, resident on each module and adjacent to the capacitors, are susceptible to noise, especially during fault conditions. Modules 5 and 6 discharged after the HVCPS had disconnected from the charging circuit.

3. Recovery

3.1 Operations Prior to Recovery

Preparations were made to assess the state of operations for the system. All modules were individually charged to 3.2 kV and discharged into a short that was connected to the breech of the railgun. The peak current attained was compared to data acquired about 3 years ago (*3*) and was found to be within ±10%—within the accuracy of the measurements and, therefore, essentially unchanged. From the perspective of the damaged center posts, it is likely that the condition existed for quite some time, even while pre-incident operations were continuing. For completeness, it appears that the HVCPS and data acquisition system were also functioning.

The life expectancy of the capacitors cannot be accurately assessed. Clearly, history plays an important role, and data from when the system was operated by GDLS is simply unavailable. It is known from (limited) published work that the system was operated at charge voltages exceeding 9 kV (*4*). Furthermore, all 90 capacitors show signs of rust, most likely due to the uncontrolled temperature and humidity conditions while the modules were in storage for roughly 5 years.

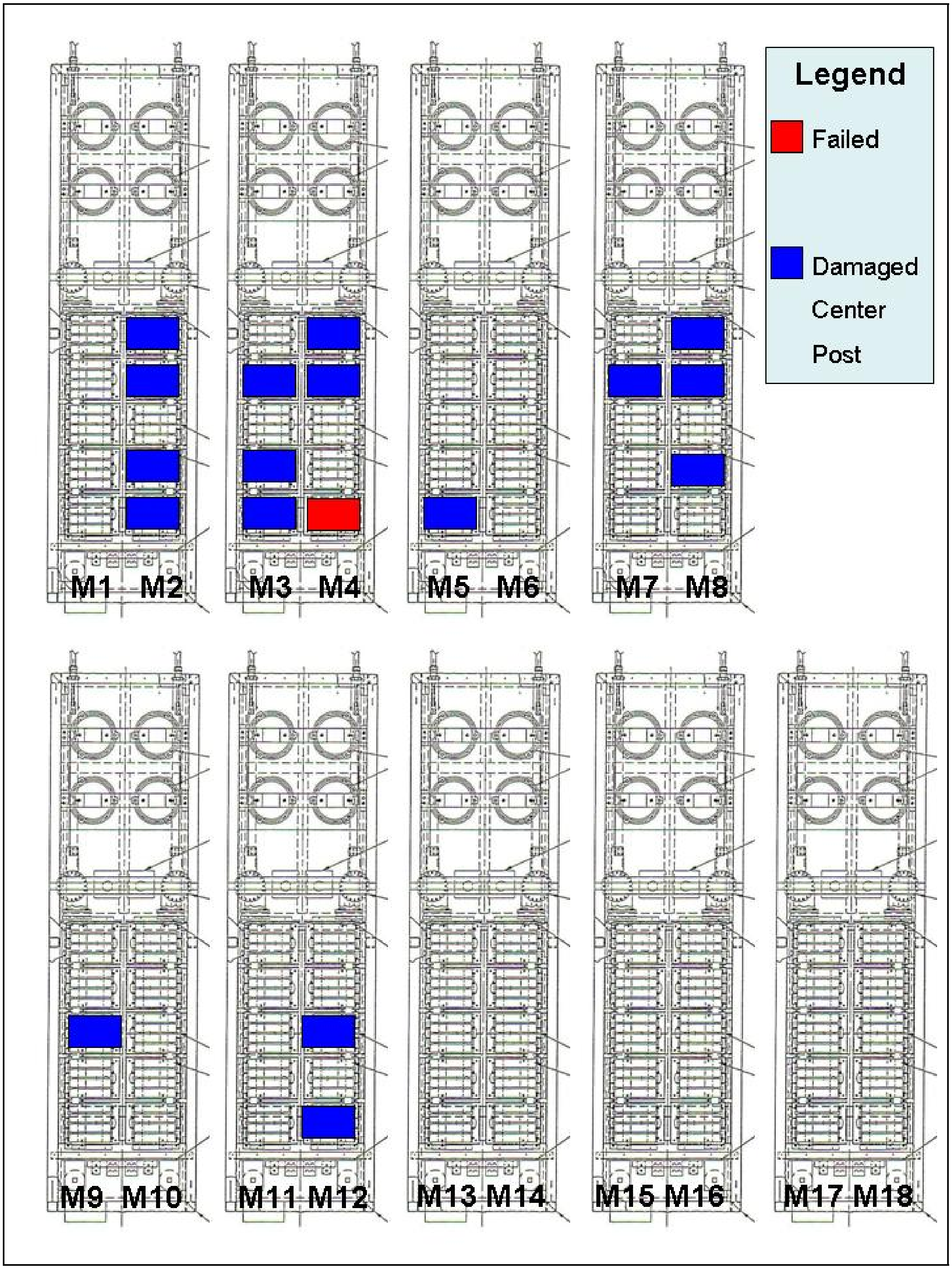

Figure 13. Schematic illustration of affected capacitors.

The type of capacitor used in this system is fabricated with multiple layers of kraft paper and is designed to operate in the corona regime—typically at greater than 85% of the full-rated voltage (~9 kV). The electrons released in the corona damage the dielectric. This damage is cumulative. Eventually, the accumulated damage can cause a breakdown of the dielectric (even at lower voltages that were safe on previous discharges). It is not uncommon for capacitors of this type to fail a life test (i.e., multiple charge and discharge cycles) during the charging cycle at a small fraction of the charge voltage (*5*).

In other facilities that use this type of capacitor technology (i.e., nonsoft failure mode), the cost due to collateral damage can be extensive (*6*). In order to fully ascertain the possibility of another fault using the remaining 89 capacitors, each capacitor would have to be removed from the modules and individually tested for maximum voltage capability. It seems likely that a test of this nature would indeed produce some failed units.

After assessing the benefits of continuing operations, a risk-mitigation plan was developed for the purpose of restoring an interim capability, while sources were sought for new capacitors. The failed capacitor was removed from the module. Also, it seemed pragmatic to operate at less than the charge voltage that initiated the incident (7.2 kV). Considering that all future relevant work for 6.2 and 6.3 Army programs involves charge voltages greater than 7.2 kV, it seems unlikely that any real benefit will be gained by postponing repair and maintenance efforts. An interim operating charge voltage of 6.7 kV seems reasonable. Additionally, there is no benefit to replacing the damaged center posts of the capacitors for the interim (a very time-intensive and laborious endeavor), as the reduced charge voltage from life time already limits the discharge current and minimizes the possibility of further damage.

3.2 Restored Capability

3.2.1 Capacitors

As already mentioned, the capacitors form the primary and essential basis for the PPS. In order to meet Army objectives in electromagnetic launcher and integrated launch package technologies, the PPS must be capable of higher energy operation in a reliable fashion.

Consider the challenge, with regard to pulse shape, that using the original Aerovox capacitors presents. The shape of the current pulse has been found to determine the time when a solid-armature contact transitions from metallic operation to a plasma interface (*7*). A less than ideal pulse shape was selected, based on charge voltage considerations, for the majority of the FY06 tasks. That pulse is shown in figure 14 for a charge voltage of 7.4 kV. The rise time is rather slow, and the duration of the flat portion of the pulse is only a small fraction of the in-bore residence time. Now consider the alternate pulse shown in figure 14, which is better for solid-armature operation and delivers 20% more kinetic energy. This modified pulse, however, relies on achieving a charge voltage of 9.2 kV.

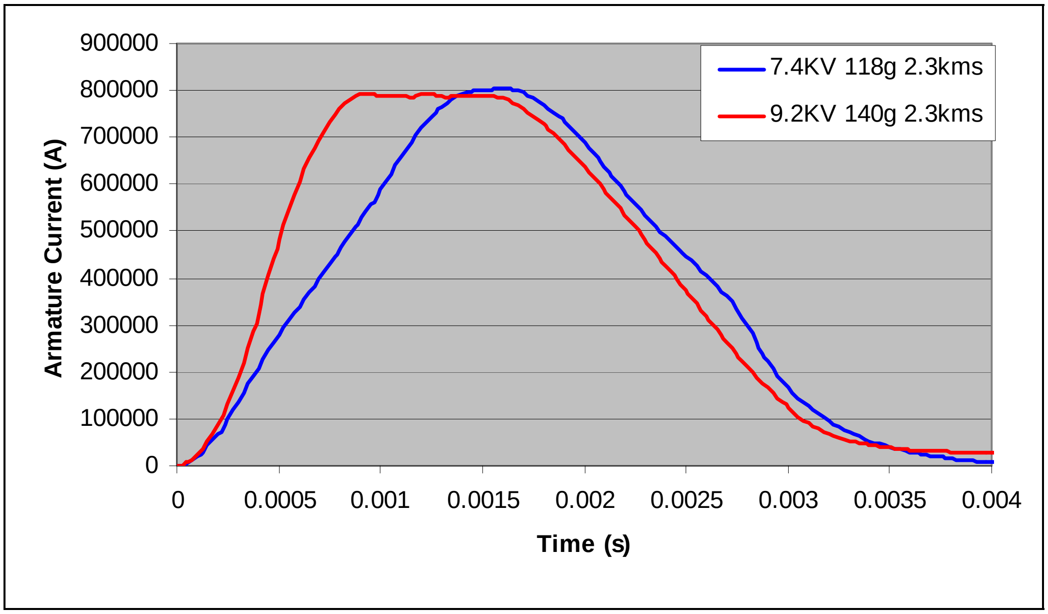

Figure 14. Comparison of pulse shapes for 7.4 and 9.2 kV.

Modern capacitors use metallized polypropylene film for the dielectric and are more robust than the original Aerovox capacitors. Up to 10% extra capacitance can be specified simply because of new manufacturing technology and essentially no impact to components located in the pulse forming network (PFN). Such capacitors are manufactured by General Atomics Electronics System, Inc. (GA-ESI) (San Diego, CA) and have roughly half the volume of the Aerovox capacitors and an increased energy density (2.68 J/cm^3 and 2.27 J/g). The GA-ESI capacitors also have the capability to be overcharged to 13.2 kV without deleterious effects, a 3000 shot life at full energy, and 10% voltage reversal. Finally, the existing bolt pattern is readily incorporated into the new capacitor design such that replacement of the bus work in each module is not necessary.

The refurbishment of the PPS required not only new capacitors but also new center post terminals. After assessing the failed center post, a new connector was designed that should be less prone to failure. This new connector design included a second nut to ensure a more robust connection in the presence of electromagnetic forces and the vibrations due to nearby conventional gun firings. Perhaps more importantly, the new connector was fabricated from brass rather than a chromated aluminum. This change in material should reduce the electrical losses between the steel center post stud and its terminal, thereby minimizing the potential for arcing. A picture of the new connection to the center terminal of the capacitor is shown in figure 15.

Since the new capacitors are half the height of the original capacitors and the bus work was not modified, the new capacitors needed to be raised to the height of the existing bus work. To accomplish this, stands were fabricated and serve as a platform on which to rest the new capacitors. The installation of five new capacitors on the accompanying platform can be seen in figure 16.

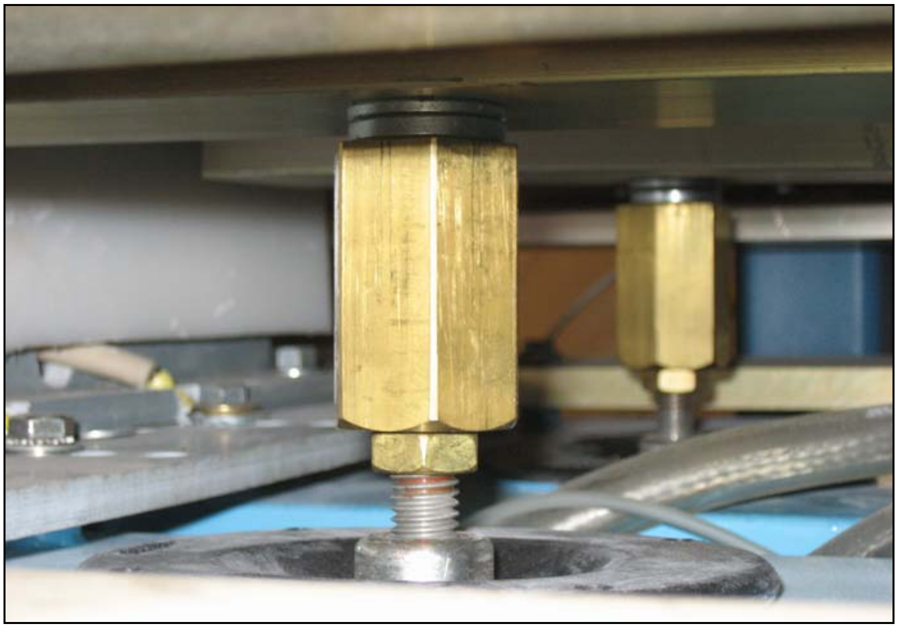

Figure 15. New center terminal connector for capacitor.

Figure 16. Picture of one module with five new capacitors installed.

3.2.2 Bus Work

The bus work that connects the PFN inductors to the coax cable is not related to the capacitor failure. However, the bus work, acceptable at 8 kV, is most likely unacceptable at higher-energy operation. New bus work was designed, fabricated, and installed at the output of each module. A picture of the new bus work is shown in figure 17.

Figure 17. New bus work installed at module output.

3.3 Commissioning

After installing new hardware, it is safe, practical, and prudent to test each module independently in a low resistance and low inductance load (i.e., short). For convenience, the short was connected to the breech. Each module was charged to 3, 5, and 7 kV, and the current was compared to prior validated simulations (*8*). The values for module capacitance were adjusted in the simulations until good agreement was obtained between the measured and calculated current waveforms. Very few adjustments were required to other circuit values. The adjusted capacitance for each module is shown in table 1.

Table 1. Adjusted module capacitance (μF).

Module	Low Inductance Modules (1–9)	Module	High Inductance Modules (10–18)
1	4755.2	10	4725.9
2	4758.3	11	4747.7
3	4738.6	12	4739.2
4	4767.1	13	4728.2
5	4748.1	14	4756.6
6	4750.5	15	4752.9
7	4739.6	16	4747.0
8	4734.8	17	4744.5
9	4735.2	18	4757.1

All modules were operated together by sequentially discharging them into the short. For this test, the peak current in the short must be limited to about 500 kA. A typical pulse shape for operating a railgun can be attained using all the modules at a charge voltage of 5 kV. A comparison of the data and simulation is shown in figure 18. As can be seen, relatively good agreement is obtained through the duration of the discharge.

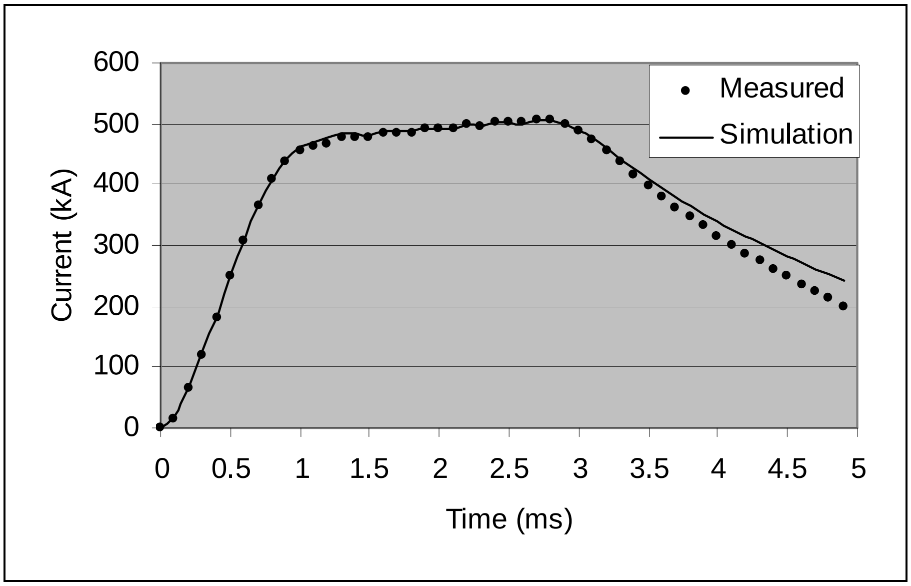

Figure 18. Comparison between data and simulation for sequential discharge test (18 modules).

Lastly, the railgun was substituted for the short connected to the breech. This high-energy operation then serves as a final check of the refurbishment and provides data needed for verifying the simulation capability.

The railgun is comprised of a pair of parallel conducting rails, an epoxy-glass composite (G-10) for bore-insulators, and a laminated steel containment (*9*). Each rail is 32 mm wide and 9.375 mm thick, and the spacing between rail conductors is 44 mm. The laboratory gun (mini-component test launcher [mCTL]) forms a 22- × 44-mm rectangular bore cross section and provides for 2.67 m of travel. A C-shaped armature and payload (nominal mass 180 g) with an armature height of 22 mm was used for the commissioning tests. A picture of the armature and payload is shown in figure 19.

The commissioning tests started at an initial charge voltage of 5 kV. The charge voltage increased as confidence in operations was gained. A comparison of the measured and simulated currents for the 6-kV shot is shown in figure 20. As can be seen, there is relatively good agreement. The majority of the discrepancy occurs during the falling portion of the current when the armature has first transitioned (t = 2.2 ms), albeit momentarily (~50 µs in duration). Thereafter, the contact recovers to a metallic sliding contact with intermittent arcing. The armature contact fully transitions to a plasma interface when the voltage exceeds 70 V at 3.1 ms.

Figure 19. Armature and payload used in commissioning tests (180 g).

Predicting transition in railguns has proven to be elusive. Fortunately, very little projectile acceleration occurs after this event and, therefore, represents very little perturbation to predicting current and exit velocity.

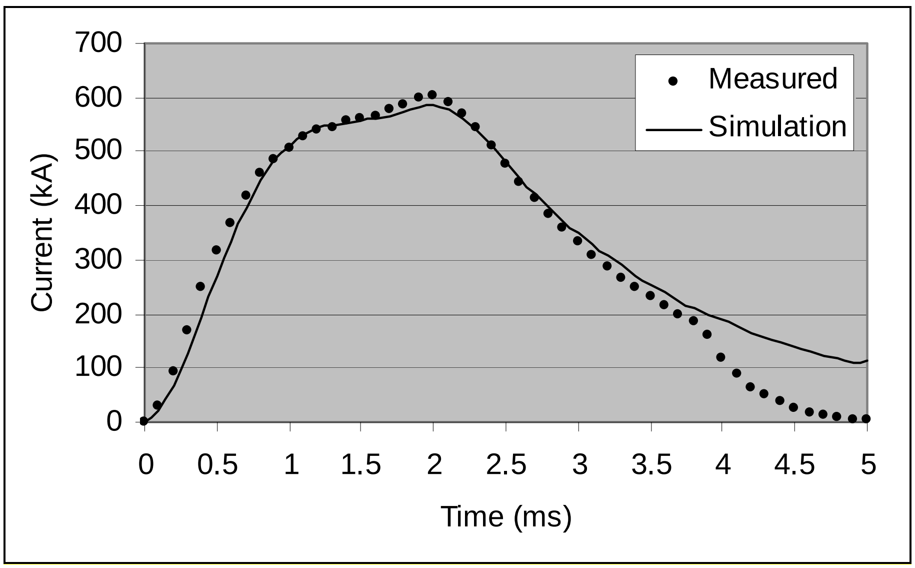

Figure 20. Comparison between measured and simulated currents at 6 kV (mCTL shot 370).

A summary of predicted vs. measured currents and time-to-peak currents are listed in table 2. The simulations assume a constant armature voltage drop of 50 V. As seen, there are at most a few percent differences between measurement and simulation with the largest discrepancy occurring at the lower charge voltages. All data is within 10% of that predicted by the simulation, which is on the order of the accuracy of the instrumentation.

Table 2. Summary of PPS metrics for commissioning shots.

Metric	**5 kV**	**6 kV**	**7 kV**	**8 kV**	**9.2 kV**
Peak Current (kA)					
Data	518	601	678	746	821
Simulation	500	586	667	741	825
Time to Peak (ms)					
Data	2.01	2.01	1.95	1.92	1.39
Simulation	2.00	1.97	1.95	1.93	1.39

The final shot of the commissioning tests was executed at a charge voltage of 9.2 kV. The summary page from the data acquisition system is shown in figure 21. All data were successfully captured and analyzed without incident.

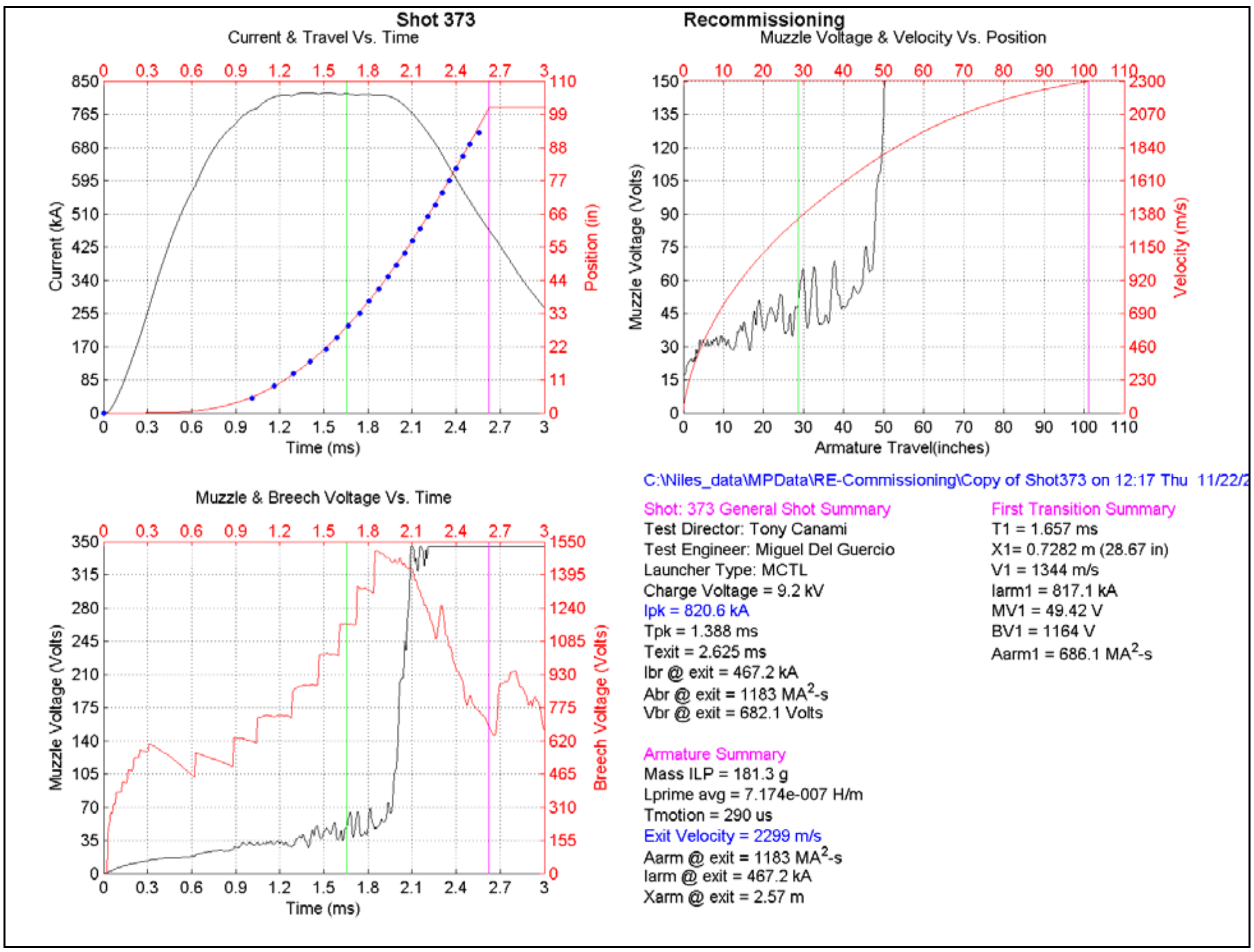

Figure 21. Data summary page from commissioning shot at 9.2 kV (mCTL 373).

4. Summary and Conclusions

An incident occurred during operation of the ARL 4.5-MJ PPS while it was charged to a relatively low voltage. The ensuing developments forced the recovery of operations using modern capacitors and permitted other modifications and maintenance to the modules. The new hardware was installed and operations were restored.

The modules were individually tested with a short at the railgun breech. Circuit values in the simulation were adjusted until good agreement was attained between measured data and simulation. Also, all modules were sequentially discharged into the short-circuit load to verify multimodule operations. Lastly, the railgun was operated with the new hardware. Commissioning tests demonstrated high-energy operations and reasonable agreement between measured data and simulations. The maximum stored energy for the capacitor-based PPS at barricade C is now at 5.2 MJ with increased reliability.

5. References

1. Hammon, H. G.; Bhasavanich, D.; Warren, F. T. Design Approaches to Pulsed Power for Electromagnetic and Electrothermal Gun Systems. *Proceedings of the Pulsed Power Conference*, San Leandro, CA, 1991.

2. Bhasavanich, D.; Strachan, D. F.; Ford, R. 4.5 MJ Modular Pulse Power Supply for ETC Gun Applications *Proceedings of the Pulsed Power Conference*, San Leandro, CA, 1993.

3. Del Güercio, M. *Multiple-Channel Peak Detector for the U.S. Army Research Laboratory's 4.5 MJ Power Supply Module Output Currents*; ARL-TR-2931; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2003.

4. Van Duesen, B. Subscale ETC Firings for Cost Efficient Optimization. Presented at the 11th Meeting of the Electric Launcher Association, Huntington, WV, September 1993.

5. MacDougal, F. General Atomics Electronics Systems, Inc., San Diego, CA. Private communication, 22 February 2006.

6. Merritt, B. T.; Whitham, K. Performance and Cost Analysis of Large Capacitor Banks Using Weibull Statistics and MTBF. Presented at the 3rd IEEE International Pulsed Power Conference, Albuquerque, NM, June 1981.

7. Michlin, A.; Del Güercio, M.; Zielinski, A. Current Pulse Shape on Armature Contact Performance. *Proceedings of the 22nd Electric Launcher Association (ELA) Meeting*, San Diego, CA, 7–9 November 2005.

8. Del Güercio, M. A. *A Spice-Based Code for ARL's 4.5-MJ Electromagnetic Launcher Power Supply System*; ARL-TR-2592; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2001.

9. Keppinger, R. *Railgun Assembly Procedures at the ARL Electromagnetic Gun Experimental Facility*; ARL-MR-574; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2003.

NO. OF COPIES	ORGANIZATION
1 (PDF ONLY)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FORT BELVOIR VA 22060-6218
1	US ARMY RSRCH DEV & ENGRG CMD SYSTEMS OF SYSTEMS INTEGRATION AMSRD SS T 6000 6TH ST STE 100 FORT BELVOIR VA 22060-5608
1	DIRECTOR US ARMY RESEARCH LAB IMNE ALC IMS 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CI OK TL 2800 POWDER MILL RD ADELPHI MD 20783-1197
	ABERDEEN PROVING GROUND
1	DIR USARL AMSRD ARL CI OK TP (BLDG 4600)

NO. OF COPIES	ORGANIZATION
1	DIR FOR THE DIRCTRT OF FORCE DEV US ARMY ARMOR CTR E BRYLA FT KNOX KY 40121-5000
1	US ARMY MATERIEL COMMAND AMC DCG-T 5001 EISENHOWER BLVD ALEXANDRIA VA 22333-0001
1	US ARMY MISSLE CMND AMSMI RD DR MCCORKLE REDSTONE ARSENAL AL 35898-5240
2	US ARMY TACOM TARDEC AMSTA TR D MS 207 J CHAPIN M TOURN ER WARREN MI 48397-5000
1	US ARMY TACOM-ARDEC AMSRD AAR AEW E (D) J BENNETT BLDG 382 PICATINNY ARSENAL NJ 07806-5000
4	INST FOR ADVANCED TECHLGY UNIV OF TX AT AUSTIN I MCNAB F STEPHANI T WATT M CRAWFORD 3925 W BRAKER LN STE 400 AUSTIN TX 78759-5316
2	UNIV OF TX AT AUSTIN CTR FOR ELECT J KITZMILLER J PAPPAS PRC MAIL CODE R7000 AUSTIN TX 78712
1	INST FOR DEFENSE ANALYSIS I KOHLBERG 1801 N BEAUREGARD ST ALEXANDRIA VA 22311

NO. OF COPIES	ORGANIZATION
1	UNIV AT BUFFALO SUNY/AB J SARJEANT PO BOX 601900 BUFFALO NY 14260-1900
2	BAE B GOODELL R JOHNSON MS M170 4800 E RIVER RD MINNEAPOLIS MN 55421-1498
1	UNIV OF TX AT AUSTIN M DRIGA ENS 434 DEPT OF ECE MAIL CODE 60803 AUSTIN TX 78712
1	SAIC J BATTEH 4901 OLDE TOWNE PKY STE 200 MARIETTA GA 30068
1	SAIC K JAMISON PO BOX 4216 FORT WALTON BEACH FL 32542
1	SAIC A WALLS 8303 N MOPAC EXPY STE B 450 AUSTIN TX 78759
2	IAP RESEARCH INC D BAUER J BARBER 2763 CULVER AVE DAYTON OH 45429-3723
1	L-3 COMMUNICATIONS PULSE SCI PULSED SCI DIV T WOLFE 4855 RUFFNER ST STE A SAN DIEGO CA 92111
1	GA ESI F MACDOUGALL GENERAL ATOMICS ELECT SYS 4949 GREENCRAIG LE SAN DIEGO CA 92123

NO. OF
COPIES ORGANIZATION

1 NC STATE UNIV
M BOURHAM
DEPT OF NUCLEAR ENGRG
BOX 7909
RALEIGH NC 27695-7909

INTENTIONALLY LEFT BLANK.