EMACK RAILGUN FIRING TEST REPORT NO. 9

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The test firing of the EMACK railgun test bed was successfully conducted on 20 December 1983 at a peak system current of 430 kiloamperes and 1.6 megajoules stored inertially in the homopolar generator. Current was successfully commutated into the launcher in 800 microseconds. The D1.1 projectile in-flight shadowgraphs were taken with a 150 KV Hewlett Packard flash x-ray system and a motion picture of the muzzle arc was taken with a 5000 frame-per-second high speed camera. The projectile weighed 566 grams and reached a velocity of 506 m/s.
20. ABSTRACT (cont)

in the 5 meter-long barrel. The improved armature design left the barrel intact and acceptable for EMACK shot no. 10.
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TABLE

1. Major Parameters for EMACK test firing 9

FIGURES

1. Launcher B dot pickup coils output versus time
2. Dl.1 before firing
3. Projectile distance, velocity, and acceleration versus time
4. Barrel muzzle voltage versus time
5. View down barrel from muzzle
6. Arc damage at muzzle
7. Range section and make switch (post shot)
8. Make switch used for triggering flash x-ray (brown coloration on face of switch is copper deposited by passing projectile)
9. Flash x-ray photograph of projectile in flight
10. High-speed photograph of muzzle flash
11. Pieces of Dl.1 recovered from catch tank
12. Post shot reconstruction of projectile armature
13. Transient recorder trigger circuit
14. Range arc strippers (post shot)
INTRODUCTION

The ninth test firing of the EMACK railgun test bed was successfully conducted on 20 December 1983 at 430 kiloamperes. This was the second test of the Dl.1 armature design and the first shot of a projected series of firings using the same set of accelerator rails.

The objectives of the test firing were to:

1. Test the Dl.1 projectile armature design at low launcher current
2. Establish the correlation between interference fit and insertion force on switch and projectile armatures
3. Make the first shot in a multi-shot barrel
4. Test a new flash x-ray diagnostic setup
5. Photograph muzzle blast and projectile flight with a high speed motion picture camera
6. Improve the catch tank vacuum
7. Employ a new arc stripper design
8. Test a new transient recorder trigger circuit
9. Correlate arc intensity and projectile position in the barrel
10. Recover the projectile intact in the catch tank

DISCUSSION

This low energy shot produced a launch velocity of 506 m/s that was calculated from the position-versus-time data obtained from B-dot pickup coils on the launcher barrel (fig. 1). The launch package (preshot) is shown in figure 2. Plots of projectile distance, velocity, and acceleration versus time are shown in figure 3 and the relevant shot parameters, both predicted and actual, are listed in table 1.

The muzzle voltage trace (fig. 4) indicates that the improved projectile armature design reduced rail damage. Also no arc was detected by the two pin diodes at the breech. Rail damage was minimal and restricted to the muzzle. The barrel and range were nearly free of soot and were generally cleaner than after any previous shot (figs. 5 through 7). After examination by borescope, the barrel was broached and swabbed with acetone in preparation for test 10. The broaching operation removed only a few slivers of copper.
Two of the three flash x-ray diagnostic stations succeeded in producing shadowgraphs of the projectile in flight. The foil triggering system after the test is illustrated in figures 7 and 8. One of the two shadowgraphs (fig. 9) illustrates the launch package's integrity during flight.

The high speed camera (5,000 frames per second) recorded the travel of an arc as the projectile left the barrel (fig. 10). The fifth frame showed debris from the foil switch being pushed downrange. The velocity of the tip of the arc is approximately 445 m/s, slightly slower than the projectile's launch velocity.

The catch tank vacuum was improved by welding all the seams and using an O-ring seal for the catch tank top. This resulted in a 35% improvement in catch tank vacuum from that obtained in shot 8.

While an attempt to soft catch the launch package failed, enough of the projectile and armature fragments were recovered to permit visual inspection (figs. 11 and 12). Examination of the armature fragments showed that there was minimal arc damage to the brushes. Melting of the copper fiber brushes was restricted to the contact surfaces (fig. 12).

The transient recorder trigger circuit (fig. 13) proved effective. The circuit divided the Rogowski coil output by 10 and then differentiated it to obtain a sharper rise time. Plots of recorded data are given in appendix B. The homopolar generator voltage data on Biomation Unit A (app A) was lost due to incorrect sensitivity settings. Preshot component inspection, switch delay tests, and homopolar generator parameters are also included in appendix A.

The effectiveness of the conical arc stripper could not be determined because of the redesigned armature and low kinetic energy; however, the stripper withstood the muzzle blast effects (fig. 14).

The actual insertion forces for the projectile and switch armature were 322 lb and 1,250 lb, respectively. The corresponding predicted values were 375 lb and 563 lb. A discussion on the calculation and correlation between the insertion force and the armature interference fit is included in appendix C.

The velocity of the rail switch armature was calculated to be 34 m/s. This calculation is as follows:

An approximation of the velocity of the railswitch armature was achieved through measurement of the volume of the displaced aluminum honeycomb material used in the switch catcher. The volume of crushed honeycomb material is proportional to the work done on it. The proportionality constant is called the resistivity

\[ W = (V) (R) \]
The honeycomb had a nominal resistivity of 600 inch-pound per cubic inch. After the test, the displaced volume of aluminum was found to be $134.14$ inch$^3$; therefore, the total work done on the impact-absorbing aluminum was

$$W = (134.14) (600) = 80,484.0 \text{ in.-lb}$$

$$= 6,707 \text{ ft-lb}$$

$$= 9,094.69 \text{ Joules}$$

If heat and other negligible energy losses during impact are neglected, the armature kinetic energy can be found from $\frac{1}{2} MV^2$.

$$W = E_K = \frac{MV^2}{2} ; M = 15.19 \text{ kg}$$

$$V = \frac{2W}{M} = \sqrt{\frac{2 (9094.69)}{15.19}}$$

$$= 34.6 \text{ m/s}$$

Methods for a continuous measurement of switch armature velocity in the severe railswitch environment are being devised for future tests.

CONCLUSIONS

Despite the discrepancies between predicted and actual values, test firing 9 produced a significant amount of data. The redesigned projectile/armature carried a maximum current of 370 kiloamperes and demonstrated how proper armature design can significantly reduce rail wear and improve launcher efficiency. The flash x-ray and high speed motion camera proved to be a useful diagnostic tool in determining projectile velocity and flight stability. The improved catch tank yielded a fragmented D1.1 projectile, yet it could still be reconstructed. Rail and insulator damage was minimal and the barrel will be used in EMACK firing 10.

RECOMMENDATIONS

1. Proceed with test firing 10 using the D1.2 projectile and the same set of rails used in test firing 9.

2. Employ improved methods for measuring the system current.
Table 1. Major parameters for EMACK test firing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Predicted</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPG stored energy (kJ)</td>
<td>2,000</td>
<td>1,600</td>
</tr>
<tr>
<td>Drive motor speed (RPM)</td>
<td>2,200</td>
<td>2,017</td>
</tr>
<tr>
<td>Generator voltage (V)</td>
<td>35</td>
<td>--</td>
</tr>
<tr>
<td>Field excitation current (A)</td>
<td>1,300</td>
<td>1,324</td>
</tr>
<tr>
<td>Peak system current (kA)</td>
<td>750</td>
<td>430</td>
</tr>
<tr>
<td>Current rise time (ms)</td>
<td>122</td>
<td>119</td>
</tr>
<tr>
<td>Commutation time (us)</td>
<td>550</td>
<td>800</td>
</tr>
<tr>
<td>Switch armature velocity (m/s)</td>
<td>--</td>
<td>34</td>
</tr>
<tr>
<td>Maximum projectile velocity (m/s)</td>
<td>800</td>
<td>506</td>
</tr>
<tr>
<td>Launch package mass (g)</td>
<td>600</td>
<td>566</td>
</tr>
<tr>
<td>Launch package kinetic energy (kJ)</td>
<td>192</td>
<td>73</td>
</tr>
<tr>
<td>Peak acceleration (kG)</td>
<td>21.5</td>
<td>8.6</td>
</tr>
<tr>
<td>Charging efficiency (%)$^1$</td>
<td>--</td>
<td>22</td>
</tr>
<tr>
<td>Accelerator efficiency (%)$^2$</td>
<td>--</td>
<td>23.8</td>
</tr>
</tbody>
</table>

$^1$ $\eta_{\text{charging}} = \frac{E_{\text{toroid}}}{E_{\text{HPG}}}$

$^2$ $\eta_{\text{ACC}} = \frac{E_{\text{projectile}}}{E_{\text{switch point}}}$
Figure 2. D1.1 before firing
Figure 3. Projectile distance, velocity, and acceleration versus time
Figure 4. Barrel muzzle voltage versus time
Figure 5. View down barrel from muzzle
Figure 6. Arc damage at muzzle
Figure 7. Range section and make switch (post shot)
Figure 8. Make switch used for triggering flash x-ray
(brown coloration on face of switch is copper deposited by passing projectile)
Figure 9. Flash x-ray photograph of projectile in flight
Figure 10. High-speed photograph of muzzle flash
Figure 11. Pieces of D1.1 recovered from catch tank
Figure 12. Post shot reconstruction of projectile armature
Figure 13. Transient recorder trigger circuit

Figure 14. Range arc strippers (post shot)
APPENDIX A

SYSTEM COMPONENT PRE-SHOT INSPECTION
List of Measured Parameters

Rotor speed
Homopolar generator field current
Homopolar generator voltage
Switch breech voltage
Barrel breech voltage
Barrel muzzle voltage
Storage inductor I dot
Barrel I dot
Projectile position in barrel
Light intensity of projectile arc
Vacuum system pressure
Homopolar generator lubrication system and gas system pressures
Homopolar generator drive system, excitation ring coolant system and lubrication system temperatures
Homopolar rotor vibration

Transient Recorder Setup

Biomation A:

CHA1 - Inductor I dot
Sensitivity: 10-V full scale
CHA2 - Homopolar generator voltage
Sensitivity: 2-V full scale

Biomation B:

CHA1 - Barrel I dot
Sensitivity: 20-V full scale
CHA2 - Switch breech voltage
CHA3 - Barrel breech voltage
CHA3 - Barrel muzzle voltage
CHA4 - Barrel muzzle voltage
CHA5 - Position coil
CHA6 - Position coil
Vacuum System Pressures

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel and range (in. Hg)</td>
<td>27.5</td>
</tr>
<tr>
<td>Catch tank (in. Hg)</td>
<td>29.0</td>
</tr>
</tbody>
</table>

Homopolar Generator Gas System Pressures

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
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<tbody>
<tr>
<td>Seal gas (psi)</td>
<td>4.0</td>
<td>--</td>
</tr>
<tr>
<td>Cover gas (psi)</td>
<td>1.0</td>
<td>--</td>
</tr>
<tr>
<td>Flow to brushes (cfm)</td>
<td>10</td>
<td>--</td>
</tr>
<tr>
<td>Bubbler gas (psi)</td>
<td>8</td>
<td>--</td>
</tr>
<tr>
<td>Accumulator (psi)</td>
<td>105</td>
<td>35</td>
</tr>
<tr>
<td>Bottle (psi)</td>
<td>2,000</td>
<td>--</td>
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</table>

Homopolar Generator Lubrication System Pressures

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Oil inlet (psi)</td>
<td>15</td>
</tr>
<tr>
<td>Pump (psi)</td>
<td>29</td>
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Homopolar Generator Drive System Temperatures

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<thead>
<tr>
<th></th>
<th>Fore</th>
<th>Aft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Journal bearings (°C)</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>Thrust bearings (°C)</td>
<td>44</td>
<td>34</td>
</tr>
</tbody>
</table>

Homopolar Generator Excitation Ring Coolant Temperatures

<table>
<thead>
<tr>
<th></th>
<th>Fore</th>
<th>Aft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (°C)</td>
<td>20</td>
<td>22</td>
</tr>
</tbody>
</table>

Homopolar Generator Lubrication System Temperatures

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet (°C)</td>
<td>30</td>
</tr>
<tr>
<td>Ambient (°C)</td>
<td>27</td>
</tr>
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</table>

Homopolar Generator Rotor Vibration

<p>| | |</p>
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Fore (in.)</td>
<td>0.16E-3</td>
</tr>
<tr>
<td>Aft (in.)</td>
<td>0.04E-3</td>
</tr>
</tbody>
</table>
### Switch Armature Mechanical Inspection

<table>
<thead>
<tr>
<th>Spec</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Length (in.)</td>
<td>20.125</td>
</tr>
<tr>
<td>Mass (lb)</td>
<td>32.5</td>
</tr>
<tr>
<td>Contact bending angle (deg.)</td>
<td>37.5</td>
</tr>
<tr>
<td>Insertion force (lb)</td>
<td>1,250</td>
</tr>
<tr>
<td>Contact thickness (in.)</td>
<td></td>
</tr>
<tr>
<td>Top front</td>
<td>2.018</td>
</tr>
<tr>
<td>Top center</td>
<td>2.02</td>
</tr>
<tr>
<td>Top rear</td>
<td>2.023</td>
</tr>
<tr>
<td>Bottom front</td>
<td>2.016</td>
</tr>
<tr>
<td>Bottom center</td>
<td>2.019</td>
</tr>
<tr>
<td>Bottom rear</td>
<td>2.022</td>
</tr>
</tbody>
</table>

The positive contact side of the armature showed little or no wear from the previous shot. The negative contact side showed some arc damage on the forward half of the armature. The rearward half was clean.

Delrin sheets were used on the arc chamber as an ablative material.

### Switch Armature Electrical Inspection

500 volts were applied across the contact surface and the tailpiece. No current leakage was observed.

### Switch Mechanical Inspection

- Ablative material in switch - GP03
- Age of ablative material - 4 shots
- Age of switch rails - 4 shots
- Condition of switch rails - minor pitting was observed, otherwise the rails were in good condition.
**Projectile**

**Type**
D1.1

**Mass of projectile**
566 g

**Mass of armature**
- Copper fiber: 259 g
- Stainless steel: 47 g

**Initial position**
(measured from breech to rear of projectile)
6.375 in.

**Barrel Mechanical Inspection**

**Terminal contact condition**
- Positive upper
- Positive lower
- Negative upper
- Negative lower
  \{ Good, no change from previous shot \}

**Contact condition of jumpers**
- Positive (steel) upper:
  - Barrel contact
  - Switch contact
- Positive (steel) lower:
  - Barrel contact
  - Switch contact
- Negative (copper) upper:
  - Barrel contact
  - Switch contact
- Negative (copper) lower:
  - Barrel contact
  - Switch contact
  \{ Good, no change from previous shot. \}

**Rail condition**
- new

**Clamp bolt condition**
- good, none damaged

**Barrel Electrical Inspection**

<table>
<thead>
<tr>
<th></th>
<th>Negative bus</th>
<th>Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied voltage (V)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Leaking current (A)</td>
<td>140E-6</td>
<td>155E-6</td>
</tr>
<tr>
<td>Resistance to ground (ohms)</td>
<td>3.58E6</td>
<td>3.23E6</td>
</tr>
</tbody>
</table>
### Switch Honeycomb Volume

<table>
<thead>
<tr>
<th>No. of pieces</th>
<th>Dimensions of each piece (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>End of catcher</td>
<td>7 X 10 X 3</td>
</tr>
<tr>
<td>Middle of catcher</td>
<td>4.25 X 8 X 3</td>
</tr>
<tr>
<td>Next to switch muzzle</td>
<td>6 X 9.75 X 3</td>
</tr>
</tbody>
</table>

### Switch Electrical Inspection

<table>
<thead>
<tr>
<th></th>
<th>Negative rail</th>
<th>Positive rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied voltage (V)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Current leakage (A)</td>
<td>0.2E-6</td>
<td>0.2E-6</td>
</tr>
<tr>
<td>Resistance to ground (ohms)</td>
<td>500E6</td>
<td>500E6</td>
</tr>
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</table>

### Switch Delay Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Switch delay time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51.2</td>
</tr>
<tr>
<td>2</td>
<td>29.8</td>
</tr>
<tr>
<td>3</td>
<td>34.8</td>
</tr>
<tr>
<td>4</td>
<td>59.4</td>
</tr>
<tr>
<td>5</td>
<td>58.9</td>
</tr>
<tr>
<td>6</td>
<td>59.2</td>
</tr>
<tr>
<td>7</td>
<td>58.5</td>
</tr>
<tr>
<td>8</td>
<td>61.0</td>
</tr>
<tr>
<td>9</td>
<td>59.1</td>
</tr>
<tr>
<td>10</td>
<td>61.7</td>
</tr>
<tr>
<td>11</td>
<td>85.8*</td>
</tr>
<tr>
<td>12</td>
<td>83.1*</td>
</tr>
<tr>
<td>13</td>
<td>83.4*</td>
</tr>
<tr>
<td>14</td>
<td>85.1*</td>
</tr>
</tbody>
</table>

Charge pressure: 300 psi  
Wet bulb temperature: 62 °F  
Dry bulb temperature: 68 °F

* Tests immediately prior to shot used to determine switch control system trigger time.
APPENDIX B

PLOTS OF RECORDED DATA
ROGOWSKI COIL OUTPUT, $\text{DI/DT}$

EXPANSION OF $\text{DI/DT}$ TRACE DURING PROJECTILE ACCELERATION

- **SWITCH COMMUTATION**
- **PROJECTILE COMMUTATION**
CURRENT PROFILE OBTAINED FROM INTEGRATION OF COIL DI/DT TRACE

EXPANSION OF CURRENT WAVEFORM NEAR CURRENT PEAK

PEAK SYSTEM CURRENT
SWITCH COMMUTATION STARTS
SWITCH COMMUTATION ENDS/
PROJECTILE ACCELERATION STARTS

PROJECTILE EXITS BARREL
REMAINING ENERGY IS DISSIPATED AS HEAT IN THE MUZZLE RESISTOR AND ARC.
LAUNCHER B DOT PICK UP COILS OUTPUT vs. TIME

VOLTS

2.00
1.00
0.00
-1.00
-2.00

TIME (SEC)

-1.00 0.00 1.00 2.00 E-2
APPENDIX C

CALCULATION OF ARMATURE INSERTION FORCE
Assuming that the magnetic field is uniform along the surface of the armature cross member, and since the magnitude of the acceleration force on the armature is known to be

\[ F = \frac{L' I^2}{2} = WIB \]

an expression relating the magnetic flux density to the inductance gradient and current through the armature can be found

\[ B = \frac{L' I}{2W} \]

The force normal to the rails caused by the Lorentz force on a current-carrying fiber is

\[ F_N = (\Delta L \sin \theta) \frac{L' I^2}{2W} \]

If the minimum contact force between armature and rail surface is 1-gram per ampere or \(10^{-2}\) newtons per ampere, then a minimum value for \(\Delta L \sin \theta\) can be obtained

\[ (\Delta L \sin \theta)_{\text{min}} = \frac{(F_{N_{\text{min}}}) (2W)}{(L'I)} \]

The normal Lorentz force combined with the mechanical force at loading must be greater or equal to the desired minimum; therefore

\[ F_N = K_1 I^2 + F_{\text{preload}} \geq K_2 I \]

where

\[ K_1 = \frac{(\Delta L \sin \theta) L'}{2W} \quad \text{(newtons per ampere}^2\text{)} \]

and

\[ K_2 = 10^{-2} \quad \text{(newtons per ampere)} \]
In order to select a preload force to satisfy this condition, the critical current at which the greatest shortfall occurs must be found for the Lorentz normal force with respect to the required normal force. Therefore

\[
\frac{dF}{dI} = \frac{dF_{N, \text{reference}}}{dI}
\]

\[
2K_1 I_{\text{crit}} = K_2
\]

\[
I_{\text{crit}} = \frac{(10^{-2}) W}{(\Delta L \sin \theta) L'}
\]

and

\[
F_{\text{preload}} = K_1 I_{\text{crit}}^2 = \frac{(10^{-4}) W}{2(\Delta L \sin \theta) L'}
\]

The normal force required for a two-sided brush is

\[
F_N = \frac{(10^{-4}) W}{(\Delta L \sin \theta) L'}
\]

and the force required to insert the projectile into the barrel is

\[
F_{\text{insert}} = (F_N)(u) \text{ (newtons)}
\]

It is significant to note that the armature insertion force is not dependent upon the brush contact area but upon the inductance gradient alone. Having developed the necessary equations, a solution can be found for the relevant parameters for both the switch and projectile armatures (table C-1).

**Table C-1. Armature preload calculation parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Switch armature</th>
<th>Projectile armature</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L' ) (\mu H/m)</td>
<td>0.2</td>
<td>0.45</td>
</tr>
<tr>
<td>( W ) (mm)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>( (\Delta L \sin \theta)_{\text{min}} ) (mm)</td>
<td>2.5</td>
<td>1.11</td>
</tr>
<tr>
<td>( (\Delta L \sin \theta)_{\text{actual}} ) (mm)</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>( I_{\text{crit}} ) (kA)</td>
<td>833.3</td>
<td>555.5</td>
</tr>
<tr>
<td>( F_{\text{insert}} ) (lbf)</td>
<td>563</td>
<td>375</td>
</tr>
</tbody>
</table>

Note: \( I_{\text{max}} = 2 \text{ MA} \)

\( \mu_s = 0.3 \)
DISTRIBUTION LIST

Commander
Armament Research and Development Center
U.S. Army Armament, Munitions and
Chemical Command
ATTN:  SMCAR-LCA-G (10)
       SMCAR-QAR-R
       SMCAR-SF
       SMCAR-TSS (5)
Dover, NJ 07801-5001

Commander
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