**LARGE AND SMALL CALIBER RAILGUN SOLID ARMATURES:
EXPERIMENTAL RESULTS**

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Large and Small Caliber Railgun Solid Armatures: Experimental Results

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Abstract: Experimental characterization of rail-gun solid/transitioning armature performance in both small (<45 mm diameter) and large-bore railguns (>45 mm diameter) has been a continuing effort at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). CEM-UT has placed considerable emphasis on the development of solid armatures for tactical railgun systems with the goal of increased system efficiency, reduced system complexity, and reduced bore damage. This paper reports solid/transitioning armature performance results of two CEM-UT railgun programs.

Solid armature experiments at CEM-UT continue for 15 and 90 mm bore guns. These armatures have been accelerated to over 2,300 m/s. For the armatures tested, typical muzzle voltage measurements show the armature drop remains less than 50 V for velocities under 1,000 to 1,200 m/s; at velocities above 1,000 m/s to 1,200 m/s, the contact transitions to form a hybrid armature. Armature performance data presented include muzzle voltage, gun current, armature resistance, total energy deposited in the armature, launch velocity, launch package muzzle kinetic energy, peak armature action, armature contact wear, and physical examination of recovered armatures. These data are separately summarized for each gun type and demonstrate armature survival at high current densities, bore pressures, and specific action.

Large Caliber Solid Armature Experimental Results

In the 9 MJ Laboratory and Range Gun Program[1], solid armature development evolved from multi-contact monolithic armatures fired from a 13 mm square bore gun, through axisymmetric monolithic armatures fired from a 45-mm bore, half-scale version of the 9 MJ laboratory gun (9MJLG)[2,3], to the 7075 T654 aluminum, single contact, U-shaped configuration

Figure 1. CEM-UT metal armature and integral payload

shown in figure 1. (The integral payload and front bore rider is included to test armature performance with a low risk accelerated mass.) Nineteen shots have been performed in the full-scale 90 mm 9MJLG (table 1). These experiments have resulted in the highest projectile package muzzle kinetic energies and armature velocities demonstrated to date in a railgun utilizing metal armature drives. Successful shots have been performed at muzzle energies up to 5.9 MJ, velocities up to 2,325 m/s and peak gun currents of 3.4 MA. After performance was demonstrated at incremental velocities and currents, armatures were fabricated sans the payload section (the material ahead of the aft bore rider), subsequently mated to appropriate launch packages and tested. These tests have demonstrated the feasibility of using metal armatures to launch sabot aerodynamic projectiles weighing over 1,600 g at high velocities and are discussed by Hayes[4] and Hayden[5]. Armature mass in these tests was ~ 1,000 g.

Table 1. Summary of 90 mm solid armature tests

Shot #	Muzzle Velocity (m/s)	Package Mass (kg)	Muzzle Energy (MJ)	Peak Current (MA)	Action at exit (GA ² ·s)	Peak Accel. (kgees)	Bore Diameter (mm)	Insertion Force (kN)	Description of Launch Package
1	1,455	1.872	2.0	2.20	15.3	48.8	88.65	52.2	U-shaped armature with integral payload.
2	1,999	1.889	3.8	3.22	21.6	102.2	89.54	75.6	U-shaped armature with integral payload.
3	850	2.435	0.9	0.47	N/A	1.7	90.30	29.8	U-shaped armature. Ford dummy projectile.
4	1,725	2.468	3.7	3.05	N/A	71.1	90.53	99.5	U-shaped armature. Ford dummy projectile.
5	1,205	2.476	1.8	3.10	N/A	73.2	90.73	69.4	U-shaped armature. Kaman nonseparating sabot/dummy dart.
6	1,724	2.467	3.7	3.01	N/A	69.3	90.86	45.7	U-shaped armature. Kaman dummy dart/separating sabot.
7	980	1.926	0.9	1.14	N/A	47.2	90.98	59.7	U-shaped armature with integral payload.
8	780	2.480	0.8	2.72	10.1	56.3	91.06	54.7	U-shaped armature. Kaman LAAP/separating sabot.
9	2,140	1.985	4.5	3.16	25.7	94.9	91.19	44.5	U-shaped armature with integral payload.
10	1,945	2.022	3.8	3.34	21.7	104.0	91.97	106.8	U-shaped armature/integral payload w fore and aft boreriders.
11	2,303	2.176	5.8	3.40	27.5	100.2	92.51	104.5	U-shaped armature/integral payload w fore and aft boreriders.
12	2,325	2.175	5.9	3.21	29.0	89.3	92.89	160.1	U-shaped armature/integral payload w fore and aft boreriders.
13	1,969	2.258	4.4	3.27	24.5	89.1	93.40	91.2	U-shaped armature/integral payload w fore and aft boreriders.
14	1,655	2.343	3.2	2.75	21.0	60.7	94.13	160.1	U-shaped armature/integral payload w fore and aft boreriders.
15	1,697	2.665	3.8	2.97	24.2	62.4	94.36	84.5	U-shaped armature. Kaman LAAP/separating sabot.
16	1,851	2.331	4.0	3.00	N/A	72.8	94.50	115.6	U-shaped armature/integral payload, fore and aft boreriders.
17	1,623	2.674	3.5	2.95	23.9	61.4	94.94	50.3	U-shaped armature. Kaman LAAP/separating sabot.
18	1,605	2.350	3.0	2.82	19.4	63.8	95.22	133.0	U-shaped armature/integral payload w fore and aft boreriders.
19	2,110	2.393	5.3	3.15	N/A	78.2	95.40	130.5	U-shaped armature/integral payload w fore and aft boreriders.

Figure 2. Gun current and muzzle voltage from 90 mm shot 12

Figure 3. Muzzle voltage vs v^* for 90 mm shots 1,2,9,10 and 12

Figure 4. Armature resistance vs v^* for 90 mm shots 1,2,9,10 and 12

Performance of the armature design used in the experiments listed in table 1 has been quite consistent. As of this writing, shot 12 has achieved the highest muzzle energy of any EM gun utilizing a metal armature. Gun current and muzzle voltage from shot 12 are shown in figure 2. Typical B-dot signals may be seen in Hayes, et al.[4].

In order to discuss U-shaped armatures with integral payload performance, data for five experiments covering a range of peak currents and velocities has been compiled. Shots 1, 2, 9, 10, and 12 are discussed below.

For these shots, armature muzzle voltage drop, armature resistance, and total energy deposited in the armature are plotted against a common velocity axis. Projectile velocity was obtained by integration of the measured gun current while assuming constant gun inductance gradient and constant launch package mass with all retarding forces neglected (friction, windage, etc.)[6]. Integration yields:

$$v^* = L' \int I^2 dt / 2m ,$$

where L' is the gun inductance gradient, I is the instantaneous gun current, and m is the total accelerated mass. Using this relationship, figure 3 displays a composite plot of muzzle voltage from several shots against this "inferred" velocity and is intended to show the trend in muzzle voltage with increasing velocity as opposed to providing detail of any particular shot. The actual voltage measurements, $V(t)$, may have suffered from the imposition of a high frequency signal resulting partially from the measurement technique. Due to the nonconstant acceleration, the transformation from $V(t)$ to $V(v^*)$ causes this signal to compress with increasing velocity, as seen in the plots (fig. 3). It is evident that the muzzle voltage varies greatly as a function of projectile velocity. This variation falls into two relatively distinct regimes: low muzzle voltage, under 50 V, at velocities under about 1,000 m/s, followed by a region between 1,000 and 2,000 m/s, where the muzzle voltage steadily climbs to values between 250 and 700 V at muzzle exit.

Figure 5. Gun current and resistive energy dissipated in the armature, 90 mm shots 1,2,9,10 and 12

Apparent armature resistance, V_{muzzle} divided by gun current, is shown in figure 4. Armature resistance stays low for low velocities, under 1000 m/s, and increases by over two orders of magnitude at exit. Armature performance may be more clearly represented by the total energy deposited in the armature (the integral of the product of muzzle voltage and gun current). This resistive energy loss and corresponding gun current vs v^* are shown in figure 5. These parameters are good indicators of the nature of armature performance in the 90 mm bore gun and show that the armature contact is consistently transitioning from solid to plasma at velocities over 1,000 m/s.

This set of curves is also useful for comparing transitioning metal armature and purely plasma armature performance in terms of efficiency (the ratio of non-armature mass kinetic energy to energy input to the breech of the gun) in launching useful (nonarmature) mass from an EM gun. The data clearly shows that the electrical energy dissipated in the armature early in the shot is quite low because of the initially low muzzle voltage; conversely, for plasma armatures with constant muzzle voltages on the order of 680 to 750 V at peak currents of 2.4 to 3.5 MA, respectively[7], (or, at lower currents, 250 to 400 V at ~1.5 MA[8,9]), the resistive energy lost in the armature is dramatic for early times. This energy is manifest primarily as heat radiated in the bore and contributes to significant rail and insulator damage for plasma armatures initiated with the projectile at rest in the gun bore; injection of projectiles into the gun at velocities of several hundred m/s prior to plasma initiation has mitigated low velocity bore damage[9,10] at the expense of increased gun system complexity. Of course, part of the energy savings realized when using a metal armature must be expended on accelerating the metal armature mass. In each case considered here, the energy expended in armature kinetic energy ranged from 1.1 to 2.7 MJ.

Hayes[4] addresses in detail armature and bore interaction observed in 9MJLG, 90 mm, solid-armature shots and discusses shot-to-shot bore dimensional increases requiring intershot honing operations to remove localized insulator delamination voids which resulted from defective bore insulator material fabrication procedures. In all shots to date, no rail or insulator damage has been observed where armatures are

accelerated from a non injected, rest position in the breech region of the gun.

In the future, evaluation of armature performance must be weighted in terms of both armature induced bore damage and efficiency in launching useful mass from the gun in order to optimize overall electric gun system designs.

Small Caliber Solid Armature Experimental Results

Demonstration of a 0.60 caliber (15 mm diameter) solid armature capable of accelerating 32 g to 2,000 m/s was required by the proposed Small Caliber EM gun program sponsored by the Joint Services Small Arms Program. In this program, a small caliber launcher was fabricated and constructed utilizing a 1.6-m laminated rail containment structure supporting an augmented railgun driven by a lightweight compulsator[11,12]. A set of armature performance demonstration experiments was performed to show operation under conditions identical to those imposed by the compulsator system, namely: peak current of 385 kA and action of $116 \times 10^6 \text{ A}^2 \cdot \text{s}$ (parameters imposed by the compulsator design) and muzzle energy of 64 kJ at 2,000 m/s exit velocity.

Because armature demonstration was required before the compulsator and gun were completed, testing was performed using an existing 1 MJ capacitor bank and an existing 1 m hydraulically prestressed gun structure. This gun frame, initially built as a prototype of the 10-m gun at CEM-UT[2], was fitted with a new set of rails and insulators.

Two sets of rails were constructed, both using Al_2O_3 dispersion strengthened copper material and castable polyurethane insulators. The first set was not augmented and was built to allow testing to commence while the augmented set was being designed and built. The augmented gun high frequency inductance gradient was measured at $0.97 \mu\text{H/m}$. Polyurethane sidewalls were cast in place after the rails and G-10 bore insulator supports were assembled. Use of a castable plastic allowed sidewall damage inflicted during the life of the gun to be easily repaired by recasting the damaged area. Several voids were trapped in the sidewalls upon casting, but proved to be of no consequence during testing.

Figure 6. Photograph of 0.60 caliber clothespin solid armature with integral payload

Figure 7. Photograph of recovered 0.60 caliber armature, shot 5, showing cuts in legs

The final armature design, dubbed the "clothespin" armature, is shown in figure 6, and is made of 7075-aluminum alloy. The tapered legs provided an initial interference fit against the rails. An approximate method for determining the size of the

legs was used to limit the leg cross section in order to keep the specific action below the critical value for melting. For these experiments, the required action was determined by the compulsator design. Dividing the required action by the bore half-area (the maximum conduction area for the armature material in the clothespin design) gives a specific action of $16 \times 10^{15} \text{ A}^2 \cdot \text{s/m}^4$, which is 64% of the specific action to melt of elemental aluminum reported by Tucker and Toth[13]. For a practical armature, not all of this area is available for current conduction. Clearly, armature design for small caliber EM guns is constrained by the minimum amount of material required to withstand the high action requirement. The actual armature mass was $\sim 7.7 \text{ g}$. An integral payload mass was added to provide in-bore stability and represent future projectile and sabot launch masses. Molybdenum disulfide impregnated nylon was used as a bore rider.

In total, 24 shots were performed in this test sequence, with 15 of those using the augmented gun. A summary of the shots and a brief description of armature performance is provided in table 2. (Only the first 18 shots are included, as shots 19 to 24 were tests of the gun, not the armature.) For the first nine shots, the nonaugmented gun was used. During the first seven of those shots, a 2.4 mm (0.094 in) diameter stress-relieving hole was placed at the base of the 0.76 mm (0.030 in) slit. As the current increased in this series of tests, recovered armatures revealed cuts in the legs which emanated from the hole and protruded perpendicular to the slit (fig. 7); the higher the action, the more severe the grooves. The material had evidently been melted, likely from the high local current density found flowing along the periphery of the hole. The armature failed at the base of the legs on shots 6 and 7 at 376 kA.

Muzzle voltage and gun current for shot 7 are shown in figure 8. Although the muzzle voltage probe picked up considerable noise due to the di/dt in the gun, the creative reader may visually average through the oscillations and see that the voltage increased dramatically at $\sim 1.67 \text{ ms}$, at which time the action was $94.2 \times 10^6 \text{ A}^2 \cdot \text{s}$. Dividing this by the square of the

Table 2. Summary of 15 mm solid armature tests

Shot #	Package Mass (g)	Peak Current (kA)	Peak Action ($\text{MA}^2 \cdot \text{s}$)	Package Velocity (m/s)	Observations of Launch Package
1	21.6	174	51.0	256	Check-out shot; test banks, buswork.
2	32.7	---	---	353	Current and voltage data lost.
3	29.5	282	66.2	430	Muzzle volts under 10 V until exit; cuts in armature at stress relief hole; contact surfaces clean.
4	29.5	270	67.7	454	Muzzle volts < 10 V until exit; cuts in armature as before; contact surfaces slightly worn toward front.
5	29.6	327	89.1	571	Severe slits in armature at stress relief hole; muzzle volts < 10 V at exit; contact surfaces clean, unworn.
6	28.1	371	90.9	697	Legs severed from body in-bore near exit; muzzle volts begins climbing just prior to exit; contact surfaces good.
7	28.9	376	95.2	761	Repeat of shot 6; legs severed in-bore, near exit; armature volts begins climbing early in shot; contact surfaces worn at edges.
8	30.1	371	98.4	657.9	Stress-relief hole from armature; repeat of shot 7; armature recovered intact, with small cuts; no unusual contact erosion.
9	29.2	400	95.2	672	Armature recovered intact; small cuts; greatest contact wear observed yet; muzzle volts climbed from 10 to 40 V during final 320 μs of travel.
10	28.8	227	51.6	789	First augmented gun shot; contacts eroded at edge of legs; armature recovered intact; muzzle voltage climbed from 50 to 91 V at exit (during final 320 μs of travel).
12	32.2	315	81.3	1,220	Contacts eroded at edges; legs blown off by muzzle arc upon exit; muzzle voltage steadily decreasing to 60 V at exit.
13	31.7	352	62.0	962	Explosive crowbar used; banks failed to discharge in proper sequence, causing low performance; armature recovered intact; muzzle volts show evidence of arc at muzzle end turn.
15	12.6	272	28.0/36.0	1,240	Mass reduced to increase velocity; very little contact wear; armature recovered intact.
16	13.4	295	47.5/52.5	1,765	Armature recovered in pieces; legs intact considerably worn; muzzle volts show arc at muzzle end turn.
17	11.6	370	66.8/68.2	2,460	Armature recovered intact; extreme erosion of contacts; no muzzle voltage data due to arc at muzzle.
18	12.4	343	57.5	2,220	Armature broke during catch; extreme erosion of contacts, though not as bad as in shot 17.

Figure 8. Gun current and muzzle voltage, 0.60 caliber shot 7

cross section of the leg at the end of the slit (the cross section that all of the current must pass through), shows that the specific action reached $22 \times 10^{15} \text{ A}^2 \cdot \text{s/m}^4$. This is lower than the action to melt reported by Tucker, however the above analysis assumed uniform current distribution through the leg cross section (certainly not the case at this velocity), neglected geometric effects on magnetic field concentrations as well as mechanical stress concentrations possibly contributing to failure. In addition, the action values reported by Tucker are for unalloyed aluminum.

Shot 8 used an armature without a hole and reached a peak current and action similar to shot 7; yet the armature was recovered intact, with the base of each leg only slightly cut. The muzzle voltage remained below 35 V during this shot. A hole was not used on subsequent shots, and the cuts, while not eliminated, were small enough to ignore in the remaining nonaugmented shots. Once the augmented gun was commissioned, the cuts became slightly more pronounced, yet never so severe as to cause a failure similar to shots 6 and 7. In each of the nonaugmented shots, the contact surfaces were evenly worn across the contact surface.

The augmented gun was installed after shot 9 and testing in this gun continued through shot 24. In an augmented gun shot, muzzle voltage is difficult to interpret since it is no longer proportional to the sum of the armature and contact impedances. An additional voltage term must be included to account for the voltage generated as the armature travels through the augmenting field ahead of the armature. Muzzle voltage and gun current for shot 12 are shown in figure 9 (the scale has been enlarged to show details of the voltage during the launch). Large amplitude oscillations are due to the effect of the augmenting loop and the muzzle voltage measuring circuit (which includes the primary rail segments ahead of the projectile) and disappear once the high di/dt in the gun current is reduced. A steady decrease in muzzle voltage between 880 μs and exit at approximately 1,400 μs is again an effect of di/dt , as the current is steadily decreasing. The muzzle voltage reached a minimum of 60 V just prior to exit. It is reasonable to say the armature drop was less than 60 V and the armature remained in good contact until exit at 1,220 m/s.

Figure 9. Gun current and muzzle voltage, 0.60 caliber shot 12

Testing continued by gradually increasing the current and action, as can be seen in table 2, until a velocity of 2,460 m/s was reached in shot 17. Since all muzzle voltage measurements were spoiled after shot 12 by an arc between the primary rails and the muzzle end turn connecting the two augmenting rails (a result of repeated muzzle flashes), conclusions regarding the state of the armature contact must be derived from the recovered armatures.

The recovered leg thicknesses were measured after each shot. These thicknesses, normalized to the preshot values, are plotted in figure 10 vs. exit velocity for the two different masses used. Although there are not enough data points to determine a correlation for the high mass case, the low mass (high velocity) armatures definitely show an increase in leg erosion with velocity. Figure 11 presents the variation of normalized leg thickness with action at exit, $\int i^2 dt (\propto \int ma dt)$. Again, the trend is downward for the low mass case. No trend could be inferred from the data for the behavior of the high mass armature erosion in either case.

During the course of augmented gun tests, armature contact surfaces were found to erode in a slightly different manner than in non-augmented shots. The edges wore considerably more than did the center of the legs. The surface ahead of each leg, where no interference fit was provided and no contact with the rails was desired, apparently carried current during the launch. This surface was undercut in the armature for shot 20 (fig. 7) with the intent of eliminating current conduction in this area. This modification reduced the erosion characteristics to roughly the same level as in the nonaugmented tests, underscoring the need to prevent unwanted contact between the armature body and rails. A similar conclusion may be drawn from the 90-mm tests, where it was found that unintentional contact in front of the armature was contributing to pitting in the rails[2].

Conclusions

Data from 15 and 90 mm bore solid armature railgun tests have been presented. Both sets of experiments indicate that solid/hybrid armature contact performance characteristics, for the guns, materials and geometries tested, transition at velocities

Figure 10. Normalized recovered leg thickness vs. exit velocity

above 1,000 m/s. No bore damage resulting from the armatures was observed in the gun breech region in either case. Computation of resistive energy deposited in large caliber armatures over a range of velocities was presented as a parameter by which performance comparisons of solid/hybrid and plasma armatures may be facilitated. These experiments were performed in support of developing high velocity, efficient, and reasonably sized railgun systems, and have demonstrated armature performance goals set early on in the program efforts. Further investigation of armature performance will proceed as both EM gun programs continue.

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Figure 11. Normalized recovered leg thickness vs. action for two masses

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