TESTING OF A RAPID FIRE COMPENSATED PULSED ALTERNATOR SYSTEM

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Presented to

The Fourth Symposium on Electromagnetic Launch Technology
Austin, TX

April 12-14, 1988

Publication PR-71

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Abstract: A compensated pulsed alternator (compulsator) has been designed and fabricated by the Center for Electromechanics at The University of Texas at Austin, to drive a rapid-fire railgun system. The compulsator stores 38 MJ at an operating speed of 4,700 rpm and is capable of 2 kV open circuit voltage at 235 Hz, resulting in 944 kA, 2.2 ms pulses in the 3-m railgun. The goal of the program is to accelerate 80-g projectiles to 2 km/s at a 60 Hz repetition rate.

Initial testing of the compulsator in September, 1986 resulted in the failure of the compensating shield at full speed. An ambitious rebuild effort was undertaken allowing testing to begin in August, 1987. Since then, several rapid-fire shots have been performed firing two, 3-m guns at a 60 Hz repetition rate. A 65-g solid armature projectile was accelerated to 1.8 km/s during the initial tests with the compulsator operating at half-speed and reduced excitation. These preliminary results suggest a high probability of success for the compulsator rapid-fire system to meet and exceed the design goals.

Introduction

System Configuration

The compulsator (fig. 1) incorporates a horizontal shaft, six-pole rotating field on a solid AISI 4340 steel rotor. The machine weighs approximately 11,000 kg and occupies only 1.7 m^3. Air gap armature conductors composed of 7 x 7 x 16 x 24 AWG copper Litz wire are epoxy bonded to a laminated steel stator. The single-phase armature windings terminate in three pairs of "in-phase" axial terminal bars located 120° apart. A coaxial busbar connects the compulsator to the 3-m railguns. Two bolted casing-type railguns are currently mounted to the compulsator bus, but the system will permit up to three guns. Multiple railguns are necessary for thermal considerations. Passive compensation is achieved by the 7050-T74 aluminum shield, thermally assembled onto the rotor. Upon discharge of the compulsator at full speed, the armature conductors must transfer 4.07 x E6 N m (3.0 x E6 ft•lb) discharge torque via an epoxy bond to the

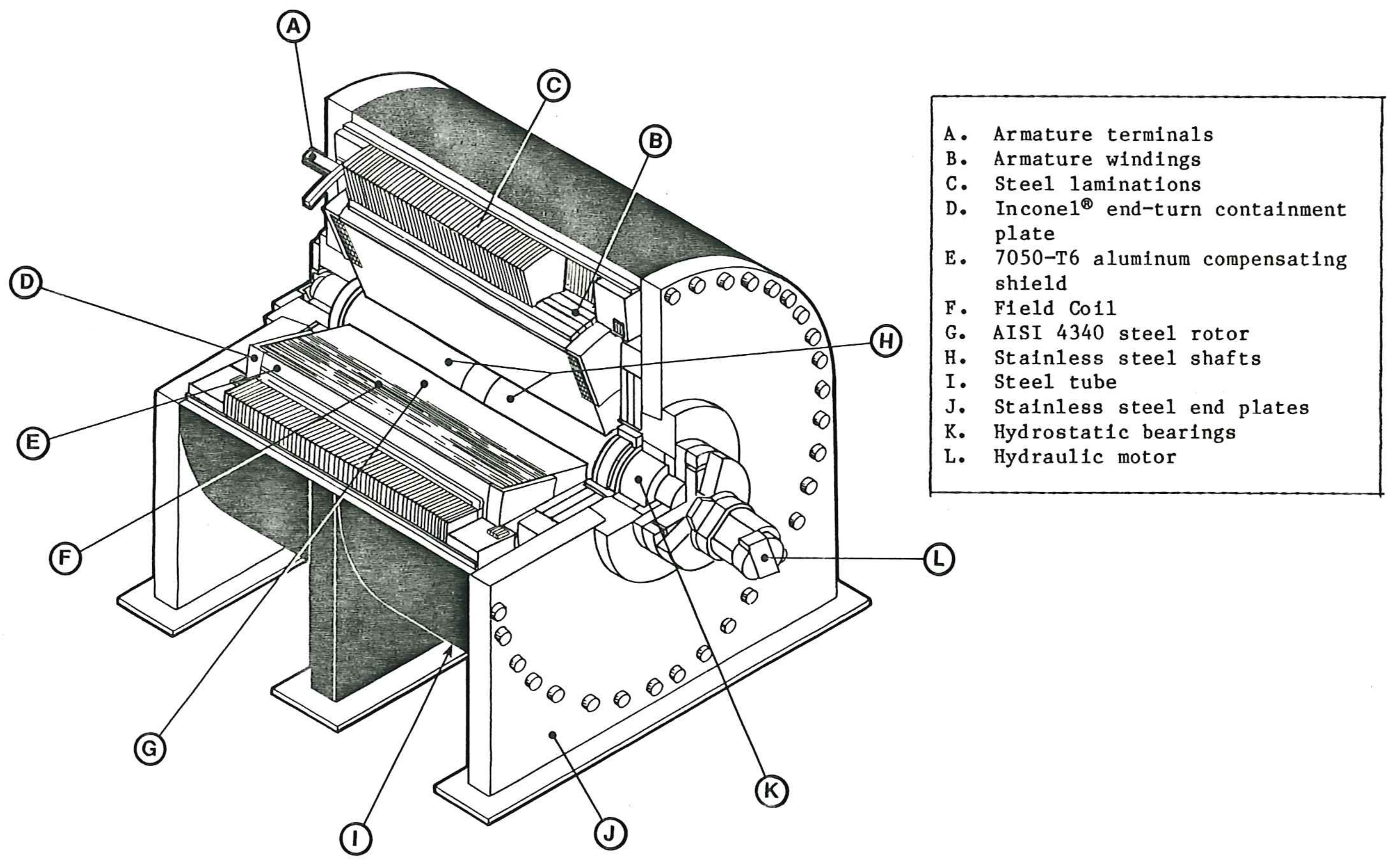

Figure 1. Isometric of 1 MJ/pulse iron-core compulsator

stator. Machine isolation is accomplished by a 10 ft diameter x 14 ft depth reinforced concrete mount. The rotor is supported by hydrostatic bearings and a four minute motoring time is achieved by two variable displacement hydraulic motors. Table 1 shows the system parameters of the compulsator.

Table 1. Compulsator system parameters

Length of Machine	1.52	m
Total Mass	11,000	kg
Rotor Speed (max)	4,700	rpm
Inertial Energy (@ 4,700 rpm)	38	MJ
Projectile Mass (max)	80	g
Projectile Velocity	2	km/s
Projectile Kinetic Energy	160	kJ
Repetition Rate	60	Hz
Barrel Length	3.0	m
Peak Current	940	kA
Peak Open Circuit Voltage	2.0	kV
Machine Inductance (@ 4,700 rpm)	0.69	μH
Machine Resistance	0.34	mΩ

The compulsator is connected directly to the 3-m railguns ("hot rail" concept). Therefore, switching occurs as the solid armature projectile makes contact with the rails, initiating the discharge pulse. Figure 2 shows a schematic of the compulsator system. An injector (high inductance gradient electromagnetic gun) is used to accelerate the projectile into the 3-m railgun. The injector and 3-m railgun rails are separated by 1.59 cm (0.625 in.) of insulating epoxy. Switching of the injector has been accomplished by either an ignitron or an explosive closing switch. The explosive closing switch has been used to characterize the injector circuit and is not intended for multiple shots through a single railgun. A typical current requirement for the injector is 150 kA. Multiple shots through a single railgun will require the use of an autoloading mechanism to load the projectiles into the injector. An explosive opening switch between the compulsator and the injector/railgun system is used to protect the compulsator windings in the event of a fault in the gun system.

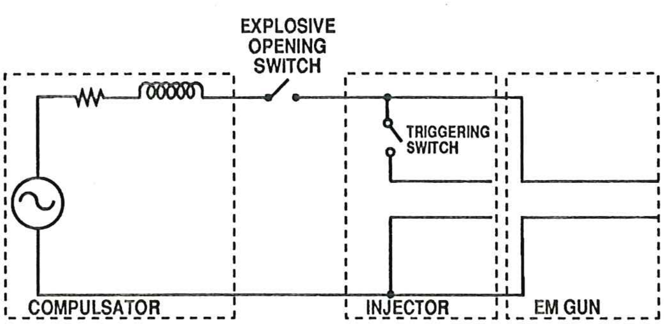

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Figure 2. Compulsator system schematic

Operational Sequence

The semiautomatic operation of the compulsator and its support system is accomplished with a programmable logic controller (PLC). The PLC checks conditions before allowing the progression of the experiment and annunciates via a CRT screen any deviations or faults. The desired motoring speed and field excitation current are pre-entered through the panel controls. Once motoring is begun, the controls for the explosive opening switch are armed and hydraulic motoring commences at a line pressure of 5 kpsi.

Once the desired speed and the discharge sequence have been initiated by the operator, the field coil brush mechanism is pneumatically actuated and the 750 kW DC field supply is energized. Excitation flux requires approximately one second to build to its full value due to eddy currents in the solid rotor and shield. At this time, the compulsator is generating full open circuit voltage, which the open bore of the 3-m railgun must hold off. Now the controller, which has been monitoring all elements of the system for faults, determines the proper rotor position and initiates the injector discharge pulse by triggering the ignitron.* The projectile leaves the injector, breaking contact with the rails and travels 1.59 cm (0.625 in.) through the insulated bore connecting the injector to the 3-m gun. As the solid armature projectile makes contact with the rails, the main current pulse is initiated.

Compulsator Testing

Preliminary testing of the compulsator in September, 1986 resulted in the failure of the compensating shield at full speed (run #52). The failure was caused by an epoxy bond failure in the end-turn region of the field coil. The unbonded portion of the field winding loaded the aluminum compensating shield, deflecting the shield until it contacted the stator bore. The failure occurred at 4,700 rpm; the first full-speed mechanical run. The accident resulted in considerable damage to the armature windings, compensating shield, and the field coil windings. With the failure fully understood, design modifications to the end-turn region of the rotor were made and an ambitious rebuild effort was launched. Containment of the field coil end turns was accomplished by Inconel® (a high strength nickel alloy) end plates thermally assembled over the ends of the rotor.

The test plan for the rebuilt compulsator adopted a low risk approach leading to the demonstration of the experimental goals. The majority of the tests presented in this paper were performed with the compulsator operating at 2,400 rpm and reduced excitation. Although, the compulsator was designed to operate at 4,700 rpm, the lower speed testing allows the system to be characterized with minimum energy in the compulsator. The lower speed testing has also proven beneficial in the development of solid armature projectiles.

The first motoring tests of the rebuilt compulsator consisted of 500 rpm runs to debug the newly reactivated control and data acquisition system. Open circuit tests were conducted at 500 rpm to characterize the magnetic saturation curve of the compulsator. Results from the open circuit test are given in figure 3 along with test results from prefailure open circuit testing.

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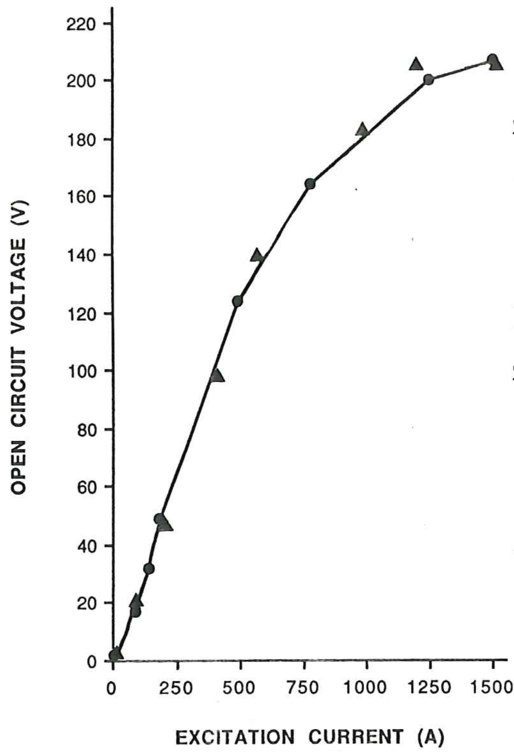
* R. F. Thelen, "Repetitive Discharge Control and Machine Protection for the Compensated Pulsed Alternator," to be presented at the 4th Symposium on Electromagneti Launch Technology, Austin TX, April 12-14, 1988.



"86" COMPULSATOR

I_p	V_{oc}
• 90	17.1
• 140	32.0
184.5	49.0
488.8	123.6
784.5	164.0
1254.0	200.1
1507.0	206.9

"87" COMPULSATOR

I_p	V_{oc}
• 100	20.3
• 200	47.4
401.25	97.5
583.0	138.8
988.1	182.1
• 1200.0	195.1
1520.0	205.0

CURRENT DATA NOT COLLECTED •
CURRENT ESTIMATED FROM FIELD SELECT.

Figure 3. Open circuit voltage magnetic saturation curve for the 1 MJ/pulse compulsator (normalized to 495 rpm)

Short-Circuit Testing

Short-circuit tests were performed at 2,400 rpm, 250 A excitation. The injector ignitron was used to initiate the short-circuit test with a shorting conductor in place of the injector. The short-circuit test was useful in characterizing the impedance of the machine vs operating frequency and in testing the explosive opening switch and the fault control monitor. Machine inductance was measured to be 0.75 μH at 2,400 rpm, which was as predicted. The fault control monitor, monitors current in the three pairs of parallel terminals and total bus current for fault conditions and initiates the operation of the explosive opening switch at current zero when a fault is detected. The circuit has numerous self-diagnostics and triple-redundant fault detection. The faults detected are: 1) an excess of selected discharge current pulses (either positive or negative polarity), 2) an excessive total integrated current over time ($\int|i|dt$), or 3) an excessive negative-polarity current amplitude. Under varying test conditions, one or more of these faults would be encountered if the bus shorted, the projectile jammed, or the railgun failed to clear at the muzzle. During the short-circuit test, the pulse-count fault circuit successfully operated to terminate the short-circuit at a current zero.

Injector Tests

Three compulsator powered injector shots were performed at 2,400 rpm and reduced excitation. Sixty-five gram projectiles were fired with the injector using an ignitron to initiate the discharge. These tests allowed the firing control instrumentation to be evaluated and the injector performance to be compared to that of the computer model. The injector test results were significant in that the friction model in the computer simulation was refined to accommodate the higher than anticipated drag of a solid armature projectile. To retain a solid armature throughout the length of the 3-m railgun, higher interference is required between the projectile fins and the gun rails than would be needed with a plasma armature. With the high force necessary to initiate projectile movement coupled with the relatively slow rising sinusoidal current pulse from the compulsator, an accurate friction model is required to establish the necessary timing for the projectile to exit the muzzle at a naturally occurring current zero.

Injector/3-m Railgun Testing

Several compulsator powered injector/3-m railgun shots have been fired with 65-g solid armature projectiles with the compulsator operating at 2,400 rpm and 77.5% excitation (i.e. field coil current set to achieve 77.5% of maximum voltage). A summary of all of the compulsator powered injector/3-m railgun shots performed from September through December 1987 is given in table 2. Figure 4 shows the compulsator test area. During the first four shots (runs #83 through 87), a solid armature projectile design was refined. Sliding contact with solid armatures was not maintained throughout the launch of the first two shots; however, once the average fin-to-rail interference was increased from 0.04 to 0.18-mm (0.0016 to 0.007-in.), the peak projectile armature voltage dropped from almost 400 to 158 V. Figure 5 shows the machine current for the second injector/3-m railgun shot (run #85). Note the perturbations in the current waveform occurring after the positive current peak. Close examination of the railgun muzzle voltage waveform revealed five voltage peaks and five voltage valleys which are believed to correspond to the five fins on the projectile being mechanically sheared. After the five voltage peaks, a steady arc drop of about 300 V was observed until the current finally passed through zero. The muzzle voltage trace indicated that current was extinguished in the gun before the explosive opening switch was automatically activated 100 ms after the discharge was initiated.

Under the influence of the high currents and magnetic fields present in the bore of the gun, the rails deflect radially outward. In order to maintain a low armature voltage drop and solid armature integrity, the armature must be capable of tracking this growth. Two mechanisms which produce a radial deflection of the armature are employed. The armature is sized somewhat larger than the bore and compressed when loaded. This provides an initial force to ensure good electrical contact early in the pulse, and allows the armature to passively track rail growths up to the amount of the precompression. With the "fishbone" armature design, in which there is an axial component of current, there is a radial force proportional to the square of the current. The radial force can be altered by changing the angle of the armature fins with respect to the axis; hence, controlling the axial current component.

Both of these mechanisms for producing radial growth of the armature drive one to design a compliant fin structure. This can be accomplished by material selection, lengthening the fins, reducing the axial thickness of the fins, and by slitting the fins axially to eliminate hoop strength. Unfortunately, these methods also generally reduce the shear and bending strength of the fin, and its thermal capaci-

Table 2. Summary of Compulsator Powered Injector/3-m Railgun Shots (Sept-Dec, 1987)

PARAMETER/RUN#	Run #83	Run #85	Run #86	Run #87	Run ††† #93 (1)	Run #94 (2)	Run #95 (1)	Run #95 (2)	Run #96 (1)	Run #96 (2)	Run #97 (1)	Run #97 (2)	Run #102 (2)	Run #106 (2)
Compulsator Speed (rpm)	2451	2451	2427	2433	2481	2375	2494	2415	††2500	2415	2487	2451	2899	2304
Excitation (A) (%)	750	750	750	750	750	750	750	750	750	750	750	750	851	750
Open Circuit Voltage (V)	792.5	777	774	775	802	757	793	714	††800	705	775	705	1030	757
Firing Angle (deg)	142.7	142.7	172.8	154.8	153	150.4	167	154.7	166.7	146.1	145.2	142.7	144.9	142.3
Length of Injector Used (in)	3.75	3.87	3.75	6	6	6	6	6	6	6	6	6	6	6
Peak Injector Current (kA)	-106.8	-98	-212.4	-150.6	-158	-147	-223	-180	-196	-145	-126/317	-138.6	-126/334	-135.6
Injector Muzzle Current (kA)	-45.6	-12.6	-211.8	-45.6	-80	-73	-209	-160	-141	-105	317	-45	334	-84
Peak Railgun Current (kA)	471.6	520.8	417	555	559	551	447	454	527	486	499	544	593	519
Railgun Muzzle Current (kA)	-114.3	-46	210	210.6	173	172	227	173	209	126	44	121	56	198
Projectile Mass Initial (g)	65.1	67.2	84.8	65.4	65.8	65.7	66	66.1	68.4	67.4	66.1	64.8	66.6	66.3
Proj./Bore Interference (mils)	3	1.6	7	7	7	7	7	8	7	10	7	7	8	7
Projectile Insertion Force (lbs)	†	†	†	3240	2640	1760	5720	3080	6600	990	2200	1100	1870	440
Projectile Velocity (m/s)	452	755	1095	1889	1702	1725	1471	1354	1378	1370	1480	1744	1790	1600
Proj. Armature Voltage, Max. (V)	358	394	158	79	185	205	139	96	161	211	115	175	133	260

†Insertion forces were not measured
††Estimated values--open circuit voltage data prior to discharge not collected
†††(#) designate gun #1 or #2 performance

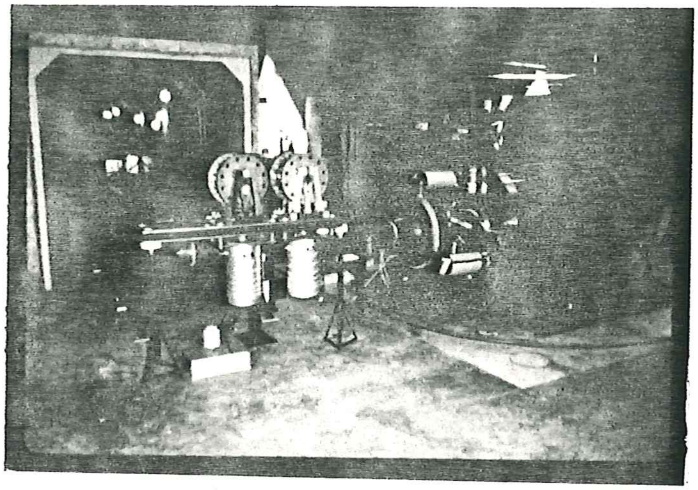


Figure 4. Compulsator test area

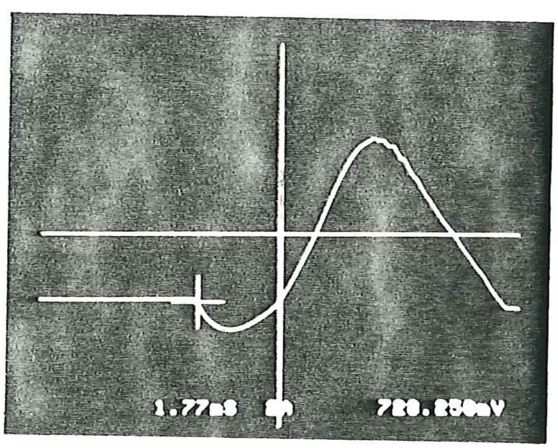


Figure 5. Machine current for injector/3-m railgun shot #2 (run #85)

tance. At this time, it is unclear if armature transition is being caused by loss of contact with the rails, simple mechanical failure, thermal failure, or some combination of these mechanisms. The analysis is complicated due to its transient nature and the difficulty in determining current distribution within the armature. The designs produced thusfar have been based on relatively simple steady-state analyses. On the fourth injector/3-m railgun shot (run #87), a projectile velocity of 1,889 m/s was obtained and the peak projectile armature voltage reached only 79 V. The projectile for run #87 is shown in figure 6. All of the projectiles for the compulsator railgun shots have been made from 7075-T6 aluminum.

Test results have indicated a relationship between the injector muzzle current and the projectile velocity. The lower the injector muzzle current, the higher the projectile velocity. It is believed that the interruption of a high injector muzzle current destroys the current carrying fins of the projectile; therefore, degrading the projectile's performance in the 3-m gun. Unpredictable injector muzzle currents are the result of an inconsistent ignitron impedance. The machine voltage when the ignitron is triggered (for 2,400 rpm and 77.5% excitation) is approximately 500 V, which is the published minimum voltage for the ignitron to trigger. Additionally, the dV/dt is negative while the current (and ignitron ionization) is rising.

In early discharge tests (runs #75 through 79), the ignitron (General Electric, GL 8205) was conditioned by warming the anode end with infrared heat lamps and cooling the cathode end with a vortex tube by venting its cool discharge through the water jacket. The differential temperature was provided to assure the condensation of the mercury to the cathode pool. When the early tests failed to achieve the current levels expected, voltage recordings indicated that the ignitron "turn-on time" was too slow. It was determined that the precooling of the cathode was inhibiting the rapid ionization of the mercury during the pulse initiation. Subsequently, in the remainder

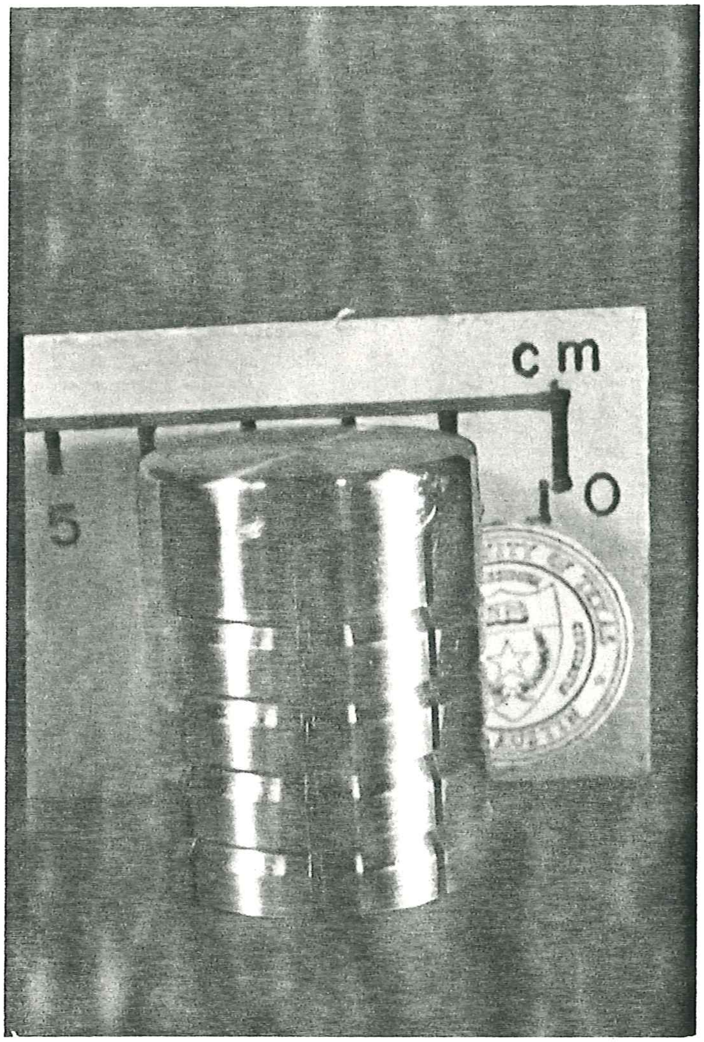


Figure 6. 7075-T6 aluminum projectile for run #87; 65-g accelerated to 1,889 m/s

of the runs which used the ignitron, it was reconditioned by warming both the anode and cathode areas with infrared heat lamps for three hours prior to the run. The ignitron resistance continued to deviate from shot to shot. The crude means of heating the anode and cathode of the ignitron resulted in inconsistent temperatures from shot to shot. These circumstances act to slow the pulse initiation such that the ignitron resistance is a significant limit to the peak injector current achieved.

To test this theory, run #106 was conducted using an explosive closing switch in place of the ignitron for a single shot. The injector performance followed the computer simulation very closely, confirming suspicions of an ignitron problem.

A total of 11 injector/3-m railgun shots were performed from September through December, 1987: three of which were rapid-fire shots firing two projectiles using two railguns at a 60 Hz repetition rate (run #95, 96, and 97). Compulsator run #95 resulted in projectile velocities of 1,471 and 1,353 m/s from guns #1 and 2, respectively. Projectile velocities were lower than expected and high injector muzzle currents were obtained again because of inconsistant ignitron impedances. Two, 1.3 cm (0.5 in.) steel plates were penetrated (fig. 7). Figure 8 shows the total gun currents along with the muzzle voltages of the respective guns. The smooth, open circuit voltage waveform between the railgun shots indicates a clean opening of gun #1 with no restrikes. The small perturbations near the peaks of negative current pulses represent the projectile exiting the injector and entering the 3-m railgun.

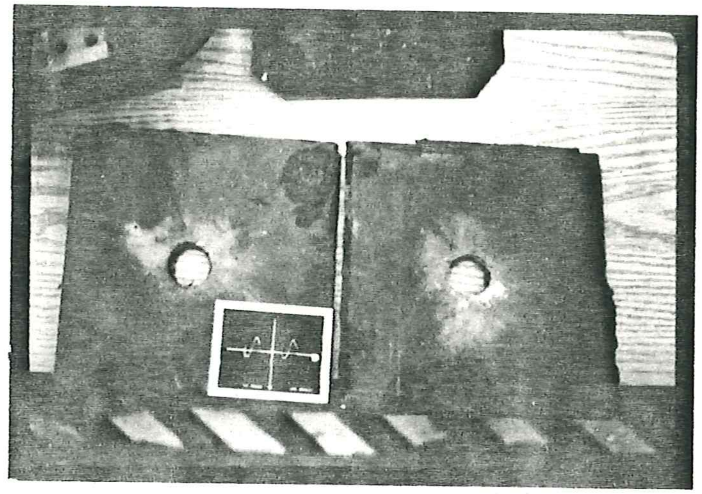


Figure 7. Two 1/2 in. steel plates penetrated by the projectile of run #95

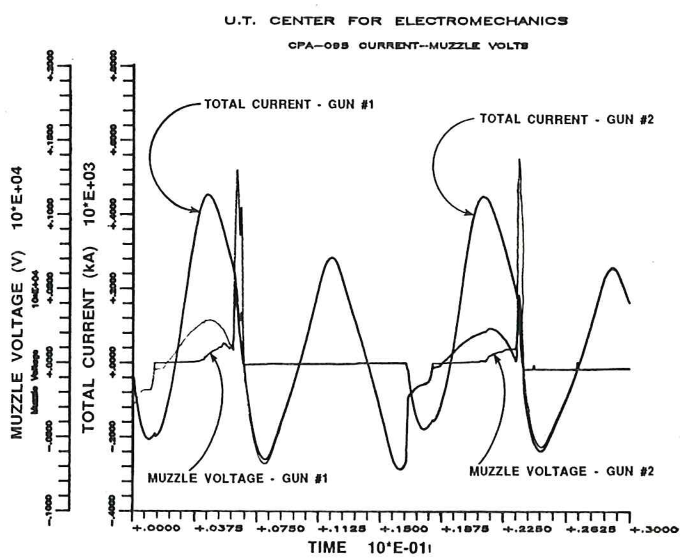


Figure 8. Total gun currents and muzzle voltages of guns #1 and 2 of run #95

Post-Shot Railgun Bore Observations

A borescope is used to check the condition of the railgun bores between shots. Fin pressure on the copper injector rails appears to be higher than the compressive yield strength of rail material. This is evidenced by a ridge left by the axial slot between projectile fins. As a result, bore dimensions between shots (when honing was not performed) increased by approximately 0.025 mm (0.001 in.).

Deposits of aluminum on the first few centimeters of the injector rails are due to frictional wear from the high insertion pressures. No significant increase in aluminum deposits have been observed past the point of current initiation in the injector and no copper melting has been noticed until the injector muzzle was reached. On shots with low injector muzzle currents (less than 100 kA), arc damage is minimal and subsequent shots may be performed without rehoning. However, muzzle currents of 200 kA and greater have been detrimental, resulting in severe rail pitting and melting. Resolidification of molten copper particles reduce the effective bore diameter by approximately 0.25 mm (0.01 in.). Additionally, the explosive energy of the larger muzzle currents cause damage to the joint seal between the 3-m railgun and the injector, thus reducing electrical isolation.

The first several centimeters of the 3-m railgun rails have had a thin and intermittent coating of aluminum similar to that found in the first section of the injector. However, after this point, heavy accumulations of molten aluminum and copper are observed. The location of these deposits correspond to the predicted location of peak current (approximately 25.4 cm) varying depending on shot timing. They also coincide with the initiation of railgun projectile armature voltage ramping. Evidence of solid contact between the projectile and the copper rails were observed after run #95 by noting the continuation of the ridge caused by the projectile fin gap. This ridge completely disappears after approximately 1.25 m (49.5 in.) in gun #1 and 1.47 m (58.0 in.) in gun #2. After this point, the rail is coated with a light blue/grey powder on the surface and a harder grey coating which adheres to the rails. It is believed that this powder is aluminum oxide formed by reaction of the molten aluminum projectile surface with the surrounding atmosphere.

Conclusion

In lieu of the recent developments in solid armature projectiles and the subsequent increase in system efficiencies due to low projectile armature voltage (with respect to plasma armatures), it is believed that the compulsator will be able to accelerate an 80-g projectile to 2 km/s with the machine operating at only 75% of the design speed (3,600 rpm). The tests conducted have 1) demonstrated the use of a two-stage railgun (injector and 3-m railgun), 2) the feasibility of the "hot rail" concept, and 3) that the railgun circuit will open at current zero. Problems with the repetitive closing switch for the EM injector remain and must be solved before repetitive shots through a single railgun can be achieved. It is clear that test results from the rapid-fire compulsator system will provide valuable insight to future rapid-fire EM gun programs.

Acknowledgements

The authors wish to thank W. F. Weldon, M. D. Driga, and J. H. Gully for technical guidance throughout the program. We would also like to thank the machinists and technicians of CEM-UT that contributed to the project. This research is supported by DARPA/ARDEC under contract No. DAAK10-83-C-0126.

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