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TITLE: DESIGN AND TESTING OF HIGH-PRESSURE RAILGUNS AND PROJECTILES

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DESIGN AND TESTING OF HIGH-PRESSURE RAILGUNS AND PROJECTILES

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Summary

The results of high-pressure tests of four railgun designs and four projectile types are presented. All tests were conducted at the Los Alamos explosive magnetic-flux compression facility in Ancho Canyon. The data suggest that the high-strength projectiles have lower resistance to acceleration than the low-strength projectiles, which expand against the bore during acceleration.

The railguns were powered by explosive magnetic-flux compression generators.[1,2] Calculations to predict railgun and power supply performance were performed by Kerrisk.[3]

Test Results

The cross sections of the railguns used in the tests are illustrated in Fig. 1 and described in Table I. Table II shows a summary of projectile descriptions and the results of selected tests.

The theoretical projectile acceleration in a railgun is

$$\frac{dv}{dt} = \frac{L' I^2}{2m} , \quad (1)$$

where v is projectile velocity, t is time, L' is the railgun inductance gradient, m is the projectile mass, and I is the armature current, so that

$$v = \frac{L'}{2m} \int I^2 dt , \quad (2)$$

$$x = \int v dt , \quad (3)$$

and

$$P = \frac{L' I^2}{2A} , \quad (4)$$

where x is projectile position, P is average pressure of the plasma armature and A is the railgun cross-sectional area. (All railgun tests described in this paper were plasma armature driven.) Projectile position measurements were made by magnetic probes and by in-flight and in-bore radiographs.

Model F. The Model F railgun was fabricated by winding a 25-mm-thick structural shell onto a rail-insulator assembly 38 mm in diam. The insulator material is polycarbonate. Figure 2 shows that the current delivered to the railgun rose from 0.4 MA to 1.1 MA in 500 µs. The projectile accelerated normally at low pressure, as indicated in the radiograph of the railgun taken during operation (Fig. 3), 300 µs after the start of current flow. This radiograph indicates that the rail separation, driven by the internal magnetic pressure, has increased ~1 mm from the breech to the projectile. We conducted only one test on the Model F railgun. Model F was eventually superseded by Model K (described in Table I), which is more resistant to structural deformation.

Post-shot inspection of the railgun suggests that as the operating pressure rose, the railgun structural shell flexed from a circular cross section to an oval cross section, causing an interference between the railgun and the projectile (Fig. 4). This gun was damaged beyond repair in firing.

Model J. We conducted several tests on the Model J design. Figure 5 shows data from a typical test. In each case, the polycarbonate slug was launched intact, as confirmed by in-flight radiograph and the projectiles survived pressures as high as 1.3 GPa while

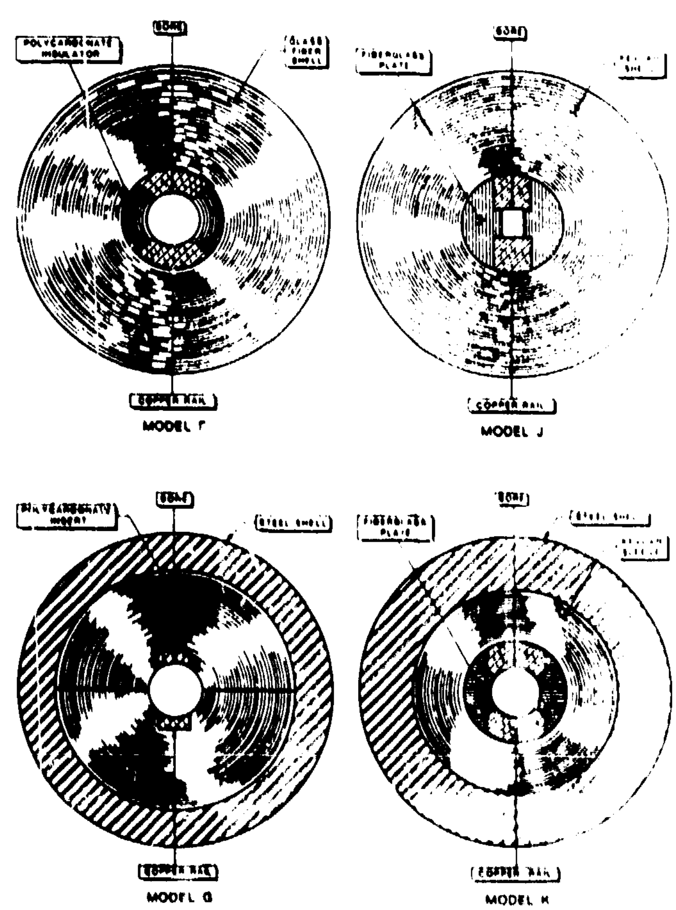

Fig. 1. Cro[...]tions of the railguns tested.

TABLE I

DESCRIPTION OF RAILGUNS TESTED

Gun Type	Bore Diameter (mm)	Length (cm)	Calculated Inductance Gradient[a] (μH/m)
F	16	60	0.39
J	13[b]	120	0.35
G	16	60	0.45
K	16	60	0.39[c]
			0.34

[a]Inductance gradients calculated by the method of Kerrisk.[4]
[b]Square bore.
[c]The inductance gradient of railgun K11, without a steel sleeve is 0.39 μH/m; of K21, with a 100-mm-i.d. steel sleeve, it is 0.34 μH/m.

TABLE II

SUMMARY OF TEST RESULTS

Test	Muzzle Velocity (km/s)	Peak Current (MA)	Projectile Mass (g)	Projectile Type
F11	1.3	1.1	17.9	I
J12	3.5	1.1	4.8	II
G11	1.3	0.7	17.2	I
G21	3.4	0.7	5.3	III
K11	2.4	1.1	18.5	IV
K21	2.2	0.7	17.2	IV

Projectile Description

I. 14-mm-diam iron sphere cast into a polycarbonate cylinder 16 mm in diam and 19 mm long.
II. 13-mm-square, 19-mm-long polycarbonate slug.
III. 6-mm-diam iron sphere cast into a polycarbonate cylinder 16 mm in diam, and 19 mm long.
IV. 14-mm-diam, 19-mm-long Ti-6Al-4V slug wrapped with a 0.8-mm-thick fiberglass-epoxy coat. A corundum disk, 16 mm in diam and 3 mm thick, is cemented to the back of the titanium slug. A 16-mm-diam, 3-mm-thick polycarbonate gas seal is attached to the back of the corundum disk.

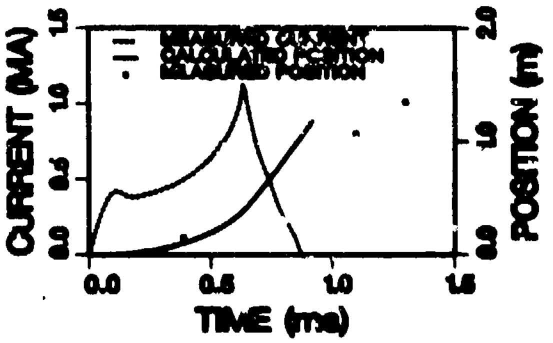

Fig. 2. Measured current, Test F11.

confined in the bore. Also in each case, the operating pressure declined substantially before the projectile exited the gun

Acceleration data suggest that below ~0.4 GPa, acceleration of polycarbonate projectiles is ~80% theoretical. Above ~0.4 GPa, the acceleration of polycarbonate projectiles is substantially less than theoretical. Figure 6 shows the in-flight radiograph

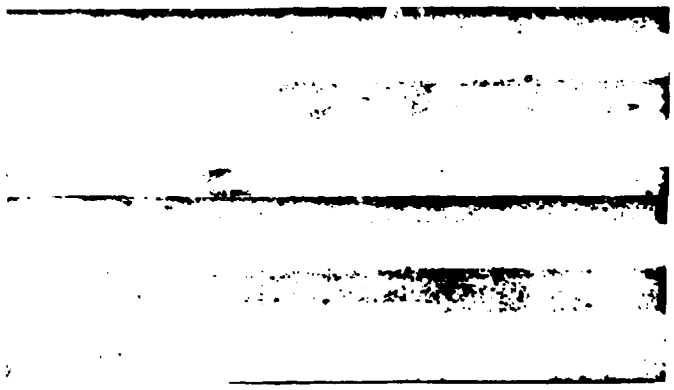

Fig. 3. In-bore radiograph of an accelerating railgun projectile, Test F11. The upper image is a static radiograph taken before the start of current flow.

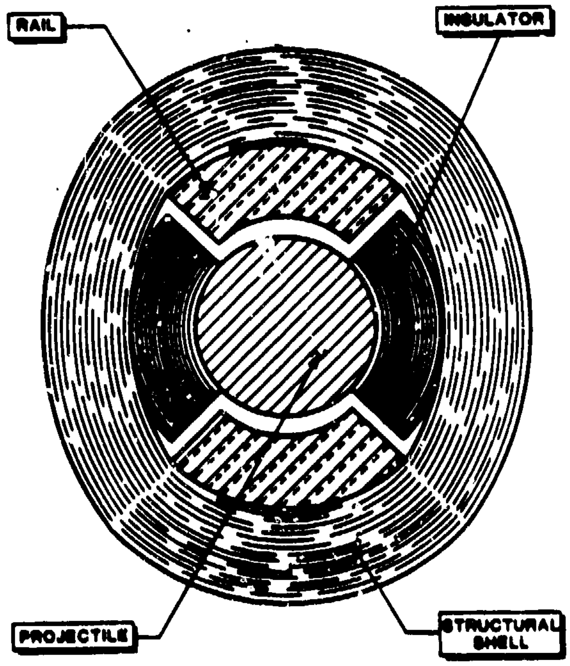

Fig. 4. Schematic illustration of the apparent mechanism for bore-projectile interference, Test F11.

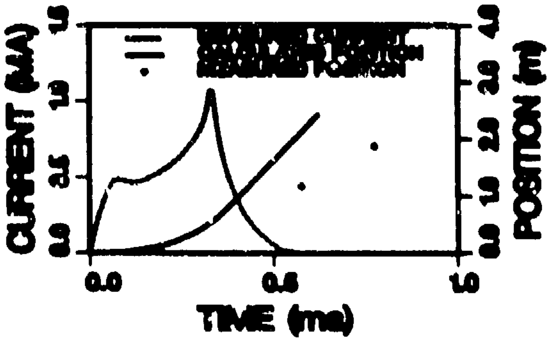

Fig. 5. Measured current, Test J12.

Fig. 6. In flight radiographs of projectile J12.

of projectile J12. The wedge-shaped appearance is believed to be the result of wear caused by the pressure of the projectile against the bore. We theorize that at high pressure, the plastic expansion of the projectile against the bore results, in effect, in the acceleration of an oversized projectile.

In some of the tests, we observed damage to the interior components of the gun, apparently because of the rebound of the rails as the magnetic pressure decayed. We did not, however, observe any damage to the Kevlar shells. We found that the guns could be refired by enlarging the bores with a broach to remove arc damage. Post-shot inspection revealed the accumulation of sooty material from the plasma armatures in the seams of the guns. Butt joints exposed to the bore are especially vulnerable. In some cases, the data suggest that a fraction of the current delivered to the gun was shunted from the armature into a spurious path within the seams of the gun.[5] The measurement of plasma armature lengths and of breech and muzzle voltage is described in Ref. 6.

Model G. Figure 7 shows data from the two tests of the Model-G design. This model was fabricated by pressing an assembly of matching polycarbonate hemicylinders with imbedded rails into a steel tube.

The acceleration of a heavy projectile versus that of a light projectile provides an interesting contrast. The heavy projectile accelerated normally at low pressure. Post-shot inspection of the gun suggests that at high pressure, an interference developed between the projectile and the rails of the type illustrated in Fig. 8. The light projectile apparently achieved sufficient velocity during low-pressure acceleration to avoid the interference that occurred from the increasing pressure. The in-flight radiograph of projectile G21 is shown in Fig. 9.

In Test G21, the polycarbonate hemicylinders suffered surprisingly little mechanical damage from the magnetic pressure against the rails. Arc damage to the polycarbonate was limited to the high-current region near the muzzle. The rails were not reusable because they suffered extensive arc damage and current heating.

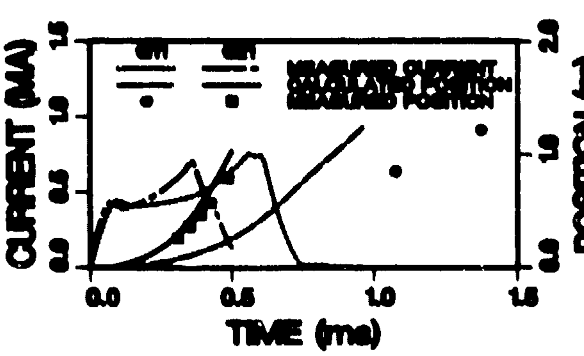

Fig. 7. Measured current, Tests G11 and G21.

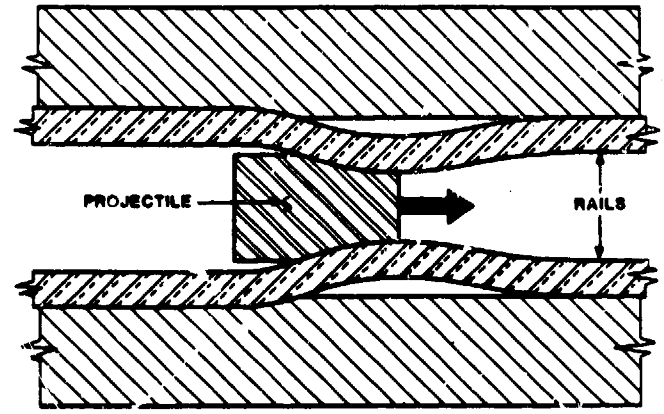

Fig. 8. Schematic illustration of the apparent mechanism of bore-projectile interference, Test G11.

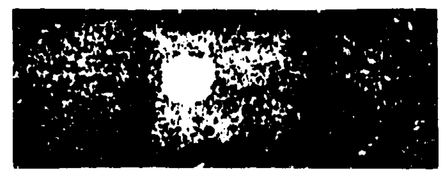

Fig. 9. In-flight radiograph of projectile G21. The 6 mm diam iron sphere, originally in the front of the sabot, has sunk to the rear of the sabot during acceleration.

Model K. Figure 10 shows data from two tests of the Model K design. Railgun K11 was fabricated with a 50-mm-thick Kevlar-wound structural shell and no steel structural shell. Railgun K21 had a 25-mm-thick Kevlar-wound structural shell. The gun was pressed into a 100-mm-i.d. steel tube that appeared to give the gun more resistance to rail deflection, but reduced the inductance gradient from 0.39 (K11) to 0.34 μH/m (K21).

Comparison of the acceleration of the titanium and polycarbonate projectiles suggests that the titanium projectiles are subject to less in-bore resistance to acceleration.

The radiographs of projectile K11 in flight reveal that approximately 50% of the titanium slug was eroded. The in-flight radiograph of projectile K21, Fig. 11, shows no erosion of the titanium slug. We do not know if the erosion of projectile K11 is the result of the high pressure of test K11 or if projectile K21 was protected by more careful bonding of the corundum disk to the titanium slug.

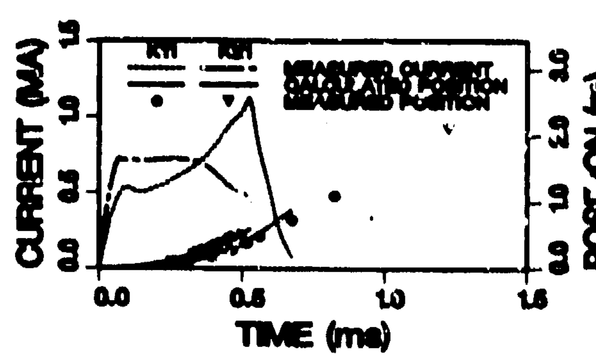

Fig. 10. Measured current, Tests K11 and K21.

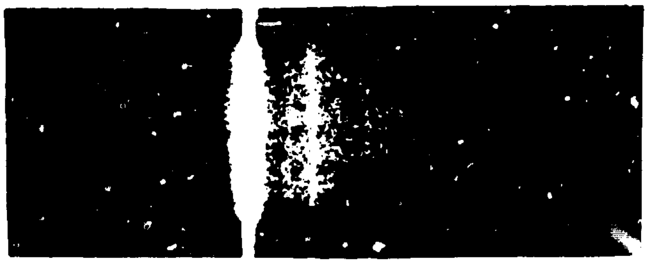

Fig. 11. In-flight radiograph, projectile K21.

We found that the Model K railguns could be refired by reaming the bores to remove arc damage. As with the Model J postshot inspection revealed the accumulation of soot in the railgun seams. The number of shots that could be fired before the accumulation of soot in the seams affected railgun performance was not determined.

Conclusions

Experimental evidence suggests that, at high pressure, the low-strength projectiles have more resistance to acceleration than the high-strength projectiles. While confined in the bore, polycarbonate projectiles can be subjected to pressures as high as 1.3 GPa without shattering. At high pressure and at low projectile velocity, interferences between bore and projectile may occur. In multishot railguns, it is necessary to prevent the accumulation of sooty material from the plasma armature in railgun seams, which can provide a spurious current path. Kevlar structural shells are capable of operating at very high pressure, but appear to allow large rail deflections. A steel structural shell with a Kevlar sleeve appears to lessen structural deflections.

Acknowledgments

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