

INSULATOR TESTS IN A HIGH PERFORMANCE, SQUARE-BORE RAILGUN

D. A. Weeks and W. F. Weldon

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Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512)471-4496

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Abstract

The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has developed a 1 m long, 1.27 cm square-bore railgun for testing different rail, insulator, and projectile materials. This railgun incorporates a unique frame assembly which allows the gun to be assembled and then pressed into the containment vessel with little pressure. After it is pressed together, an external clamp is assembled around it in order to provide the necessary preload to activate the bore seals. The unique feature of the gun assembly allows stock geometry, 2.54 cm x 0.635 cm (1 in. x $\frac{1}{4}$ in.) cross section, insulating materials to be installed and tested with minimal down time between shots.

To date the 1-m long, 1.27 cm square-bore railgun has been used to test the following insulator materials: float glass, polycarbonate, 40% glass filled polycarbonate, G-7 laminate, and quartz glass. The best results have been obtained with quartz glass and glass-filled polycarbonate.

Copper and molybdenum flame-sprayed copper have been tried as rail materials with the latter showing greatest success.

Currently molybdenum flame sprayed copper rails and glass filled polycarbonate insulators have been repetitively fired at 350 kA levels while maintaining a rail-to-rail resistance of greater than a megohm.

During the experiments performed at CEM-UT, much effort was invested in producing a consistent, high-quality bore finish. The indication is that candidate materials to be tested cannot be accurately evaluated if the bore finish is not accurate and smooth.

INTRODUCTION

The Center for Electromechanics at The University of Texas at Austin is currently doing work under DARPA contract number DAAA21-85-C-0212 which requires a 1-gram mass to be accelerated to 50 km/s. In order to achieve the velocity goal in a reasonable length launcher, bore materials and gun structures designed to operate in the 600 to 700 kA regime must be identified. The following table represents the gun length and current required to accelerate a projectile to the contract goal. It neglects frictional forces, assumes a constant acceleration and uses a typical value for L' of 0.36×10^{-6} H/m.

Table 1. Railgun current vs. length requirements to accelerate 1 gm to 50 km/s

Length (meters)	1	2	5	15	20	25	50	75	100
Current (MA)	2.64	1.86	1.18	0.68	0.59	0.53	0.37	0.30	0.264

The materials currently used in most railguns limit gun performance to below the ideal expectations made using the aforementioned assumptions. Before velocities of 10 km/s can be routinely obtained, radical changes must take place in the materials used to line the railgun bore. This paper discusses the use of laminated composite insulators designed specifically for railguns and reports on experimental results using them.

LAMINATED SIDEWALL INSULATORS

The problem in determining suitable bore materials is that the most appropriate insulators are often poor structural materials.^[1] Ideally, the insulating materials that line the bore of a railgun would be very hard, have a high melting point, high stiffness, non-brittle and have a high arc-tracking resistance. A single material that meets all these requirements is difficult to find, so CEM-UT has developed a technique for laminating materials in order to test candidate insulators.

A support sidewall structure is machined from NEMA grade G-10 glass reinforced epoxy laminate with a cavity in it for installing the candidate insulator material. To insure that the insulator and the sidewall are in the same plane, the lamination is performed on a glass plate (fig. 1). All surfaces are coated with a release agent to save clean up time (fig. 2). A strip of epoxy saturated fiberglass tape is placed in the sidewall cavity and then the insulator material is set on top of it (fig. 3). The assembly is then flipped over onto the glass plate and held firmly in place with a box style clamp arrangement (fig. 4). After curing overnight, the clamps are removed and excess epoxy is scraped off with a dull blade. This procedure yields a laminated surface that typically has less than 0.013 mm (0.0005 in.) of deviation along its length.

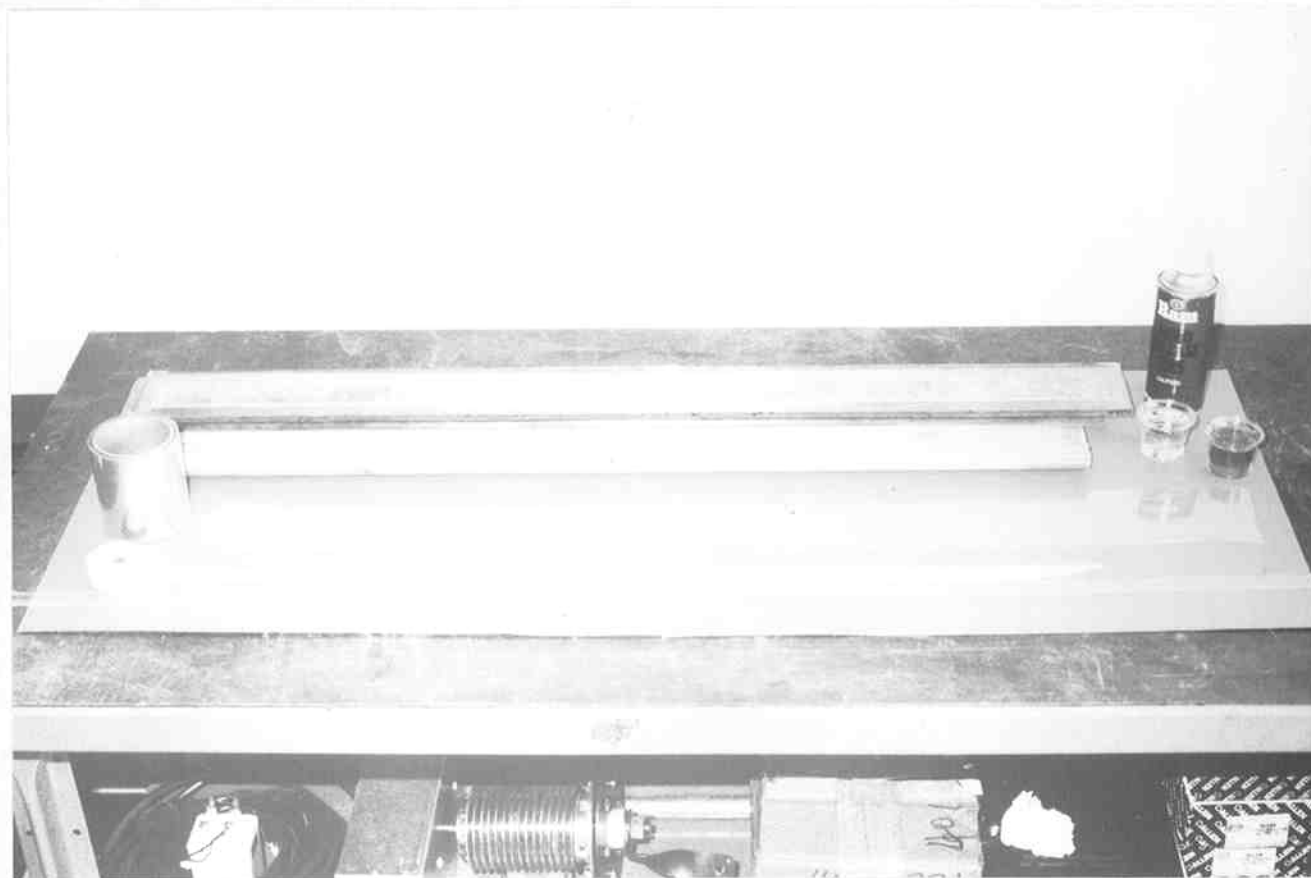


Figure 1. Material preparation for 1 m sidewall insulation lamination

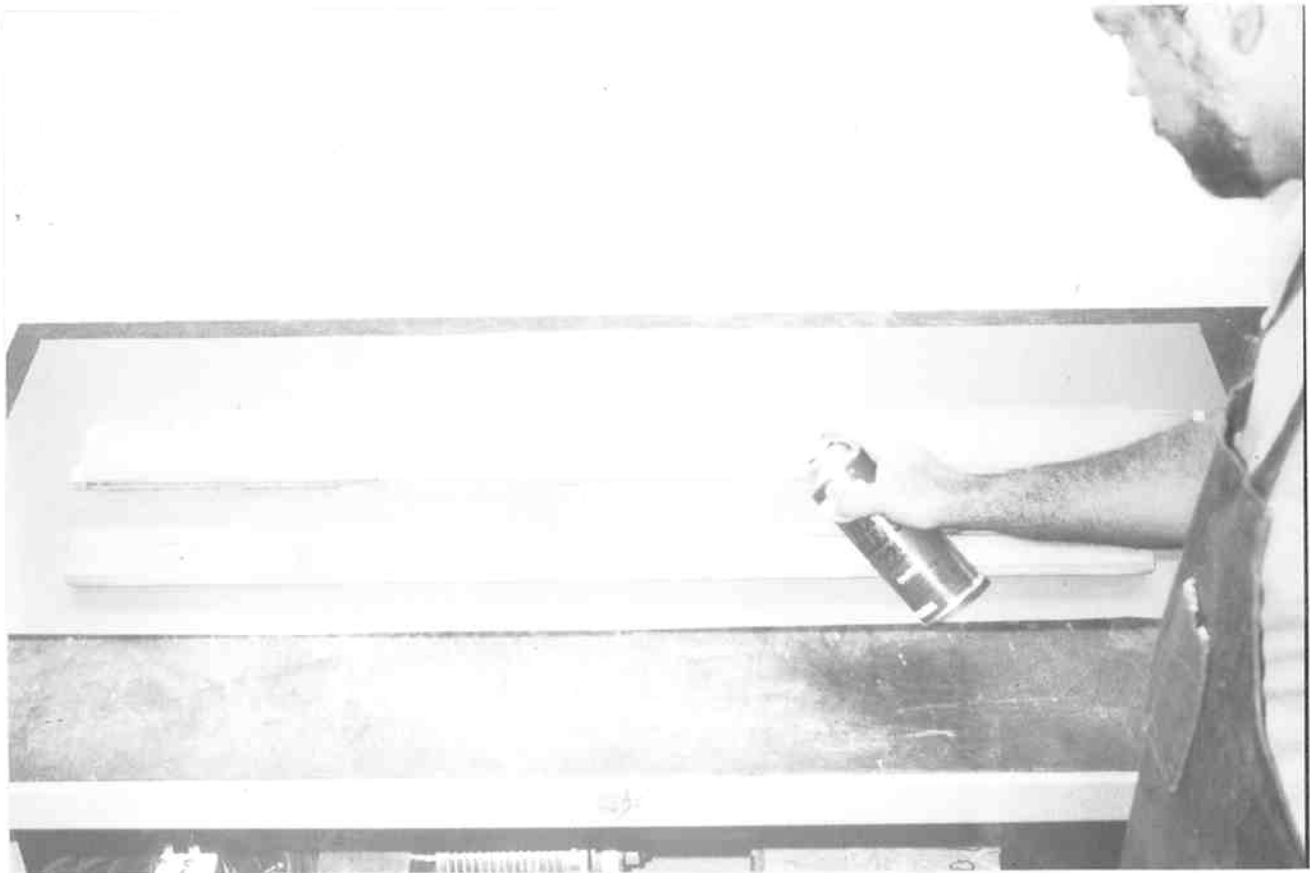


Figure 2. Coating lamination materials with mold release

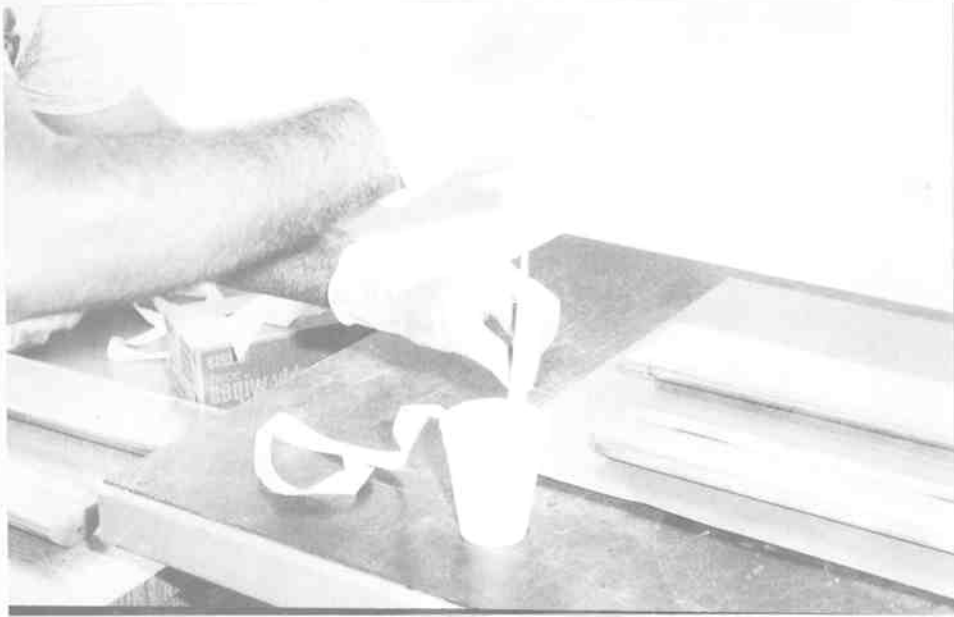


Figure 3a. Wetting fiberglass tape with epoxy

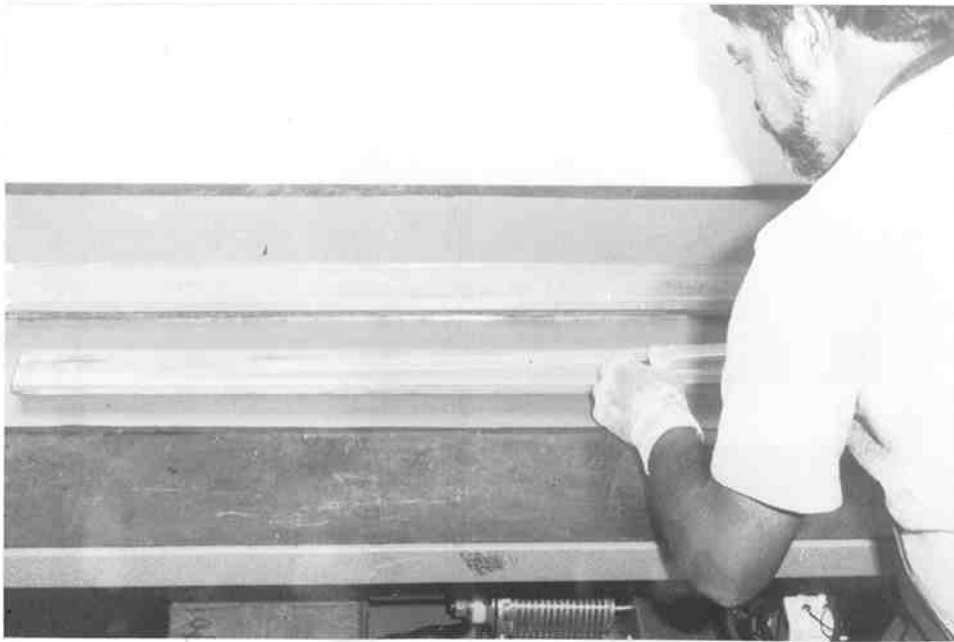


Figure 3b. Placing candidate insulator material in sidewall pocket

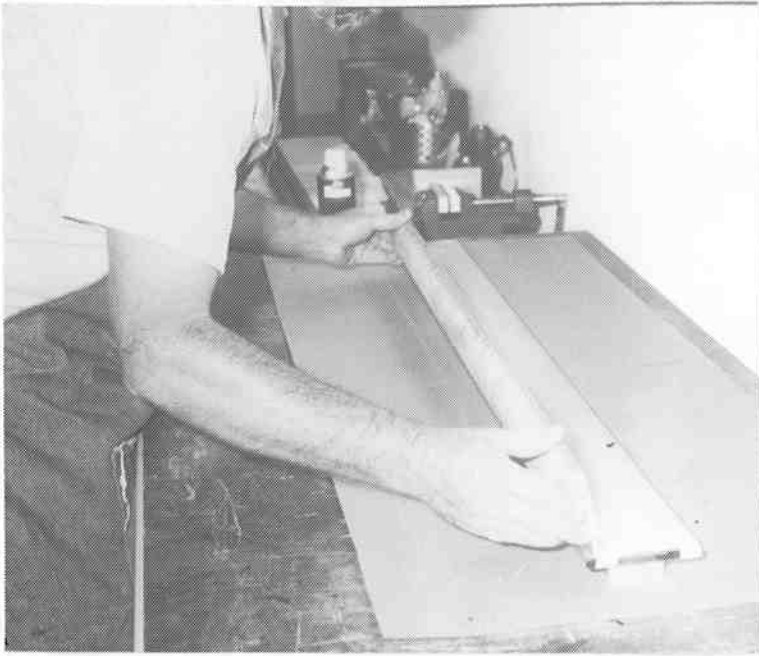


Figure 4a. Flipping sidewall on to glass plate

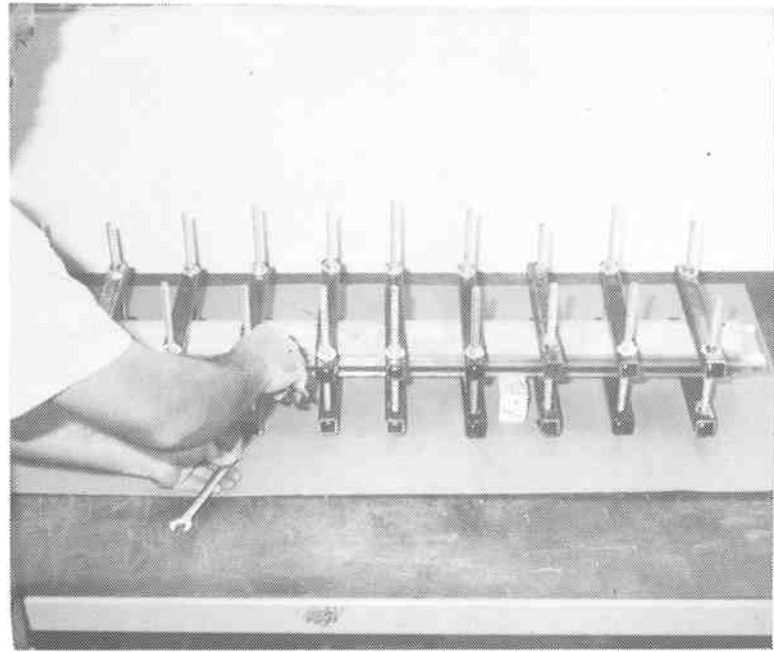


Figure 4b. Assembling box clamps on sidewall

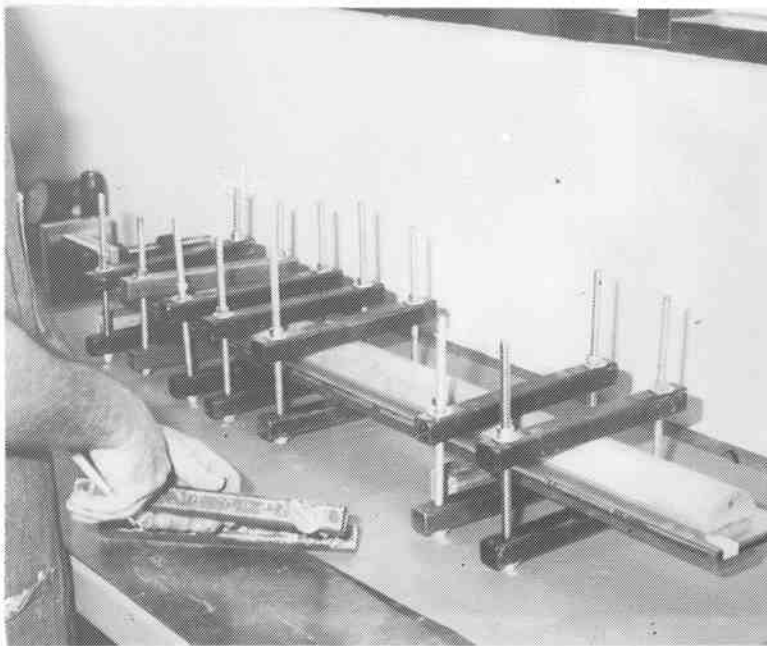


Figure 4c. Tightening box clamps for sidewall

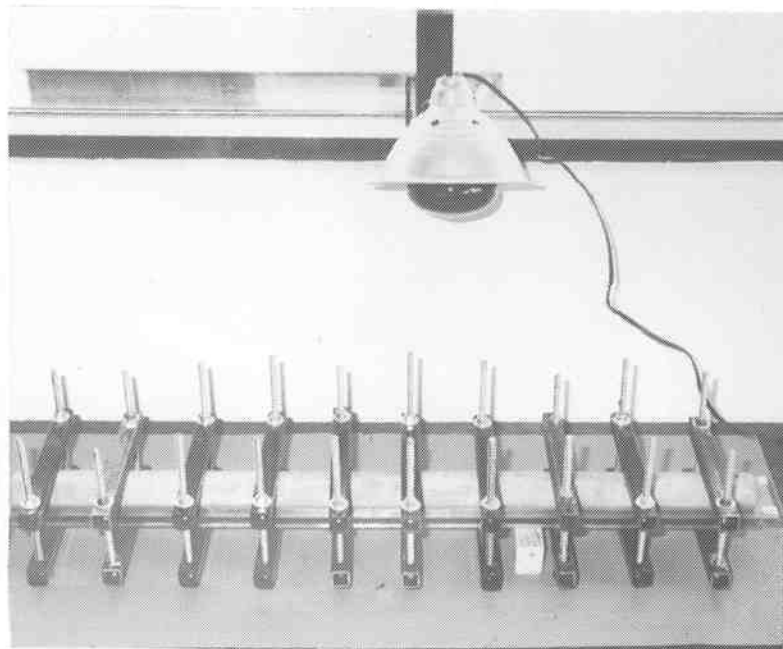


Figure 4d. Heat lamp to accelerate curing of epoxy

INSULATOR TESTS

The first few shots of the 1 m long, 1.27 cm square-bore railgun were to evaluate the performance of several different insulating materials in a railgun with copper rails. To date, soda lime glass, polycarbonate, G-7 laminate, and quartz glass have been tested. Table 2 lists some of the physical properties of the insulators tested.[2] The criteria for evaluating an insulating material is an inspection for visual damage and microscopic damage. The results of these tests are dependent on the following conditions: the rails were made of 110 copper alloy, the bore was honed and polished to high precision and approximately 1.27 cm ($\frac{1}{2}$ in.) square,[3] the polycarbonate projectile was fit such that a constant 110 to 130 newton (25 to 30 lb) force was required to push it through the gun, no injector was used and the arc was initiated by a 0.13 mm (0.005 in.) thick copper or aluminum fuse, the seals of the gun are not compromised by the expansion of the bore,[4] the gun is stiff enough to withstand magnetic pressures to 3.5×10^6 N/m² (50,000 psi) without plasma leakage, the railgun was fired in a 1×10^{-5} Torr vacuum, and finally the current level on all shots was approximately 350 kA with 70 to 100 usec rise to peak.

When soda lime glass was used as an insulator, the greatest damage occurred at the projectile location corresponding to peak current. Typically, a region approximately 25 to 40 cm (10 to 16 in.) long centered about peak current suffers major glass blowout (fig. 5). Often, a copper tint was observed on the glass after a shot. The copper tint appeared to be melted into the surface because it could not be cleaned off, so a scanning electron microscope (SEM) was used to verify this assumption (fig. 6). Under the magnification of the SEM, the glass no longer appeared to have a uniform coating of copper, but instead the surface is covered by scattered craters that are 1 to 10 microns in diameter. Additionally, the craters were often 10 to 20 microns apart and in several instances contained small spheres thought to be copper that condensed from the plasma armature. An analysis of the craters reveals that they were not formed by impact, but rather they melted into the surface of the glass.[5] Interestingly the craters are densely populated around the breech and the surrounding glass appears smooth. In the muzzle region, the craters are sparse and the surrounding glass appears coarse. During honing, the entire surface of the glass takes on the coarse appearance so it has been suggested that in the breech region where the arc dwells for a longer time, the glass melts. This also accounts for the greater density of craters in the breech area. In several instances, the SEM reveals cracks splitting craters in half, if the assumption that the craters are formed by molten copper from the arc is correct, then this indicates that the cracks form after the plasma and projectile pass by. In summary, the glass insulators do not survive for a second shot, yet they seem to stay intact while the projectile is passing, the insulators provide a witness plate for making observations of the plasma structure, and microspheres of copper are suspended in the body of the arc.

Polycarbonate was the next material tested as an insulator. Gun performance was similar to that obtained using glass and there were no regions where the polycarbonate was blown out of the sidewalls (fig. 7). However, it seems that there was more carbon soot after the polycarbonate test than there was after the glass test. A few gouges appear on the insulators which most probably occurred from the projectile tripping in the bore. Aside from this, the polycarbonate seems to be a good insulator with repetitive shot capabilities. The SEM revealed scratches that are

textured surface of honed glass (fig. 8). The post shot appearance of the polycarbonate is smooth and features some craters indicating that the surface was probably melted by the arc.

Table 2. Published Properties of Insulators Tested at CEM-UT

Properties	Polycarbonate		Fiberglass G-7	Glass	
	Unfilled	40% glass		Soda lime	Quartz
Specific Gravity	1.19-1.22	1.52	1.66	2.52	2.20
Tensile					
Strength, 1000 psi	8.5-9.0	23	18.5-23	-	7
Modulus, 1000 psi	325-340	1680	1800	10,600	10,500
Flexural					
Strength, 1000 psi	12-13.5	27	15-18	-	50
Modulus, 1000 psi	310-345	1400	1200-1400		
Compressive strength 1000 psi, 2% offset	10-12.5	21	flat,45	-	>160
Impact strength Izod(notched),ft-lb/in	12-16	2.5	5.5-6.5	-	-
Hardness	M68-74	M93	M100	-	5.5-6.5 Mohs
Coef. of static friction					
self	-	-	-	.9-1	-
steel	.23	.181	-	.5-.7	-
Thermal conductivity BTU-in/hr-sq.ft-°F	1.35-1.41	1.53	.17	-	9.58
Coef. of therm expansion $10^{-5}/^{\circ}\text{F}$	3.75	.93	.6	.47	.031
Specific heat BTU/lb-°F	.30	-	.25	-	.18
Volume resistivity ohm-cm	8.2×10^{16}	4×10^{16}		10×10^6 @622 °F	4×10^{10} @622 °F
Dielectric strength v/mil	380-425	450	thick 350 length 32		
Arc resistance, sec	120	120	220		

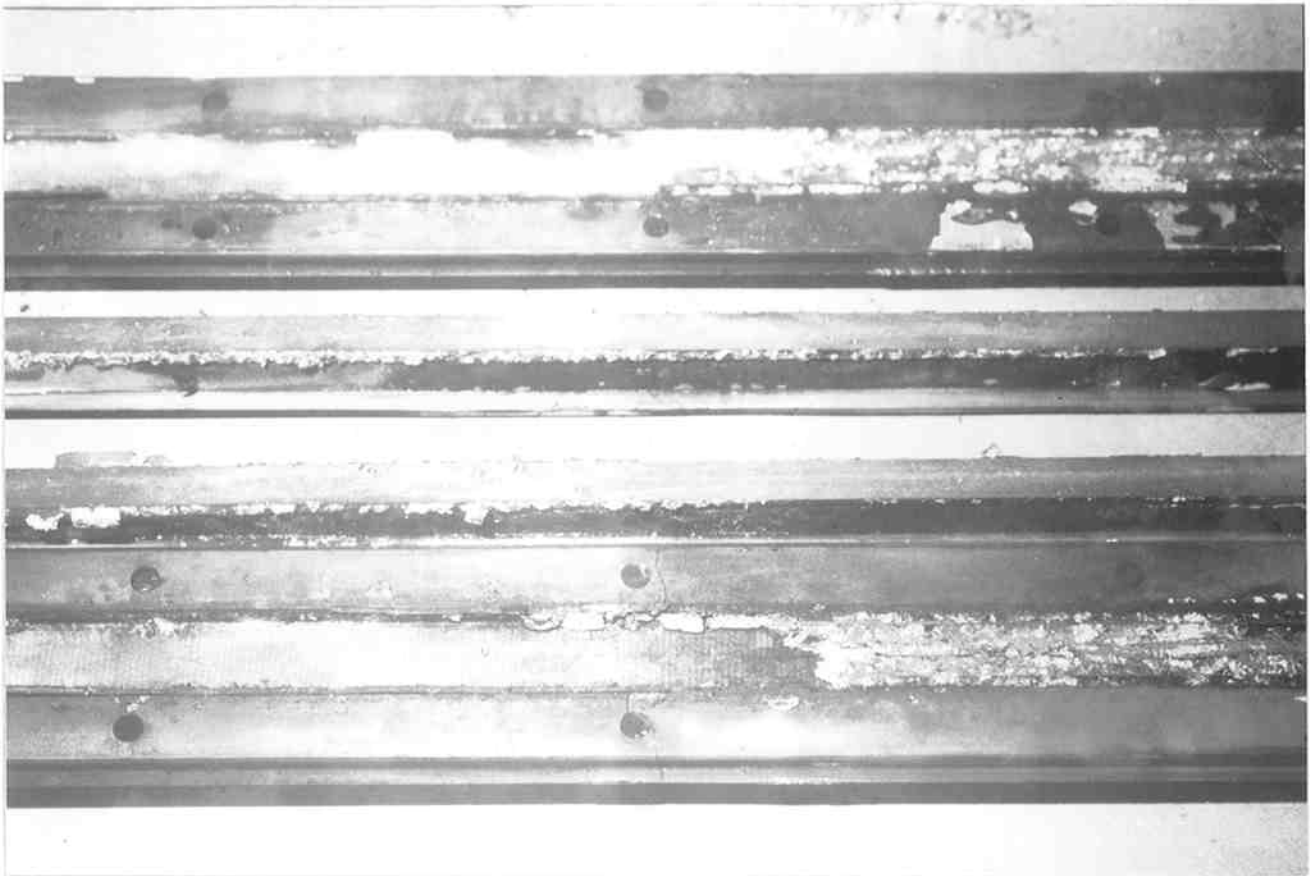
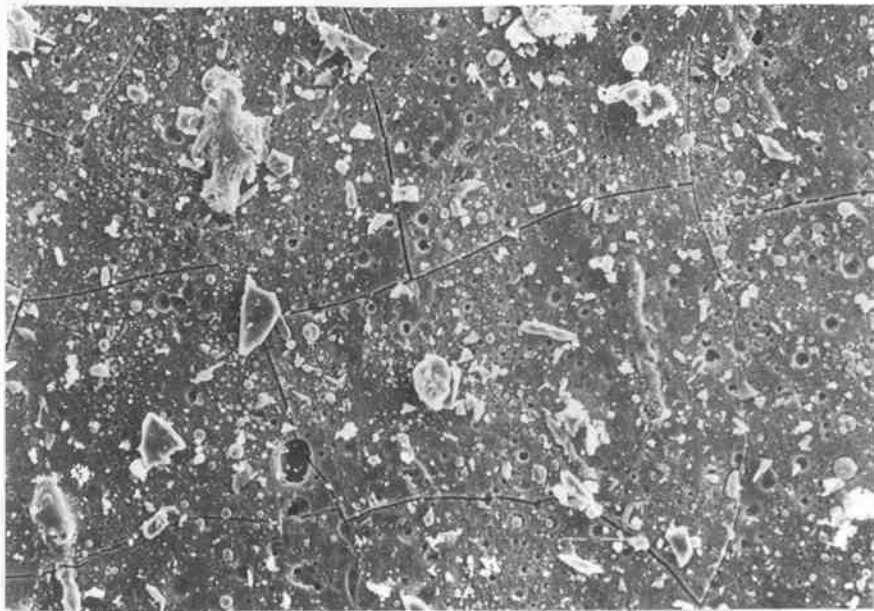
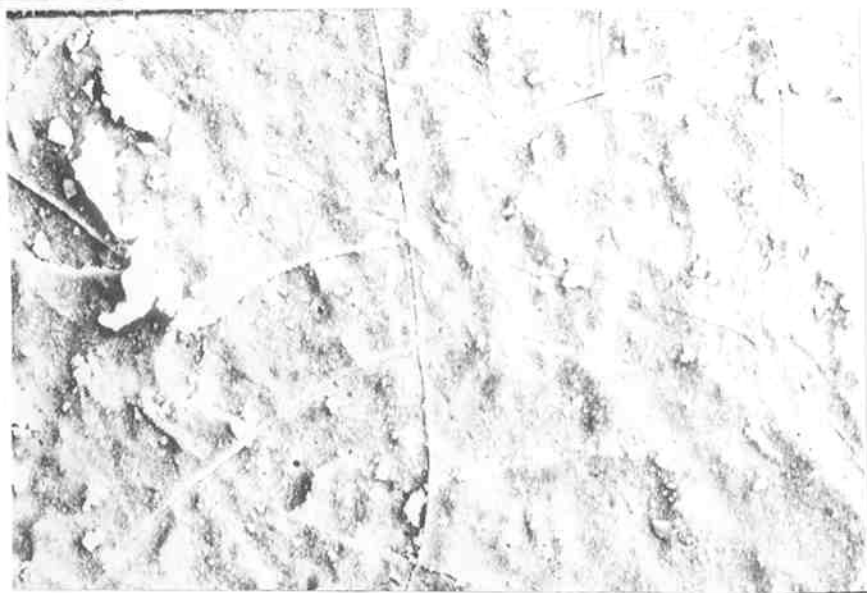


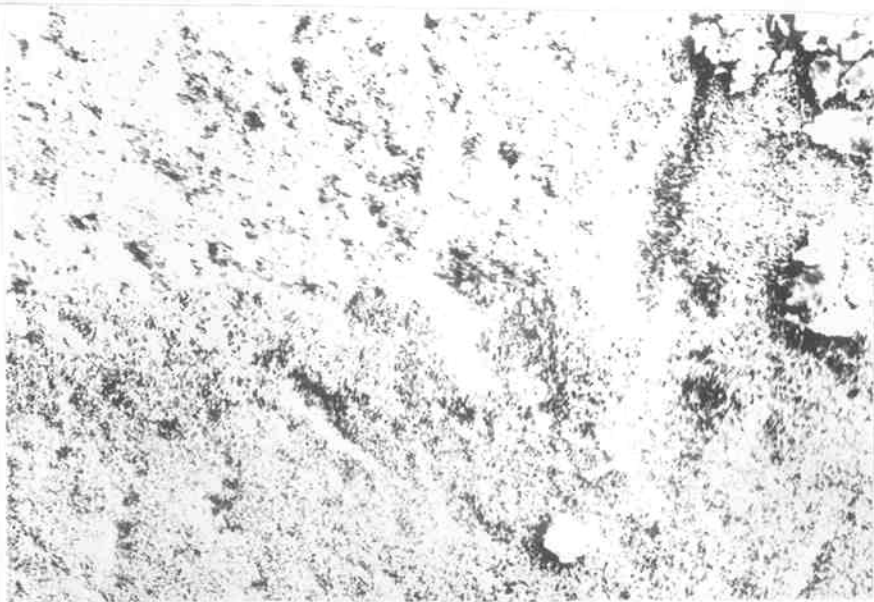
Figure 5. Soda lime glass insulator after 350 kA shot



a. Breech region



b. Muzzle region



c. Honed soda-lime glass prior to shot

Figure 6. Soda lime glass SEM photos (300x) after 350 kA shot



Figure 7. Polycarbonate insulator after 350 kA shot

A laminated fiberglass with a silicone based matrix (NEMA grade G-7) was the next insulating material tested. It was chosen in an attempt to eliminate the carbon in the epoxy matrix so that less conductive carbon soot would be left in the gun after a shot. There were no gouges or fractures visible in post-shot observation and less carbon soot was developed than with polycarbonate (fig. 9). The major disadvantage of G-7 is the amount of time required to hone the material. This can be attributed to its laminated structure and the chalk-like character of the silicone matrix. Also during projectile loading, the insulators were damaged because of their softness which required the gun to be re honed. SEM analysis was not very revealing because of the glass fibers in the material (fig. 10). The glass fibers give such an unusual surface texture to the material that craters and cracks were not noticeable.

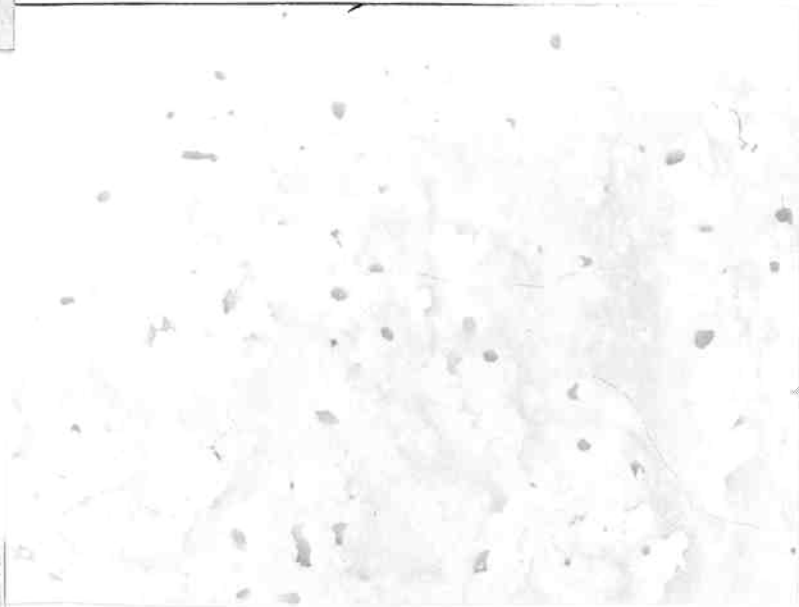
The last insulator material tested was quartz. Its greater compressive strength along with increased flexibility are witnessed by the light damage it receives as compared to other insulating materials (fig. 11). An additional benefit of using quartz is that it can be welded to form whatever length is necessary from short pieces and can be locally annealed to preserve characteristics. In contrast to the other insulators tested, the SEM photos of quartz show no craters and no remelting of the surface (fig. 12). It is felt that this is a step toward a truly reusable insulator. Since the hone marks are clearly visible in all areas of the insulator, it is felt that the SEM may be able to give some feedback as to how well the quartz is being polished during the last stages of honing.

In review, CEM-UT has tested float glass, quartz glass, polycarbonate, and G-7 fiberglass as railgun insulators in a copper-rail accelerator. Through visual and microscopic observation, it has been determined that the quartz glass and polycarbonate show the greatest promise for a reusable insulator.

Currently, CEM-UT is evaluating the performance of molybdenum flame sprayed on copper rails using a homopolar generator as the power supply. The molybdenum was expected to significantly reduce rail ablation so as to dramatically increase the gun performance, while reducing the cratering that was observed on most of the insulators tested before and thereby increase their expected life. The first insulator tested was 40% glass-filled polycarbonate. It was chosen because earlier tests indicated that polycarbonate might have multishot capabilities. The glass-filled material was chosen to help prevent the cracking that occurred when plain polycarbonate was used. Other than using molybdenum flame-sprayed rails, the conditions of the tests were the same as above. The results of the first test were startling, the gun current was 320 kA and except for a light coating of carbon soot that was easily rinsed away, it appeared as if the railgun had not been fired. Post-shot gun resistance at 1,000 volts was greater than 2 megohm. It was decided to refire the gun without disassembly to determine the usable lifetime of the insulators and rails. Between shots the gun was pneumatically gauged to measure the bore runout and then re honed. The pneumatic gauge indicated the runout was less than 0.025 mm (0.001 in.) and only an hour of honing was required to bring the gun back into tolerance. The second shot was equally spectacular achieving a velocity of 4.4 km/s with a gun current of 350 kA. Once again, the bore looked unfired and the resistance across the insulators was greater than 2 megohm. This gun will be fired without disassembly until some damage appears in the bore. At that time SEM photos and careful observation will be used to evaluate the performance of glass-filled polycarbonate as an insulator.



a. Breach region



b. Muzzle region



c. Honed polycarbonate prior to shot

Figure 8. Polycarbonate SEM (300x) after 350 kamp shot