DESIGN, ANALYSIS, AND FABRICATION OF TWO LIGHTWEIGHT, HIGH L’ RAILGUNS

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Design, Analysis, and Fabrication of Two Lightweight, High L' Railguns

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Abstract–**Previous work in railgun design at the Center for Electromechanics at The University of Texas at Austin has focused on the development of laboratory-based launchers designed for maximum stiffness under rather permissive mass and cost constraints. To develop a portable system to be used on a mobile platform required significant reduction in the mass of the launcher. This goal was achieved by utilizing a stainless steel, laminated-containment structure. Laminating the containment structure inhibits the formation of eddy currents, therefore allowing the steel structure to be closer to the rails, decreasing the rail-to-rail deflection during launch. Design, analysis, and fabrication of two railguns with 90- and 30-mm bores utilizing a laminated containment structure will be discussed. Laminations are insulated from each other by layers of sheet adhesive and a composite overwrap is applied to the laminations for longitudinal stiffness. The 90 mm bore gun is being fabricated for testing as the 9 MJ range gun. Performance specifications for the 90 mm bore gun are 3.2 MA peak current, 4.0 km/s maximum velocity, and 12 MJ muzzle energy. The 30 mm bore gun is a one-third scale version of the 90 mm bore gun, built to develop construction techniques and verify performance. It is designed to be operated at 1 MA with a maximum muzzle energy of 400 kJ.**

CONCEPTUAL DESIGN

In the past few years, the envisioned role of electromagnetic (EM) guns has shifted toward accelerating larger projectiles to the 2- to 10-km/s regime. During this period, the barrel's structure has been identified as a primary factor affecting launcher performance. Considerable progress has been made in producing stiffer gun structures, yielding corresponding increases in performance. Unfortunately, the evolution of the barrel structure has resulted in a very massive and bulky structure that is not suited for use in mobile platforms or in situations requiring high slew rates.

Design has focused on the need to take advantage of a variety of desirable design features identified from Task B work, offering structural performance comparable to the Task-B gun at greatly reduced weight. These features include cross sectional shape optimization, a stiff sidewall structure, efficient preloading techniques, and optimal property orientations.

Although composites are attractive as a structural material for this problem initially (due to minimal preloading requirements), it was believed that high rail temperatures may preclude their use. Ceramics appear to require a large preload, more than that available with composite pressure vessels. Electromagnetic performance constraints preclude the use of steel preloading tubes for the small outer gun diameters desired. For these reasons, a laminated steel structure was studied. This is a desirable structure configuration, provided the EM performance of the system is not adversely affected. Electromagnetic performance of the laminated structure is dependent upon the thickness of the laminations. In general, higher frequency means thinner laminations required.

Task B work focused on the development of a laboratory-based launcher designed for maximum stiffness under rather permissive cost and weight constraints. It has been shown that properly preloaded ceramic-steel systems can substantially outperform composite steel railgun designs in this role. However, the development of lightweight, low cost EMLs demands a different design approach; substantial reductions in the size and weight of the outlined laboratory based design require the development of improved structural ceramics. Recognizing the limitation of fiber reinforced composite designs, a new railgun concept was suggested which employs a laminated steel construction to limit the development of eddy current in the conducting inner support structure. The laminations can be insulated from each other and from the rails by thin nonconducting epoxy or composite layers. It is, in principle, possible to build an inexpensive, high tensile strength, high modulus inner support structure and thereby decrease the cost and weight of high performance launchers. Such a lightweight design concept incorporates a composite outer shell for preloading and longitudinal stiffness. Preloading of the rail/insulator package might involve the pressurized injection of epoxy between the package and outer support structure, fiber winding a composite tube onto the assembled laminations, or the use of a thermal-shrink fit. Stress preloading achievable with these techniques is limited by the stiffness shortcomings of composites as well as the potential for plastic extrusion of solidified epoxy at high operating pressures.

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DESIGN AND ANALYSIS

Shape Optimization

The majority of the structural finite element analysis (SFEA) performed on the electromagnetic launcher (EML) focused on the cross section of the barrel. Geometry of the cross section evolved both as a result of an interactive design and analysis process and as solutions were found for the various fabrication issues. Many different models were constructed and various material selections were examined in an iterative process until a configuration emerged which offered the desired stiffness/weight ratio, acceptable stresses and ease of fabrication.

Fig. 1 shows four cross sections of the barrel which capture major stages of the design evolution. The original design with an elliptical and circular containment structure are shown in Figs. 1a and 1b respectively. SFEA results for the two cross sections showed that the rail to rail separation for the elliptical containment structure was approximately half of that for the circular containment structure while the mass of the elliptical design was only 20% greater than that of the circular design. Further analysis showed that the more vertical the orientation of the sides of the containment structure were the better was the stiffness to weight ratio of the cross section. Fig. 1c shows the application of this discovery to the design as well as changes to the design to allow fabrication. These fabrication related changes included elimination of the rail pocket, straightening of the rail back and separate side wall insulators and rail back insulators. Initially, the rail design was based upon the fabrication concept of welding two tubes together, so that each rail would have two centrally located coolant passages . The final design of the cross section is shown in Fig. 1d and shows some additional trimming of the containment structure, straightening of the rail-sidewall interface and relocation of the coolant channels from the center of the rail to the back of the rail.

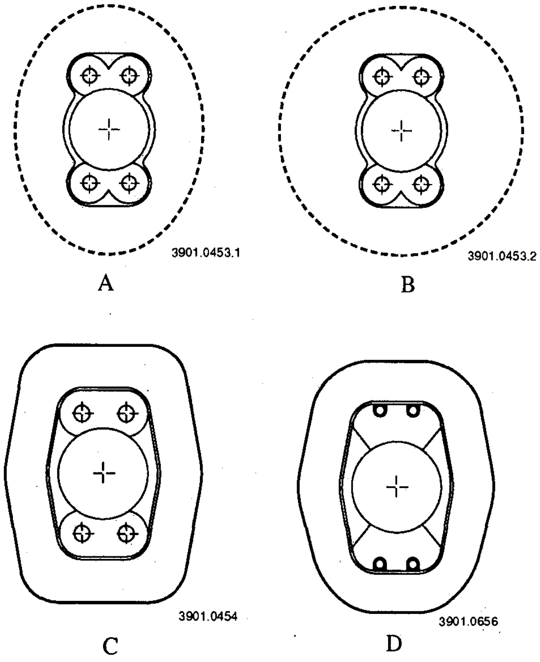

Fig. 1. Evolution of full scale launcher cross section

Changes to the containment structure were made to allow better filament winding of the laminated structure. Discussions with both the Center for Electromechanics at The University of Texas at Austin (CEM-UT) employees and companies which provide winding services indicated that the rapid directional changes of the outer surface of the structure could cause fiber slackness at the corners. Thus, the radii of the corners were increased to provide a greater transition region.

Concern over the fragile nature of the sharp point on the sidewall insulators led to straightening of the rail-insulator joint. Not only was this point structurally weak due to its geometry, but also because it would be impossible to 'place' fiber into this region during the pultrusion process.

The coolant channels were relocated to the back of the rail to reduce the stress levels under the channels. This reduced the stress concentration factor associated with the holes. Thermal analysis showed that this location was nearly as suitable as down the middle of the rails in removing bulk heat between shots.

Stresses and Deflections

Analyses were performed on one quarter of the cross section and employed 2-D plane strain elements. In general, material behavior was assumed to be linear, isotropic, and homogeneous. Interface elements were inserted with stick-slip capabilities in those regions where relative motion between elements was possible. Loading of the structure was restricted to a static pressure distribution on the surface of the rails which simulated the predicted magnetic pressure distribution at peak current.

Magnetic pressure distribution on the rails and a value for inductance per unit length was obtained through the use of the LPRIME computer code. This program was based on a model developed by J. A. Leuer, which 'solves the Laplace equation in a two-dimensional domain using discrete current sheets and a least square minimization solution technique'. The model divides the conductor boundary into a number of current sheet elements and assumes the high frequency limit - currents only flow on the surface of the conductor and the magnetic vector potential on the surface is constant Calculated L' of this geometry is 0.488 μH/m. When measured @ 100 kHz, the 30-mm gun had an L' of 0.52 μH/m. Some reduction of this value is expected during operation. Once the element current densities were solved for, the magnetic pressure distribution was calculated through the use of the equations:

$$B = \mu_0 K \qquad P = \frac{B^2}{2\mu_0}$$

Fig. 2 shows the magnetic pressure loading on one of the rails at the peak operating current of 3.2 MA. Magnetic pressure plot begins at the in-bore corner of the rail, transverses the the flat edge of the rail, continues around the back side including the channel notches (location of coolant tubes), moves across the other flat edge, and finally transverses the in-bore side of the rail. The spiky nature of the plot reflects the sharp discontinuities (edges) of the rail model which will be smoothed during fabrication. This

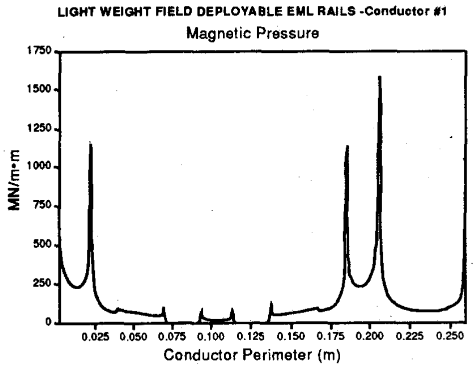

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Fig. 2. Magnetic pressure profile at 3.2 MA

smoothing should reduce the valley to peak rise by 30 to 40%. Total vertical force on the rail was calculated to be 96.1 kips/in. An average in-bore pressure of 41.95 ksi was obtained by dividing this number by the rail arc length and an average rail back pressure of 32.0 ksi was calculated by dividing by the width of the rail.

Magnetic pressure loading was applied to a quarter model of the launcher. Interface elements were present between the rail and the containment structure, between the rail and the sidewall insulator and between the sidewall insulator and the containment structure. Interface contact properties were used which would not allow relative nodal motion across the interface elements until a stress of 5,000 psi was exceeded. The sidewall insulator and rail back insulator were given material properties for epoxy, the rail for copper and the containment structure for a volume ratio weighted steel and epoxy composite. Fig. 3 is a displacement plot that has had the nodal displacements greatly magnified. Gaps between the rail and the sidewall insulator and between the sidewall insulator and containment structure are clearly discernable. The rail to rail vertical separation was predicted as 28 mil with two, 10-mil gaps appearing at the rail sidewall insulator boundary. This gap between the rail and sidewall insulator was a cause of concern, as was the separation of the sidewall insulator from the laminated containment structure. This is discussed later in more detail.

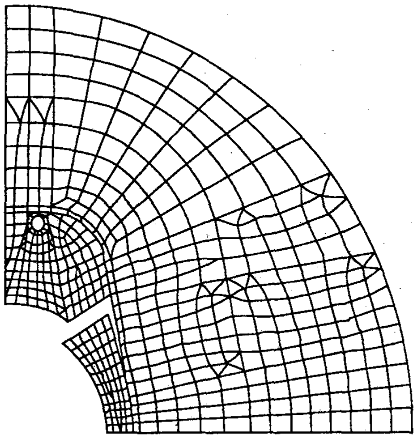

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Fig. 3. Displacement plot of full scale launcher at 3.2 MA

A von Mises stress contour plot is shown in Fig. 4. The plot shows that the highest stress concentrations reside on the in-bore corner of the rail (84 ksi) and on the coolant tube (78 ksi). The plot also shows the highest stress in the laminates (54 ksi) to exist at the in-bore side at a location midway between the rails (this is well below the yield strength of half hard 301 stainless steel–105 ksi). This occurs due to a bending motion which adds to the tensile stress in this region while countering the tensile stress towards the outer surface.

Table I summarizes the analysis results. The rails are made of dispersion strengthened copper which has a yield strength of 70 ksi and an ultimate strength of 78 ksi. The coolant tube is composed of a high strength brass which has a yield strength of 60 ksi and an ultimate strength of 75 ksi. While the yield strength for the copper was exceeded at the corner, the ultimate strength was not. Two things will happen which limit the permanent deformation of the rail. First, the material will strain harden as it deforms. Second, deformation will affect the magnetic pressure loading, tending to drop as the corner is rounded off. Similarly, the brass tube hardens as it deforms and also as it deforms, the surrounding rail material will bear more of the load.

Pressure Preload

A number of simulations were performed which focused on methods of preloading the lightweight field deployable EML. The sole purpose of preloading this structure was to prevent the rails from separating from the insulators during launcher operation. The opening of a gap between the rails and insulators would allow the deposition of carbon and other contaminates between the seamless insulator and the bore components (the rails and the insulators).

In order to keep a gap from opening, the insulator would have to be compressed an amount equal to twice the size of the gap (gaps open at both sides of the insulators where they meet the rails) which finite-element analysis indicated would occur if the structure was not preloaded. This reflected the fact that whether the gun was preloaded or not, the rails would separate the same amount at equivalent operating conditions. At an operating current of 2.8 MA, a 9.6-mil gap would open.

Four possible preloading options were examined via finite-element analysis. The first option was to apply a uniform pressure to the in-bore surfaces of the rails and the insulators causing the rail to rotate down into the bore, placing the insulator under compression and opening a gap between the rail and the laminated containment structure. This gap would

TABLE I

SFEA ANALYSIS RESULTS AT 3.2 MA

Quantity	Value
Insulator separation	-10.72 mil
Rail separation	27.98 mil
Von Mises stress in rail under channel	60.00 ksi
Von Mises stress in rail at in-bore corner	84.00 ksi
Stress in coolant tube	78.00 ksi
Stress in continuous insulator behind rail	36.00 ksi
Maximum stress in laminate	54.00 ksi

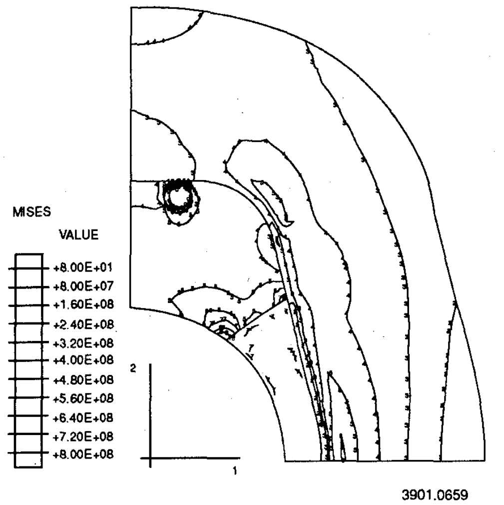

Fig.4. Von Mises stress contour plot of full scale launcher at 3.2 MA

then be filled with epoxy and the pressure loading released (after the epoxy hardens). Injected epoxy would prevent the rail from returning to its original position and the insulator would remain under compression. The structure would respond primarily to the pressure loading on the insulator, since the laminated structure was much more flexible in this direction (due to the long moment arm associated with the long side of the structure). Uniform pressure loading would be applied by a hydraulic hose placed in the bore and then pressurized.

The second option placed a pressure loading only on the rail in order to open gaps between the rails and the sidewall insulators which would be filled with epoxy. Subsequent release of the rail would compress the sidewall insulator by an amount approximately equal to the total thickness of the epoxy layers injected to either side of the insulator. This required an amount of force per unit length equal to the peak magnetic force loading on the rail. Structural deformation, due to this preloading technique, more closely resembles that caused by the actual magnetic pressure application but differed in that a substantial portion of the magnetic loading was applied to the portion of the rail at the rail to sidewall insulator seam. Since this option applied no force in this area, the same total amount of force would have to be applied to a lesser area causing higher stress levels in the rail. This method of preloading would require a more elaborate inflator, perhaps a mandrel with hydraulic pancakes mounted 180° apart.

The third option required the seamless insulator to be formed under high pressure so that a constant pressure can be applied to the out-bore surfaces of the rails and the insulators. Injection of epoxy at high pressure into the fiber filled region between the bore components and the steel laminates would present some sealing difficulties, but the primary concern with this option was whether a large enough pressure could be developed without over stressing the relatively thin and fragile sidewall insulators. An injection pressure under 3 ksi can be easily obtained. While injection pressures up to 10 ksi can be obtained, difficulties associated with sealing the gun and preventing epoxy injection between the glued steel laminates would be proportional to the injection pressure.

The fourth option was to apply an external pressure to the exterior of the laminates in the insulator axis direction (in the direction of an axis which passes through the middle of both insulators and is 90° rotated from the rail axis), in order to press the laminates into a shape similar to that which occurs during launcher operation. The seamless insulator would be formed while the structure was held in the deformed shape. Release of the preload pressure after curing would cause the structure to contract in the rail axis direction, thus compressing the insulators. Primary concern with this option was whether enough pressure would be applied to the exterior of the overwrap to produce the desired deformation without exceeding the allowable radial stress loading of the composite (15 ksi).

The first preloading option (a uniform pressure application to the in-bore side of the rails and the insulators) failed to provide sufficient compression of the insulator to prevent rail separation during launcher operation at peak currents above 1 MA. The insulator was compressed by 2.6 mil and the peak compressive stress in the insulator was 1.5 ksi. As mentioned previously, the desired insulator compression was at least 19.2 mil.

The second preload option utilized a 30-ksi pressure on the in-bore side of the rail. Resultant structural deformation more closely resembled that which occurred when the launcher was operated than preload option one and it was possible to open a gap between the rail and the sidewall insulator. Results of the analysis showed that a 6.2-mil gap was opened.

The next preload option examined was the formation of the seamless insulator under high pressure. Analysis showed that an injection pressure of approximately 3 ksi would compress the insulators by 20.4 mil. Maximum stress in the insulators reached 32 ksi at the midpoint of the insulator and was compressive in nature. This option provided the desired insulator compression with acceptable stress concentrations in the sidewall insulator and was the most attractive option from an assembly viewpoint.

The last preload option evaluated was application of pressure to the exterior of the steel laminates in order to force the laminated containment structure to grow in the rail-axis direction and thus create a gap either above the rails or between the rails and the insulators. It was determined that a 15 ksi pressure applied to the sides of the laminates over a 4.7 in. length (along the insulator sides of the laminate in the model) was sufficient to open the desired gap. This would amount to an exterior force per unit length of 70.5 kips/in. down the length of the gun. While a structure could have been built which would apply the needed force per unit length, it would have been costly and if bolts were the mechanical means of force application, it would have been a very laborious task. A 1 in. diameter grade-8 bolt every 1 in. of gun length (implies bolt staggering) would have been needed.

In summary, preload option one did not provide the necessary compression of the sidewall insulator and while preload options two and four did, they were difficult to implement. Preload option three provided the necessary insulator compression and was implemented. The 3 ksi epoxy injection pressure was adequate at a maximum current of 2.8 MA and increasing the pressure to 4 ksi would allow the launcher to operate at 3.2 MA if desirable. Injection pressures as high as 6 ksi have been obtained from an ordinary grease gun. The main difficulties associated with this technique were associated with sealing the cavity into which the epoxy was injected.

Rail Cooling

Due to the requirement of nine shots in three minutes, provision must be made for cooling the rails. Because of the limited space available on the skid, a cooling system currently in place was utilized instead of developing a completely new system. The system being used is for bearing oil cooling and consists of a 40% ethylene glycol and 60% water solution supplied at 100 psi and maximum possible flow rate of 40 gal/min of which 15 gal/min will be used for the rails. Original design concepts for the rails consisted of extruded rounds that incorporated a cooling channel in the center of the cross section. Two of these extrusions would be welded together to form a rail. Analysis showed that stresses in the vicinity of the coolant holes were exceeding the yield strength of the material. It also became apparent that the extrusion would be difficult and expensive to fabricate. After numerous attempts to simplify the rail geometry and include coolant passages, the current design with tubes brazed into the backside of the rail was selected. A three dimension transient thermal analysis was performed to determine the temperature history of the rails during a five-shot burst. A limit of 130°C was selected as the maximum allowable temperature due to the material properties of the bore insulators. High temperature transients are very short lived and occur at the sharp corner of the finite-element model where current tends to flow. In reality, the rail has some radius which reduces the peak temperatures.

Longitudinal Stiffness

The containment structure of the launcher was fabricated by laminating stainless steel sheet material with sheet adhesive. Although the structure is strong and stiff radially, the longitudinal properties are dominated by the sheet adhesive. Deflections at the muzzle end of the gun are excessive if it is cantilevered at its midpoint. To increase the longitudinal stiffness of the containment structure, a 33 cm diameter overwrap is applied which consists of axially oriented S-glass fibers in an epoxy resin. This allows for the gun to be supported for two thirds of its length and the muzzle deflection is approximately 0.3 mm. Outside diameter will be ground to provide a surface on which the gun can mounted on a bearing assembly to allow for recoil motion.

GUN SUBSYSTEMS

Autoloader

An autoloader and magazine assembly is required for repetitive firing of the gun. The magazine must be capable of holding nine projectiles and correctly positioning them in the autoloader for loading. The ramming device must have a stroke the sum of two projectile lengths (1,400 mm), breech connection thickness (230 mm), and two bore diameters to develop inductance (180 mm) or a total of 1.8 m. Under normal operating condition,s the autoloader has 20 s in which to load the projectile; however, for a burst rate of two shots in 5 s, the time is reduced to 1 to 2 s for loading (time is required for the gun to recoil and return to the firing position). This system is currently under design and the approach is to use a hydraulic cylinder as the ramming device and a vertical magazine.

Breech Connection

Breech connection for the 90 mm range gun will be similar to the breech currently in use on the 90 mm SSG at CEM-UT with some minor modifications. It must be capable of 3.2 MA and 6 kV and accept the gun bus cables coming from the compulsator. The basic breech consists of eight parallel plates of alternating polarity. A laminated breech design of this type reduces the inductance of the breech connection thereby increasing performance and reducing the plate-to-plate repulsion forces. This set of plates is insulated by G-10 insulators and the assembly is vacuum/pressure impregnated (VPI) with epoxy. Ends of the rails are machined with an hourglass shape in which two wedges are placed facing each other. As the two wedges are brought together by a draw bolt, they spread the end of a rail. With the breech connection in place over the rail ends, the wedges are tightened, making electrical contact and mechanically securing the breech to the rails. To assist this joint in the management of the recoil force, a wedge assembly is provided on the breech end of the gun in which through bolts attach the breech to the containment structure.

Recoil Mechanism and Support Structure

In an effort to increase the accuracy of EM launchers, a recoil mechanism has been incorporated into the design of the mount structure for this gun. The rod end of a pair of tension dampers will attach to the breech connection and the cylinder end will be anchored to the support structure. The pair of dampers have been designed so the gun will recoil and return to firing position in 2 to 2.5 s.

Mount structure consists of a support for the gun that allows for the recoil motion, supports to ground, and an elevating mechanism. Originally the gun was to be placed on the compulsator skid. Since the mounting function will be performed by the mobile platform in the final application, this was deemed an unnecessary constraint and the gun has been moved to the ground behind the compulsator skid. Support to ground incorporates a linear-bearing system that allows the gun to travel through its 25 cm recoil stroke. This system must be capable supporting the gun mass and accurately positioning the gun and maintain that position while the projectile is in-bore. Forward support consists of a motor driven mechanical linear actuator which provides elevation and depression of the gun from +15 to -5° from horizontal.

FABRICATION

Rails

Previous rail sets for the 9 MJ SSG had been extruded from ETP copper; therefore, it was desirable to have the rail set for this launcher to also be extruded. However, an increase in strength of the material was desired, making the extrusion process more difficult. Originally the preferred material was molybdenum with an alternate material being an alloy of copper (i.e., aluminum dispersion strengthened copper, zirconium copper, chromium copper, etc.). After working with a large molybdenum manufacturer, the fabrication of an extrusion of this length and cross section was found to be expensive and high risk. The straightness and dimensional stability of the extrusion could not be guaranteed and the extruded shape was an approximation of the rail shape, requiring considerable machining. Machine shops that were consulted for the final machining were not capable of providing a fixed price for machining based on the unknowns of the supplied extrusion.

Aluminum dispersion strengthened copper (Glidcop® AL-60) was selected after investigating the other copper alloys. This alloy could be extruded in the lengths of interest, and longer, had high yield strength (482 MPa), and acceptable conductivity (78.5% IACS). The original extrusion was extruded near net shape and then drawn to net shape. Some final machining was required to put the coolant channels in the back of the rail and the bore radius was also machined. Once in-house, the coolant tubes, which are a high strength brass alloy, were brazed in place.

Since the 30 mm launcher was a scale version of the 90 mm gun, it was desired that all materials were the same. To invest in the die for extruding the third scale rails would have been prohibitive, an extruded bar was purchased and the rails were machined from this bar stock. Again the coolant tubes were brazed in place once they were received.

Insulators

After using G-10 insulators in the 90 mm SSG with poor results, it was decided that a pultrusion would be used. This is a process similar to extrusion where glass fibers are pulled through epoxy resin and then a die where it is formed and cured. For the application of the range gun, a 70% fiber fraction was used. The insulator was fabricated by using both roving (filaments) and cloth. The cloth was pulled in such a way that the fiber orientation is at 45° with the direction of projectile motion. The roving that is intermingled with the cloth is pulled in the direction of projectile motion.

Containment

Laminations: The laminated containment structure is fabricated from half hard 301 stainless steel. This material was selected for its high strength (760 MPa), non-magnetic properties and relatively low cost. Sheets 1 m x 3 m were purchased and sent to a stamper where they were sheared in half and an approximation of 17 lamination shapes were partially stamped in each sheet. Small sections at the four corners were left connected so that the entire sheets could be laminated together reducing the number of parts being handled. The sheets were then sent to a manufacturer who chemically etched and primed the sheets to clean the surface and prepare it for bonding.

The 1 m x 1.5 m sheets were then laminated together using FM 123-2 sheet adhesive manufactured by American Cyanamid. After curing a 5 cm thick stack of the sheets the individual lamination shapes were cut from the sheets using an abrasive water jet cutter. This operation resulted in 204, approximately 5 cm thick, laminated stacks that were approximately the shape of the final lamination. These pieces were sent to a machine shop that finish machined the lamination stacks to final shape. An assembly mandrel and table were fabricated so the 5 cm stacks could be glued together to form the full length of the containment structure.

Overwrap: Since the laminated containment structure has poor longitudinal bending stiffness, an overwrap was applied. The overwrap is fabricated on the filament winding machine at CEM-UT. Special end plates were fabricated to allow the machine to wind low angle axial layers such that the fibers lay along the length of the gun. On top of these axial layers, high angle hoop layers were applied to keep the axial layers tight on the laminations. Layers were built up until the structure could be machined to form a 33 cm diameter barrel.

FINAL ASSEMBLY

At this point the gun is ready to be assembled. Rails and insulators are assembled onto a circular mandrel and a Teflon™ heat shrink tube is applied for the entire length. A 45° woven S-glass sleeve is also fit to the outside of the rail/insulator set. This assembly is placed into the containment structure. Seal plates are placed at each end of the assembly and epoxy is pumped into the assembly gap formed between the rail/insulator set and the containment structure. The shrink tube provides a pressure boundary and the epoxy is pressurized to 21 MPa to preload the rail/insulator set. This preload is required so that the gap between the rails and insulator does not open during EM loading. This finishes the assembly of the barrel itself, and an isometric view is shown in Fig. 5. The breech connection is attached as described above, and the gun is mounted in the support structure.

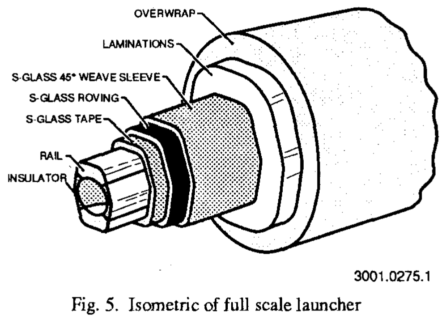

Fig. 5. Isometric of full scale launcher