Status of the 9 MJ Range Gun System

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Abstract: **The 9 MJ range gun system under construction at the Center for Electromechanics at The University of Texas at Austin is designed as a self-contained, field portable electromagnetic launch system to accelerate a salvo of three projectiles to a muzzle energy of 9 MJ at velocities ranging from 2.5 to 4.0 km/s. The range gun system will consist of a self-excited air-core compulsator, a 90 mm bore railgun launcher, prime power and auxiliary systems, solid state switches for field rectification and gun discharge, and the controls and data acquisition required to operate the system. The compulsator is designed to deliver 3.2 MA current pulses to the railgun launcher at a peak power rating of 10 GW.**

Originally, a passively compensated compulsator design was developed until a projectile acceleration limit was imposed. This forced a redesign of the system, incorporating several design refinements and utilizing selective passive compensation to shape the compulsator output pulse. Design of the selectively passive compulsator was finalized in 1989 and fabrication of the system components was initiated. System fabrication was well underway when an attempt to install a rotor flywheel ring during January 1992 resulted in a fatal crack through the rotor flywheel and field excitation armature winding. After an extensive review of the original rotor design and system performance requirements, a rotor rebuild program was initiated in May of 1992. The rotor rebuild program included frequent design evaluations, extensive material characterization, support from experts in the design and fabrication of composite structures, and a reduction in the system salvo fire requirements.

Final design and fabrication of other system components paralleled the rotor rebuild effort, allowing testing of the other system components. Prime power and auxiliary systems testing was successfully completed in August of 1993 and motoring of the compulsator using a test shaft is planned for April of 1994. The lightweight 90 mm railgun, breech connection, and flexible bus cables developed for the range gun system are currently being tested at the Electric Armaments Research Center at Picatinny Arsenal, New Jersey. Final assembly and laboratory testing of the selectively passive compulsator will begin in July of 1994, with range testing of the complete system beginning in October of 1994.

This paper will describe some of the innovations incorporated into the design of the 9 MJ Range Gun system compulsator and present the current status of the fabrication and testing efforts. Initial performance of the 90 mm railgun during testing at the Electric Armaments Research Center will also be presented.

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Introduction

The 9 MJ range gun system under construction at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) is designed as a self-contained, field portable electromagnetic launch system to accelerate a salvo of three projectiles to a muzzle energy of 9 MJ at velocities ranging from 2.5 to 4.0 km/s [1]. The 9 MJ range gun system will consist of a self-excited, air-core compensated pulsed alternator (compulsator) a 90 mm railgun launcher, prime power and auxiliary systems, solid state field rectification and gun discharge switch systems, and the control and data acquisition systems required to operate and evaluate the performance of the system.

Compulsator

The 9 MJ range gun system compulsator is an air core design with a stationary excitation field winding and rotating primary and field excitation armature windings. The compulsator is self-excited, with the energy required to provide the excitation field extracted from the rotor prior to compulsator discharge into the railgun. The graphite/glass/epoxy composite compulsator rotor stores approximately 180 MJ at 7,500 rpm and is designed to deliver 17 MJ at 5.15 kV and 2.6 MA per pulse to the 90 mm railgun load when accelerating a typical SLEKE type armature. Typical operating parameters of the 9-MJ range gun system compulsator are presented in table 1.

Table 1. Compulsator basic operating parameters

Operating Speed	7,500 rpm
Discharge Speed	6,100 rpm
Projectile Energy	9 MJ
Projectile Mass	4.15 kg
Projectile Velocity	2.1 km/s
Peak Gun Current	2.6 MA
Gun Active Length	7 m

The compulsator design also incorporates a stationary, multi-conductor compensating winding to provide selective passive compensation, shaping the output pulse toward an optimum square wave configuration. The 140 turn compulsator excitation field coil operates at 15 kV and 41.4 kA, providing 5.15 kV of primary armature voltage.

Compulsator Rotor

The basic structure of the compulsator rotor is constructed of concentric graphite and glass fiber reinforced epoxy rings, supported on two metallic stub shafts. The primary armature and field excitation armatures terminate in slip rings on the connection end shaft, and axial mechanical and electromagnetic forces are reacted to the stator structure through the thrust end shaft. Fabrication of the compulsator and system components was well underway when an attempt to install a rotor flywheel ring during January 1992 resulted in a fatal crack through the flywheel and field excitation armature winding. After a detailed review of the system performance requirements and original rotor design, a rotor rebuild program was initiated in May 1992. The rotor rebuild program included frequent design reviews and extensive material characterization testing, along with support from Oak Ridge National Laboratory and Custom Analytical Engineering Services (CAES), experts in the design and fabrication of composites structures. In addition to the use of improved materials, the current rotor incorporates several improvements to the original design. Fabrication of the rotor is scheduled to be complete during July 1994. Figure 1 shows a simplified cross section of the current compulsator rotor, identifying the major components of the new design.

Keyed Rotor Shafts

In the design of the previous rotor, the two independent stub shafts were held in position by the radial preload imposed by the full length flywheel rings. Prior to epoxy encapsulation of the conductors passing through this region and installation of the first full length flywheel ring, stub shaft alignment was difficult to maintain. The current rotor design improves this situation by keying the stub shafts together prior to conductor encapsulation and installation of the rotor flywheel rings. The two stub shafts were pressed together using a tapered press fit and bonded. After keying the shafts together, measurements have shown the stub shafts to be well within alignment requirements prior to installation of the first flywheel ring.

Composite Materials for the Rotor Flywheel Rings

In light of the crack initiation and propagation during assembly of the previous rotor's flywheel rings, the program sponsor directed CEM-UT to conduct a thorough materials selection program. The purpose of the program was to select, through an extensive composites test program, the best available resin and fiber system for the rotor's composite flywheel rings. Emphasis was focused on toughened resin systems to prevent and arrest crack propagation. Construction techniques and ring laminate designs were also evaluated, with both wet wound and towpreg methods investigated.

Most of the flywheel rings required the higher modulus of elasticity of graphite fiber to limit spin growth and to reduce radial interferences which ease ring assembly requirements. Therefore, the materials selection program mainly addressed graphite systems. Hercules IM7 graphite fiber was selected due to its proven track record and reasonable cost.

Manufacturers' data on several dozen resin systems were closely scrutinized. Of these, three towpreg and four wet wound systems were selected for further evaluation. Trial rings were fabricated, and test specimens were prepared for resin/fiber tests to determine transverse tensile and hoop properties.

The two superior resins identified from the materials selection program, with comparable toughness and strength characteristics, were Fiberite 977-2 and Hercules 8553-50. Both are toughened towpreg systems, which were found to deliver more consistent fiber fraction than wet wound systems. Due to slightly better performance over the Hercules system, the selected resin for the flywheel rings is the Fiberite 977-2 system.

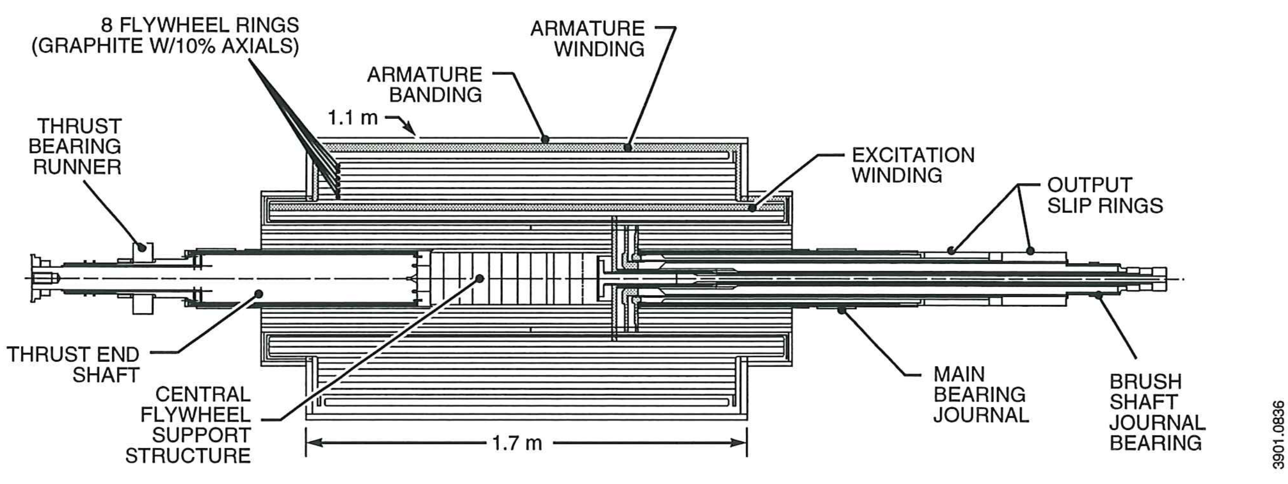

Figure 1. Simplified rotor cross section

In addition to the use of toughened resin systems, a 0°/90° laminate design was developed to provide additional crack arrestment characteristics. Hoop wound IM7 graphite layers are interspersed with axially oriented S2 glass unidirectional fibers. For all hoop wound rings, ring loading transverse to the radial plane is the weakest direction for a composite ring and a more likely site for crack formation. Inclusion of the glass axial reinforcement was found to greatly increase the load carrying capability in the transverse direction as well as arrest the propagation of an existing crack. These results were determined by performing fracture toughness tests as described below.

Trial rings were fabricated for three laminate designs, including a Fiberite IM7 hoop wound ring, a Hercules IM7 hoop wound ring with 5% glass axial reinforcement, and a Hercules IM7 hoop wound ring with 10% glass axial reinforcement. Both notched and unnotched fracture toughness specimens were axially cut from trial fabrication rings. Specimens were tested in a four point bending fixture and loads at the point of crack initiation were recorded.

As seen in figure 2, addition of glass axial reinforcement contributes to the material's bending moment carrying capability. Crack initiation loads for 5% axial material is only slightly higher than the Fiberite material without axials. However, the 10% axial material shows a significant increase in loads to initiate cracks as compared to the 5% material. This difference is due to the amount of glass axials, more uniform distribution of the axial layers with the 10% build-up, and the presence of axial layers nearer to the surface with the 10% build-up.

Crack arrestment with axial layers was a key reason for performing these tests. With both the 5% and 10% fracture toughness specimens, initiated cracks in the graphite layers approached but never penetrated the glass axial layer. Cracks reached the glass layer and then turned 90° and propagated in the axial direction with increasing load. Due to the superior load carrying capability of the 10% glass reinforcement, this approach was integrated into the ring laminate design.

Inclusion of the glass axials also significantly increased transverse tensile strength as shown in figure 3. Figure 3 presents transverse tensile strengths for an all IM7 hoop wound ring and a ring with 10% glass reinforcement. The all hoop Fiberite ring, without glass reinforcement, has a transverse tensile strength of about 12,300 psi at room temperature. Glass axial reinforcement increases the transverse tensile strength to 17,500 psi. This is the point of matrix failure with the glass axials still intact. Failure of the glass occurred at 28,500 psi. Elevated temperature properties did not deviate significantly from the room temperature test results.

Material testing of the high modulus graphite fibers required for the outer primary armature banding revealed an incompatibility with the toughened resin systems. The schedule delays associated with identifying and qualifying alternative resin/fiber systems was not acceptable, so an all Fiberite IM-7 rotor is being constructed. To reduce risk and improve design stress margins, the rotor design speed was reduced to 7,500 rpm. While this reduces stored energy and compulsator voltage, the system will be capable of accelerating SLEKE type launch packages to the 9 MJ kinetic energy goal.

Rotor Armature Winding Design

An improved armature winding design has also been integrated into the current rotor design. The new armature winding is a helical design incorporating obliquely oriented litz conductor windings. This design covers the rotor surface and eliminates the spacers required for the previous armature winding design. Elimination of the conductor spacers elimi-

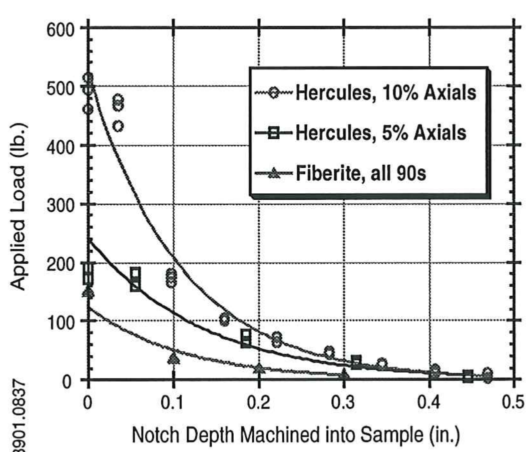

Figure 2. Applied crack initiation load vs. sample notch depth for composite samples with and without 0° axial reinforcement

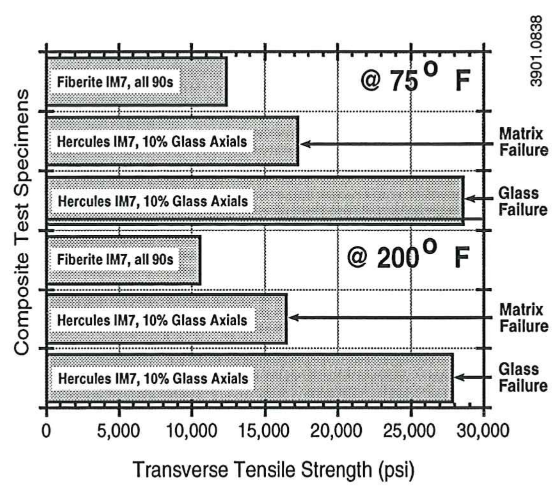

Figure 3. Composite transverse tensile strength at room and elevated temperatures

nates material discontinuities and results in a more homogeneous, robust structure, reducing the risk of crack initiation. Since potted litz wire and spacer material densities are comparable, the new armature winding mass has not changed.

An electromagnetic (EM) analysis and a detailed finite element stress analysis have been completed for the new helical armature winding design, and the winding is currently being fabricated.

Stator Fabrication and Assembly

The compulsator stator consists of a multi-turn compensating winding with a laminated stainless steel support structure, an aluminum excitation field coil and support structure, a stainless steel stator casing and main end plates, hydrostatic bearings, seals, support pedestals, and current collection systems for the field excitation and main armature circuits [1]. Figure 4 is a cross section of the compulsator, identifying the major components of the stator structure.

The selectively passive compensating winding is a two pole configuration, with 26 shorted turns per pole. The compensating winding is located on the inner bore of the stator structure and is supported against electromagnetic loads by a series of 1 in. × 1 in. slots in the laminated stainless steel stator structure [1].

The original compensating winding design used slots in the inner bore of the laminated support structure to provide mechanical support for the electromagnetic loads imposed on the compensating winding conductors during discharge. A detailed finite element model of a conductor and support slot was constructed, to examine the stress distribution after cooling to room temperature. The finite element analysis (FEA) model was based on a stress free state in the winding at a temperature of 180°F, the temperature at which the potting epoxy gels. Results of the model indicated a significant stress concentration in the area near the tooth tip, and significant residual tensile stresses across the conductor/slot bond line. These residual stresses are the result of the large variation in the coefficient of thermal expansion (CTE) between the conductor/epoxy composite and the stainless support structure, and seriously degrade the tensile shear strength of the bond.

Several approaches were considered to overcome the mismatch in the CTE between the conductor and finally, it was decided to eliminate the teeth in the stainless support structure and replace them with a composite material. The composite support structure is potted at the same time as the compensating winding conductors and has a CTE that closely matches the conductor/epoxy composite. The winding is fabricated on a separate internal mandrel and then potted in a cylindrical external mold. After curing, the winding is transferred into the cylindrical bore of the laminated support structure and preloaded with a thermal shrink fit. The preload creates a compressive circumferential (hoop) stress, improving the tensile shear strength of the conductor/support structure bond. The preload also generates compressive radial stresses, which tend to offset the inward radial electromagnetic loads experienced in some regions of the winding.

Switches and Controls

The power electronics of the 9 MJ range gun system are comprised of the primary gun switch, which allows simple loading of a de-energized gun, and the field excitation rectification/inversion bridge [2]. Figure 5 shows the basic power circuit diagram of the 9 MJ Range Gun system.

The gun switch is comprised of 24 double modules, packaged as back-to-back gun switch modules (GSMs) to improve the overall system size and weight specifications. Each double module accepts current via two hexapolar cables

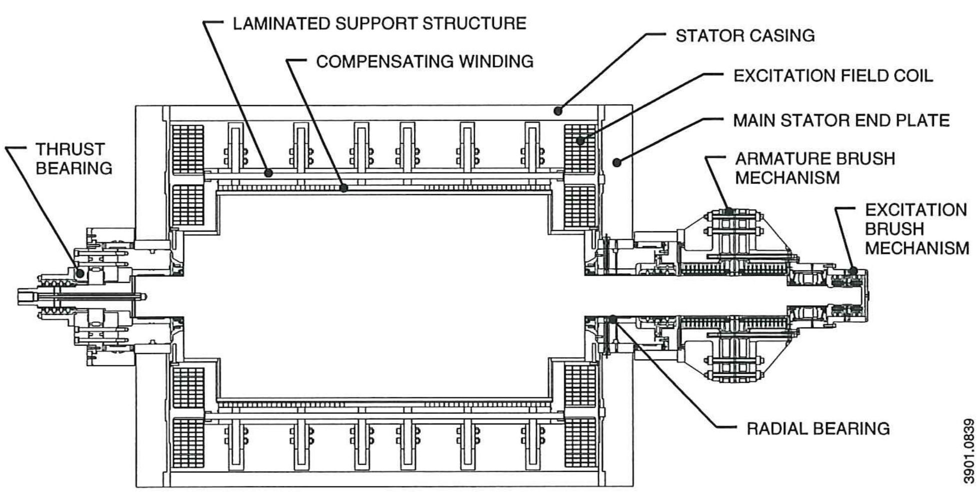

Figure 4. Task C compulsator - cross section view

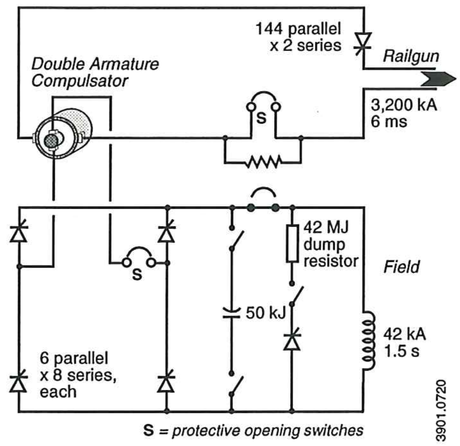

Figure 5. 9 MJ EM range gun power schematic

[3] from the compulsator armature brush mechanism and switches a maximum of 150 kA into a single hexapolar cable to the railgun. The cable impedances assist in the even distribution of current to the various parallel-active modules. Matching of thyristor characteristics is responsible for the distribution equity within the switch module itself. Each GSM has three matched thyristors in close parallel mounting, in series with a second group of three parallel units. The two subsets are further matched to provide close forward voltage-drop matching among multiple GSMs. An independent snubber circuit is provided for each group of three thyristors. The photograph in figure 6 shows an assembled double GSM. The GSM modules are scheduled for completion in April of 1994. Design improvements over the course of this project have reduced the overall gun switch volume by 28%, to 1.2 m^3, and the mass estimate by 59%, to 1,140 kg (2,500 lb).

The field excitation bridge was originally conceived as a modular design, but was modified to a smaller and lighter monolithic package. The new bridge occupies 0.9 m^3 and weighs 860 kg (1900 lb), an improvement of 35% over initial design volume and 52% over initial design weight. Each string of eight thyristors is assembled into a 60° wedge, with the six parallel assemblies forming a compact quadrant of the single-phase full-wave bridge. Each wedge assembly has four snubber boards which serve two thyristors apiece. Hexapolar cables will supply both ac and dc currents to and from the bridge.

A sophisticated hard logic controller has being assembled to control the bridge gating during the three-modes of operation. Acting as a full wave rectifier, the bridge applies charging current to the field winding. At the desired field level, the same controller causes the field current to "free wheel" through the bridge while the gun switch is activated for a single pulse discharge. Afterwards, the bridge is gated at an advanced angle to cause load-commutated inversion of the field current to the compulsator ac winding. This causes a transfer of energy from the inductive store of the field winding to the rotational store of the compulsator rotor. The controller is referred to as the system firing and fault control module (FFCM) and will also monitor for malfunctions in the operating sequence and operate the protective opening switches as needed.

90 mm Railgun Fabrication and Testing

After completion in January 1994, the 90 mm railgun constructed for the 9 MJ range gun system was transferred to the Electric Armaments Research Center at Picatinny Arsenal, NJ for testing on the 52 MJ capacitor bank power supply [4]. This will allow full scale testing of the lightweight, laminated railgun during completion of the 9 MJ range gun system compulsator. The basic construction of the 90 mm railgun is shown in figure 7, and a photograph of the railgun and recoil system installed at the Electric Armaments Research Center is shown in figure 8.

During initial testing of the 90 mm railgun an inductance gradient of 0.54 μH/m was measured, closely matching the calculated value of 0.49 μH/m [5]. Testing of the 90 m rail-

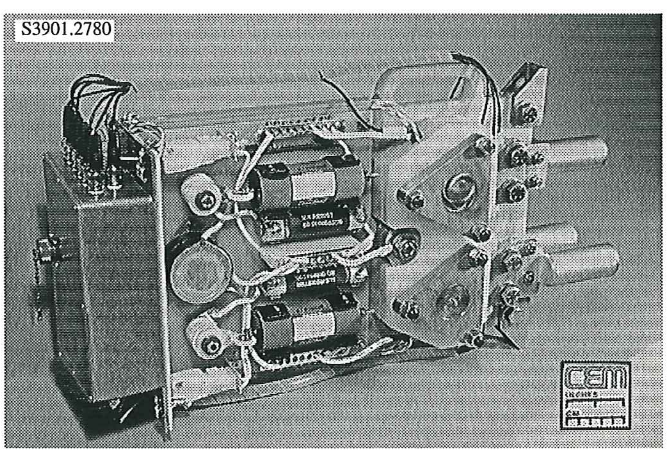

Figure 6. Assembled double GSM

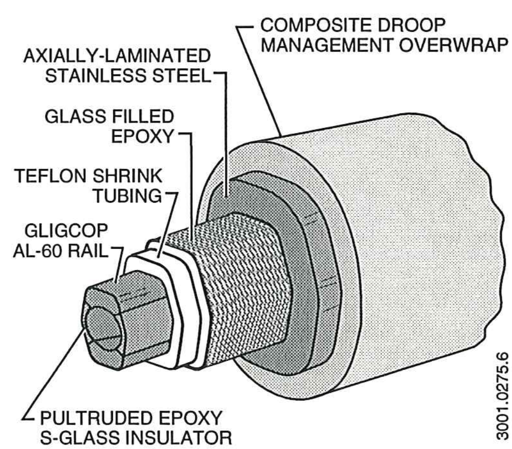

Figure 7. 90 mm laminated railgun construction

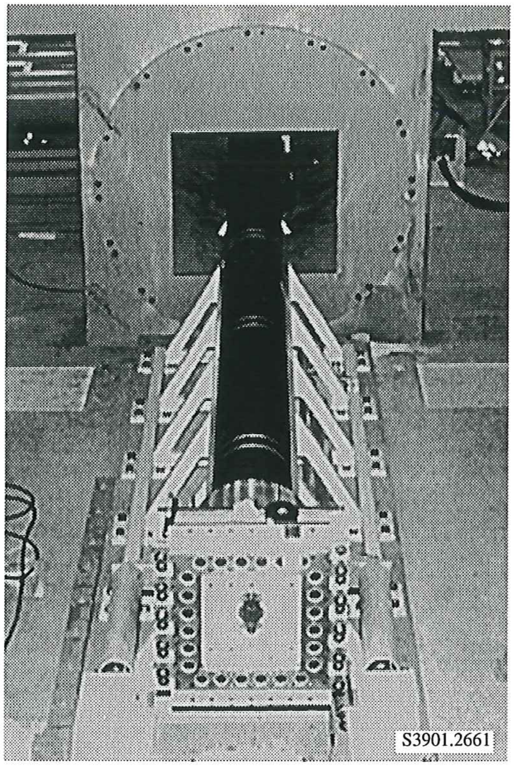

Figure 8. 90 mm railgun and recoil mechanism at EARC

gun at the EARC facility began in March 1994. To date, two launches have been performed, using projectile designs developed in the SLEKE program at CEM-UT.

Prime Power and Auxiliaries

The prime power and auxiliaries skid for the 9 MJ Range Gun System provides all of the required auxiliaries for operation of the 9 MJ range gun system. The system includes a 700 hp Pratt & Whitney PT-6A auxiliary turbine, and a 5,000 hp General Electric LM500 prime power turbine, along with the hydraulic systems required to support the compulsator hydrostatic bearing systems. Figure 9 shows a photo of the completed auxiliaries skid. After completion, the turbines and auxiliary skid systems were fully tested at CEM-UT, using a 1,000 hp waterbrake load. This test program demonstrated successful operation of the LM500 turbine controls and monitoring systems in all operating control modes.

During a maintenance run in September 1993, a failure in the auxiliary turbine fuel control system resulted in a power turbine overspeed and turbine disk failure in the auxiliary power unit turbine. The damage to the APU turbine has been repaired and additional instrumentation has been installed to improve turbine speed control and provide additional overspeed protection.

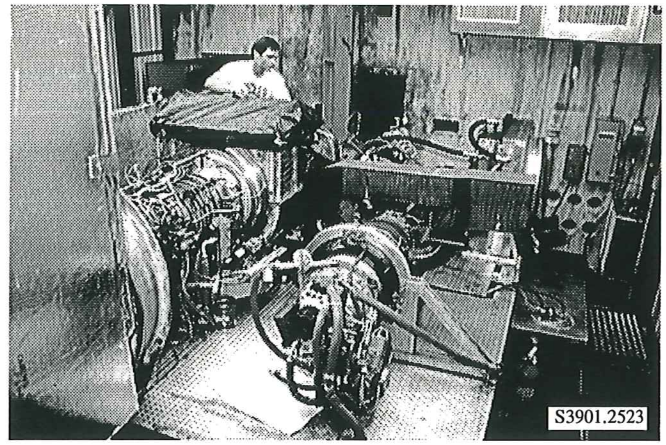

Figure 9. Auxiliaries skid

Conclusion

Fabrication of the 9 MJ Range Gun system compulsator is nearing completion, with final assembly of the compulsator scheduled for June 1994. Rectifier/invertor and gun switch modules are currently being fabricated and assembled, with completion scheduled for May 1994. The prime power and auxiliaries skid has been completed and tested in the spin test facility and is ready for final connection to the compulsator. Laboratory testing of the 9 MJ Range Gun system at the Center for Electromechanics at The University of Texas at Austin is scheduled to begin during July of 1994. After several months of lab based testing, the system will be transported to the U.S. Army Yuma Proving Ground in Yuma Arizona for field testing. The field test program will demonstrate operation of a 9 MJ electromagnetic launch system in a field environment and will allow down range and terminal ballistics characterization of EM projectiles.

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