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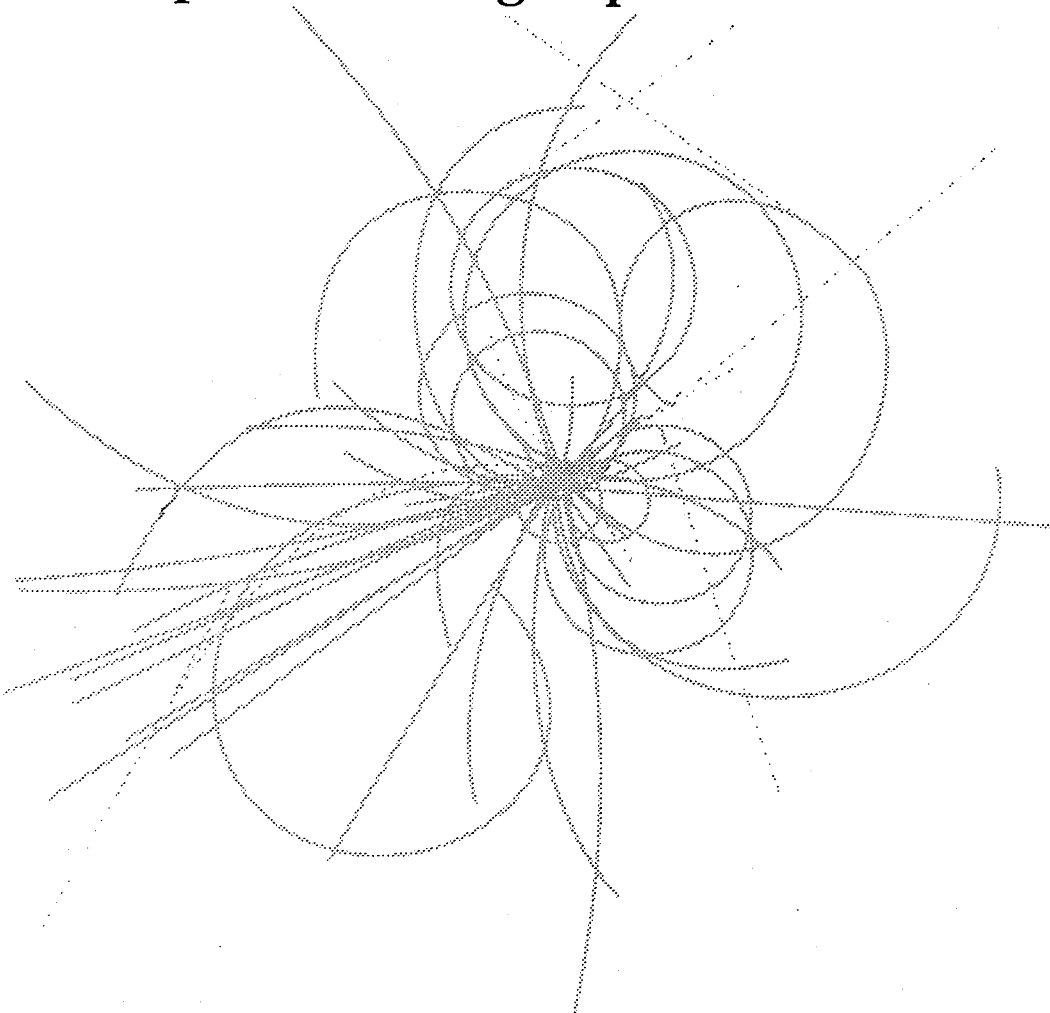
Superconducting Super Collider Laboratory



Designing, Fabricating and Testing Cost Effective Structural Composite for the SSCL Magnets

F. Nobrega

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Superconducting Super Collider Laboratory†
2550 Beckleymeade Avenue
Dallas, Texas 75237

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Fred Nobrega

Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue, Mail Stop 1009
Dallas, Texas 75237

ABSTRACT

The Superconducting Super Collider (SSC) is a proton - proton particle accelerator used to study the fundamental forces and particles of nature. When completed in 1999, it will be the world's largest particle accelerator with a total collision energy of 40 TeV. One of the most important components of the collider is the superconducting magnets. They are used to bend and focus the particle beam around the ring. Magnet designs involve sharp bending of the superconducting niobium-titanium copper cable used in making coils. The end turns of the coils are supported with end spacers and saddles made of composite materials. This paper addresses the design, fabrication, testing and cost of these coil end parts.

INTRODUCTION

The SSC is an evolution of ideas and experiments by scientists to explain and understand the constituent parts of an atom. Physicists use what is known as the Standard Model to explain the first generation of the inner structure of atoms which is made of electrons, neutrons and protons. Electrons are elementary particles which cannot be split into smaller pieces. However, protons have two "up" quarks and one "down" quark joined together and neutrons are made of two "down" quarks and one "up" quark. The SSC will be the instrument used by scientists to study these constituents which comprise protons and verify the Standard Model.

Particle accelerators like the SSC use superconducting dipole magnets to bend the particle bunches around the 54 mile ring and superconducting quadrupole magnets to focus the particles. The heart of these magnets is the superconducting niobium-titanium copper cable which carries extremely high current because the internal resistance is zero at liquid helium temperatures. With these high currents, the magnets generate large magnetic fields on the

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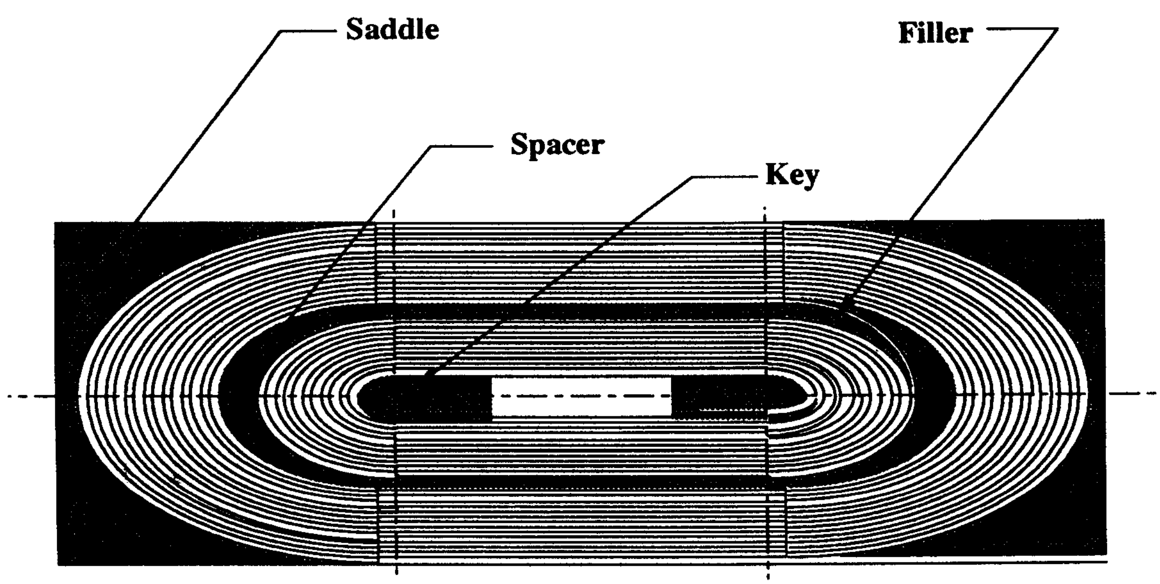
order of 6.7 Tesla (Tesla = 10,000 Gauss). The earth's magnetic field is less than 1 Gauss and household magnets are a few hundred Gauss.

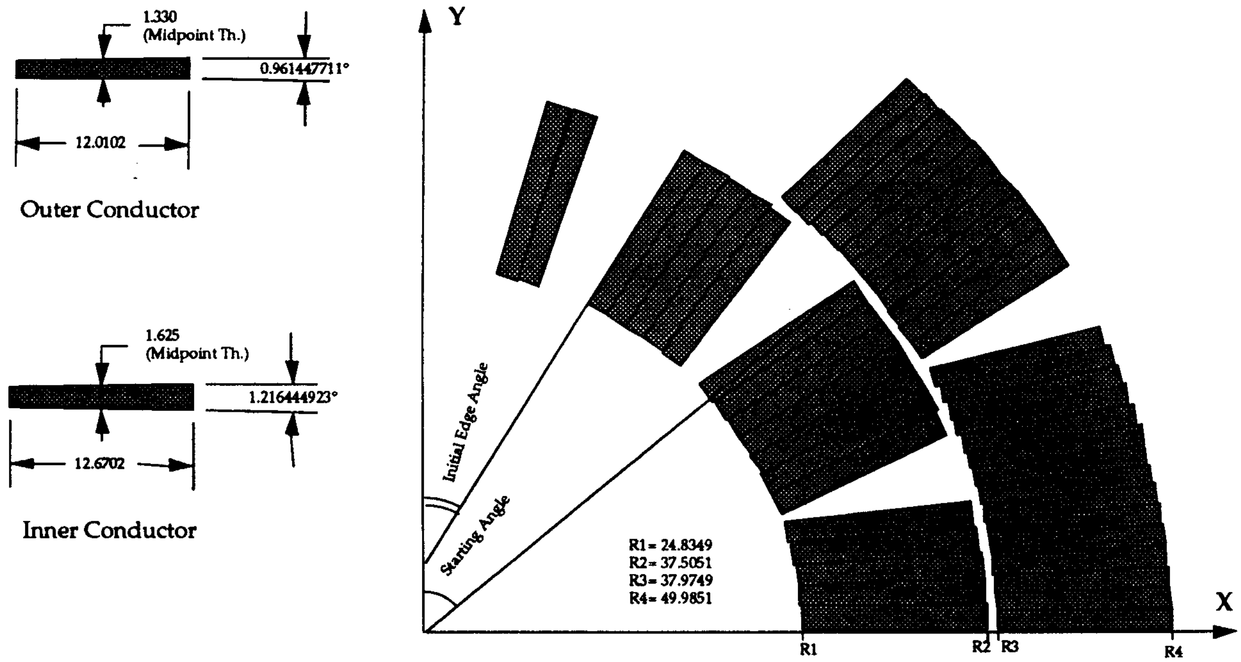
The superconducting cable is insulated with a wrap of polyimide film on the first layer and a second layer wrap of either a polyimide film with adhesive or a fiberglass epoxy prepreg. The insulated cable is wound into long coils and cured. All coil materials must withstand temperature extremes from 220°C (428°F) to -269°C (-452°F) at loads as high as 104 MPa (15 ksi) due to the curing cycle. In addition, all magnet components must survive for 25 years with a total radiation dose of 1000 MRad. The parts at the end of the coil in Figure 1 are used to support and restrain the conductors during magnet energization. The most common end part materials used to date have been G-10 and G-11 fiberglass and epoxy tubes and laminates in NEMA grades and CR type. Developments in polyimides like bismaleimides, copolymers like the newly developed PT resins and advanced epoxy blends like CTD101 and CTD102 are materials of choice for magnet components because of their radiation resistance. An extensive testing program is currently underway by the SSCL to measure the radiation degradation of these and many other materials at the Radiation Effects Facility (REF) at Brookhaven National Laboratory.



Coil Flat Pattern
Figure 1

END PART DESIGN

End part design begins with a 2D cross section supplied by a physicist as shown in Figure 2. Conductor parameters such as width, keystone angle, mid-thickness and other information are used with program BEND. This Fortran program optimizes conductor geometry to minimize strain and maximize cable bend radius in the coil end region



High Energy Booster Dipole 2D Cross Section

Figure 2

The numerical output from the program BEND defines the surfaces that support the conductor. The keys, spacers, fillers and saddles are machined directly from the programs geometric output.

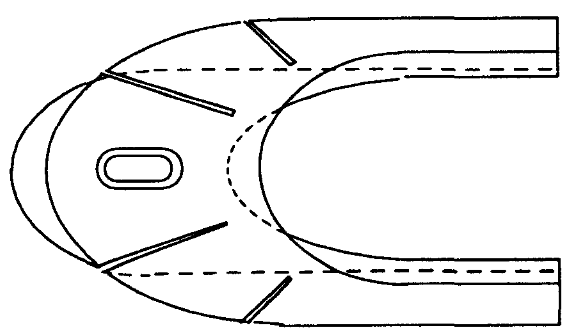
The minimum strength requirements of the end parts have not been fully characterized. For years, G-10 and G-11 type materials have been used successfully in the Tevatron accelerator at Fermi National Laboratory. However, the radiation requirements for the Supercollider are orders of magnitude higher than the Tevatron. This precludes using a generic epoxy resin system. Table 1 lists the estimated material requirements for the end parts which is based on the glass-epoxy systems used to date. They are not firm requirements, but instead are used as a guide for material selection.

Table 1

Material Requirements

Magnetic Cycles: 20,000 (Load Cycles)
Design Load: 124 MPa (18 ksi) Compressive
Quench Cycles: 100 (Thermal Fatigue Cycles) 4.35K-300K in 1 sec.
Thermal Cycles: 50, 300K (68°F) - 55K (-360°F) - 300K (68°F) in 2 hours
Temperature Range: 3.5K (-453°F) - 495K (430°F), (495K (430°F) for 30 min.)
Coefficient of Thermal Expansion: $\alpha\Delta T < 4 \times 10^{-3}$ (0.4 % from 300K to 4K)
Flexural Strength: 276 MPa (40 ksi)
Tensile Strength: 173 MPa (25 ksi)
Compressive Strength: 173 MPa (25 ksi)
Modulus of Elasticity: 13.8 GPa (2×10^6 psi)
Dielectric Strength: 1kV/25 μm up to 75 μm - 3kV more than 75 μm
Radiation Resistance: (25 year life)
Ionizing Radiation: 1000 MRad
Neutrons: 6×10^{12} Neutrons/cm^2

The ideal end part totally supports the end turns, is flexible enough to accommodate the uncured cables during the winding process, and after curing the coil assembly, meets the strength and radiation requirements. The mechanical and thermal loads on the end parts during coil curing, collaring and magnet operation are high. During winding, the coil is uncompressed and somewhat larger than the final cured size. A "low" flexural modulus is desirable for the saddle and spacer end parts because all end parts are designed to the final cured size of the coil. The end parts must be flexible enough to accommodate the larger uncured coil. The keys have very high loads during curing and therefore a higher modulus is preferred. The flexural problem with G-10CR was temporarily solved at the SSC by adding slots to the saddles and spacers as shown in Figure 3. During magnet assembly and operation, flexural and compressive strength and coefficient of thermal expansion become the important material parameters.



QSE101 Quadrupole End Spacer

Figure 3

FABRICATION

There are several fabrication methods that can be employed for end parts. They include injection, compression and resin transfer molding of thermoplastic and thermoset materials. Metal castings, either coated with organic insulators or anodized, is another viable fabrication technique. An additional requirement for metal end parts is that they must be nonmagnetic. Machining solid end parts from G-10 or G-11 tube has been the standard method at the laboratories due to the small quantities of parts required and the high cost of the other fabrication methods.

Injection Molding

> "Injection molding of thermoplastics is a process by which plastic is melted and injected into a mold cavity. Once the melted plastic is in the mold, it cools to a shape that reflects the form of the cavity. The resulting form usually is a finished part needing no other work before assembly into or used as a finished product."[1]

Due to the high cost of tooling and low part count, injection molded end parts were machined from injection molded tubes at Fermi.[2] Three thermoplastics, Torlon 5030, PEEK (polyetheretherketone) and PEK (polyetherketone) all with 30% glass fiber were investigated. Lack of adhesion between the cured coil and the end part was a problem particularly with Torlon 5030.

Compression Molding

> "The most apparent advantage of compression molding of thermosets is the simple system involved. The material is placed in a heated cavity and is pressurized for the required cure time. Tooling costs are inexpensive because of the simplicity. Fillers and reinforcements are random and lead to fair strength properties. Material is not wasted because of the absence of sprues and runners."[3]

Compression molded end parts using filled epoxy systems were also studied by Fermi.[2] The study focused primarily on the manufacturing process as opposed to material selection.

Resin Transfer Molding (RTM)

When producing intermediate volume of reinforced plastic parts, RTM is a cost effective technique.[4] Low viscosity resin is injected into a mold at low injection pressures. Typically the mold cavity contains a fiber preform with fiber orientation determined by strength requirements. Compound transfer molding is very similar to RTM however the resin contains chopped fibers and the compound is injected into the mold. For low and moderate part counts, RTM tooling is more cost effective than injection molding.

Unlike injection molding, where the tooling needs to be made of steel because of the high temperatures and pressures, RTM molds can be made from composite materials for low quantity production runs. Mass cast epoxy tooling is being used to evaluate a phenolic triazine resin, Cryorad by Allied Signal. This resin as with other cyanate ester resins has the ability to be B-staged or undercured into adhesives, laminates and end parts. Figure 4 is an alumina oxide filled mass cast epoxy mold made by Grumman Aerospace used for molding Cryorad quadrupole end parts. Also shown is the structural preform made by Cooper Composites. The low cost composite molds can also be made into multicavity molds. Figure 5 shows a RHIC epoxy end saddle with a woven glass ply preform and a filler with chopped fibers.

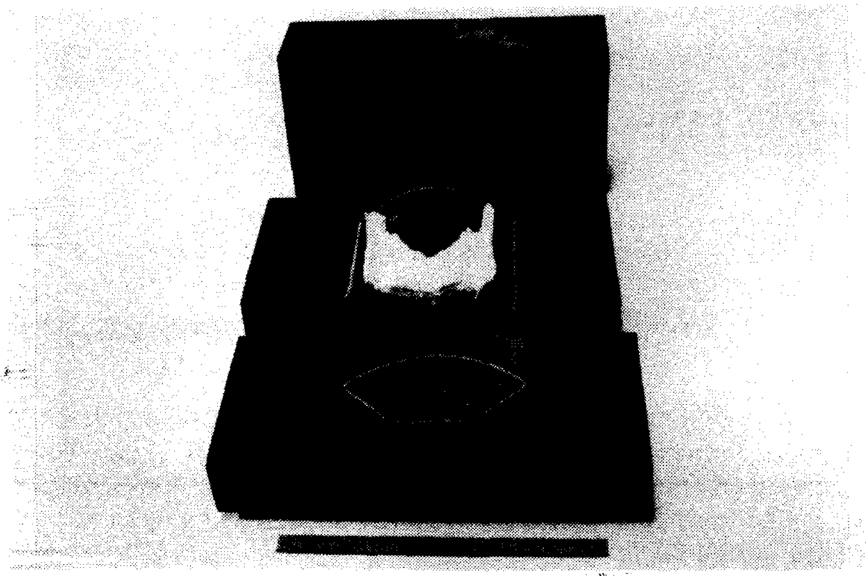


Figure 4

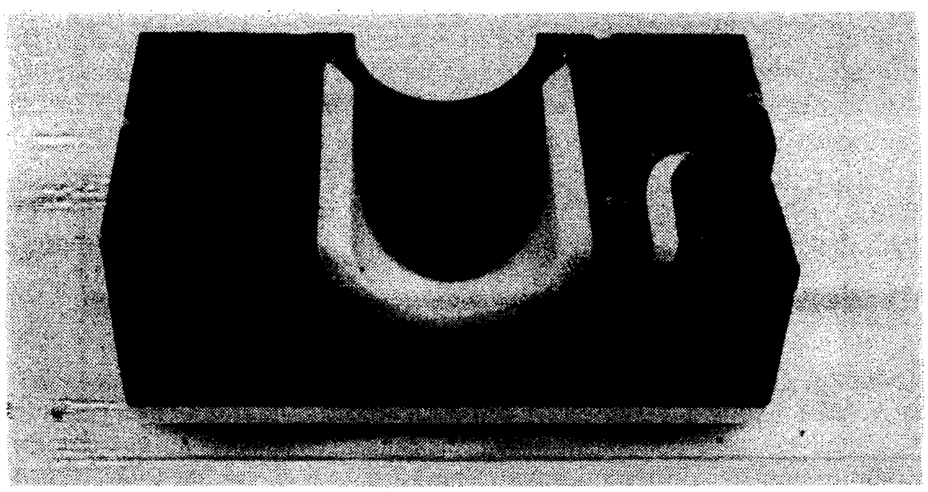


Figure 5

TEST RESULTS

To demonstrate the feasibility of an undercured, conformable end part, the SSC, Grumman Aerospace, Allied Signal and Cooper Composites pooled their expertise to make Cryorad end saddles. Figures 6 and 7 show an aluminum master and a computer controlled sewn fiberglass preform. Figure 8 is the first coil wound and cured using a Cryorad end part.

The preform was similar to one shown in Figures 6 and 7 and the master was a SSC provided G-10 end saddle. This end part was 50% cured and had about the same mechanical strength properties as the G-10 part it replaced. Figure 8. While in the curing press at 135°C, the Cryorad part cured more, further increasing its strength properties. After a thorough visual inspection and coil measurement, the coil was potted and sectioned. The sectioned parts were inspected for conductor insulation damage, conductor placement and compaction, and for voids and defects in the molded part. No voids were found and conductor placement, compaction and insulation were very good. One of the more important goals was also met as shown in Figure 9. The Cryorad end saddle formed or flowed during the curing cycle into a small gap between the last conductor and the shelf which demonstrates the parts will indeed conform to the conductor group. This is very important as a coil made entirely of Cryorad or cyanate ester type end parts would provide total and rigid conductor support.

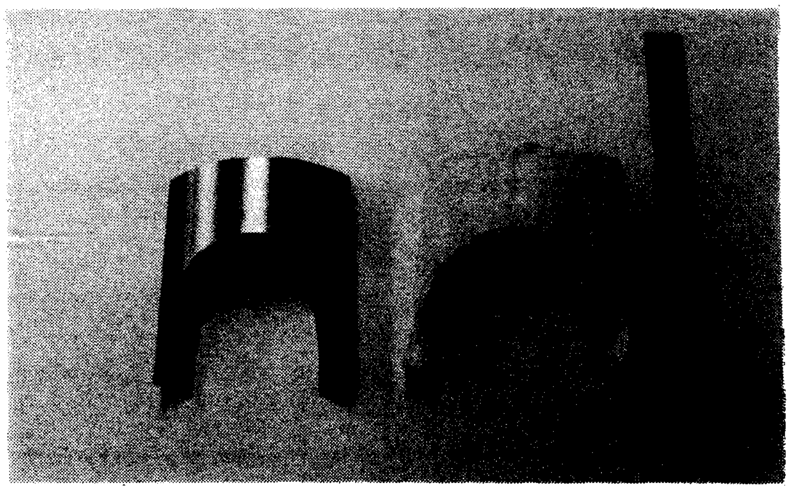


Figure 6

Figure 7

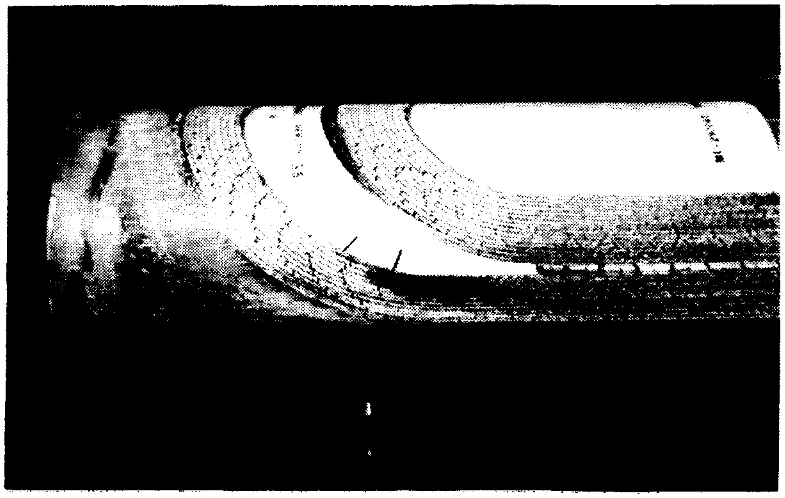


Figure 8

Figure 9

Using undercured or B-staged end parts has the obvious advantage of being flexible during coil winding. Depending on the amount of undercure, the end part resin is still not fully cross linked after curing. It is believed that the radiation environment that the end parts will be exposed to will further cure the resin.[5] This theory will also be investigated at the REF.

Cryorad manufacturing and material costs have been of great concern even though according to Jacobs[3], the cost of a given RTM tool can be from 2 to 25% of the cost of an injection mold tool. As recent as March 1992, Grumman has lowered its price estimate to below $100 per benchmark part at production quantities. However, when compared to injection molding of thermoplastics at $10 to $25 for the same part, more effort is required to lower the RTM part cost. It must be remembered that several of the salient features of the cyanate ester thermoset resins mentioned above are not possible with thermoplastics.

Insulation breakdown tests of 50mm dipole aluminum lead end winding keys were preformed at Fermi.[6] The three insulation coatings studied were a polyimide, polyphenylene sulfide and epoxy ester The number of coats was varied from one to two. The low breakdown voltage was for the epoxy ester at 1200 volts and the high breakdown voltage occurred at 2800 volts using two coats of the polyimide.

Using different sealers on hard anodized aluminum discs and testing for dielectric breakdown was another test performed at Fermi.[7] The sealers used were teflon, dichromatate and nickel acetate. The breakdown voltage of a hard anodized disc without a sealant was the lowest at 717 volts and 34.5 MPa (5 ksi) load. The highest breakdown voltage occurred with the teflon sealant at 1066 volts and 34.5 MPa (5 ksi) load.

FUTURE PLANS

Dipole magnet DSA334 will have all coil end parts made from Cryorad. This will be the first magnet tested using Cryorad end parts at 4.3K and 6600 amps. Testing should begin in September 1992.

Magnet programs at the SSCL, such as the quadrupole model magnet program and the vertical bending dipole magnet program, will investigate Cryorad and other similar resins.

CONCLUSIONS

There are several cost effective fabrication methods available for end parts. The resin selected will play a major roll in the fabrication method chosen. More R&D and testing is necessary to develop the optimum end part material and manufacturing process.

ACKNOWLEDGMENTS

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