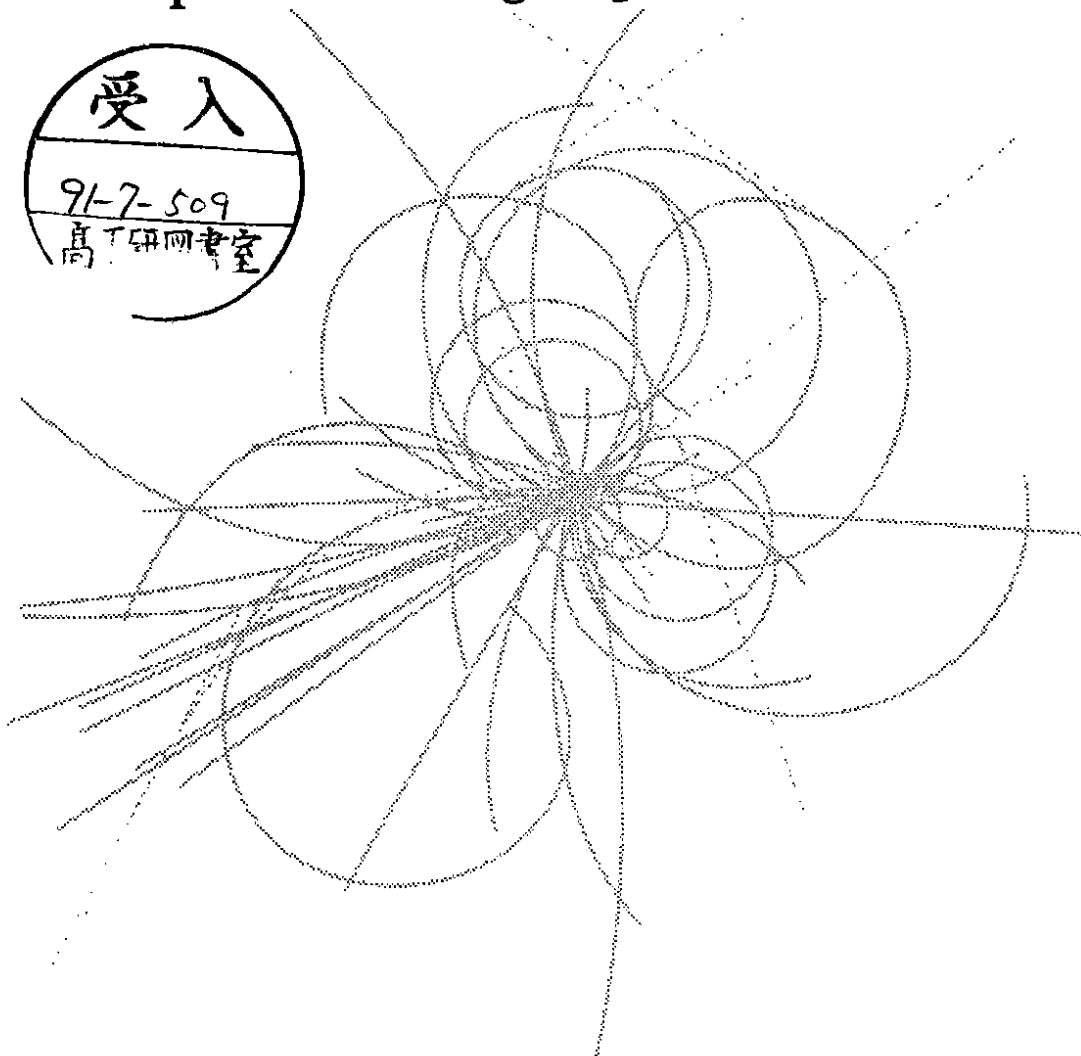# Superconducting Super Collider Laboratory

# Alternative Concepts for Structurally Supporting the Cold Mass of a Superconducting Accelerator Magnet

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March 1991

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# ALTERNATIVE CONCEPTS FOR STRUCTURALLY SUPPORTING THE COLD MASS OF A SUPERCONDUCTING ACCELERATOR MAGNET*

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**Abstract:** Experimental and analytical studies toward the goal of replacing the fiberglass reentrant support posts and their end restraint systems with lower cost injection molded posts are described. Thermoplastic resins with chopped fiberglass reinforcement having lower thermal conductivity were investigated. Experimentally obtained data from creep, shear, and tensile tests on actual injection molded posts of Ultem and Noryl are included. Discussion of flaws and quality control is included. These studies for the Relativistic Heavy Ion Collider (RHIC) and the Superconducting Super Collider (SSC) are continuing at Brookhaven National Laboratory and at the SSC Laboratory.

## INTRODUCTION

The cryostat houses the superconducting magnet "cold mass" and includes a support system to hold the magnet in a known position inside the vacuum tank and heat shield(s), plus insulation to minimize the heat leak from room to helium temperature.

Early cold-iron magnet cryostat designs utilized a technique borrowed from NASA which used fiberglass straps to hold the cold mass in a hanging position inside the vacuum tank. While thermal conduction of the straps is minimal, the superinsulated "cold mass" and heat shields must be slid into the vacuum tank as an assembly and lifted to connect the straps to adjustable trunions through flanged port holes in the wall of the vacuum vessel. Working through side holes for positioning of the magnetic field and assuring the quality of the superinsulation after assembly requires special effort. Nevertheless, this approach has been used with success at Brookhaven National Laboratory (BNL) and more recently at DESY for the HERA project.

# THE COMPACT POST

Fermilab engineers designed an improved cryostat for Superconducting Super Collider (SSC) use based upon different principles. Their approach benefits from using reentrant or folded posts to support the cold mass which provides ample mechanical strength and reduced overall height while preserving the desired low heat leak through long thermal paths to the warm outside. The compact post consists of thin-wall, concentric G-11CR tubes as the support elements (Figure 1). But fastening to high-strength composites is always a problem, since the joints are usually the limiting factor in ultimate load-carrying capability. The Fermilab design uses shrink-fitted rings to clamp the tube ends. When these are properly constructed, one can use the full potential of the material.
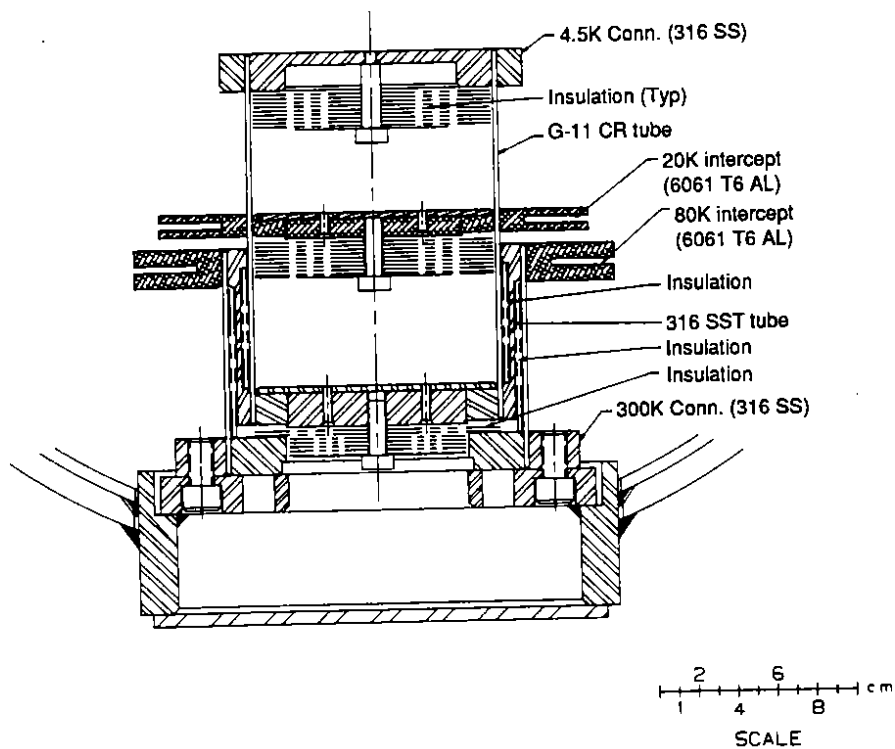


Figure 1. The Fermilab compact post of reentrant G11 fiberglass tubes.

Compact posts can meet all mechanical design requirements except for a possible dynamic axial pneumatic thrust force that could be present under some unique upset conditions. Fermilab engineers met this requirement by attaching carbon fiber tubes between the posts to equally divide the load among the five supports.

The great advantage of the post-type cryostat is realized during the assembly process. An assembly stand is utilized to position the cold mass upon the posts outside the vacuum tank. Here it is in broad view, making the application of insulation blankets a simplified task by helping to assure that all seams are well sealed against infrared radiation. The shields are assembled and insulated in similar fashion. When complete, the whole assembly, supported by the posts, is pulled into the vacuum tank to the proper position and bolted in place, assuring high thermal insulation efficiency and accurate positioning.

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Early cryostats for Brookhaven's RHIC project were the strap type. Because of the advantages stated above, a modified SSC version was adopted a few years ago. Today numerous cryostats of both SSC and RHIC design have been constructed and used successfully for individual magnet and full-cell testing.

## LOOKING FOR ALTERNATIVES

Review of the cost data of commercially supplied RHIC cryostats found that one-third of the total was in labor and materials charges for the compact posts and restraints against dynamic axial loads. The cost of the rest of the cryostat was minimized by redesign, but clearly the greatest saving could be realized in the area of posts and restraints. An alternative could be to replace the compact post assembly with a simple cylindrical column which had low enough thermal conductivity so as not to increase the heat load and was strong enough to support the cold mass under all load conditions without the need for additional thrust restraints.

Work toward this goal began a few years ago. It became clear after searching, extrapolating, and guessing at the cryogenic properties of metals, ceramics, woods, and polymers that some members of the polyimide family of thermoplastics should be able to meet the thermal and mechanical requirements. Since the low temperature properties of most plastic materials are not known, a program was initiated at BNL to measure polymer mechanical properties down to helium temperature. A calorimeter was constructed to quantify thermal conductivities throughout the range of interest.

After testing many candidates, Ultem© 2100 polyetherimide, a General Electric engineering thermoplastic, was selected. The 2100 grade is reinforced with glass fibers about 0.1 mm in diameter and 3 mm in length to make up 10% of its weight. It resides at the bottom of the mechanical properties table of the polyimides, but has low thermal conductivity and excellent radiation resistance. Ultem is an inexpensive material, and since it can be injection molded in large sizes it is also inexpensive to form into the required shape. The choice of using 10% glass fill was a tradeoff between mechanical and thermal properties. Increased glass content raises both heat leak and stiffness, while the neat resin has lower thermal properties but permits greater displacement of the cold mass under load. Both hand and finite element calculations showed that a RHIC post assembly made of two flanged cylinders bolted together, capturing the 55K heat shield at mid-plane, would meet all mechanical and thermal requirements. Figure 2 compares the thermal conductivity of Ultem 2100 measured at low temperatures to that of G-10CR and G-11CR fiberglass tubes.

Ultem 2100 has a lower thermal conductivity because the reinforcing fibers, which have a conductivity higher than the resin, are discontinuous. The fibers are randomly oriented and distributed in the melt but they take on an orientation when injected in the mold, so the actual strength and thermal conductance of the resulting piece is indeterminable at the outset. But, because Ultem has a thermal conductivity which ranges from 1/2 to 1/4 that of G-11 fiberglass, it seemed possible to use a thicker tube wall and to shorten the tube length while holding the total conductivity of the post to about the same low level as the fiberglass post. The fact that the tube length can be shortened permits the support post to be a single column from the vacuum vessel to the cold mass, rather that a reentrant assemblage of concentric columns.
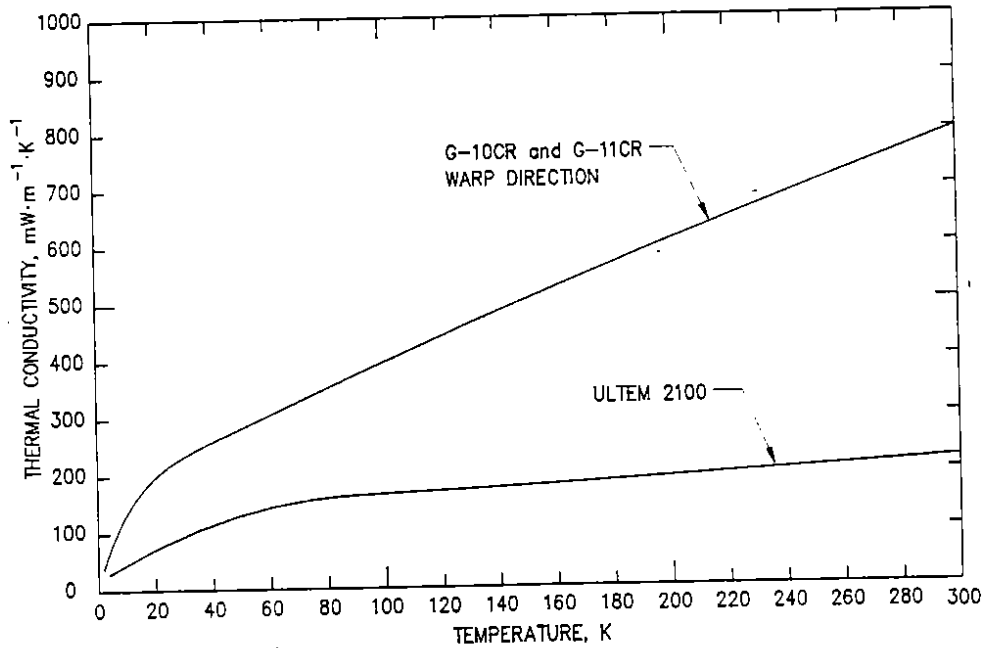
Figure 2. Thermal conductivities at cryogenic temperatures.

## The RHIC Mark IV Cryostat Posts

The redesigned cryostat for the RHIC dipole using an Ultem 2100 post, which is an injection molded composite (IMC) material, is shown in Figure 3. The redesigned post consists of two "hat" sections, shown in Figure 4, of the IMC material. They are identical, but the upper one is inverted so that its brim attaches to the cold mass cradle. The lower hat section bolts to the vacuum vessel saddle. The upper and lower sections bolt together at their inside flanges so that they sandwich the plate supporting the 55°K heat shield.

Each hat section essentially consists of a cylindrical shell, approximately 8-1/2 in. in diameter and 4-1/2 in. long, having a thickness of 3/16 in. The shell has a 1/2-in.-thick flange at each end for bolting. The flange is external at one end of the shell and internal at the other. The sections are connected with twelve 7/16 bolts on the external flange and twelve 3/8 bolts on the internal flange.

The shell has a slight conical angle of 1-1/2°, which is a draft angle to facilitate removal of the casting from the mold. The upper and lower sections can be made from the same mold. The heat-softened material is injected though a knock-out diaphragm which feeds the inner flange. The material stays in one mass as it flows from the inside flange, through the cylinder, to the outside flange. During the testing program, knit-lines caused by the mass separating and coming back together, proved to be an unacceptable source of flaws. In order to avoid knit-lines, the holes in the flanges are now drilled after casting, rather than cored. Tests also proved that for shear strength of the post, the outer flanges must be backed up with a metal flange for bolting. But in spite of these refinements, it is expected that the IMC posts will still account for only 10% of the cost of a fiberglass post.

The cost is further reduced by the elimination of the sophisticated tie rods between the posts which equally divide the axial load among the supports. The goal was to design an IMC post strong enough, without help from its neighbors, to resist the dynamic axial thrust force which can occur due to pressure imbalances across the length of the cold mass under quenchconditions. In order to meet this requirement, a design criterion of 12,500 lb of end
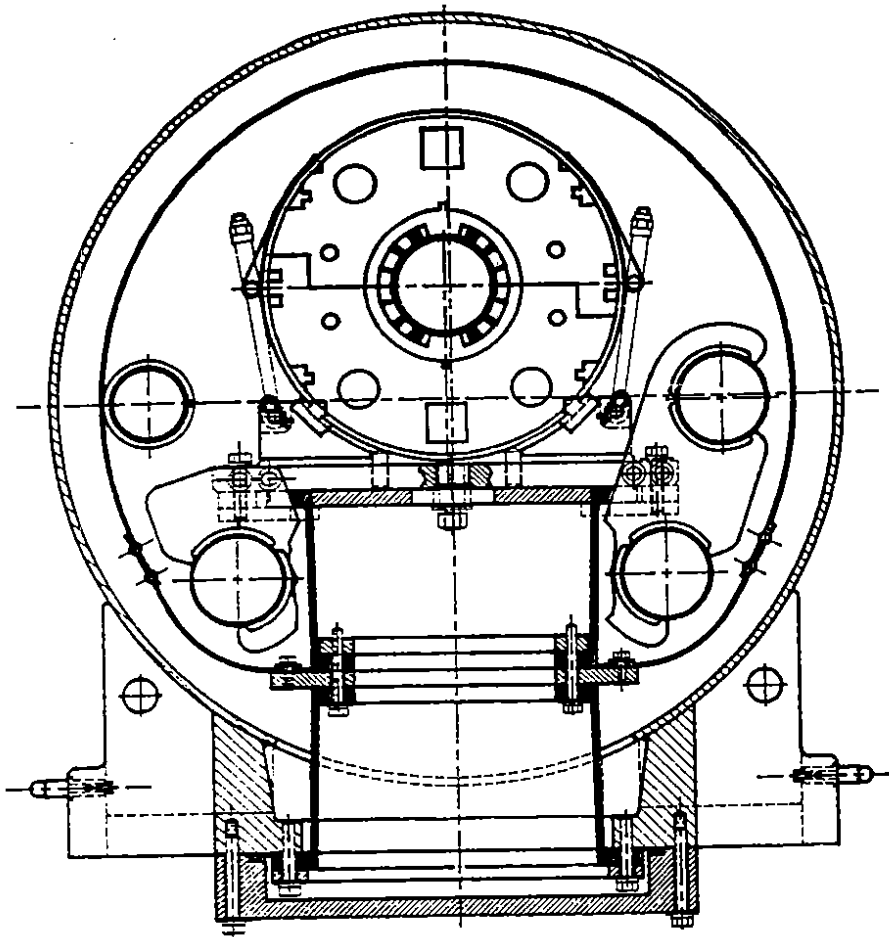
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Figure 3. The redesigned posts for the RHIC dipole, using an injection molded composite material.
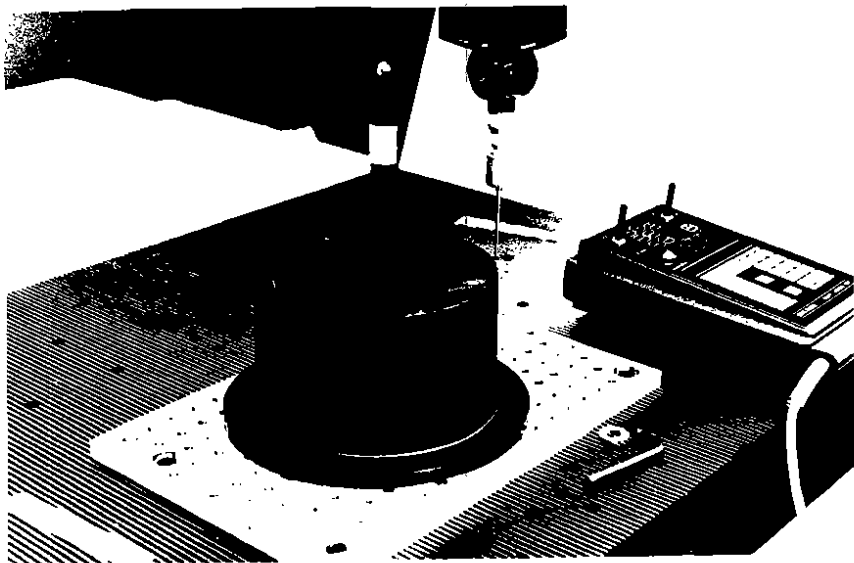


Figure 4. An injection molded hat section being inspected.

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load was set early in the program. This is a value that could be approached only by a catastrophic short to ground that would destroy the magnet at any rate. Pressure differentials measured during survivable quenches suggest end loads many times lower than 12,500 lb.[1]

## THE STRUCTURAL CONCEPT FOR IMC POSTS

In terms of the adverse effects upon the posts, the end load is a more severe condition than are the dead weight, seismic, or the dynamic transportation loads.[2] A 12,500 lb end load governs the conceptual design of the structural system for supporting the cold mass. The system conceived for RHIC, without axial straps, is shown schematically in Figure 5. The support cradles at the top of the two side posts allow the cold mass to expand and contract axially. There are stops on these cradles which contact the side posts when the cold mass is fully cold so that one or the other of them can help, depending upon which way the end load acts. But, the cradle atop the center post is fixed to both the cold mass and the post in all rotational and translational directions. The reaction moments on a RHIC center post can be seen in Figure 6.
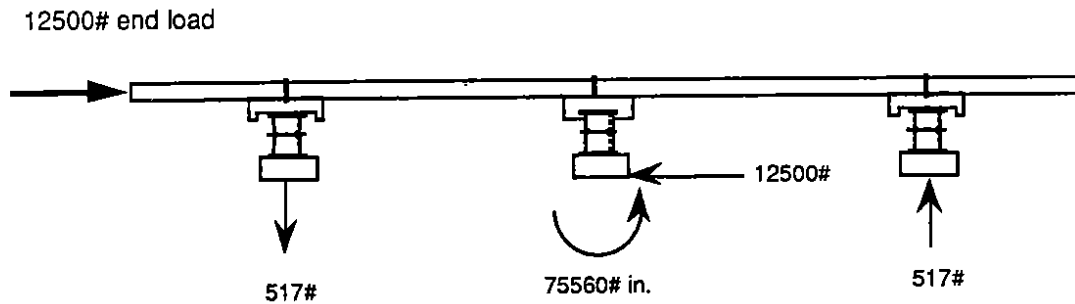
12500# end load



Figure 5. Support reactions on the RHIC fixed center post and sliding side posts due to an end load caused by a catastrophic quench.
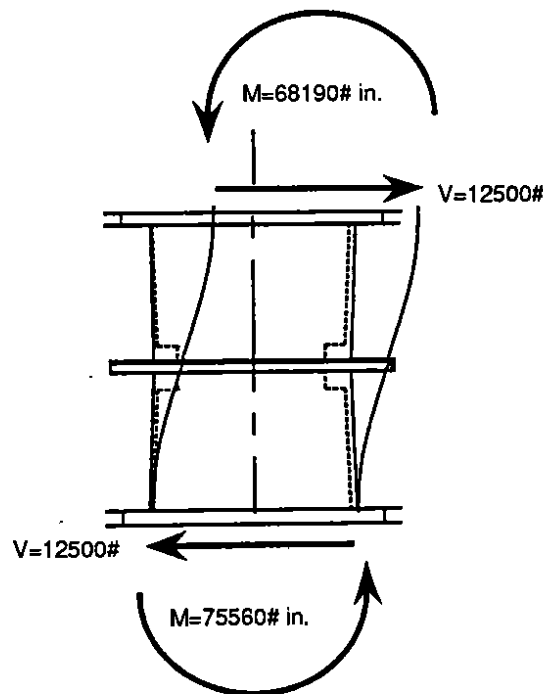


Figure 6. Forces, moments and deflections of the center post.

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Since the center post does all the work of resisting the end load, that post carries a large shear force and bending moment. The highest Von Mises stress intensity was calculated to be about 8 ksi, which occurs at the bottom of the center post where the bending moment is the greatest. The bending moment at the top of the center post is opposite in direction but only slightly less than that at the bottom. If the cradle were not able to transfer the bending moment to the cold mass, the stress intensity at the bottom would then be increased to an unacceptable level, and the axial movement of the cold mass would be doubled. Therefore, the cradle must bolt rigidly to the center post.

With the stronger IMC post, it is unnecessary to tie posts together with rods or to otherwise provide restraining straps to assist with the end load. However, the single post, which is called upon in any design to do the end load duty, must be bolted to a cold mass cradle which is designed to be rigid enough to transfer a reacting bending moment from the cold mass.

## CREEP

Two candidates, Ultem® 2100 and SE1-GFN3 Noryl®, were chosen for the IMC material during this testing program.[3] Noryl is an alloyed resin with glass fibers making up 30% of its weight. Both Ultem and Noryl are thermoplastic rather than thermosetting plastic materials.

In direct compression the Ultem post failed at 66 kips and the Noryl at 80 kips. The post sections fail by inelastic buckling of the cylindrical shell. An injection molded composite (IMC) post, of either Ultem or Noryl, is more than 20 times stronger in compression than is required to support the static weight of the cold mass at room temperature. At room temperature, the vertical stiffness of the IMC post is 415,000 lb/in. if made of Noryl and 323,000 lb/in. if made of Ultem. The vertical stiffness of the IMC post was accurately predicted at room temperature using the modulus of elasticity from a test piece. Presumably the stiffness at cryogenic temperatures can be similarly predicted, although compression tests have not yet been done at low temperatures.

Since the posts are so lightly loaded compared to their strengths in compression, attention was turned to the question of creep. Creep tests were conducted over a period of 100 hours for Ultem and 70 hours for Noryl. The results were plotted on a log-log graph as shown in Figure 7. From these tests, the creep rate of an Ultem or a Noryl post can be projected to be about 8 mils, under the constant cold mass weight of 3500 lb, over 10 years at room temperature.

While a 10-year projection from a 100-hour test is arguable, most will agree that creep appears to be a negligible effect in the operation of RHIC. However, the data suggest that temperatures higher than room temperature may produce an unsatisfactory amount of creep. Magnets on IMC posts should be shipped and stored in air-conditioning during the summer. This is consistent with what is needed to control the creep of the Kapton insulation on the superconducting cable of the magnet. Further creep tests at higher temperatures should be conducted on these posts.
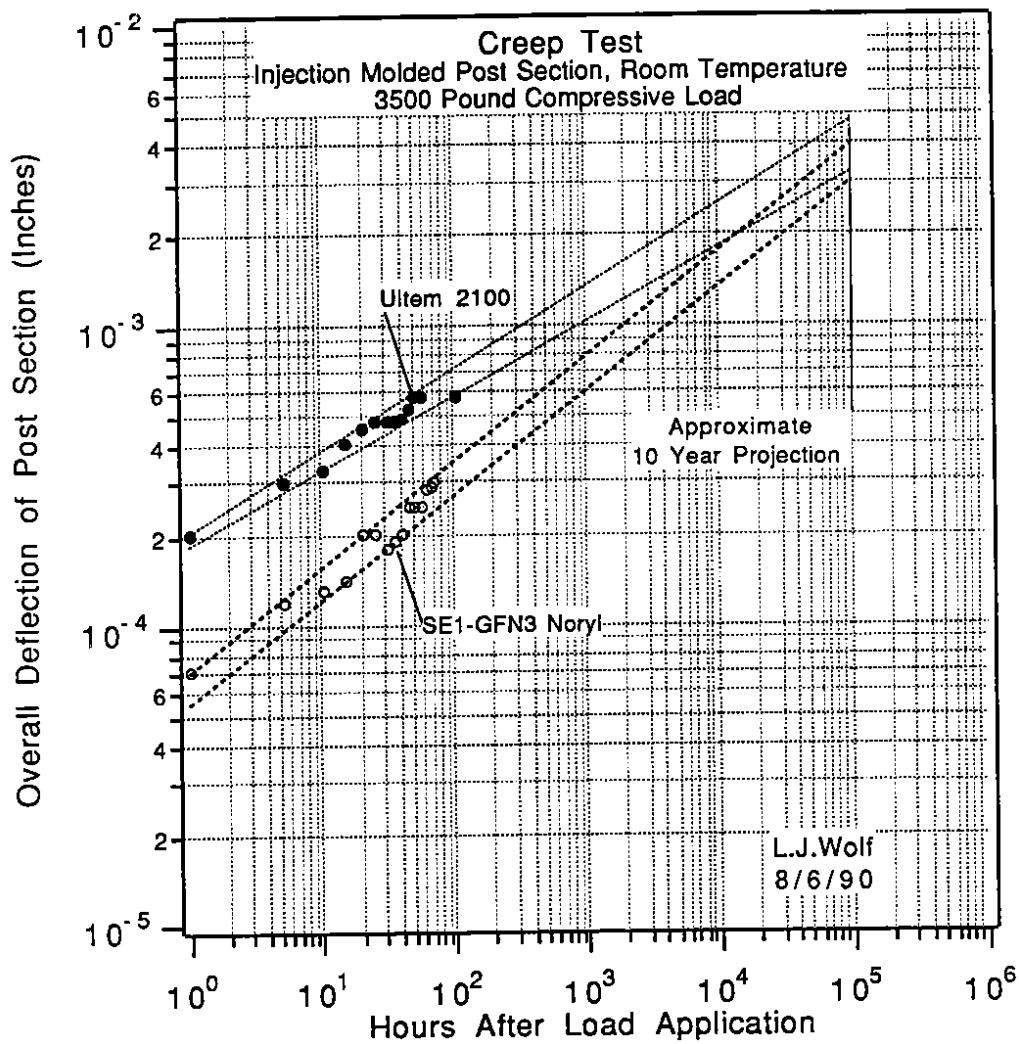
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Figure 7. Room temperature creep test results.

## SHEAR

The fixture in the photo of Figure 8 was used to test the posts under the shearing force and bending moments.[4] The test fixture was carefully designed and constructed to have about the same bending stiffness as the cold mass itself so as to give a truly representational test. Two identical posts were tested together in order to get the opposing bending moments at the opposite ends of the posts, as diagrammed in Figure 6. A force of 3,000 lb was applied horizontally using a hand-pumped hydraulic cylinder to simulate the dead weight of the cold mass. The 12,500 lb end load was simulated by a hydraulic testing machine acting directly down from above between the two post assemblies. Since there are two posts sharing the load in the test fixture, the testing machine force needs to be twice the 12,500 lb shear force for which the posts are designed.

The first shear tests were unsuccessful because the early castings were of insufficient quality and because stainless steel backup rings proved to be needed on the saddle and cradle flanges of the posts in order to carry the 12,500 lb load. Backup rings are not needed on the heat shield flange.
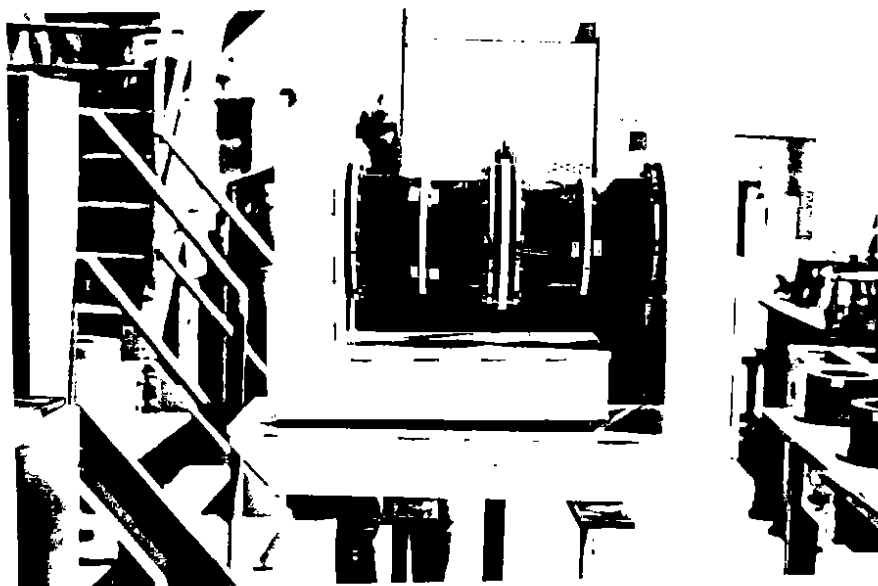
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Figure 8. Posts after failure in a test fixture simulating the end load.
(Photo courtesy of Barbara Wolf.)

Shear tests were conducted on both Ultem and Noryl, but no casting of Noryl was able to pass the quality control test described in the next section of this paper. The Noryl posts that were tested in shear, without first passing the quality test, also failed the shear test. This leads to the conclusion that the quality test is not overly severe. The first batch of Ultem post sections also failed the quality tests. However, when the Ultem pellets were preheated for 6 hours at 275°F before molding, the castings passed the quality control test and then went on in every case to meet the rated load in shear.

The shear tests on Ultem were successful at room temperature and at the temperature of liquid nitrogen, as shown in Figure 9. Since at liquid nitrogen temperature, Ultem has more than 95% of the strength and stiffness that it will have at liquid helium temperature,[5] the cold test was representative of the actual operating conditions of the magnet from a structural sense.

The lateral stiffness of a RHIC center post made of Ultem 2100 when cooled to magnet operating temperatures is about 55,000 lb/in., versus 45,000 lb/in. at room temperature. The post stiffness at the low magnet operating temperatures is relatively constant over the full-load range.

The end posts, which are weaker than the center post because they do not benefit from a moment transfer connection to their cold mass cradles, have the ability to add at least a 50% safety margin to the end load capacity of the RHIC dipole support system.
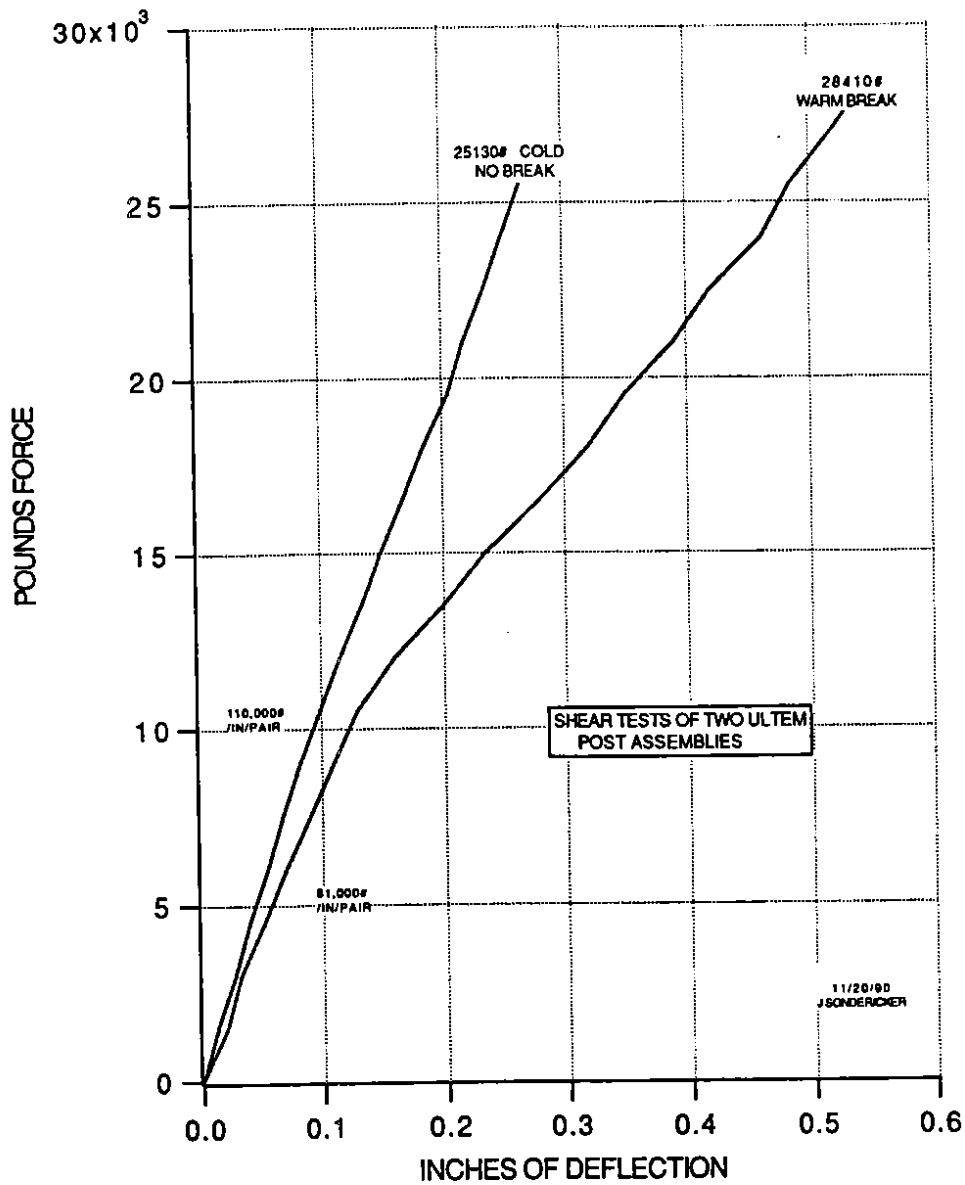
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Figure 9. Shear tests of two Ultem post assemblies at room temperature and at nitrogen temperature.

## QUALITY CONTROL

Tensile tests of injection molded composite (IMC) post sections, using data from room temperature and helium temperature tests on coupons taken from a sample of the castings is a workable means of quality control.[6] The tensile tests can be done on a fixture as shown in Figure 10. When the cylinder is put into a uniform tension of a specific value, a flaw of critical proportions will reveal itself simply by causing the post section to break during the test.

The level of load to be applied to the fixture, and thus to the post section to be tested, is first determined from tensile tests conducted on coupons cut from a good casting selected from the injection molding run. To arrive at a quality control procedure, coupons were cut

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from the 0.188-in.-thick cylindrical wall of a Noryl and an Ultem post section. They were milled flat, giving them a thickness of about 0.170 in. Half the coupons were notched with a square-edged slit saw in order to simulate a flaw. Unnotched specimens, having the same stress width of 0.250 in., were prepared as samples of the good material. The notched and unnotched specimens were tested at room temperature and at liquid helium temperature. A complete set of coupons from one test casting is pictured in Figure 11. These resulting tensile tests constitute an inexpensive, albeit crude, application of fracture mechanics principles.
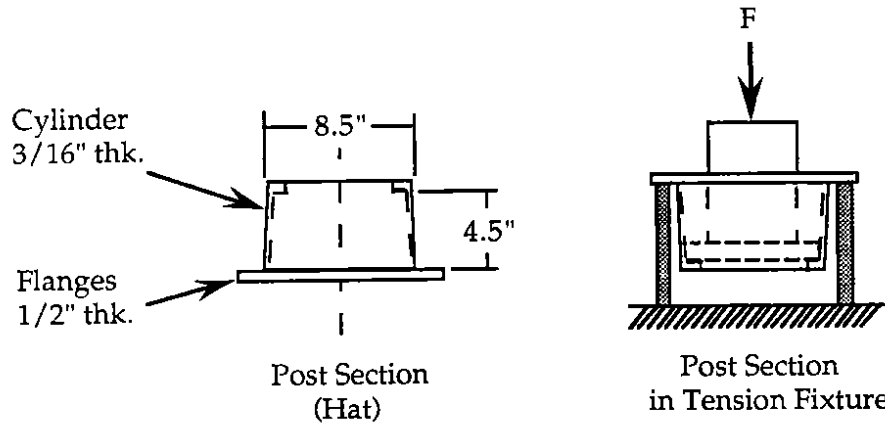


Figure 10. The quality control testing fixture.

The data from the coupon tests can be used to determine the required quality control test force, F, in the following way:

$$F = \sigma_T \cdot A,$$

where A is the cylindrical shell cross sectional area of 5 square inches, and $\sigma_T$ is computed from:

$$\sigma_T = \sigma_C \left(\frac{\sigma_{UR}}{\sigma_{UH}}\right)\left(\frac{\sigma_{NR}}{\sigma_{NH}}\right).$$

The calculated stress, $\sigma_C$, from the finite element analysis, is multiplied by the ratio of the room-temperature ultimate strength over the helium-temperature ultimate stress, $\sigma_{UR}/\sigma_{UH}$. This factor has the effect of reducing the test load because the material is stronger at low temperature.

The result is further multiplied by the ratio of the room-temperature notch strength over the cold notch strength, $\sigma_{NR}/\sigma_{NH}$. This tends to increase the test load because the material is normally more notch-sensitive when cold. If less than one, as was the case with Noryl, this ratio should be replaced with one.

The resulting test stress, $\sigma_T$, is then calculated using the above formula; $\sigma_T$ could be greater than or less than $\sigma_C$.

The calculated maximum value of stress that the center post will experience under the worst-case loading condition is approximately $\sigma_C = 7,000$ psi. This worst-case condition consists of 3,000 lb of cold mass weight and 12,500 lb of hydrostatic end thrust.
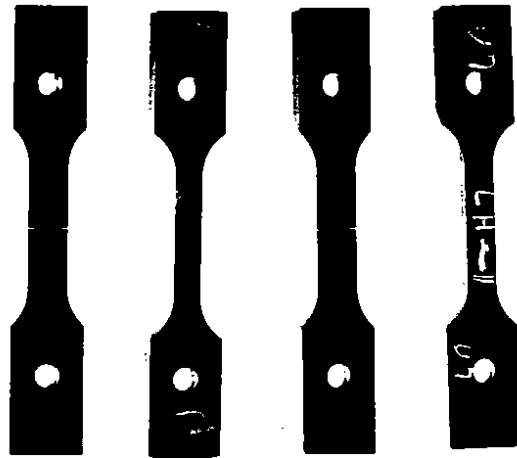
Figure 11. A set of test coupons, two notched and two unnotched, cut from an IMC post section selected at random from the production run.

## FLAWS

Even though the castings may have appeared to be perfect, flaws were found in all of them when sectioned or broken during test. The flaws were found in the 1/2-in.-thick flanges, which are the thicker parts of the castings as shown in Figure 12. Only rarely did the flaws occur in the thinner cylindrical shell. The flaws took the form of voids or porosity, which in some cases looked like foam comprising 30% of the flange's interior cross-section. None of these flaws extended to the surface.

Most of the flaws occurred at the knit-lines of the casting. Knit-lines form where masses of the injected material come back together after the flow has been separated by hole cores or by having several different gates in the mold. Due to the orientation of the glass fibers in IMC materials, the knit-lines are clearly visible on the surface of the castings.

Since the fractures produced during the quality control tests initiated at or near a knit-line, it became apparent that molds for high performance structural parts like magnet posts need to be free of knit-lines. The decision was made to change the mold to remove the hole cores and to replace the four injection gates with a single diaphragm gate feeding along the edge of the inside flange. In the castings produced in the revised mold, the holes have to be drilled, but the post sections are free of knit-lines. It was further decided to use material with no coloring compound, so that large flaws can be seen when the translucent castings are held up to a light.

The reduction of the wall thickness with a carefully machined stress relief profile had the effect of strengthening the Noryl castings to the point where they would pass the quality test. A more sophisticated profile between the cylindrical shell and the flanges of the post sections has the potential of further strengthening the IMC posts. Therefore, the corner radius between the flanges and the cylinder was increased when the mold changed. Ultem castings from the revised mold have now been received. All of them passed the quality control tensile test.
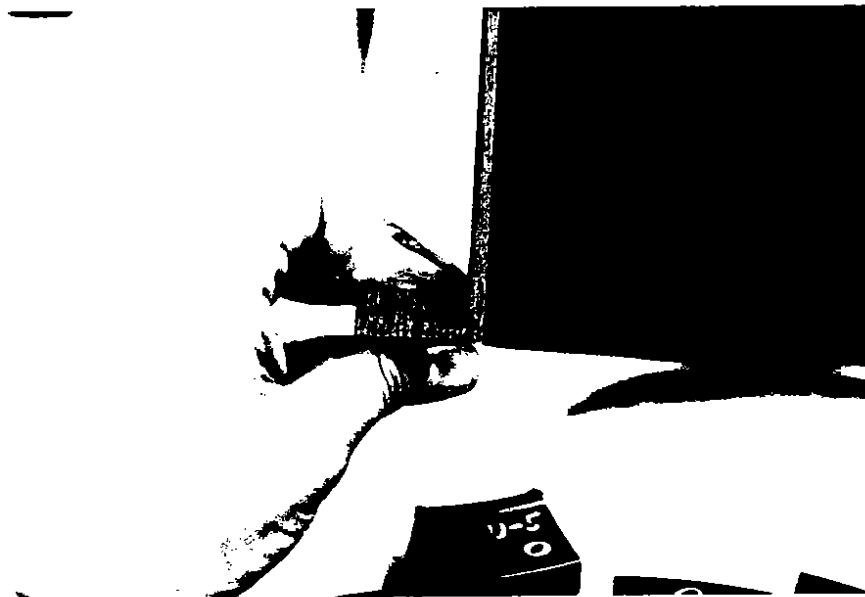
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Figure 12. Porosity flaw near a knit line of the casting.

## THE SSC POSTS

After the initial success with RHIC posts, a similar development program was initiated for the 5 cm SSC dipole magnets. But since the SSC magnets have two heat shields rather than one, the configuration is greatly complicated. Preliminary heat load calculations and finite element analysis have shown that a strong post with a high thermal resistance can be constructed. Therefore, a design configuration study was initiated, assuming that the heat shield, the cradle, and the access port designs could be changed as needed to suit the new posts.

The most obvious configuration is one employing three post sections using identical IMC castings, as shown in Figure 13. Since this design has the possibility of stack-up tolerances, it was decided to bring two other concepts in parallel through the design-and-analysis process. The other two designs use two unequal IMC castings. One of them requires machining on one of the castings after removal from the mold. The other requires the 20°K heat shield to be supported from the 80°K heat shield. The latter concepts offer some advantages over the three-piece post, along with some disadvantages. But, since the lowermost section of all three designs is the same, it has been decided to put off the decision between the three design alternatives while a molding and testing program is initiated on the single IMC part common to them all.

Lessons learned on the RHIC posts were used on the SSC posts. The cast parts will not have any holes, requiring neither drilling nor coring. The sections will not have thick flanges where porosity can congregate and where shrinkage is difficult to control. Instead, the stainless steel back-up flanges will simply engage nubbins around the rim of the cylindrical shell.

And finally, a sophisticated shell wall profile is used on the transition from the shell wall to the flange nubbin. This profile forms a transition which, for all loading combinations, keeps the high stresses from accumulating near the flanges. It ensures true cylindrical shell

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action. Finite element analysis indicates that this post is likely to be stronger and more rigid than the RHIC posts even though it has a lesser wall thickness.
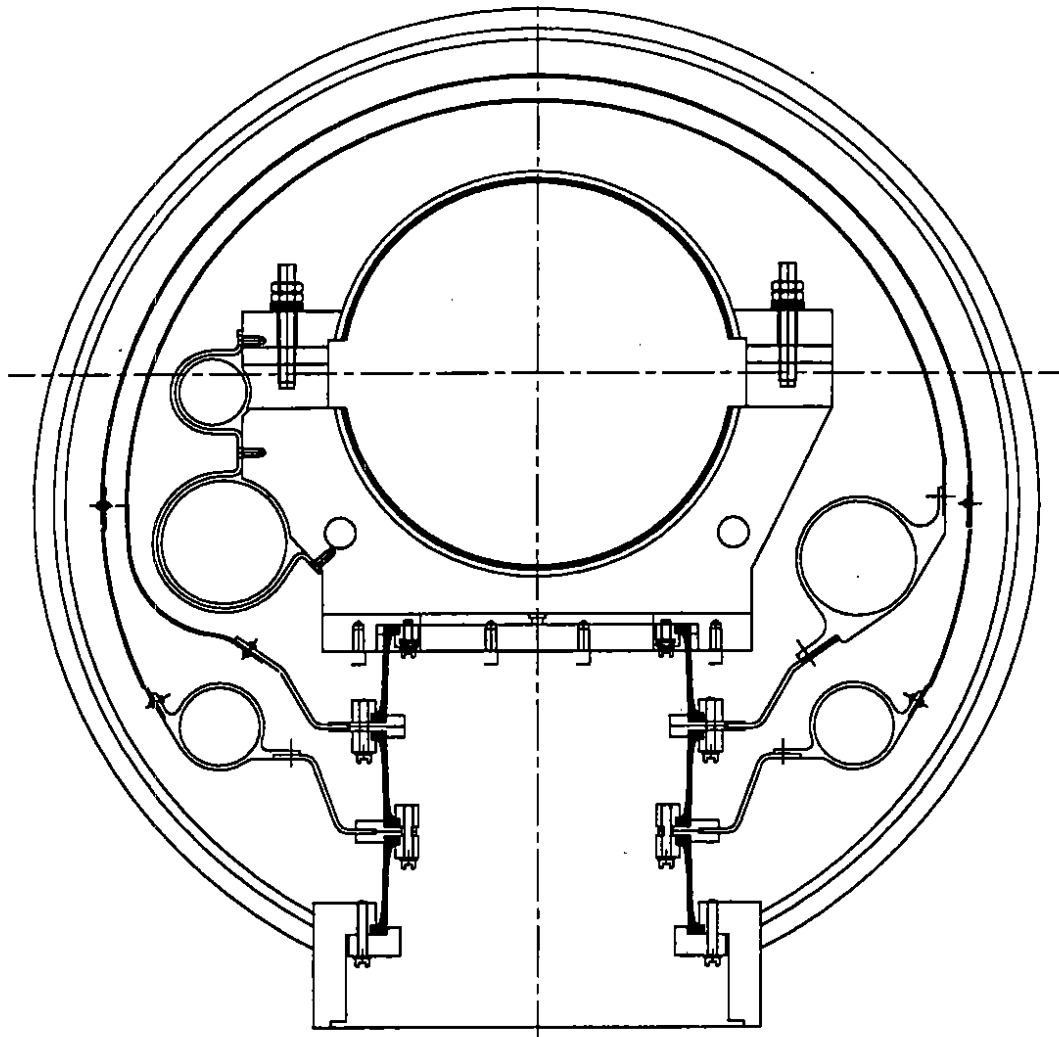


Figure 13. The SSC cryostat redesigned for a post constructed of three identical injection molded composite sections.

A request for quotations has been prepared for an injection mold which will give either a 3 mm or a 4 mm shell wall thickness, depending upon the selection of an interior mold core. The RFQ will also include sample castings of Ultem, Noryl, and PEEK for the testing program. Fixtures for testing the SSC post sections have also been designed and are now out for bids.

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