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SSC 50 MM Collider Dipole Cryostat Single Tube Support Post Conceptual Design and Analysis

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INTRODUCTION

Superconducting Super Collider (SSC) dipole magnet cold masses are connected to the cryostat vacuum vessel at five places equally spaced along their length. Five supports limit sag of the cold assembly due to its own weight to a level consistent with the final magnet alignment specifications.[1] The supports currently used in the 50 mm dipoles being built at Fermilab and Brookhaven are adaptations of the design developed during the 40 mm design program at Fermilab. The design essentially consists of two composite tubes nested within each other as a means of maximizing the thermal path length. In addition it provides an ideal way to utilize materials best suited for the temperature range over which they must operate. Filament wound S-glass is used between 300K and 80K. Filament wound graphite fiber is used between 80K and 20K and between 20K and 4.5K. S-glass is a better thermal performer above approximately 40K. Graphite composites are ideally suited for operation below 40K. The designs for both the 40 mm and 50 mm reentrant supports are well documented in the literature.[2-5] Complete coverage is outside the scope of this report. Figure 1 illustrates a cross section through the current design for 50 mm collider dipoles support post.

The current design of the reentrant support has two major drawbacks. First, it requires very tight dimensional control on all components; composite tubes and metal attachment parts. Second, it is expensive, with cost being driven by both the tolerance constraints and by a complex assembly procedure. It seems clear that production magnets will require a support structure which is considerably less expensive than that which is currently used. The unit cost for support posts for 50 mm prototype magnets is on the order of $2500 in quantities sufficient for 20 magnets (100 supports).

Work at Brookhaven National Laboratory and the SSC Laboratory over the past two years on RHIC cryostat support structures led to the development of a support post fabricated using Ultem-2100, an injection molded, chopped glass fiber, composite material.[6] Due to its apparent cost

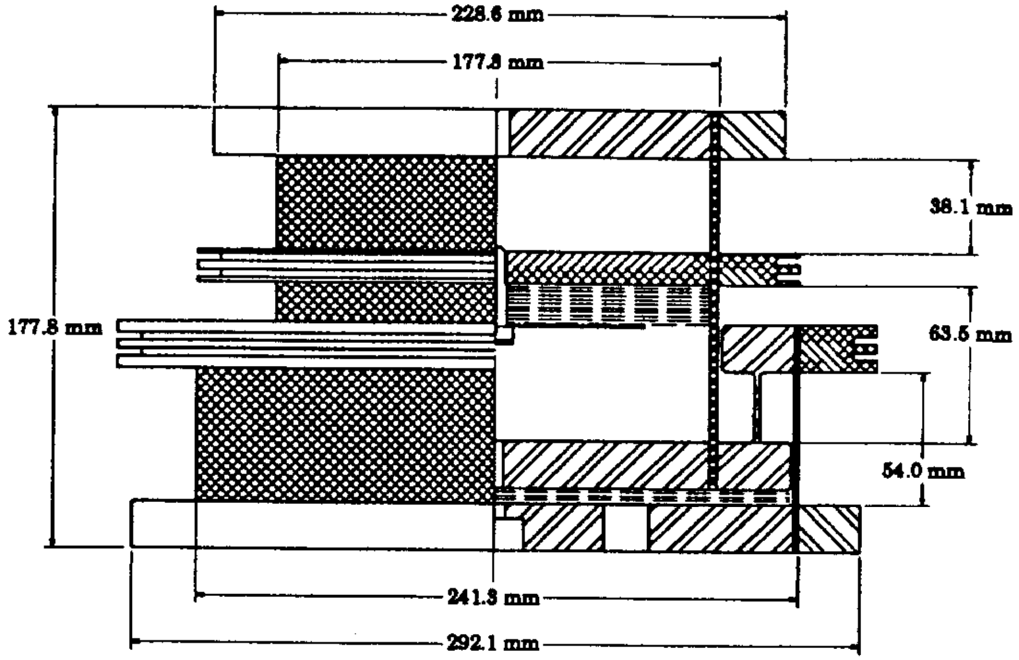

Figure 1. Current 50 mm collider dipole reentrant support post cross section.

advantage, the injection molding concept has found strong support among industrial contractors working on the design of production collider dipoles and quadrupoles. It may not, however, be the panacea that it is perceived to be for SSC dipoles. Space is limited in collider dipole cryostats so an injection molded assembly which provides sufficient strength and low heat load may be difficult to incorporate in the design. In addition, the SSC design requires an intercept at 20K which RHIC magnets do not utilize, further complicating the assembly. Finally, injection molded composite materials don't exhibit the combination of stiffness, strength, and low thermal conductivity required in the SSC collider dipole design.

It seems clear that a design alternate for reentrant support posts will be required for production dipoles primarily due to their cost. It seems less clear that injection molded composite materials are the ideal choice.

This report describes the conceptual design for a support post whose function is identical to that of the current reentrant design, which requires very few modifications to surrounding cryostat components, is thermally equivalent to the current 50 mm support post, and is nearly equivalent structurally. The focus of this work is on a design aimed specifically at application in SSC 50 mm collider dipoles, however, the conceptual design presented here is applicable to other cryogenic systems.

DESIGN OVERVIEW

The reentrant supports used in 40 mm and 50 mm SSC collider dipoles have shown themselves to be very capable of meeting their design requirements structurally and thermally, both in prototype magnets and in individual component tests. Filament wound tubes are superior to tubes fabricated from cloth lay-ups or prepregs due to the ability, inherent in the filament winding process, to tailor the material properties in each of three principal directions. They are superior to injection molded tubes in strength and stiffness by virtue of their continuous fibers. Injection molded components either use chopped fibers randomly oriented in a resin matrix or a resin alone.

The method of joining the composite tubes to their metal end attachments in current reentrant supports has also proven very reliable over the broad temperature range to which the assemblies are subjected. Shrink fitting is used to capture the composite tubes between inner discs and outer rings.[2-5] Epoxy joints and other forms of mechanical fasteners are less reliable when subjected to temperature extremes which range from 300K to 4.5K.

This is the starting point for the subject design. It utilizes filament wound composite tubes connected to metal end fittings and thermal intercepts via shrink fitting. The difference is that it no longer utilizes the reentrant tube concept and so contains fewer metal attachment parts and is easier to assemble.

DESIGN ANALYSIS

The design analysis for this or any other suspension system component consists of two parts; estimation of both structural and thermal performance. In this case each is accomplished by separate finite element models which are parameterized to allow many different design options to be considered. The structural model allows the deflections and stresses in the composite tubes to be estimated and compared with the design requirements and with the composite material properties. The thermal model allows heat loads to 80K, 20K, and 4.5K to be estimated and compared with the heat load budget. Tables 1 and 2 illustrate the structural and thermal requirements placed on the support structure for 50 mm SSC collider dipoles.

Table 1. 50 mm collider dipole structural criteria.

Overall cold mass weight:	11,360 kg
Lateral load requirement:	1.0 g
Vertical load requirement:	2.0 g
Axial load requirement:	1.5 g
Allowable composite material stress:	50% σ_{ult}

Table 2. 50 mm collider dipole heat load budget per support.

Thermal station	Budget heat load
4.5K	0.032W
20K	0.480W
80K	3.160W

The first step in the initial design process for both 40 mm and 50 mm SSC dipole supports was to determine something about the available physical envelope into which the assemblies would fit. The intent here is not to launch into a completely new cryostat design, but rather to develop a replacement which requires as few modifications to other components as possible. Given that, the overall height of the support proposed here is identical to that of the current 50 mm collider dipole, i.e. 177.8 mm. There is some flexibility in the overall assembly diameter. Preliminary analysis indicated that the largest tube diameter possible would result in the lowest overall thermal conductivity and highest structural strength. Space limitations inside the cryostat represent a physical limit to what is practical. In this case, a 235 mm outside tube diameter represents a reasonable compromise between performance and minimum impact on the existing cryostat design. It was also clear from work on 40 mm and 50 mm supports that fiberglass reinforced composite material (FRP) is ideally suited for operation between 300K and 20K and that graphite reinforced composite (GRP) was the material of choice for operation between 20K and 4.5K.[3-4] The difference in material for the operating temperature regions is due to the thermal conductivity of each vs. temperature. FRP has a lower thermal conductivity integral between 300K and approximately 40K than GRP. GRP, on the other hand, is a better thermal performer below 40K. Additionally, GRP provides superior structural strength, allowing smaller material cross sections leading to even better thermal performance of the structure.

The structural and thermal performance of this and all other superconducting magnet support systems are generally at odds with one another. Load and stiffness specifications imply materials with high strength. Low allowable heat loads imply good insulators which are typically not good structural materials. The goal of this or any such design is to strike a reasonable balance between the two.

After choosing a physical envelope, the tube wall thicknesses were determined using the support thermal model. A single tube can be machined such that the wall thickness is optimized between thermal intercepts. Optimized in this case means that the conductive heat load to each thermal intercept just meets the budget. Figure 2 illustrates the equivalent thermal model used in the analysis. The tube thicknesses between each intercept are determined which result in cross sectional areas that meet the heat loads in table 2. The cold mass cradle A/ℓ is explicitly assumed to be 0.85 cm based on thermal tests of 40 mm cradle assemblies. Given these parameters, successive iterations of the thermal analysis resulted in the tube thicknesses and thermal path lengths shown in table 3. A closed form solution does not exist due to the temperature dependent nature of the material thermal conductivities.

Table 3. Material, thermal path length, and wall thickness for each tube section (mm).

Tube section	Material	Thermal path	Wall thickness
300K to 80K	FRP	51.9 mm	2.15 mm
80K to 20K	FRP	36.4 mm	1.64 mm
20K to 4.5K	GRP	26.0 mm	1.52 mm

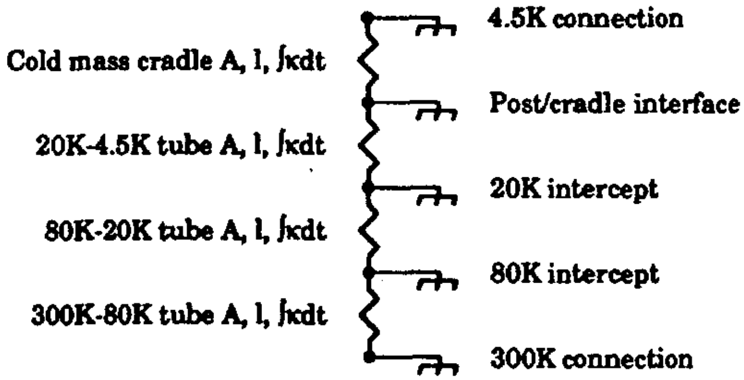

Figure 2. Single tube support equivalent thermal model.

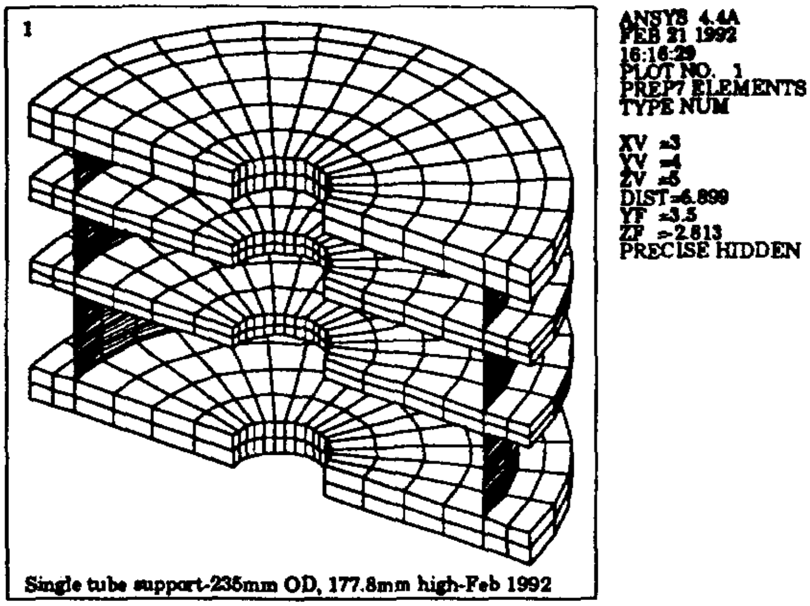

Figure 3. Structural model - finite element mesh.

Given the above geometry, the next step in the analysis is to determine the structural adequacy of this design. The structural finite element model simulates a complete 3-d cross section of the support. The worst case load is that which occurs at the cold mass centerline, i.e. 1.0 g lateral applied 359.8 mm above the base of the support due to shipping and handling loads. For this analysis a 1.0 g vertical load is superimposed on the lateral load to simulate the cold mass weight. The axial load is ignored due to the fact that a shipping restraint will be installed at the magnet ends to limit any axial load on the suspension during shipping. Figure 3 illustrates the finite element mesh used in the structural analysis. Table 4 contains the maximum tensile, compressive, and shear stresses resulting from the structural analysis.

Table 4. Maximum compressive, tensile, and shear stresses in single tube support composite members (MPa).

Support section	σ(compr)	σ(tens)	τ(max)
300K-80K tube	-133.7	102.6	28.2
80K-20K tube	-163.9	120.7	37.6
20K-4.5K tube	-188.7	146.8	40.3

The allowable stresses for each of the two composite materials is 138 MPa for the FRP section between 300K and 20K and 207 MPa for the GRP section between 20K and 4.5K. Given the tube thicknesses, materials, and thermal path lengths determined in the thermal analysis, we conclude that this assembly also meets the structural requirements of the 50 mm collider dipoles.

ASSEMBLY DETAILS

Figure 4 illustrates the overall assembly of the completed single tube support whose geometry was determined above. The term 'single tube

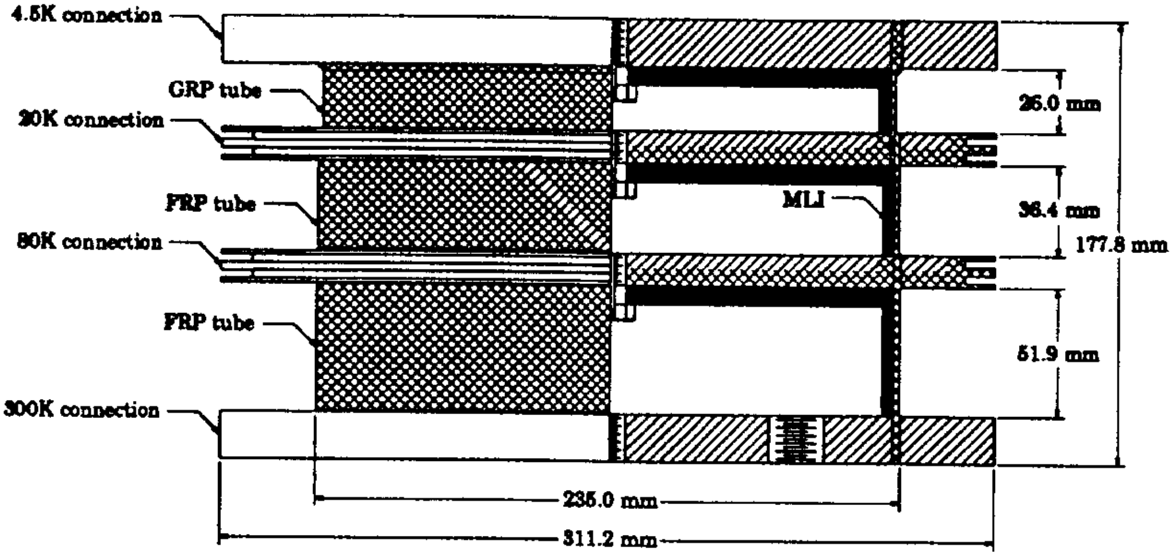

Figure 4. Completed single tube support assembly.

support' is somewhat misleading for this design. The term originally referred to the non-reentrant nature of the design. Still, however, we utilize two composite tubes assembled as a single tube. The joint between these tubes is effected by capturing overlapping sections of each composite material between the 20K disc and ring, both of which are 6061-T6 aluminum. These two components are sized such that an interference fit exists at assembly. The contact pressure from this shrink fit joint is 58.6 MPa which is more than adequate to resist tensile, compressive, and bending loads imposed on the assembly. Figure 5 illustrates the details of the joint between the FRP and GRP tube sections. No adhesives or mechanical fasteners are used in the assembly. Each of the other joints are made identically. The outer rings at each thermal station are machined such that they are a line to line fit with the tube OD. The inner discs are machined such that they oversized to a prescribed amount based on the overturning moment requirements at each joint. They are cooled to LN_2 temperature and slipped into the tube with tooling that ensures they are lined up with the outer rings. MLI is installed during the assembly process to minimize radiation heat transfer through the assembly.

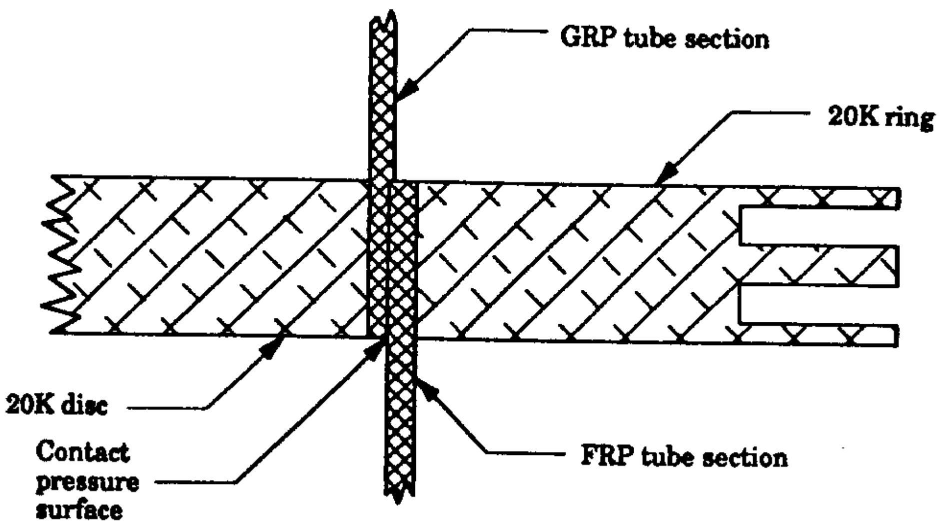

Figure 5. FRP/GRP tube connection detail.

FINAL DIMENSIONAL AND PERFORMANCE PARAMETERS

Table 5 lists some of the dimensional and performance parameters for the single tube support described in this report as well as comparable values for the current 50 mm support post design.

Table 5. Final dimensional and performance parameters for a single tube support and the current 50 mm dipole reetrant support.

	Single tube support	Reentrant support
300K to 80K section		
OD:	235.0 mm	241.3 mm
thickness:	2.15 mm	2.16 mm
thermal path length:	51.9 mm	63.5 mm
material:	FRP	FRP
max tensile stress*:	102.6 MPa	60.4 MPa
80K to 20K section		
OD:	235.0 mm	177.8 mm
thickness:	1.64 mm	3.18 mm
thermal path length:	36.4 mm	54.0 mm
material:	FRP	GRP
max tensile stress*:	120.7 MPa	70.4 MPa
20K to 4.5K section		
OD:	235.0 mm	177.8 mm
thickness:	1.52 mm	3.18 mm
thermal path length:	26.0 mm	38.1 mm
material:	GRP	GRP
max tensile stress*:	146.8 MPa	51.5 MPa
Overall assembly height:	177.8 mm	177.8 mm
Cold mass deflection:	2.33 mm	2.76 mm
Heat load to 4.5K:	0.032W	0.033W
Heat load to 20K:	0.482W	0.518W
Heat load to 80K:	3.164W	3.107W

*:all stresses are calculated at centerline loads of 1.0 g lateral, 1.0 g vertical

Several things are clear from the above comparison of the current support design and that proposed in this write-up. First, both are capable of meeting the prescribed heat load budget. The reentrant design is slightly over budget at 20K due to a slight error in initial calculations. It could easily meet the budget with a slight reduction in the GRP tube wall thickness and adjustment in the position of the 20K intercept. Second, the reentrant design is clearly superior in terms of structural strength. It was initially sized for a lateral load of 1.5 g which is the reason for such low stresses at 1.0 g. We owe the superior structural strength to the reentrant design which maximizes the thermal conduction path without increasing the overall bending moments on the component tubes. Lastly, the single tube support is marginally superior in terms of stiffness. Although not explicitly defined as a design criteria, stiffness is important in the dynamic performance of the support structure. There is some flexibility in the design envelope for the single tube support. More detailed analysis may yield design parameters somewhat different than those outlined here. These, however, serve as a reasonable starting reference.

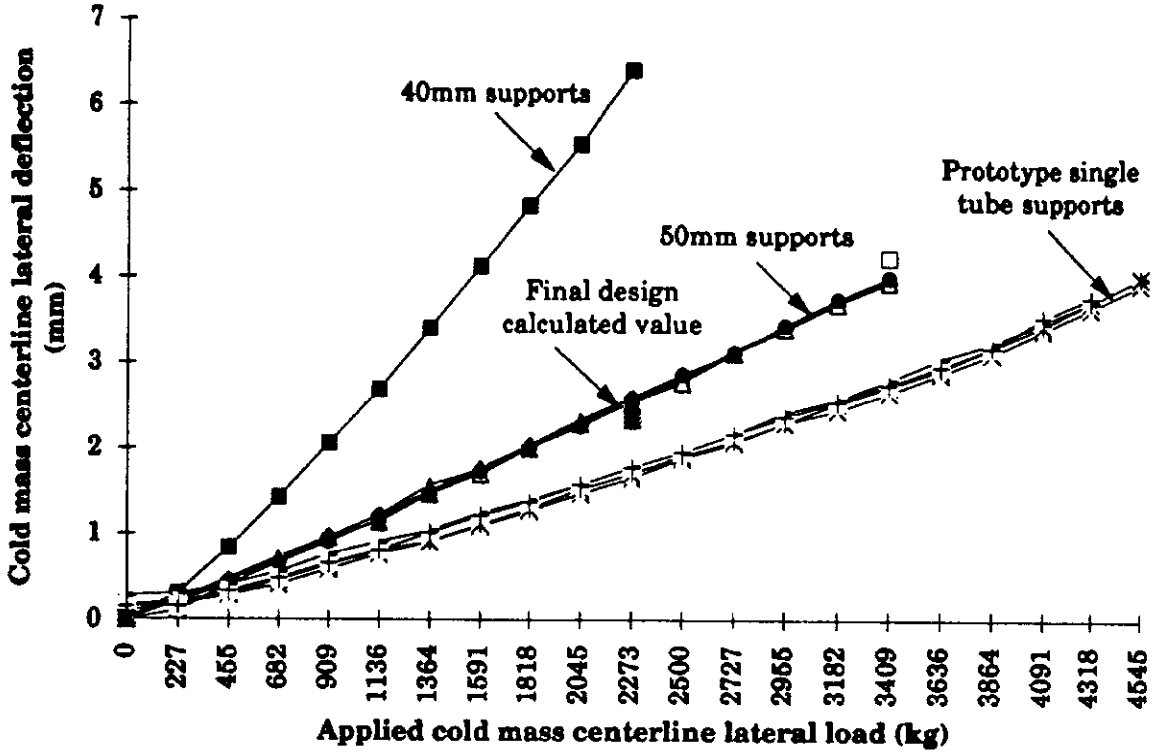

Figure 6. Reentrant and single tube support bending test results.

TEST RESULTS

The development program thus far has included assembly of four single tube supports for mechanical testing only. These supports were larger than the design described above. The tubes were 240 mm OD with wall thicknesses of 2.79 mm, 2.29 mm, and 2.03 mm along the 300K to 80K, 80K to 20K, and 20K to 4.5K sections respectively. The overall height of the test assemblies are 203.2 mm. Using this geometry enabled us to make use of an existing filament winding mandrel, saving both time and development costs. Figure 6 illustrates the results from these tests as well as test results from 40 mm and 50 mm dipole reentrant supports.

Thermal tests have not been conducted to date, but are critical in validating the calculated heat loads to each thermal station. Sufficient prototype assemblies are planned to enable us to complete this testing later in 1992. These tests will be documented and published when available.

SUMMARY AND CONCLUSIONS

The above analysis indicates that a support post fabricated from a single composite tube can meet the structural and thermal specifications proposed for the SSC 50 mm collider dipole suspension system.

Initial estimates from vendors familiar with assembly of reentrant supports indicate that the total cost of a single tube support in quantities sufficient for the entire collider dipole production program would be on the order of $500 to $600, compared with $2500 for smaller quantities of reentrant supports. It is difficult to imagine a support fabricated from an injection molded material resulting in cost savings much more significant.

A test program has been initiated which confirms the predicted structural performance of this assembly. One which confirms the thermal performance is in process. Development work needs to be done to determine whether or not it is feasible to fabricate a single tube with both S-glass and graphite fibers in the same structure in quantity. Filament winding or resin transfer molding may both be viable fabrication techniques.

It is possible that development work at the SSCL or at one of the industrial contractors will yield a support structure which successfully utilizes injection molded materials. The above analysis is one more alternative and one which is based firmly on proven design concepts.

ACKNOWLEDGMENTS

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