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# Single Tube Support Post Thermal Analysis and Test Results

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# SINGLE TUBE SUPPORT POST
# THERMAL ANALYSIS AND TEST RESULTS

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## INTRODUCTION

Cold mass structural supports used in prototype Superconducting Super Collider (SSC) 50 mm dipole magnets built at Fermilab and Brookhaven are adaptations of the design developed during the 40 mm design program at Fermilab.[1,2] 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. An alternate design for supports which uses a single composite tube has been developed at Fermilab and continues to be refined by the industrial contractors.[3] The advantage of the new design is cost reduction due to a significantly simpler assembly and incorporation of many common parts. This report describes the thermal analysis and testing of a single composite tube support post whose function is identical to that of the current reentrant design.

## THERMAL ANALYSIS

Characterizing this support design as being a single tube is somewhat misleading. It actually consists of two separate composite tubes joined at the 20K intercept by clamping the tube overlaps between the outer ring and inner disc, both of which are aluminum, and which are machined to effect a shrink fit joint. Single tube in this context refers to the non-reentrant design of the assembly which is what distinguishes it from all SSC prototype assemblies. The support structure used in the thermal analysis and test is shown in Figure 1. It consists of a fiberglass reinforced epoxy tube (FRP) between the 300K connection and 20K intercept and a graphite reinforced epoxy tube (GRP) between the 20K intercept and the top ring.

Equations 1 through 4 are expressions for the heat load to each thermal intercept in terms of the support geometry and material properties. Table 1 lists the relevant geometry and material property values used in the analysis. Note that thermal conductivity integrals are shown only for the case in which the low temperature intercept is at its nominal operating temperature of 20K.

Typically when making thermal conductivity measurements the temperature of the low temperature intercept is varied as a means of documenting support performance at points away from nominal conditions. Data points are taken with this shield at 10K, 20K, 30K, and 40K. The results of the thermal analysis at these four operating conditions are summarized in Table 2.

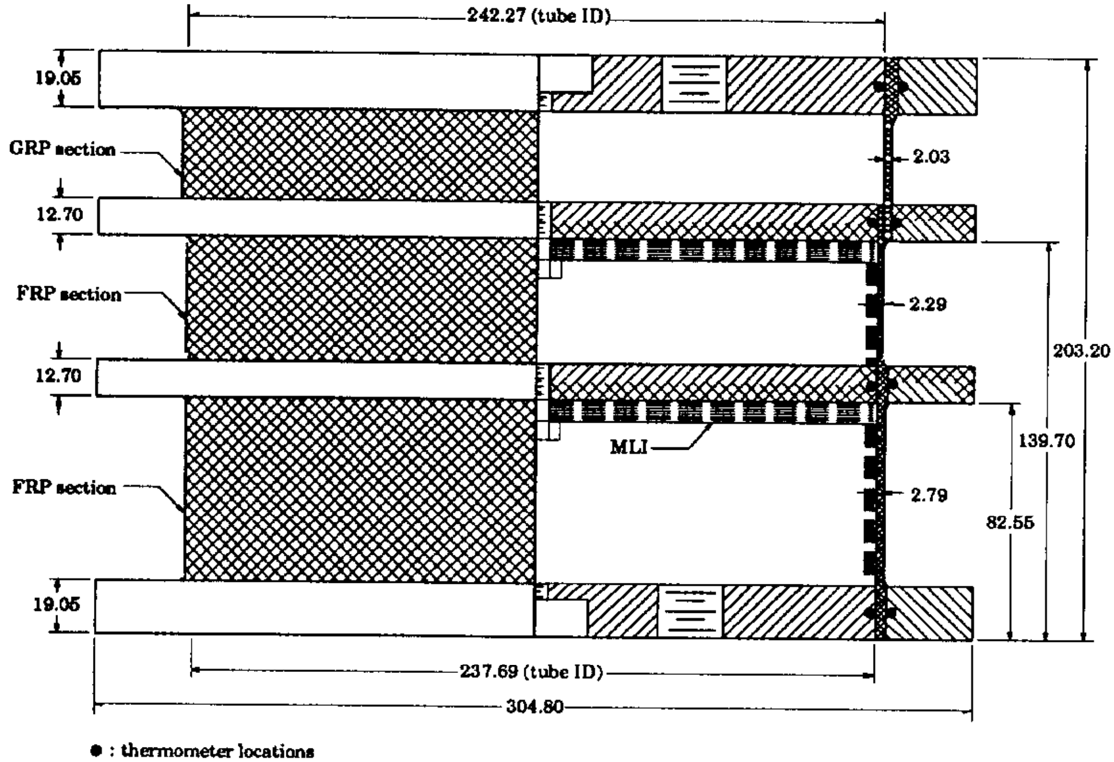


**Figure 1.** Cross section of the single tube support used in thermal analysis and testing

$$Q_{4.5} = \frac{A_3}{L_3}\int_{T_{top}}^{20} \kappa_{grp} dT \qquad (1)$$

and

$$Q_{4.5} = \frac{A_{eq}}{L_{eq}}\int_{4.5}^{T_{top}} \kappa_{ss} dT \qquad (2)$$

where

$$\frac{A_{eq}}{L_{eq}} = \frac{1}{\frac{\ln\left(r_o / r_i\right)}{2\pi t} + \frac{L_{hm}}{A_{hm}}} \qquad (3)$$

$$Q_{20} = \frac{A_2}{L_2}\int_{20}^{80} \kappa_{frp} dT - Q_{4.5} \qquad (4)$$

$$Q_{80} = \frac{A_1}{L_1}\int_{80}^{300} \kappa_{frp} dT - Q_{20} - Q_{4.5} \qquad (5)$$

where:

$A_1$, $A_2$, $A_3$ = cross sectional areas of the lower, middle, and upper tube sections
$A_{eq}$ = equivalent cross sectional area of the top post disc and heat meter
$A_{hm}$ = cross sectional area of the heat meter active element
$L_1$, $L_2$, $L_3$ = thermal path length of the lower, middle, and upper tube sections
$L_{eq}$ = equivalent length of the top post disc and heat meter
$L_{hm}$ = length of the heat meter active element
$\kappa_{ss}$ = thermal conductivity of stainless steel
$\kappa_{grp}$ = thermal conductivity of graphite reinforced composite
$\kappa_{frp}$ = thermal conductivity of glass reinforced composite
$r_i$, $r_o$, $t$ = top disc inner radius, outer radius, and thickness
$T_{top}$ = temperature at the top support ring

| Table 1. Thermal analysis parameters | | |
|---|---|---|
| Parameter | Units | Value |
| $A_1$ | $mm^2$ | 2110.90 |
| $A_2$ | $mm^2$ | 1723.48 |
| $A_3$ | $mm^2$ | 1559.55 |
| $A_{hm}$ | $mm^2$ | 285.02 |
| $L_1$ | mm | 63.50 |
| $L_2$ | mm | 44.45 |
| $L_3$ | mm | 31.75 |
| $L_{hm}$ | mm | 8.53 |
| $r_o$ | mm | 121.14 |
| $r_i$ | mm | 12.70 |
| t | mm | 19.05 |
| $\int\kappa_{ss}$ (9K-4.5K) | W/mm-K | 0.002 |
| $\int\kappa_{grp}$ (20K-9K) | W/mm-K | 0.001 |
| $\int\kappa_{frp}$ (80K-20K) | W/mm-K | 0.016 |
| $\int\kappa_{frp}$ (300K-80K) | W/mm-K | 0.122 |

| Table 2. Thermal analysis results | | | | |
|---|---|---|---|---|
| Low temp intercept (K) | $T_{top}$ (K) | $Q_{4.5}$ (W) | $Q_{20}$ (W) | $Q_{80}$ (W) |
| 10 | 6.03 | 0.012 | 0.658 | 3.386 |
| 20 | 8.92 | 0.043 | 0.564 | 3.449 |
| 30 | 12.06 | 0.096 | 0.434 | 3.526 |
| 40 | 15.81 | 0.189 | 0.254 | 3.613 |

## THERMAL TEST

Thermometers were positioned along the conductive path of the support assembly to map the temperature of the various metal components under different operating conditions. 100 ohm platinum RTD's were inserted into the 80K and 300K discs and rings. 100 ohm carbon resistors were used as thermometers on the 20K and 4.5K metal components. Thermal performance measurements were conducted in a Heat Leak Test Facility.[4] The support assembly was installed in a helium dewar in much the same way it is installed in a magnet cryostat. Each shield is cooled by internal cryogen lines and the top of the support is attached to an LHe vessel. Total heat flow to 4.5K through the support assembly was measured by means of a heat meter that measures heat flow as a temperature gradient across a thermal impedance with an accuracy of ± 1 mW at 4.5K.[4] Unfortunately, the current configuration of the measuring system does not permit measuring heat flow to the intermediate shields.

One goal of the measurement program was to measure the heat load to 4.5K at different 20K shield temperatures. This provides not only multiple points at which to confirm the analysis, but also provides information on total magnet system performance at degraded operating conditions. Precise flow control of the cooling gas to the 20K shield allows operation of this shield at any temperature. For this test, we chose to perform measurements with this shield at 10K, 20K, 30K and 40K.

Table 3 presents a tabulated summary of the measurement data. When comparing this with the calculated results in Table 2 it is clear that there is reasonably good agreement between the predicted performance at 20K shield temperatures of 30K and below. Agreement would be improved with thermal conductivity data specific to each composite material used in the support assembly. In addition to heat load, this table provides insight into other support performance characteristics, most notably the thermal efficiency of the shrink fit joints. Small temperature gradients across each joint are indications that these joints provide a good means by which to transfer heat out of the composite tubes to each thermal intercept.

| Table 3. Thermal test results | | | | | | |
|---|---|---|---|---|---|---|
| | | Low Temperature Intercept (K) | | | | |
| Sensor location | Sensor type | 10 | 20 *(meas 2)* | 20 *(meas 1)* | 30 | 40 |
| 4K disc | Carbon resistor | 6.567 | 9.070 | 9.168 | 13.659 | 16.337 |
| 4K ring | Carbon resistor | 6.435 | 9.142 | 8.981 | 13.815 | 15.978 |
| 20K disc | Carbon resistor | 15.779 | 22.847 | 22.865 | 34.595 | 40.275 |
| 20K intercept | Carbon resistor | 9.924 | 19.142 | 19.162 | 31.752 | 37.439 |
| 80K disc | Platinum RTD | 85.798 | 85.664 | 85.859 | 86.355 | 86.531 |
| 80K intercept | Platinum RTD | 83.650 | 83.519 | 83.728 | 84.191 | 84.312 |
| 300K disc | Platinum RTD | 282.044 | 282.223 | 282.189 | 282.287 | 282.891 |
| 300K ring | Platinum RTD | 281.842 | 282.022 | 281.984 | 282.084 | 282.689 |
| 20K shield | Carbon resistor | 8.311 | 19.118 | 19.140 | 33.357 | 39.852 |
| 80K shield | Platinum RTD | 81.730 | 81.611 | 81.816 | 82.262 | 82.340 |
| Vacuum | Glass ion gauge | 1.36E-6 | 1.34E-6 | 1.67E-6 | 1.34E-6 | 1.04E-6 |
| Heat load to 4.5K (W) | Heat meter | 0.010 | 0.030 | 0.029 | 0.088 | 0.130 |

## SUMMARY

Thermal analysis and test capabilities at Fermilab have evolved a great deal over the course of the prototype SSC magnet development program. The results presented here are encouraging in the sense that they provide some assurance that system performance, determined largely on the basis of analysis results, is predictable assuming that care is taken in the magnet cryostat fabrication process. This work also points out areas in which our current analysis and measurement capabilities could be strengthened. First, better correlation between calculated and measured results would be improved with material specific thermal conductivity data. Cost constraints precluded development of a system to accurately measure thermal conductivity from 300K to 4.5K. Second, overall performance predictions would be improved by developing the capability of measuring heat flow to the 80K and 20K shields.

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