Fermilab

SDC SOLENOID DESIGN NOTE #114

TITLE: Thermal Shield on Inside of Coil--Preliminary Thoughts

AUTHOR: Ron Fast and Ang Lee

DATE: Aug 31, 1990

ABSTRACT: This Design Note presents the idea of a thermal shield on the inside of the superconducting coil. The analytical, first-guess thermal analysis shows that the use of very pure aluminum as a shield material gives a satisfactory temperature distribution along the shield, even if heat sinked only at the ends.

INTRODUCTION

The solenoid at CDF has one unexpected thermal characteristic: the coil cannot be energized to full current if the insulating vacuum gets above about 5 microns. This characteristic was discovered when a leak developed from the helium circuit to the insulating vacuum space and we had to install additional vacuum pumps in order to operate at full current. The most likely cause of this characteristic is an increased gas conduction heat load from the inner LIN-cooled shield to the inside of the coil, which causes either a hot spot or a general warming of the coil. The outside of the coil is shielded from this effect by the heat sinking of the outer support cylinder. Unfortunately, our temperature and vacuum instrumentation is not adequate for us to calculate this additional heat load.

Whether or not this additional heat load is the cause of the problem at CDF, it is true that the inside of the coil is not as well shielded from heat radiated and conducted to it from the LIN-cooled shield as the outside. I (RF) believe that we should consider another shield or intercept between the inside of the coil and the inner LIN shield.

Some months ago Akira Yamamoto (KEK) proposed bonding pure aluminum strips to the inside of the coil as a means of increasing the longitudinal quench velocity. I occurred to me that if these strips were anchored to 4.5 K at the ends of the coil, they would serve as a heat intercept.

COMPUTATIONAL METHOD

Ang Lee recently looked at this idea and, treating it analytically as a fin with uniform heat load, calculated the maximum temperature as a function of fin thickness and the purity of the aluminum used for the fin. He used 3 mW/ft^2 as the heat flux from the LIN shield; this is the value used in the CDF Design Report. We did not look for the functional dependence of thermal conductivity on aluminum purity, but took advantage of the Wiedemann-Franz correlation, which states that, for pure metals, the product of the electrical resistivity and thermal conductivity varies linearily with absolute temperature. We had good reference data for the electrical resistivity of aluminum as a function of temperature for several values of RRR [RRR = residual resistivity ratio = $\rho(300\ K)/\rho(0\ K)$] from 100 to 30,000. Ang's calculations are given in the appendix; his results are shown in Table 1.

CONCLUSIONS

If the strips have a thermal conductivity greater than about 5000 W/m-K (RRR > 1000) and if the heat flux is less than about 5 mW/ft^2, then the strips will function effectively to intercept heat from the LIN shield and will not transfer heat by solid conduction to the coil. However, the ability of the strips to alleviate the hot spot problem caused by poor vacuum while not causing another depends on the as-built thermal conductivity of the strips and the heat flux to them.

If one were confident that the as-built conditions would be quite close to those used in the calculations, the strips could be glued to the inside of the coil. However, if the RRR of the strips were degraded by cold working during installation, then the centers of the strips could be sufficiently warmer than the coil to cause a hot spot in the coil if the strips were in good thermal contact with it. If the actual heat flux were more than that used in the calculation, the same effect could occur.

It appears that the question to be answered is, How well should the strips be thermally isolated from the coil? Perhaps the electrical insulation which is required anyway (if the strips are bonded to the coil) will provide enough isolation or perhaps a thin layer of something like styrofoam would be adequate. Separating the coil and strips by a vacuum space is the most conservative approach, although this suggests the use of a non-high purity aluminum of greater mechanical strength but lower thermal conductivity (4 W/m-K for 5083-0 alloy at 5 K).

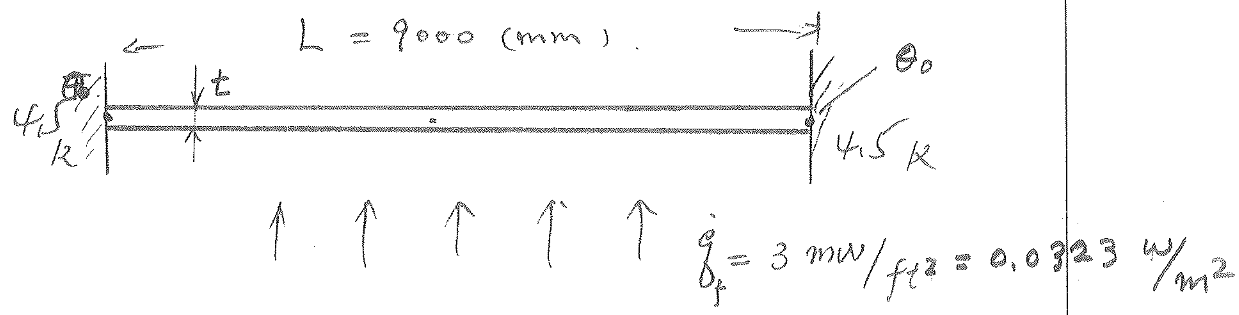
We have shown that a 1 or 2 mm aluminum sheet, heat sinked only at the ends to 4.5 K, can effectively intercept heat coming in from the LIN shield. More thought and calculations are needed to determine whether this intercept should be bonded to the coil or vacuum insulated from it.

Table 1

	$t = 1$ (mm)	$t = 2$ (mm)	$t = 5$ (mm)	ρ_c ($\Omega \cdot m$)	K ($\theta = 5K$) W/m·K	RRR
θ_{max} (K)	5.188	4.857	4.646	2.5×10^{-10}	490	RRR-100
θ_{max} (K)	4.731	4.617	4.547	8.0×10^{-11}	1531.3	RRR-300
θ_{max} (K)	4.574	4.537	4.515	2.5×10^{-11}	4900	RRR-1000
θ_{max} (K)	4.524	4.512	4.505	8.0×10^{-12}	15312.5	RRR-3000
θ_{max} (K)	4.507	4.504	4.501	2.5×10^{-12}	49000	RRR-10,000

Appendix

Given:

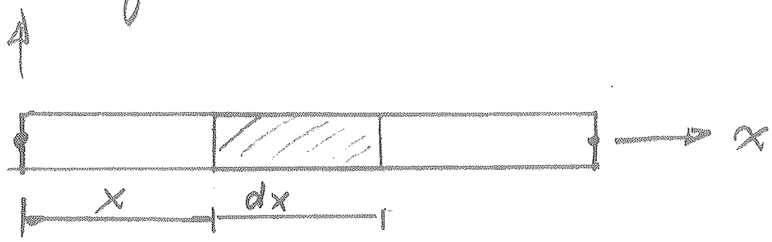


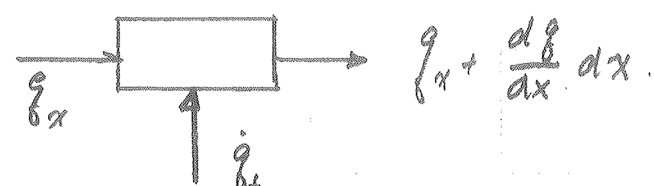
Find. θ_{max} at $t = 1$ (mm), 2 (mm), 5 (mm).

for RRR = 100, RRR = 1000, 3000, 10,000

Solution:

Heat Balance equation





$$q_x - \left(q_x + \frac{dq}{dx} dx\right) + \dot{q}_f = 0$$

$$\Rightarrow \boxed{\frac{d}{dx}\left(k \cdot t \, \frac{d\theta}{dx}\right) + \dot{q}_f = 0}$$

$$\frac{d}{dx}\left(k(\theta) \cdot t \cdot \frac{d\theta}{dx} \right) + \dot{q}_{bf} = 0 \qquad (1)$$

with B.C.

$\theta(x=0) = \theta_0$

$\theta(x=L) = \theta_0$

STEP 2:

Solv (equation-1)

$$\frac{d}{dx}\left(k(\theta) \cdot \frac{d\theta}{dx} \right) = -\frac{\dot{q}_{bf}}{t}$$

$$k(\theta) \cdot \frac{d\theta}{dx} = -\frac{\dot{q}_{bf}}{t} x + C_1$$

$$\Rightarrow \int_{\theta} k(\theta) \cdot d\theta = \int_{x} \left(-\frac{\dot{q}_{bf}}{t} x + C_1 \right) dx$$

$$\boxed{\int_{\theta} k(\theta)\, d\theta = -\frac{\dot{q}_{bf}}{2t} x^2 + C_1 x + C_2} \qquad (2)$$

Assuming: $k(\theta)\rho(\theta) = L_0 \theta$ (W-F law)

$$k(\theta) = \frac{L_0 \theta}{\rho(\theta)}$$

$$\boxed{\int_0 \frac{L_0\, \theta}{\rho(\theta)} = -\frac{\dot{q}_f}{2t} x^2 + C_1 x + C_2} \quad (3)$$

We have to find $\rho(\theta) = f(\theta)$. from chart(11, R1),
We know $\rho(\theta)$ is constant at $\theta \le \theta_c$.
For the first calation, we assime $\theta \le \theta_c$, so
that the $\rho(\theta)$ becomes.

$$\rho(\theta) = \rho_c \quad \text{(for a given RRR value)}$$

$$\int_0 \frac{L_0\, \theta}{\rho_c}\, d\theta = -\frac{\dot{q}_f}{2t} x^2 + C_1 x + C_2$$

$$\Rightarrow \quad \frac{L_0}{2\rho_c}\theta^2 = -\frac{\dot{q}_f}{2t} x^2 + C_1 x + C_2 .$$

B.C.

$\theta = \theta_0 \ (x=0) \quad \Rightarrow \quad C_2 = \frac{L_0}{2\rho_c}\theta_0^2$

$\theta = \theta_0 \ (x=L) \quad\quad C_1 = \frac{\dot{q}_f}{2t}\cdot L .$

$$\frac{L_0}{2\rho_c}\theta^2 = -\frac{\dot{q}_f}{2t}x^2 + \frac{\dot{q}_f}{2t}\cdot L x + \frac{L_0}{2\rho_c}\theta_0^2$$

$$\theta^2 = \frac{2\rho_c}{L_0}\left(\frac{\dot{q}_f}{2t}L x - \frac{\dot{q}_f}{2t}x^2\right) + \theta_0^2$$

$$\therefore \boxed{\theta^2 = \frac{\rho_c \cdot \dot{q}_f}{L_0\, t}\left(L\cdot x - x^2\right) + \theta_0^2 .}$$

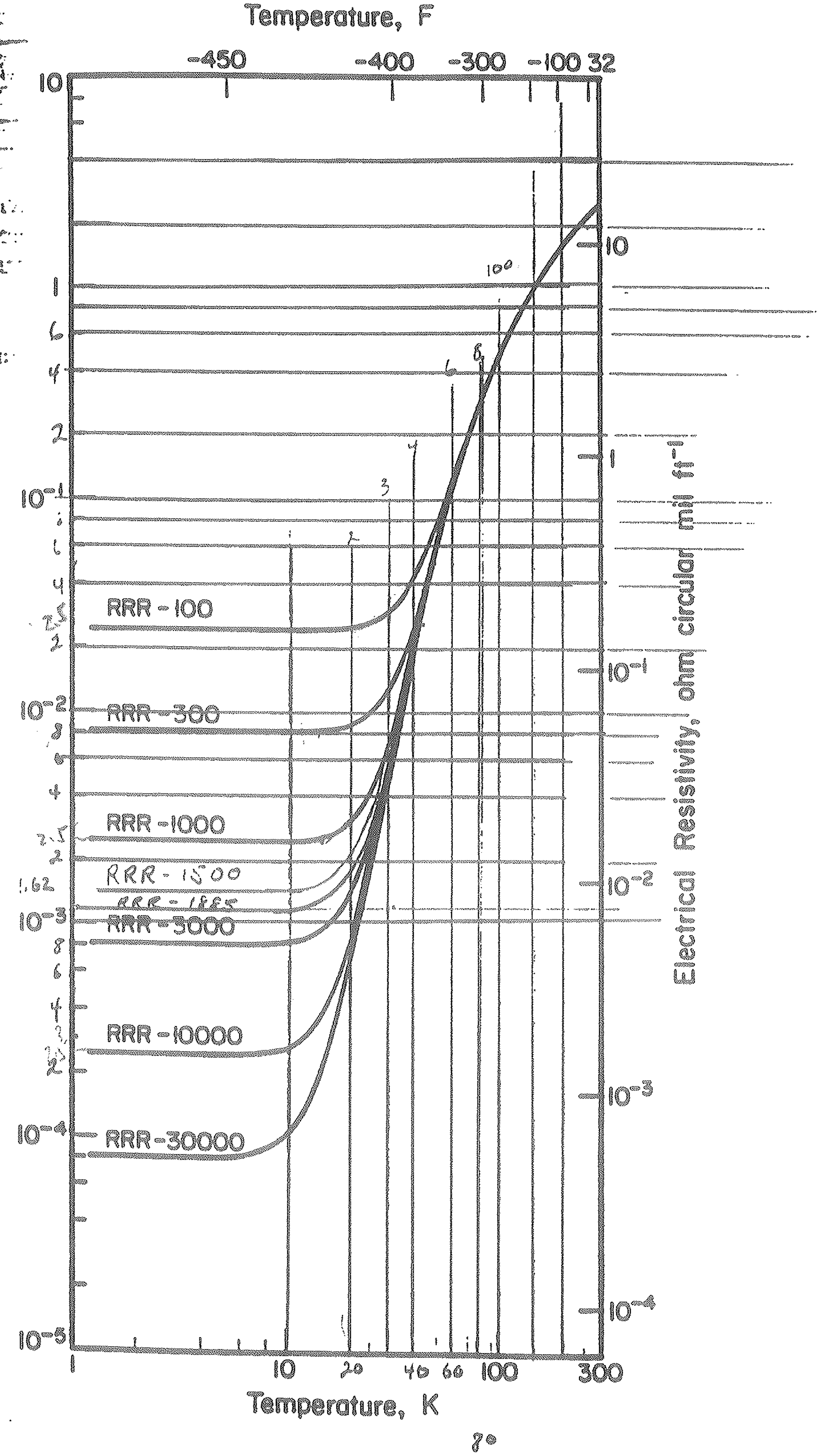
OR:

$$\theta^2 - \theta_0^2 = \frac{\rho_c \cdot \dot{q}_f}{L_0 \cdot t}\left(L\cdot x - x^2\right).$$

$$\theta_{max}^2 (x=4.5) = \frac{\rho_c \cdot \dot{q}_f}{L_0 \cdot t}\left(L\cdot 4.5 - 4.5^2\right) + \theta_0^2 (4.5\,K)$$

The value of θ_{max} at $t = 1, 2, 5$ mm for different RRR is tabulated at next page.

* $\dot{q} = 0.0323$ W/m²
$L = 9000$ mm $= 9$ m
$L_0 = 2.45\times10^{-8}$ $W\cdot\Omega\, K^{-2}$ (Ref).



1.1-R1. ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR ALUMINUM