Lessons Learned Concerning the Use of 4 K Coolers to Cool LTS Magnets

Michael A. Green

Lawrence Berkeley National Laboratory
Berkeley, CA 94720

ABSTRACT

Cryocoolers have been used to cool MRI magnets for many years. The key to keeping these magnets cold has been having a low heat leak cryostat. For the most part, MRI magnets have not had to deal with powered leads. Since the late 1990's cryocoolers have been used to cool LTS magnets that run continuously through powered leads [1], [2], [3]. While there have been many successes in the use of cryocoolers to cool LTS magnets, there have been many instances where the cryocoolers were unable to cool-down the magnet or they were unable to keep the magnet at the proper operating temperature using the cryocoolers alone. This report deals with the mistakes that have been made and the steps that need to be taken to make it possible to cool-down and keep cold an LTS magnet operating at temperatures from 4.2 K to 4.6 K.

INTRODUCTION

This paper is the type of paper rarely seen in conference proceedings or formal publications. Most authors do not want to admit that mistakes were ever made on a project. The funding process used by many government funding-agencies discourages the reporting of mistakes in device design and fabrication. This is a report about mistakes that can be made or have been made when an LTS magnet is designed and built, and is cooled using small 4 K cryocoolers. The mistakes made with MRI magnets are not discussed in this report. MRI-magnet mistakes are not reported by the manufacturers of such magnets, because this information is considered proprietary. However, one can be assured that all of the mistakes reported here have been made at one time or another during the process of product development by the companies that fabricate MRI magnets and cool them with cryocoolers. The examples of mistakes in this report are from the government-funded organizations in the LTS magnet community.

Mistakes can be classified into a number of categories, which are as follows:

1. Estimates of the heat leaks onto the magnet cold mass and shield are usually optimistic, which can result in too few cryocoolers being installed.
2. Poor workmanship during the assembly of the magnet cryostat is often the root of many cooling problems.
3. The magnet radiation shield and cold mass support intercept temperatures are often too high, which leads to higher heat flow to the 4 K cold mass.
4. The connections between the 4 K cold heads and the cold mass are not properly designed. The result is a higher cold mass temperature and longer cool-down times.

Cryocoolers 18, edited by S.D. Miller and R.G. Ross, Jr.

5. The leads that connect the tops of the HTS leads to room temperature are often not properly designed. This results in larger heat loads to the HTS leads and cryocooler first-stages.
6. The insulated connectors that thermally connect the leads from room temperature and the tops of the HTS leads to the cryocooler first-stages are often not correctly designed, which can result in HTS lead failure due to excess heat at the top of the HTS lead.
7. It is difficult to determine what went wrong with the magnet when you don't have good cryocooler performance curves. Many devices are built without knowing how the cryocooler performs, particularly during cool-down.
8. Finally, there are a insufficient number of calibrated temperature sensors installed in the system to know what went wrong when the cryocoolers don't keep the magnet cold.

DESIGN AND FABRICATION ERRORS THAT RESULT IN HIGH HEAT LEAKS

Any superconducting magnet design includes estimating the heat leak into the magnet cryostat. When a magnet is cooled using two stage cryocoolers, there are two sets of heat leak calculations that have to be made. The heat flow into both stages of the cryocoolers is important. Often the heat loads to both stages of the cryocoolers are under-estimated, sometimes by a factor of two or more.

Heat Loads to the Cryocooler First-stage

The cryocooler first-stage cools the magnet thermal shield. This shield has radiation and conduction heating from 300 K, heat from the cold mass support intercepts, heat from the intercepts on vent and fill lines, heat from the intercepts on instrumentation wiring, and heat from the bottoms of the metallic current leads that carry the magnet current from room temperature to the tops of the HTS current leads that carry the current to the 4 K magnet coil. The heat load to the first-stage of magnet cryocoolers is higher than the heat load to the first-stages of cryocoolers used to cool electronic devices. Magnets usually have a larger mass and one has to deal with forces caused by interaction of the magnetic field with other magnets and or ferromagnetic material. Magnets are usually larger than electronic devices, so the shields are larger. Magnets have much larger currents than electronics devices. These currents can be delivered to multiple coils. Larger currents mean that there are larger heat flows to the cryocooler first-stages. Magnets often have a helium vessel of some sort, which means the vessel must have helium fill lines and safety vent lines. The helium fill and vent lines add to the first-stage heat load.

Calculating the heat load to the shield due to the cold mass supports is straight forward, provided the dimensions, thermal and stress properties of all of the parts of the cold mass supports are known. Often the heat flow estimate is made early in the design before the parts have been fabricated. The connection between the intercept and the shield is also very important.

Calculating heat loads to the shield due to vent lines and fill lines should be straight forward, but one has to avoid direct radiation between room temperature (300 K) and the shield. This means that there should be at least one bend in a vent or fill line. Instrumentation wiring between room temperature and the shield should have high resistivity (low thermal conductivity) wires and a small wire cross-section. There are good commercially available instrumentation wires from reliable vendors. The current leads that connect from 300 K to the tops of the HTS leads will be described in another section.

If the dimensions and material properties of the cold mass supports, piping and instrumentation wiring are known, one can estimate the heat load from these sources with reasonable accuracy (say 10 to 20 percent). The biggest challenge is determining the heat load to the shield through the insulation between room temperature and the shield temperature. One can come up with an estimate for this heat load, but this estimate will nearly always be low. The heat leak through the insulation can be underestimated by an order of magnitude for a variety of

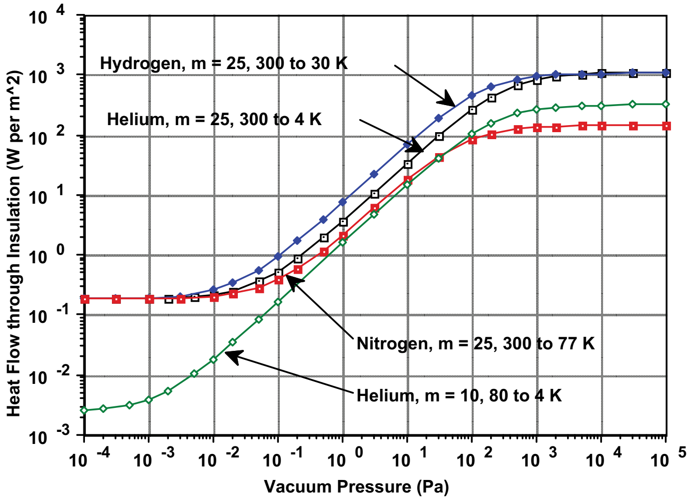

Figure 1. The heat flow per unit area through MLI from 300 K to 77 K, 20 K and 4 K as a function of area for 25 layers of insulation with an average emissivity of 0.03 as a function of vacuum pressure and the type of gas. The bottom curve is the heat flow per unit area through MLI from 80 K to 4 K through 10 layers of insulation with an average emissivity of 0.03 as a function of helium gas pressure in the vacuum space [4]. In both cases the layer spacing is assumed to be 1 mm. Solid heat conduction within the MLI is not included.

reasons. The most important design reason for high heat leaks between the room temperature vacuum vessel and the shield is a failure to use of the best techniques to design the multilayer insulation between the shield and the room temperature vacuum vessel. This includes designing an insulating vacuum vessel or piping that inherently leaks. Figure 1 shows the heat leak per unit area from 300 K to 77 K, 20 K, and 4 K through 25 layers of MLI with an effective emissivity of 0.03 as a function of the vacuum pressure and the type of gas in the vacuum space [4].

Figure 1 shows the effect of free molecular conduction through the gas in the vacuum space. Free molecular gas conduction is a function of pressure until the point where the mean free path within the gas is less than the layer spacing. At this point bulk thermal conduction through the gas takes over. The minimum heat flow from 300 K through 25 layers of MLI (m = 25) with an emissivity of 0.03 is ~0.2 W m^{-2}. The minimum heat load is proportional to the average emissivity and inversely proportional to the number of layers m. Free molecular conduction is negligible from 300 K when the vacuum is less than 0.001 Pa (~10^{-5} Torr). For the space between a shield at 40 to 80 K and the 4 K cold mass, the vacuum must be two orders of magnitude better than an acceptable vacuum outside of the shield.

Achieving an average shield heat flux of 0.2-W m^{-2} can be difficult, even when the vacuum is very good. Any region that is uncovered on the shield can see high heat loads (> 100-W m^{-2}). Compression of the MLI can increase the heat load, but if the insulation is compressed, the force should be applied over a small area rather than spread across a wide area [5]. Penetrations through the shield MLI for piping, instrumentation wires, and cold mass supports will increase the heat load. The way joints are made between MLI blankets can have a large effect on the shield heat leak. Radiation heat transfer from 300 K to the shield must be avoided.

Heat Loads to the 4 K Cold Mass

The heat loads to the cold mass from the shield come from the following sources, 1) the cold mass supports, 2) radiation heat transfer from the shield to the cold mass, 3) helium piping from room temperature, 4) HTS leads between the shield and the cold mass, and 5) instrumentation leads between the shield intercept and the cold mass. Heat loads to the cold mass are greatly influenced by the thermal shield and cold mass support intercept temperature. Specific recommendations on how to reduce the shield temperature and ensure that the shield temperature is more uniform are dealt with in another section of this report. The temperature distribution within the cold mass is greatly influenced by how the cryocooler second-stage is connected to the cold mass [6]. This is particularly true for cryogen-free systems. For this reason, large LTS magnet systems are cooled using some variation of a thermal siphon cooling system [3]. This same type of system can be used to cool-down a magnet as well [7], [8].

The radiation heat transfer to the cold mass is usually underestimated, even for low temperature shields. The radiation heat load from a 50 K shield is a factor of six times lower than from an 80 K shield. This does not mean that the radiation heat flow from a 50 K shield will be <0.001 W m^{-2} as suggested by the values given in Fig. 1, divided by six. MLI does not behave the same at temperatures below 40 K as it does above 80 K. The typical MLI has an aluminum layer that is about 30 nm thick. Infrared radiation produced at temperatures of 40 K and below will go through the aluminum layer of the MLI by radiation tunneling. In order for MLI to be effective in the low temperature range, the MLI should be made from sheets of aluminum that are > 1 μm thick. In general, there is no need for MLI between the shield and the cold mass, as long as both the cold mass and the shield are covered with a low emissivity material thick enough to avoid radiation tunneling. A good cryostat vacuum is essential. Radiation heat transfer from 300 K must be avoided. A likely source of radiation shine is along the cold mass supports and down a fill pipe or vent pipe. Both can be avoided by proper design and fabrication. All pipes and wires going from the cold mass to 300 K should have intercepts that are close to the cryocooler first-stage.

The HTS lead heat leak is a function of the design current for the lead and the lead's upper end temperature. HTS-110 leads have their design current rated with no external magnetic flux (only the self field at the design current) with a warm end temperature of 62 K. A pair of HTS-110 leads with a design current of 500 A will have a heat leak of 155 mW between 62 K and 4K. The heat leak down the HTS-110 leads is approximately proportional to the upper end temperature squared. An external magnetic field reduces the lead design current depending on magnitude of the field and its orientation [9]. The magnet must be designed so that an HTS lead can be replaced in the event of a lead failure. The effect of the field on the HTS leads has implication during a power failure [10]. This means that the magnet must be quench protected using back-wheeling diodes and resistors. Diodes and resistors will reduce the internal voltages in the magnet and they protect the magnet in the event of a break in the current in the HTS leads, the copper leads, and LTS leads between the diodes and the bottoms of the HTS leads [11].

THE SHIELD TEMPERATURE AND SHIELD TEMPERATURE DISTRIBUTION

Two stage cryocoolers typically produce temperatures in the range from 30 to 70 K on their first-stages depending on the heat load applied to the first-stage. Figure 2 shows the operating characteristics for a Cryomech PT415 two-stage pulse tube cryocooler that develops 1.5 W of heat life at 4.2 K on the second-stage while developing about 42 W of heat life at 41 K on the first-stage [12].

The heat flow into the cold mass and the cryocooler second-stages increases as the shield and cold mass intercept temperatures increase. Ideally one should operate the two-stage cryocoolers so that the first-stage temperatures are around 40 K. Ideally, the shield, the cold mass support intercepts, and the tops of the HTS leads should be less than 50 K. The heat flow into the cold mass is approximately proportional to the shield and intercept temperatures squared. This includes the HTS leads as well. There are three key factors that determine the shield temperature and the cold mass intercept temperatures. They are; 1) the heat load to the shield and the heat flow to the cold mass intercepts, 2) the material and the length divided by the cross-sectional area (L/A) of the connections between the shield and the cryocooler first-stage, and 3) the thickness of the shield and the shield material.

The shields and connections between the shield and the cryocooler first-stages can be made of aluminum or copper. If the shield and the connection to the cryocooler first-stages are made

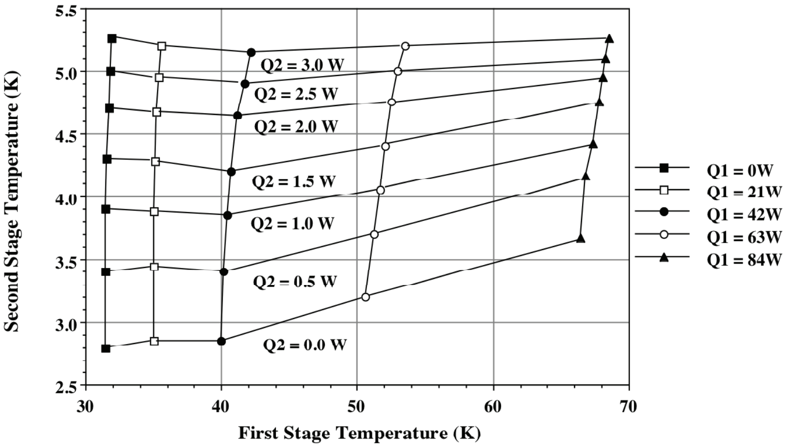

Figure 2. Operating temperature diagram for the first stage temperature T1 and the second stage temperature T2 of a PT415 pulse tube cooler as a function of the first stage heat load Q1 (W) and the second-stage heat load Q2 (W). Data was taken at Florida State [12]

from either of these materials, the metal RRR should be at least 25. Alloys of Aluminum or Copper with an RRR of 25 have a thermal conductivity that increases as temperature goes down (150 K > T > 35 K) [13]. The biggest single factor that reduced the heat load to the cryocooler second-stage in the MICE spectrometer solenoid was changing the shield and connector material from 6061-T6 aluminum (RRR = 1.6) to annealed 1100-O aluminum (RRR = 25) [14]. A second factor that improved the shield temperature uniformity in the MICE spectrometer solenoid was distributing the cryocooler first-stage along the length of the magnet shield [14]. Having a more conductive shield meant that the shield had to be subdivided to reduce quench induced eddy currents and forces [15].

One can also reduce the temperature of the tops of the HTS leads when total lead current to the magnet is large by adding cooling from a single stage cryocooler that produces a large amount of cooling in the temperature range from 30 to 40 K [16]. This approach was used on the MICE spectrometer solenoid. This approach reduced the temperature of the copper plate to which the HTS leads were thermally connected, but it did little to reduce the shield temperature and cold mass support intercept temperature. Changing the material in the shield and the connection from the shield to the cryocoolers did far more that just adding more cooling to the copper plate that was connected to the shield and the HTS leads. Even when the copper plate to which the tops of the HTS leads are connected is at 40 to 50 K, one may have problems with the HTS leads. The copper leads from 300 K, the HTS leads, and the LTS leads that connect the HTS leads to the magnet are discussed in the next section.

COPPER CURRENT LEADS TO 300 K, HTS LEADS, AND LTS LEADS

Current leads can be and have been a problem for magnets cooled with cryocoolers. In most cases the current leads are in the cryostat vacuum space. The author of this report has been involved with projects where the copper leads, the HTS leads, and the LTS leads connecting the HTS leads to the magnet have failed or caused excessive heat flow into the cryostat.

Leads from 300 K to the tops of the HTS leads

The leads that go into a magnet from room temperature to the tops of the HTS leads are cooled only from the ends, because there isn't a source of gas for cooling. Wilson's book [17] discusses the design of conduction-cooled leads. The minimum heat flow down conduction-cooled leads is almost independent of the metal used to fabricate the leads. A conduction-cooled lead is optimized so that the net heat flow at the 300 K end is zero. When a conduction-cooled lead is operating at its optimum current I_o, all of the heat leaving the lead cold will be from resistive heating. At zero current the heat load down the leads is by conduction. The heat leak down a lead to the cryocooler first-stage can be calculated using the following expression;

$$Q_l = [L_o(T_R^2 - T_1^2)]^{0.5} I_0 \approx 3.6 \frac{k_B T_R}{e} I_0 \tag{1}$$

where Q_l is the heat leak down an optimum lead carrying a current I_o with an upper end temperature T_R (T_R = ~300 K.) and a lower end temperature T_1 (T_1 = ~50 K). L_o is the Lorenz number (L_o = 2.45 x 10^{-8} W ∧ K^{-2}); k_B is Bolzmann's constant; (k_B 1.38 x 10^{-23} J K^{-1}); and e is the charge of an electron (e = 1.6x10^{-19} coulomb). When the lead operates at I_o with T_R = 300 K and T_1 = 50 K, Q_l/I_o = 0.047 W A^{-1} per lead.

The other lead design issue is the I_oL/A function that relates the lead design current I_o to the lead length L_L and cross-section area A_c. One can calculate the IL/A for a current lead with a design current I_o by using the following approximate expression [18];

$$\left[\frac{I_0 L_L}{A_c}\right]_{opt} = j_0 L_L = \frac{Q_1}{I_0 \rho_{eff}} = \frac{1}{\sqrt{L_O}} \int_{T_1}^{T_R} \frac{k(T)dT}{\sqrt{(T_R^2 - T^2)}} \tag{2}$$

where L_L is the lead length; A_c is the lead cross-section area; j_o is the lead current density; ⟩(T_l) is the lead conductor resistivity at the bottom of the lead (at temperature T_l) and ⟩$_{eff}$ is the effective resistivity of the lead. It is clear that leads made from high RRR material (a pure metal) have a lower ⟩$_{eff}$, and as a result, leads will be longer. Leads that are made from pure metals (such as RRR = 300 copper) do not operate well when the current is even 20 percent over the design current. Low RRR leads are much shorter, and they can operate off their optimum current without much penalty [17].

The biggest problem with the leads that carry current from room temperature to the tops of the HTS leads is calculating IL/A. The problem was not knowing the properties of the materials used in the lead as a function of temperature. A number of magnets have been built, where the heat flow to the cryocooler first-stages was excessive. The evidence for this is heat flow from the room-temperature ends of the leads. If the upper end is above room temperature, the peak temperature in the lead will be even hotter, which increases the heat flow to the cryocooler first-stages. In general, one would like the leads to have an RRR between 5 and 10. Calculation of copper leads with an RRR = 10, show the IL/A = ~3.2 x10^6 A m^{-1} [18]. The original leads used in the MICE spectrometer magnets have had an IL/A = ~5.2 x10^6 A m^{-1}. The heat to the cryocooler first-stages was too high by almost a factor of 2 when the magnet was operated at its design current. At design current the tops of the copper leads were hot to the touch.

Copper leads and HTS leads were tested in an experiment that allowed the leads to be powered while cooling was being measured on both stages of a Cryomech PT415 pulse tube cryocooler [19]. When the experiment was run, we found that we got near optimum lead performance with copper leads with an IL/A of ~3.3 x 10^6 A m^{-1}. Resistances were measured for the copper leads, the HTS leads and the LTS leads in the system as a function of current. The temperature drop between the top of the HTS leads and the cryocooler first-stage was also measured. With the proper leads, the heat flow to the cryocooler first-stage was near optimum. The tops of the leads were at room temperature when the leads operated at design current. The resistance of all of the superconducting parts of the circuit showed that the circuit was superconducting.

HTS and LTS Lead Problems

The lead and cryocooler experiment illustrated the importance of reducing the temperature drop between the tops of the HTS leads and the cryocooler first-stages. During the course of testing MICE magnets, a number of the commercial HTS leads have burned out. Overheating at the top of an HTS lead is the cause of the failures. It was learned that HTS leads do fail. The magnet should be designed for the easy replacement of the leads. Problems that lead to HTS lead failures can be lumped into two categories: 1) heat transfer coming down the metal leads from room temperature to the first-stages of the cryocoolers must flow to the first-stages of the cryocoolers through layers of electrical insulation and 2) direct connection between the metal leads coming from room temperature to the tops of the HTS leads can be a problem that leads to added resistive heating at the top of an HTS lead. Connection of the LTS leads at the cold ends of the HTS leads can be a problem as well, but the added resistance usually doesn't cause an HTS lead to fail. The resistive heating at the cold of the HTS lead adds to the cold mass heat load.

The thermal connection between the metal leads coming from room temperature and the cryocooler first-stage cold heads is very important. In the lead cryocooler experiment we measured temperature drops from the tops of the HTS leads to the cryocooler first-stage cold head were as high as 14.3 K [19]. While this temperature drop is acceptable in most cases, reducing the total temperature drop to a few degrees is always better. The HTS leads will have a have a higher temperature margin if the warm end of the HTS lead temperature is lower. This may be critical when the HTS leads are in a magnetic field [9]. The heat from room temperature should be spread over a wide area and the heat should enter the system between the tops of the HTS leads and the cryocooler first-stage cold heads. The maximum current for a magnet lead pair should be less than 250 A for a two-stage cryocooler. If the shield area is large and the cold mass support intercept heat load is high, the maximum magnet current per lead pair should be lower for each two-stage cryocooler. Added cooling from a 30 to 40 K single-stage cryocooler can increase the allowable current for a two stage cryocoolers. Intercepting heat at liquid nitrogen temperature can also increase the allowable lead pair current for two-stage cryocooler. The use of liquid nitrogen and an extra single-stage cryocooler to intercept heat from room temperature can also cause problem.

The connection of resistive leads from 300 K and LTS leads from the cold mass to the ends of HTS leads has been a problem with leads made by certain manufacturers. Often commercial HTS leads do not have a large enough tab to make the connection. Both sides of the tab should be used to make the connection. The connection should be a soldered joint that is well clamped. The preparation of the solder joint is important to ensure there is a good low resistance bond. A manufacturer of BSSCO HTS-leads told us that the temperature of the solder used for lead connections should melt at <120 C [20]. This leaves out lead-tin eutectic solder (melting point 185 C), which makes low resistance joints that don't crack or peel [21]. The author has not tested any 120 C solder joints at low temperatures for electrical resistance or joint peel. The author recommends that one have adequate mechanical clamping in addition to the solder joint.

The connections from the magnet to the low temperature end of the HTS leads are made with LTS conductor. Unsupported sections of LTS conductor can quench due to conductor motion in a magnetic field [22]. Many of the LTS leads are in the cryostat vacuum, where there is no cooling except from the cold mass. LTS lead failure can occur when the conductor minimum propagation zone length is less than the unsupported lead length and when the conductor is not cryogenically stable. To avoid LTS lead failure, 1) the lead should be well supported so no motion occurs; 2) the minimum propagation zone length should be longer than the lead length; and 3) the LTS lead should be well cooled so that the temperature drop between the lead and the cold mass is less than the temperature margin of the LTS lead superconductor. Finally, the resistor and diode magnet quench protection system should be as close to the magnet coil as possible, in order to protect the magnet from any power lead failure [11].

THE NEED FOR CRYOCOOLER DATA AND GOOD TEMPERATURE MEASUREMENTS

Measured data of typical two-stage cryocooler performance is essential if one is going to understand how the magnet and cryocooler system works. Without cryocooler data, one doesn't know how much refrigeration has been applied by either stage of a two-stage cryocooler. Fig. 2 is an example of the kind of cryocooler data that is needed to determine whether the magnet is being cooled properly. For example, if a superconducting magnet isn't superconducting (the magnet temperature is above 9.4 K for a niobium titanium magnet) and the cryocooler second-stage is below 4.2 K, there is little or no cooling being transferred to the cryocooler second-stage. If there is liquid helium in the system, there should be a liquid level gauge. If the liquid level is dropping, either helium boil-off is occurring or the system is getting colder and the liquid helium is contracting (about 20 percent per degree from 3.7 to 4.7 K) as the magnet is cooling. If the system is open to the atmosphere and the liquid level is dropping, the heat leak exceeds the refrigeration from the cryocooler second-stages. A 1 atm. Helium gas-flow measurement can be used to determine the cooling deficit. If one is cooling down a magnet using a two-stage cryocooler, the diagram shown in Fig. 2 should be extended to higher heat flows to both the first and second-stages.

When one is determining the performance of the cooling system for a magnet, one needs accurate temperature measurement. Uncalibrated temperature sensors are a foolish waste of money (including installation effort). Temperature data that is not accurate to 1 percent is a waste of time and money. The author recommends the use of calibrated Cernox sensors below 25 K and calibrated platinum resistor sensors at temperatures above 25 K. The sensors should be mounted in copper discs that bring the incoming wire temperature to the temperature being measured. The discs should be screwed and be glued onto the object whose temperature is being measured. The only thing that is more useless than an un-calibrated temperature sensor is one that has become detached from the object whose temperature is being measured. If the cold mass has a helium vessel or piping that contains two-phase helium, a pressure sensor should measure the pressure within the helium vessel or pipe. A helium vessel should have a liquid level gauge that indicates the liquid helium level at the top of the helium vessel. Calculating excess heating by looking at the change of liquid level is less accurate than measuring the helium mass flow with a gas meter. The wiring for the temperature sensors should have a low thermal conductivity and a small diameter. In order to reduce the 4 K heat load, the wiring should be staged to the copper plate attached to the cryocooler first-stages. If possible, a small current (say ~1 mA) should be run through the superconducting coils as they are being cooled from 300 K to 4 K. A current passing through the coils allows one to measure the average coil-resistance, as the magnet is cooled-down from 300 K to 4 K. The cryostat vacuum pressure should be monitored.

Relief devices that leak should not be used. These devices tend to leak air into the cryostat at pressures below the surrounding atmosphere. The same type of device often begins to leak well before it reaches the relief pressure. The helium make-up circuit should be designed so that the make-up helium is pre-cooled to the cryocooler first-stage temperature before it enters the cryostat helium space. If one pre-cools the helium entering the cryostat, the cryocoolers may be able to liquefy the make-up helium.

CONCLUDING COMMENTS

The concluding comments for this report can be summed up in a number of statements, which are as follows:

1. Plan to use more cryocoolers not fewer cryocoolers. The number of cryocoolers needed to cool a magnet is often dictated by heat loads to the cryocooler first-stages rather than the cryocooler second-stages.
2. The cryocooler first stages should be run at a temperature around 40 K. The shield and cold mass support intercept temperature should be as close to the cryocooler first stage temperature as possible.
3. The shield and the interconnections between the shield and the cryocoolers should be made from alloys of copper or aluminum with RRR > 25. The shield should completely enclose the cold mass and the cold mass supports from the cold mass support intercepts inward, to eliminate 300 K radiation shine.

4. Good workmanship while applying the multilayer insulation is critical when using cryocoolers. The inside surfaces of the shield and the surfaces of the cold mass must have a low emissivity.
5. The IL/A of the current leads between room temperature and the tops of the HTS leads must be near the optimum value at design current.
6. The thermal connection between the bottom of the lead from 300 K to the cryocooler first-stages is important.
7. The magnet design should permit the replacement of HTS leads in the event of lead failure.
8. The LTS leads should be well cooled and have a minimum propagation zone length greater than the lead length.
9. Calibrated temperature sensors should be used on both the shield and the cold mass. It is recommended that the sensors be screwed and glued to the cold mass.
10. In order to find out what goes wrong with a magnet cooled using cryocoolers, the cryocooler performance should be measured for both stages (see Fig. 2). If the cryocooler will be used to cool down a magnet, the cryocooler performance on both stages should extend to temperature up to >100 K.

ACKNOWLEDGMENTS

This work was supported by the Office of Science of the United States Department of Energy under DOE contract DE-AC-02-05CH11231.

REFERENCES

1. Zabasnik, J., et al, “Tests of a GM Cryocooler and High Tc Leads for Use on the ALS Superbend Magnets,” *Adv. in Cryogenic Engineering*, Vol. 45B, Kluwer Academic/Plenum Publishers, New York (2000), pp 635-642.
2. Green, M. A., et al, “Design Issues for Cryogenic Cooling of Short Period Superconducting Undulators,” *Adv. in Cryogenic Engineering*, Vol. 49B, Amer. Institute of Physics, Melville, NY (2004), pp 783-790.
3. Green, M. A., “Cooling the MICE Magnets Using Small Coolers,” www.MICE.itt.edu, MICE Note 109 (2004).
4. Green, M. A., “Heat Transfer through a Multi-layer Insulation System as a Function of Pressure in the Cryostat Vacuum Space," *Adv. in Cryogenic Engineering*, Vol. 43B, Plenum Publishing Corp., New York (1998), pp 1313-1308.
5. Black, I.A., and Glaser, P.E., “Effects of Compressive Loads on the Heat Flux through Multilayer Insulations,” *Adv. in Cryogenic Engineering,* Vol. 11, Plenum Publishing Corp., New York (1965), p 26.
6. Green, M.A., and Yang, S.Q., “Heat Transfer into and within the 4.4 K Region and the 40 K Shields of the MICE Focusing and Coupling Magnets,” www.MICE.itt.edu, MICE Note 101 (2004).
7. Green, M.A., and Wang, S.T., “Tests of Four PT-415 Coolers Installed in the Drop-in Mode,” *Proceedings ICEC-22 in Seoul Korea*, (2008), pp 105-110.
8. Green, M.A., Chouhan, S.S. and Zeller, A.F., “Design Limitations on a Thermal Siphon 4 K Helium Loop for Cooling-down the Cyclotron Gas Stopper Magnet Coils,” *Adv. in Cryogenic Engineering*, Vol. 59, Amer. Institute of Physics, Melville, NY (2014), pp. 1543 – 1550.
9. Green, M. A., and Witte, H., “Using High Temperature Superconducting Leads in a Magnetic Field,” *Adv. in Cryogenic Engineering*, Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp 1251-1258.
10. Green, M. A., “The Effect of Magnetic Field on HTS Leads, What happens when the power fails at RAL?”, www.MICE.itt.edu, MICE Note 162, (2007).
11. Green, M. A., et al, “Protecting the Leads of a Powered Magnet that is protected with Diodes and Resistors,” *IEEE Trans on Applied Superconductivity* **22**, No. 3, p 4702204, (2012).

12. Choi, Y. S. et al, "Helium Liquefaction by Cryocoolers for High-field Magnet Cooling," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 665 -671.

13. *Handbook of Materials for Superconducting Machinery*, Metal and Ceramics Information Center, MIC-MB-04, National Bureau of Standards, Boulder CO, (1977), p. 4.1.1-2 and 5.1.1-2.

14. Green, M. A., Pan, H. and Preece, R. M., "Changes Made on a 2.7-m Long Superconducting Solenoid Magnet Cryogenic System that allowed the Magnet to be kept cold using 4 K Pulse Tube Coolers," *Adv. in Cryogenic Engineering*, Vol. 59, Amer. Institute of Physics, Melville, NY (2014), pp. 1551-1558.

15. Green, M. A., and Virostek, S. P., "Using a Single-Stage GM Cooler to Augment the Cooling of the Shields and Lead of a Magnet Cooled with Two-Stage Coolers," *Adv. in Cryogenic Engineering*, Vol. 57, Amer. Institute of Physics, Melville, NY (2012), pp 589-596.

16. Pan, H., "Eddy-currents and the Force Analysis for the Thermal Shields of a Superconducting Solenoid with Separately Powered Coils," www.MICE.itt.edu, MICE Note 420, (2013).

17. Wilson M. N., *Superconducting Magnets*, Oxford University Press, Oxford UK (1983)

18. Wang, L., et al, "Design of Current Leads for MICE Coupling Magnet," co-authored with L. Wang, L. K. Li, H. Wu H, H. Pan, F. Y. Xu, X. K. Liu, and L. X. Jia, *Proceedings International Conference of Cryogenics and Refrigeration* **22**, Shanghai China, (2008), pp 347-350.

19. Green, M. A., and Wang. S. T., "Test of Copper and HTS Current Leads with a Two-Stage Drop-in Cooler," *Adv. in Cryogenic Engineering*, Vol. 57, Amer. Institute of Physics, Melville, NY (2012), pp 581-588.

20. Private communication with HTS-110 concerning the soldering of their standard HTS leads to the LTS leads at the cold end and the copper leads at the warm end.

21. Wu, H., "Resistance and Strength of Soft Solder Splices between MICE Coil Conductors," *Transactions on Applied Superconductivity* **21**, No. 3, (2010), pp 1738-1741.

22. Green, M. A., "What Caused the Lead Burnout in Spectrometer Magnet 2B," www.MICE.itt.edu, MICE Note 324, (2010)