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The connection of refrigeration to a superconducting magnet with a minimum amount of cryogen

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Abstract. The shortage of helium, particularly liquid helium, has made the use of cryogen free magnets attractive. The attractiveness of cryogen free magnets depends on the operating temperature of the magnet, the distance from the cold head to the magnet being cooled, the thermal conductivity of the connection and the size of the magnet being cooled down. Connecting a cold source to something being cooled can be like connecting a vacuum pump to a magnet through a pipe. This paper discusses cooling down and cooling a magnet that operates over a temperature range from 4 K to 80 K using coolers. Two approaches are discussed. The first is by conduction through high thermal conductivity metal straps. The second is by using a natural convection thermal-siphon cooling loop. The thermal siphon cooling loop can operate like a cryogen free magnet where all the fluid is stored in the cooling loop.

1. Introduction

The cooling and cooling down of cryogenic superconducting magnets using a liquid-cryogens was the norm fifty years ago. The technique used required that the liquid cryogen be delivered to the bottom of the tank as far away from the vent as possible. This allowed the sensible heat as well as the latent heat of vaporization to be used in the cooling process. When liquid nitrogen was used to cooldown a magnet from 300 K to 80 K, one had to make sure that there was no liquid nitrogen left in the tank before liquid helium was used to finish the cooldown, because the nitrogen would freeze. A common method used to ensure that there was no nitrogen left in the tank was to measure the magnet resistance. The resistance of a Nb-Ti magnet is determined by the resistivity of the copper and the copper to superconductor ratio. The high residual resistivity copper ($RRR > 30$) goes down in resistance by a factor of about eight between 300 K and 77 K. As a rule of thumb, the liquid nitrogen cooling is stopped when the magnet or copper coil resistance goes down a factor of five or six. One waits about one diffusion time constant and then circulates warm helium gas in the tank from the bottom before pumping on the tank to remove the gas. Once the magnet temperature is stabilized at a temperature above 85 K or so, the remainder of the cooldown could be done using both the sensible and the latent heat in liquid helium.

When a superconducting magnet is cooled using a refrigerator that supplies helium gas under pressure, the route the helium gas takes around the superconducting magnet during a cool-down must be such that most of the sensible cooling in the helium gas is used [1]. The technique often used involved taking the helium gas leaving the cryostat and by-passing the cold box and returning the gas to the intake



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of the refrigerator compressor [2], [3]. As the thin detector solenoids were developed, large quantities of liquid helium within the magnet cryostat were eliminated. Forced cooling with helium in tubes became the norm. Both supercritical helium cooling and forced two-phase helium cooling have been used. Forced two-phase cooling results in a lower magnet temperature without the use of helium pumps to circulate the helium through the tubes attached to the magnet [4], [5]. Large detector magnets can be cooled using natural convection thermal-siphon cooling-loops [5].

This paper is restricted to the cooling and cooling down of magnets using coolers that don't supply a stream of cold helium gas for cooling down a magnet. Two methods of cooling are described. They are; conduction cooling from the magnet being cooled to the cooler cold head (the so-called cryogen-free cooling method) and connecting the cooler cold head to the magnet being cooled using a natural convection thermal siphon cooling loop. Both methods have been used to cool and cool-down of superconducting magnets

2. Conduction cooling a cryogen-free magnet

Cryogen-free magnet superconducting magnets are usually connected directly to the cooler cold-heads. This approach works when the magnet is small enough that thermal contraction is not a problem. The connection of a cooler head to the load being cooled often requires a flexible high-thermal conductivity strap so the effects of differential thermal contraction can be accommodated without excessive force on the cooler or the magnet being cooled. There will always be a temperature drop ΔT_1 across strap between the cooler cold-head and to the place on the magnet being cooled where that strap is connected, because there is heat flow from room temperature into the magnet that is cold. There will always be a temperature drop ΔT_2 between the hot spot within the magnet being cooled and the place where the strap is connected to the magnet. The acceptable temperature drop $\Delta T_A = \Delta T_1 + \Delta T_2$. The acceptable value of ΔT_A depends on the operating temperature of the magnet. When a magnet is at 4.5 K, ΔT_A can be from 0.2 to 0.5 K. At 20 K, ΔT_A might be between 0.7 K to 2 K. As one goes up or down in operating temperature, one can assume that ΔT_A is proportional to the operating temperature. When a magnet is cooled by conduction, ΔT_1 and ΔT_2 are often designed to have about the same value once the magnet has been cooled-down. During a cooldown, ΔT_1 and ΔT_2 may have very different values from one another.

2.1 Steady state cooling when the magnet is cold

The temperature drops during steady state cooling can be calculated without a computer for relatively simple shapes. Otherwise a code such as ANSYS can be used to estimate the temperature distribution within the magnet and the flexible strap connecting the magnet to the cooler cold-head. The conducting strap is usually a simple shape of length L_S and constant cross-section A_{CS} . The length of the strap for a magnet may be determined by the stray magnetic field from that magnet and the type of cooler used to cool the magnet [6], the HTS lead position [7], and needs for adequate cooler maintenance. The ratio of L_S/A_{CS} (given in units of m^{-1}) for a connecting strap at $T < 30$ K can be calculated as follow;

$$\frac{L_S}{A_{CS}} \approx \frac{k(T_{ave})}{Q(T_{cool})} \Delta T_1 \quad (1)$$

where Q is the cooler refrigeration at T_{cool} and $T_{ave} = T_{cool} + \Delta T_1/2$. $k(T_{ave})$ is the thermal conductivity of the strap OFHC copper at temperatures T_{ave} from 1 K to ~ 18 K. An expression for $k(T_{ave})$ is as follows;

$$k(T_{ave}) \approx 1.52 T_{ave} RRR \quad (2)$$

where RRR is the residual resistance ratio of the copper in the strap. For straps with $RRR = 50$, $T_{ave} = 4.3$ K, a cooler temperature $T_{cool} = 4.2$ K and, $Q(T_{cool}) = 1.5$ W, $L_S/A_C = \sim 43.6$ m^{-1} . If $L_S = 0.5$ m, then $A_{CS} = \sim 0.0115$ m^2 . The strap must be subdivided so that there is enough flexibility to prevent excessive stress on the cooler parts or the magnet. With the strap dimensions given, $\Delta T_1 = \sim 0.2$ K.

The calculation of ΔT_2 within a magnet more difficult, because the structures are more complicated and there may be several materials with differing thermal conductivity. The coil thermal conductivity differs depending on the direction. Coil thermal conductivity along the conductor is much higher. This

is illustrated in Figures 1 through 4 for the MICE experiment focusing and coupling magnets [9]. The four figures are ANSYS calculations of the steady state temperature in the MICE focusing and coupling magnets. In figures 1 and 2, the cooling is applied on a 100-mm wide strip on the outside of the magnet along its length. In figures 3 and 4, the temperature is uniform on the outer radial surface of the magnet. In all cases the temperature on the cooled surface is at 4.3 K, and the heat flow into the cryostat is evenly distributed on the magnet surface at the rate of 1 W m^{-2} . Both coils are solenoids wound with copper matrix MRI conductor (4 to 1 Cu to S/C ratio). The coils are surrounded by 6061-T6 aluminum shell.

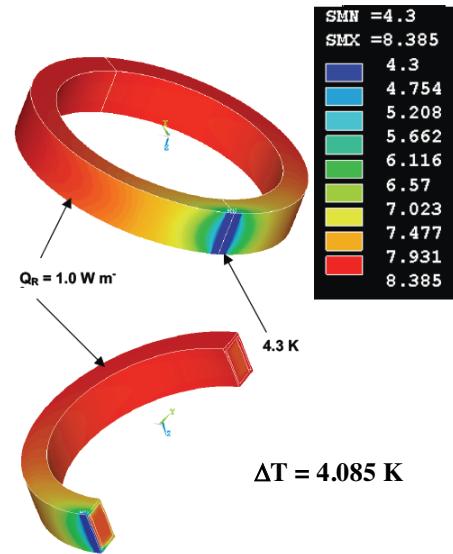
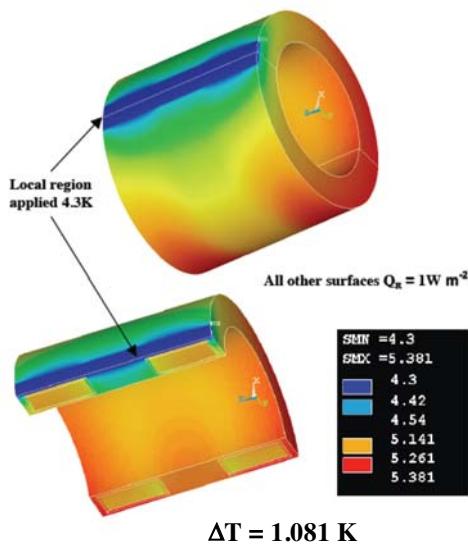


Figure 1. Temperature distribution in the MICE focusing coil with cooling on a single line. The coil area is 3.07 m^2 ; the coil average diameter is 0.62 m; and the cooling needed is 3.07 W.

Figure 2. Temperature distribution in the MICE coupling coil with cooling on a single line. The coil area is 4.31 m^2 ; the coil average diameter is 1.66 m; and the cooling needed is 4.31 W.

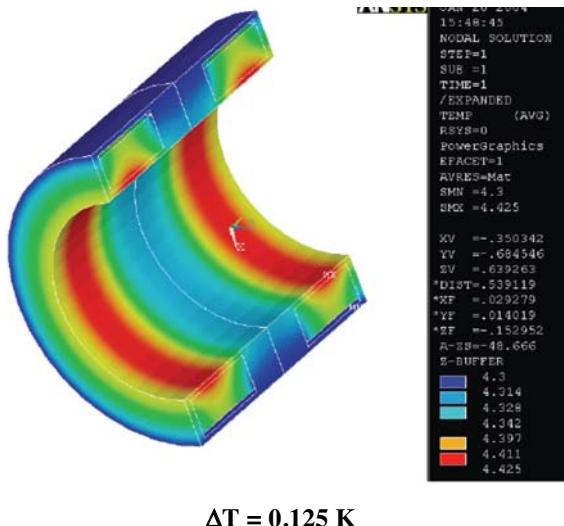


Figure 3. Temperature distribution in the MICE focusing coil with cooling on the single surface.

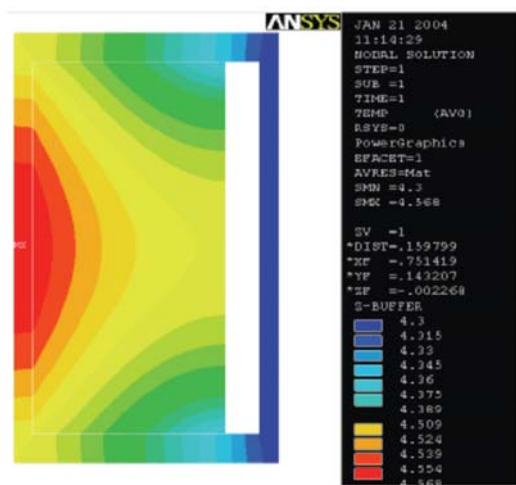


Figure 4. Temperature distribution in the MICE coupling coil with cooling on the outer surface.

Both magnets shown in figures 1 and 2 have temperature drops that are too large. In both cases the coil temperature drops are too large. The coil in figure 1 was designed to be cooled using two 1.5 W

coolers above the magnet coil. The coil shown in figure 2 was also designed to be cooled using two coolers. If the two coolers were 180 degrees apart around the coil, the value of ΔT_2 could be a factor of four lower. The cryostat design and the stray magnetic field didn't permit separating the cooler by 180 degrees. With the cooling in figures 3 and 4, the magnet temperature drops are acceptable. There is a lot to gain from distributed cooling on the magnet surface. If a magnet is long compared to its diameter the coolers should be distributed along the length of the magnet as well. The coolers near the ends should be close to the cold mass supports so that the support intercept is as cold as possible. The magnet shield should be made from a material that has a thermal conductivity that increases as one goes from 80 K to 35 K [9]. Materials such as OFHC copper and 1100-O aluminum have this property. This author recommends using an 1100-O aluminum shield. For a given shield mass, the shield will be much stiffer mechanically and the temperature uniformity is better. If the shield is coupled to the coils magnetically, the shield will have to be slit to prevent eddy currents from forming during a quench. The shield slits must be covered by aluminized-Mylar tape to prevent radiation leaks.

2.2 Temperature drops as the magnet is cooled down

Cooling down any magnet using a cooler or any other kind of refrigerator from 300 K to 4 K involves removing ~ 80 kJ of thermal energy per kg of the mass cooled. This is certainly true for superconducting magnets made from copper-based superconductor, stainless-steel, aluminum and the insulating materials found in magnets [10]. There is very little difference when cooling down to 20 K or 40 K. Ninety percent of the energy removed from a magnet is removed by the time the temperature reaches ~ 80 K. The thermal conductivity of copper from RRR = 20 to RRR = 200 changes only a little between 300 K and 80 K, so most of the energy is removed during a temperature range of relatively uniform thermal conductivity. The cooldown of a magnet by a cooler through a copper strap is controlled by ΔT_1 and ΔT_2 . ΔT_1 is proportional to the length of the strap L_S , the capacity of the cooler $Q(T_C)$, and it is inversely proportional to the strap cross-section area A_{CS} . ΔT_2 is controlled by the same factors. The cooling length within magnet divided by the heat transfer cross-section is of the same order as the strap. Except for small magnets and with a large cross-section, $\Delta T_2 = \sim \Delta T_1$ especially at the start of a cool-down.

If one assumes that ΔT_1 dominates the cool-down process, one can come up with an estimate of the cool-down cooler refrigeration $R(T_R)$ as a function of the cold head temperature T_R using the equation;

$$R(T_R) = \int_{T_R}^{T_D} k(T) dT \frac{A_{CS}}{L_S} \quad (3)$$

If one knows $R(T_R)$ and $k(T)$ as a function of T_R and T , one can solve the equation above interactively using a spread sheet program. It is clear from the equation above that increasing the cross-section of the strap is desirable from the standpoint of speeding up the cool-down. The effect of ΔT_2 within the magnet will increase the cooldown time by as much as a factor of two.

Figure 5 shows the k for RRR = 50 copper [10]. The k is linear with T to ~ 18 K and nearly constant between 18 and 30 K. k is nearly constant at $400 \text{ W m}^{-1} \text{ K}^{-1}$ from 80 K to 300 K. The thermal conductivity integral for RRR = 50 copper between 80 K and 300 K is about 88000 W m^{-1} . From 4 K to 80 K, the thermal conductivity integral is about 67000 W m^{-1} . When RRR = 150, the thermal conductivity integral from 80 to 300 K is about 95000 W m^{-1} , and the thermal conductivity integral from 4 to 80 K is increased about a factor of two to 180000 W m^{-1} . If the strap is designed for RRR = 150 at 4 K, the strap area is reduced a factor of three for a given value of ΔT_1 .

Figure 6 shows the cooling on the both stages of a Cryomech PT-415 cooler as a function of temperature on both stages [11]. When one looks at figure 6, one can see the refrigeration delivered by a PT415 cooler second stage is nearly linear with temperature from 4 to 85 K, when there is 40 W delivered to the cooler first stage. At second stage temperatures above 85 K, the amount of refrigeration per degree rise of the cold head temperature decreases rapidly. A 300 K, PT415 the second stage can deliver about 150 W of cooling when a first stage temperature is 80 K. The measurement that were done by the author didn't include and second-stage temperatures above 85 K. When a cooler like the PT415 is turned on to cool-down a magnet, the shield and intercepts are being cooled down at the same time.

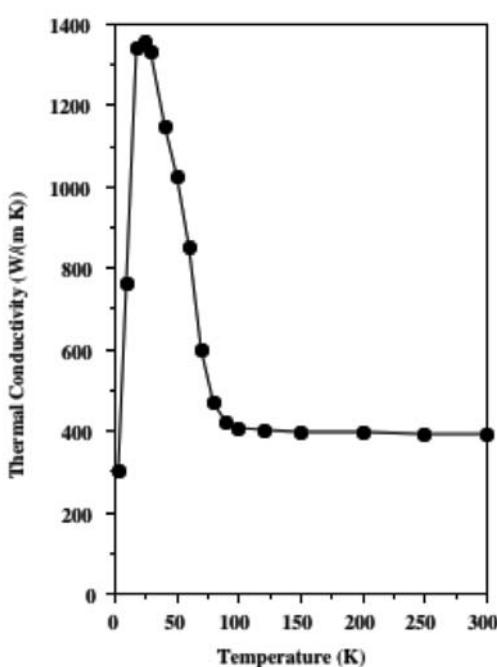


Figure 5. The thermal conductivity of RRR=50 copper from 4 K to 300K.

The cooling within a magnet is by diffusion [12]. The thermal diffusivity $\alpha = k(T)/c(T)$ (given units of $\text{m}^2 \text{ s}^{-1}$), where $k(T)$ is the thermal conductivity as a function of temperature and $c(T)$ is the specific per unit volume as a function of temperature. At 4.5 K, $\alpha = 390 \text{ m}^2 \text{ s}^{-1}$ for copper and only $0.089 \text{ m}^2 \text{ s}^{-1}$ for 304 stainless-steel. At 300 K $\alpha = 11.4 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ for copper and $0.40 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ for 304 stainless-steel. The primary direction for heat flow is along the coil windings where the thermal diffusion is the highest. ΔT_2 is proportional to the diffusion time along the coil. For heat to diffuse half way around a 1.66 m diameter coil that is 64 percent copper, will take ~ 20 hours. The diffusion time to the edges of the magnet package will be about the same, given the materials the rest of the magnet is made from. For a large conduction cooled magnet, ΔT_2 can be quite long, which is why a magnet immersed in liquid nitrogen takes a long time to cool-down to 80 K.

3. Cooling a superconducting magnet with thermosiphon cooling

Figures 3 and 4 show the advantages of distributed cooling. Thermosiphon with a small amount of liquid cryogen in tubes has several advantages over conduction cooling. These are: 1) The coolers can be much farther from the magnet being cooled or cooled down. The cooler can be away from magnetic fields and it allows cooler vibration to be isolated. 2) To first order ΔT_1 during normal operations is independent of the distance from the cooler to the magnet, if the cooler is physically above the magnet. At 4.2 K, ΔT_1 is < 0.1 K. At liquid hydrogen temperatures ΔT_1 can be < 0.2 K. 3) More heat per unit area can be transferred through tubes than through copper straps. 4) A thermosiphon circuit can have drop-in coolers, which can simplify shipping and maintenance. 5) Multiple coolers can share the same flow circuit. 6) Thermosiphon cooling can cooldown the circuit and liquefy the cryogen. 7) If the circuit volume is less than 5 L, all the cryogen can be stored in gas form some distance from the magnet. This means that closed cycle cooling heat transfer system can be used in along with the coolers.

The first magnet with a built-in thermosiphon was an ECR magnet fabricated in 2002. The original design called for the cooler cold head to be immersed in liquid helium. The heat transfer from the magnet to the cold head was poor. If a condenser was attached to the cold head so that helium boiled from the

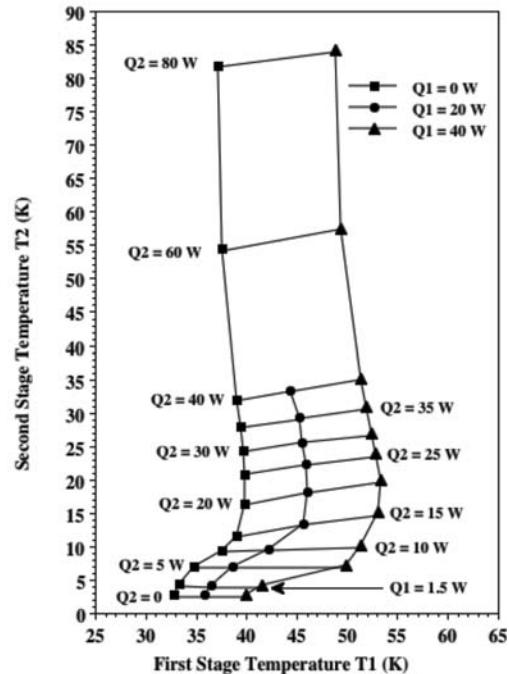


Figure 6. The 1st and 2nd stage temperatures as a function of the heat loads on these stages on a PT415 cooler.

magnet cryostat was re-condensed the temperature difference ΔT_1 between the cooler cold head and the magnet coil decreased greatly [13]. When one does an analysis of the process on finds that ΔT_1 is the sum of the nucleate boiling temperature drop [14] and the temperature drop in the condenser [15]. For ΔT_1 to be about 0.09 K for boiling liquid helium and condensing helium gas, the heat flux into the condenser should be less than 50 W m^{-2} and the heat flux boiling the helium on the magnet surface should be less than 4 W m^{-2} [16].

Because coolers were to be used on the MICE experiment, LBL in conjunction with Wang NMR Inc. did a series of experiments with drop-in PT415 coolers. We chose a drop-in configuration so that the coolers could be shipped separate from the magnets to the United Kingdom from the United States. It was understood that operating the PT415 cooler in the drop-in mode, one would reduce the effective refrigeration from the cooler by ~ 10 percent. A series of tests were run on a test facility at Wang NMR. Two of the three configurations tested are shown in Figure 7. In the configuration on the left, the make-up helium was injected below the top plate of the cooler so that the sensible heat could be removed from the gas from the cooler tubes and the cooler first and second-stages. In the configuration on the right, the make-up helium was injected into the helium tank without pre-cooling. The configuration on the left cooled down the tank and liquefied helium into the tank. The configuration on the right, which is a standard re-condenser system, cooled the tank and the gas in the tank, but it was at a slower rate than the configuration on the left. No liquid helium could be liquefied.

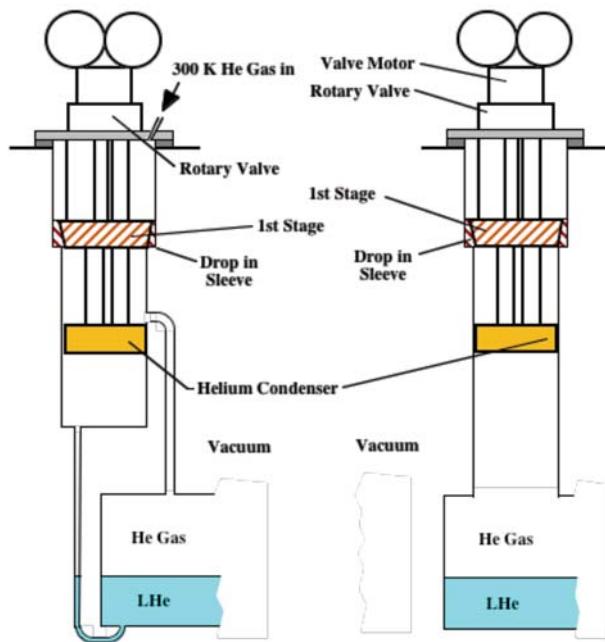


Figure 7. Drop-in cooler systems. The system on the left permits a magnet to be cooled-down using a thermosiphon cooling loop. The system on the left will liquefy He gas at room temperature. On the right is a standard re-condenser. This system will re-condense He and thus provide cooling to the magnet. The re-condenser on the right will cool-down a magnet, but it is not very efficient. The system on the right won't liquefy He gas at room temperature [17]

The thermosiphon configuration on the left was not used on any of the MICE magnets, because liquid nitrogen was used to pre-cool the magnets to 80 K. It is difficult to remove nitrogen from the tube going into the bottom of the tank. If one is going to use nitrogen to precool a magnet, the nitrogen must flow in a separate tube. The construction of a full-blown thermosiphon cooling loop that allowed the magnet to be cooled-down with coolers didn't happen until the Michigan State University cyclotron gas-stopper magnet was fabricated between 2012 and 2014 [18]. Efficient cooling with a thermosiphon helium loop was demonstrated on the LBL ECR magnet in 2003, but cooling-down 2.5 metric tons of cold mass with coolers and a cooling loop was not demonstrated until 2014.

Much of the MSU magnet and its cooling system was designed and fabricated before the decision was made to cool-down the magnet using the coolers. The gas-stopper magnet cryostat was very tight around the magnet coil package. Instead of large passages there were small passages with a lot of momentum jumps. In the process of analyzing the operation of the cooling system we came up with

recommendations that can be passed on to others who want to cool a magnet using a cooling loop. From the MSU experience loop cooling experience, we offer the following comments [18]: 1) The flow channels in the magnet should be open without changes in channel area. This permits one to increase the free convection flow through the magnet during the cool-down. The mass flow per unit cross-section area must be as low as possible [19]. 2) Increasing the pressure in the flow circuit increases the gas mass flow through the coil and reduces the cool-down time. We recommend that the system design pressure be increased up to at least 0.4 MPa. This means that any bellows in the system must be able to operate at pressures above 0.4 MPa. 3) When multiple coolers are being used to cool-down the magnet, each cooler circuit must have the same flow resistance. If the cooler circuit flow resistances are not equal, the cool-down time will be longer. 4) Precooled make-up helium must be injected into the manifold going to all the cooler condenser heat exchangers. This decreases the time that it takes to fill the system with liquid helium produced by all the coolers.

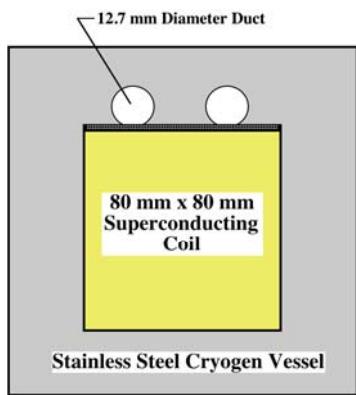


Figure 8. The cross-section of a 1250 kg coil with two 12.7-mm diameter cooling tubes

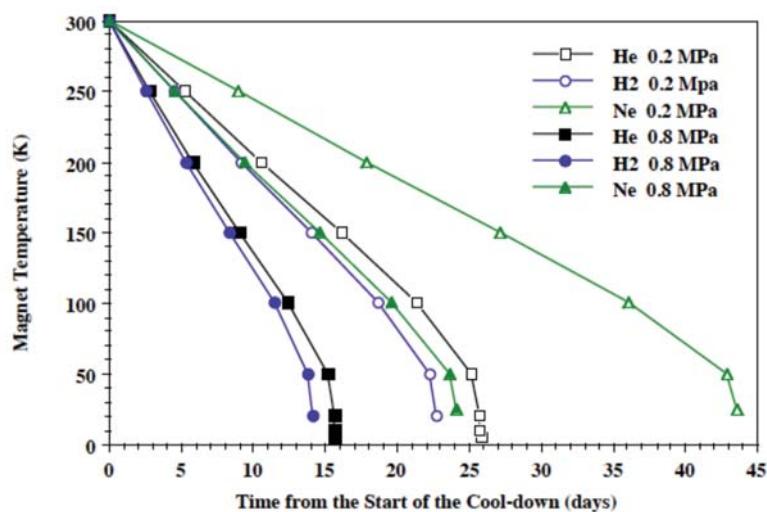


Figure 9. Calculated temperature versus time for the cool-down of a 1250 kg coil using a PT415 cooler. The loop gases are He, H₂ and Ne at loop starting pressure of 0.2 and 0.8 MPa.

Thermosiphon cooling loops can be used with other gases. We have looked at cooling loops with He, H₂, Ne, and N₂ as the working gas in the cooling loop. [16], [19] and [20]. Figure 8 shows the cross-section of a coil that is 2.4 m in diameter with a cold mass of 1250 kg. The cooling tubes are 12.7 mm in diameter. Figure 9 shows the temperature versus time for the coil cross-section shown in figure 8. Hydrogen is the best coolant despite its low density, because $C_p = 14200 \text{ J kg}^{-1} \text{ K}^{-1}$. It takes twice as long to cool-down a neon loop as a hydrogen loop with the same geometry and mass. Neon is the worst of the three coolants. The total volume of the liquid tubes around a 2.2-m diameter coil plus a liquid tube from the condensers to the magnet can be < 3 L. This gas can be stored in 900 L storage tank at a pressure of < 0.4 MPa. For gases such as hydrogen and neon one would like to store all the gas in the loop in a tank, when the loop is warm.

4. Concluding comments

Cryogen free cooling will work well for magnets that are small. The temperature drop from the magnet hot spot and the cooler cold head during normal operation is reasonable. Small magnets are relatively easy to cool-down with the coolers attached to the cold mass through a flexible strap. The cool-down rate of a conduction cooled magnet is often determined by heat transfer within the cold mass. Thermosiphon cooling loops can solve the temperature drop problem in large magnets. The cooling can be put uniformly on the outside surface of the magnet with liquid cryogen in tubes. The temperature drop between the cooler and the cooling tube on the outside of the magnet is almost independent of

distance. This allows the cooler location to be set by other factors besides the length of a copper strap. For a given temperature drop, more heat can be transferred through tubes in a cooling loop than through a copper straps. With proper design, magnets can be cooled down using a thermosiphon cooling loop. The liquid cryogen in the cooling system can also be liquefied by the coolers. In a helium system, one can reduce the helium inventory in the magnet cryostat. With good design the cryogen inventory in the magnet can be small enough to store in a room temperature tank, so there is no cryogen lost during a magnet quench or an accidental warm up of the magnet. This is important if hydrogen is used as a magnet coolant.

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