Connecting Coolers to Superconducting Magnets with a Thermal-Siphon Cooling Loop

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ABSTRACT

Coolers are used to cool-down and cool cryogen-free superconducting magnets and other devices that operate at temperatures from 4 K to 40 K. Coolers are also used to re-condense helium boil-off gas in superconducting magnet cryostats, such as for MRI and NMR magnets. There is an in-between case where a natural-convection thermal-siphon cooling loop is used to connect the cooler cold heads to the load being cooled and cooled down [1]-[3]. This case works well when the magnet is indirectly cooled by the coolant flowing through tubes attached to the magnet cold mass. A thermal-siphon loop fluid can work with fluids other than helium, which permits a magnet to be liquid-cooled (over the two-phase temperature range for the fluid) and thus ensure that the temperature variation within the magnet is minimized. For a flammable gas like hydrogen or a rare gas like neon, the loop must be prefilled and sealed at room temperature. A thermal-siphon loop will work when the coolers are remotely located from the magnet provided that the cold head heat exchanger is above the highest point in the magnet cryostat. This type of cooling system is used to cool and cool-down the 4 K cyclotron gas-stopper magnet at Michigan State University [4], [5]. Calculated cool-down times will be compared for a cooling loop between a cold mass of 1250 kg and a single Cryomech PT415 pulse tube cooler for the cases when the cooling loop is filled with helium, hydrogen, and neon for pressures of 0.2 MPa, and 0.8 MPa.

INTRODUCTION

In a typical cryogen free magnet, heat from the load is conducted to the cooler's or coolers' cold head through a copper or aluminum strap from the part of the magnet closest to the cooler. During the cool down and during normal operation there is a temperature drop ΔT_1 between the part of the magnet closest to the cooler cold head, and the cooler cold head. In addition, there is a second temperature drop ΔT_2 between the points on the magnet that is farthest from the cooler connection point to the cooler connection point. For a large magnet, ΔT_2 can be large [6]. The total $\Delta T = \Delta T_1 + \Delta T_2$ between the magnet and the cooler is directly proportional to the heat that can be taken into the cooler cold head and the conduction path length. The ΔT is inversely proportional to the thermal conductivity of the conduction path and the cross-section area of the path carrying the heat. For large 4 K magnets, this ΔT may cause the magnet to fail to reach its design goal.

When one cools a cryogen free magnet by conduction, the heat is conducted through a pure metal strap with a high thermal conductivity. The strap must be flexible to allow for thermal

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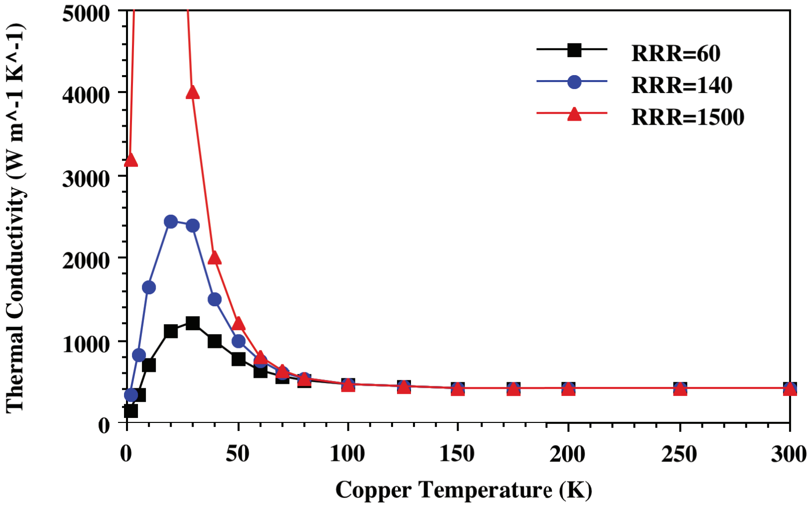

Figure 1. The thermal conductivity of three different annealed copper samples as a function of temperature and copper purity. RRR = 60 copper is 0.9995 pure. RRR = 140 copper is 0.9998 pure and annealed. RRR = 1500 copper is 0.99999. All three copper samples are very soft. Cold working will reduce the copper RRR and decrease the thermal conductivity.

contraction of the magnet being cooled relative to to the cold head of the cooler, which is usually fixed with respect to the cryostat vacuum vessel. To allow for movement, the pure metal strap is long and has a small relative cross-section. In general, the strap is made from a metal-like copper with a residual resistance ratio RRR greater than about 30. The RRR of a metal is dependent on the metal purity and the state of cold work. Figure 1 shows a plot of copper thermal conductivity as a function of temperature for three copper materials with an RRR = ~60, an RRR = ~140, and an RRR= ~ 1500 [7]. At temperatures above 80 K, the three materials have nearly the same thermal conductivity. Below 80 K, the thermal conductivity is different for the materials.

If one wants to calculate the heat flow Q through a strap of length L with a constant cross-section area A_c from temperature T_1 to temperature T_2 one can use the following expression;

$$Q = K_{1-2}\frac{A_c}{L}, \tag{1}$$

where an expression of K_{1-2} is as follows;

$$K_{1-2} = \int_{T2}^{T1} k(T)\,dT\,. \tag{2}$$

and $k(T)$ is the thermal conductivity of the strap material as a function of temperature T.

$K_{1-2,}$ the thermal conductivity integral (with units W m^{-1}), is an interesting function. For all of the copper materials between 80 K and 300 K, K_{1-2} is nearly the same. This is the region where a magnet has ninety percent of its heat capacity between zero and 300 K. For example, the RRR=60 copper has a K_{1-2} of 91,000 W between 80 K and 300 K, whereas the RRR=1500 copper has a K_{1-2} of 91,300 W m^{-1} over the same temperature range. In the low heat capacity temperature range from 5 K to 80 K, the RRR=60 copper has a K_{1-2} of ~63,000 W m^{-1}, but the RRR=1500 copper has a K_{1-2} of ~300,000 W m^{-1} over the same temperature range. For a copper with a high RRR at temperatures <80 K, one has a large thermal conductivity integral at low temperatures, but the heat removed is relatively small compared to the total heat that must be removed during the magnet cool-down. The thermal conductivity of a high RRR copper will degrade with the cold working of the metal over time. One should use a metal with a RRR>25 for magnet shields that are designed to operate at temperatures ~ 40 K, because the thermal conductivity of the metal is greater than a factor of two higher at 40 K than it is at 80 K [8], [9].

During a cool-down, this ΔT between the magnet and the cooler cold head determines the cooler cold head temperature, which in turn determines the amount of refrigeration that can be applied to the load being cooled down. The cool-down of a magnet with the cooling applied at a single point can be estimated with a spreadsheet. Iteration is required because the heat being removed from the magnet must be matched with capacity of the cooler as a function of the cold head temperature. With a two-stage cooler, the first stage cold head temperature has an effect on the cooling capacity of the second stage.

Even after the magnet is cooled-down, the temperature drop between the warmest place in the magnet and the cold head can have an effect on the operating temperature margin of the superconducting magnet. When the heat flow to the cooler is too large for a magnet with a low operating temperature, the magnet may not reach its design goal [6]. For this and other reasons, it is often desirable to use a two-phase natural-convection thermal-siphon cooling loop.

TWO-PHASE THERMAL-SIPHON COOLING LOOP

A two-phase thermal-siphon natural free-convection cooling loop spreads the cooling around the magnet when there is liquid cryogen in the tube. The temperature drop from the inner surface of the tube to the cold head of the cooler is very low for helium. If the heat transfer to the condenser is < 40 W per square meter, and the heat transfer boiling heat transfer of the tube inner surface is < 6 W m^{-2}, the ΔT between the magnet cooling tube is < 0.1 K for liquid helium at 4.2 K for flow circuits <5 m in length. For a liquid hydrogen system, the total ΔT is <0.2 K for circuits <5 meters in length. For circuits with neon or nitrogen, the ΔT is <0.5 K for circuit lengths <5 m. The ΔT between the cooled surface and the cold head is much lower that it would be for a RRR = 100 copper strap of the same length and cross-sectional area [10].

There are a number of other potential advantages of using a thermal-siphon cooling loop in place of a cooler solidly connected to a magnet as is the case in the typical cryogen-free cooling system. These advantages include: 1) There can be good vibration isolation between the magnet and the cooler. 2) One can use drop in cooler [11], which permits magnet shipment without the coolers and the coolers can be easily changed for maintenance while the magnet is cold. 3) For gases like hydrogen and neon, all of the needed gas can be contained in a sealed system for very low gas loss and enhanced (hydrogen) safety [12], [13] (a closed system rather than a system that is potentially open to the air). 4) Coolers can liquefy room temperature gas provided the gas is pre-cooled to remove as much of it's sensible heat as possible before the gas goes through final cooling and condensation [14], [15], [5]. Figures 2a and 2b show an open free-convection cooling loop and a closed free-convection cooling loop. Both types of cooling loops can be used to cool-down a magnet as well as keep the magnet at its desired operating temperature. A closed loop can be used with any cryogen, but it is essential to use a closed loop for hydrogen and neon. The open cooling loop was used for the cyclotron gas-stopper magnet at Michigan State University (MSU). The liquid helium volume in each cryostat is about 12 liters. In order to make the closed sealed system viable, it is useful to limit the amount of liquid cryogen in the loop to the 3 to 5 liters. The surge tank volume in Figure 2b is a function of the system liquid cryogen volume and the maximum working pressure of the surge tank. Figure 2b shows the surge tank inside if the cryostat vacuum vessel and the shield. This tank can be located outside of the cryostat vacuum vessel at any reasonable distance from the cryostat. The surge tank should be designed and fabricated in accordance with the applicable pressure vessel codes.

Experience with the MSU magnet showed the following [15], [16]: 1) The cool-down is faster if the magnet has open channels. The mass flow per unit area should be as low as possible for a rapid cool-down of a magnet. 2) When multiple coolers are used, the flow channels to and from each condenser heat exchanger must be identical, so that each cooler contributes the same amount of cooling to the cooling loop [15]. 3) A cooling loop system should be designed to have a working

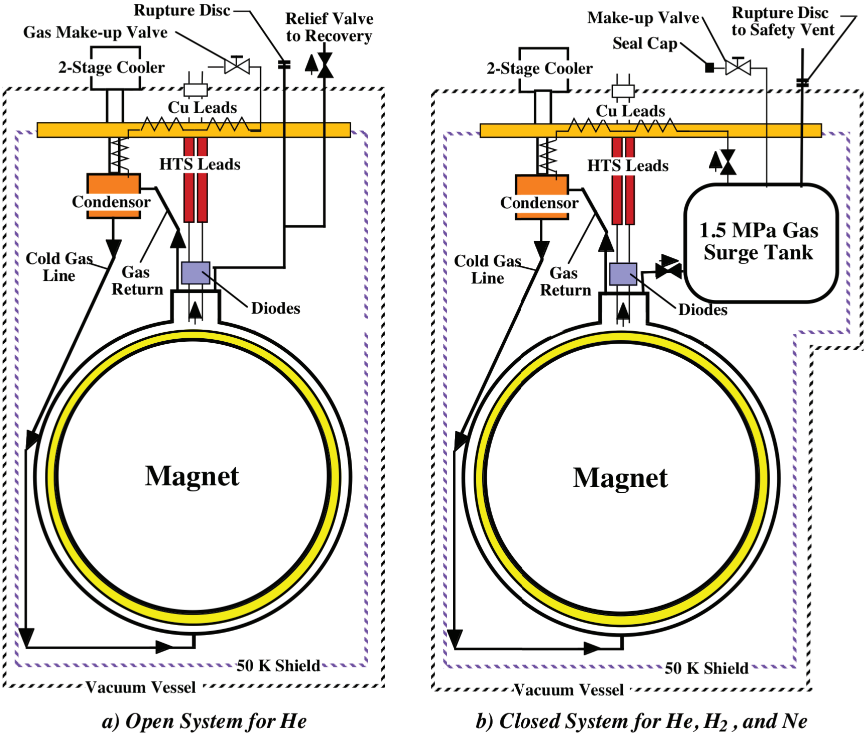

Figure 2. Open and closed two-phase, free-convection thermal-siphon cooling loops for use with cryogens such as helium, hydrogen and neon. Helium can be used in either an open loop or a closed loop. Hydrogen, a highly flammable gas is best used in a closed loop with the loop pre-charged and sealed. The tank and piping must be designed for a flammable gas. Neon is a very expensive gas, so it is best put into a closed sealed circuit to avoid loss of the gas.

pressure of at least 0.4 MPa. The bellows design pressure is important for achieving high cooling circuit operating pressures. High cryostat pressures during the cool-down will result is a shorter cool-down time, especially when the channel area is small [5], [16].

THE COOLER AND ITS PERFORMANCE AT ELEVATED TEMPERATURES

The Cryomech PT-415 pulse tube cooler (see Figure 3) was selected for the study of cooling loops using liquid helium from 4.2 to 4.7 K, liquid hydrogen from 15 K to 28 K and liquid neon from 28 K to 35 K. A PT415 cooler produces ~1.5 W of cooling on the second-stage with ~40 W of cooling on the first-stage. This cooler has been used for cooling superconducting magnets operating at 4.2 to 4.7 K. MSU is using six of the remote motor version of this cooler on the cyclotron gas stopper magnet. Six coolers are used to cool-down the two coils, but only four coolers are needed to keep the magnet at 4.3 K. The PT415 has been tested over a range of first stage and second stage temperatures [17], [18], [19]. This cooler will produce ~20 W at 20 K and ~40 W at 35 K with 40 W going into first-stage at ~52 K (see Figure 4).

COOL-DOWN CALCUATION FOR A MAGNET COOLING CIRCUIT

The author calculated the cool-down time using a spreadsheet program for a loop that has four channels from the bottom to the top. Each channel attached to the cold mass of 1250 kg is 3.8-meters long. The channels are round with an inside diameter of 12.7 mm. A magnet coil cross-section

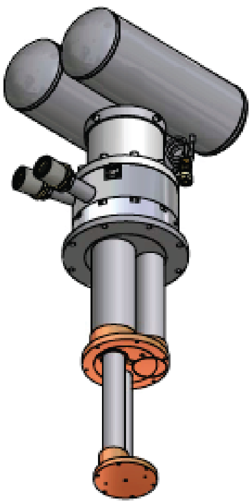

Figure 3. PT415 cold head [17]

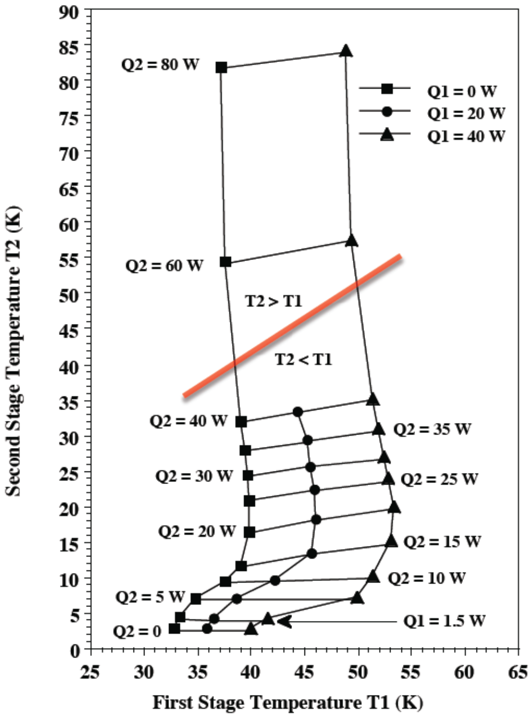

Figure 4. Performance curves for a PT415 cooler with zero to 80 W on the second stage and zero to 40 W on the first stage [19].

is shown in Figure 5. A single tube 4.0-meters long with an ID of 12.7 mm carries the fluid from the condenser heat exchanger to the bottom of the magnet. The tube leaving the top of the magnet and returning to the condenser heat exchanger has an ID of 25.4 mm. The total liquid volume in the magnet tubes and the tube from the condenser is about 2.5 liters, which is under the 3 to 5 liquid liters suggested for a sealed closed circuit system. If 0.5 m of the tube between the top of the magnet and the condenser contains liquid cryogen, the total cryogen in the system is ~2.8 liters. The heat transfer area within the condenser heat exchanger is 0.184 m^2. The surface

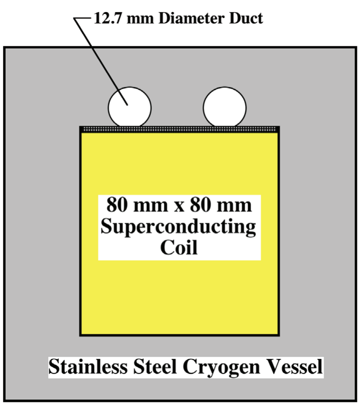

Figure 5. The superconducting coil cross-section with two 12.7 mm ID cryogen cooling-tubes. The flow area is 253.4 mm^2 and the inner surface area is ~0.62 m^2 [16].

area of the cooling tubes that are part of the cold mass is ~0.62 m^2. Cross-section area of the tubes in the magnet is 0.0002354 m^2. The tube from the condenser has a flow area of 0.00005885 m^2, and the cross-section are of the tube back to the condenser is the same as the four tubes carrying cryogen in the magnet coil.

The circuit is a free-convection circuit to get the circuit to flow the gas within the condenser durin cool down by the cooler cold head. The temperature of the cold head decreases rapidly until the cold dense gas begins to flow down the tube to the bottom of the magnet. Once the flow circuit starts to flow, the cold head temperature goes up because there is warm gas entering the condenser heat exchanger from the top of the magnet. This effect was clearly seen during the cool-down of the MSU cyclotron gas-stopper magnet coils [15]. Once the circuits start to flow the circuit continues to operate until the magnet is cooled-down and the cooler starts to liquefy the gas.

The rate of liquefaction is dependent on the excess refrigeration available. The MSU gas stopper magnet coolers were able to make about 6 liters a day of helium with about 1.2 W of refrigeration available to liquefy the helium. Each of the two coils in the cyclotron gas stopper magnet was cool-down using three PT415-RM coolers that can develop 1.35 W at 4.2 while delivering 36 W on the first stage at 40 K. Once the helium was liquefied in the magnet cryostat, one of the three coolers was turned of. Each coil was kept cold with two operating coolers. The MSU cyclotron magnet coils have nearly the same parameters as the coils in this study.

The magnet cool-down was modeled using a single PT415 cooler to cool-down 1250 kg of cold mass that consists of stainless steel, copper and about ten percent organic material. The total energy removed from the coils during the coil down from 300 K to 4.2 K (with helium gas) was 104 MJ. Slightly less energy was removed when cooling the cold mass to 20 K (with hydrogen gas) and 25 K (with neon gas). The cool-down calculations were done with a gas pressure of 0.2 MPa (about two atmospheres absolute) and 0.8 MPa (about eight atmospheres absolute). The object of the calculation was to determine the cool-down time as a function of the gas and a function of the gas pressure.

The cool-down time for a single PT415 cooler to cool-down a 1250 kg coil as a function of temperature is shown in Figure 6. From Figure 6, one can see that the cool-down is fastest when when hydrogen is used as a cooling loop fluid. This is true both at 0.2 MPa and 0.8 MPa. The cool-down was slowest when neon was the gas circulating within the loop.

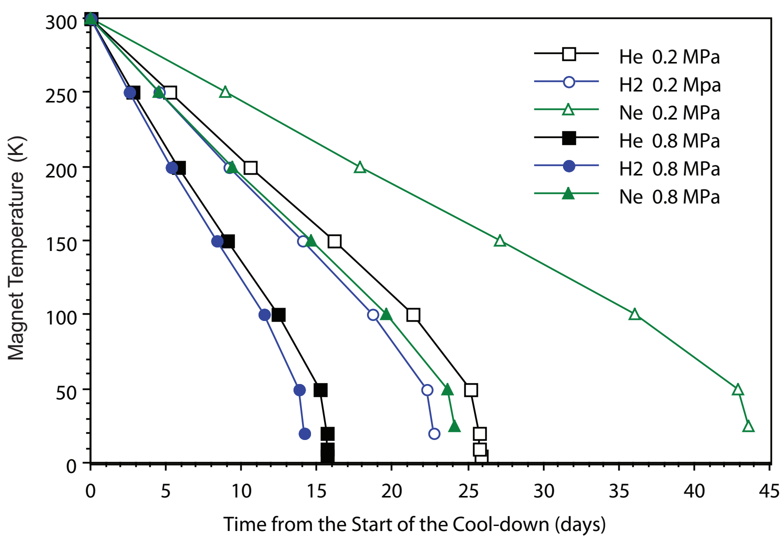

Figure 6. This figure shows cool-down time using a single PT415 cooler as a Function of temperature and loop Pressure for a single Loop with a mass of 1250 Kg using He, H_2 and Ne in the cooling loop. Helium is a black square; hydrogen is a blue circle and neon is a green triangle. Open data points are for the cases with a loop pressure of 0.2 MPa. Filled data points are for the cases with a loop pressure of 0.8 MPa.

Table 1. Properties of Helium, Hydrogen, and Neon [20]

Parameter	Cryogen		
	He	H_2	Ne
Molecular Weight	4	2	20.2
Gas Density @ STP (kg m^{-3})	0.1786	0.0893	0.902
Triple Point T (K)	2.17	13.81	24.6
Triple Point P (MPa)	0.0051	0.007	0.0423
Boiling T $T_{b\,at}$ 0.1013 MPa (K)	4.22	20.4	27.2
Liquid Density at T_b (kg m^{-3})	125	70.8	1212
Critical T (K)	5.19	32.3	44.4
Critical P (MPa)	0.221	1.292	2.710
Heat of Vaporization (J g^{-1})	20.9	442	86.0
C_p Liquid at T_b (J g^{-1} K^{-1})	~2.5	~9.8	~0.44
C_p Gas at T > $2T_b$ (J g^{-1} K^{-1})	~5.2	~14.2	~1.03
k_f Liquid at T_b (W m^{-1} K^{-1})	0.027	0.119	0.04
k_f Gas at T_b (W m^{-1} K^{-1})	0.011	0.021	0.014
μ liquid at T_b (kg m^{-1} s^{-1})	3.5×10^{-6}	1.3×10^{-5}	~7×10^{-5}
μ gas at T_b (kg m^{-1} s^{-1})	0.9×10^{-6}	1.1×10^{-6}	~4.3×10^{-6}

As seen in Table 1, hydrogen is a better working fluid than helium. The reason that hydrogen is better than helium is that its specific heat is 2.7 times the specific heat of helium. For a given amount of cooling. the mass flow of hydrogen is 36 percent of that of helium. A free convection loop is a balance between mass flow pressure drop and the driving force, which is proportional to density. Helium has twice the density of hydrogen, but this does not make for the advantage hydrogen has with respect to the mass flow.

Neon on the other hand has a specific heat that is a factor over a factor of five lower than helium. As a result, the mass flow must be at least a factor of five higher than for helium. The density difference between neon and helium is about a factor of five favoring neon. The momentum pressure drop is proportional the mass flow squared. The driving force is proportional to the density. While at low Reynolds number the friction factor can approach 1, but overall the pressure drop cut the flow of neon enough to make the rate of cooling about sixty-one percent of the rate of cooling for helium.

Increasing the pressure increases the rate of cooling almost a factor of two for all of the gasses. The loop pressure effect has been demonstrated experimentally at MSU [5]. Whenever a system is designed for free-convection cool-down, it is desirable to increase the pressure. For an open helium-cooling loop like the one shown in Figure 2a, it is desirable to set the maximum pressure to a least 0.4 MPa. For a closed cooling loop like that shown in Figure 2b, one should design the loop for higher pressure to keep the surge tank volume down to a reasonable size.

CONCLUDING COMMENTS

The cooling system for the MSU cyclotron gas-stopper magnet has shown that a low-temperature superconducting magnet can be designed to be cooled-down and be kept cold using small coolers. The liquid cryogen can be liquefied into the magnet cooling system by the cooler provided the warm gas entering the magnet cryostat is pre-cooled with liquid nitrogen and/or the first stage of the cooler, if the unit is a two stage cooler.

This paper shows that a magnet can be cooled-down and be kept cold using a cooling loop filled with helium, hydrogen or neon. For a rapid cool-down of the cold mass, it is best to use more than one cooler, such as the PT415. For cooling circuits containing hydrogen that can operate at 15 to 20 K or neon at temperatures from 26 to 30 K, one can use multiple PT415 coolers and use the first stages to cool the leads and shields. One can also use a single stage cooler such as the Cryomech AL-325 [21], [16] single stage GM cooler in the temperature range from 15 to 30 K to cool-down an MgB_2 or HTS magnet and liquefy hydrogen or neon in a closed loop. Both a PT415 cooler and an AL-325 cooler will go to temperatures below the triple point of para hydrogen and neon. A cold head of either of these coolers must be prevented from going down to the triple point temperature of either gas. If one uses an AL325 cooler, the leads and shields must be liquid nitrogen cooled. A single stage cooler can also cool and cool-down an MgB_2 magnet or an HTS magnet with helium gas in the loop. The maximum temperature in the cooling loop must be low enough to provide adequate temperature margin for the magnet.

Both hydrogen and neon must use a closed sealed loop. A hydrogen loop must be sealed to prevent the migration of hydrogen into air. A hydrogen loop must be designed with the appropriate safety systems and engineering design margins commensurate with the flammable-gas pressure vessel code. Closed neon loops must use a larger surge tank for a given liquid volume because its expansion ratio is over 40 percent higher than for either helium or hydrogen. A neon loop must be leak tight to avoid losing an expensive gas. In the view of this author, there is little to be gained from using a neon loop as compared to a hydrogen or helium loop. The cool down time for a neon loop is nearly double that of a hydrogen loop for a given mass being cooled down and a given cooler. Using helium in a cooling loop extends the cool-down time about ten percent over hydrogen. If an MgB_2 magnet can be operated in a helium gas cooled loop (with no liquid helium), there is almost no need for a cooled loop filled with hydrogen.

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