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Thermal Analysis of the ILC Superconducting Magnets

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ABSTRACT

Thermal Analysis of the ILC Superconducting Magnets. IAN ROSS (Rose-Hulman Institute of Technology, Terre Haute, IN 47803) JOHN WEISEND (Conventional and Experimental Facilities Department, Stanford Linear Accelerator Center, Stanford, CA 94025)

Critical to a particle accelerator's functioning, superconducting magnets serve to focus and aim the particle beam. The Stanford Linear Accelerator Center (SLAC) has received a prototype superconducting quadrupole designed and built by the Centro de Investigaciones Energticas, Medioambientales y Tecnolgicas (CIEMAT) to be evaluated for the International Linear Collider (ILC) project. To ensure proper functioning of the magnet, the device must be maintained at cryogenic temperatures by use of a cooling system containing liquid nitrogen and liquid helium. The cool down period of a low temperature cryostat is critical to the success of an experiment, especially a prototype setup such as this one. The magnet and the dewar each contain unique heat leaks and material properties. These differences can lead to tremendous thermal stresses. The system was analyzed mathematically, leading to ideal liquid helium and liquid nitrogen flow rates during the magnet's cool-down to 4.2 K, along with a reasonable estimate of how long this cool-down will take. With a flow rate of ten gaseous liters of liquid nitrogen per minute, the nitrogen shield will take approximately five hours to cool down to 77 K. With a gaseous helium flow rate of sixty liters per minute, the magnet will take at least nineteen hours to cool down to a temperature of 4.2 K.

INTRODUCTION

Particle accelerators, which hold the key to unlocking many of the universe's deepest mysteries, require a high energy, tightly focused beam in order to probe the sub-microscopic world. The International Linear Collider (ILC) is the next step in a long series of experiments attempting to gain a peek of insight into the universe's inner workings. This next-generation particle accelerator is still in its planning stages and is projected to be completed in the late 2010s. The 30 km long accelerator will smash electrons and positrons together at a collision energy of 500 GeV [1]. As with all accelerators, success of the planned experiments relies on the ability to precisely steer and focus the beams of particles as they are accelerated down the beamline. Magnets known as dipoles are used to steer the beam, while quadrupoles are used to focus the beam. As particles reach higher energies, the magnetic fields must increase in strength in order to keep the beam properly aligned. At the beam's highest energies, the quadrupoles in the ILC must produce a magnetic field of almost 6 T, requiring a current of 100 A [2]. In traditional electromagnets, a current this large would wreak havoc through Ohmic heating, the power dissipated when a current flows through a resistive wire. As a result, the magnets designed for use in the ILC will be cooled down to their superconductive temperatures. Superconducting materials are interesting in a number of ways. They offer no electrical resistance, giving them the ability to carry enormous currents without any loss. Additionally, superconductors have the unique property of being perfectly isolated from external magnetic fields [3]. There are, however limits to these properties. In addition to a critical temperature, there are also both a critical current density and field strength above which materials lose their superconductivity [4].

The cooling process is critical not only to the magnet but to the entire particle accelerator. The superconducting quadrupole built by the Centro de Investigaciones Energticas, Medioambientales y Tecnolgicas (CIEMAT) for the International Linear Collider (ILC) project has been brought to the Stanford Linear Accelerator Center (SLAC) in order to undergo a number of tests. The primary test will probe the produced field's magnetic center, to a precision of one micron. This center will be compared for a range of input currents, as the device was designed to be sufficiently versatile to be successfully used at all points in the beam line. As the input currents and the induced magnetic field increase, the magnet itself may significantly shift and deform due to internal magnetic stresses. A magnetic center that shifts substantially for different currents would imply that the magnet would not be suitable for use in every stage of the accelerator.

The focus of this study is to determine how best to cool the magnet to its cryogenic state. Thermal stresses must be kept to a minimum, in order to ensure safety of the magnet. The primary goal of the study is to determine reasonable estimates for cooling time, warming time, and the amounts of liquid nitrogen and helium to be used during the cooling process.

MATERIALS AND METHODS

General Setup

The quadrupole itself is composed of three concentric cylinders, with a bore through their centers. This axial hole is the tunnel through which the particles travel. The thin, innermost cylinder contains the turns of tiny superconducting ribbons of wire mixed with copper, embedded into an epoxy. Outside of this cylinder lies the iron yoke, whose function is to shape and strengthen the magnetic field produced by the current. The outermost shell is an aluminum compression ring; it maintains its shape, even as the iron and copper deform during the cooling.

The magnet is housed inside of a vessel, which is initially filled with liquid helium (LHe) through the bottom. After the vessel is filled, the bottom line is shut off, and the helium level is maintained by filling as necessary from the top. The rate of this filling process, and the corresponding cooling, are to be calculated. The area outside of this vessel is a vacuum, in order to reduce unwanted heat loss through convection. In order to gain administrative permission to use these vessels, it had to be shown that they comply with the American Society of Mechanical Engineers (ASME) pressure vessel codes [5] (see Appendix 1). Between the helium and vacuum vessels is a copper housing cooled by liquid nitrogen (LN_2). This shielding is designed to cut down on unwanted heating of the helium vessel via radiation.

Cooling of the Nitrogen Shield

The nitrogen shield, composed of copper, is conductively cooled by passing LN_2 through tubes wound around it. A method of energy balance was used to estimate the absolute least time necessary to cool the copper down to 77K, the temperature at which LN_2 boils. By equating the copper's heat loss with the LN_2's gain (in vaporization plus heating, ideally, back to room temperature) and assuming LN_2 flow rates, the time was computed using the following equation:

$$m_{copper} \Delta u_{copper} = \dot{m}_{N_2} \left[L_{N_2} + h_{N_2}(300K) - h_{N_2}(77K) \right] \Delta t \tag{1}$$

Where m_{copper} is the mass of copper, Δu_{copper} is the change in internal energy of the copper, $\dot{m}_{N_2}$ is the mass flow rate of the liquid nitrogen, L_{N_2} is the heat of vaporization for the liquid nitrogen, h are the enthalpies of the copper, and Δt is the change in time. The internal heat of the copper was calculated according to the Debye model:

$$u(T) = \frac{9R\Theta_D}{8} \left[1 + \frac{8T^4}{\Theta_D^4} \int_0^{T/\Theta_D} \frac{x^3 dx}{e^x - 1} \right] \tag{2}$$

where R is the material's gas constant, Θ_D is the material's Debye characteristic temperature, and T is the material's temperature. This model inherently considers the copper's changing thermal properties as its temperature drops [6]. Calculations of a similar type were repeated, with different N_2 exiting temperatures, slight heat leaks, and different flow rates. Heat leaks, or the amount of heat picked up by the vessel due to inherent imperfections, were included as a rate of heat loss times the amount of time taken for the cooling. Previous estimates not conducted in this study indicated a maximum heat leak rate of 20 W.

Warming of the Nitrogen Shield

Also of interest to us is the rate at which the nitrogen shield warms up after the LN_2 stops flowing. Should repairs or alterations be necessary to the shield, little work could be done at the low temperatures at which it functions. By calculating the amount of heat radiated into the vessel, we should be able to acquire a general feeling about how the shield is warming. Convection and conduction effects were not included in this calculation. The vessel is wrapped in 30 layers of multilayer insulation. As a result, the total radiation is passed through 31 transfers: from the shield to the first layer of insulation, through 29 insulation gaps, and from the last insulation layer to the walls of the vacuum vessels. The radiation transfer equation is calculated as:

$$T_2^4 - T_1^4 = \frac{\dot{Q}}{A}\frac{1}{\sigma}\sum\frac{1}{F_n} \tag{3}$$

where T_2 is the external temperature, T_1 is the internal temperature, $\frac{\dot{Q}}{A}$ is the rate of heat radiated between the surfaces per unit of area, σ is Boltzmann's constant, and F_n is the overall emissivity factor between two interfaces [6].

Cooling of the Magnet

The cooling process of the magnet is estimated in much the same way as that of the nitrogen shield. Again, a basic calorimetry calculation was done:

$$m_{magnet}c_{magnet}\Delta T_{magnet} = \dot{m}_{He}[L_{He} + h_{He}(300K) - h_{He}(4.4K)]\Delta t \tag{4}$$

where c_{magnet} is the magnet's specific heat and the other variables are defined in Eqn. 1 above. In order to calculate the cooling of the magnet, two factors must be taken into account. First, as mentioned above, the magnet is composed of three different materials: copper, iron, and aluminum. The thermal properties of each are very different. To compensate for these differences, the Law of Mixtures was invoked. The approximation of the entire magnet's specific heat is simply the sum of each component's specific heat times its volumetric fraction.

$$c_{magnet} = c_{Cu}\frac{V_{Cu}}{V_{total}} + c_{Fe}\frac{V_{Fe}}{V_{total}} + c_{Al}\frac{V_{Al}}{V_{total}} \tag{5}$$

where c represents each material's specific heat, V is each material's volume, and V_{total} is the total volume of the magnet.

The second factor to consider is the material properties' variation with regard to the material's temperature. In particular, specific heats tend to decrease at lower temperatures. In order to take into account these changes, the cool-down was broken into steps of temperature change, allowing use of a certain property value for each temperature interval. This calculation was done for a number of values for two key variables. First, the exit temperature of the helium gas was altered. Second, this value was held constant and the flow rate of the helium was varied.

RESULTS

Cooling of the Nitrogen Shield

Using Equation 2, we can estimate that the vacuum vessel, composed entirely of copper and weighing 39 pounds, will require 1,282 kJ of energy removal to cool to 77 K. The latent heat and enthalpy gain of liquid nitrogen vaporizing and heating back to room temperature can provide 432.3kJ per kg of N_2. Thus, $\frac{1{,}282kJ}{432.3\frac{kJ}{kg_{N_2}}} = 2.97kg$ of N_2 will be needed. With a conservative flow rate of 10 gaseous liters per minute, this would equate to 3.95 hours of cooling. A pump rate of 60 gaseous liters per minute reduces this cooling time to only 39.5 minutes.

With the estimated heat leak into the copper shield of 20W, the cooling time required increased to 5.06 hours at 10 gaseous liters per minute and 41.0 minutes for 60 gaseous liters per minute.

Warming the Nitrogen Shield

Solving Equation 3 for $\frac{\dot{Q}}{A}$, it is calculated that the vessel can only absorb 0.384 W$/m^2$ through radiation. For every second that goes by, the shield can gain 0.384 Joules of heat for each square meter of its surface area. This heat gain is minuscule, especially when compared to the heat required to warm from 77K to 300K (1,282 kJ, from the left hand side of Eqn. 1). The nitrogen shield will also gain heat through conduction through its supports and the various leads and pipes into the system, though no calculations were done in this study to estimate this heat flow.

Cooling of the Magnet

Using Equation 4, it was determined how long it will take the magnet to traverse intervals of temperature. In Figure 5, the estimated amount of time needed to reach a temperature was plotted for a number of different helium flow rates. The total amount of time to reach cool-down clearly depended on this flow rate, ranging from 5.95 hours for 200 gaseous liters per minute all the way up to 119 hours for 10 gaseous liters per minute.

Figure 6 was generated by varying the temperature at which the helium exits the system after vaporizing. A constant flow rate of 60 liters per minute (gaseous) was used. We would like the helium to heat all the way up to room temperature, sucking as much heat as possible away from the magnet. In this case, the magnet would take 19.8 hours to cool to 4.2K. If the helium leaves at only 5K, it would take nearly 50 days to cool. These results are summarized in Tables 1-3.

DISCUSSION AND CONCLUSIONS

Cooling of the Nitrogen Shield and Magnet

The results obtained from the simple energy balance are certainly logical, but it is difficult to determine whether or not they are in fact accurate without some sort of experimental verification. One may expect that the magnet, with significantly more mass and a required temperature of 4.2K, would take much longer to cool than the nitrogen shield. As anticipated, the results show that magnet will indeed take a much longer time to cool down.

It is interesting to note that the two coolants have surprisingly different properties. Compared to nitrogen, helium has a greater ability to pull away enthalpic heat as it warms to room temperature. To go from a saturated vapor to room temperature, it can absorb 1541.8 J/g, compared to nitrogen's 233.4 J/g. On the other hand, the helium takes very little energy away as it changes phase (only 20.7 J/g, compared to nitrogen's 198.9 J/g). [7]

It is clear that higher mass flow rates and higher fluid exiting temperatures mean a significant decrease in the amount of time necessary for cooling. The results obtained are expected and logical. They are also quite useful, as they provide us with an idea of what types of parameters will be needed to reach cool-down within a certain timeframe.

The graphs of the magnet's temperature against time reveal a key point about the cooling process of the magnet. Initially, the magnet will be slow to cool down. However, as it cools down, its specific heat decreases, allowing it to cool down more rapidly. This is what causes the distinct downward concavity of the curves.

Warming of the Nitrogen Shield

The thirty layers of superinsulation clearly impede the vessel's ability to warm back up, but they also keep the vessel from warming up when we want it cold. We would rather have the insulation then not for this reason. The vessel's heating rate will decrease further as it gets closer to room temperature, further slowing the warm-up process. At this rate, it could easily take days to heat up the system so that it could be worked on; a costly waste of time. It should be noted, however, that these calculations only include radiation effects. Conduction through the supports holding the shield in place, the leads, and the piping were not included.

Conclusions

A simple energy balance method was used to calculate the amount of time necessary to cool down the ILC superconducting quadrupole for a number of difference flow rates and helium exit temperatures. The graphs of temperature against time confirm our beliefs about how the magnet will cool. Cooling will be slow initially, then pick up substantially around 100K, due to the decrease in specific heat at lower temperatures.

Further studies would definitely be beneficial to the question of the model's accuracy. Applying a finite difference method was attempted, but as of the time of writing, the results were inconclusive. Accuracy of the model could be tested using a small, isolated experimental setup. By using LN_2 to cool a much smaller piece of material and monitoring its temperature using thermocouples, we could easily determine whether or not the model used was appropriate.

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APPENDIX 1: THE ASME PRESSURE VESSEL CODES

A secondary objective for my research this summer was to ensure that the vacuum and helium vessels meet the pressure vessel codes put forth by the American Society of Mechanical Engineers (ASME). The ASME codes provide a framework of calculations to ensure that vessels which are under pressure (be it external or internal) have sufficiently safe thickness, stiffness, axial strength, and reinforcement.

Materials and Methods

The American Society of Mechanical Engineers requires that all designed vessels under pressure meet its minimum safety requirements. In order to conduct the experiments, we had to show that both the vacuum and helium vessels were safe. The housings were treated separately, as different codes exist depending on whether the vessel is facing internal or external pressure. The codes were explicit in their direction, and were mostly straightforward.

The vacuum vessel was considered first. Because the inside of the tank is a vacuum, the codes for pressure vessels under external pressures were used (ASME Section VIII, Division 2, Part AD, Article D-3 codes were those being used). We had to first show that the walls of the cylindrical tank were thick enough to withstand the external pressure acting on it (atmospheric pressure), complying to code AD-310.1. The next requirement was to ensure that the flanges on each end of the vessel were sufficiently stiff to resist unwanted torques, meeting code AD-331. The axial compression code, AD-340, determines whether the vessel is compressed to a dangerous amount. Finally, we had to ensure that the opening for the top housing (see figure) was appropriately reinforced. The opening was treated as a large nozzle, which, due its size, fell under the special codes of UG-37. The only required internal pressure codes for the helium vessel were checking its wall thickness (AD-201) and the thickness of the endplates (AD-702) [5].

Results

The first code checked was that of the vacuum vessel's thickness. This calculation revealed that the thickness used was adequate to an external pressure of up to 162 *psi*, much greater than the atmospheric pressure it will face. The second code proved that the flanges provide a moment of 0.507 in^4, much greater than the necessary moment of 0.020 in^4. Next, the vacuum vessel would be able to withstand 12,600 *psi* of compressive stress. It is expect to face 300 *psi* at most. Finally, the large opening at the top requires 2.16 in^2 of reinforcement. The shell to opening wall shape itself provides 2.71 in^2 of support.

The thickness checks for the helium vessel showed that the thickness required was only 0.056", while 0.250" is the actual thickness. The lateral endcaps must have a thickness of at least 0.552" and the top endcap must have a thickness of 0.260". The actual thicknesses are 1.12" and 0.375", respectively.

Discussions and Conclusions

The calculations done for the ASME Pressure Vessel Codes clearly indicated that the vessels which house the magnet are more than safe in all the required ways. Their shell thickness, reinforcement rings, opening reinforcements, and endcap thicknesses all passed the requirements. Many of the dimensions of our vessels were, in fact, several times greater than that required. Considering this along with the inherent safety factors in the code, there is no doubt that the construction is sound. Pumping the outer vessel down to its vacuum state corroborated these findings: no problem of any kind occurred.

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FIGURES

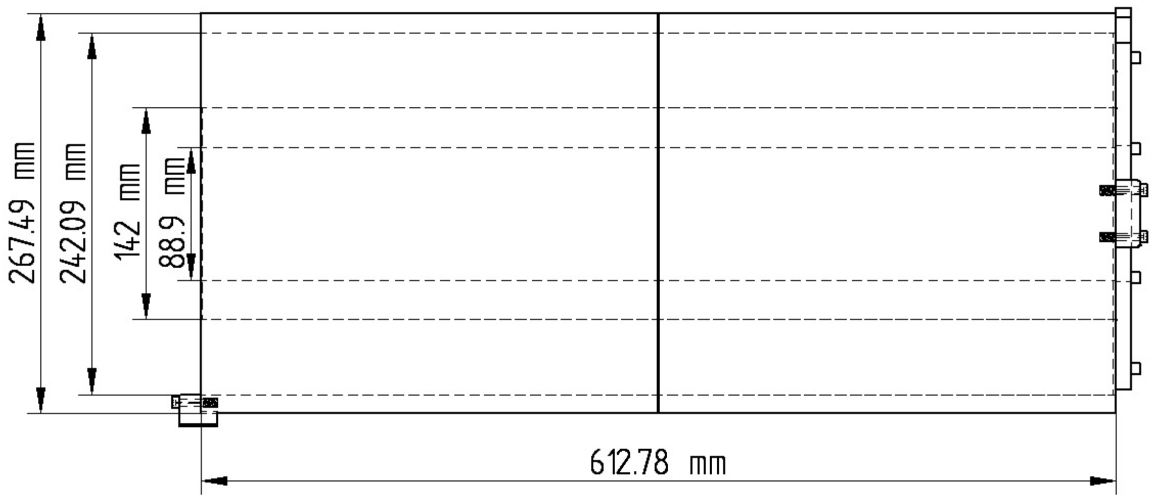

Figure 1: A schematic of the magnet, as viewed from the side.

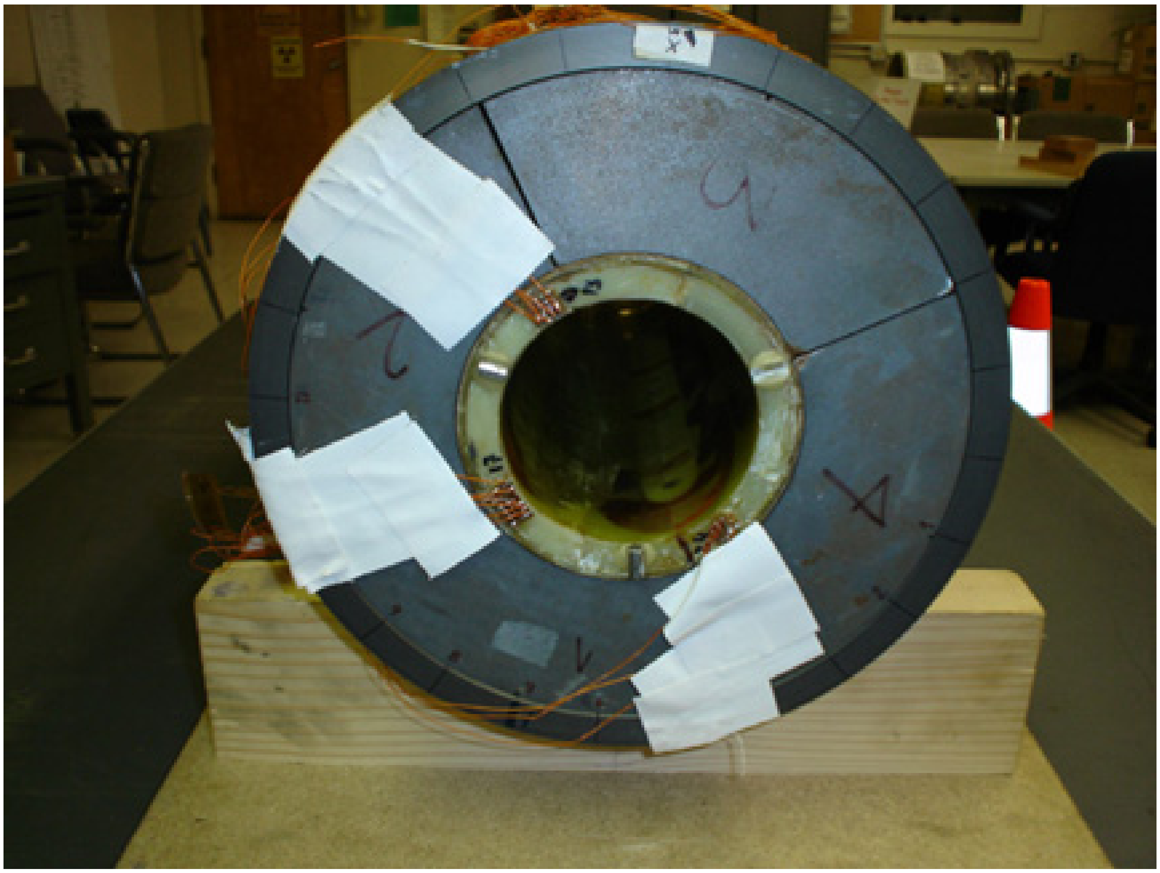

Figure 2: A photograph of the magnet. Note the inner layer of epoxy, with the embedded superconducting wires, the four quarters that compose the iron yoke, and the outer aluminum compression ring.

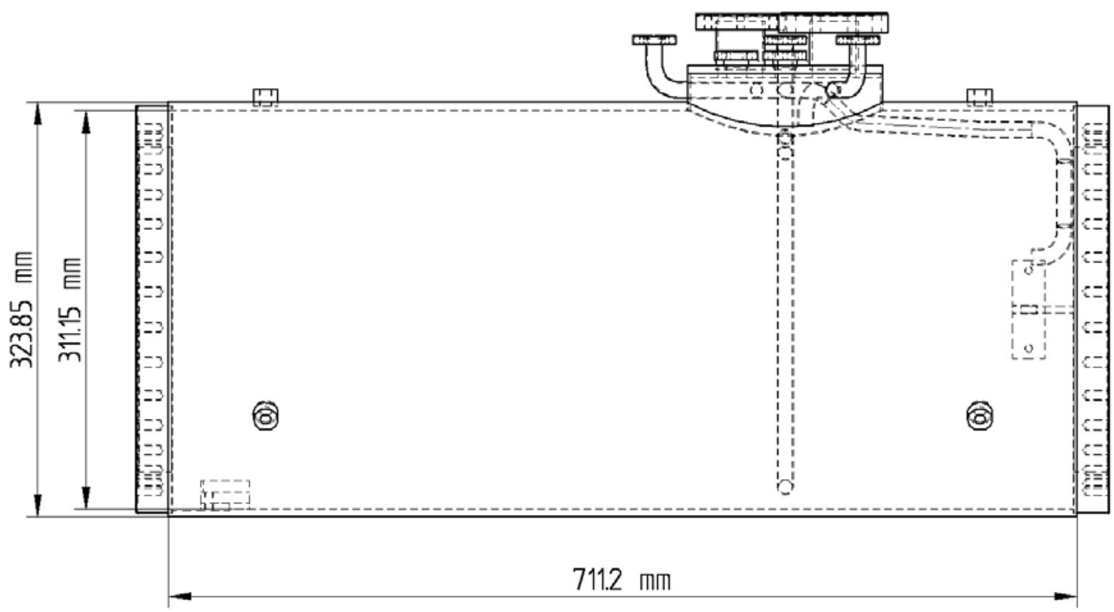

Figure 3: A schematic of the helium vessel, as viewed from the side. The magnet sits inside. LHe is pumped into the vessel via the bottom fill line until the vessel is full, at which point the level is maintained using the top fill line.

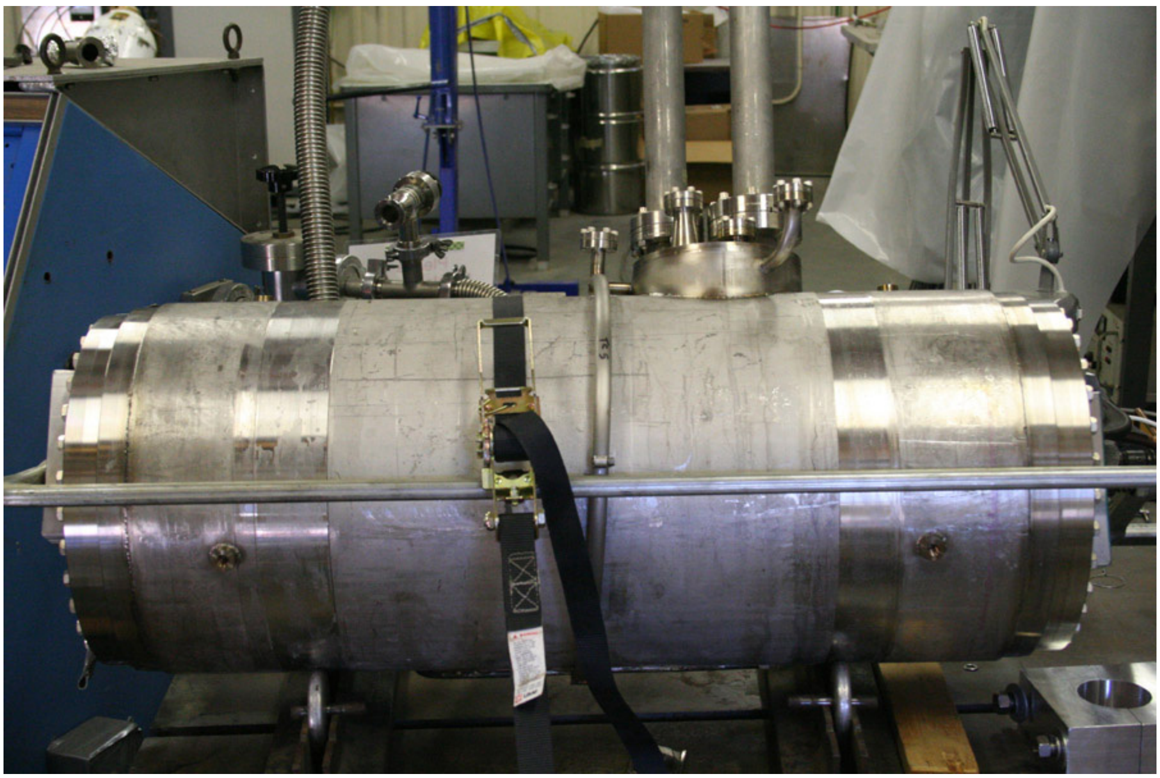

Figure 4: A photograph of the helium vessel.

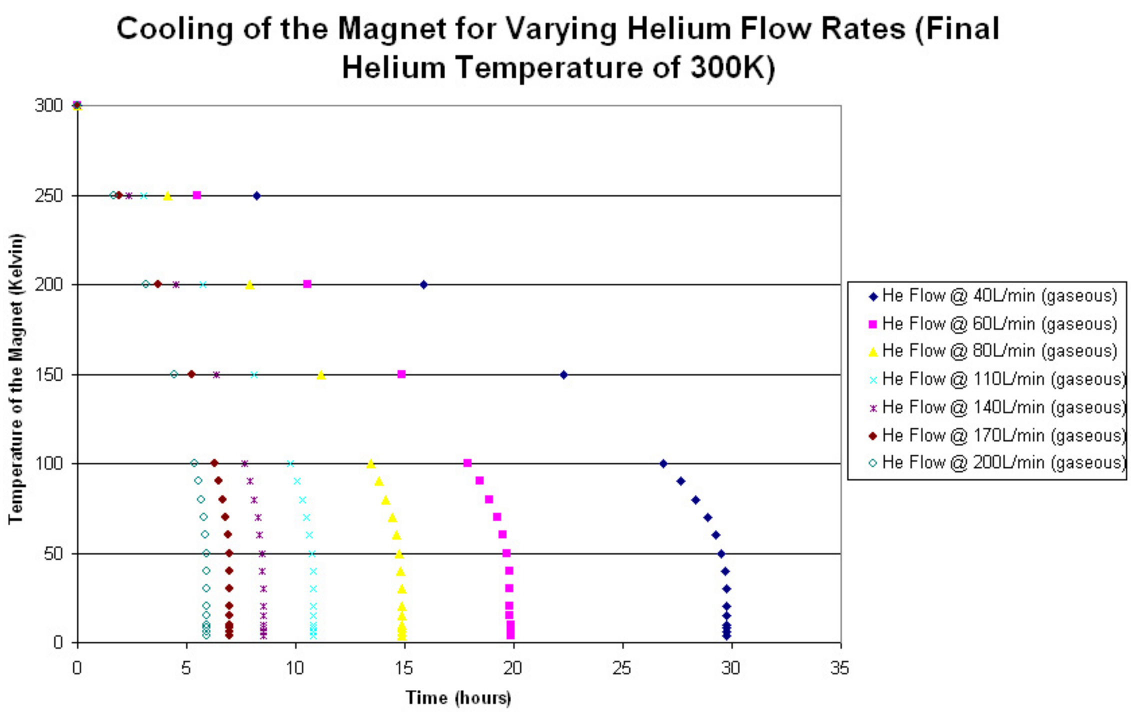

Figure 5: The magnet's calculated temperature in time, with varying helium flow rates with an exiting temperature of 300K.

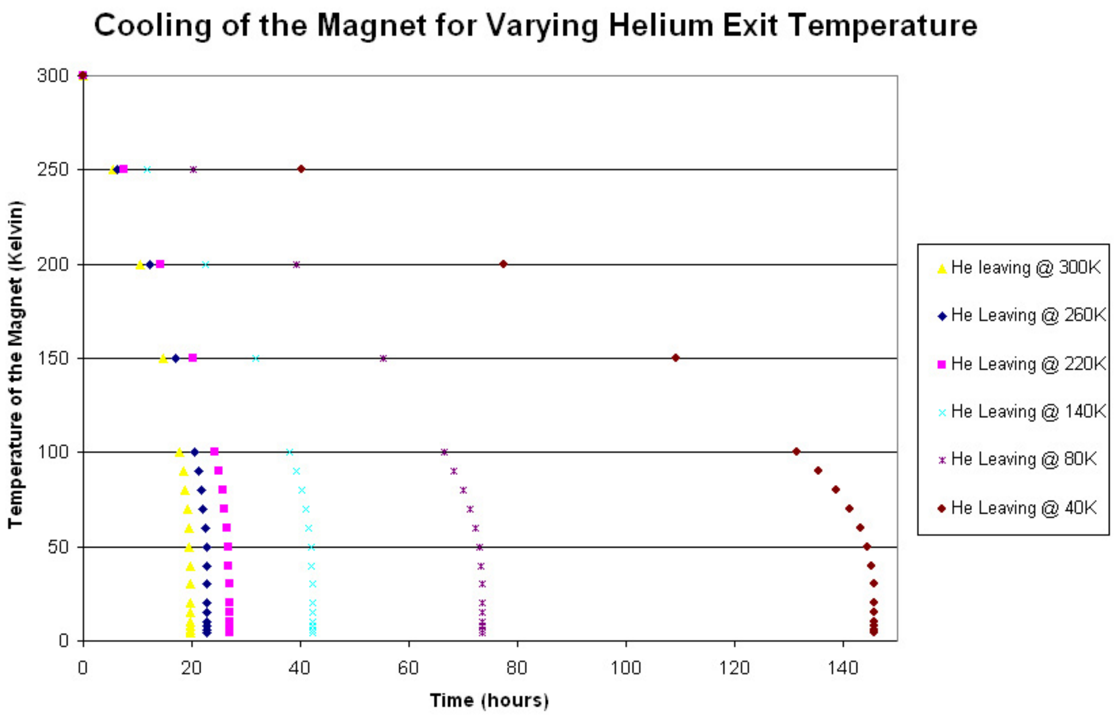

Figure 6: The magnet's calculated temperature in time, with varying helium exit temperatures at 60 gaseous liters per minute.

TABLES

He Exit Temperature (K)	Time for Magnet to Reach 4.2K (hours)
300	59.34
260	68.44
220	80.83
140	126.71
80	220.75
40	437.30

Table 1: Cooling times for a number of different helium exit temperatures for a gaseous helium flow rate of 20 L/min.

He Exit Temperature (K)	Time for Magnet to Reach 4.2K (hours)
300	19.78
260	22.81
220	26.94
140	42.24
80	273.58
40	145.77

Table 2: Cooling times for a number of different helium exit temperatures for a gaseous helium flow rate of 60 L/min.

He Exit Temperature (K)	Time for Magnet to Reach 4.2K (hours)
300	8.48
260	9.78
220	11.55
140	18.10
80	31.54
40	62.47

Table 3: Cooling times for a number of different helium exit temperatures for a gaseous helium flow rate of 140 L/min.