Critical Current Probe

Senior Design Final Report – April 2012

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3. Abstract

The project is to design and build a Probe based on the current model. This probe is to be used in critical current test the critical current for super conducting short or spiral samples. This probe must use less liquid helium per test. Implementing new technology, identifying all sources of heat in and out of the system, and optimizing the design will be the approach taken to accomplish this task.

4. Introduction

The purpose of this project is to design a probe that tests superconducting samples at very low temperatures while conserving as much coolant as possible. The National High Magnetic Field Laboratory (NHMFL) and the Applied Superconductivity Center (ASC) have identified some weaknesses that cause excess helium burnoff in existing critical current probes. A critical current probe is used to test samples of superconducting material. These tests determine the sample's resistance to varying current at a temperature of 4.2K. Liquid helium is used to obtain 4.2K. Each sample will have a critical current at this temperature which will cause it to leave the superconducting state. This data is recorded by a computer during the test and can be analyzed by the experimenter. There is concern over the rate of burn off of the liquid helium as the cost of liquid helium is rather high. Critical current probes are placed in a bath of liquid helium inside a cryostat and extend out of the cryostat into ambient temperature.

4.1 Needs Assessment

The National High Magnetic Field Laboratory in Tallahassee, Florida routinely does extensive tests in superconductivity research. However, because of the nature of superconductivity, very low temperatures close to three and four Kelvin must be achieved. This is accomplished by using both liquid nitrogen and liquid helium due to their naturally low temperatures.

4.2 Problem Definition

4.2.1 Goal Statement

The customer has very specific design criteria for this particular probe. An efficient probe which can effectively test 6-8 samples as well as a spiral sample and conserve helium must be produced. The probe should be able to withstand and deliver 1000 amps through the samples. This probe must also withstand several hours of extremely low temperatures without deformation as the samples are required to stay in the same location during testing.

4.2.2 Objectives

In order to do this, the heat leaks must be minimized, materials must be analyzed, a stage for the samples must be designed, potential heat leaks may be insulated, and in depth analysis and modeling must be completed. The objectives of this project are seen below.

Table 1 – Objectives

Objectives
Conserve helium
Test 6-8 short samples
Test one spiral sample
Deliver 1000 Amps to the samples
Durability

4.2.3 Testing Environment for Objectives

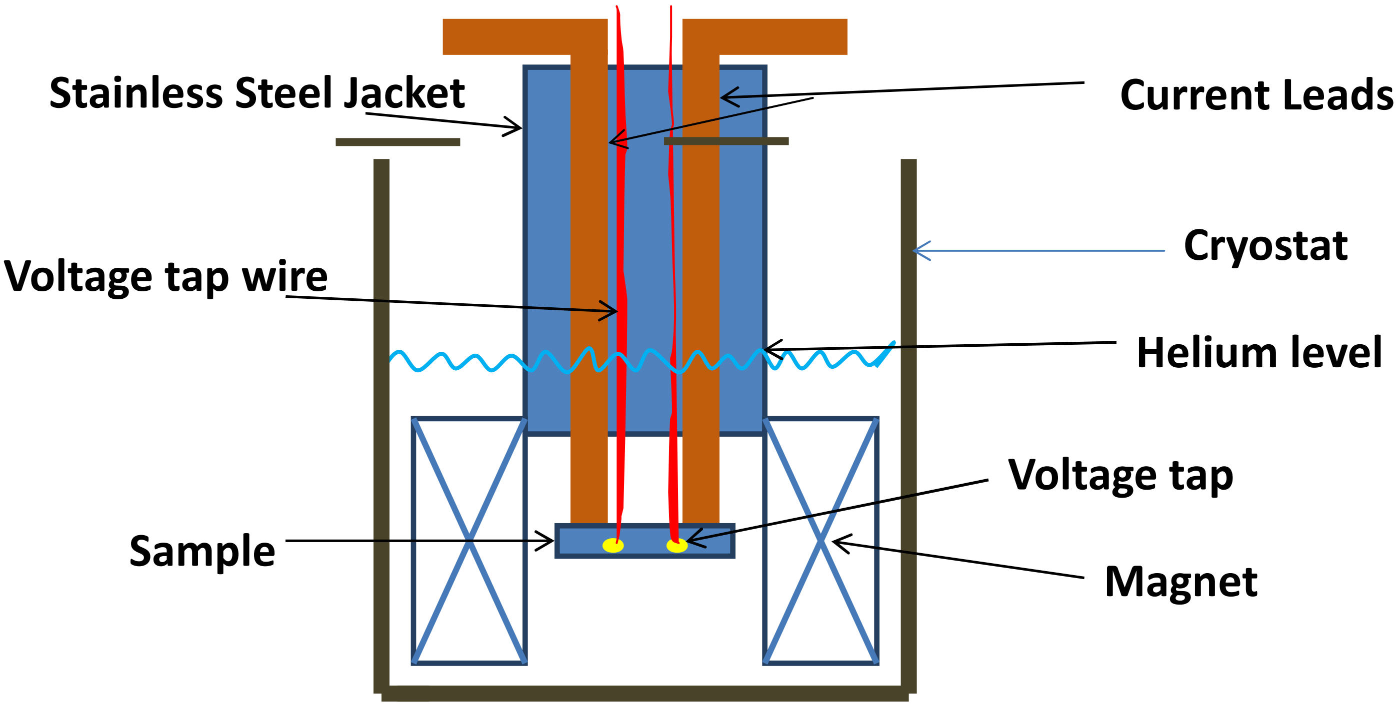
The probe will be tested in a cryostat filled with liquid helium at the NHMFL where it will continue to be used in future critical current tests. The amount of helium used by this probe will be compared with previously used probes. The probe will be connected to the existing computer software which will monitor the voltage across the samples as well as the voltage across the current leads. Up to 1000 Amps will be delivered to the samples through the probe using this computer system. The durability of the probe will be tested over time.

4.2.4 List of Constraints

- Constant Casing Diameter of 110mm
- Minimum length to reach the center of the magnet (1363.5mm)
- Test 6-8 samples
- Budget of $4000

The constraints on this project included a relatively generous budget, a specific casing diameter, and a minimum length. The casing diameter is important for the probe to properly fit into the dewar. This particular probe will be used regularly during testing and should be able to be used in multiple dewars but was designed for one in particular that required a minimum length to be able to get the short samples in the middle of the magnet.

4.3 Functional Diagram



The general idea of this project is to create a probe that tests superconducting short samples. The probe consists of copper current leads that run down to a sample holder. Samples are mounted on this sample holder which is lowered into the cryostat until the sample is placed directly in the center of the magnet. This is the location that the sample must maintain during testing. A stainless steel jacket covers the copper leads to protect them, act as a radiation shield, and prevent cold helium from escaping the system. The helium level in the cryostat varies slightly over time as some is burned off and more is let into the dewar. Voltage taps across the sample record the information using a computer system that is set up separately.

4.4 House of Quality

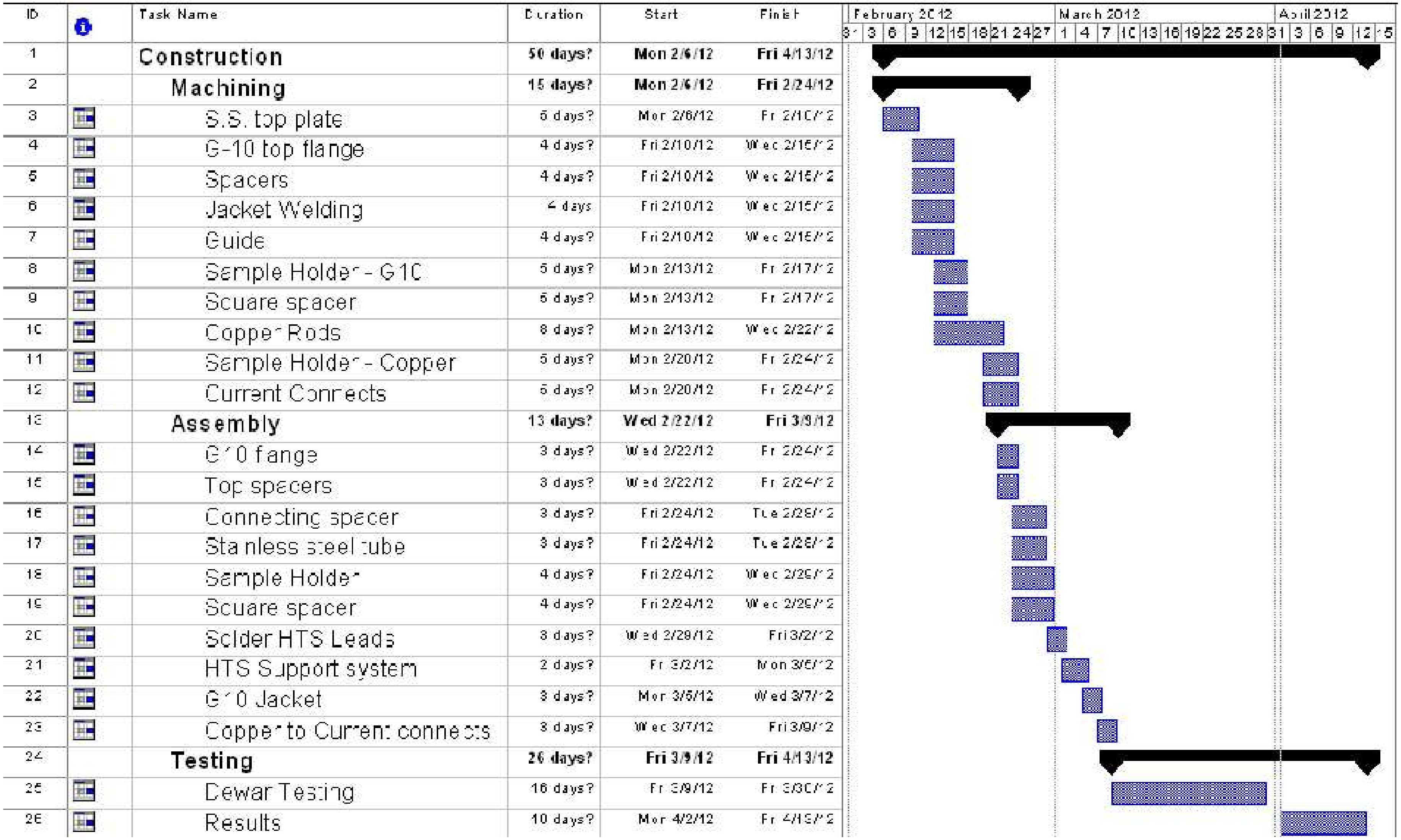
Costumer Requirements		Customer Importance	Technical Requirements	Number of Leads	Material of casing	Material of leads	Length of Probe	Position of HTS	Our Product	Exisiting Product	Overall Weighting	Percentage of total
	Attribute											
Probe Attributes	Weight	1		5	9	3	8	0	1	0	0.5	1.04%
	Number of Samples	8		9	0	0	0	0	8	8	8	16.67%
	spiral sample	2		0	0	0	0	0	2	0	1	2.08%
	Reach center of magnet	10		0	0	0	10	8	10	10	10	20.83%
	cost	4		7	3	5	5	0	4	2	3	6.25%
Performance Attributes	Durability	8		0	10	7	2	2	8	8	8	16.67%
	Reduction of heat Transfer	10		10	10	10	6	9	10	5	7.5	15.63%
	Run up to 1,000 amps	10		0	0	10	0	0	10	10	10	20.83%
			Technical Priorities	205	201	279	204	186				
			Percentage of Total	19.07%	18.70%	25.95%	18.98%	17.30%				

Table 2 - House of Quality

4.5 Project Plan

The probe was originally scheduled to be complete during the first week of March 2012. This would allow an entire month of testing. The following Gantt chart was the original plan for this project. It allowed enough buffer days to allow problems to arise without major impacts on the schedule. This plan did not allow enough time for the machining as the machine shops were very busy with other projects. In the original plan, the machining was supposed to be completed before March. In reality, the machining was finished April 1st. This still left the HTS leads to be soldered together and then soldered to the Copper leads. This was not completed until April 4th which really put things behind schedule and left only a partial day for testing the probe.

Although, everything was completed on time, there was no margin of error towards the end of the project. If any other problems had arisen, there would not have been any time to correct them. This will be taken into account for future projects.



ID		Task Name	Duration	Start	Finish
1		**Construction**	**50 days?**	**Mon 2/6/12**	**Fri 4/13/12**
2		**Machining**	**15 days?**	**Mon 2/6/12**	**Fri 2/24/12**
3	▦	S.S. top plate	5 days?	Mon 2/6/12	Fri 2/10/12
4	▦	G-10 top flange	4 days?	Fri 2/10/12	Wed 2/15/12
5	▦	Spacers	4 days?	Fri 2/10/12	Wed 2/15/12
6	▦	Jacket Welding	4 days	Fri 2/10/12	Wed 2/15/12
7	▦	Guide	4 days?	Fri 2/10/12	Wed 2/15/12
8	▦	Sample Holder - G10	5 days?	Mon 2/13/12	Fri 2/17/12
9	▦	Square spacer	5 days?	Mon 2/13/12	Fri 2/17/12
10	▦	Copper Rods	8 days?	Mon 2/13/12	Wed 2/22/12
11	▦	Sample Holder - Copper	5 days?	Mon 2/20/12	Fri 2/24/12
12	▦	Current Connects	5 days?	Mon 2/20/12	Fri 2/24/12
13		**Assembly**	**13 days?**	**Wed 2/22/12**	**Fri 3/9/12**
14	▦	G10 flange	3 days?	Wed 2/22/12	Fri 2/24/12
15	▦	Top spacers	3 days?	Wed 2/22/12	Fri 2/24/12
16	▦	Connecting spacer	3 days?	Fri 2/24/12	Tue 2/28/12
17	▦	Stainless steel tube	3 days?	Fri 2/24/12	Tue 2/28/12
18	▦	Sample Holder	4 days?	Fri 2/24/12	Wed 2/29/12
19	▦	Square spacer	4 days?	Fri 2/24/12	Wed 2/29/12
20	▦	Solder HTS Leads	3 days?	Wed 2/29/12	Fri 3/2/12
21	▦	HTS Support system	2 days?	Fri 3/2/12	Mon 3/5/12
22	▦	G10 Jacket	3 days?	Mon 3/5/12	Wed 3/7/12
23	▦	Copper to Current connects	3 days?	Wed 3/7/12	Fri 3/9/12
24		**Testing**	**26 days?**	**Fri 3/9/12**	**Fri 4/13/12**
25	▦	Dewar Testing	16 days?	Fri 3/9/12	Fri 3/30/12
26	▦	Results	10 days?	Mon 4/2/12	Fri 4/13/12

Table 3 - Gantt Chart

5. Design Approach

5.1 Identifying Heat Leaks

Heat leaks are spots where heat "leaks" into or out of the system depending on whether the desired system is to be kept cold or hot. Since the cryostat is to be kept cold to preserve liquid helium heat leaks will be where heat is leaking into the system. Identifying the major heat leaks of the original probe was the launching pad for the design of the new probe. To identify the heat leaks a closer look at the probe and its use was needed. The probe is specifically designed for a cryostat used in one of the labs at the NHMFL. Heat that enters the cryostat system is from the radiation on the cryostat and from the probe through conduction and radiation. The focus is on the probe so only heat leaks from the probe will be considered.

The identified heat leaks under consideration are from the thermal conduction of the copper leads and the stainless steel tube combined with the radiation. Measures to prevent radiation from entering the system on both the probe and the cryostat were implemented on the original designs. Since the radiation compared to conduction is small and in consideration of time radiation will be ignored and conduction will be the focus. This leaves the conduction of the copper leads and the stainless steel casing as the major heat leaks in the system. Now that the major heat leaks have been identified the next step is the produce concepts that will reduce or prevent these heat leaks.

5.2 Concept Generation

During this stage of the project concepts on how to conserve liquid helium by reducing the transfer of heat from the ambient air, 298K, to the inner He bath at 4.2K. Many concepts have been generated and are presented as means to conserve He. These concepts look at different parts and areas of the existing probe in an attempt to look at all possible heat leaks the probe has. These concepts are presented as options in this section and will need further thought, research, and experimentation before accepted as a viable means of conserving liquid helium.

5.2.1 Concept #1 – Heat exchanger

Of the identified heat leaks the copper current leads are thought to be the largest source of heat transfer from the ambient temperature to the liquid helium bath. The copper leads are exposed to the ambient air temperature only at the top of the probe, see Figure 1. At this point the copper is at the maximum temperature difference of 298K as compared to the liquid helium bath 4K at the bottom. If the copper at this point were to be cooled and thus the temperature gradient reduced then the rate at which liquid helium is being burned off would decrease.

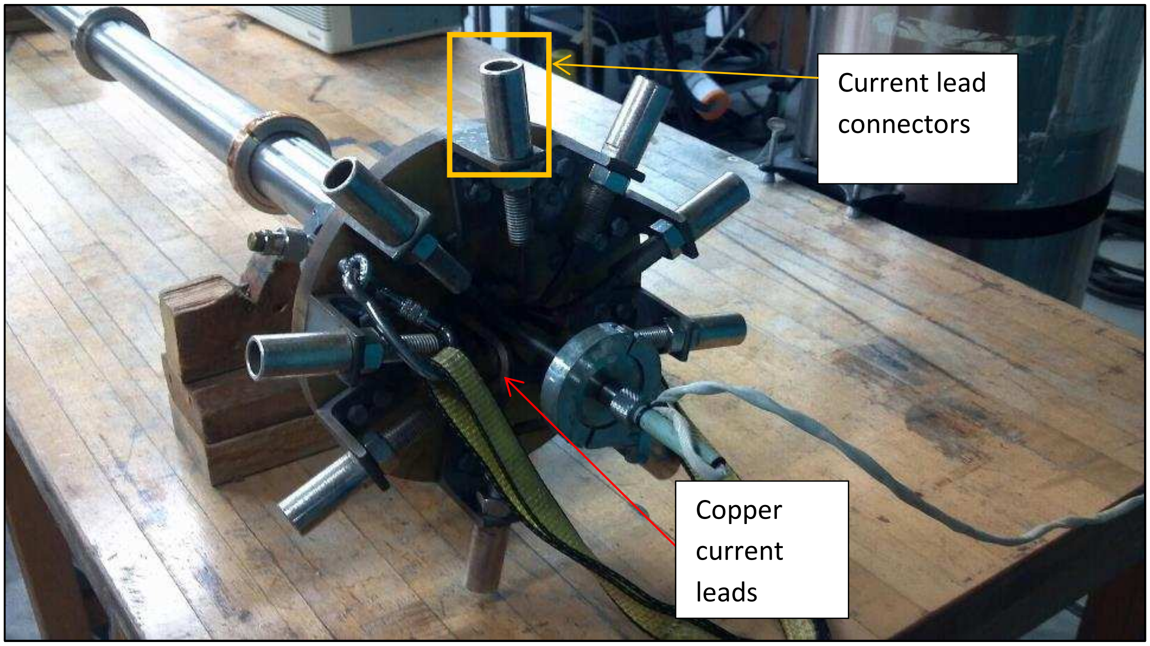


Figure 1 - Top view of probe showing exposed current leads

Figure 2- Side view of heat exchanger

To cool the current leads at the top a cylindrical cap would be made to cover the current leads while leaving the current connection exposed out of the side, see figure 1. The cap would be air tight and around the protruding current connections and at the base of the top flange. This cap would be insulated so to keep the volume inside the cap cooled. This cylindrical heat exchanger would be cooled by the escaping helium gas burned off from the liquid helium bath. The gaseous helium would travel the cylindrical stainless steel tubing cooling the copper leads all the way up to the top. A vent will be at the top of the cylindrical heat exchanger to allow the excess helium gas to escapes so pressure does not build inside the probe, cryostat, or heat exchanger, see figure 3.

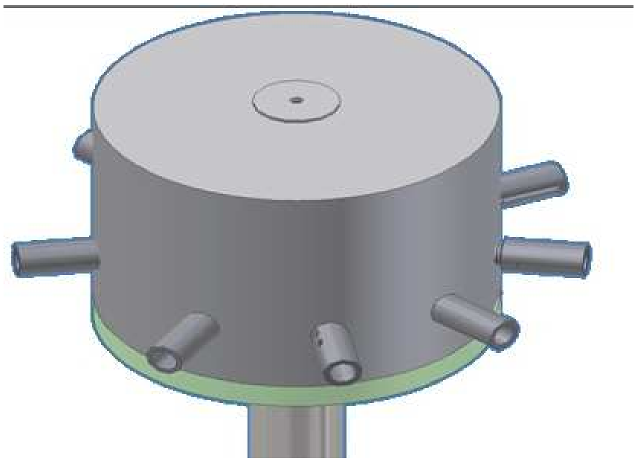


Figure 3 - Angled top view of the heat exchanger on top of the probe

5.2.2 Concept #2 – Spoke thermal cap

During testing a large portion of the stainless steel tube is exposed to the ambient air. Stainless steel is fairly ideal for all the requirements needed from this part of the probe. For this reason we have decided to not try and replace the stainless steel but rather impede the thermal conductivity of the stainless steel. To accomplish this, a modification of an already existing component of the current probe would be implemented, see figure 5.

This part is called the current lead support. Acting as a spacer for the current leads as they travel through the probe this spacer could also hinder the thermal conduction of the stainless

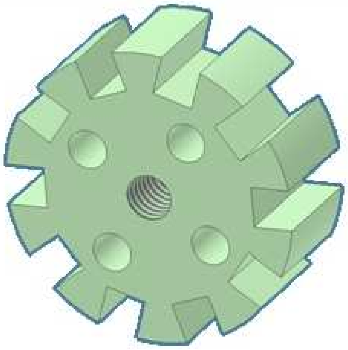


Figure 4 - Spacer

steel tube. The current lead support is made of a fibrous material called G-10 that has a thermal conductivity of .27 W/m(K) which I is much lower than that of stainless steel at 16 W/m(K). Extending the square notches so that they protrude through and are flush with the outer diameter of the stainless steel tube will impede the thermal conduction of the tube. This is due to the increased thermal resistance from the G-10 because its low thermal conductivity is lower than that of stainless steel. The equation for resistance by conduction from one material to the next is expressed below.

$$R_{material} = \frac{L}{kA}$$

$$R_{total} = R_1 + R_2 + R_1$$

$$R_{total} = \frac{L_1}{k_1 A_1} + \frac{L_2}{k_2 A_2} + \frac{L_1}{k_1 A_1}$$

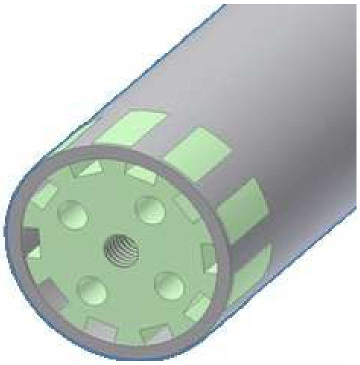


Figure 5 - current lead support modification

(R) in these equations is resistance,(L) is length, (k) is the thermal conductivity, and (A) is the area. This shows as (k) decreases in value the resistance increases which proves, in theory, that interrupting the stainless steel with G-10 will increase the thermal resistance. With the increase thermal resistance more liquid helium can be save during I_c measurement test.

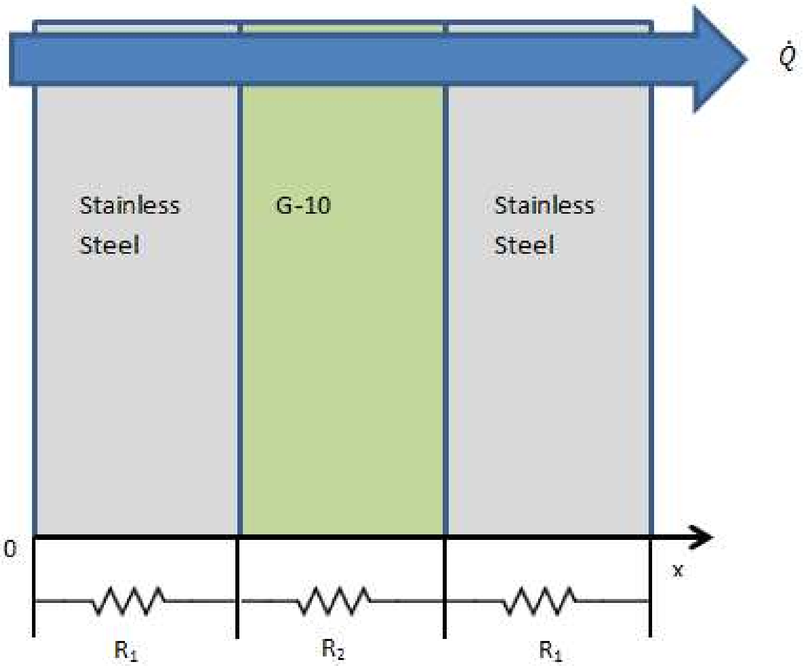


Figure 6 - Thermal heat conduction through Stainless steel and G-10 layers.

This concept is not easily implemented due to machining issues, so a new design of the same concept is used later on to replace a portion of the stainless steel jacket with a G-10 piece.

5.2.3 Concept #3 – Helium gas insulation

Another concept is using the burn off gas to create an insulating layer between the leads and the liquid helium. If the heat transfer rate between the leads and the liquid helium exceed about 10^4 watts per meter Kelvin, then Film boiling will occur which

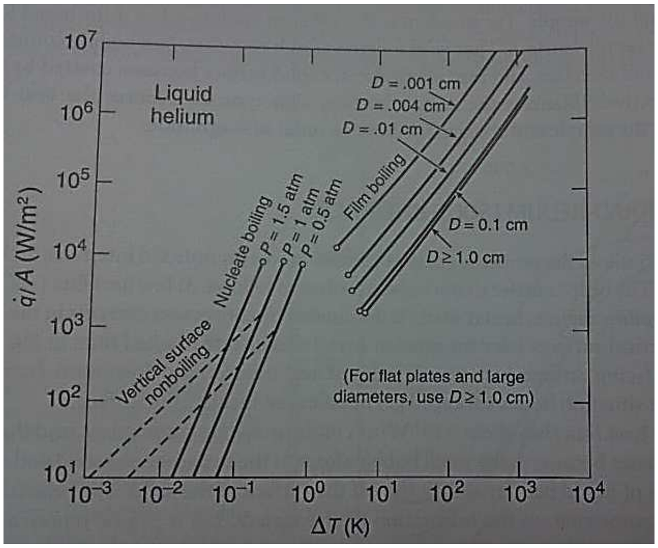


Figure 7 - Film Boiling

means a constant layer of liquid gas at the contact point of the lead. Figure 7 shows the rate of heat transfer at different stages of boiling and how the rate at which heat transfer increases due to temperature difference will slow down during film bonding. The way the probe is positioned vertically in the cryogenic fluid, allows for the highest heat transfer rate due to the fact that the gas is being evaporate directly up and not being hindered by any outside obstructions, as can be seen in figure 8 (a). Since the object of this project is to decrease the heat transfer rate, the leads could be put at a certain allowable angle (depending on the constraints of the tank) impeding the rate at which the gas that could escape, causing a thin layer of gas to form and insulate the surface. Figure 8 (c) would be showing the ideal horizontal situation, however this would not be practical to the constraints of our design. If this orientation cannot be achieved, small wells placed alongside the leads could trap some of the gas and create pockets of helium gas that could slow down the rate of heat transfer, as shown in figure 8(b).

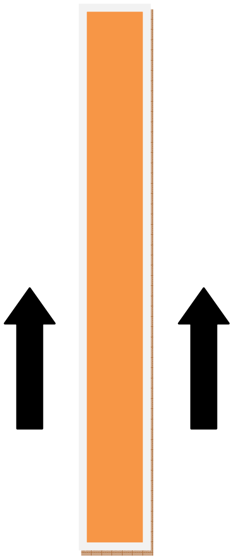


figure 8

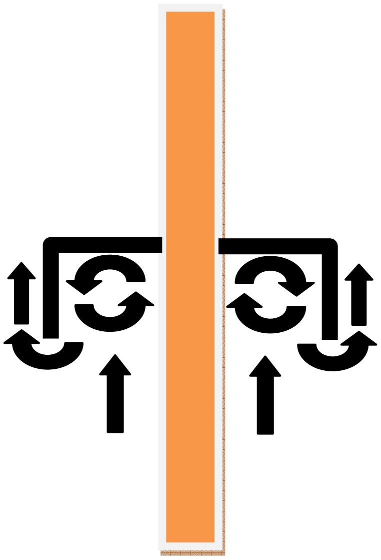


figure 8

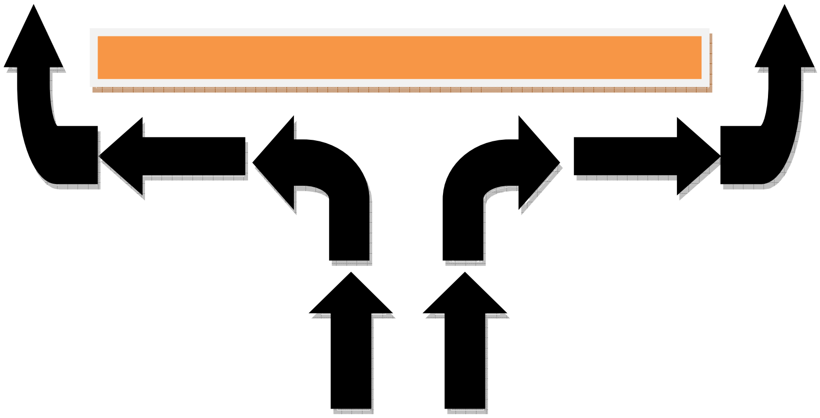


figure 8

5.2.4 Concept #4 - Fins

By adding fins to the top portion of the copper leads not immersed in the liquid helium, the heat would be taken out of the rod faster and therefore cause a lower temperature gradient by preventing heat being transferred to the lower portion of the rod. Since the main driving force behind the three methods of heat transfer is a temperature gradient, reducing this would in turn reduce the amount of heat transferred at the base of the leads in the fluid. The focus on this part is the copper leads and not the steel casing on the outside, this is because our steel casing is constrained to fit in a certain diameter hole from the tank leaving no space for fin extrusions. The idea is that these fins will provide a greater surface area for the rising cool helium gas to come into contact with and therefore a higher heat transfer rate out of the leads. However optimization and the efficiency of the fins will play a huge role in determining how plausible. For example, adding more copper to the probe would increase its resistance and therefore the power being generated. As seen in figure 9, the fin efficiency can vary with lengths and gap distances.

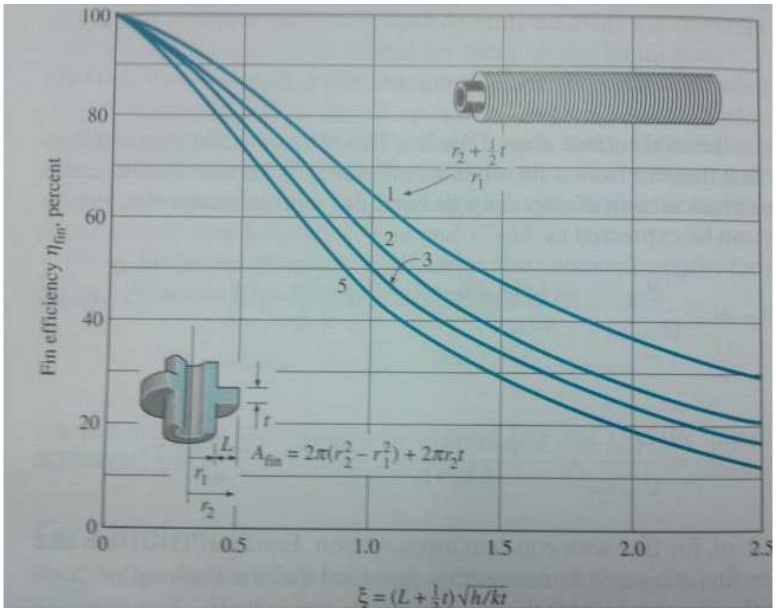


Figure 9 – Graph of circular fin efficiency to effectiveness

5.2.5 Concept #5– HTS Leads

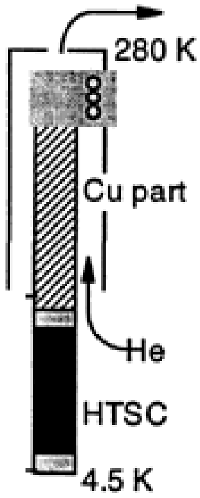


Figure 10: Conceptual Probe Lead

The copper leads cause a high rate of helium consumption. A concept reducing the depletion of helium by the leads will greatly enhance a probe which tests super conductors. To achieve this, high temperature super conducting leads (HTS leads) could be used to replace the standard copper leads. Electrical resistance causes heat which will cause the temperature to rise. This probe needs to be able to test samples at very low temperatures (4.2K). If the leads have a large resistance, they will cause the temperature to rise quickly. This rise in temperature will burn off the liquid helium and require more liquid helium to be put into the system. To reduce the amount of helium needed to keep the system at the prescribed temperature, the resistance in the leads may be reduced. HTS leads function at relatively high temperatures compared to low temperature superconductors. They do not necessary need to be kept at low cryogenic temperatures to retain superconducting qualities. This means that even as the temperature gradient changes from 4.2K (the temperature of liquid helium) to room temperature, there is some point in between that will be suitable to replace the copper leads with non-resistive HTS leads. This should reduce the rate of helium burn off during testing. The placement of the HTS leads is crucial to optimize performance and avoid quenching. Figure 10 shows the basic concept of how the copper leads may be replaced with HTS leads at a certain point to reduce resistance.

The traditional copper leads may be replaced with super conducting leads to reduce the resistance. Low temperature superconductors will not be very effective in this case because of the low temperatures required to keep a zero resistance. HTS leads will be much more effective in reducing the heat generation caused by passing current through the leads because of the larger temperature range they may be exposed to without losing superconducting properties. This is why HTS leads will be used instead of LTS leads. Figure 11 depicts the difference between the two.

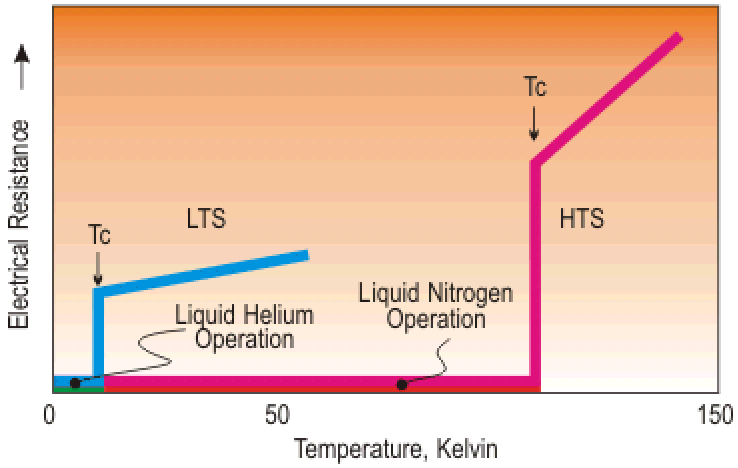
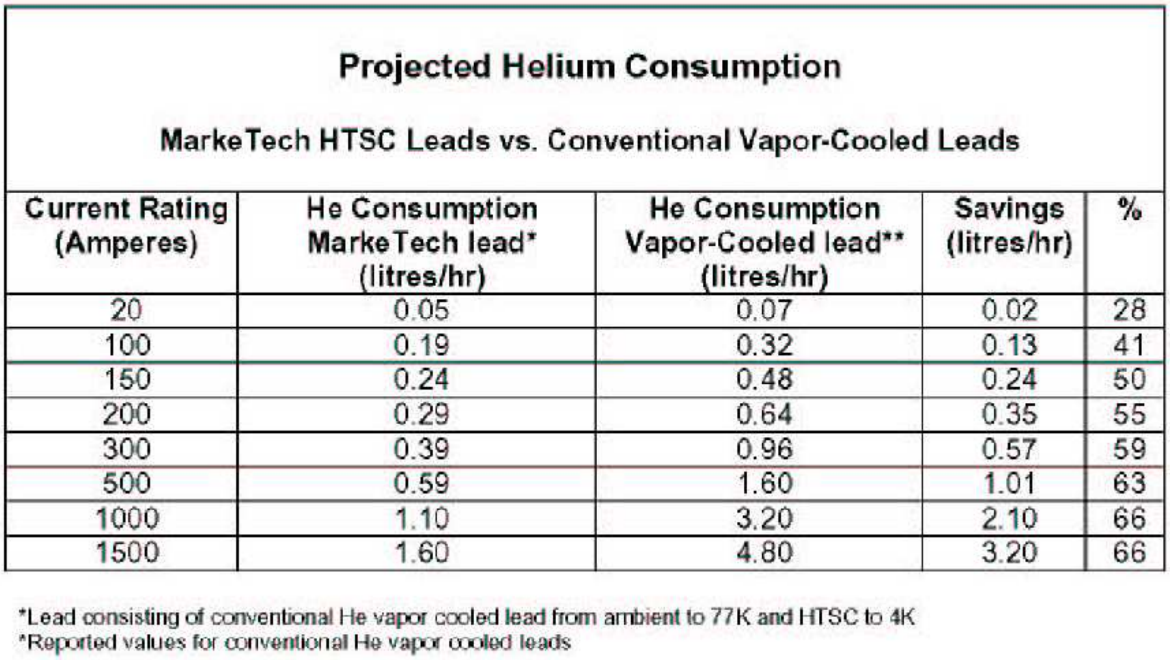


Figure 11: LTS vs. HTS leads

Current Research/Implementation

MarkeTech develops Bi-2223 HTS leads which replace the copper leads at under 77K and reduce the consumption of helium. Table 2 shows this reduction.

Table 4 – Helium Savings from use of MarkeTech HTS leads



Projected Helium Consumption

MarkeTech HTSC Leads vs. Conventional Vapor-Cooled Leads

Current Rating (Amperes)	He Consumption MarkeTech lead* (litres/hr)	He Consumption Vapor-Cooled lead** (litres/hr)	Savings (litres/hr)	%
20	0.05	0.07	0.02	28
100	0.19	0.32	0.13	41
150	0.24	0.48	0.24	50
200	0.29	0.64	0.35	55
300	0.39	0.96	0.57	59
500	0.59	1.60	1.01	63
1000	1.10	3.20	2.10	66
1500	1.60	4.80	3.20	66

*Lead consisting of conventional He vapor cooled lead from ambient to 77K and HTSC to 4K
*Reported values for conventional He vapor cooled leads

The main objective of replacing the copper leads with HTS leads at some determined position down the probe is to reduce the surface area of the relatively thermally conductive copper. So, the surface area of the copper may be reduced and used solely as structural support for the HTS lead. The current will take the path of the HTS lead because it will provide a path with no resistance. This will leave the reduced area copper as a support only.

5.2.6 Concept #6 – Structural Support

The current probe in use at the NHMFL has a stainless steel casing which houses the leads. This casing goes from room temperature all the way down the probe into the liquid helium bath. This makes it a heat leak. There is reason to believe that this casing may be made out of a different material with a lower thermal conductivity. Theoretically, the heat leak would be minimized. This should be analyzed to see if replacing or removing the stainless steel could reduce the consumption rate of the helium. Several materials will be looked at and analyzed to determine the amount of helium which could be saved.

This casing may also be able to be removed completely. The necessity of the casing will need to be analyzed to determine the casing's function at certain points. Being able to remove part of or all of this casing would eliminate a major heat leak.

The concern may be brought up that HTS leads from the previous concept will not be structurally sound. HTS leads are generally very thin tape or wire. The structural integrity of the HTS leads is low. Thus, using the HTS leads may require some type of structural support. There are forms of structural support that will not create another significant heat leak. Some type of encasement may be used for structural support. Cryosaver current leads employ the use of a fiberglass shell as seen in figure 12.

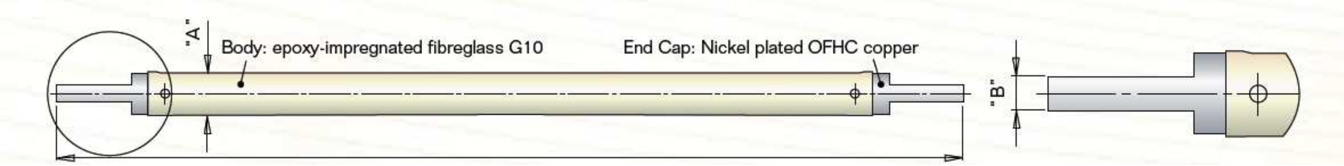


Figure 12: Cryosaver HTS shell

Possible ideas:

- Remove stainless steel casing entirely
- Use less thermally conductive material for:
    - Jacket
    - HTS supportive shell

Pros to these ideas:

- Reducing a major heat leak
- Providing durability

If this concept could be further developed and properly implemented, the result should be a probe with reduced heat leaks that can withstand several tests without failure.

5.2.7 Concept #7- Number of Leads

The amount of leads going into the system may be reduced. The fewer leads into the system, the less heat will be generated. If less heat is generated, then less helium will be used. Electrical engineering concepts will be used to explore possibilities for reducing leads.

The process of reducing leads is an optimization problem. The specifications require a holder that can test 6-8 samples during one experiment. A design which tests six samples will require less leads than one which tests eight. This will reduce helium burn off per testing, but may require multiple tests in certain instances. Multiple tests require more pre-cooling and cooling time. So, optimizing the amount of samples being tested versus the amount of tests being done will reduce the depletion of helium.

There also is some interest is designing a probe which tests samples in series. This can be an issue if the samples are not similar but conceptually, one could test multiple samples with only two current leads. Another idea is to create a modular probe. This probe would allow eight samples to be tested, but if only four samples needed to be tested, the experimenter could easily remove the unnecessary leads. This removal of the leads would reduce the heat leak.

- Optimization Problem
  - Less leads = less samples = more tests
  - Must optimize the amount of samples being tested
  - 24 sample probe will not efficiently conserve helium
    - Large amount of heat leak into the system from ambient air
  - 1 sample probe will not efficiently conserve helium
    - Must be pre-cooled and submerged in the liquid helium for a test that takes less than a minute
    - Too much handling
  - Must optimize between 6-8 samples

5.3 Concept Selection

The heat exchanger and the gas insulation were both rejected before any analysis was performed. The gas insulation concept is not valid when HTS leads are used which is a main focus of the design. The heat exchanger is not necessary if the probe is designed long enough. The fins and the HTS lead support system were both accepted but modified from the original ideas seen in the previous section. Table 3 shows the rejected, accepted, and modified concepts.

Table 5 - Concept Selection with approximate helium savings

Concept Selection Table			
Concepts	Accepted	Helium Savings (per test)	Final
Heat Exchanger	No	---	No
HTS Lead and Support	Yes	≤ 26%	Modified
Number of Leads	Yes	≤ 22%	Yes
Fins	Yes	9%	Yes
Gas Insulation	No	---	No
Jacket Design	Yes	0.2%	Modified

5.4 Decision Matrix

Table 6- Decision Matrix

Concepts	Conserves helium	Machinable	Test multiple samples	Cost	Total
Heat Exchanger	2	2	5	5	14
HTS Lead and Support	9	3	5	3	20
Number of Leads	9	8	9	8	34
Fins	5	2	5	5	17
Gas Insulation	4	3	5	5	17
Jacket Design	6	7	5	6	24

From this decision matrix and the Concept Selection Table, the HTS leads, reduction in number of leads, and the jacket design, were chosen to be a part of the final design. This final design implements all three of these in order to meet the objectives without going outside of the constraints.

6. System Analysis

6.1 Givens and Assumptions

In order to reduce the complexity of the system analysis, a number of assumptions were made. This includes that the leads at the top of the cryostat are at room temperature or 300 K and that the leads at the bottom of the cryostat were at the saturated liquid helium temperature at 4.2 K. It was also assumed that the temperature of the helium gas varied exponentially as a function of distance starting from the base of the cryostat up to the 300K point at the top. It is also assumed that the stainless steel casing prevents most of the incoming radiation so the only heat transfer methods analyzed are conduction and convection. It was also assumed that the liquid helium would be at the saturated liquid stage. Also the type of copper being used was 99% annealed.

6.2 Analysis on existing probe without convection:

In order to simplify the process the current probe was analyzed in steps, the first was by heat transfer and temperature profile only accounting for conduction. Because the copper leads exists at much lower temperatures the thermal conductivity varies greatly and is represented by integral tables and the following equation.

$$k = \int_{4K}^{T} \gamma(T)dT$$

Where A is the cross sectional area, L is the total length in which the heat transfer is being analyzed (in this case it would be the length of the leads), T is the end temperate, and k(T) is the thermal conductivity as it varies with temperature. Using tables provided by the text *Experimental techniques for low temperature measurements*, the average thermal conductivity was found to be about 15 W/(m^2*K). The standard heat conduction was then used to find the heat being transferred to the liquid helium, as shown below.

$$Q_{cond} = \frac{A}{L} \int_{4K}^{T} k(T)dT$$

The total heat transferred was calculated to be 160 W and was plugged back into the conduction equation in order to find a temperature distribution as a function of distance along the copper lead.

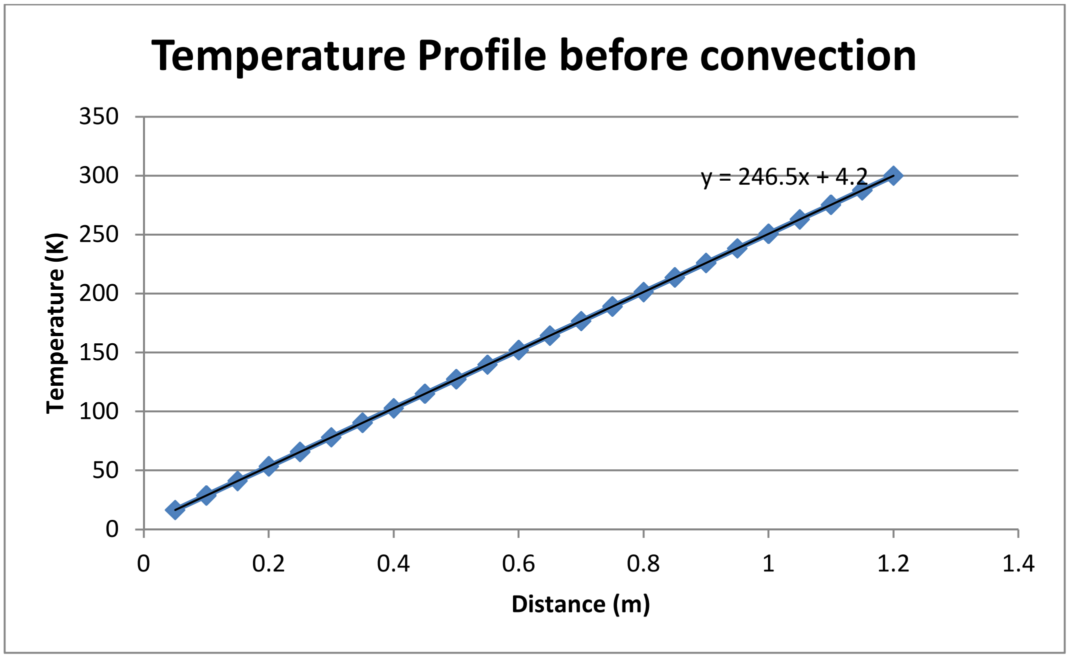


Figure 13

By using this base temperature profile and the estimated temperature profile of the gas, convection calculations are the next step in the process.

6.3 Analysis on existing probe with convection:

Because the gas is being burned off at a certain rate, the type of convection occurring is forced convection. In order to calculate the amount of heat being taken away from the leads, certain constants need to be determined all of which will be temperature based. According to a paper written by Helge Petersen, the constants were approximated to be the following.

$$\mu_{he} := \left[1.865\cdot 10^{-5}\left(\frac{T_{he}(x)}{273.3}\right)^{0.7}\right]\frac{kg}{m\cdot s}$$

$$\rho_{he} := \left[0.17623\frac{P_{he}}{\left(\frac{T_{he}(x)}{273.3}\right)}\left[1 + .053\cdot 10^{3}\cdot\frac{P_{he}}{\left(\frac{T_{he}(x)}{273.3}\right)^{1.2}}\right]^{-1}\right]\frac{kg}{m^{3}}$$

$$k_{he} := \left[.144\left(1 + 2.7\cdot 10^{-4}\cdot P_{he}\right)\left(\frac{T_{he}(x)}{273.3}\right)^{\left[.71\left(1-2\cdot 10^{-4}\cdot P_{he}\right)\right]}\right]\frac{W}{m\cdot K}$$

Where the constants are dynamic viscosity, density, and thermal conductivity of the helium gas respectively from top to bottom. These equations make the assumption that the gas is kept at a constant pressure of 1 atmosphere, which is accurate of the cryostat. The only variable would be the temperature of the gas which is assumed to vary at an exponential rate. Knowing that an average experiment burns off about 50 Liters of liquid helium an hour and given the density equation above, the average velocity of the steam can be approximated by the following equation.

$$V = \frac{Mflow}{\rho * CSA}$$

Where the inner diameter of the steel casing, mass flow rate, and density are Mflow, row, and CSA respectively. From here, the Reynolds, Nusselt, and Prandtl number need to be calculated by using the following equations.

$$Re = \frac{V * x}{v}$$

$$Pr = \frac{C_{p\_he} * \mu_{he}}{k_{he}}$$

$$Nu = .435 * Re^{.5} * Pr^{\left(\frac{1}{3}\right)}$$

Because most of these constants vary with the temperature, and therefore the position of where it is at, it was easier to see how each of these properties changed by finding the values at point .05 meter increments staring from .05 meters up from the center of the magnet to the top of the cryostat at 1.2 meters. These graphs relative to this position distribution are referenced in the appendix section C.1. From these constants, the Nusselt number equation can be used to solve for the range of convection coefficients along the length of the critical current probe as seen below.

$$Nu = \frac{h * x}{k_{he}}$$

Where h is the Nu is the Nusselt number and x and k is the position and thermal conductivity of the gas respectively. From the convection coefficient, the heat transferred out of the leads can be determined by the standard convection equation

$$Q_{conv} = h * SA * \Delta T$$

Where SA is the surface area and ΔT is the temperature difference between the gas and the copper leads. In order find an accurate rate of heat transfer, it was calculated over an incremented range of .05 meters up the probe while using the convection coefficient at that point. This is more explicitly shown in the appendix C.1.

The heat taken away by convection was found to be about 5.322 W and using this with the heat transfer equation, an new temperature profile was found as seen below.

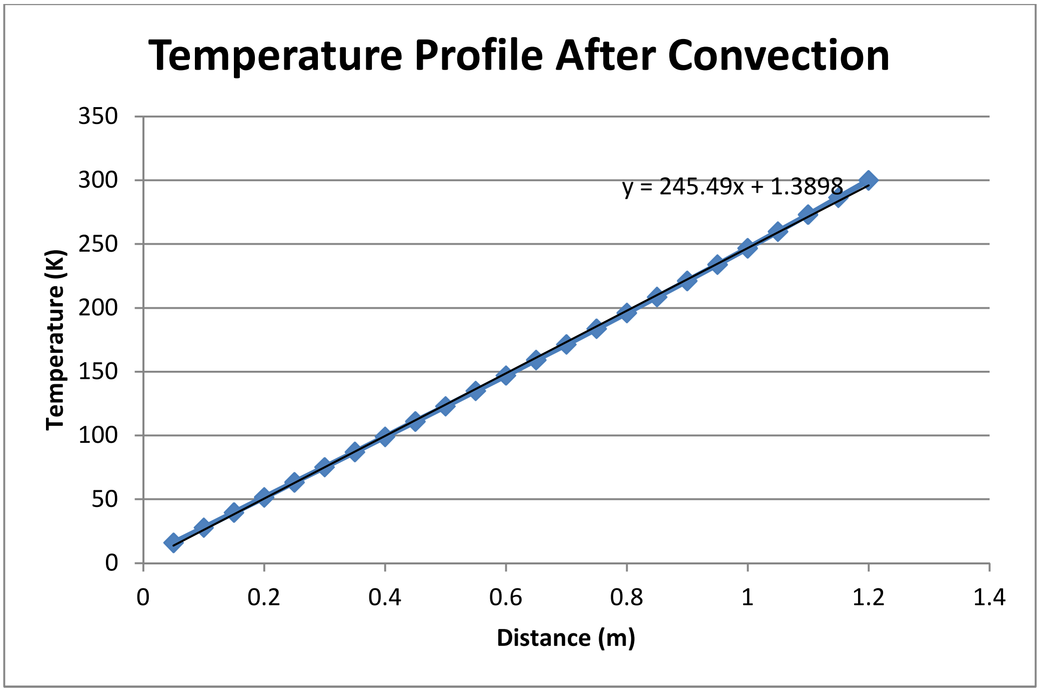
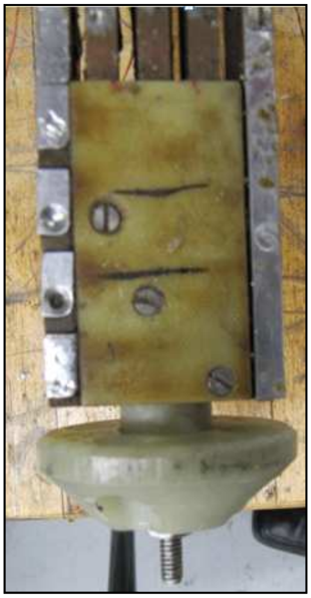


Figure 14

From this graph it is determined that the 33K point, or the point where the HTS leads need to be attached, is .1218 meters up from the center of the magnet.

Once the HTS lead is place, the matter of finding the heat transfer for the HTS follows the same process as for the copper just with different material properties. Currently there was an error in the calculations that provided an unreasonable heat transfer rate into the liquid helium, however it did show a reduction in heat transfer. This will be better calculated by actual experimentation when the probe is built.



6.4 Current lead Optimization

The most basic concept to reduce the rate of helium burn off is to optimize the number of current leads used to perform the critical current test. The probe currently used can test 1- 8 superconducting short samples per test. There is, on average, one critical current test per week with 6-8 sample mounted on the probe during the test. The number of leads inside the system is dependent on the number of samples that can be tested at one time. By using a common positive lead for samples 1-4 and 5-8 as shown in figure 15 the number of leads per sample has been maximized in this manner. The samples are not put in series, resulting in one positive and one negative lead, because of the danger of a burnt out. A burn out is when a short sample is destroyed due to any number of reasons as simple as a slight bend in the sample. If a sample burn out it will no longer conduct current and preventing the testing of the other samples in series.

Another reason a series set up is not used is that different types of short samples are tested that are rated for different currents during one test. If different short samples are in series the current needed to test one of the samples may burn out another. These two reasons keep the set up as is. The optimum number of leads per sample is shown in table 7 below.

Table 7 – Leads per sample

Number of Samples	1	2	3	4	5	6	7	8
# Leads	2	3	4	5	7	8	9	10

To find the optimum number of leads to use in the new probe an estimation was made using data from the existing probe. The average amount of liquid helium used during a 3 hour test was 150 liters with 8 samples mounted on the probe. The test can be broken up into three parts: cooling down the cryostat magnet, ramping the magnet, and the actual critical current testing.

It is assumed that cooling down the cryostat magnet is independent of the probe. One hour is needed to cool down the cryostat magnet which is 1/3 of the total testing time so it is estimated that 50L of liquid helium is used during this part. This 50L will be constant independent of the changing number of leads.

It takes 45 minutes to ramp up the magnet inside the cryostat for the critical current test. This time is set and will not change. The amount of helium burned off is dependent on the number of leads used for the probe since the probe is in the cryostat during the ramping. The rate at which one current lead burns off liquid helium is needed in order to know how much helium is burnt off during ramping. Knowing that 150L of liquid helium was used in three hours with a probe with 10 leads it can be determined that 5 L/hour is burnt off per lead. Complete calculations can be found in the appendix

The only other information need is the amount of time it takes to perform the critical current test per sample. Since 1 hour and 45 minutes is set for ramping and cooling of the cryostat magnet 75 minutes is used for testing with 8 samples. Using the estimate that this time is broken up evenly over the 8 samples would yield 9.37 minutes per sample. Table 5 below shows the results of these calculations.

Table 8 – Lead Optimization

Number of Samples	**Number of Leads needed**	**He losses During Magnet ramping (L)**	**He losses During Testing (L)**	**He Losses During Magnet cool down (L)**	**He Losses for single test (L)**	**Number of test required**	**He Losses over total test (L)**
1	2	7.50	1.56	50.00	59.06	6	354.38
2	3	11.25	4.69	50.00	65.94	3	197.81
3	4	15.00	9.38	50.00	74.38	2	148.75
4	5	18.75	15.63	50.00	84.38	2	168.75
5	7	26.25	27.34	50.00	103.59	2	207.19
6	8	30.00	37.50	50.00	117.50	1	117.50
7	9	33.75	49.22	50.00	132.97	1	132.97
8	10	37.50	62.50	50.00	150.00	1	150.00

The loss of helium is the lowest for a probe designed to test a maximum of 6 short samples at a time. Table 9 summarizes the important results of table 8, highlighting the number of leads that burnoff the least amount helium during a full critical current test.

Table 9 – Selected number of leads

Number of Leads	He Losses per total test (L)
2	354.38
3	197.81
4	148.75
5	168.75
7	207.19
8	117.50
9	132.97
10	150.00

To better show that 8 leads is the minimum amount of helium lost per test an optimization graph, figure 16, was made from the data from table 5. Figure 16 plots the total helium losses over the total number of test versus the number leads. As can be seen from the graph two minimums exist at a lead number of 4 at 148.75 liters and 8 at 117.50 liters. A six sample probe will be chosen since the 8 leads is the optimum number of leads to save helium since it is the lowest minimum.

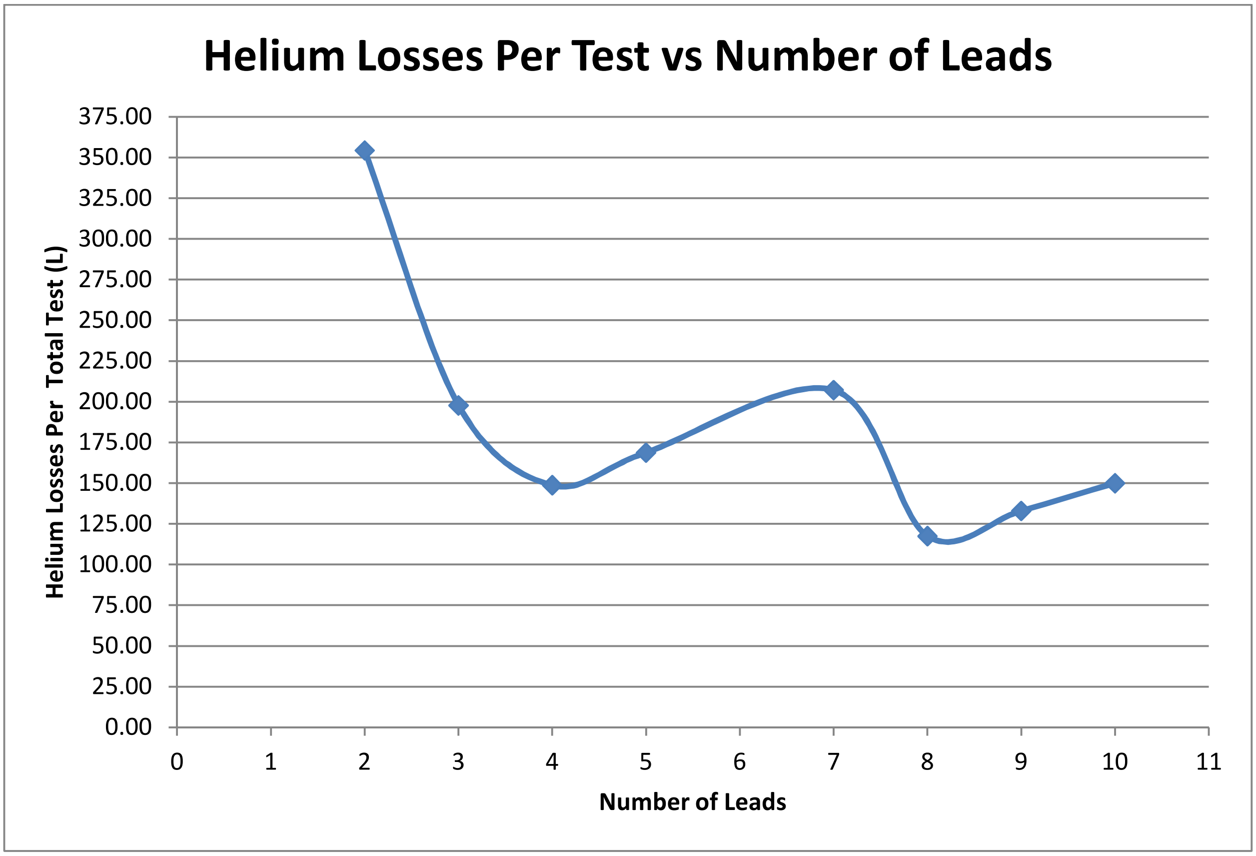


Figure 16

Optimization of current leads:

It was shown that eight current leads would save more helium than six leads in the long run because of the decreased number of test that would have to be preformed. But after some clever thinking it was discovered that eight samples could in fact be tested with only six leads. This would be optimum configuration of samples to leads as deduced from the data previously discussed.

To test eight samples, one at a time, with only six leads requires two common positive current leads and four negative current leads. To explain this there are two positive leads connected to a common negative lead each by a superconducting wire. When power is flows through the negative wire the electricity will take the path of least resistance. Since the superconductors conduct with no resistance the electricity will flow through the super conductor connected to which ever positive lead completes the circuit. in this way, by switching the connection between the two positives, eight samples can be tested, one at a time, with six leads.

6.5 Jacket

The heat transfer rate of the jacket needs to be reduced to conserve helium. To reduce the heat transfer rate, the material of the jacket may be changed. Previously, stainless steel was used as a heat shield and jacket for the copper leads. Stainless steel has a higher thermal conductivity than G-10 making it less effective. The new jacket will be made out of stainless steel and G-10. The G-10 will connect to the stainless steel at an optimum point. A lower amount of stainless steel will theoretically allow for a better heat transfer rate.

Table 10 – Known values

Jacket Dimension	Value
Cryostat Depth	1363.5mm
Length	1.74m
Thickness	5.84mm
Radius	55mm
Cross sectional area	107.146mm^2
Length	1.74m
Top Surface Temperature*	300K
Lower Surface Temperature*	4.2K

*Assumed values

To determine the most effective length of the stainless steel, several needed values are shown in Table 10. When calculating the rate of heat transfer through the jacket, the thermal conductivities of each material are going to change with temperature. The thermal conductivity change for stainless steel from 300K to 4.2K is significant, while for G-10 it is relatively small. Therefore, when calculating for an all stainless steel jacket, the following conduction equation must be used.

$$\dot{q} = \frac{A}{L}\int_{4K}^{T} \lambda \, dT = \frac{A*k}{L} = 0.188\ W \qquad \text{where,}$$

$$k = \int_{4K}^{300K} \lambda \, dT = 3.06\ \frac{kW}{m} \quad \text{from Cryogenic tables}$$

$$A = Jacket\ cross\ sectional\ area$$

$$L = length\ of\ stainless\ steel\ jacket$$

The heat transfer rate for a jacket made entirely of stainless steel is 0.188W. Assuming the change in the thermal conductivity of G-10 is negligible and the temperature of the jacket at the joint is 270K, the heat transfer rate for the new design is 0.083W. This is a significant drop in heat transfer and will help conserve helium without sacrificing structural support as the G-10 will not be a support member.

G-10 is a more effective material than stainless steel for the jacket but it cannot be used as a structural support. It also must not be used at the entrance to the cryostat. This limits the dimensions of the new jacket. The lengths of the stainless steel and G10 portions of the jacket can be seen in table 11. These lengths were altered in the final design.

Table 11 - Jacket Lengths

Jacket portions	Length
Stainless steel	0.711 m
G10	1.029 m

6.6 Fins

Due to manufacturability, placing fins on the copper leads could present an issue because of their length. These fins may effectively reduce the burn off of the liquid helium and are worth exploring.

Assumptions made for fins on the copper leads:

1) Fin temperature varies only in one direction when, $\frac{h\delta}{k} < 0.2$
2) $\sqrt{\frac{2h}{k*t}} * L > 2.5$ for 99% heat transfer performance
3) Adiabatic tip because using triangular fins will allow for negligible heat loss through the tip, $Q_{tip} = 0$
4) Annular fins of a rectangular profile will be similar to the threaded fins for calculation purposes

The fins on the copper leads are analyzed using these assumptions. The heat transfer rate with the fins must be compared with the leads without a fin. For simplicity, the temperatures for these equations are chosen at a point one meter down from the cryostat.

Analysis of Unfinned Lead

The analysis of an unfinned circular copper lead must be done prior to analyzing the finned lead. The restrictions on the system allow for a maximum radius of 3.937mm. The heat transfer rate of one copper lead is determined from the following equation.

$$Q_{nofin} = hA_{nofin}(T_b - T_\infty) = 6.337W$$

Where h is the average convection rate determined from previous calculations, A is the surface area of the copper lead without fins, and T_b is the surface temperature at a specific point x, and T_∞ is the temperature of the gas at the same point x. The temperatures used are found from previous calculations and are shown in table 12. The heat transfer rate for an unfinned copper lead is calculated to be 6.337W.

Table 12 - Calculated Temperatures

	Temperature at L=1m
Surface	250K
Gas	105K

Analysis of Finned lead

The finned lead also has the same restriction in diameter. This means the fin radius is at a maximum of 3.937mm. The concept is to increase the surface area of the lead. The rate of convection is taken to be the average value found from previous calculations. The thickness and spacing will have to be designed.

Table 13 - Affect of thickness on heat transfer

Thickness (mm)	**Assumption 2 (m*L)**	**Tanh(m*L)**	**Qfin (W)**
0.1	9.747	1	11.182

0.25	6.164	1	10.821
0.4	4.873	1	10.511
0.5	4.359	1	10.33
0.6	3.979	0.999	10.164
0.75	3.559	0.998	9.944

The thickness will not be constrained by assumption 1 because the value obtained from this expression ends up being very high. However, assumption 2 does influence the thickness. Table 13 shows the effect of the thickness on the heat transfer rate as well as how it influences assumption 2. The design calls for a relatively high heat transfer rate and a hyperbolic tan value of 1. The table shows four different thicknesses that meet these qualities. The strength and durability of these copper leads is important to consider. A fin with a thickness of 0.5mm is chosen due to its strength and relatively low change in the heat transfer rate.

Table 14 - Calculated Fin Dimensions

Fin Dimensions	**Value**
Lead length, L_{Cu}	1,087 mm
Convection heat transfer rate, h	1.639 W/m^2K
Thermal conductivity, k	401 W/m*K
Inner radius, r1	2.0 mm
Corrected radius, r2c	4.187 mm
Corrected Length, Lc	1,078 mm
Corrected Area, Ap	539.125 mm^2
Area of fin	85.018 mm^2
Spacing	2.0 mm
Area of section with no fin	25.133 mm^2

With the thickness, the corrected radius, length, and area can be calculated. Using these values from Table 14 the fin efficiency can be determined using annular fin charts and the following equations.

$$L_{Cu}^{\frac{3}{2}} * \sqrt{\frac{h}{k_{Cu} * Ap}} = 0.504$$

$$\frac{r2c}{r1} = 2.093$$

$$\eta = 0.81$$

With the fin efficiency, the rate of heat transfer by the fin can be calculated to be 0.016W. The rate of heat transfer of the portion between fins is calculated to be $5.973*10^{-3}$W. There will be 431 fins throughout the length of the lead. This makes the total heat transfer rate of the finned surface copper lead 9.628W. This shows a significant increase in the heat transfer rate and justifies adding fins to the current copper lead design. The overall surface area of the lead is increased 0.021m^2. For more detailed calculations see the appendix.

Table 15 - Heat transfer of finned vs. unfinned leads

Heat transfer	
Finned Copper Lead	9.628W
Unfinned circular copper lead	6.337W
Increase	3.291W

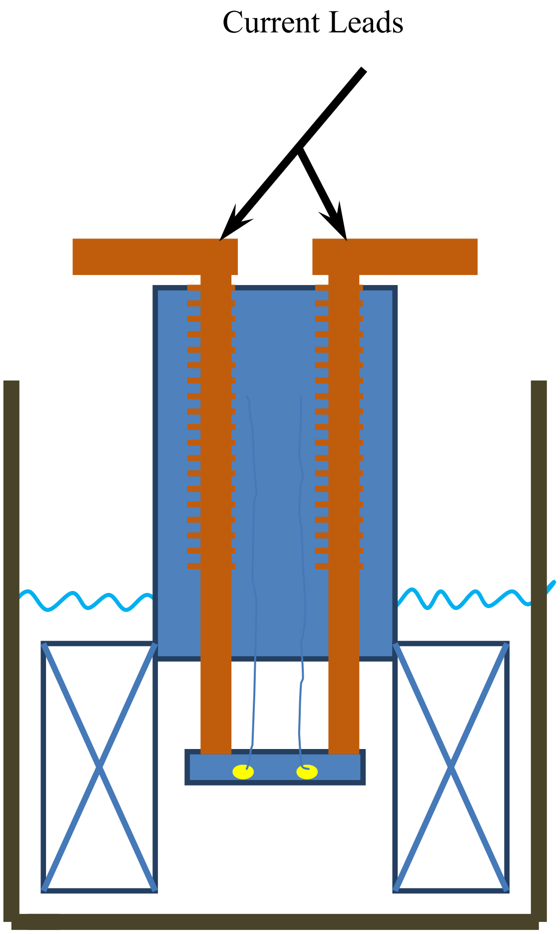


Figure 17 - Simple schematic with finned leads

Figure 17 shows a simple schematic of the current leads with fins. These fins will be placed in the gaseous helium region only. The leads could be narrowed and threaded to create fins which will increase the surface area and therefore, increase the heat transfer.

7. Final Design

Figure 18

After the analysis on each of the concepts had been completed the final step was putting all of the accepted concepts together to get the final design of the probe. A picture of the final design for the probe can be seen in figure 18.

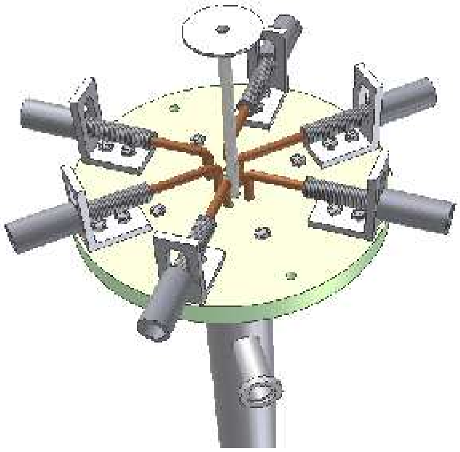


Figure 19

The full body image shows the implementation of the G-10 jacket replacement and the optimized number of leads. To show the optimization of the leads clearly a zoom in of the top portion of the probe is shown in figure 19. There are six leads which are creatively arranged into a sample holder which can test eight samples at a time. As the current sample holder is designed this is the optimum number of leads for a probe with eight samples. The gray tube with the circular flange on top coming out of the center of the top G-10 flange in figure 21 is the instrumentation wire guide for any necessary equipment needed for the experiment. The two figures below, figure 20 and figure 21 show the G-10 jacket replacement concept. The stainless steel jacket and the G-10 jacket are held together by an elongated G-10 insert that will connect the two. This insert has been machined down to the appropriate size on each side to accommodate the different inner diameters of each jacket.

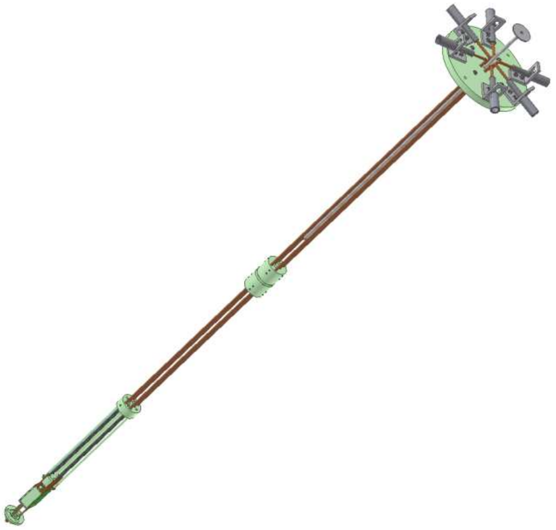


Figure 21

Figure 22

These figures also show how the G-10 spacers throughout the body work. These spacers will make sure that the copper leads will not touch through the whole length of the probe.

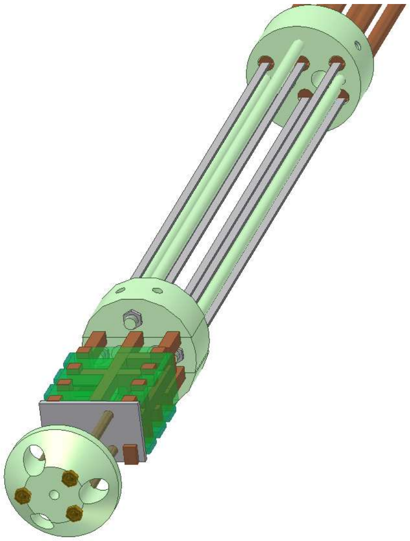


Figure 22

To remove the copper leads from touching the liquid helium bath HTS lead are implemented. These leads, as discussed before are made up of 8 different strips of the HTS material to carry the required amount of current with a factor of safety added in. The HTS lead will be connected by a solder joint at the top, connected to the circular copper lead and at the bottom to the sample holder. The sample holder has copper bars, 0.25in x 0.25in, that are used to connect to the HTS leads, the bottom solder joint, and to the superconducting samples. One inch deep slots were cut through the copper bars as well as the top portion of the copper leads to allow for good contact between the copper and HTS leads after soldering. Copper is used to connect to the superconducting samples because this will not damage the copper rods. If the samples were soldered onto the HTS directly, heating and reheating would destroy the HTS material within 3 or 5 tests. The gray strips in figure 23 are the stacked HTS leads.

8. Design and Manufacturing and Assembly

The design, manufacturing, and assembly of this project proved to have a few difficult components.

- Design

During the design process a few issues arose. We had to modify the jacket design due to machinability. The original spoke design was nearly impossible to implement so the design was changed to incorporate changing the material of the entire lower half of the jacket to G-10. The original sample holder that we had chosen to use last fall was scrapped for a newer better design that allows for less current leads testing more samples and therefore, conserving more helium. The current leads were placed in a new configuration to accommodate this new sample holder. Another design issue encountered was the design of the bottom spacer. This spacer had to be in three parts to allow for assembly. This was not noticed until later and had to be redesigned and machined.

- Manufacturing

The redesigned sample holder proved to be a very difficult part to machine. The G-10 portion of the sample holder which separates the copper leads had to be outsourced to Exotic Machining which put the project behind schedule. The stainless steel tube and G-10 top flange were machined early on and assembled together but the stainless steel flange holes came smaller than the G-10 holes and had to be re-drilled to allow assembly. Also, the G-10 top flange drawings went into the shop incorrect and did not allow for a thread for the eye hook holes which suspend the probe. This was taken care of by supporting the eye hooks that wrapped around the hanger by 4 nuts, two on each eye hook.

An extra hole was placed in the spacers to allow for other instrumentation wiring to be used if needed later on. A design to plug this hole when not in use was not thought through as well as possible and the realization of the need for a plug came up very late in the project. This was solved by using a rubber stopper.

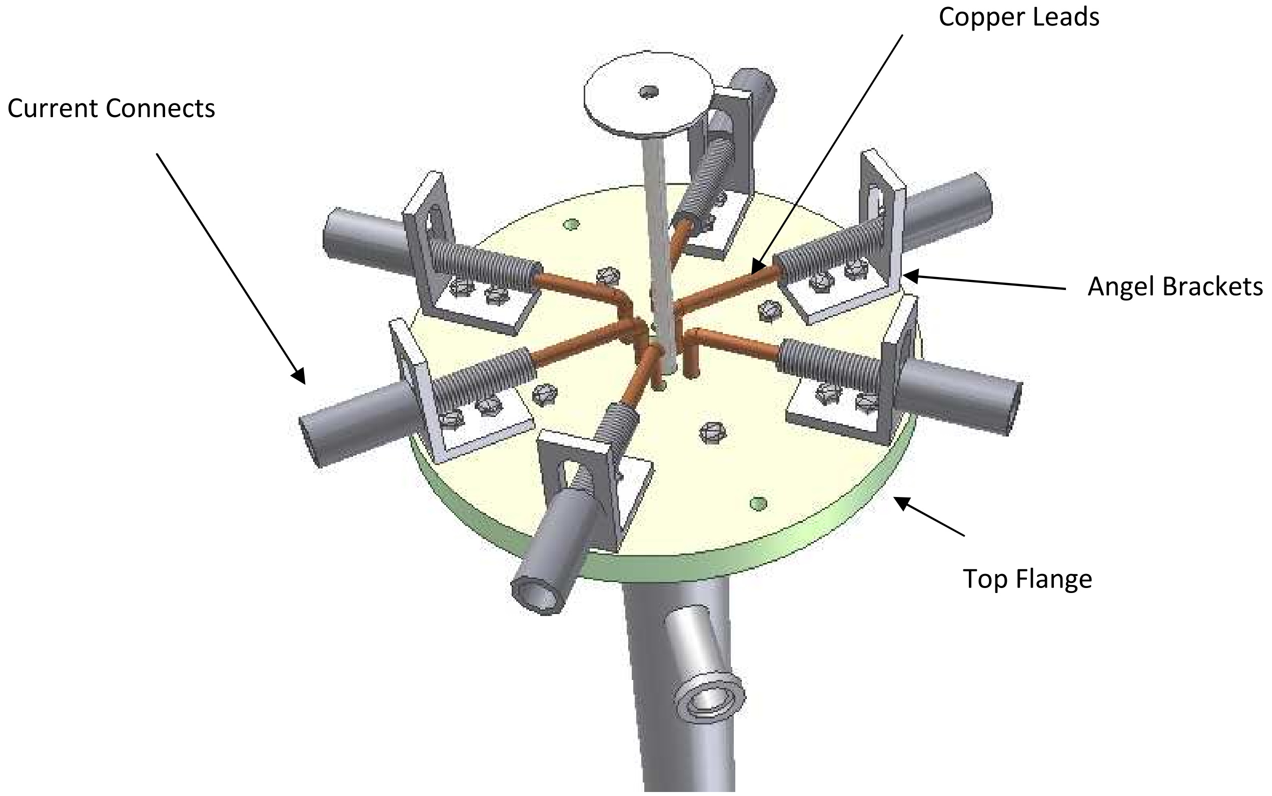
The stainless steel jacket is connected to the G-10 portion by a G-10 connector piece that also acts as a spacer. This connector fits tightly into each jacket and must be secured using screws. The holes for these screws were placed out of alignment with the copper leads which caused a twist of the copper leads down the probe. These holes had to be resized to fix this problem. Originally we planned on using screws and filing them flush with the surface of the stainless steel tube to secure the lower jacket to the upper jacket. The idea of set screws was presented later on and set screws replaced the previous idea. The set screws still have to be entirely flush with the jacket otherwise the casing diameter constraint will be breached and the probe will not enter the cryostat.

The heating blocks were specifically designed for the soldering of the HTS tapes and consisted of two aluminum blocks with a grove in the bottom block for the tape to lie and a wedge in the top to create pressure when the two blocks were placed on top of each other. At each of the ends of the two blocks were half inch holes for cartridge heaters connected to a control box that allowed the heat to be raised to a set temperature, in this case 200 degrees Celsius. Since this is very new technology and no information on soldering 8 HTS tapes could be found, many practice runs were used on copper strips. The practice runs of soldering the tapes together went smoothly and appeared usable. After soldering the HTS together, it is necessary to solder them to the copper leads and because the heater blocks would not heat up the copper to soldering temperatures, a different way to solder the HTS tapes to the copper leads had to be determined. With the aid of the NHMFL machine shop, an inductance heater was provided which he could solder our leads together with in a more controlled setting.

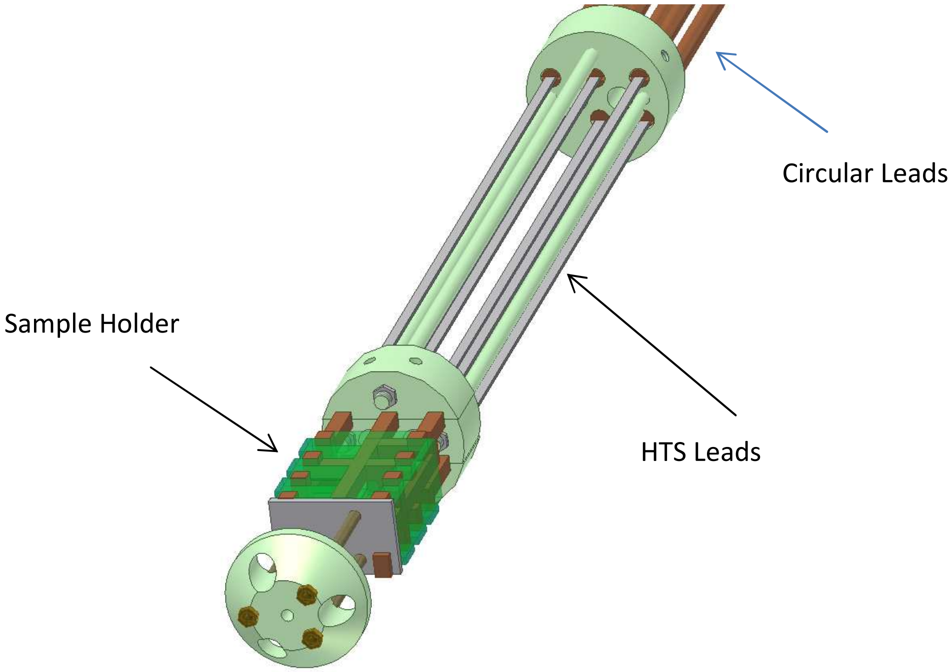
Another manufacturing issue was the fit of the bottom spacer. The bottom spacer was designed to fit tightly on the square current leads and did not take into account the slots being cut in the copper into which eight HTS tapes are soldered. The soldering of the HTS material into this slot expanded the square copper lead making it more of a rectangular shape. This caused the bottom spacer to not sit flush with the current leads, resulting in the G-10 Jacket not being able to fit over the bottom spacer. To make it fit flush, filing of the square grooves and sanding of the outside diameter was chosen. This was successful for the project but a redesign would be necessary for production.

- Assembly

Assembly of this probe had to be carefully planned out due to the fact that when some pieces were put on, others were prevented from being adjusted or moved altogether. Once all the parts had been machined, the first task was to assemble the top portion of the probe which included the current connects, copper leads, angle brackets, top flange, and top spacer.



Once all of these parts were together, the G-10 connector was added, which acted as a middle spacer and the connection point for the G-10 casing. Simultaneously, the sample holder was being assembled, so the next step in the process was to solder the HTS tapes to the round upper leads and the square ends of copper coming out from the sample holder. This can be shown in the picture below.



Once this was completed, voltage taps were threaded through and soldered to the HTS strips in order to test the resistance and to see if they were superconducting. The last step in this process would was to slide the connecting G-10 tube and connect it using set screws.

9. Engineering Economics

Table 16 - Material Costs

material	quantity	cost
110 Alloy Copper rods	6	$291.00
G-10 Tube	1	$611.04
G10 Plate	1	$88.24
Stainless steel plate	1	$81.49
G10 rod	1	$125.77
G-10 plate	1	$67.40
90deg angles steel	1	$44.06
Sockets threaded, current connects	6	$180.00
copper plate	1	$60.95
copper bar	1	$62.52
G-10 Plate	1	$60.18
aluminum bar	1	$49.34
cartridge heater	7	$247.24
cartridge heater	2	$40.52
wing nut	1	$11.21
compression springs	2	$26.72
Exotic Machining	1	$400.00
	Total	$2,447.68

- The 110 Alloy Copper rods were absolutely necessary in completing the project. One foot extra length was added to each order in order to fix any mistakes before the final cut was placed. This, although needed, added little extra to the cost

- The G-10 tube was needed as a replacement for part of the stainless steel casing and to act as a protection for the HTS leads. Since this was such a specific part, it needed to be ordered and was only available in bulk and thus resulting in a much higher price.

- The two one inch thick G-10 plates were used to cut out the spacers throughout the probe which prevented the copper leads from touching and disrupting the current flow. It was also used to cut out the top flange which connected to the angle brackets holding up the current connects.

- The stainless steel plate was used to cut out the top flange which connected the steel casing with the G-10 Flange by the use of welding and bolts

- The G-10 rods were ordered to use as a support system for the fragile HTS portion on the probe. The rods prevented any twisting motion between the spacers connection the probe leads to the sample leads and with a nut resting on the threaded end, allowed the bottom spacer a place to rest instead of placing the entire strain on the HTS strips

- The socket threaded current connects, and the 90 deg angle steel brackets were used to hold up and create the system that would allow the current to flow through the probe.

- The copper plate and copper bar was used in the making of the intricate designs of the sample holder, located at the base of the probe

- The aluminum bar and cartridge heaters were used to create a system in order to quickly and safely heat the HTS for soldering without damaging its superconductivity.

- The wing nut and compression springs were used with the aluminum heater block to add compression, resulting with the HTS being flattened better and having more contact with the block.

- Exotic Machining was required because the university shop was unable to meet the requirements of our design. This was solved by outsourcing to a local shop for a fee.

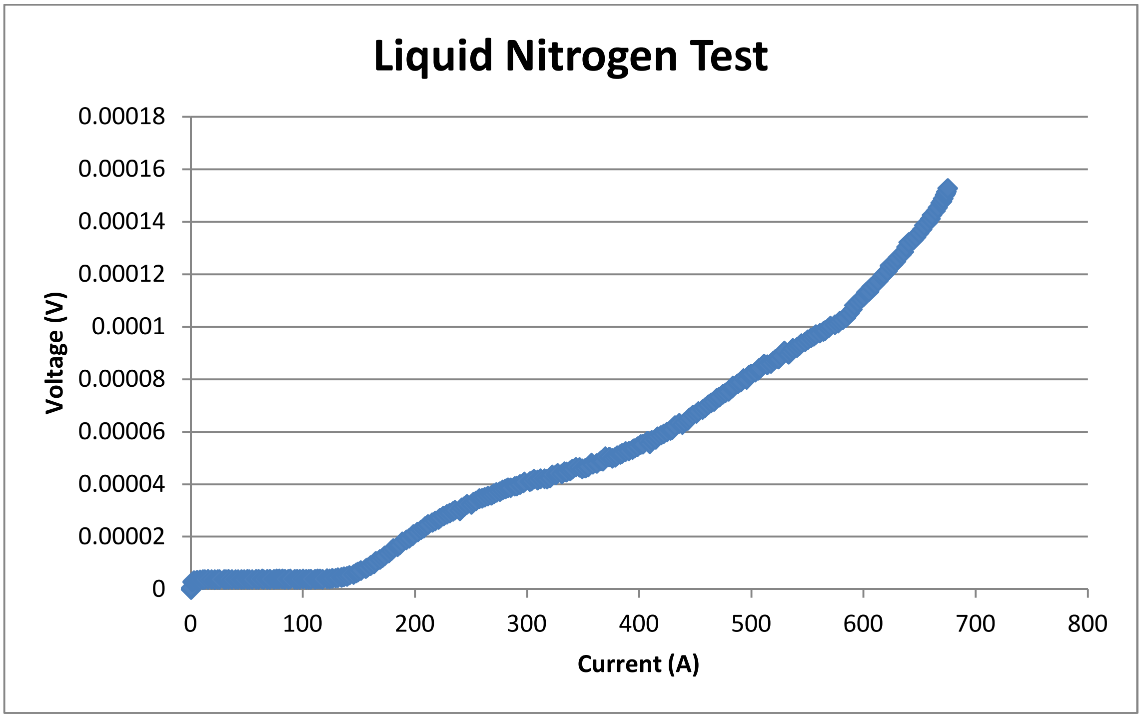
- Just to note that most of the parts used were provided from scrap by the machine shop. This greatly reduced the cost of buying said material from outside companies.

10. Results and Discussion

The main concern throughout the entire project was keeping the fragile HTS tapes superconducting while they were being heated up and moved around constantly. The actual fragility of HTS is widely debated. While some scientist claim that heating it up to 200 degrees Celsius more than once will absolutely destroy it, others say that it can be heated up to 250+ degrees Celsius and suffer no negative consequences. Since this was not an exact science the HTS was heated up only once to 200 degrees Celsius in order to have a relatively safe safety factor.

The first test was done with liquid nitrogen which can reach temperatures near 77 Kelvin. The reason for this test was to see if the HTS taps that replaced a section of the current leads would still be superconducting in spite of the ways that could have damaged it mentioned in the last paragraph. It is important to note that only one lead was tested and not all eight due to the limited amount of resources that were available, the liquid nitrogen. Two leads were tested with current ramping up from 0 to 640 amps at 4 volts. The graph below shows the voltage vs. current graph and since voltage is related to current by the equation

$$V = IR$$



the flat line at the beginning shows that even though the current increased, the voltage did not. This means that there was no resistance in the tape and by definition, superconducting. The spike in the graph is represented by what is known as critical current density or when the current is so great that the wire or tape superconducting will revert back to its normal state. This critical current is different for all materials at various conditions. A closer look at the graph below will show that the tape stops being superconducting at about 150 amps.

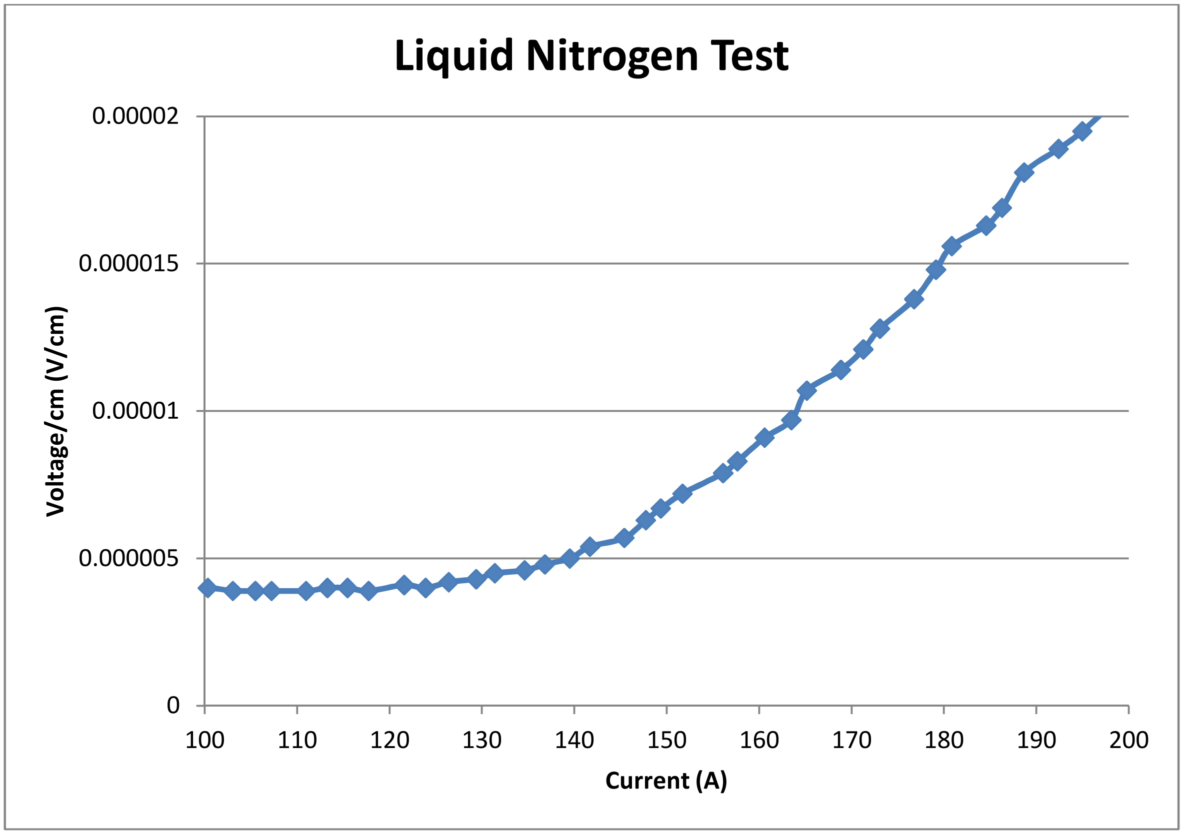


Figure 10

Although this test may look inconclusive, one must remember that liquid nitrogen is only at 77 Kelvin and that the actual sample tests will be performed at liquid helium temperatures which are 4.2 Kelvin. This temperature difference will vastly affect the superconducting properties of the HTS tape. It is also important to note that while the voltage is increasing, it is doing it very slowly, as one can see from the Y axis, showing that it is transferring into a mixed state of superconductivity and not fully returning to its static properties.

Once the liquid nitrogen test proved successful, the probe was put into liquid helium at actual testing temperatures. Judging from the graph below, the test was successful due to the graphs trend line being horizontal and not at an incline or in any exponential form.

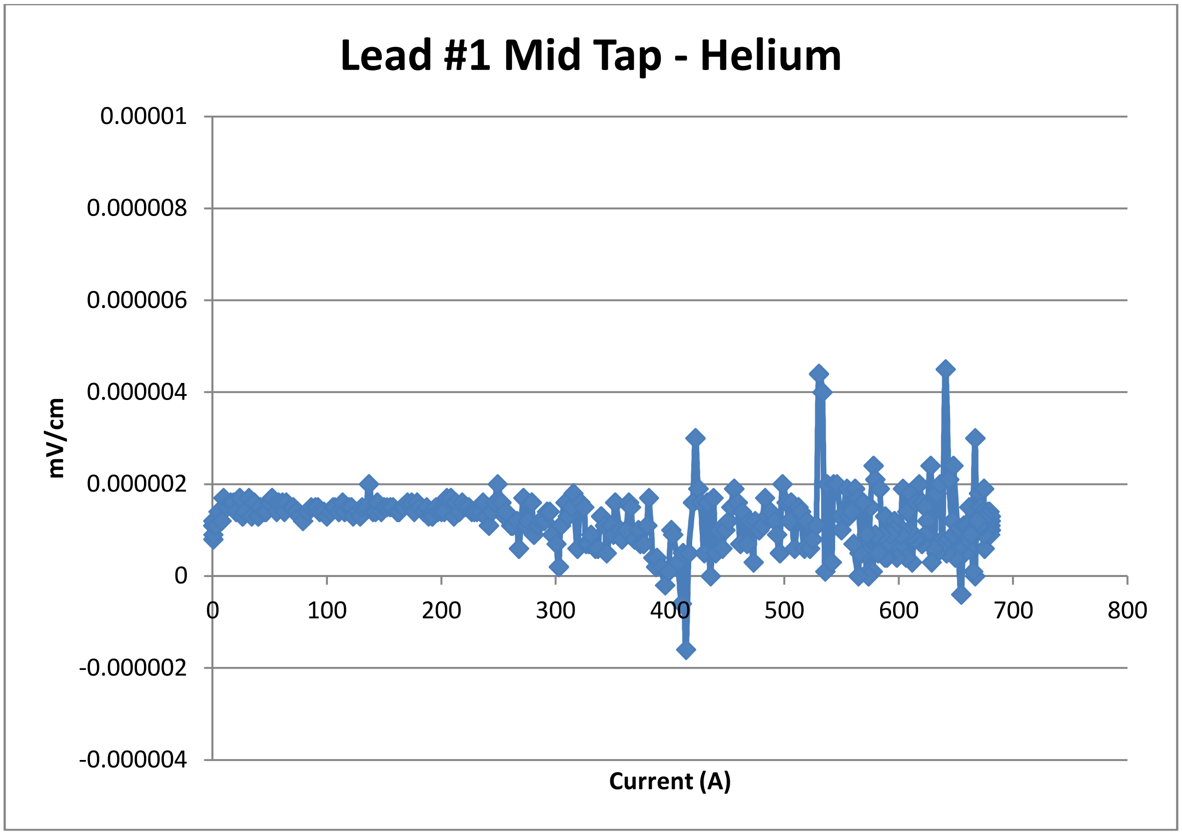


Figure 11

This shows that there was no resistance in the graph while the current was increasing. The fluctuations shown are the result of faulty voltage tap wiring and the lagging of the voltage taps with the change of the system current density. Note that the graph is labeled mid tap, meaning that the voltage taps were placed in the center of the HTS strip and not on the ends, measuring only the resistance in the center of the tape. This becomes important when looking at the graph below showing voltage taps that span the entire length of the HTS strip from end to end.

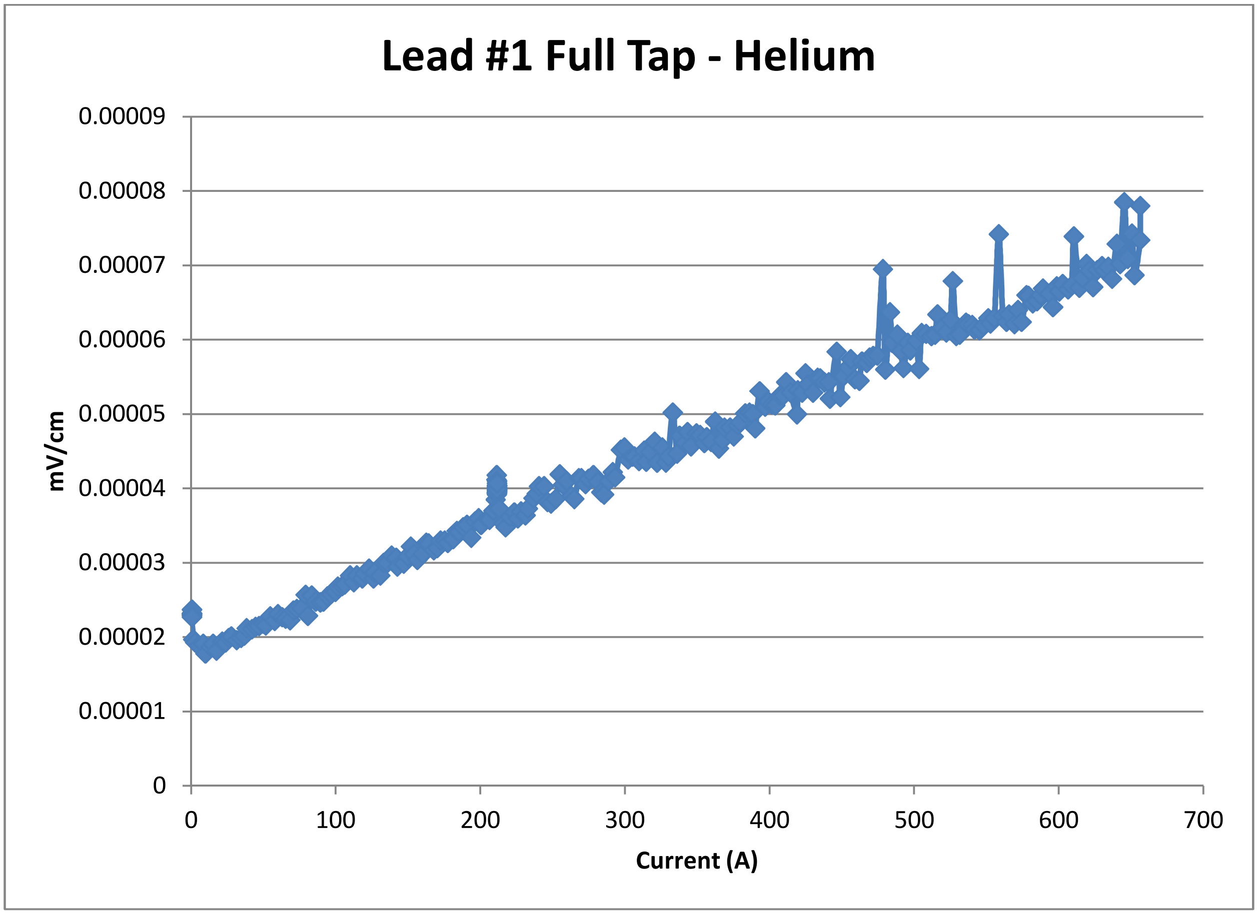


Figure 12

As one will notice the voltage is increasing with respect to current, showing that there is resistance in the lead. When the current is flowing through the system there is a length in the superconducting material where some of the current is shared in the surrounding copper layers and not yet fully transitioned into the YBCO, or HTS, material. The length is known as the current transition length with the current sharing taking place in the tape. This means that the resistance shown is in the copper layer and not the superconducting YBCO. The two graphs shown along with similar graphs for other leads can be found in the index.

Some problems that were run into during are testing included the samples being poorly soldered on to the sample holder. This was mainly due to the small surface area in which to solder and will not be encountered with the actual testing samples as they are small wires rather that thick tapes that were used in this testing. Another problem would be faulty voltage tap wiring for some of the leads that made it impossible to get accurate recordings for. However, the unmeasured leads still had superconducting properties because if they weren't, a mass flux of helium gas would have be forced out of the exhaust vent due to the quenching of a sudden generation of heat from resistance.

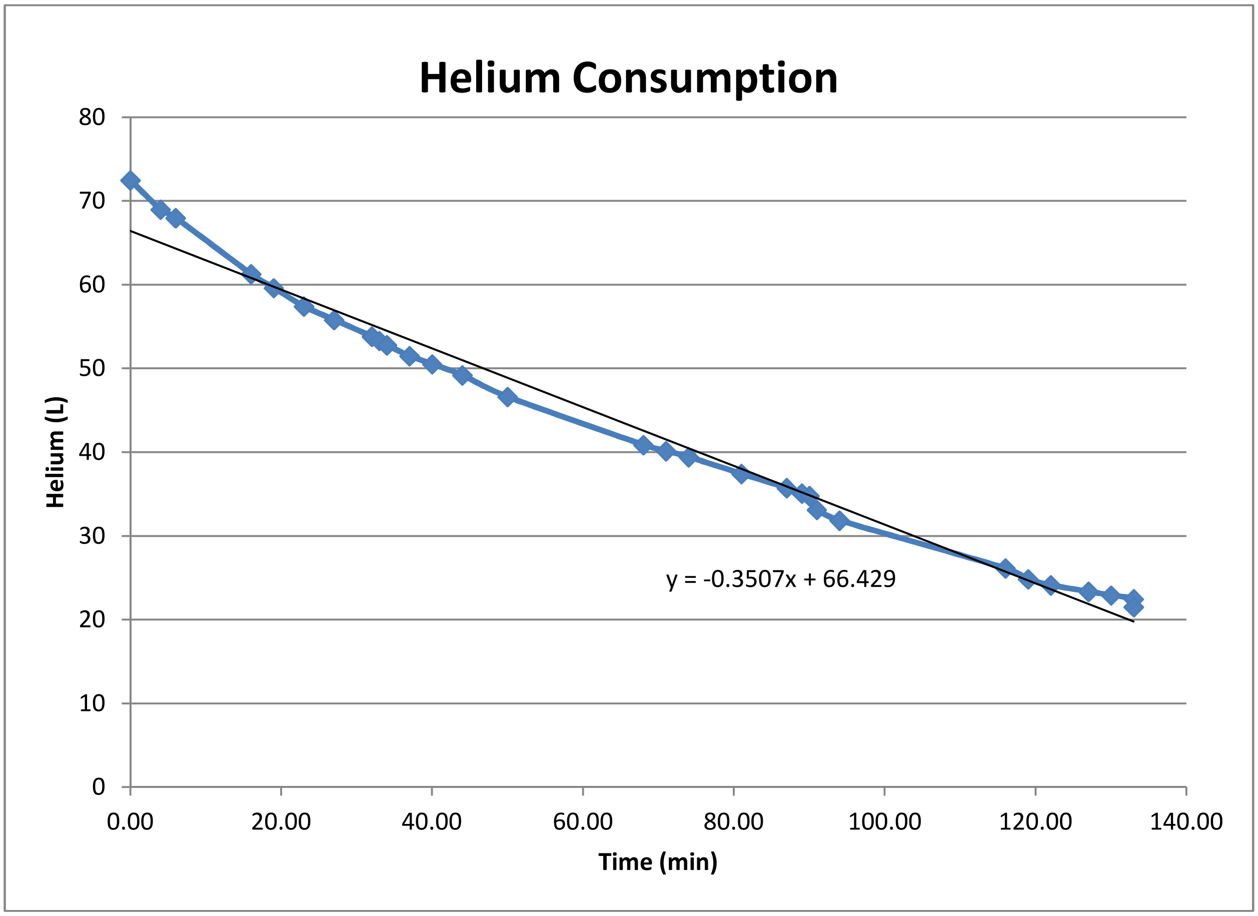


Figure 13

The graph above shows the helium consumption throughout the entire test. At different intervals throughout the testing, the time and liquid level was noted in the cryostat containing the cryogenic probe. The average rate of consumption was about .35 liters per minute, and a total of 53 liters was lost during the entire testing cycle which lasted about 130 minutes. From previous tests with the original probe it was measured to have lost 100 liters in the same amount of time. This gives an average of 50% liquid helium and $250 savings per test.

11. Environmental, Health and Safety Issues

The assembly, manufacturing, preparing, and testing of this critical current probe was not without a few toxic chemicals and hazardous activates that will be discussed in the following pages.

Toxic Materials/ Harmful Devices

- **G-10**
  G-10 is a glass based epoxy resin and is made by producing thin cloth like layers and stacking them atop on another in order to be heated to form a solid, fibrous, composite structure. The primary benefit of G-10 is its very low thermal conductivity and good insulation, which is valued with working in cryogenic conditions that require little to no heat transfer from the surrounding air. In this project G-10 was used as spacers to keep the current leads from contacting one another within the steel casing and to hold together the sample holder located at the bottom of the probe. These parts required machining and as a result G-10 dust was kicked up into the air from grinding down or drilling holes into. Because of its abrasive fibrous nature, G-10 dust can damage the lungs if inhaled and over time could even cause serious forms of cancer. This is why a face mask was used on whoever was handling G-10 in this manner.


Figure 23 - G10 material

- **Flux**
  Flux is a chemical used in soldering that helps prevent oxidation and acts as a wetting agent that helps keep the contact of the solder to the material. Flux was used in the project to

Figure 24 - Flux

solder together a total of 48 strands of HTS (High Temperature Superconductor) into 6 different strips. Flux is very toxic. Its fumes, when inhaled, can cause occupational asthma and its chemical composition can be very harmful to humans. This is why when working with flux, gloves, goggles, and ventilation were always used.

- **Cutting Fluid**

  Cutting fluid was used when machined metal in order cool down the constantly heated drills. This was probably the least concerning chemical agent, but it was necessary to avoid contact by properly washing the material of the cutting fluid. Cutting fluid can irritate the skin due to its chemical composition and synthetic fluids are also hosts to growing bacteria as they can capture dust, hair, and skin that regularly fall off people.
- **Machining Hazards**

  The machines used to create the parts also came with their own hazards. This ranged from bits of metal flying off the mills to proper use of the equipment. This was easily avoided by wearing gloves and eye protection where appropriate and using caution around the machines.
- **Heating Hazards**

  Large Aluminum blocks were used to heat the leads and HTS tapes in order to form a complete soldering of our materials. Because of the delicate nature of the HTS tapes a controlled temperature was needed between 190 and 200 Degrees Celsius to melt the solder, but not damage the HTS leads. This specific temperature was achieved by using cartridge heaters, long cylindrical rods that when attached to a voltage source it outputs large amounts of heat. The cartridge heaters were attached to a temperature control device that would not allow the aluminum blocks to go over a certain temperature. These high temperatures were represented in the aluminum which would easily burn the skin if one was not wearing furnace gloves to properly handle them.

Figure 25 - Heating device

Preparing Safety Precautions

- **Handling of Liquid Helium/Nitrogen Dewar**

  As stated many times before, liquid nitrogen and oxygen are necessary in order to complete our experiment and to obtain results. Due to the highly compressed nature of these two fluids, the temperatures reach 77 Kelvin and 4.2 Kelvin for Nitrogen and Helium respectively and both must be stored in large dewars as shown below. To prevent the rapid expansion of air, a vacuum layer between the liquid agent and the air in the dewar is required to hinder any heat being transferred in. If one is transporting a dewar, large, well ventilated areas must be accessible at all times or suffocation from the removal of air by the helium or

Figure 26 - Liquid Helium

nitrogen gas may result. The freezing temperatures of the liquids and gas must also be watched and must never come into contact with skin at any time. Any contact will result in freezer burn/frostbite or loss of limb.

- **Electric Current**

  To test the samples, an upwards of 1,000 amps of electrical current can run into any of the 6 top connectors and down through the current leads. While the test is being run, absolutely no contact must come within the testing probe in general as to avoid a deadly electric shock.

- **Weight**

  The critical current probe can weigh an upwards of 50 to 100 pounds and must be lifted with a small crane in order to fit within the cryostat. Avoidance of the probe during lifting was taken in order to reduce the chances of the crane falling and causing harm.

- **Environment**

  During the critical current test there is no harm to the environment. Escaping helium gas is minimal and is not dangerous to the environment. Most of the evaporated gas from the experiment is recycled into the NHMFL helium system for future use.

  The health and safety issues building the probe are the standards health and safety issues for machine shops. The probe will be created and partially built in one of the NHMFL machine shops so all safety protocols will be followed according to NHMFL lab safety standards. During the actual testing there are safety issues for those who operate the test. Only trained personnel who have taken NHMFL safety courses can operate the test. These and all other safety issues associated with liquid helium and critical current testing are covered in these safety courses. If all safety instructions and protocols are followed there is little danger to the operator of the test.

12. Conclusions

When this project was assigned, little knowledge about the subject was known by the design members. An entire semester was dedicated to researching currently used probes and cryogenics, in addition to designing a useful probe that will save helium. Several different concepts to reduce heat transfer as well as increase productivity were developed. Some of these solutions were discarded for reasons such as impracticality or being unbeneficial. This included the fins being added onto the copper leads, due to the fact that there was no thread long enough in order to make fins inside the copper. The solutions that were shown to be practical within a certain time frame and resources, were used in the final design. This design was approved by our sponsors for production and implementation.

The manufacturing of this probe began with ordering materials from various different wholesaler and distributers. Every part had to be properly analyzed in order to determine the amount and seller from which it would come. This helped to increase spending efficiency and allowed better use of the little money provided for the project. However, a few problems did arise; for example, the G-10 tube that was ordered to become the G-10 jacket came in pieces rather than as one portion. This led to an overflow of material and a very high cost which should have been an of hand expenditure. Luckily, this was not an issue because the length of one portion was just long enough to create the G-10 jacket and the cost did not run over the budget assigned. Another issue with was a bottleneck through the ordering of parts. Because a majority of the parts on this project was interdependent, certain areas could not be completed until a part came in and this caused a backup resulting in the loss of valuable time.

As the parts arrived, they were submitted to the appropriate machine shop with the appropriate drawings for completion. The machine shops were easy to deal with and finished the parts relatively quickly. Simple problems were encountered such as the holes for screws, set screws, or bolts did not match up or were the incorrect size and had to be resized.

During assembly, a few problems existed that were easily fixed. This included the bottom spacers being too big to fit inside the G-10 casing and the wedges in the copper leads had to be re cut because they were too small. The assembly had to be approached systematically and a top to bottom assembly method was created due to the fact that once one part was one on, another would have been prevented from taking back off and on again. The probe may be taken apart relatively easily. Each time the probe is disassembled, however, it is more likely that the HTS tapes will be damaged and more will have to be made. This is a time consuming process that should not have to be done more than the initial first time.

Preliminary tests were done on the probe using liquid nitrogen. Leads 1 and 5 were tested to see if soldering the HTS tapes together damaged their superconducting properties. The test was run with the current increasing to 0 to 640 amps with 4 volts while the probe was submerged in the helium bath, with the liquid level being well above the HTS portion. According to the results of the first test, the voltage, and therefore the resistance, did not increase with increasing current up to 150 amps and therefore the leads remained superconducting after assembly.

Once the preliminary tests were over, the probe was placed inside the cryostat to begin testing with liquid helium. Aside for minor problems such as faulty voltage taps and lagging, all of the leads proved to be superconducting. Some resistance was shown in the graph, however this was later found out to be due to the transition length and current sharing being picked up by the voltage taps. The helium rate of consumption was at a steady average of about 0.35 liters per minute with an average of about 50% helium savings per test compared to the existing probe.

It is important to note that this kind of probe stands out among the rest at the National High Magnetic Field Laboratory as it possess 100% HTS leads without the support of exterior copper. This being, said the making of the leads was based on very little prior knowledge and although the process worked, much room for improvement and for things to be learned.

13. Acknowledgments

Dr. Hovsapian, Adjunct Faculty, Florida State University, Mechanical Engineering, Ph.D.

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Dr. Trociewitz, Associate Scholar/Scientist, ASC

Dr. Matthieu Dalban-Canassy, Postdoctoral Associate

Applied Superconductivity Center

NHMFL

Bill Sheppard, NHMFL Machine Shop

Robert Stanton, NHMFL

Bill Starch, ASC Machine Shop

Dimitri Arnouts

14. Engineering Drawings

See attached file on website for drawings

15.References

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16.Biographical Sketch

Amy Eckerle (23)

Amy Eckerle is a Mechanical Engineering student at Florida State University. She started her college career doing dual enrollment through her high school at Pensacola Junior College in Spring 2006. She graduated Salutatorian of Pine Forest High School in 2006. She spent one year in Auburn University's Mechanical Engineering program. In addition to being a full time student, she owns a successful business which is called Amy Eckerle, LLC in which she teaches horseback riding lessons to equestrians of all ages and takes several horses in training each month. She has spent the last 8 months working on a critical current probe with this design team and has worked closely with the Applied Superconductivity Center and the National High Magnetic Field Laboratory during this time.

Andrew Whittington (23)

Andrew Whittington is a Mechanical Engineering student at Florida State University. He will be graduating April 2012. He has worked as a research assistant at the ASC since Jan 2011 and hopes to pursue a masters degree in Mechanical engineering with an emphasis on materials science. He has spent the last 8 months working on a critical current probe with this design team and has worked closely with the Applied Superconductivity Center and the National High Magnetic Field Laboratory during this time.

Philip Witherspoon (22)

Philip Witherspoon is a Mechanical engineering student at Florida State University and will be graduating in April 2012. He was born in Japan and lived in India for four years. He has been enlisted in the Navy since February 2010. He plans to get an MBA and open an engineering firm in the future. He has spent the last 8 months working on a critical current probe with this design team and has worked closely with the Applied Superconductivity Center and the National High Magnetic Field Laboratory during this time.

17. Appendix

Appendix A – Copper and HTS Lead Calculations

A.1 One Dimensional Heat Conduction on Copper Leads

One Deminsional Heat Conduction: no convection

$k_{cu} := 15\frac{kW}{m \cdot K}$ $\quad T_s := 300K$ $\quad L := 1.2$ $\quad kJ := 1000J$

$A_{cu} := (6.7mm)^2$ $\quad T_f := 4.2K$ $\quad h_{fg\_he} := 21\frac{kJ}{kg}$

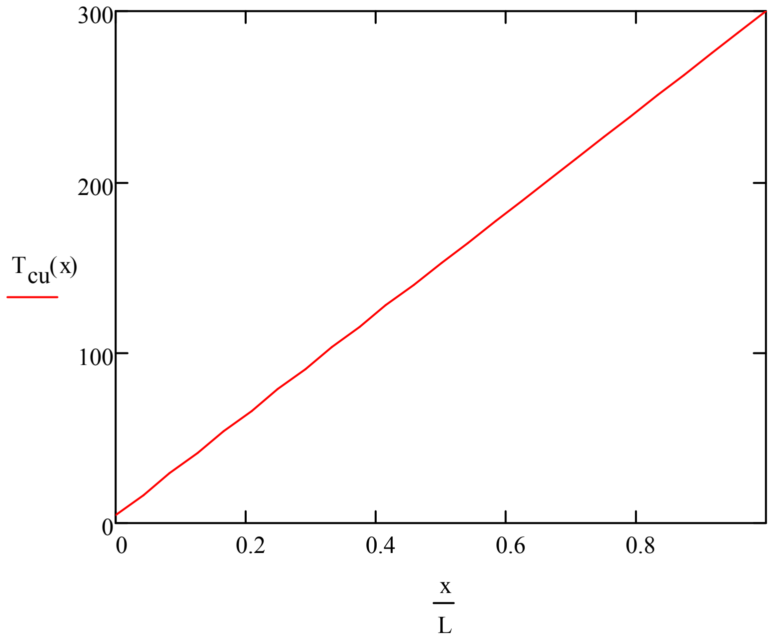
$$Q_{cond} := k_{cu} \cdot A_{cu} \cdot \frac{T_s - T_f}{L \cdot m}$$

$$Q_{cond} = 165.981 \cdot W$$

$$\frac{d}{dx}T_{cu}(x) = \frac{Q_{cond}}{k_{cu} \cdot A_{cu}}$$

$$x := 0m, .05m .. L \cdot m$$

$$T_{cu}(x) := \frac{Q_{cond}}{k_{cu} \cdot A_{cu}}x + 4.2K$$



$$m_{burnoff\_cond} := \frac{Q_{cond}}{h_{fg\_he}}$$

$$m_{burnoff\_cond} = 7.904 \times 10^{-3}\frac{kg}{s}$$

A.2 One Dimensional Heat Conduction and Convection on Copper Leads

Constants for calculations with convection

$$ID_{steelcasing} := 2.375in - 2 \cdot .035in$$

$$h_{fg} := .0845 \frac{kJ}{mol} \qquad MW_h := 4 \frac{gm}{mol} \qquad m_{flow} := \frac{Q_{cond}}{\frac{h_{fg}}{MW_h}} \qquad C_{p\_he} := (5.193) \frac{kJ}{kg \cdot K}$$

$$m_{flow} = 7.857 \times 10^{-3} \frac{kg}{s} \qquad P_{he} := 1.0132$$

$$A_{steelcasing} := \pi \frac{\left(ID_{steelcasing}\right)^2}{4}$$

Distance in meters starting in the cryogenic portion

Temperature Profile of Leads before convection

$$x := \begin{pmatrix} 0.05 \\ 0.1 \\ 0.15 \\ 0.2 \\ 0.25 \\ 0.3 \\ 0.35 \\ 0.4 \\ 0.45 \\ 0.5 \\ 0.55 \\ 0.6 \\ 0.65 \\ 0.7 \\ 0.75 \\ 0.8 \\ 0.85 \\ 0.9 \\ 0.95 \\ 1 \\ 1.05 \\ 1.1 \\ 1.15 \\ 1.2 \end{pmatrix} \qquad T_{cu} := \begin{pmatrix} 16.525 \\ 28.85 \\ 41.175 \\ 53.5 \\ 65.825 \\ 78.15 \\ 90.475 \\ 102.8 \\ 115.125 \\ 127.45 \\ 139.775 \\ 152.1 \\ 164.425 \\ 176.75 \\ 189.075 \\ 201.4 \\ 213.725 \\ 226.05 \\ 238.375 \\ 250.7 \\ 263.025 \\ 275.35 \\ 287.675 \\ 300 \end{pmatrix}$$

Temperature profile of gas

$$T_{he}(x) := 4.2 \cdot \exp(3.219 \cdot x)$$

$T_{he}(x) =$

	0
0	4.933
1	5.795
2	6.807
3	7.996
4	9.392
5	11.032
6	12.958
7	15.221
8	17.879
9	21.001
10	24.669
11	28.976
12	34.037
13	39.98
14	46.962
15	55.163
16	64.795
17	76.11
18	89.401
19	105.013
20	123.351
21	144.891
22	170.193
23	199.913

Various Constants of helium dependent on temperature

$$\mu_{he} := \left[1.865 \cdot 10^{-5} \left(\frac{T_{he}(x)}{273.3} \right)^{0.7} \right] \frac{kg}{m \cdot s}$$

$$\rho_{he} := \left[0.17623 \frac{P_{he}}{\left(\frac{T_{he}(x)}{273.3} \right)} \left[1 + .053 \cdot 10^{3} \cdot \frac{P_{he}}{\left(\frac{T_{he}(x)}{273.3} \right)^{1.2}} \right]^{-1} \right] \frac{kg}{m^{3}}$$

$$k_{he} := \left[.144 \left(1 + 2.7 \cdot 10^{-4} \cdot P_{he} \right) \left(\frac{T_{he}(x)}{273.3} \right)^{\left[.71 \left(1 - 2 \cdot 10^{-4} \cdot P_{he} \right) \right]} \right] \frac{W}{m \cdot K}$$

$$\beta := \frac{1}{T_{he}(x)} \cdot \frac{1}{K}$$

$$\text{thermaldiffus} := \frac{k_{he}}{\rho_{he} \cdot C_{p\_he}}$$

$$\nu := \frac{\mu_{he}}{\rho_{he}}$$

Surface contact, Raleigh, Prandtl, and Nusselt for vertial plates forced convection

$$T_{surface} := \frac{T_{cu} \cdot K + T_{he}(x) \cdot K}{2}$$

$$Pr := \frac{C_{p\_he} \cdot \mu_{he}}{k_{he}}$$

$$Ra := \frac{V_{he} \cdot x \cdot m}{\nu}$$

$$Nu := \overrightarrow{\left[.453 Ra^{0.5} \cdot Pr^{\left(\frac{1}{3} \right)} \right]}$$

Measured mass flow rate/Velocity

$$m_{flow\_measured} := \frac{50l}{hr} \cdot .125 \frac{kg}{l} \qquad m_{flow\_measured} = 1.736 \times 10^{-3} \frac{kg}{s}$$

$$V_{he} := \frac{m_{flow\_measured}}{\rho_{he} \cdot \frac{\left[\pi \cdot (.254m)^{2} \right]}{4}}$$

Range of values for the dimensionless constants

Ra =

	0
0	$1.526\cdot10^{3}$
1	$2.727\cdot10^{3}$
2	$3.654\cdot10^{3}$
3	$4.353\cdot10^{3}$
4	$4.862\cdot10^{3}$
5	$5.213\cdot10^{3}$
6	$5.433\cdot10^{3}$
7	$5.548\cdot10^{3}$
8	$5.576\cdot10^{3}$
9	$5.536\cdot10^{3}$
10	$5.441\cdot10^{3}$
11	$5.303\cdot10^{3}$
12	$5.133\cdot10^{3}$
13	$4.939\cdot10^{3}$
14	$4.727\cdot10^{3}$
15	$4.505\cdot10^{3}$
16	$4.277\cdot10^{3}$
17	$4.046\cdot10^{3}$
18	$3.816\cdot10^{3}$
19	$3.589\cdot10^{3}$
20	$3.366\cdot10^{3}$
21	$3.151\cdot10^{3}$
22	$2.943\cdot10^{3}$
23	$2.744\cdot10^{3}$

Nu =

	0
0	15.709
1	20.988
2	24.284
3	26.49
4	27.98
5	28.956
6	29.548
7	29.842
8	29.902
9	29.778
10	29.505
11	29.113
12	28.627
13	28.066
14	27.445
15	26.778
16	26.077
17	25.35
18	24.605
19	23.848
20	23.087
21	22.324
22	21.564
23	20.81

Pr =

	0
0	0.7
1	0.698
2	0.697
3	0.696
4	0.695
5	0.694
6	0.693
7	0.692
8	0.691
9	0.69
10	0.689
11	0.687
12	0.686
13	0.685
14	0.684
15	0.683
16	0.682
17	0.681
18	0.68
19	0.679
20	0.678
21	0.677
22	0.676
23	0.674

Convection coefficient and range of values

$$h := \frac{\overrightarrow{\left(Nu \cdot k_{he}\right)}}{x \cdot m}$$

$h =$

	0
0	2.618
1	1.961
2	1.696
3	1.555
4	1.473
5	1.424
6	1.396
7	1.383
8	1.381
9	1.388
10	1.401
11	1.421
12	1.446
13	1.476
14	1.51
15	1.548
16	1.591
17	1.637
18	1.688
19	1.742
20	1.801
21	1.863
22	1.93
23	2.001

$\cdot \frac{W}{m^2 \cdot K}$

```
$h_{avg} :=$
    $i \leftarrow 0$
    $h_{tot} \leftarrow 0$
    while $i < 24$
        $h_{tot} \leftarrow h_{tot} + h_i$
        $i \leftarrow i + 1$
    $\frac{h_{tot}}{i}$
```

$$h_{avg} = 1.639 \frac{W}{m^2 \cdot K}$$

$\Delta x := (x_1 - x_0)m$ $\quad SA_{lead} := 4\cdot 6.7mm$ $\quad hours := 3hr$ $\quad Numtest\_year := 50$ $\quad dollar := 1$

$\Delta x = 0.05m$

$\rho_{he\_L} := .125\frac{kg}{L}$ $\quad cost := 5\frac{dollar}{L}$

```
Q_conv := | i ← 0
          | Q_conv ← 0
          | while i < 24
          |     | $Q_{conv} \leftarrow Q_{conv} + SA_{lead}\cdot(\Delta x)\cdot h_i\cdot\left(T_{cu_i} - T_{he}(x)_i\right)K$
          |     | i ← i + 1
          | Q_conv
```

$Q_{conv} = 5.322W$

$Q_{tot} := Q_{cond} - Q_{conv}$

$Q_{tot} = 160.659W$

$$m_{burnoff\_cond\_conv} := \frac{Q_{tot}}{h_{fg\_he}}$$

$$m_{burnoff\_cond\_conv} = 7.65\times 10^{-3}\frac{kg}{s}$$

$\Delta m_{burnoff} := m_{burnoff\_cond} - m_{burnoff\_cond\_conv}$

$$\Delta m_{burnoff} = 2.534\times 10^{-4}\frac{kg}{s}$$

$He_{saved\_year} := \Delta m_{burnoff}\cdot hours\cdot Numtest\_year$

$He_{saved\_year} = 136.845kg$

$$He_{saved\_cost} := \frac{He_{saved\_year}}{\rho_{he\_L}}\cdot cost$$

$He_{saved\_cost} = 5.474\times 10^{3}\cdot dollar$

Temperature Profile of Lead with Convection

Equations from line of best fit through excel

$h(y) := 2.2296y^2 - 2.7301y + 2.207$

$\text{He\_temp}(y) := 4.2 \cdot \exp(3.219)$

$SA_{lead} := \left(\frac{6.7}{1000} \cdot L\right)$

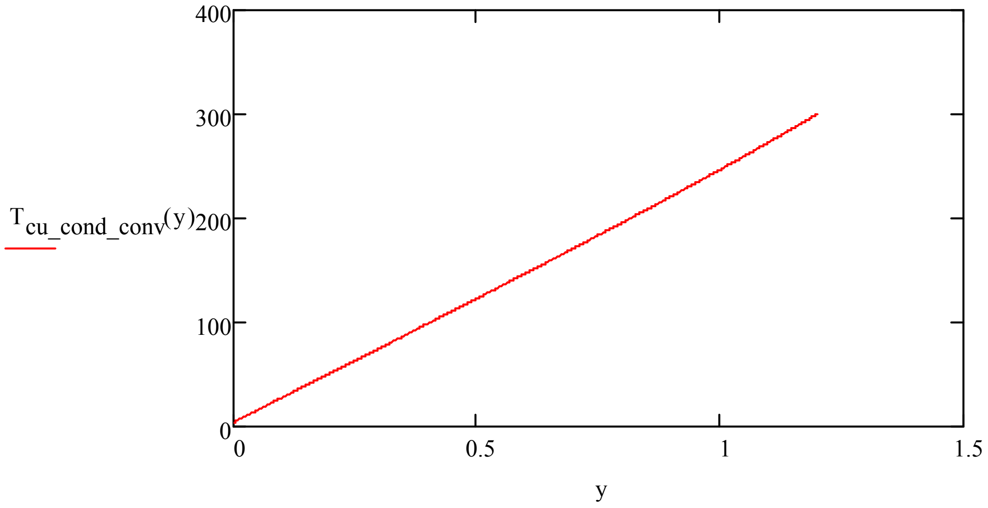
$T_{cu\_cond}(y) := -9.323y^2 + 260.2y$

Given

$$\frac{d}{dy} T_{cu\_cond\_conv}(y) = \frac{Q_{tot} \cdot \left(\frac{1}{W}\right) + \left(7.275y^2 + 2.7835y + 1.7945\right) \cdot SA_{lead} \cdot \left[\left(-9.323y^2 + 260.2y\right) - (4.2 \cdot \exp(3.219))\right]}{15000 A_{cu} \cdot \left(\frac{1}{m^2}\right)}$$

$T_{cu\_cond\_conv}(0) = 4.2$

$T_{cu\_cond\_conv} := \text{Odesolve}(y, 1.2, 24)$



```
T_cu_cond_conv_profile := | i ← 0
                          | c ← 0.05
                          | T ← 0
                          | while i < 23
                          |     | $T_i$ ← $T_{cu\_cond\_conv}(c)$
                          |     | i ← i + 1
                          |     | c ← c + .05
                          | T
```

Temperature after convection (incremented by .05 m)

$T_{cu\_cond\_conv\_profile} =$

	0
0	16.02
1	27.845
2	39.678
3	51.518
4	63.37
5	75.237
6	87.122
7	99.032
8	110.972
9	122.949
10	134.97
11	147.044
12	159.18
13	171.387
14	183.677
15	196.059
16	208.547
17	221.153
18	233.892
19	246.776
20	259.821
21	273.042
22	286.457
23	

Temperature before convection (incremented by .05 m)

$T_{cu} =$

	0
0	16.525
1	28.85
2	41.175
3	53.5
4	65.825
5	78.15
6	90.475
7	102.8
8	115.125
9	127.45
10	139.775
11	152.1
12	164.425
13	176.75
14	189.075
15	201.4
16	213.725
17	226.05
18	238.375
19	250.7
20	263.025
21	275.35
22	287.675
23	300

A.3 Analysis of HTS leads

Calculation for New HTS Probe

$$T_{cu\_cond\_conv}(.1218) = 33.003$$

0.1218 meter up from the center of the magnet will be how long the HTS lead will need to be for the starting point to be at 33K, according to temperature profile of existing lead

$$k_{HTS} := 15000 \frac{W}{m \cdot K} \qquad A_{cross\_cu} := \frac{\pi \cdot (.3125in)^2}{4} \qquad A_{cross\_HTS} := 4.1mm \cdot \left(8.8 \cdot 10^{-6} m\right)$$

$$k_{cu} := 15000 \frac{W}{m \cdot K} \qquad \Delta T_{cu} := 300K - 33K \qquad A_{cross\_HTS} = 3.608 \times 10^{-8} m^2$$

$$\Delta T_{HTS} := 33K - 4.2K$$

Heat flux balance between copper lead and HTS lead without convection

Given

$$1.2 \cdot m = L_{cu} + L_{HTS}$$

$$\frac{k_{HTS}}{L_{HTS}} \Delta T_{HTS} = \frac{k_{cu}}{L_{cu}} \Delta T_{cu}$$

$$\mathrm{Find}(L_{cu}, L_{HTS}) \rightarrow \begin{pmatrix} \frac{534 \cdot m}{493} \\ \frac{288 \cdot m}{2465} \end{pmatrix}$$

the HTS length according to heat flux balance is .1168 meters, this means that we can assume the orginal length of 0.1218 meters with convection is accurate.

$$L_{HTS} := .1218m \qquad L_{cu} := 1.2m - .1218m$$

$$A_{cross\_HTS} = 3.608 \times 10^{-8} m^2$$

Cross sectional area of the whole HTS lead, just the copper part could not be found

The heat tranfered by the HTS lead to the helium bath

$$Q_{transfered\_HTS\_cond} := \frac{k_{HTS} \cdot A_{cross\_HTS}}{L_{HTS}} \Delta T_{HTS}$$

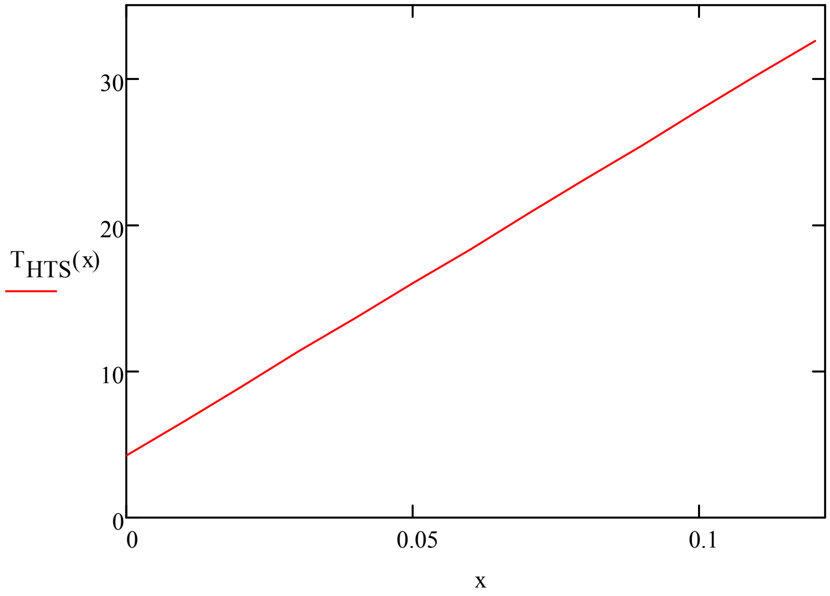
$$Q_{transfered\_HTS\_cond} = 0.128W$$

A.4 Analysis of HTS leads with One Dimensional Conduction

Temperature Profile of HTS lead without convection

$x := 0, .01 .. .1281$

$$T_{HTS}(x) := \frac{Q_{transfered\_HTS\_cond}}{\left(k_{HTS} \cdot A_{cross\_HTS}\right)} \cdot x \cdot m + 4.2K$$



Distance Profile in meters

$$x := \begin{pmatrix} 0.001 \\ .01 \\ .02 \\ .03 \\ .04 \\ .05 \\ .06 \\ .07 \\ .08 \\ .09 \\ .1 \\ .11 \\ .12 \\ .13 \end{pmatrix}$$

```
T_HTS := | i ← 0
         | c ← 0
         | while i < 13
         |     | T_{i+1} ← T_HTS(c)
         |     | T_0 ← T_HTS(.001)
         |     | c ← c + .01
         |     | i ← i + 1
         | T
```

Temperature Profile

$T_{HTS} =$

	0
0	0
1	4.2
2	6.565
3	8.929
4	11.294
5	13.658
6	16.023
7	18.387
8	20.752
9	23.116
10	25.481
11	27.845
12	30.21
13	32.574

K

A.5 Analysis of HTS leads with One Dimensional Conduction and Convection

Temperature profile of gas

$$T_{he}(x) := 4.2 \cdot \exp(3.219 \cdot x)$$

Various Constants of helium dependent on temperature

$$\mu_{he} := \left[1.865 \cdot 10^{-5} \left(\frac{T_{he}(x)}{273.3}\right)^{0.7}\right] \frac{kg}{m \cdot s}$$

$$\rho_{he} := \left[0.17623 \frac{P_{he}}{\left(\frac{T_{he}(x)}{273.3}\right)} \left[1 + .053 \cdot 10^{3} \cdot \frac{P_{he}}{\left(\frac{T_{he}(x)}{273.3}\right)^{1.2}}\right]^{-1}\right] \frac{kg}{m^{3}}$$

$$k_{he} := \left[.144\left(1 + 2.7 \cdot 10^{-4} \cdot P_{he}\right)\left(\frac{T_{he}(x)}{273.3}\right)^{\left[.71\left(1-2 \cdot 10^{-4} \cdot P_{he}\right)\right]}\right] \frac{W}{m \cdot K}$$

$$\beta := \frac{1}{T_{he}(x)} \cdot \frac{1}{K}$$

$$thermaldiffus := \frac{k_{he}}{\rho_{he} \cdot C_{p\_he}}$$

$$\nu := \frac{\mu_{he}}{\rho_{he}}$$

Surface contact, Raleigh, Prandtl, and Nusselt for vertial plates forced convection

$$Pr := \frac{C_{p\_he} \cdot \mu_{he}}{k_{he}}$$

$$Ra := \frac{V_{he} \cdot x \cdot m}{\nu}$$

$$Nu := \overrightarrow{\left[.453 Ra^{0.5} \cdot Pr^{\left(\frac{1}{3}\right)}\right]}$$

Measured mass flow rate/Velocity

$$m_{flow\_measured} := \frac{50 l}{hr} \cdot .125 \frac{kg}{l} \qquad m_{flow\_measured} = 1.736 \times 10^{-3} \frac{kg}{s}$$

$$V_{he} := \frac{m_{flow\_measured}}{\rho_{he} \cdot \frac{\left[\pi \cdot (.254 m)^{2}\right]}{4}}$$

Temperature profile of gas

$$T_{he}(x) := 4.2\cdot \exp(3.219\cdot x)$$

Various Constants of helium dependent on temperature

$$\mu_{he} := \left[1.865\cdot 10^{-5}\left(\frac{T_{he}(x)}{273.3}\right)^{0.7}\right]\frac{kg}{m\cdot s}$$

$$\rho_{he} := \left[0.17623\frac{P_{he}}{\left(\frac{T_{he}(x)}{273.3}\right)}\left[1 + .053\cdot 10^{3}\cdot\frac{P_{he}}{\left(\frac{T_{he}(x)}{273.3}\right)^{1.2}}\right]^{-1}\right]\frac{kg}{m^{3}}$$

$$k_{he} := \left[.144\left(1 + 2.7\cdot 10^{-4}\cdot P_{he}\right)\left(\frac{T_{he}(x)}{273.3}\right)^{\left[.71\left(1-2\cdot 10^{-4}\cdot P_{he}\right)\right]}\right]\frac{W}{m\cdot K}$$

$$\beta := \frac{1}{T_{he}(x)}\cdot\frac{1}{K}$$

$$thermaldiffus := \frac{k_{he}}{\rho_{he}\cdot C_{p\_he}}$$

$$\nu := \frac{\mu_{he}}{\rho_{he}}$$

Surface contact, Raleigh, Prandtl, and Nusselt for vertial plates forced convection

$$Pr := \frac{C_{p\_he}\cdot\mu_{he}}{k_{he}}$$

$$Ra := \frac{V_{he}\cdot x\cdot m}{\nu}$$

$$Nu := \overrightarrow{\left[.453 Ra^{0.5}\cdot Pr^{\left(\frac{1}{3}\right)}\right]}$$

Measured mass flow rate/Velocity

$$m_{flow\_measured} := \frac{50l}{hr}\cdot .125\frac{kg}{l} \qquad m_{flow\_measured} = 1.736\times 10^{-3}\frac{kg}{s}$$

$$V_{he} := \frac{m_{flow\_measured}}{\rho_{he}\cdot\frac{\left[\pi\cdot(.254m)^{2}\right]}{4}}$$

Range of values for the dimensionless constants

$Ra =$

	0
0	13.578
1	133.058
2	260.187
3	381.585
4	497.443
5	607.95
6	713.285
7	813.624
8	909.138
9	999.992
10	$1.086\cdot10^{3}$
11	$1.168\cdot10^{3}$
12	$1.246\cdot10^{3}$
13	$1.32\cdot10^{3}$

$Nu =$

	0
0	1.483
1	4.641
2	6.489
3	7.857
4	8.97
5	9.915
6	10.739
7	11.468
8	12.121
9	12.711
10	13.247
11	13.737
12	14.185
13	14.597

$Pr =$

	0
0	0.701
1	0.7
2	0.7
3	0.7
4	0.7
5	0.7
6	0.699
7	0.699
8	0.699
9	0.699
10	0.698
11	0.698
12	0.698
13	0.698

Convection coefficient and range of values

$$h := \frac{\overrightarrow{\left(Nu\cdot k_{he}\right)}}{x\cdot m}$$

$h =$

	0
0	11.047
1	3.53
2	2.525
3	2.085
4	1.827
5	1.653
6	1.526
7	1.429
8	1.352
9	1.29
10	1.238
11	1.194
12	1.156
13	1.124

$\cdot\frac{W}{m^{2}\cdot K}$

```
$h_{avg} :=$  $i \leftarrow 0$
              $h_{tot} \leftarrow 0$
              while  $i < 13$
                  $h_{tot} \leftarrow h_{tot} + h_{i+1}$
                  $i \leftarrow i + 1$
              $\frac{h_{tot}}{i}$
```

$$h_{avg} = 1.687\cdot\frac{W}{m^{2}\cdot K}$$

$L_{side1\_HTS} := 4.1\,\mathrm{mm}$ $\quad L_{side2\_HTS} := 8.8\cdot 10^{-6}\,\mathrm{m}$

$\Delta x := (x_2 - x_1)\,\mathrm{m}$ $\quad SA_{HTS} := 2\cdot L_{side1\_HTS} + 2\cdot L_{side2\_HTS}$

$\Delta x = 0.01\,\mathrm{m}$ $\quad cost := 5\,\frac{dollar}{l}$ $\quad dollar := 1$ $\quad hours := 3\,\mathrm{hr}$ $\quad Numtest\_year := 50$

$\rho_{he\_L} := .125\,\frac{kg}{l}$

$Q_{conv\_HTS} :=$

```
$i \leftarrow 0$
$Q_{conv} \leftarrow 0$
while $i < 13$
    $Q_{conv} \leftarrow Q_{conv} + SA_{HTS}\cdot(\Delta x)\cdot h_i\cdot\left(T_{HTS_i} - T_{he}(x)_i\cdot K\right)$
    $i \leftarrow i + 1$
$Q_{conv}$
```

$Q_{conv\_HTS} = 0.012\cdot W$

$Q_{transfered\_HTS\_cond} = 0.128\,W$

$Q_{HTS\_tot} := Q_{transfered\_HTS\_cond} - Q_{conv\_HTS}$

$Q_{HTS\_tot} = 0.116\,W$

$$m_{burnoff\_HTS} := \frac{Q_{HTS\_tot}}{h_{fg\_he}}$$

$m_{burnoff\_HTS} = 5.505\times 10^{-6}\cdot\frac{kg}{s}$

Calculations of helium burn off rate are incorrect due to errors

$m_{burnoff\_old\_probe} := 7.65\times 10^{-3}\,\frac{kg}{s}$

$\Delta m_{burnoff\_HTS\_old\_probe} := m_{burnoff\_old\_probe} - m_{burnoff\_HTS}$

$\Delta m_{burnoff\_HTS\_old\_probe} = 7.644\times 10^{-3}\,\frac{kg}{s}$

$$He_{saved\_year} := \frac{\Delta m_{burnoff\_HTS\_old\_probe}\cdot hours}{\rho_{he\_L}}$$

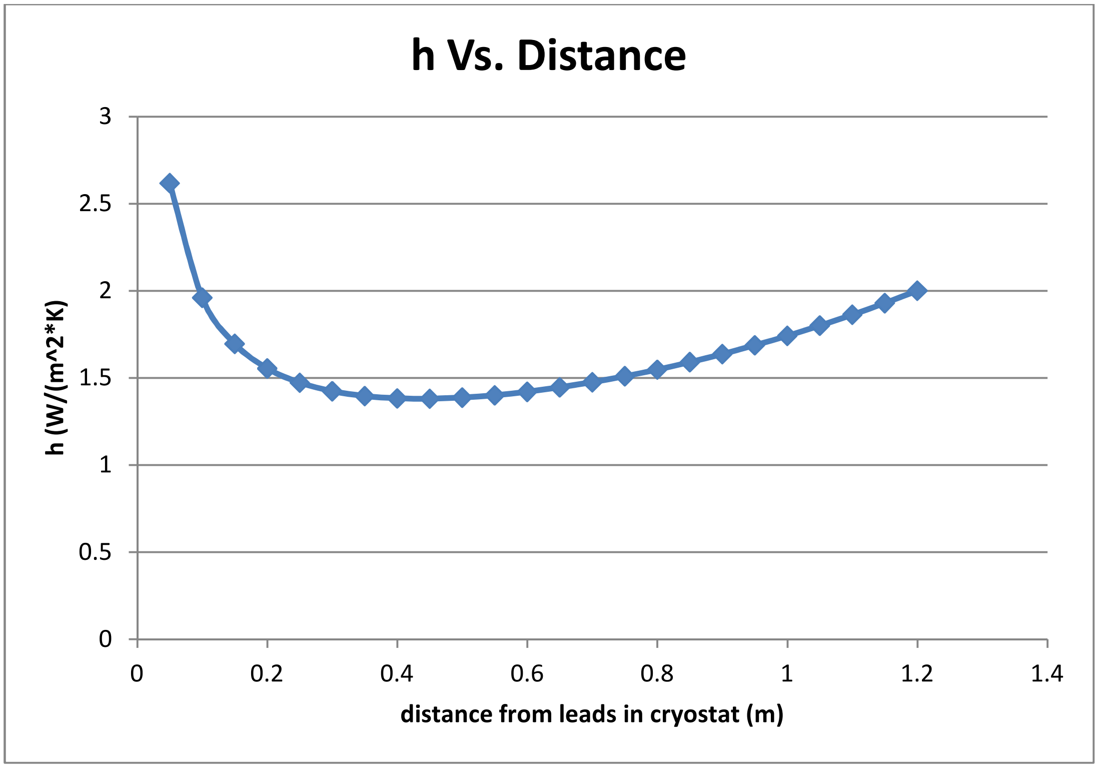
$He_{saved\_year} = 660.484\,l$

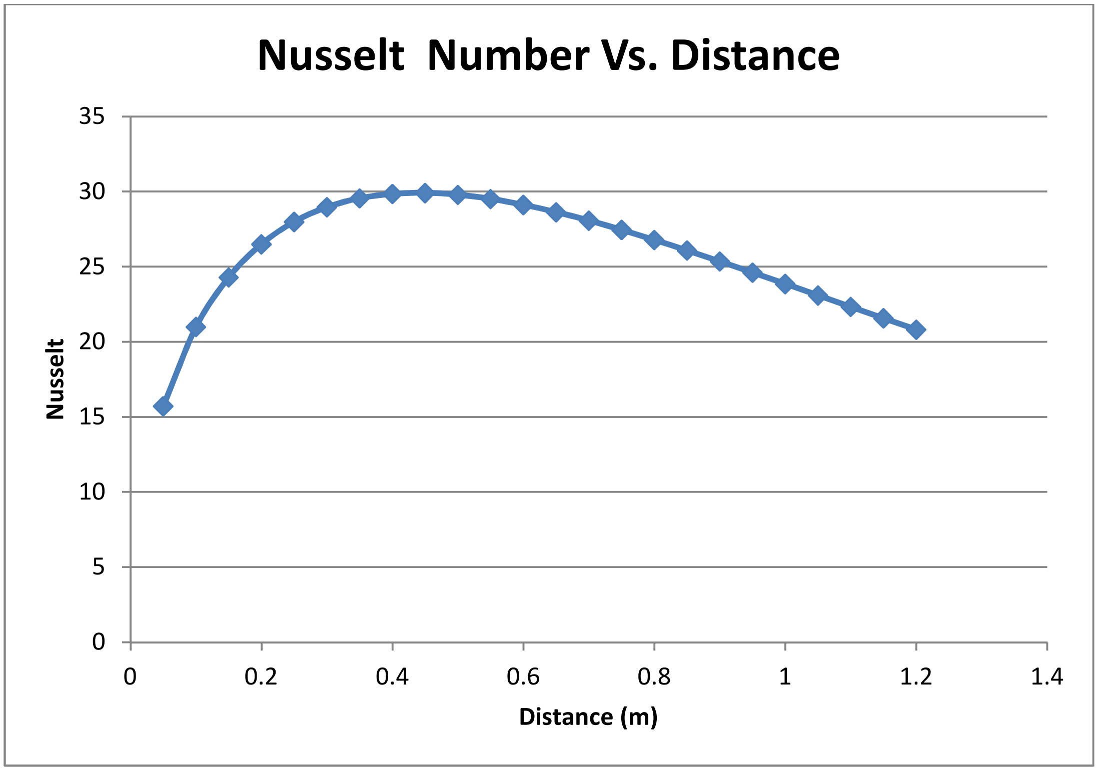
$He_{saved\_cost} := He_{saved\_year}\cdot cost$

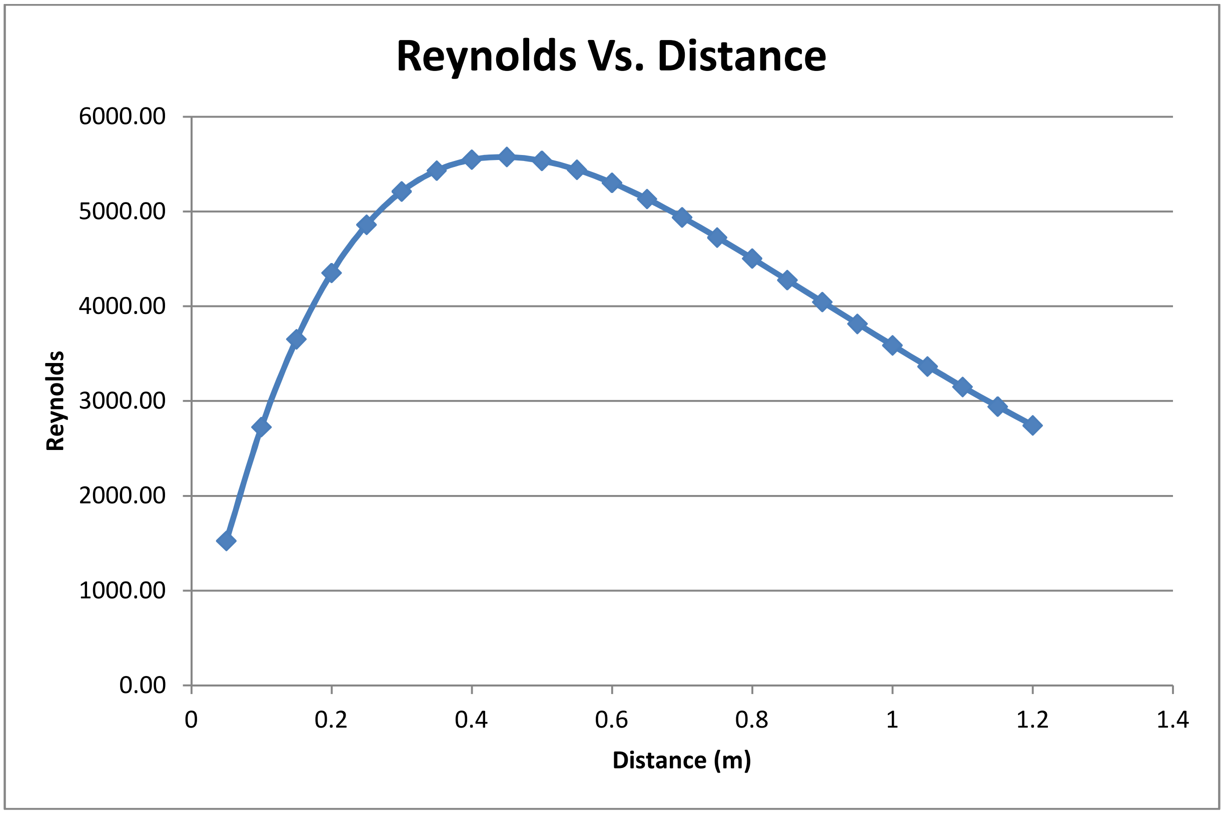
$He_{saved\_cost} = 3.302\times 10^{3}\cdot dollar$

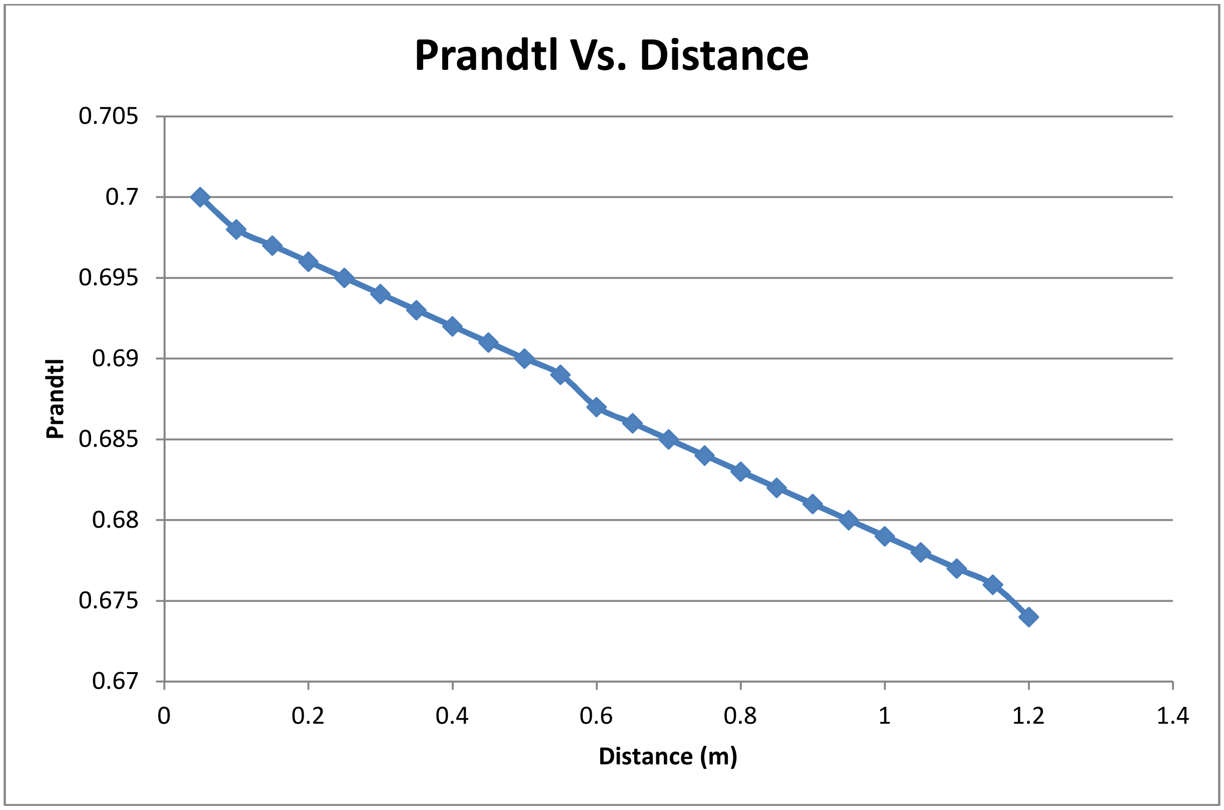
Appendix B – Heat Transfer Graphs

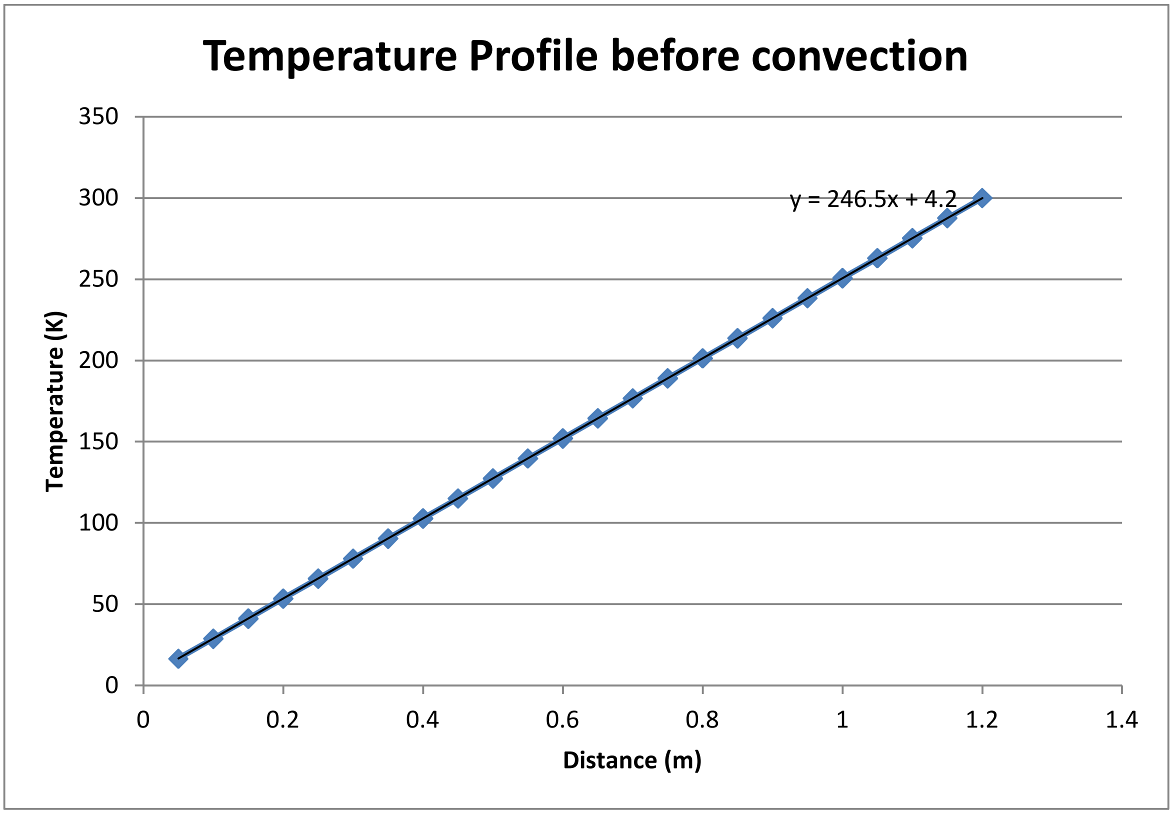
C.1 Data for Copper Leads

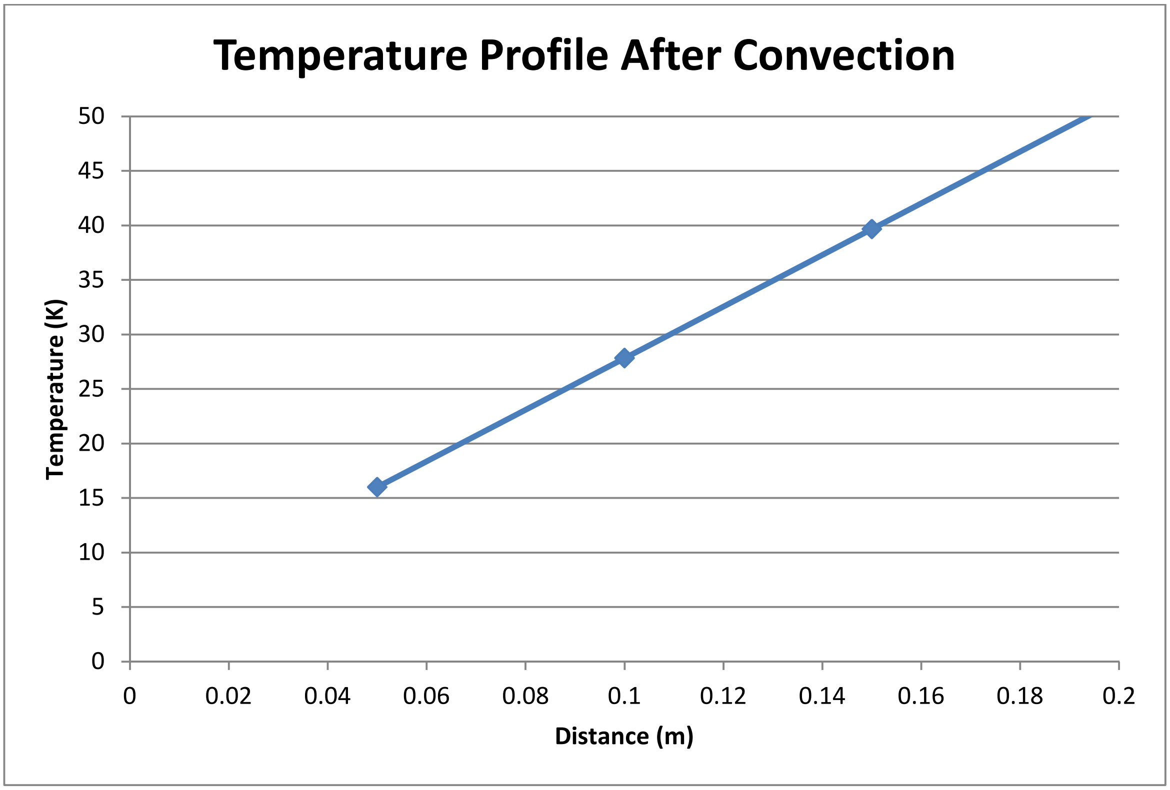




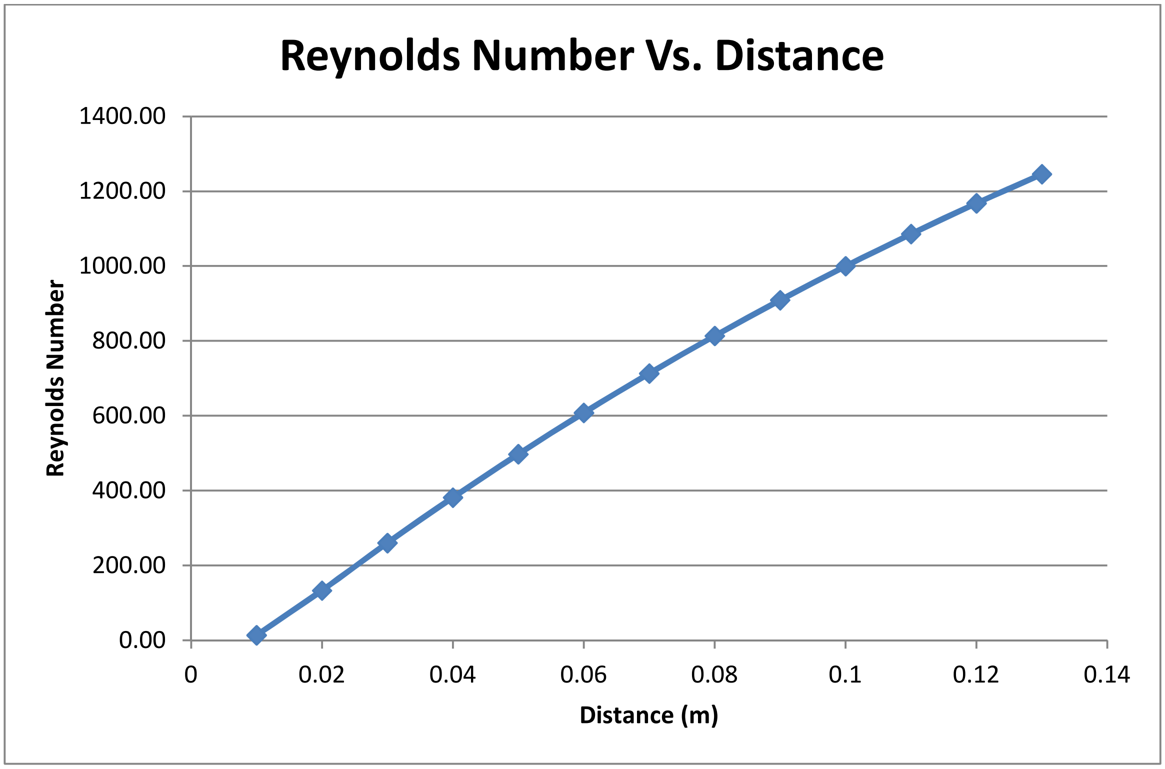

Reynolds Vs. Distance
Reynolds
6000.00
5000.00
4000.00
3000.00
2000.00
1000.00
0.00
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Distance (m)

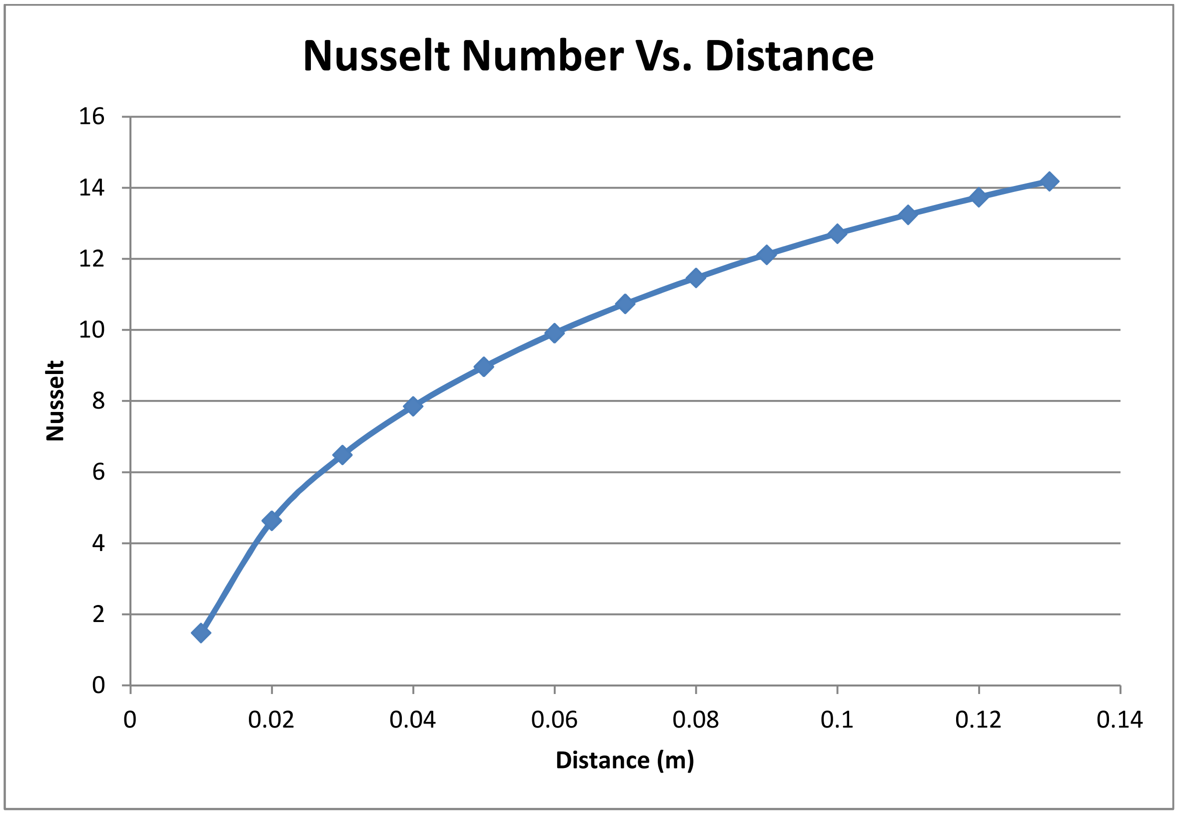

Prandtl Vs. Distance
Prandtl
0.705
0.7
0.695
0.69
0.685
0.68
0.675
0.67
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Distance (m)

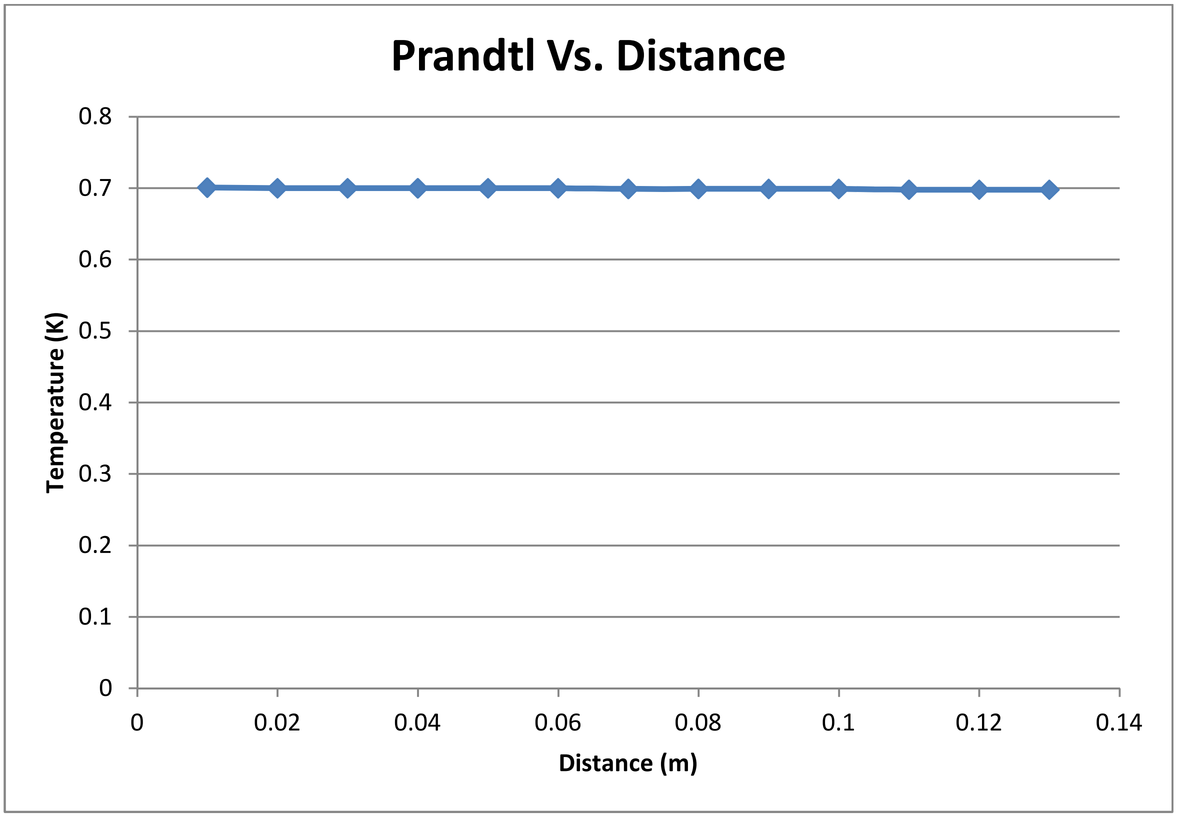

Temperature Profile before convection
y = 246.5x + 4.2
Temperature (K)
350
300
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Distance (m)

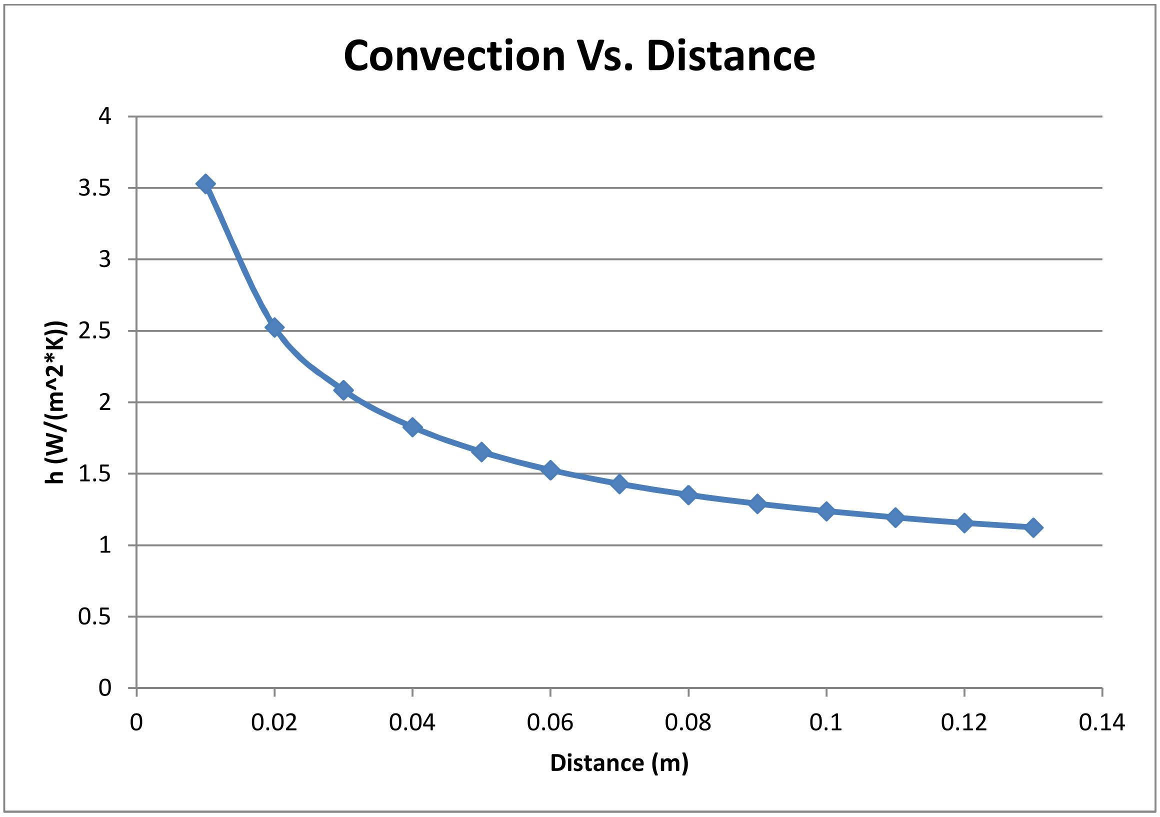

Temperature Profile After Convection
Temperature (K)
50
45
40
35
30
25
20
15
10
5
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Distance (m)

B.2 Data for HTS






Prandtl Vs. Distance
Temperature (K)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Distance (m)


Convection Vs. Distance
h (W/(m^2*K))
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Distance (m)

Appendix C – Fin Analysis

$$\sqrt{\frac{h \cdot p}{k \cdot Afin}} \cdot L > 2.5$$

$L_{Cu} := 1.078\text{m}$ $\qquad L_{Cu} = 1.078 \times 10^{3} \cdot \text{mm}$

$k_{cu} := 15 \frac{\text{kW}}{\text{m} \cdot \text{K}}$ $\qquad d := 0.31\text{in}$ $\qquad r_{cu} := \frac{d}{2}$

this is what we can fit

$r_{cu} = 3.937 \cdot \text{mm}$

$thickness := .5\text{mm}$

$t := thickness$

$\delta := thickness$ $\qquad r2 := r_{cu}$ $\qquad d2 := 2 \cdot r2$ $\qquad threadsize := 2\text{mm}$

$d2 = 7.874 \cdot \text{mm}$

$r1 := 2.0\text{mm}$ $\qquad d1 := 2 \cdot r1$

$r1 - r_{cu} = -1.937 \cdot \text{mm}$

$\frac{h\delta}{k_{cu}} < 0.2$ $\qquad Si := threadsize$

$r2c := r2 + \frac{t}{2}$ $\qquad r2c = 4.187 \cdot \text{mm}$

$lt := Si + t = 2.5 \times 10^{-3}\,\text{m}$

$Lc := L_{Cu} + \frac{t}{2}$ $\qquad Lc = 1.078 \times 10^{3} \cdot \text{mm}$

$Ap = 539.125 \cdot \text{mm}^{2}$ $\qquad Ap := Lc \cdot t$ $\qquad numberofspacefin := \frac{L_{Cu}}{lt} = 431.2$

$\frac{r2c}{r1} = 2.093$ $\qquad n := numberofspacefin - .2$

$Tinf := 105\text{K}$

$Afin := 2\pi\left(r2c^{2} - r1^{2}\right) = 85.018 \cdot \text{mm}^{2}$

$Tb := 250\text{K}$

From Table:

$\tanh(5) = 1$

$h := 1.639 \frac{\text{W}}{\text{m}^{2}\text{K}}$ $\qquad L_{Cu}^{\frac{3}{2}} \cdot \sqrt{\frac{h}{k_{cu} \cdot Ap}} = 0.504$ $\qquad \frac{r2c}{r1} = 2.093$ $\qquad \tanh(4.359) = 1$

$\tanh(3.559) = 0.998$

from table:

$\sqrt{\frac{2 \cdot h}{k_{cu} \cdot t}} \cdot L_{Cu} = 0.713$

$\eta := 0.81$ $\qquad \tanh(3.979) = 0.999$

$Qfin := \eta \cdot h \cdot Afin \cdot (Tb - Tinf)$

$Qfin = 0.016\,\text{W}$

$Aunfin := \pi\, d1 \cdot Si$

$Qunfin := h \cdot Aunfin \cdot (Tb - Tinf)$ $\qquad Aunfin = 25.133 \cdot \text{mm}^{2}$

$Qtot := n \cdot (Qfin + Qunfin) = 9.628\,\text{W}$ $\qquad Si = 2 \cdot \text{mm}$

$Anofin := \pi 2 \cdot r_{cu} \cdot L_{Cu}$

<--------- this is calculations based off of the full size r.cu
lead book uses d1 not r.cu

$Qnofin := h \cdot Anofin \cdot (Tb - Tinf)$

$Qnofin = 6.337\,\text{W}$

$Q := Qtot - Qnofin = 3.291\,\text{W}$

$Q := Qnofin - Qtot = -3.291\,\text{W}$ $\qquad fineffectiveness := \frac{Qtot}{Qnofin} = 1.519$

Area increase of the new Copper leads

$A_{Cu} := 2 \cdot \pi\, r_{cu}^{2} + 2\pi \cdot r_{cu} \cdot L_{Cu} = 0.027\,\text{m}^{2}$

$Anew := n \cdot (Afin + Aunfin) = 4.747 \times 10^{4} \cdot \text{mm}^{2}$

$A_{Cu} - Anew = -0.021\,\text{m}^{2}$

Appendix D – Jacket Analysis

The heat transfer rate of the G10 is lower than the Stainless steel when used as a casing.
This can be seen from the following calculations

$T1 := 300K$ $T2 := 4.2K$ $rcasing := \frac{110mm}{2}$ $a := 3.06 \cdot 10^{3} \frac{W}{m}$

$Lss1 := 28in$ $kss := 16 \frac{W}{m \cdot K}$ $t := 5.84mm$ $a = 3.06 \times 10^{3} \cdot \frac{W}{m}$ from Cryogenic Tables

$Lg10a := 40.5in$ $kg10 := 0.35 \frac{W}{m \cdot K}$ $rcasing = 55 \cdot mm$

$Lss1 = 711.2 mm$ $Lg10a = 1.029 \times 10^{3} \cdot mm$ $Ltot := Lg10a + Lss1 = 1.74 \times 10^{3} \cdot mm$

$rhollowcasing := rcasing - t$

$kss := 16 \frac{W}{m \cdot K}$ assume between 250-300K average

$Llower := Lg10a$

$Acasing := (rcasing - rhollowcasing)^{2} \cdot \pi$

$Aspacer := Acasing$ $Acasing = 107.146 mm^{2}$

Heat transfer for solely stainless steel casing

$qsstot := \frac{a \cdot Acasing}{Lss1 + Lg10a}$ $qsstot = 0.188W$

Heat transfer rate of the stainless steel casing in the cryostat assuming 4.2K at the bottom surface and 300K at the top surface

G10 and Stainless steel casing

Heat transfer for portion of stainless steel casing

$Rss := \frac{Lss1}{kss \cdot Acasing}$ $qss1 := \frac{T1 - 270K}{Rss}$ $qss1 = 0.072W$

Heat transfer rate of the lower casing made out of G10 instead of stainless steel. This rate is much lower and therefore more efficient to use

$Rg10 := \frac{Lg10a}{kg10 \cdot Aspacer}$ $kg10 = 0.35 \frac{W}{m \cdot K}$

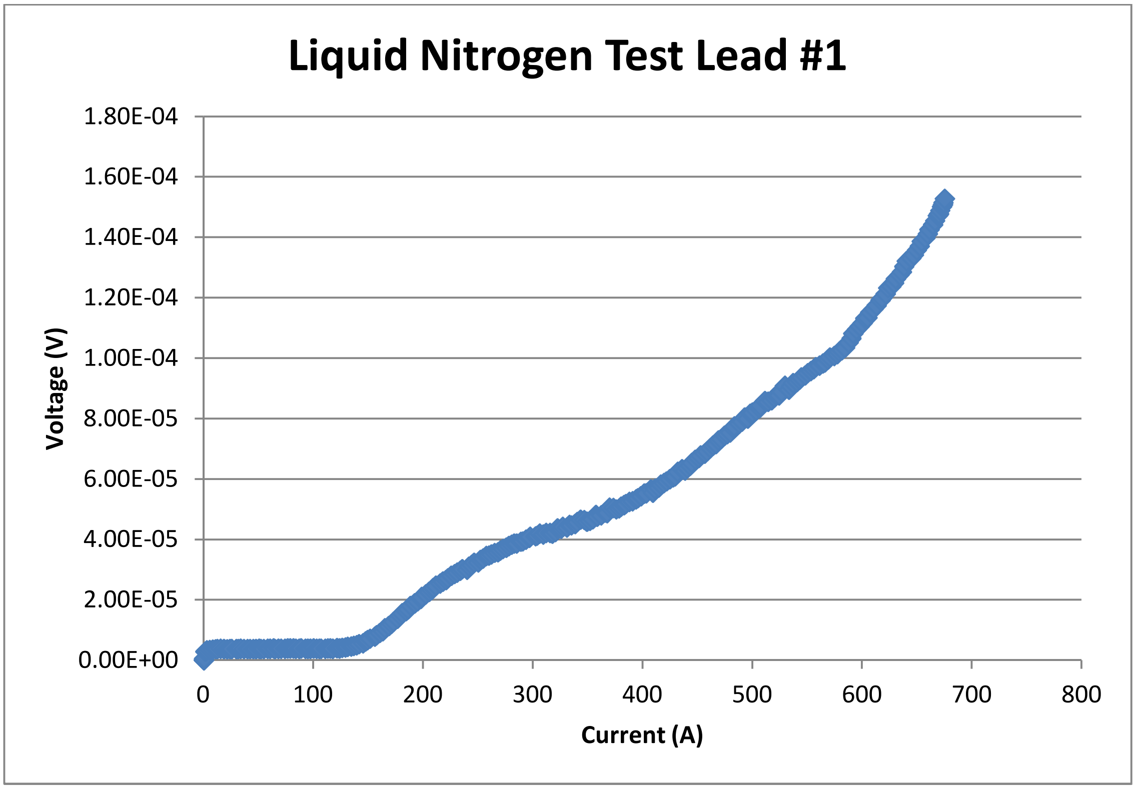
$qg10 := \frac{270K - T2}{Rg10}$ $qg10 = 9.69 \times 10^{-3} W$

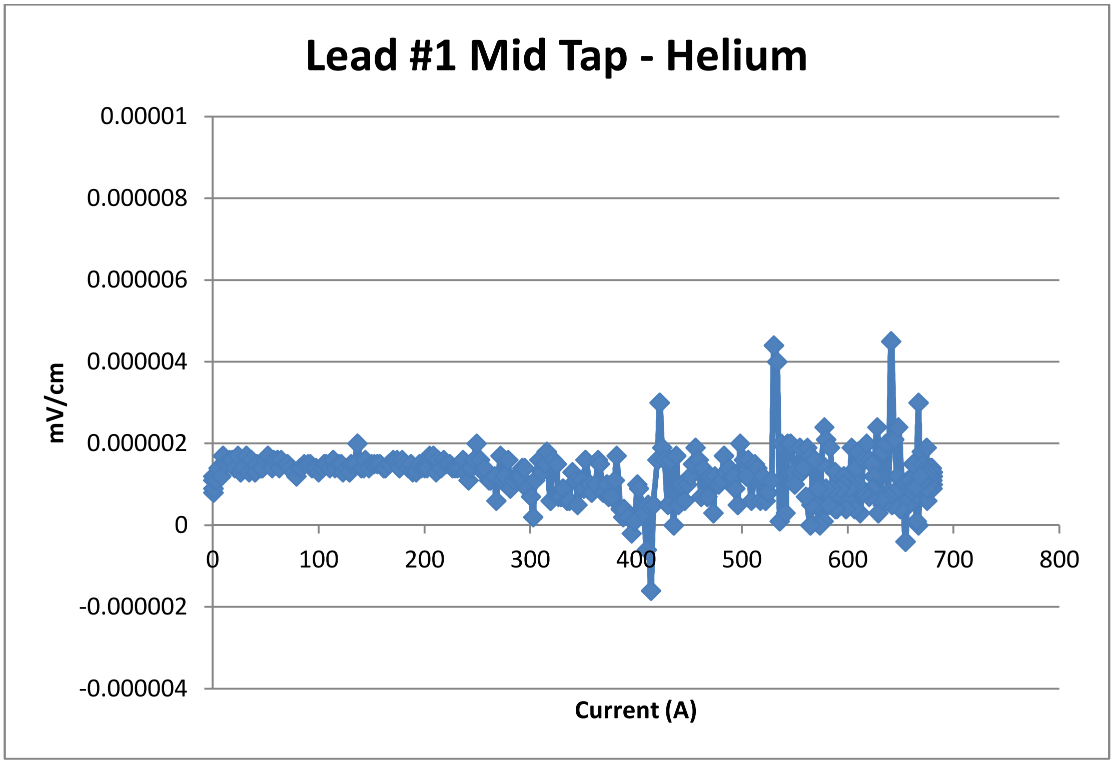
$qg10ss := qg10 + qss1$

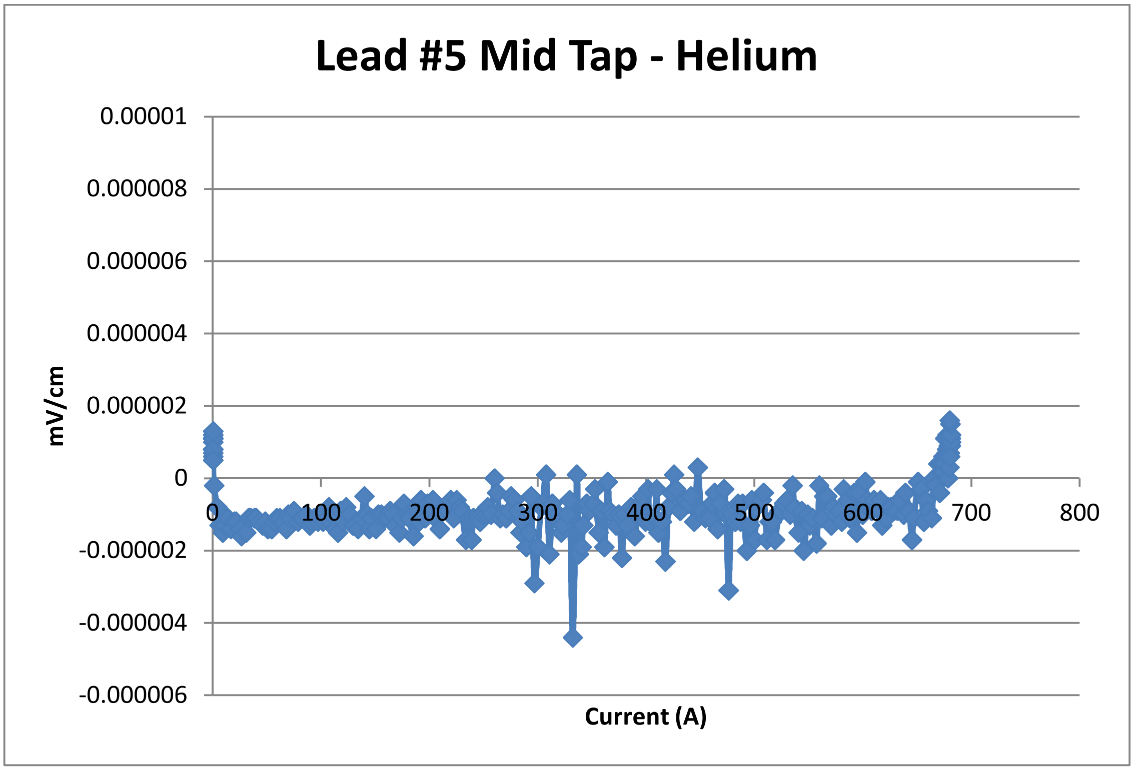
$qg10ss = 0.082W$ <------ this is the heat transfer rate of the proposed design for the casing

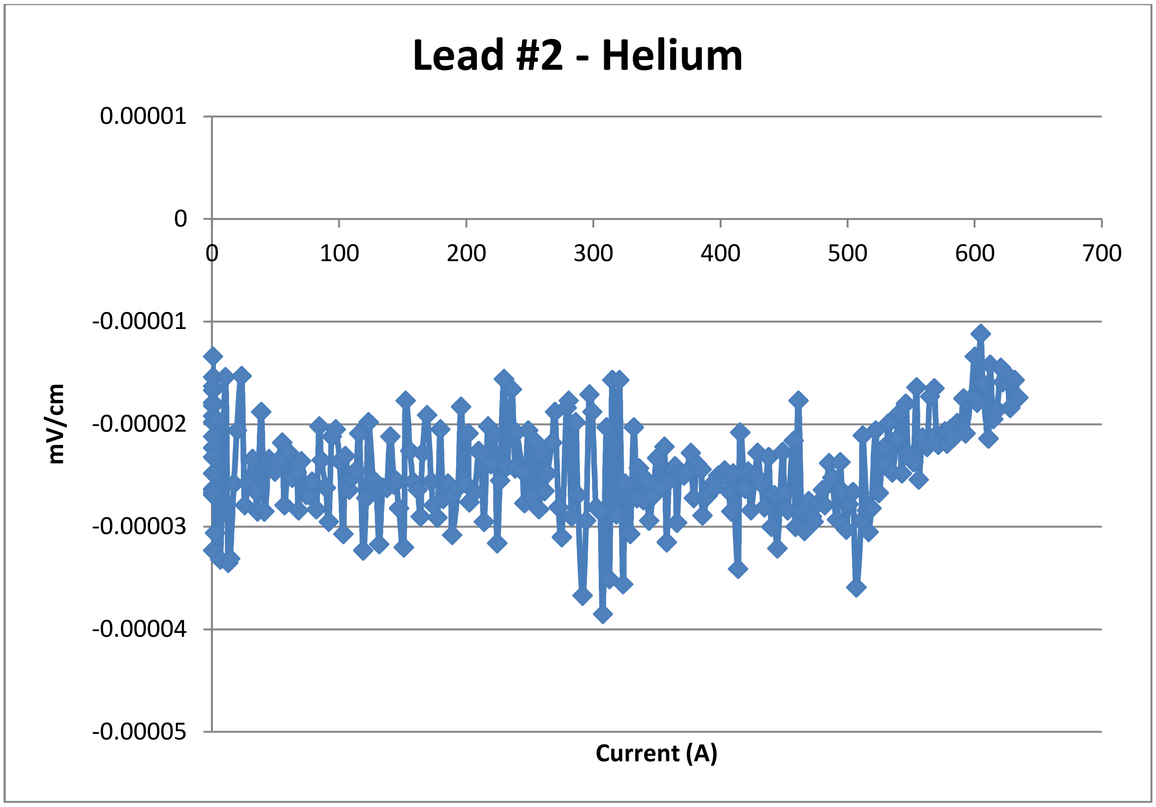
$difference := qsstot - qg10ss = 0.106W$ difference

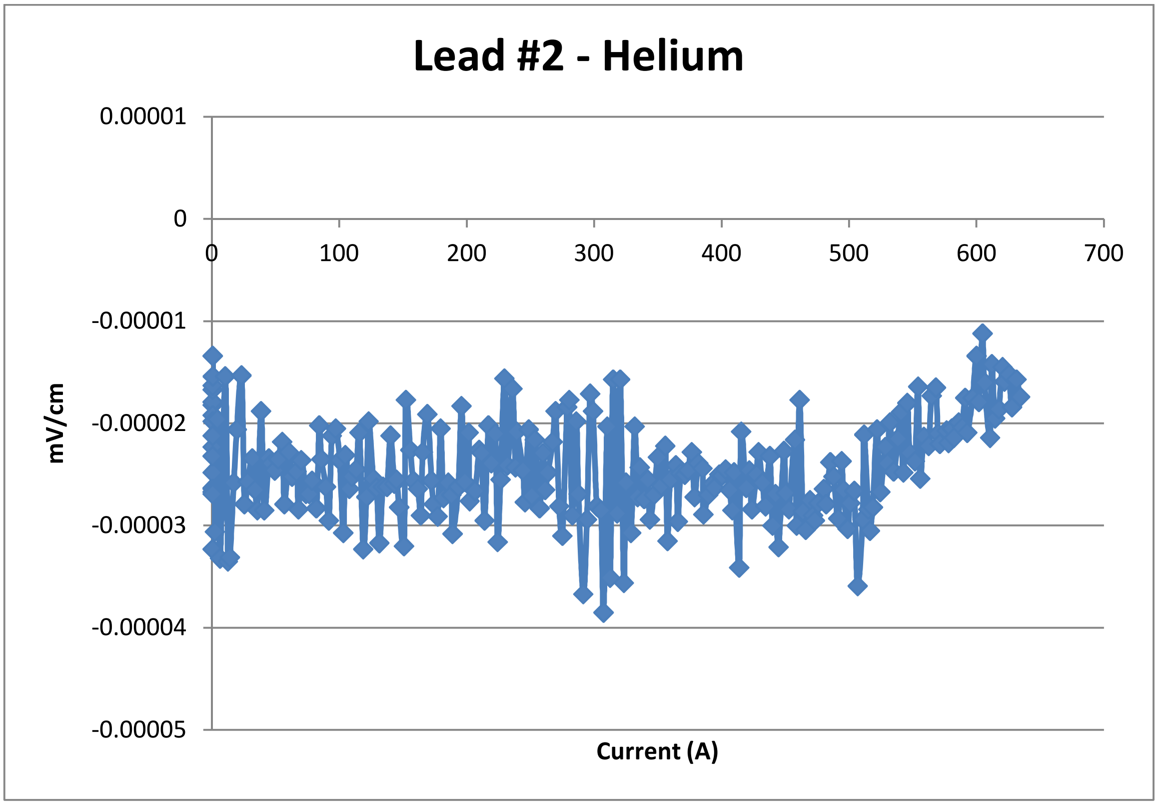
Appendix E – Testing Graphs

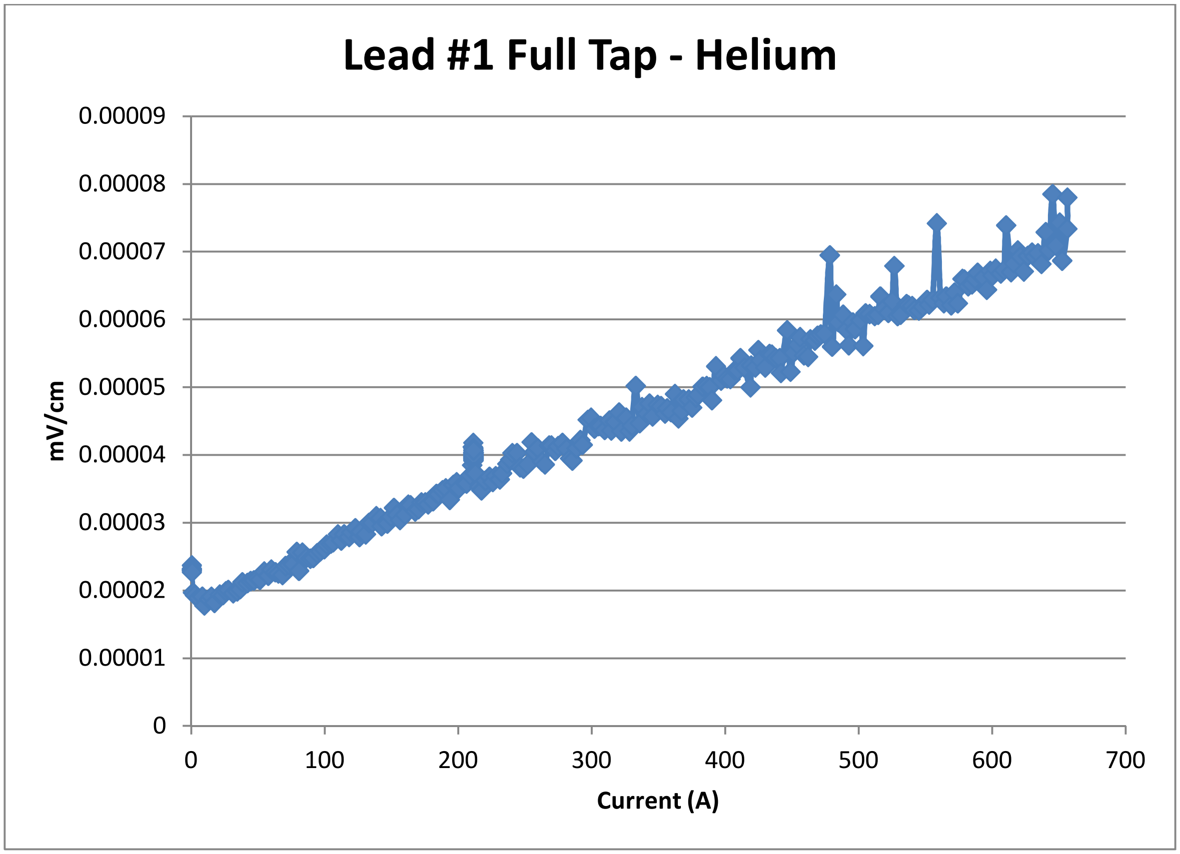


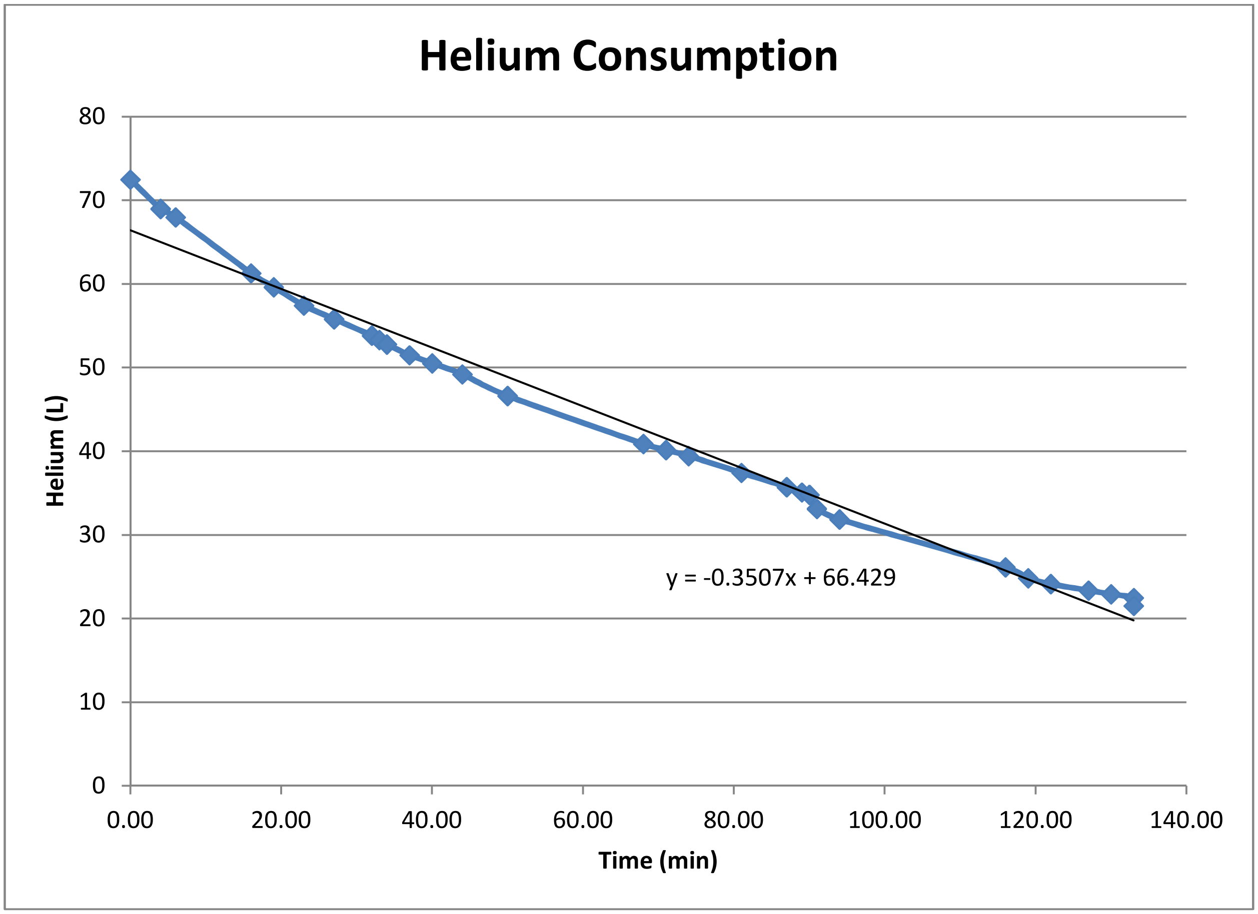



Lead #5 Mid Tap - Helium
0.00001
0.000008
0.000006
0.000004
0.000002
0
-0.000002
-0.000004
-0.000006
mV/cm
0
100
200
300
400
500
600
700
800
Current (A)


Lead #2 - Helium
0.00001
0
-0.00001
-0.00002
-0.00003
-0.00004
-0.00005
mV/cm
0
100
200
300
400
500
600
700
Current (A)


Lead #2 - Helium
0.00001
0
-0.00001
-0.00002
-0.00003
-0.00004
-0.00005
0
100
200
300
400
500
600
700
mV/cm
Current (A)


Lead #1 Full Tap - Helium
0.00009
0.00008
0.00007
0.00006
0.00005
0.00004
0.00003
0.00002
0.00001
0
0
100
200
300
400
500
600
700
mV/cm
Current (A)


Helium Consumption
80
70
60
50
40
30
20
10
0
Helium (L)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
Time (min)
y = -0.3507x + 66.429