Cryostat Design:
Alternative Design of Heat Sinks for Current Leads

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Abstract

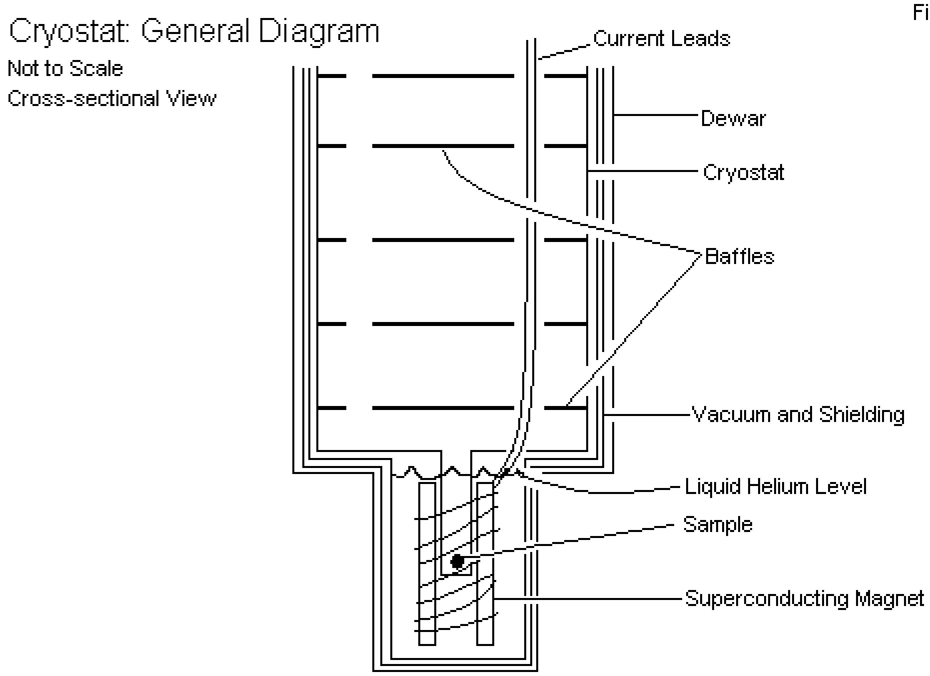
Superconducting magnets must be kept at ultra-low temperatures in order to maintain the high currents used to create strong magnetic fields. These temperatures can be reached using liquid helium. Most of the current leads going to the magnet are not made of superconducting material and thus generate heat as the current flows through them. Our group designed heat sinks to place between the current leads and the baffles of the cryostat to draw heat away from them before it contributes to liquid helium evaporation. While these heat sinks are thermally conductive, they are also electrically insulating in order to prevent undesired current flow. The sinks have been made, along with the device to measure their thermal conductivity. Future work will determine this property. This project also consisted of developing a computer program to model the effects of these heat sinks when placed in a cryostat as used by the group.

Introduction

Electron physics conducted at low temperatures often requires a device capable of maintaining helium in liquid state at 4.2 K. In cryogenics, such a device is known as a dewar (because it acts like a thermos, which was originally created by James Dewar). The dewar contains a vacuum space and many layers of shielding. This prevents a great deal of heat energy from passing through the vessel toward the sensitive materials inside. In the bottom of the dewar rests the liquid helium. The superconducting magnet resides immersed in the helium.

Use of a cryostat allows the sample to be cooled significantly lower than liquid helium temperature. It also securely holds the sample within the high magnetic field of the superconducting magnet. The cryostat fits inside the dewar. This design makes it possible for a great deal of heat to enter the apparatus by way of the magnet current leads that enter through the top of the cryostat, which is at room temperature (298 K). Baffles are placed throughout the cryostat to both reflect heat back out through the top of the unit and to disperse it into helium gas that is already on its way out of the dewar. Figure 1 shows the general picture of this setup.

Figure 1



The superconducting magnet can maintain a 16 Tesla field once enough current has been passed through its wires and their temperature has fallen into the superconducting range. A current of 60 A must be passed through these wires to reach the desired magnetic field, after which the current may be turned off and the field maintains itself by the superconducting current flow through the wires. During the ramping stage when the current is being increased, the current leads which go from the power supply to the superconducting wires of the magnet generate a great deal of heat. Some of this heat is removed from the system by helium gas that has previously been boiled off. A more efficient method of removing heat from these leads may consist of heat sinking them to the baffles, which have a better thermal contact to the helium gas.

Computer Modeling

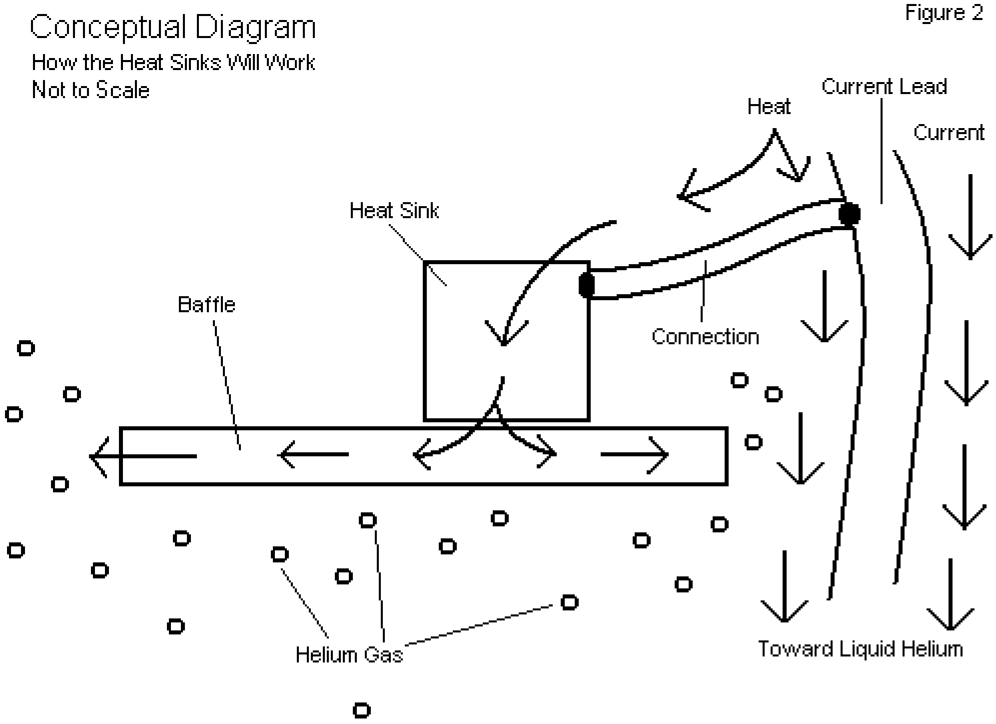
The computer program is in the process of being rewritten. Revision is needed to better account for the heat capacity of the helium gas as it makes its way out of the cryostat. It will work by beginning with an estimated value for the heatleak into the system and using that value to calculate the temperature at a specific position within the cryostat. After determining the temperature the program will calculate a new heatleak value for a slightly different position. This will continue until a baffle is reached, at which point the contribution of the heat flowing out of the system through the baffle is taken into account.

These loops are performed in between the baffles, eventually producing a temperature for the top of the cryostat. This temperature is known to be approximately 293 K (room temperature). The program is written to adjust its initial estimate of the heatleak to arrive at a reasonable final temperature. During these loops the program is calculating its values by considering outside radiation, thermal conductivity through cryostat materials, joule heating caused by the current leads, and unavoidable helium gas boiloff.

Heat Sinks: Design and Production

Professor Gramila provided the general idea for the heat sinks. Figure 2 is a conceptual diagram of the manner in which heat sinks (drawn as a square) can be used to draw heat away from the current leads. The current lead shown is one that is carrying current down toward the liquid helium that surrounds the superconducting magnet in the bottom of the dewar. The heat flow ordinarily follows the same path as the current flow and causes liquid helium to boil away. Some liquid helium will boil away regardless of design. Using heat sinks to draw away some of the heat produced by the current leads may cause much less helium to be lost.

Placing a heat sink on one of the baffles will create a second path for heat flow. The sink is attached by soldering the bottom of its inner section to the baffle. Electrical connection is prevented by machining away a small amount of the outer cylinder as to prevent it from contacting the baffle. Figure 2 shows that some of the heat produced by the current lead will travel through the heat sink and baffle and then by taken out of the system by the already vaporized helium. Other cryostat designs use the outbound helium gas to cool the current leads directly. Problems with this method include maintaining a proper gas flow and designing current leads that always remain in good thermal contact with the gas.



Previous work with this type of heat sink concept has been done by this group with sinks consisting of two copper disks epoxied on top of each other. The epoxy spacing was approximately 4 mils. Current work with this concept aims to improve the heat sinks by changing their design, thus allowing them to conduct more heat away from the liquid helium in the bottom of the dewar.

The new design calls for two concentric copper cylinders to be epoxied together with a space of 3 – 10 mils (1 mil = 0.001 inches) between them. As shown in Figure 3, this design consists of an outer cylinder of approximately 1 inch in diameter. The thermal conductivity of the heat sink is proportional to its height, which we set at 1 inch to make production more efficient.

Construction of this design proved to be challenging. It is difficult to epoxy the two copper cylinders together without bringing them into contact. This problem is solved by joining copper pieces that are larger than needed and then cutting them down to the desired size. As illustrated in Figure 3, the copper cylinders can be fitted together in such a way as to leave a small gap between them. The size of this gap is determined by the dimensions of the two pieces. For ease of production it is possible to make one piece standard and only vary the dimensions of the other piece.

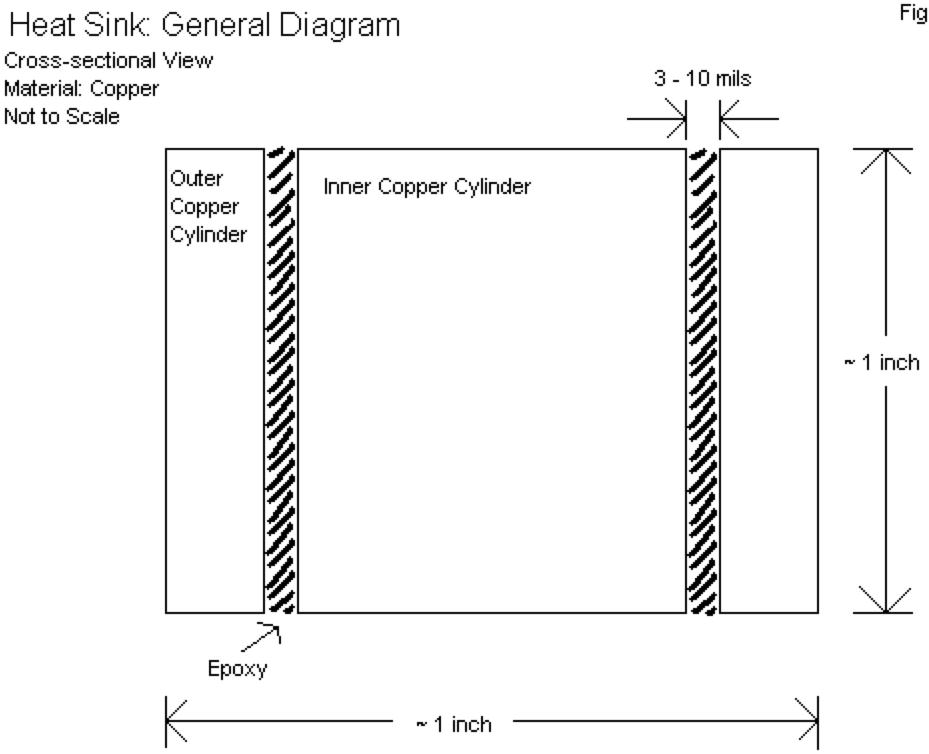


Figure 3

The Final Setup shows holes in the outer cylinder. These are drilled after machining, and allow for epoxy to be injected into the gap. A needle is soldered into one of the holes, and epoxy is injected until it begins to come out of the other hole. The syringe can produce sufficient pressure to force the epoxy uniformly between the cylinders. This process is made easier by heating the copper cylinders and epoxy to just below 100°C. At this temperature the epoxy is less viscous and therefore easier to inject. The injection can then ensure that epoxy has spread throughout the gap. After the epoxy sets, the heat sinks are completed by cutting the ends off of the entire unit. By making the cylinder lengths on the order of six inches, one can get five separate sinks through cuts at every inch after removing the ends. A lathe must be used to finely face the ends of the heat sinks and prevent the development of shorts that occur when a small fragment of one cylinder crosses over the epoxy to electrically contact the other cylinder.

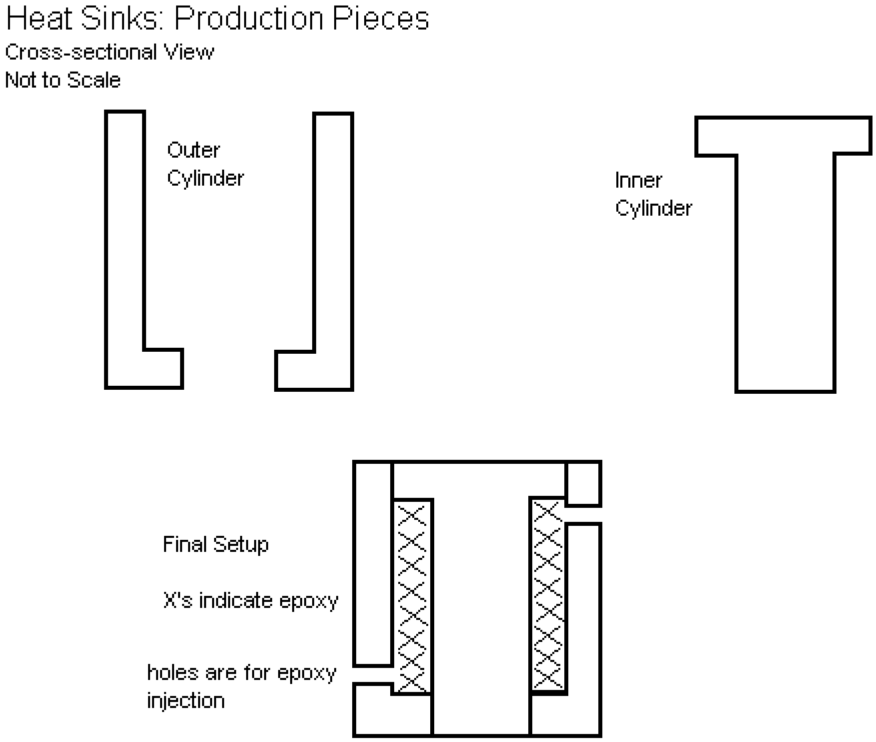


Figure 4

Heat Sinks: Testing

The thermal conductivity of the heat sinks must be determined. This temperature dependent value is used in the computer model to account for the contribution the sinks make in removing heat from the cryostat. While the helium gas is the primary outlet for current lead heat, sinks with a large thermal conductivity can direct heat flow across the baffles. This heat can then be more efficiently removed because the baffles have a large surface area that places them in good thermal contact with the helium gas.

The thermal conductivity between two points is related to the heat flowing through those points and the temperature difference between those points by the following relation.

$$Q = \kappa(T) \cdot \Delta T, \qquad (1)$$

where Q is the heat flow in J/s, $\kappa(T)$ is the thermal conductivity with respect to the temperature T, and ΔT is the temperature difference between the two points. Equation 1 is easily solved for $\kappa(T)$, which makes it relatively simple to find $\kappa(T)$ experimentally when one knows the other two variables. Such is the basis for my experiment.

The heat sink is attached to a solid piece of copper. Platinum resistance thermometers are placed on both the sink and the solid piece (base). These resistors allow for the temperature of each piece to be known at all times. Heaters are placed on each piece. With the heaters we can regulate the temperature of the setup and apply a known heat load. The base is heated using two resistors in a parallel circuit. By running a current through the circuit the resistors act as heaters by the process of Joule heating. The sink heater consists of resistive brass wire wound around its outer shell. This wire heats up as a current is run through it, producing an amount of heat that can be determined by the I^2R relationship.

The heat flow in the system is determined by finding the heat produced on the sink during a certain time. Heaters on the base are used to keep the temperature of that piece constant. A constant temperature on the base allows for the sink temperature to be made slightly higher, which in turn causes the heat to flow from the sink to the base. At this point we are able to determine the temperature difference between the two pieces from the resistance readings and the heat flow through the system from the heat output of the sink resistance wire.

These heat sinks will be used at liquid nitrogen temperatures (77K) and below. Thermal conductivity is temperature dependent and must therefore be measured at these temperatures. This is accomplished using a cryo-stick and the Thermal Conductivity Measuring Device (TCMD). The cryo-stick is an instrument used to make electronic measurements at low temperatures. This low temperature environment is usually a storage dewar full of either liquid nitrogen or helium. The cryo-stick is a long probe with space on one end to attach the sample and connectors on the other end to allow for instrumentation. Such a unit is needed because the largest neck diameters of storage dewars are typically on the order of 1 ? inches.

The TCMD consists of two pieces made of oxygen-free high conductivity copper. The base provides a surface for the heat sink to thermally contact, creating an end point for the thermal conductivity measurement. The other piece is a shield screwed tightly to the base enclosing the heat sink and wires within. By placing heaters on the outer surface of the heat sink and on the base we are able to perform the thermal conductivity measurement. The value we determine is the conductivity between the outside of the heat sink through to the bottom of its center cylinder. This is the path for the heat that will be drawn away by the heat sinks.

Data

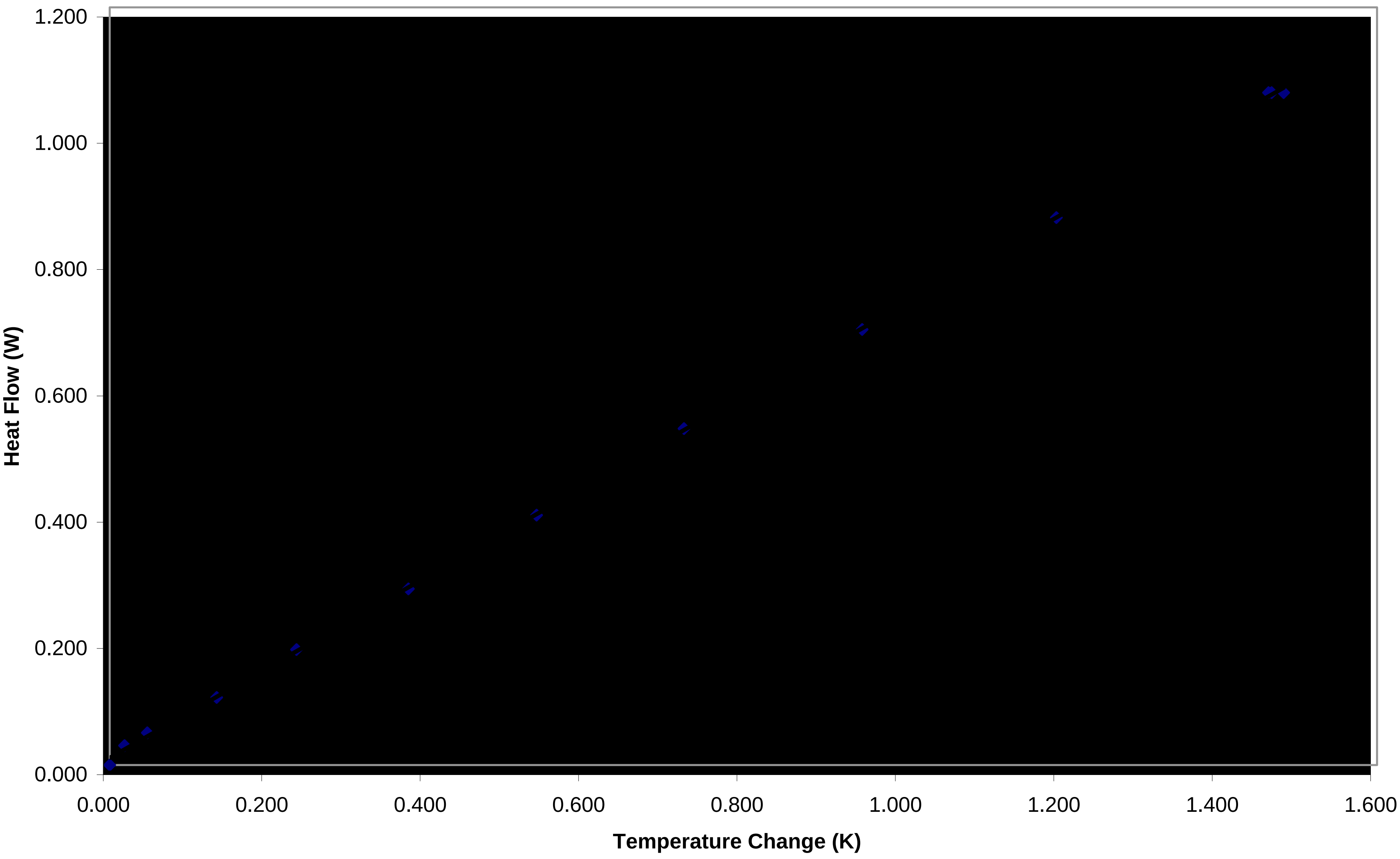
We were able to collect data concerning the thermal conductivity of a heat sink with a 10 mil gap. This sink has been tested at 100K and the resulting plot of heat flow versus temperature change is shown in Graph 1.

Analysis

From Equation 1 we know that the thermal conductivity of the heat sink in Graph 1 is the slope of the line. This slope is found to be 0.716 W/K.

Conclusion

Graph 1



Thermal Conductivity of a 10 mil Heat Sink at 100K

By the completion of this summer research program the heat sinks have been designed, with one having been tested and three more needing minor machining. The Thermal Conductivity Measuring Device was designed and then built by the physics shop. This device had to be slightly modified to accommodate for the inclusion of the platinum resistance thermometer. The wiring has been secured to the base of the TCMD to allow for multiple heat sinks to be tested using the same base and shield. New sinks need only be soldered to the secured wiring to be ready for testing. Future work will consist of actually testing many different heat sinks. The first to be tested will be a 10 mil gap sink, followed by tests with 5 mil gaps.

Further testing will be done until there is enough data to determine the thermal conductivity of the heat sinks with respect to the range of temperature experienced in the cryostat. The data set included in this paper seems to indicate that a heat sink with a 10 mil gap will not be thermally conductive enough to implement in a cryostat. Our goal is to develop heat sinks with thermal conductivities of at least 2 W/K throughout the given temperature range.

The computer program continues to be revised. Future work includes debugging and including parameters to allow users the option of running with current on or off, and with or without heat sinks.

Acknowledgments

I would like to thank Dr. Gramila for his mentorship in developing this project and seeing it through to results. I am also grateful to Tony Ragucci for his efforts to explain the physics behind the group's work, and for his excellent problem solving while we were taking measurements. Final thanks are extended to Ioan Tudosa who was instrumental in helping me to find large amounts of existing data needed for the computer program.