Various techniques for the filtration of electromagnetic noise within a $^3$He-$^4$He dilution refrigerator are analyzed. The techniques presented are the use of low pass RC and pi filters, as well as the utilization of the blackbody characteristics of standard resistors. A short discussion of the inner-workings of the dilution refrigerator is also included.
I. Introduction

While conducting low temperature physics experiments, the injection of electromagnetic noise into the system can create problems when one wishes to isolate a specific variable for measurement. One problem that electromagnetic noise can be responsible for is the unwanted heating of the electrons in the sample. This heating defeats the purpose of conducting low temperature measurements in the first place. A second problem arises when electromagnetic noise directly interferes with a measured signal.

The main goal of this REU project was to research the different forms and sources of electromagnetic noise that can penetrate a $^3$He-$^4$He dilution refrigerator system, and devise methods of filtering out said electromagnetic noise. Secondary to the filtering aspect of the project, the reconstruction of the laboratory after moving to the new building proved to be more time-consuming than expected. Also, some time was spent learning about the fundamental principles behind the dilution refrigerator itself.

II. $^3$He-$^4$He Dilution Refrigeration

The $^3$He-$^4$He dilution refrigerator utilizes some of the unique properties of $^3$He and $^4$He to obtain milliKelvin temperatures. The following are the respective phase diagrams for $^3$He and $^4$He:
1a. Phase diagram for $^3$He

![Phase diagram for $^3$He](image1)

1b. Phase diagram for $^4$He

As indicated on its phase diagram, at pressures close to zero, $^3$He retains a normal liquid phase down to about 1 mK. $^4$He, on the other hand, remains a normal liquid only down to 2.17 K; at lower temperatures, $^4$He becomes a superfluid$^1$. When $^3$He and $^4$He are mixed together a composite phase diagram results; the follow is the phase diagram of a mixture of $^3$He and $^4$He$^2$:

![Two-phase region of $^3$He-$^4$He mixtures](image2)
The “unstable” region is a region where the $^3$He and $^4$He separate into two phases. One phase is superfluid $^4$He with some specific concentration of $^3$He mixed in; because of the nature of superfluidity, the $^3$He acts like a gas, floating in an inert background of $^4$He. The second phase is composed almost entirely of $^3$He. In the case of dilution refrigerators, the $^3$He phase floats on top of the $^4$He-rich phase, where the concentration of $^3$He is approximately 6%. The following is a diagram of a typical dilution refrigerator:

![Diagram of a $^3$He-$^4$He dilution refrigerator](image)

3. Diagram of a $^3$He-$^4$He dilution refrigerator

The process by which cooling occurs is a good example of fundamental thermodynamics. As previously stated, the %6 concentration of $^3$He acts like a gas
floating in the superfluid \(^4\text{He}\). The heater is used to bring the temperature of the still into the region where \(^3\text{He}\) undergoes a liquid to gas phase transition and \(^4\text{He}\) remains a superfluid, 0.7 K seems to be a common value for this temperature\(^1\). The distilled \(^3\text{He}\) vapor is then pumped off, creating a \(^3\text{He}\) concentration gradient from the mixing chamber to the still, and resulting in a net flow of \(^3\text{He}\) across the phase boundary in the mixing chamber. Cooling is achieved by the energy expended to satisfy the latent heat of vaporization of \(^3\text{He}\) in the mixing chamber. The walls of the mixing chamber are in thermal contact with the sample that is to be analyzed; therefore, the sample’s temperature is directly related to the temperature of the mixing chamber. The heat exchangers are present to facilitate the entrance of the circulated \(^3\text{He}\) into the upper phase of the mixing chamber. Specifically, the heat exchangers cool the incoming \(^3\text{He}\) with the \(^3\text{He}\) that is leaving the mixing chamber. The circulation of \(^3\text{He}\) in this manner allows for the continuous operation of the refrigerator. This, as opposed to a single-shot refrigerator, where time must be spent re-cooling after the initial amount of \(^3\text{He}\) is expelled.

III. Electromagnetic Noise and Filtering Techniques

The two major sources of electromagnetic noise in the laboratory are radio frequency (rf) noise from equipment unassociated with the refrigerator and Johnson noise from electrical devices that are connected to the refrigerator. To account for the rf noise from the outside world, the entire refrigerator apparatus is placed inside a shielded rf enclosure. While the rf enclosure does filter out high frequency noise from outside sources, it does not help in the filtration of Johnson noise, which comes from the electrical equipment used in conjunction with the refrigerator.
Johnson noise is the noise voltage associated with any resistor operating at a
temperature greater than absolute zero\textsuperscript{3}:

\[ V_{\text{noise (rms)}} = (4k_B T R B)^{1/2} \]

In the above equation, \( K_B \) is Boltzmann’s constant, \( T \) is the absolute temperature, \( R \) is the
resistance, and \( B \) is the bandwidth at which the measurement is made. It is clear from the
above equation that there is a direct relationship between the absolute temperature of a
resistor and the noise associated with that resistor. During low temperature physics
experiments, where the sample temperature is in the mK range, the Johnson noise from
room temperature equipment can become problematic. For this reason, the implemented
filters must attenuate in a temperature region of 1-300 K; this temperature region
corresponds to a frequency bandwidth of 20 GHz- 6 THz\textsuperscript{4}.

Currently, there are two filtering methods being implemented in the dilution
refrigerator apparatus in Dr. Birge’s laboratory. The refrigerator has 18 lines fed into it
from the room temperature portions of the cryostat via the refrigerator probe; therefore,
all 18 lines are filtered by the two current methods. The first filtering method utilizes
what are called “pi filters,” while the second method is a simple RC filter.

Pi filters consist of two capacitors and an inductor pieced together in the
following way:

![Diagram of a pi filter](image)

4. Diagram of a pi filter

A qualitative analysis of this circuit reveals how it behaves as a low-pass filter. Because
of the inverse relationship between frequency and impedance in each capacitor, the high
frequency noise will travel to ground, while the low frequency signal will travel through the inductor and eventually to the sample. All 18 pi filters are soldered into a die-cast aluminum box attached to the top of the refrigerator probe.

The 18 RC filters are located towards the bottom of the probe, so that when an experiment is running, the temperature of the resistors is cold enough to ensure that their Johnson noise does not pose a problem. A low pass RC filter is simply an in-series resistor connected to a parallel capacitor, which is then connected to ground. Upon examining the impedance of the RC filter, one can resolve the following equation for its attenuation:

\[
V_{\text{out}} = V_{\text{in}} \cdot (1 + \omega^2 R^2 C^2)^{-1/2}
\]

As you can see, the level of attenuation will increase as \( \omega \) approaches infinity. The values for \( R \) and \( C \) in this refrigerator are 1 k\( \Omega \) and 1 nF respectively. This corresponds to a noticeable attenuation beginning at approximately 160 kHz.

The preceding examples of filtering are methods that are currently in use. In the future, the Birge group wishes to conduct experiments at temperatures below what the refrigerator can currently operate at; therefore, more filtering is needed on the lines going into the refrigerator.

One method of filtering that could be implemented is to simply place resistors on each line of the refrigerator probe. The logic behind this method is that resistors can be viewed as one-dimensional blackbody radiators\(^5\). The resistors absorb the energy coming from the room temperature parts of the cryostat, and reradiate energy that is directly proportional to their temperature. So, if this method is to be implemented, the resistors should be added to a section of the probe that is sitting at a relatively low temperature. It
is difficult to predict how efficient this method would be at filtering out electromagnetic noise. It is unknown whether or not some of the electromagnetic radiation will simply “jump” over the resistor entirely. Also, the total resistance of the room temperature sections is immeasurable; therefore, there is no way to predict exactly how much energy each “cold” resistor would be forced to absorb.

The second filtering technique that could be implemented is to use pi filters to filter the lines that are connected to diagnostic thermometers. These are thermometers used to measure the temperature of points in the refrigerator, other than the sample. These lines are currently unfiltered, as they do not feed in through the refrigerator probe. It is possible that electromagnetic noise may be reradiated from the diagnostic thermometers to lines in the refrigerator that measure variables associated with the sample. This is a more passive method of filtering, as the refrigerator probe would remain unaltered. Steps have been taken to implement these pi filters. A brass project box will be used to house the 18 pi filters; within the box each filter will be soldered into a brass-grounding plane. The grounding plane is present to reduce the amount of capacitive coupling in the filters. Fisher connectors will be used to connect each brass project box to the electrical equipment on one end and the refrigerator on the other. A schematic for this project box is located in the appendix to this report.

IV. Future Work

There is much left to do in terms of filtering out unwanted electromagnetic noise within the refrigerator, as well as in setting up the laboratory after the move from the old physics building. Once the pi filters are added to the top of the refrigerator, tests should be done to determine whether or not lower sample temperatures are accessible. If the
desired temperatures still cannot be reached, resistors may have to be added to the refrigerator probe itself. Of course, the tests that must be done depend on the refrigerator being operational, so the next goal of the project is to finish setting up the laboratory, and make sure that the refrigerator operates smoothly.
Bibliography


