Thermal testing of the STAR Forward GEM Tracker disks

by

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Abstract

In my thesis project, I worked on the Thermal Model for the FGT detector. The purpose of this thermal model is to simulate the cooling system for the electronics of the FGT. In this thesis report, I go over the construction of the model disks for the thermal model and the measurements I made on one disk. I also discuss the LabVIEW program I worked on to monitor the temperature of the readout cards over time. The measurements I made with the LabVIEW program concerned the orientation of the disks. The two orientations I took measurements for were for a disk placed upside down in a horizontal surface and for a disk placed vertically on a pipe. After analyzing the data, I found that these two orientations have no effect on the heating and the cooling of the readout cards.

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Title: Associate Professor, Department of Physics

Acknowledgments

I would first like to thank Professor Bernd Surrow for giving me the opportunity to join his research group and work on this project. Next, I want to thank Research Scientist Gerrit van Nieuwenhuizen for helping me with LabVIEW. Without his help, I would have never been able to finish the DAQ program during the time of this thesis project. I also want to thank Gerrit for providing me with an outline for this report and giving me great suggestions on improving this paper. I also want to thank Project Technician Glen Dale Ross for his guidance on preparing the disks for the Thermal Model and for answering all my questions about the Thermal Model. Another person I want to thank is Research Scientist Douglas Hasell for his help on telling me how to arrange the readout cards on the disks and for telling me where to put the temperature sensors on the readout cards. Finally, and certainly not least, I would like to thank Barry Brian Barrios for rereading, and rereading, and rereading this paper again and for not hesitating to point out any errors he found in this thesis.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The Solenoidal Tracker at RHIC (STAR) is one of two large detector systems constructed at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). The STAR physics program at RHIC can be divided into three main categories: a study of high density QCD, measurement of the spin structure function of the proton, and a study of photon and pomeron interactions from electromagnetic fields of the passing ions at RHIC [1]. The spin physics program at RHIC at BNL focuses on the collision of polarized protons to gain a deeper understanding of the spin structure and dynamics of the proton. Recent results of the RHIC also provide strong evidence for the formation of a new state of strongly interacting matter. [2]

A tracking detector is currently being prepared by the STAR collaboration at BNL. This upgrade will allow for further investigations of the fundamental properties of a new state of strongly interacting matter produced in relativistic-heavy ion collisions at RHIC and it will allow for fundamental studies of the proton spin structure and dynamics in high-energy polarized proton-proton collisions at RHIC. The approved Forward GEM (Gas-Electron Multiplier) Tracker (FGT) project will focus on novel spin physics measurements in high energy polarized proton-proton collisions.

The FGT upgrade to the STAR experiment is needed to provide the required tracking precision for charge sign discrimination. This upgrade will consist of six triple-GEM detectors with two dimensional readout cards arranged in disks along the beam axis (Z). A Schematic diagram of the 6 disks of the FGT project and a picture

of the surface of one disk are given in Figure 1-1.

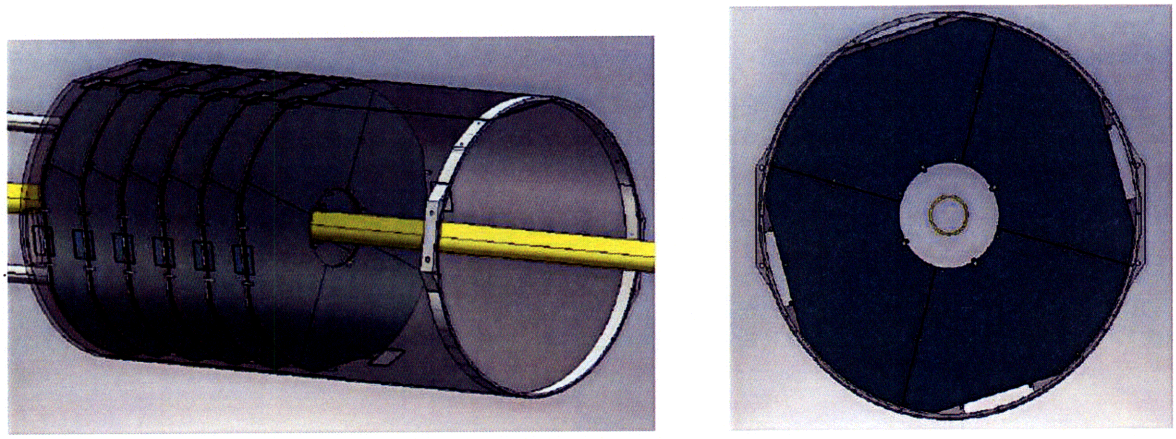

Figure 1-1: The picture on the left shows how the 6 disks are going to be positioned in the FGT. On the right, and a clear view of one of the disks is shown.

This configuration provides a rather cost effective solution based only on triple-GEM technology. GEM technology is widely employed by current and future experiments in nuclear and particle physics. Prototype test detectors of the FGT project have been successfully tested in a test beam experiment at FNAL (Fermi National Accelerator Laboratory) including the final chip readout system.

The readout electronics of the FGT detector will consist of APV25-S1 readout chips [3]. APV25-S0 chips, older versions of the APV25-S1 chips, were used successfully with GEM detectors in the COMPASS (**Co**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy) Experiment at CERN [4]. These APV (Analogue Pipeline Voltage) chips will be connected to the readout cards in the FGT. Each of these APV chips will generate an I^2R heating of about 1/3 Watts. This means that the 6 disks in the FGT will generate dissipation heating of about 144 Watts. To cool the readout electronics of the FGT detector, there will be an air cooling system.

For this thesis project, I worked on setting up a cooling test to simulate the performance of the FGT air cooling system. This model for the FGT air cooling system will be referred to as the Thermal Model. In the thermal model, the heat sources (APV chips) will be modeled by resistors. The specific parts of the thermal model I worked on were the completion of the 6 model disks of the FGT, the writing

of a data acquisition program to monitor the temperatures of the readout cards, and the testing of the heating and cooling of one of the 6 model disks.

Chapter 2

Construction of Thermal Model

The thermal model in its current state is shown in Figure 2-1. This model consists of

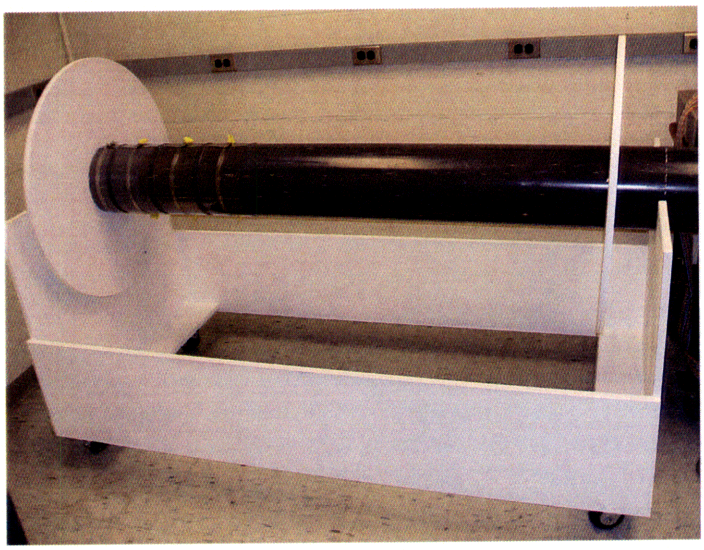

Figure 2-1: The pipe in the thermal model which will have air flowing through it is shown.

a big pipe suspended in a cradle. Air will be flown inside the pipe and some of this air will flow out of 1-inch diameter holes to cool the readout cards. A schematic of how the airflow will go through the model is shown in Figure 2-2. The 1-inch diameter holes will be drilled on the pipe right before the locations of the disk so that the air can escape and cool the readout cards. To vary the airflow through the holes, sheets of plastic will be put on the pipe. These plastic sheets, or collars, will be able to slide over the holes to adjust their sizes.

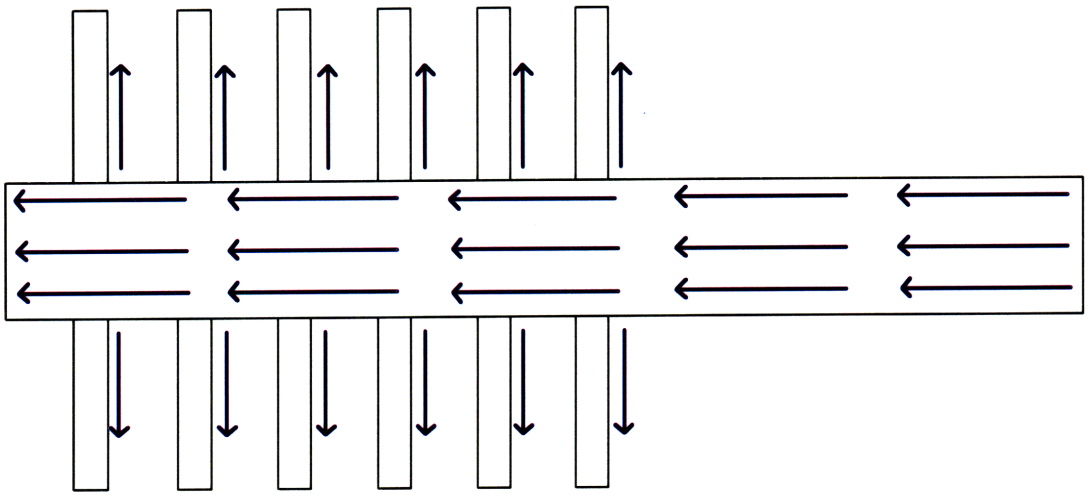

Figure 2-2: Schematic of airflow in the thermal model. The blue arrows represent air. It can be seen that air will flow out of the pipe in a radial direction right before the disks.

One of the tasks I completed while working on this thesis project was putting all the components onto the 6 disks. The disks of the thermal model were made out of wood and painted white. A picture of one disk with all the components attached is shown in Figure 2-3. The big hole in the middle of the disks was made so that the

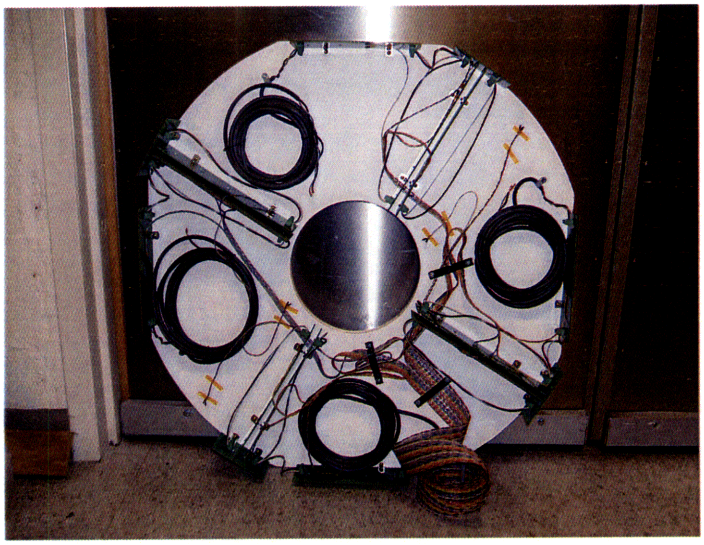

Figure 2-3: Image of a completed disk.

disks can fit tightly into the pipe.

The first component of the disks I worked on was preparing the readout cards. There are 3 different types of readout cards which we can be distinguished by their

sizes. The small readout cards and the medium readout cards each take four 80.6Ω resistors. Large readout cards each take five 191Ω resistors. A close up view of one of the large readout cards is now shown in Figure 2-4. In this picture, the numbered

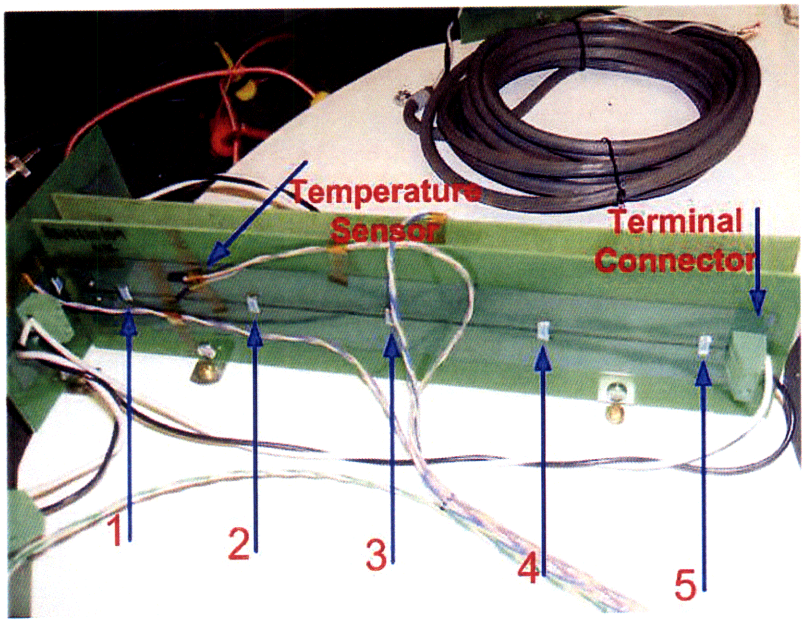

Figure 2-4: Close up view of one of the large readout cards.

arrows on the bottom point to the five resistors. The method I used to attach the resistors to the readout cards was soldering. After the resistors were soldered, terminal connectors were soldered on both ends of the readout cards. One terminal connector is also pointed out in Figure 2-4. The cables through which current will run to heat up the resistors are the black and white cables connected to the terminal connectors in Figure 2-4.

Now that the readout cards were prepared, I moved on to attaching the readout cards to the disks. The surfaces of each disk are separated into 4 quadrants. In each quadrant, two large readout cards, one medium readout card, and one small readout card are attached. For clarity, Figure 2-5 shows the configuration of the readout cards in one quadrant.

In this picture we see that the large readout cards are placed side by side. The small readout card is placed at the edge of the disk so that its center is in between the two large readout cards. Finally, the medium readout card is also placed at the edge

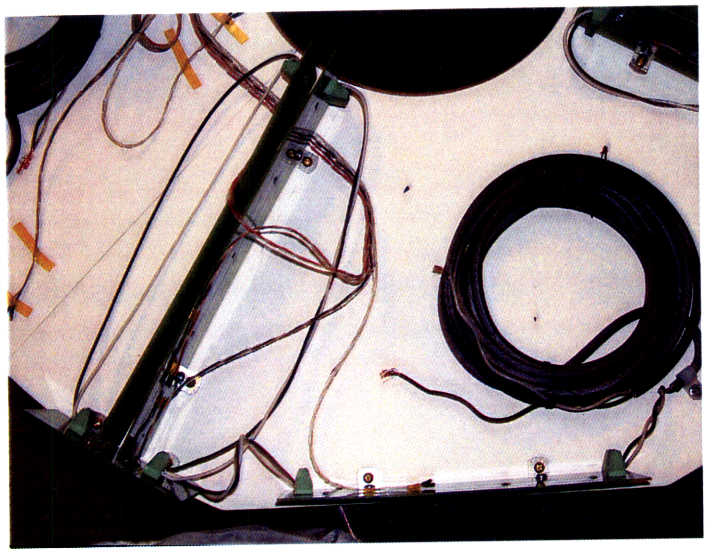

Figure 2-5: One quadrant of a disk. The two large readout cards and small readout cards are on the left. The medium readout card is on the right.

of the disk and to the right of the other three readout cards. After I had one quadrant prepared, I moved on to attaching the readout cards to all remaining quadrants for all 6 disks.

Now that the readout cards are in place, I will discuss the circuit in each quadrant. The circuit diagram for the configuration of readout cards is given in Figure 2-6. The power supply is connected to the medium readout card. The medium readout card is then connected to the small readout card in parallel. This small readout card was then attached to one of the large readout cards in parallel. Finally, the two large readout cards were also connected in parallel.

To connect the medium readout cards to the power supply, I attached four 15-feet long cables to the disks. These four cables are the 4 gray cables rolled up in circles in Figure 2-3. One of the ends of these cables was attached to one of the terminal blocks in the medium readout card. Banana plugs were placed on the other end of each of the 15-feet long cables to connect these cables to the power supply. A picture of this end of the cable is shown in Figure 2-7. The power supplies we used were Hewlett Packard E3614A Power Supplies [5] and one of them is also shown in Figure 2-7.

The final step to complete the preparation of the disks was the preparation of the temperature sensors. This was one of the most difficult tasks because the temperature

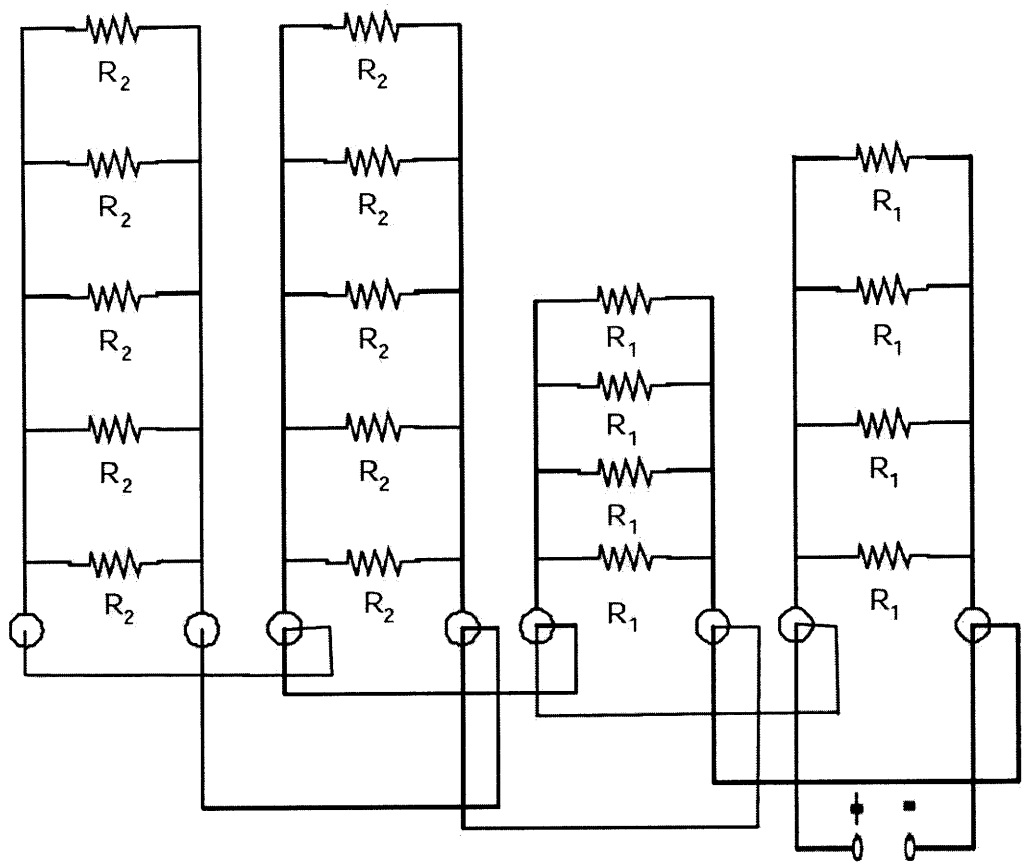

Figure 2-6: Circuit diagram for the 4 readout cards in a quadrant. It can be seen that the resistors in each of the readout cards are in parallel and also that the connections between all the readout cards are in parallel. The values for the resistors are $R_1 = 80.6\Omega$ and $R_2 = 191\Omega$.

sensors are very small and delicate. The temperature sensors were attached to all the channels in a cable used for reading 20 channels. A picture of this cable is shown in Figure 2-8.

Once the temperature sensors were attached to all the channels, the temperature sensors were attached to the disks and readout cards with tape. A temperature sensor tapped to one of the large readout cards is pointed out in Figure 2-4. Each of the 16 readout cards on each disk received a temperature sensor. On the medium readout cards, the temperature sensors were attached directly to a resistor to measure a quick response in the rise of temperature. This left us with 4 extra temperature sensors. Two of the remaining temperature sensors were attached close to the hole in the

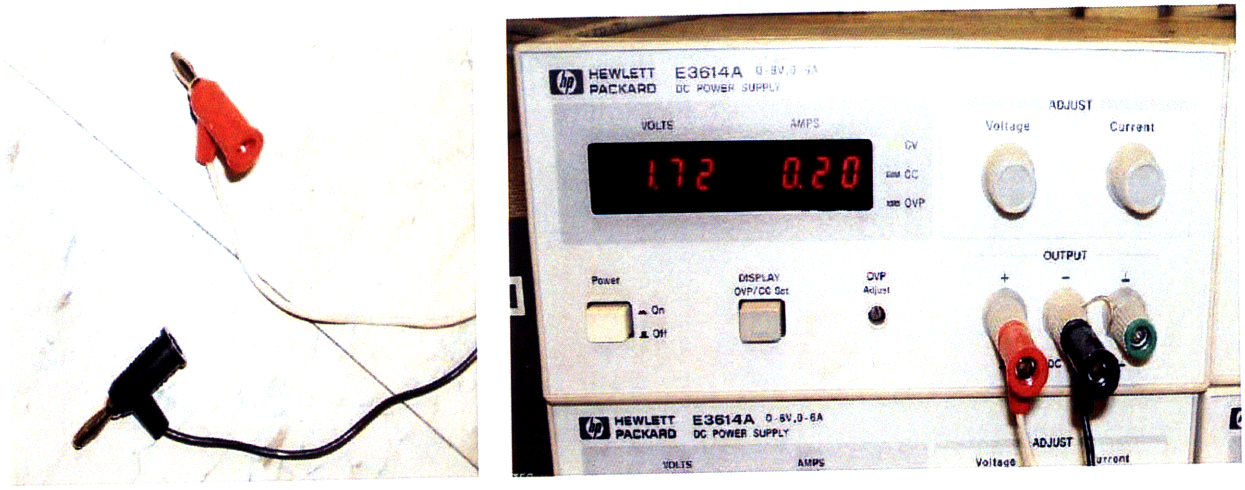

Figure 2-7: On the left, banana plugs are attached to one end of a 15-feet long cable. On the right side, the banana plugs are attached to a power supply.

middle of the disks to measure the incoming airflow and the other 2 temperature sensors were attached close to the edge of the disk to measure the exhaust air.

The other end of the 20 channel cable was attached to a connector block. This connector block was then attached to a Keithley Model 2000 Multimeter [6]. This connector block and one of the multimeters we used are displayed in Figure 2-9. With the temperature sensors now connected to the multimeters, the temperature sensors are now ready to be used to measure temperature. To monitor the temperature over time, we wrote a LabVIEW DAQ (Data Acquisition) program. The LabVIEW program is discussed in full detail in Appendix A but I will briefly discuss here what the program does.

Our LabVIEW DAQ program first tells the muiltimeter to scan through all 20 channels. The multimeter then measures the resistances of the temperature sensors. The resistances the multimeter measures are then created to temperature readings in units of degrees Celsius by the LabVIEW program. Our program then takes the temperature readings for all the channels and displays them over time in a graph. The 4 temperature readings for each quadrant are displayed in one graph. This means that we have 4 graphs displaying temperatures over time with each graph displaying 4 temperature readings. The remaining 4 channels attached to the disk are displayed in another graph. Finally, the LabVIEW program also inserts all of the temperature

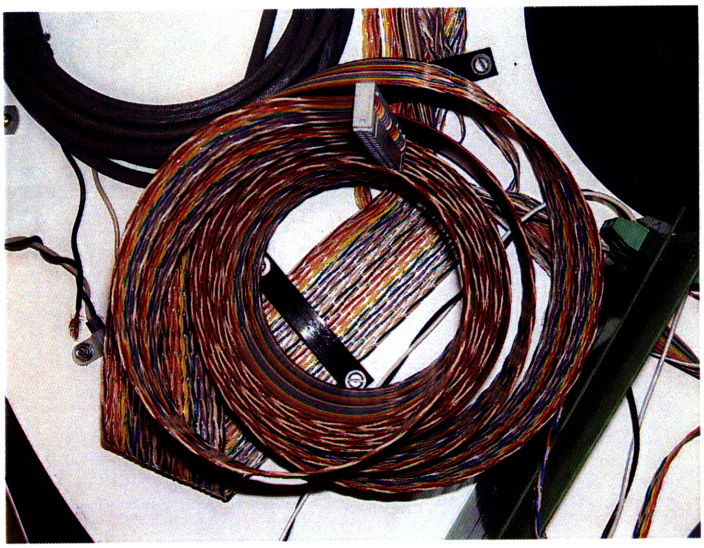

Figure 2-8: 20 channel cable used for attaching the temperature sensors and for reading out the values of the temperature sensors.

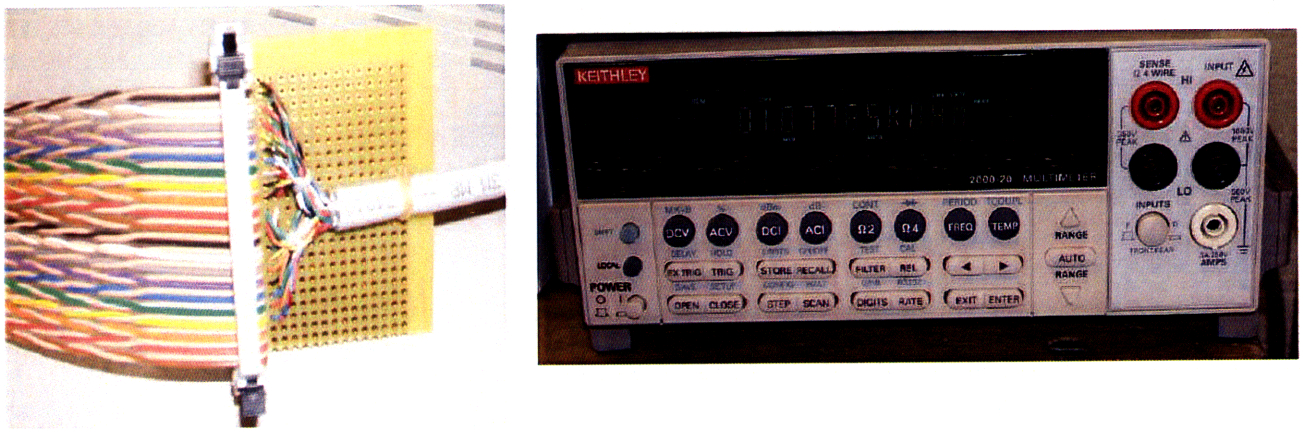

Figure 2-9: On the left, the 20 channel cable is attached to a connector block. This connector block was attached to the multimeter on the right.

readings into a file so that the data can be analyzed later.

Chapter 3

Measurements

In this section, I will discuss the measurements I took to see if the orientation affects the temperature readings. The two orientations I took measurements for are shown in Figure 3-1. In the horizontal orientation, the disk is placed upside down on a flat

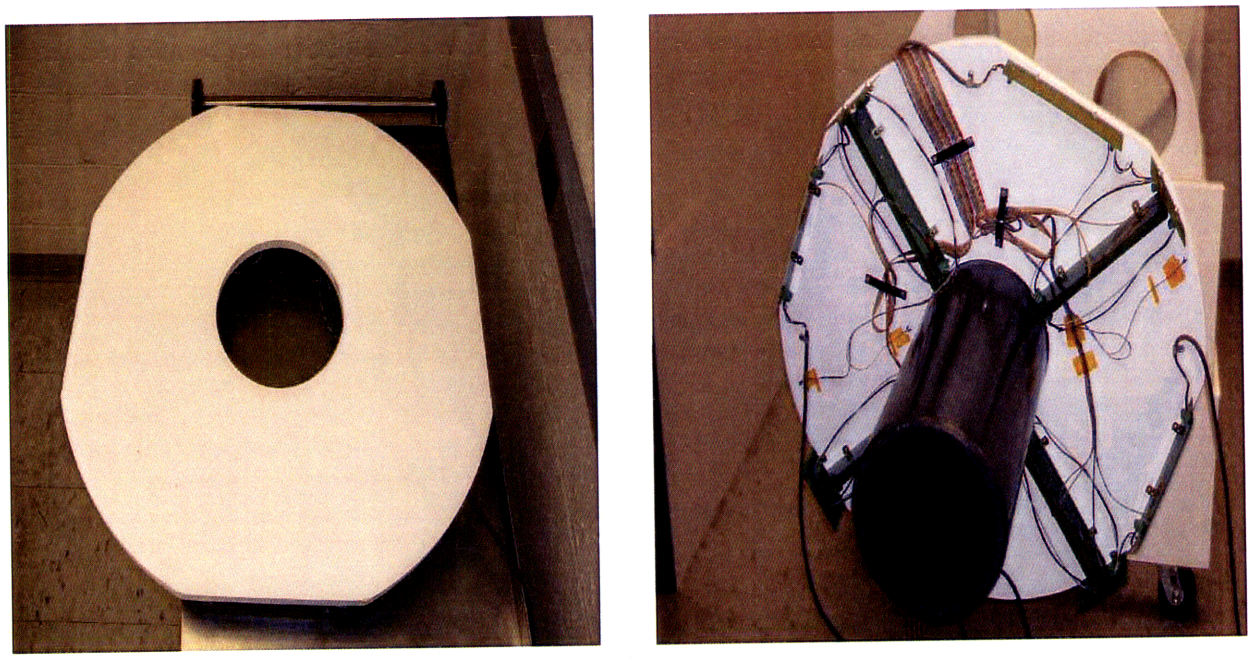

Figure 3-1: This figure displays the two different orientations. The horizontal orientation is on the left and the vertical orientation is on the right.

surface. The vertical position corresponds to the disk being placed on the pipe in the orientation it will be when the thermal model is completed.

The graphs of the LabVIEW program are set up so that we can observe the four

temperatures of each quadrant in one graph. The temperature sensors are connected so that channels 1-4 correspond to quadrant 1, channels 5-8 correspond to quadrant 2, etc. Also, the first channel in each quadrant (channel 1 for quadrant 1, channel 5 for quadrant 2, channel 9 for quadrant 3, channel 13 for quadrant 4) were connected directly to resistors. The second channel in each quadrant was connected to the small readout card. The third channel in each quadrant was connected to the large readout card closest to the medium readout card and the last channel in each quadrant was connected to the other large readout card.

Before moving on to the heating of the readout cards, I ran the program without connecting the power supply to any quadrant. Figure 3-2 displays the measurements for the disk in the horizontal position and Figure 3-3 displays the results for the vertical position.

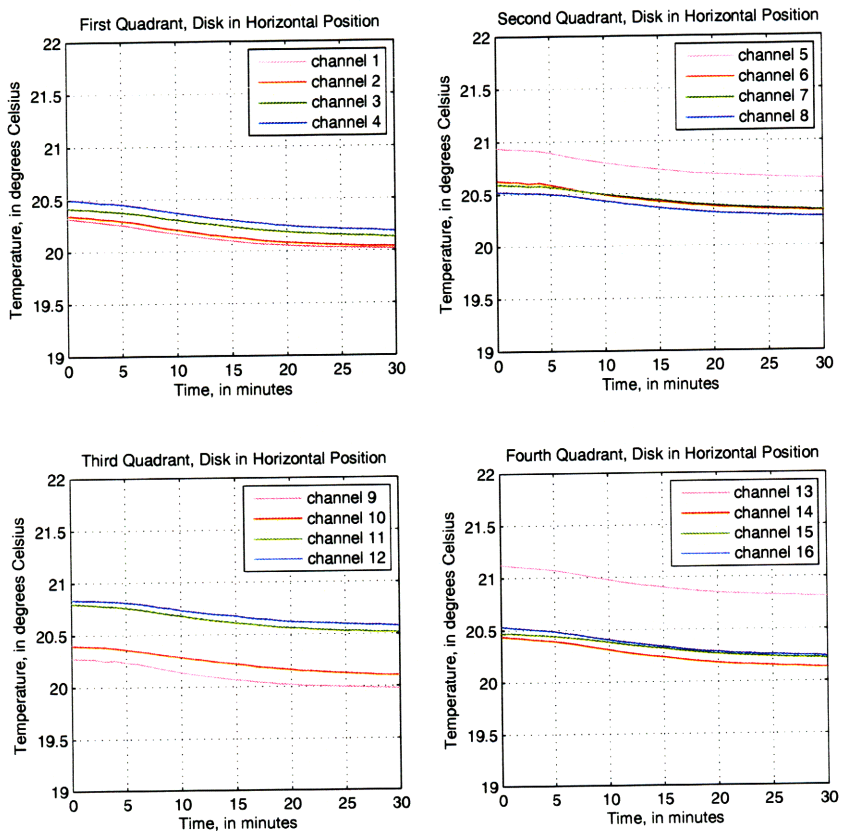

Figure 3-2: Measurements of disk in horizontal position with no currents.

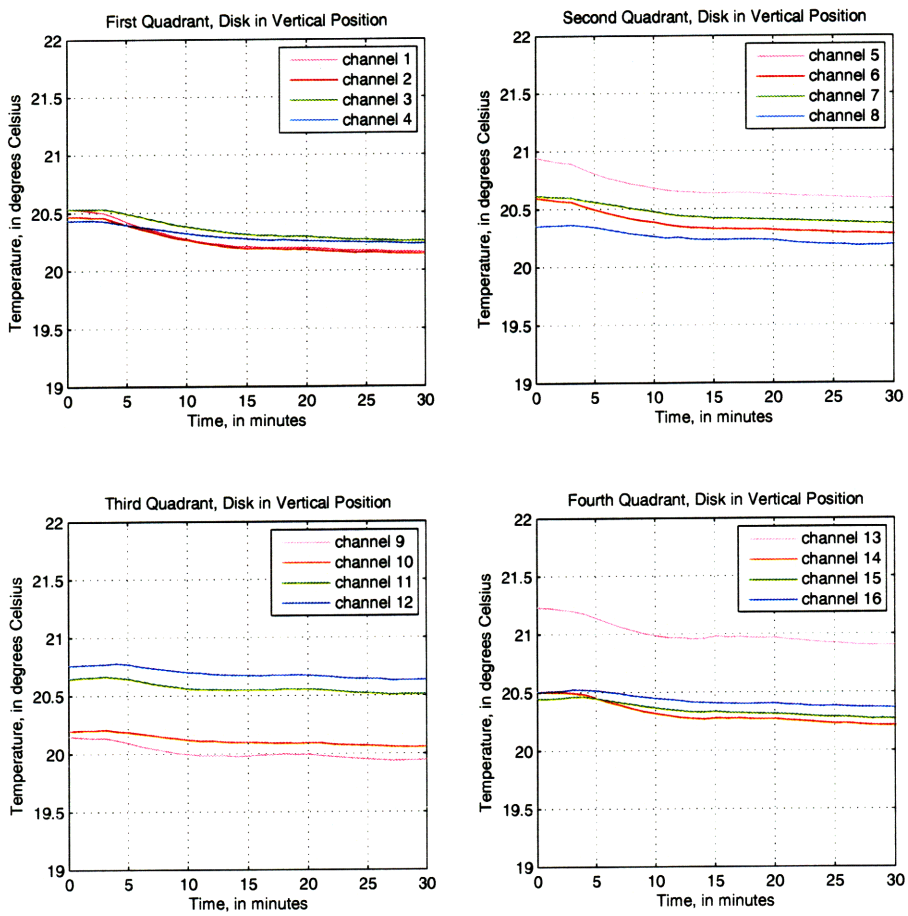

Figure 3-3: Measurements of disk in vertical position with no currents.

In both configurations, we see that the temperatures start off high in all the quadrants and then begin to fall. We expected the graphs to display constant temperatures because the sensors weren't being heated or cooled. In the end, we could not come up with an explanation for this decay of temperatures but this fall in temperature is not more than a degree Celsius. We do have about a 1 degree experimental error in this experiment. Since the graphs are within this experimental error, these graphs are not enough evidence to show that there is a problem with the readings of the temperature sensors.

3.1 Heating of Readout Cards

For this part of the experiment, I heated up all the quadrants at the same time. The procedure I took to heat up all the readout cards is the following. First, I connected all the banana plugs to the power supply in parallel but with the power supply turned to $0A$. I kept the power supply on $0A$ for 5 minutes to let things stabilize. After the 5 minutes were up, I increased the current in the power supply to $.5A$. Since the LabVIEW program is set to take measurements every minute, after a minute passed, I noticed a sudden jump in the temperatures.

After 5 minutes passed from the time I increased the current, I increased the current by another $.5A$ so that the current would now be given by $1A$. I continued this pattern of waiting for 5 minutes and then increasing the current by $.5A$ until I reached $4A$. When I reached $4A$, I waited another 10 minutes and then stopped the program. The figures for the temperature readings for all the quadrants heated at the same time for the horizontal and vertical positions are given in Figures 3-4 and 3-5 respectively.

The most striking behavior that can be seen from these plots is the rise in temperature of the channels connected to the resistors. By the end of the 50 minutes of taking data, the temperatures of the resistors are well above the temperatures of the readout cards. An interesting note is that the resistor in the fourth quadrant is at least 10 degrees hotter than the other resistors. This is a pattern that was seen every time I took heating measurements.

Also, at every 5 minutes, the effects of the rise in current can be seen. Before the 5 minute waiting period, it seems like the temperatures are beginning to stabilize but then the increase in current causes a sharp increase in the temperatures. This can be seen in all channels in the vertical and horizontal positions. Also, the three channels not on the resistor in each quadrant seem to have very similar increases in temperatures. Throughout the measuring period, the temperature readings of these 3 channels are very similar. When making comparisons between the horizontal results and the vertical results, no significant changes between the measurements can be seen.

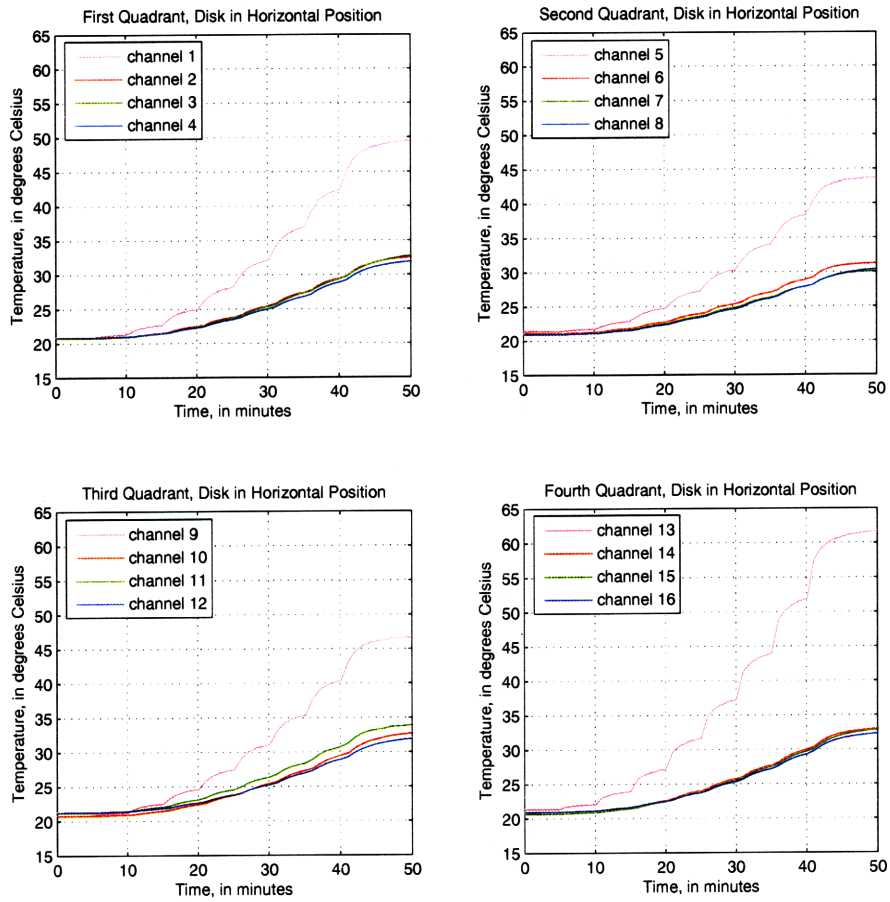

Figure 3-4: Graph for the heating of all the quadrants in the horizontal position at the same time.

Although the final temperature readings for each channel are not always the same, the differences in the final temperatures are only a few degrees.

3.2 Cooling of Readout Cards

After the 50 minutes of taking measurements for the previous experiment were up, in this part I quickly unplugged the banana plugs from the power supply and then ran the program again to monitor the cooling of all the readout cards. In this experiment I cooled the readout cards for 30 minutes. The data for the cooling of the horizontal position is shown in Figure 3-6 and the data for the cooling of the vertical position is

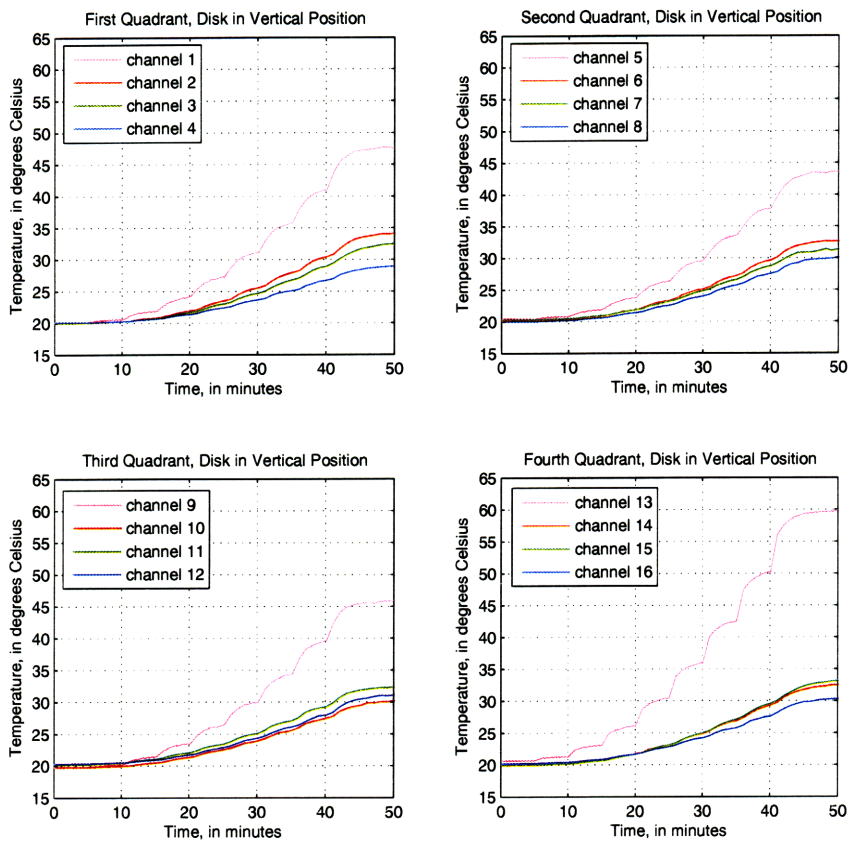

Figure 3-5: Graph for the heating of all the quadrants in the vertical position at the same time.

shown in Figure 3-7.

As shown in all of the plots, the channels with the resistor on them are observed to have the highest initial temperatures. What is interesting about these plots though is that the initial temperatures shown in these plots don't correspond with the final temperatures on the heating plots. The resistors in the first three quadrants cool more than 10 degrees Celsius in the two minutes it takes to make the first cooling measurement and the resistor in the fourth quadrant cools by more than 25 degrees. The resistors in all the quadrants also have similar initial temperatures around 30 degrees Celsius. The channels not on the resistors can be seen to cool by about 2-3 degrees Celsius when the first temperature reading of their cooling is made.

After 10 minutes, the channels in each quadrant read around the same temper-

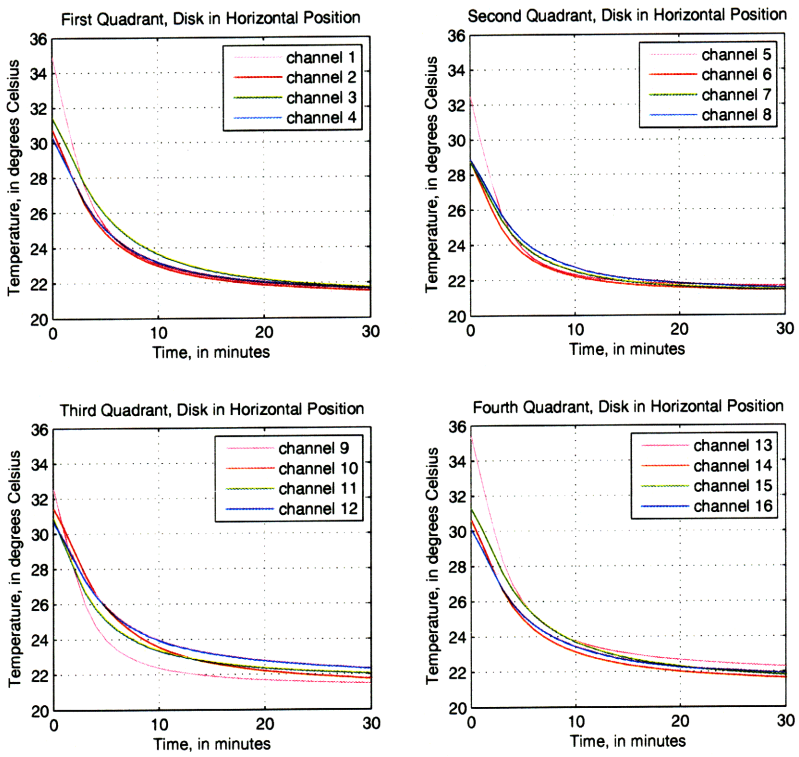

Figure 3-6: Graph for the cooling of all the quadrants in the horizontal position at the same time.

ature and after the 25 minutes all the channels have cooled to room temperature. When the measurements are compared to see if any difference between the horizontal configuration and the vertical configuration can be seen, no differences are seen. The temperature readings for each quadrant in the horizontal configuration closely resemble the temperature readings for the same quadrant in the vertical position. The particular quadrants of the two configurations display the same cooling behavior and reach the same final temperature.

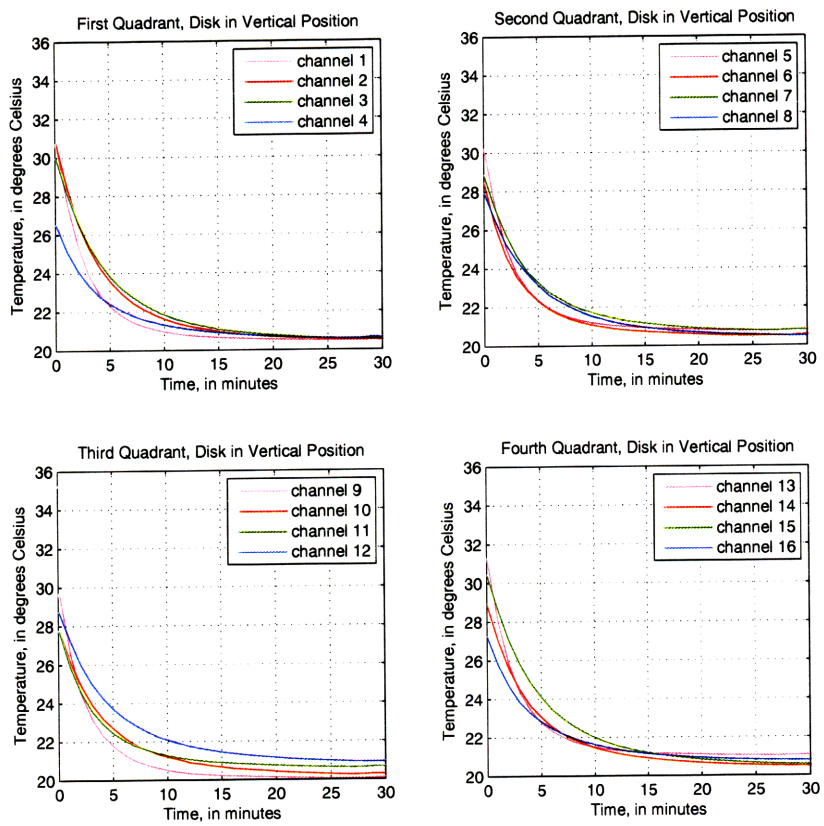

Figure 3-7: Graph for the cooling of all the quadrants in the vertical position at the same time.

Chapter 4

Conclusion

In this thesis report, we first saw how the disks for the Thermal Model of the FGT were prepared. With the disks now ready, the experimental setup was completed with a power supply and a multimeter. The power supply was used to heat up the readout cards and the multimeter was used to measure the resistance of the temperature sensors. Then, a LabVIEW DAQ program was written to convert the resistance readings to temperatures and to monitor the temperatures over time. This LabVIEW program was used to test whether the orientation of the disks affected the heating or the cooling of the readout cards. After analyzing the data, I concluded that the orientation of the disk does not affect the heating or the cooling of the readout cards.

Appendix A

LabVIEW DAQ Program

LabVIEW (**Lab**oratory **V**irtual **I**nstrumentation **E**ngineering **W**orkbench) is the programming language we used to display the temperatures as a function of time and to write the data to a file. This program was developed by National Instruments and it is a popular programming language for the use of data acquisition. The LabVIEW environment consists of a front panel and a block diagram. A picture of the front panel of our program is shown in Figure A-1 for reference.

In the front panel, the temperature readings are displayed in two columns and also 4 channels are plotted as a function of time in each graph. This program was created for the reading of 40 temperatures so there are 10 graphs in total. Since I only used 20 channels for this paper, I will only display the 5 graphs that plot these 20 channels. The legend for each graph is shown in the top right of each graph. The first graph, or waveform chart, displays channels 1-4, the second waveform chart displays channels 5-8, the third waveform chart displays channels 9-12, etc. Looking at the legend for waveform chart 1, plot 0 is drawn in white and it displays channel 1, plot 1 is drawn in red and plots channel 2, etc. Plot 0 in waveform chart 2 corresponds to channel 5, plot 1 in waveform chart 2 corresponds to channel 6, etc. This pattern is the same for the other waveform charts.

LabVIEW is a graphical programming language and the program written to display the results in the front panel is created in the block diagram environment. The program is written by inserting functions in the block diagram and making connec-

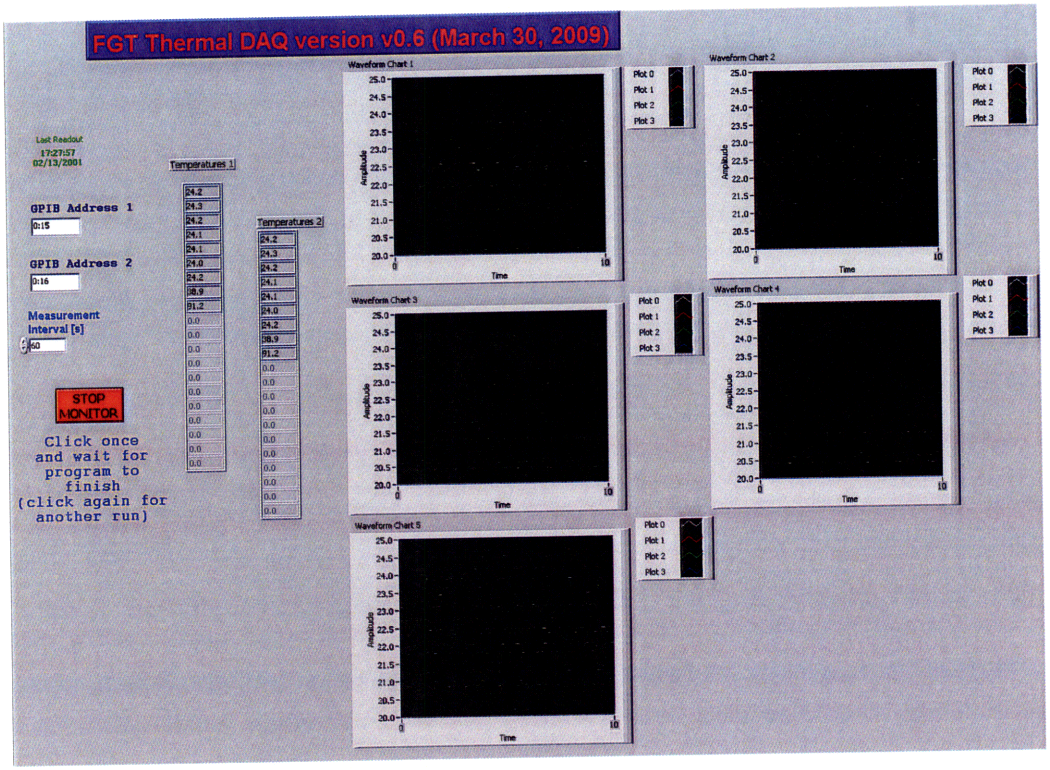

Figure A-1: Figure of LabVIEW Front Panel.

tions between the different functions. I will now move on to discussing the different sections of the block diagram for our program.

The first step in this program is to communicate with the multimeters. This part of the program is illustrated in Figure A-2. When the program is run, the program tells each of the 2 multimeters we are using to scan through the 20 channels. The program first has one multimeter scan through the 20 channels and then the program has the other multimeter scan through the other 20 channels. The way we know which multimeter scans first and which multimeter scans second is by specifying the GPIB (**G**eneral **P**urpose **I**nterface **B**us) addresses of the multimeters. We specify the GPIB addresses over which we want to scan through in the front panel. In the front panel, we see that the first multimeter has a GPIB address of 15 and the second multimeter has a GPIB address of 16.

After the multimeters scan through all the channels and take readings of the resistances of the temperature sensors, we insert a step to convert these resistances to temperatures. The block diagram of this particular step is shown in the bottom

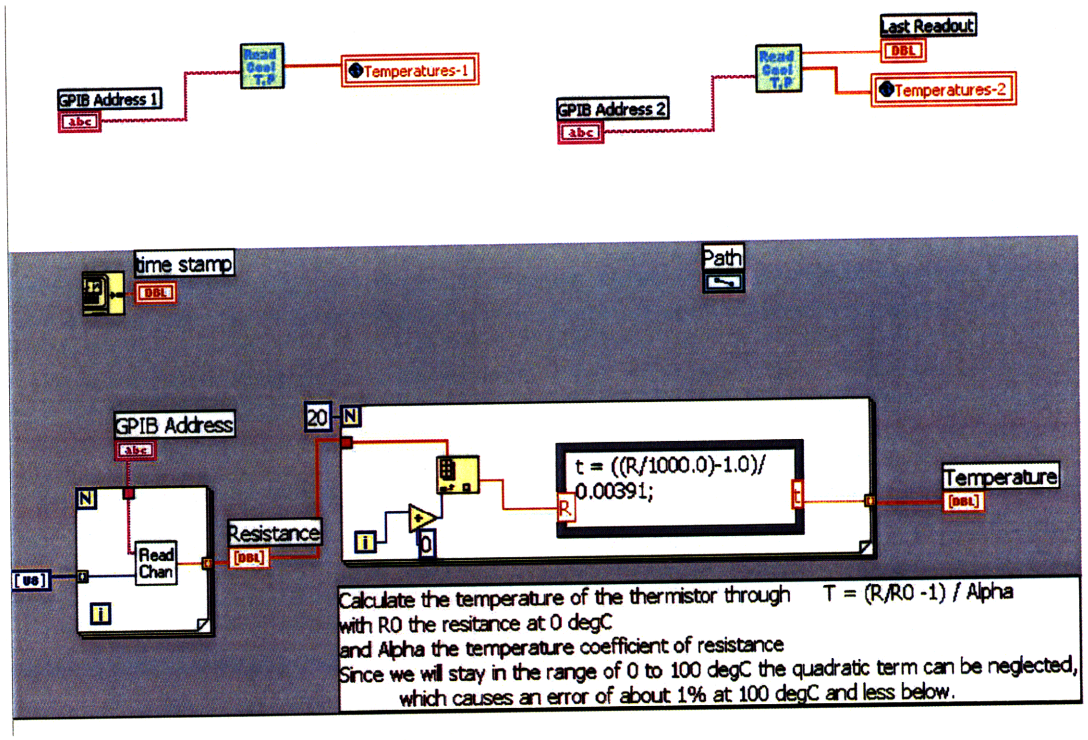

Figure A-2: Block diagram of the part of the LabVIEW program that tells the multimeters to scan the temperature sensors and the part that converts resistances to temperatures.

of Figure A-2. In the block diagram of this step, we see that in the left, after the multimeters have scanned through all the channels, the values of the resistances measured are converted to temperatures. The function that converts temperatures to resistances for the temperature sensors we used is given by the following expression [7]:

$$R_T = R_0[1 + aT - bT^2 - cT^3(T - 100)]. \tag{A.1}$$

In this equation, R_T is the resistance at a certain temperature T and R_0 is the resistance at 0° Celsius. The coefficients a, b, and c depend on the ranges over which one is measuring temperature. The particular values these coefficients take are shown in Table A-1 [7].

Since we will only be measuring temperatures at or above room temperature, $c = 0$ for our purposes. Furthermore, we ignore the quadratic term in the equations since ignoring this term only causes a 1 percent error in temperature readings when we stay in temperatures between 0° C and 100° C. Making these modifications and

Table A.1: Values for the coefficients a, b, c, for different ranges of temperatures for the temperature sensors we used.

Temperature	a	b	c
$T < 0°C$	3.90830×10^{-3}	5.7750×10^{-7}	4.1830×10^{-12}
$T \geq 0°C$	3.90830×10^{-3}	5.7750×10^{-7}	0

solving for the temperature, we see that relation for converting between resistances and temperatures is given by the following expression

$$T = \frac{R_T/R_0 - 1}{a}. \tag{A.2}$$

After this function is used to convert the resistances to temperatures, the values for the temperatures are displayed in units of degrees Celsius in the front panel in two columns. Column one displays the temperatures from the first GPIB address and column two displays the temperatures from the second GPIB address. The values in these two columns of temperatures are then converted to double variables. The step in the program that does this computation is shown in Figure A-3.

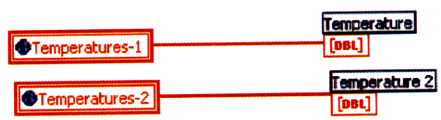

Figure A-3: Temperature readings are converted into double variables.

The final step plots the temperatures from 4 channels as a function of time in a waveform chart. The way this is done is by first inserting the measurements from the two 20 temperature columns into an array with 40 entries. The first 20 entries contain the 20 temperatures from the first GPIB address and the next 20 entries contain the temperatures from the second GPIB address. After this step, I use LabVIEW's split array function to divide the array of 40 entries into 10 arrays with each array having 4 entries. The block diagram for this step of the program is shown in Figure A-4.

In the figure it can be seen that the Temperatures-1 block and Temperatures-2 block are connected to the insert into an array function. Then, the array is taken

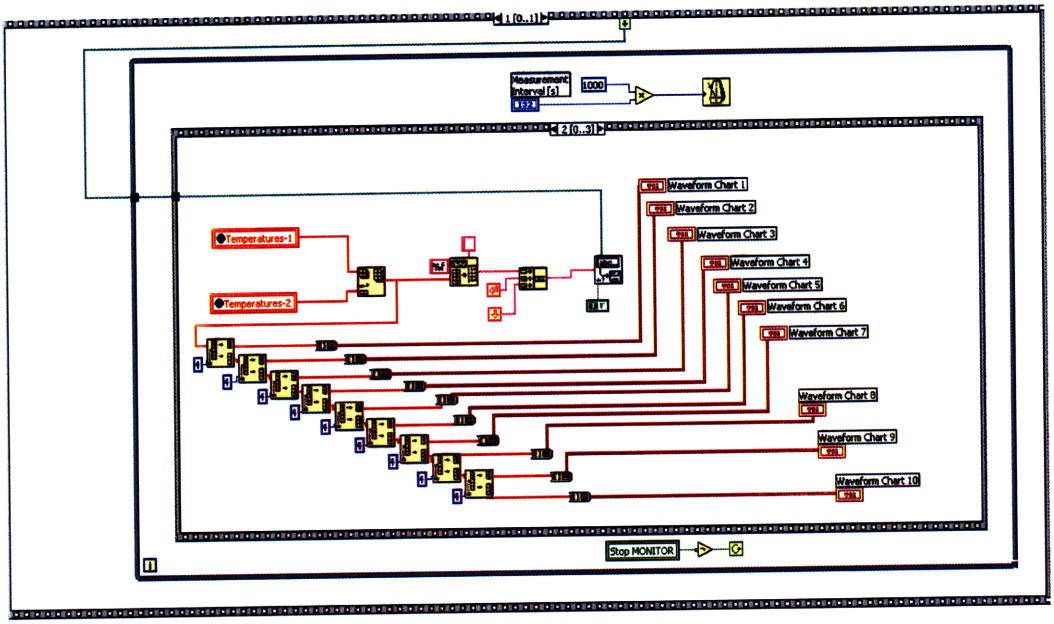

Figure A-4: The temperature readings are inserted into an array with 40 elements. Then, this array is split into 10 arrays with 4 elements to each array. Finally, the 10 arrays are plotted in waveform graphs.

to the bottom left where the split array function is used 9 times to create 10 arrays with 4 elements to each array. What I have the split array function do is first take the array with 40 elements and split that array into 2 different arrays. The first array contains the first 4 entries of the array with 40 entries (corresponding to channels 1-4) and the second array contains the next 36 entries of the 40 element array. The array with 4 entries is then created into a structure so that it can be displayed in a waveform chart over time.

The same method is used to display the next set of 4 temperatures. What I do is I invoke the split array function again on the array with 36 entries to create 2 new arrays. The first array contains the first 4 entries of the 36 entry array (corresponding to channels 5-8) and the next array contains 32 elements. The array with 4 elements is then created into a structure and channels 5-8 are displayed as a function of time in the second waveform chart. I use the split array function 7 more times to split the array until I have 10 arrays with each array having 4 entries. This is the last step of our program and now our program is capable of displaying temperature readings over time.

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