

Design, Construction, and Testing of the Radiometer at the Canadian Light Source

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1.0 Introduction

During the summer of 2009, I was an employee at the Canadian Light Source Synchrotron, working in the Controls and Instrumentation Development division. The primary focus of my work was on the design, construction, and testing of the radiometer for the CLS. In my lab notebooks I recorded detailed notes of every task I took on related to the radiometer. The following pages are a summary of those notes. Within this document you can find everything that you need to understand why the radiometer was built, how it was done, and how to successfully operate it.

2.0 Basic Concepts

The Canadian Light Source synchrotron at the University of Saskatchewan produces large amounts of energy in the form of light, with wavelengths from infrared to x-rays and everything in between. For some experiments, it is important for the scientists to know exactly how much of a certain wavelength of light is being used to study their sample. The goal of the radiometer currently being constructed at the U of S is to accurately count the flux of x-rays of a chosen wavelength being produced by the synchrotron. With the measurements from the radiometer, the scientists will be able to calibrate the photo-diodes used to measure x-ray flux during experiments.

The radiometer is made of two copper cryostat chambers, an outer protective chamber, and a pot where the x-ray absorber is located. The x-ray absorber is made of a sheet of 40mm x 45mm x 0.002" copper foil rolled into a tube with a tapered back end. Attached to the absorber is a 6.2 k Ω resistor that acts as a heater, and a sensor to measure the temperature of the absorber. The absorber is connected to its holding structure via eight AWG 36 tinned copper wires and eight AWG 36 beryllium copper wires, all held together with a special epoxy that is thermally conducting at low temperatures. The holding structure is screwed onto a mounting plate within the pot of the radiometer, which is thermally connected to the inner cryostat chamber.

How all these pieces fit together to make something that measures x-ray flux is actually quite simple. There are two possible methods that can be used. One works by measuring the change in temperature of the absorber, and the other measures the change in electrical power fed through the attached resistor.

The change in temperature method works in the following way. The radiometer will be placed in a position so that the beam of x-rays enters it and strikes the absorber. The absorber will absorb close to 100% of the x-rays that strike it and convert their energy into heat energy, which will raise the temperature of the absorber. The absorber is thermally connected to the liquid helium filled inner cryostat chamber that acts as a heat sink. The temperature difference between the absorber and the heat sink will cause some of the heat energy to flow away from the absorber. Initially, the amount of heat energy that is gained from the incoming beam will be greater than the amount of heat energy lost to the heat sink. However, more heat will be lost as the temperature gradient between the heat sink and absorber increases. Once the absorber reaches a certain temperature, the amount of heat gained from the incoming beam will equal the

amount of heat lost to the heat sink, and the temperature will cease to change. This final value of temperature is very important, and will be recorded.

Once a steady temperature has been established, the radiometer will be removed from the beam and the absorber allowed to cool back to liquid helium temperature. Now the second stage of the measurement begins. Running a current through the 6.2 k Ω resistor will cause it to act as a source of power to heat the absorber. By controlling how much current is put through the resistor, we can control how much heat energy is given off. The current will be adjusted until the absorber is heated up to and remains at the same value it reached when the beam was the source of power. When this occurs, we know that the power being put into the absorber from the resistor is the same as the power that was being put into the absorber from the beam. By measuring the current through and the voltage across the resistor, we can calculate how much power this is by using the equation

$$P = IV \quad (1)$$

Where P is the power, I is the current, and V is the voltage.

With the value of the power now known, we can calculate the flux of the x-rays. This is done in the following way:

The wavelength of the x-rays can be accurately chosen, and as such we can calculate the frequency of the x-rays:

$$f = \frac{c}{\lambda} \quad (2)$$

Where f is the frequency, c is the speed of the wave (in this case, the speed of light), and λ is the wavelength. With the frequency known, we can calculate the energy of one x-ray:

$$E = hf \quad (3)$$

Where E is the energy and h is Planck's constant (6.626×10^{-34} J·s). If we know the energy of a single x-ray and we also know the power of the beam, then we can finally calculate the flux of the beam.

$$\Phi = \frac{P}{E} \quad (4)$$

Where Φ is the flux of x-rays.

The change in electrical power method works in a similar way to the one described above, except some of the steps are reversed. An absorber temperature is chosen by the user and the absorber is brought to this temperature by running the

proper amount of current through the resistor. The power being applied to the absorber is again:

$$P_1 = I_1 V \quad (5)$$

Once a steady state has been reached, the absorber is exposed to the beam. This exposure to the beam will increase the absorber temperature again. The current through the resistor will then be adjusted so that the combined power from the resistor and the beam will be the same as the when the resistor was the only power source, thus bringing the temperature back to the user's chosen temperature.

$$P_2 = I_2 V + P_B \quad (6)$$

$$P_1 = P_2 \quad (7)$$

$$P_B = V(I_1 - I_2) \quad (8)$$

With the power of the beam known, equation 4 can again be used to calculate the flux of x-rays.

3.0 Disassembly/Reassembly of Dummy Chamber

Before attempting to do any type of work on the actual radiometer, it is a good idea to familiarize yourself with the disassembly/reassembly procedure. Fortunately there is a dummy chamber provided for just such a purpose. The procedure for taking it apart and putting it back together is very similar to the procedure for the actual radiometer.

Required Tools:

3/32 Allan wrench
 9/64 Allan wrench
 4 small containers to place sets of screws and washers
 Aluminum Foil
 Lint-free cloth/Kimwipes
 Latex Gloves

3.1 Dummy Chamber Disassembly Procedure

1. Ensure that the pressure inside the chamber is in equilibrium with the atmospheric pressure outside the chamber. If it is not, slowly open the top valve and allow the system to balance.
2. Remove the outer snout by removing the 6 screws attaching it to the main chamber with the 9/64 Allan wrench. Be sure to not let the snout fall, and pull it directly away from the chamber when the screws are removed. There are

- smaller snouts inside the outer one that could be damaged if the outer snout is removed carelessly. Once removed, wrap the snout in lint free cloth, and wrap the open end in aluminum foil.
3. Inside the outer snout is a copper snout attached to the chamber in a bayonet-like fashion. To remove this snout, loosen each of the 4 screws one complete revolution with the 3/32 Allan wrench, and twist the snout clockwise. Remove the snout carefully by pulling directly away from the chamber. Again, there is a smaller snout inside that may be damaged. Wrap the snout in lint-free cloth and set aside.
 4. Once the copper snout is removed, a smaller copper snout will be visible. Remove this snout in the same manner as step 3, except twist the snout counter-clockwise once the screws are loosened.
 5. Remove the outer casing of the chamber by removing the 4 screws located in the overhang of the top of the chamber with the 9/64 Allan wrench. Once the screws are removed, lift the top of the chamber straight up out of the casing, taking care not to bang the copper chamber still attached to the top against the outer chamber. Rest the top on its side, and set aside the outer chamber.
 6. To remove the now visible copper chamber, use the 9/64 Allan wrench to remove the 8 screws located on the overhang of the top of the copper chamber. Again, be sure to support the chamber as the screws are removed, and pull it directly away from the top when it is free. There is another copper chamber inside that may be damaged. Also, make sure to keep track of all screws and washers. Each screw has an accompanying lock washer and flat washer. The flat washers may become stuck on the copper when the screw is being removed. They can be dislodged with a GENTLE tap from a flat head screwdriver. If gentle tapping does not remove them, then leave them stuck there, and be sure not to put another flat washer over top of them when re-assembling. Once the chamber is removed, set it aside on a lint-free cloth.
 7. In the same manner as described in step 6, remove the now exposed small copper chamber by taking out the 12 screws located on the overhang of the top with a 9/64 Allan wrench.
 8. With all of these pieces removed, the mounting plate for the absorber will be visible and ready for any maintenance/adjustments required.

3.2 Dummy Chamber Reassembly Procedure

Throughout the reassembly, be mindful to not place flat washers on screws that will be going into holes that have flat washers stuck around them.

1. With the top of the chamber lying on its side, carefully slide the small copper chamber over the absorber holding unit and secure with the 12 given screws using the 9/64 Allan wrench. Make sure to align the holes properly.
2. Install the large copper chamber in the same manner as the small one, using the 8 given screws and the 9/64 Allan wrench.
3. Carefully place the top of the chamber (now with copper chambers connected) into the outer chamber. Secure them together with the 4 given screws and the 9/64 Allan wrench in the holes located on the overhang at the top of the chamber.

4. Connect the small copper snout by carefully guiding it through the hole in the chamber and overtop of the smallest circle of 4 visible screws. Then rotate the snout clockwise and tighten each screw with the 3/32 Allan wrench.
5. Connect the large copper snout in the same manner as the small one, again using the 3/32 Allan wrench to tighten the screws, this time on the large circle of 4 screws. Be careful not to bump the small snout as you pass the large snout over top of it.
6. Finally, attach the outer snout by carefully guiding it over the large copper snout and securing it with the 6 given screws and the 9/64 Allan wrench. Be sure not to bump the copper snout when moving the outer snout over it, and do not let the outer snout hang on the copper snout. Doing either of these could cause the copper snout to be bent or scratched, causing unnecessary damage.

4.0 Disassembly/Reassembly of Pot

Once you've got the hang of working with the dummy chamber, working with the actual pot should be relatively simple.

Required Tools:

3/32 Allan wrench
9/64 Allan wrench
4 small containers to place sets of screws and washers
Aluminum Foil
Lint Free Cloth/Kimwipes
Latex Gloves
Step Stool

4.1 Pot Disassembly Procedure

This is a two person job!!

1. Ensure that the pressure inside the chamber is in equilibrium with the atmospheric pressure outside the chamber. If it is not, slowly open the pressure release valve and allow the system to balance.
2. Remove the bolts on the support flange that connect the radiometer to its support structure.
3. Have one person stand on the step stool and lift the radiometer up about three inches. The second person should then slide the two 2" square support bars underneath the support flange, and the first person can then lower the radiometer onto these support bars.
4. Remove the outer snout by removing the 6 screws attaching it to the pot with the 9/64 Allan wrench. Be sure to not let the snout fall, and pull it directly away from the chamber when the screws are removed. There are smaller snouts inside the outer one that could be damaged if the outer snout is removed carelessly. Be sure to remove the O-ring and safely set it aside. Once removed, wrap the snout in lint free cloth, and then wrap the open end in aluminum foil.

5. Inside the outer snout is a copper snout attached to the pot in a bayonet-like fashion. To remove this snout, loosen each of the 4 screws one complete revolution with the 3/32 Allan wrench, and twist the snout clockwise. Remove the snout carefully by pulling directly away from the pot. Again, there is a smaller snout inside that may be damaged. Wrap the snout in lint-free cloth and set aside.
6. Once the copper snout is removed, a smaller copper snout will be visible. Remove this snout in the same manner as step 3, except turn this one counter-clockwise once the screws are loosened.
7. Remove the outer casing of the pot by removing the 4 screws located in the overhang that connects the pot to the rest of the chamber with the 9/64 Allan wrench. Once the screws are removed, lower the outer casing straight down, taking care not to bang it into the copper chamber (which is the liquid nitrogen heat shield) still attached to the radiometer. Be sure to also remove the O-ring and set both the O-ring and the outer casing aside.
8. To remove the now visible copper casing, use the 9/64 Allan wrench to remove the 8 screws located on the overhang of the top of the copper chamber. Again, be sure to support the chamber as the screws are removed, and lower it straight down when it is free. There is another copper chamber inside that may be damaged. Also, make sure to keep track of all screws and washers. Each screw has an accompanying lock washer and flat washer. The flat washers may become stuck on the copper when the screw is being removed. They can be dislodged with a GENTLE tap from a flat head screwdriver. If gentle tapping does not remove them, then leave them stuck there, and be sure not to put another flat washer over them when re-assembling. Once the chamber is removed, set it aside on a lint-free cloth.
9. In the same manner as described in step 6, remove the now exposed small copper chamber by taking out the 12 screws located on the overhang of the top with a 9/64 Allan wrench.
10. With all of these pieces removed, the absorber will be visible and ready for any maintenance/adjustments required. To remove the holding structure and absorber, use the 3/32 Allan wrench to remove the 6 screws attaching the holding structure to the mounting plate.

4.2 Pot Reassembly Procedure

Throughout the reassembly, be mindful to not place flat washers on screws that will be going into holes that have flat washers stuck around them.

1. Attach the absorber and holding structure to the radiometer with 6 size 4-40 screws, using the 3/32 Allan wrench.
2. Carefully slide the small copper chamber back over the absorber holding unit and secure it with the 12 given screws using the 9/64 Allan wrench. Make sure that the hole for the snouts is pointing in the correct direction.
3. Install the large copper chamber in the same manner as the small one, using the 8 given screws and the 9/64 Allan wrench.
4. Carefully insert the large O-ring into the groove on the underside of the radiometer, and then guide the outer casing over the large copper chamber.

- Secure the outer casing to the radiometer with the 4 given screws and the 9/64 Allan wrench in the holes located on the overhang of the top of the casing.
5. Connect the small copper snout by carefully guiding it through the hole in the chamber and overtop of the smallest circle of 4 visible screws. Then rotate the snout clockwise, and tighten each screw with the 3/32 Allan wrench.
 6. Connect the large copper snout in the same manner as the small one, again using the 3/32 Allan wrench to tighten the screws, this time on the large circle of 4 screws. Be careful not to bump the small snout as you pass the large snout over top of it.
 7. Attach the outer snout by carefully guiding it over the large copper snout and securing it with the 6 given screws and the 9/64 Allan wrench. Be sure not to bump the copper snout when moving the outer snout over it, and do not let the outer snout hang on the copper snout. Doing either of these could cause the copper snout to be bent or scratched, causing unnecessary damage.
 8. Have one person stand on the step stool and lift the radiometer so that the second person can remove the support bars. The first person then carefully lowers the radiometer until the support flange contacts the holding structure. The radiometer can be secured there with the given nuts and bolts.

5.0 Cryostat Filling Procedure

In order for the radiometer to work successfully, the absorber must be cooled down to the temperature of liquid helium (approximately 4 K). To do this, one will require the following items:

- Face Shield
- Cryogenic Gloves
- Lab Coat
- Step Stool
- Small Funnel
- Dewar small enough to hold at head height for five minutes when filled
- Liquid Nitrogen
- Liquid Helium
- Liquid Helium Transport Hose
- Dirty Vacuum Pump and Hoses

To cool the absorber down to the required temperatures, follow these steps:

1. Attach the vacuum pump to the radiometer via the vacuum port located on the front of the radiometer, about 4/5 of the way to the top. Pump the radiometer down to vacuum level. If possible, use a vacuum gauge and pump down the radiometer to a level of 0.1 mTorr or lower.
2. Fill the liquid nitrogen heat shield. This is accomplished by pouring liquid nitrogen down one of the three liquid nitrogen ports located on the top of the radiometer. To make this easier, use the small funnel to guide the liquid into the port. Be sure to pour the liquid nitrogen slowly, especially at first. Most of the nitrogen poured in the first few minutes will boil off very quickly, and pouring too fast may cause the liquid to spurt back out of the port and all over the

- surrounding area, a less than desirable scenario. It should take approximately 2 five litre dewars to fill the outer jacket.
3. If you wish to only do tests with the absorber at liquid nitrogen temperature, then repeat the previous step, instead filling the inner chamber using one of the inner chamber ports. Again, this should take about 2 five litre dewars to fill. For liquid helium filling instructions, move on to step 4.
 4. Let the system cool down to liquid nitrogen temperature (77 K) overnight. Be sure to top up the liquid nitrogen jacket before you leave for the night. The nitrogen takes 8 – 10 hours to evaporate from the jacket, so it will most likely be gone by morning.
 5. Once the system is at liquid nitrogen temperature, helium filling can begin. **HELIUM FILLING REQUIRES TWO PEOPLE.** Use the vacuum pump to pump the liquid helium transport hose down (let it pump for 5 minutes or so). Once the transport hose is pumped down, have one person stand on a ladder next to the radiometer, and the other person stand next to the dewar of liquid helium. Open the necessary valves, and have each person simultaneously lower their end of the transport hose into either the radiometer or the dewar. Once the transport hose reaches the bottom of either device, raise the hose up about one inch and secure it with the nuts on the hose. Helium should begin to flow automatically.
 6. During the first few minutes of the fill, all of the helium will be instantly boiled off due to the temperature difference between the helium and the radiometer. Once the temperature monitor drops to a value of around 5 K, turn on the liquid helium depth sensor. At this point, liquid will be accumulating in the chamber. Close the valves once you have reached your desired depth.
 7. To remove the hose, loosen the nuts that were securing it and raise each end of the hose out of its device at the same time. Be sure not to touch any part of the hose that has been exposed to liquid helium. Set the hose aside and begin your testing!

6.0 Using the Radiometer GUI

The radiometer at the CLS can be remotely controlled from any Linux terminal window in the building. To use the controlling GUI, open a terminal and change directories to the following:

- /home/control/Radiometers/Prototype

From this directory, the following files are available:

- runGUI
- runMultiMeters
- runTempMonitor
- runCurrentSource
- runPID

Executing the runGUI file should cause the control GUI to appear on the screen. For normal operations, this should be the only file that is required. Running any of the other files will bring up the low level controls for the corresponding device. If a device isn't working properly, checking these low level controls is usually a good place to start.

Once the GUI is up and running, it is possible to control all aspects of the radiometer (as long as it is connected to the electronics rack and the rack is plugged in). The GUI displays the current source controls, the voltage, current, and power of the circuit, the temperature of the absorber, and the PID controls.

Operating the current source

The current source is very simple to control using the GUI. Simply enter the amount of current that you would like to put through the resistor and press the "on" button. In practice though, the current source is operated by the PID loop, so the user never actually enters a value of current to use.

The PID loop and how to operate it

The PID loop is what will find the proper current to reach the desired temperature. PID stands for proportional, integral, and differential. The proportional component of the PID computes the required change in the current necessary to achieve the wanted temperature. In an ideal world, this would be all we need. But since there is a finite response time of the PID to changes in current, the system actually sets us up to overshoot the temperature. By choosing the correct P value, the desired temperature can eventually be reached, but it will likely require a couple of overshoots by the PID loop, which can add a significant amount of time to the procedure.

The integral component is useful mainly when we do not know what our present value of the current is. Since we will always be able to tell what the value of the current is, the integral component is not likely to be used.

The differential component helps to reduce the effect of the proportional components overshoot. When the system is initialized, the temperature jumps and the current slowly adjusts to it, so that by the time the desired temperature is reached the current is too large. The differential component kicks in and lowers the current when it starts to notice the temperature change slowing. In this way, the differential component acts like a brake and helps us to reach the desired temperature sooner.

Using the PID loop consists of entering four numbers and watching how the system develops. One simply enters the desired temperature, the values of the P, I, and D components, turns on the current source (make sure it is initially set to zero) and then turns on the PID loop. A strip chart is a very handy tool for observing how the system develops. If good values of P, I, and D are chosen, then one can expect the temperature to reach and stay at the desired temperature after only one or two overshoots. To choose the values of P, I, and D, follow these steps:

1. Turn off close-loop.
2. Set I and D to zero.
3. Measure or estimate how much the temperature changes for a given change in current.
4. Take 10-20% of that and enter it as P.
5. Set the current such that the temperature is significantly off the set point (call this the test starting value).
6. Cycle between turning on close-loop and resetting to the test start values.
 1. Increase P until the temperature overshoots the setpoint, oscillates, and shows no sign of damping out.
 2. At that point back P down and turn on closed-loop if it isn't already on
 3. Wait for the temperature to stabilize.
7. If the temperature remains consistently off, set I to the frequency (Hz) of temperature readings going into the PID controller [since we are applying the output to the previous current, we shouldn't need to set the integral. Feel free to skip this if you don't suspect an offset problem].
 1. Adjust I so that the temperature stabilizes at the set point.
 2. Since I is cumulative, you may want to zero it by manually entering '0'
8. Turn on (or off) the heat source on the absorber.
9. If the controller significantly overshoots and takes some time to recover, set D to the typical time (seconds) of increase (decrease) in temperature at the point of onset.
 1. Alternate between heater on and off.
 2. If possible without causing oscillations, try to set D such that the derivative contribution is comparable or larger than the proportional contribution as the temperature approaches the setpoint.
 3. Adjust D to optimize the recovery time of the temperature.
 4. In principle, it should be possible to increase P and D even further for quicker response times, but noise in the temperature readings will be amplified, so a conservative tune is recommended.

By following these, you should be able to use the GUI to accomplish what needs to be done with the radiometer.

For the initial liquid helium temperature testing, the change in electrical power method was used. The PID values used for these tests were:

$$P = 0.2$$

$$I = 0$$

$$D = 0.2$$

With these values, a temperature change of up to 0.5 K was observed, with a settling time of approximately 10 seconds.

7.0 Design and Construction of the Absorber and Holding Structure

The goal of the radiometer at the CLS synchrotron is to measure the flux of x-rays by absorbing them and converting their energy into heat energy. The design of an x-ray absorber to accomplish this task was a major objective in the construction of the radiometer.

7.1 Basic Design

The basic design for the absorber was to have something that would absorb 100% of the x-rays that crossed its path and convert their energy into heat energy, which would raise the temperature of the absorber. The absorber would be connected to a heat sink of liquid helium, so raising the absorber temperature would create a temperature gradient, and some of the heat energy would be lost to the liquid helium. As the x-rays are continually absorbed by the absorber, the temperature gradient will get larger and larger, and more heat will flow from the absorber to the heat sink. This process will continue until the heat flow in (from the beam) equals the heat flow out (lost to the heat sink). At this point the temperature of the absorber will stop changing and become constant.

It was agreed that a sheet of copper foil shaped into a tube with a tapered back end would be the basic structure for the absorber. It would be connected to the heat sink through a number of wires and a holding structure made of copper. The holding structure would be shaped like a box with open sides, with holes for the screws to attach it to the heat sink and a larger hole to allow the beam to pass through. The absorber would be connected to the holding structure by gluing the wires to both the absorber and the holding structure.

With the basic design decided upon, it was necessary to determine exactly how much of everything (wire length, absorber mass, etc.) was needed to make the radiometer function properly. Parameters we had to take into account were the limited amount of space the absorber had to fit in, the desired total change in temperature, and the desired amount of time to reach equilibrium.

7.2 Explanation of Code Used for Simulations

The simplest way to find combinations of material that work (in theory) is to write a short piece of code to calculate temperature change and power output, with input parameters that can easily be altered. The computer program MATLAB was used for this task. The code takes in information about the input x-ray beam and the physical parameters of the absorber, and as output produces graphs of the expected temperature change and the difference between power input and output. It also displays the time constant for the temperature change.

Parameter	Units	Symbol in Formulas	Name in Code
Photon Flux	Photon/sec	Φ	flux
Photon Energy	keV/Photon	E	energy
Initial Temperature	K	T_0	basetemp
Testing Time	sec	-	time
Number of Tinned Copper Wires	-	n_{CU}	numbSnCu
Radius of Tinned Copper Wires	m	r_{CU}	rSnCu
Length of Tinned Copper Wires	m	L_{CU}	lengSnCu
Thickness of Tin Shielding	m	S	tinthick
Number of Beryllium Copper Wires	-	n_{BE}	numbBeCu
Radius of Beryllium Copper Wires	m	r_{BE}	rBeCu
Length of Beryllium Copper Wires	m	L_{BE}	lengBeCu
Surface Area of Absorber	m^2	A	SA
Mass of Absorber	g	m	m
Thermal Emissivity of Absorber	-	ϵ	eps
Specific Heat of Absorber	J/(g·K)	c	c
Thermal Conductivity of Copper	W/(m·K)	k_{CU}	kCopper
Thermal Conductivity of Tin	W/(m·K)	k_{SN}	kTin
Thermal Conductivity of Beryllium Copper	W/(m·K)	k_{BE}	kBeCu

Table 1 - Input Parameters for MATLAB Simulation

With these parameters, it is possible to simulate how a particular system would react to a specific beam of x-rays. If we assume that the beam parameters are constant, then the input power, or heat gain, can be found from:

$$P_{in} = \Phi E \quad (9)$$

And if we assume that 100% of the photons are absorbed, then we can calculate the rate of change of absorber temperature due to the beam:

$$T_{in} = \left(\frac{P_{in}}{mc} \right) \left(1.602 \times 10^{-16} \frac{J}{keV} \right) \quad (10)$$

This shows that the rate of temperature increase due to the beam is a constant. However, the rate of temperature decrease due to heat loss in the absorber is not a constant. The absorber loses heat in two primary ways: Through conduction via the connection between the absorber and the heat sink, and through thermal radiation. The equation describing heat flow through a homogeneous wire with different temperatures at its ends is:

$$P_{con} = \frac{kn(r^2\pi)\Delta T}{L} \quad (11)$$

Where P_{con} is the output power and ΔT is the difference in temperature between the two ends. Because we have two different types of wires, we need to break this into three separate equations: One for the copper section of the tinned copper wires, one for the tin section of the tinned copper wires, and one for the beryllium copper wires.

$$P_{CU} = \frac{k_{CU}n_{CU}\pi(r_{CU} - S)^2 \Delta T}{L_{CU}} \quad (12)$$

$$P_{SN} = \frac{k_{SN}n_{CU}\pi(r_{CU}^2 - (r_{CU} - S)^2)\Delta T}{L_{CU}} \quad (13)$$

$$P_{BE} = \frac{k_{BE}n_{BE}(r_{BE}^2\pi)\Delta T}{L_{BE}} \quad (14)$$

The equation describing thermal radiation is as follows:

$$P_{rad} = \varepsilon\sigma A(\Delta T)^4 \quad (15)$$

Where P_{rad} is the output power and σ is the Stefan-Boltzmann constant. Combining these four equations will give the total power output, or heat loss in a given amount of time, of the absorber.

$$P_{out} = P_{CU} + P_{SN} + P_{BE} + P_{rad} \quad (16)$$

Clearly, the output power is dependent on the difference in temperature between the absorber and the heat sink. We can therefore expect that when the experiment is first begun and the absorber is at the same temperature as the heat sink there will not be much heat lost from the absorber. As the temperature difference increases,

however, we should see much more heat being lost from the absorber, until the amount of heat being lost equals the amount of heat being gained. The computer program simulates this in the following way: The system is made discrete (each discrete data point will be identified by an integer in brackets, i.e. $P_{out}(1)$) and sampled once every second. The simulation assumes that the beam first contacts the absorber at time = 0. The temperature difference between the absorber and the heat sink after the first second is approximated as T_{in} . T_{in} then becomes the first value of ΔT , $\Delta T(1)$, and is used to calculate $P_{out}(1)$ in equation 12.

$$P_{out}(1) = \frac{k_{CU} n_{CU} \pi (r_{CU} - S)^2 \Delta T(1)}{L_{CU}} + \frac{k_{SN} n_{CU} \pi (r_{CU}^2 - (r_{CU} - S)^2) \Delta T(1)}{L_{CU}} \\ + \frac{k_{BE} n_{BE} (r_{BE}^2 \pi) \Delta T(1)}{L_{BE}} + \varepsilon \sigma A (\Delta T(1))^4$$

The temperature drop from the loss of heat energy is calculated using the formula

$$T_{out}(1) = \frac{P_{out}(1)}{mc} \quad (17)$$

The difference between the ΔT and T_{out} is calculated as

$$\delta T(1) = \Delta T(1) - T_{out}(1) \quad (18)$$

This value of δT will be then be plotted on a graph of Temperature Difference vs. Time. The difference between power input and power output at that second is also calculated and plotted, using the equation

$$\delta P(1) = P_{in} - P_{out}(1) \quad (19)$$

This completes the analysis for the system at one second. The system then repeats itself every second. ΔT for the two second point, and every point afterward, is calculated as

$$\Delta T(x) = \delta T(x-1) + T_{in} \quad (20)$$

Where x is the number of the current point being evaluated. All the other formulas remain the same, and the system repeats itself every second until it reaches the users' desired time. When this is finished, all the data points are plotted, and the result is something like figure 1.

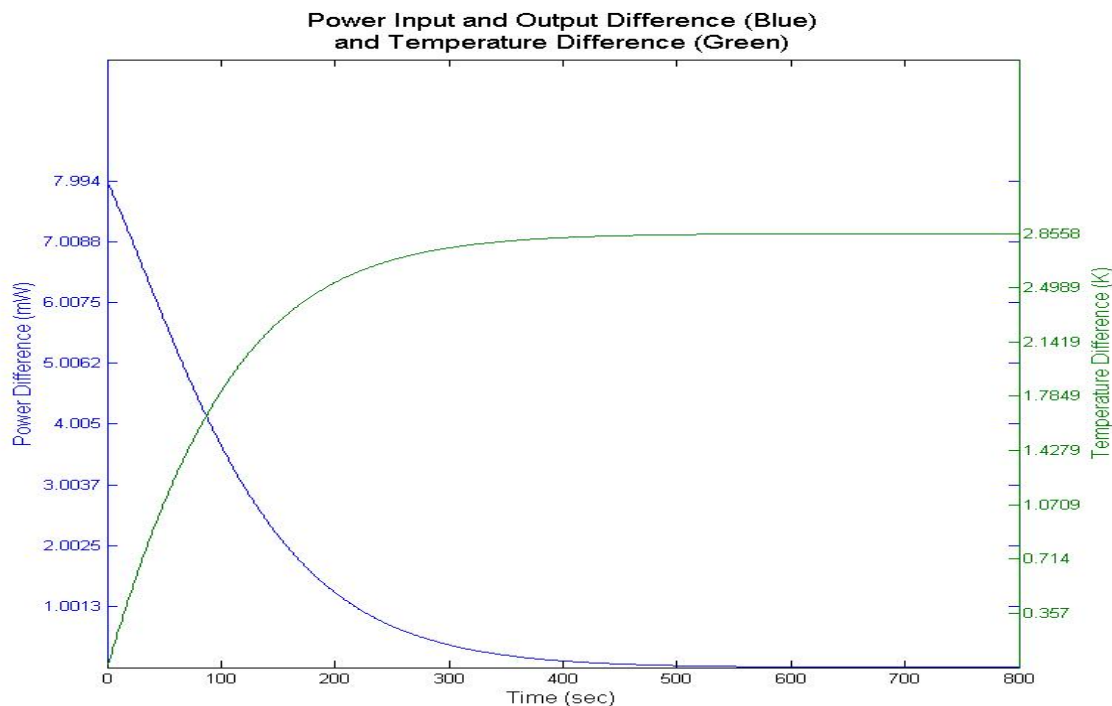


Figure 1. Expected Result of MATLAB Simulation

This plot shows that the results are what we were hoping for; the temperature eventually levels out and the power output eventually equals the power input.

To simplify life for anyone who wants to use this code, it was put into the form of a graphical user interface (GUI). The GUI contains spaces to enter all of the required data, and the user simply presses the compute button to see how those parameters would react. A graph of the temperature difference is produced, as well as values for the input beam power, final temperature difference, and time constant. A screenshot of the GUI is shown below:

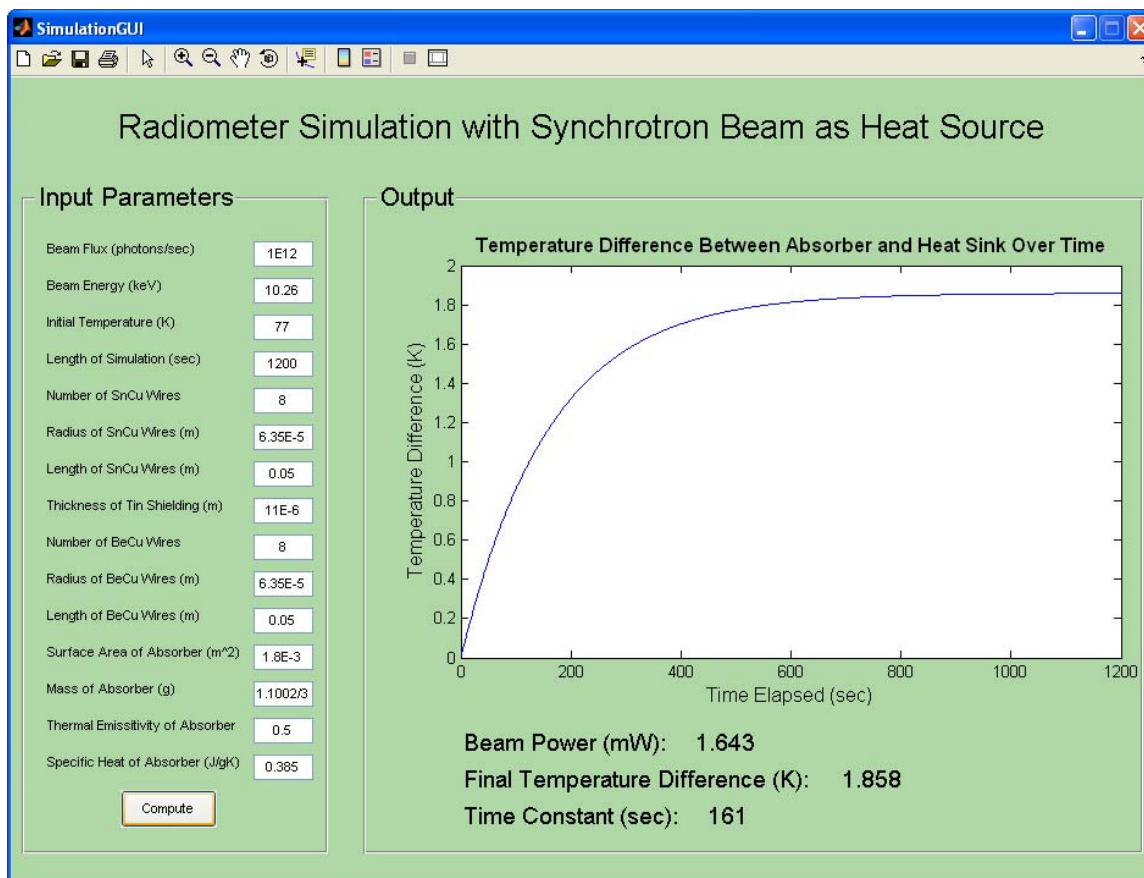


Figure 2 - Radiometer Simulation GUI

7.3 Determination of Parameters

The use of this code quickly made it apparent that the vast majority of the heat would be lost via conduction through the wires. Thermal radiation would not play a significant role because the small changes in temperature would not be large enough to overcome the small surface area and the value of the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$). With this in mind, we can assume that the output power will be directly proportional to the number of wires used, the difference in temperature between the absorber and heat sink, and the thermal conductivity of the wires, proportional to the square of the radius of the wires, and inversely proportional to the length of the wires.

Simulations were run using beam parameters of a flux of 1×10^{12} photons/sec and an energy range of 1-50 keV. Different beam energies resulted in different output powers, and thus different final temperatures. It was decided to try to find a combination that resulted in a temperature change of a few K at the highest beam energy (50 keV) and change between 0.1 – 0.5 K for the lowest beam energy (1 keV). After numerous simulations, a working combination that could be built with the materials available to us was found. It consisted of eight AWG 36 tinned copper wires, each approximately 0.05 m long, holding a copper absorber that weighed 0.8 g. The resistor

and temperature sensor would each be connected to their respective devices by four AWG 36 beryllium copper wires, again approximately 0.05 m long.

7.4 Results

This design was tested using the change in electrical power method. The results of the test showed a discrepancy between the predicted results and what was actually observed. While the simulation predicted that the system would stabilize within approximately a minute of being placed in the beam, the system actually stabilized with a matter of a few seconds. The results of all the tests completed with the beam are shown in the table below.

Temp. (K)	Gap	Beam Current (mA)	Beam on Power (uW)	Beam Off Power (uW)	Power Difference (uW)	Comparative Difference
7	35 x 60	192.80	261	1318	1057	0
7	35 x 60	192.18	266	1318	1052	1055
7	35 x 60	190.96	275	1317	1042	1052
7	35 x 60	189.90	285	1318	1033	1049
7	35 x 60	188.47	291	1318	1027	1051
5.9	10 x 15	186.66	18.3	120.4	102.1	0
5.9	10 x 15	186.28	19	120.5	101.5	101.7
5.9	10 x 15	185.71	19.3	120.5	101.2	101.7
5.9	10 x 15	184.86	20.2	120.5	100.3	101.3
5.9	10 x 15	184.33	20.9	120.8	99.9	101.2
5.925	10 x 15	248.02	17.11	145.3	128.19	96.5
5.925	10 x 15	246.05	17.12	145.3	128.18	97.2
5.925	10 x 15	243.44	15.9	145.6	129.7	99.4
5.925	10 x 15	240.63	16.8	145.6	128.8	99.9

Table 2 - Results of Testing With Synchrotron Beam

As the results show, the chosen configuration yields an electrical power difference on the order of hundreds of microwatts, depending on the amount of beam being allowed to strike the radiometer. This is an acceptable difference that the measurement instruments can easily distinguish. Why there is such a discrepancy between the simulation and the actual results is still unclear. Fortunately, the results were better than the simulation predicted and as such were able to verify that the radiometer is capable of absorbing x-rays from the synchrotron beam and converting their energy into a measurable temperature difference in the absorber in a sufficient amount of time.

7.5 Construction of Holding Structure and Absorber

With the parameters decided upon, it was time to begin construction of the absorber and its holding structure. The holding structure was the first thing constructed. The holder had to fit into a volume that was 80 mm long, 56 mm wide, and 62 mm high. It was made from a sheet of 0.25 mm copper, and folded into a box with

open sides. The box with open side design was chosen to allow maximum contact between the holder and the heat sink, while still providing easy access to the absorber. It was attached to the heat sink with six 4-40 size screws. An 18 mm diameter hole was also made in the front face of the structure to allow the beam to pass through to the absorber.

The holding structure was bent into shape by placing a thin steel rod (2 mm) where the bend was desired, and bending the copper with our hands. With this built, we could focus on building the absorber. The absorber was made from a 40 mm x 45 mm x 0.002" sheet of copper. It was bent into its desired shape (a tube with one tapered end) by wrapping it around a 1/2" aluminum rod with approximately 1.5 cm hanging over the edge of the rod, and bending the copper hanging over into a tapered shape. With the absorber in its desired shape, the next step was to attach the resistor that would act as a heat source when we were finding the electrical power equivalent. To do this, follow these instructions:

The resistor that was chosen was a 6.2 k Ω metal film resistor. It is attached to the absorber by using Lake Shore Low Temperature Conductive Epoxy (all components and wires are attached to the absorber and holding structure with this epoxy). The epoxy requires heat to cure, so the absorber itself has to be heated. This is accomplished by placing the absorber back on the aluminum rod that it was shaped around and placing this rod on a hotplate, with the absorber hanging just off the end. The hot plate is then turned to a temperature that increases the temperature of the absorber to 100°C (when water boils on the absorber). The hotplate that was used had to be set to 375°C for this to be accomplished. At this temperature, it takes the epoxy approximately an hour to cure. When doing this, one must be very careful not to let the epoxy contact the leads of the resistor. Doing this will create a short that will yield the resistor ineffective.

The next step is to attach the absorber to the holding structure with the chosen wires. This is done with more of the same epoxy. The simplest way to do this is to take four wires approximately 20 cm long, and twist pairs of them together to create a loop for the absorber, as shown in the figure below.

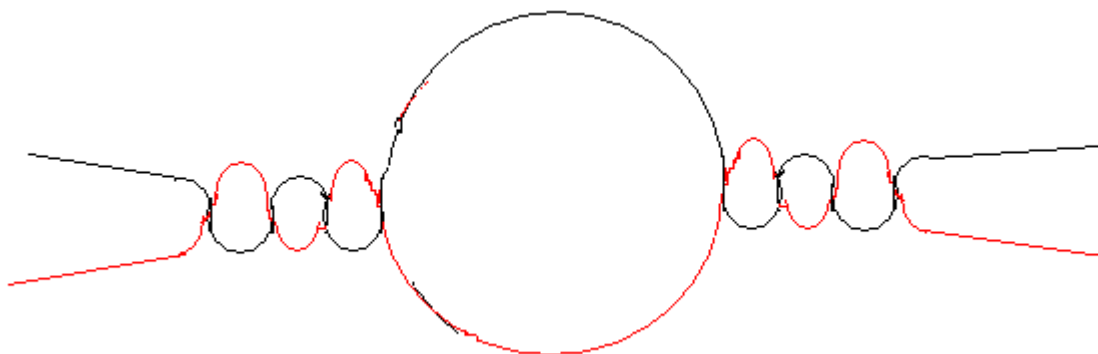


Figure 3. Loop Created by Twisting Two Wires Together

The four wires twisted together create two loops to hold the absorber with eight lengths of wire to connect it to the holding structure. Place these loops around the absorber, one at the front and one at the back (make sure they fit tightly). When satisfied with their position, apply epoxy to the loops and heat the absorber in the same method as used to attach the resistor (If one is confident, you can attach these loops at the same time as the resistor).

The best way to connect these eight wires to the holding structure is to flip the holding structure over so it rests on its top (with the screw holes down) and bend four wires over the bottom of the holding structure so that the absorber can hang from them, as shown below

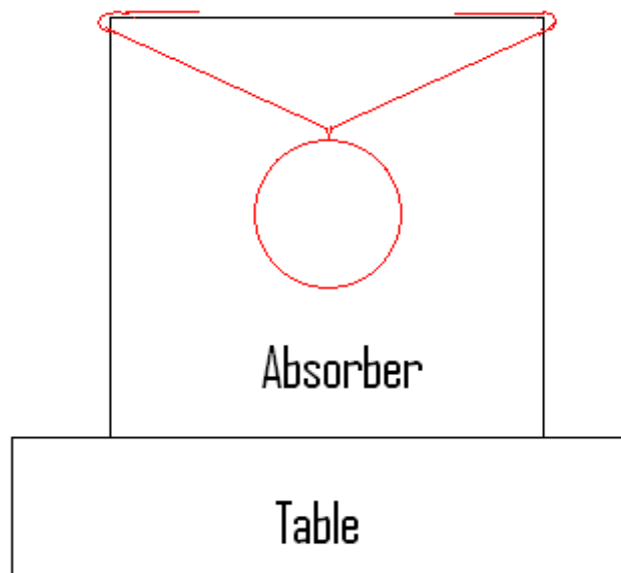


Figure 4. How to Attach Absorber to Holding Structure

With the absorber hanging, bend the four remaining wires so that they touch the top of the absorber (the part touching the table). Once all eight wires are in contact with the absorber and the absorber is in the center of the holder, apply the epoxy to the wires at the holding structure end. Also make sure to connect the wires leading from the resistor to the holding structure with epoxy, so that the resistor is thermally isolated from the outside world. When all the wires are connected to the holding structure with epoxy, place the holding structure on the hot plate, and slowly increase the heat until water bubbles (not boils) on the section of the holding structure touching the hot plate. It is VERY IMPORTANT that the temperature of the holding structure does not exceed 100°C. If it does, the insulation on the wires connected to the resistor could melt away, creating a short and rendering the resistor useless. Since the epoxy that is raised above the hot plate will be at a much lower temperature than the epoxy near the hot plate, the holding structure must be left with the heat on for a longer time than the absorber was (4-5 hours).

Once all epoxy has dried, the resistor and its wires need to be checked for shorts. Make sure that the ends of the wires show the proper resistance of the resistor, and that there is no short between the resistor and the absorber or the ends of the wires and the holding structure. If there are any shorts, the resistor will have to be replaced.

The final step to building the absorber and holding structure is to attach the temperature sensor. This is attached in a very similar manner to the resistor. To attach it, place the absorber back onto the aluminum pipe that was used before, and place the pipe on the hot plate. Support the holding structure with a block of wood or aluminum of the appropriate height. Attach the sensor with the epoxy, and heat it to the same temperature as used to attach the resistor, and cure for the same amount of time. BE VERY CAREFUL when applying the epoxy to the sensor. Make sure that epoxy only touches the mounting surface of the sensor. If any epoxy gets on the sides of the sensor, wipe it off immediately. Once the epoxy has dried, check to make sure there are no shorts between the absorber and the sensor, and that the resistance of the sensor is the proper value ($\sim 70\Omega$ at room temperature).

Lastly, attach the wires of the temperature sensor to the holding structure in the same manner as done with the resistor wires in order for the sensor to be thermally isolated. Again, be sure that the temperature of the holding structure where the epoxy is curing does not rise above 100°C . This should be left to cure for about an hour. Once it is cured, the absorber and its holding structure are ready to be placed in the radiometer.

7.6 Complete Copy of Simulation Code

The MATLAB code used to simulate the absorber (As of Aug. 19, 2009):

```
%This function will find the difference between input energy from the
%x-ray beam and output energy from the loss of heat, as well as the
%difference in temperature between the detector and its surroundings,
%as functions of time.

%Check for existing structs that need to be deleted.
A = exist('dT');
if A == 1
    clear dT;
    clear ED;
end
%Define the constants needed for this code
flux = 1E12;    %Photon Flux (photons/sec)
energy = 10.26; %Photon Energy (keV)
basetemp = 77;  %Initial Temperature of System (K)
time = 1200;   %Length of Time to Run Simulation for (sec)
%=====
=====
numbSnCu = 8;    %Number of tinned copper wires
rSnCu = (0.127E-3)/2; %Radius of tinned copper wires (m)
lengSnCu = 0.05; %Length of tinned copper wires (m)
tinthick = 11E-6; %Thickness of tin shielding (m)
%=====
=====
numbBeCu = 8;    %Number of beryllium copper wires
rBeCu = (0.127E-3)/2; %Radius of beryllium copper wires (m)
lengBeCu = 0.05; %Length of beryllium copper wires (m)
%=====
=====
SA = 1.8E-3;    %Surface area of absorber (m^2)
m = 1.1002;    %Mass of absorber (g)
eps = 0.24;    %Emissivity of absorber
c = 0.385;    %Specific heat of absorber (J/gK)
%=====
=====
%Now for the actual computations
Awire = pi*rSnCu^2;
Acopper = pi*(rSnCu-tinthick)^2;
Atin = Awire - Acopper;
Qin = flux*energy*1.602E-16; %Input and equilibrium energy (J)
deltaT.index(1) = 1;
deltaT.data(1) = Qin/(m*c);
for t = 1 : time
    %Specify which type of wires are to be used now(Copper, BeCu,
    %StainlessSteel, Aluminum1100, Aluminum5083, Aluminum6063,
    %TinThermalCon):
    kCopper.data(t) = Copper(deltaT.data(t) + basetemp);
    kTin.data(t) = TinThermalCon(deltaT.data(t) + basetemp);
    kBeCu.data(t) = BeCu(deltaT.data(t) + basetemp);
    Qout.data(t) = numbSnCu*kCopper.data(t)*Acopper*deltaT.data(t)/lengSnCu +
    numbSnCu*kTin.data(t)*Atin*deltaT.data(t)/lengSnCu +
```

```

numbBeCu*kBeCu.data(t)*pi*(rBeCu^2)*deltaT.data(t)/lengBeCu + eps*5.67E-
8*SA*(deltaT.data(t)^4);
    Tout.data(t) = Qout.data(t)/(m*c);
    dT.data(t) = deltaT.data(t) - Tout.data(t);
    deltaT.data(t+1) = dT.data(t) + Qin/(m*c);
    ED.data(t) = (Qin - Qout.data(t))*1000;
    ED.index(t) = t;
    kCopper.index(t) = t;
    kTin.index(t) = t;
    kBeCu.index(t) = t;
    Qout.index(t) = t;
    Tout.index(t) = t;
    dT.index(t) = t;
    deltaT.index(t+1) = t+1;
end
dTdata = dT.data';
dTindex = dT.index';
%And finally the necessary plot
close(findobj('type','figure','name','Energy and Temp Plot'))
figure('Position',[275 250 800 750], 'Name', 'Energy and Temp Plot', 'NumberTitle','off')
[Ax, h1, h2] = plotyy(ED.index, ED.data, dT.index, dT.data);
set(get(Ax(1),'Ylabel'),'String','Power Difference (mW)','fontsize',12)
set(gca,'ytick',[Qin*1000/8,Qin*1000/4,Qin*3000/8,Qin*1000/2,Qin*5000/8,Qin*3000/4,Qin*7000/8,
Qin*998])
set(get(Ax(2),'Ylabel'),'String','Temperature Difference (K)','fontsize',12)
set(Ax(2),'ytick',[(dT.data(time))*(1/8),(dT.data(time))*(2/8),(dT.data(time))*(3/8),(dT.data(time))*(
4/8),(dT.data(time))*(5/8),(dT.data(time))*(6/8),(dT.data(time))*(7/8),dT.data(time)])
title({'Power Input and Output Difference (Blue)', 'and Temperature Difference (Green)'),'FontSize',14)
xlabel('Time (sec)','fontsize',12)

%=====
%=====
%The following piece of code will calculate the time constant in seconds for the
%temperature difference graph. There needs to be sufficient time for the
%system to reach equilibrium to calculate the time constant. The greater
%the precision, the longer it needs to be run for. This is an
%approximation, in which if the final temperature difference and the
%temperature 30 seconds before differ by less than the specified precision,
%the time constant will be calculated.
%=====
%=====

precision = 0.001; %Desired amount of precision for the difference in temperature reading (K)
samples = length(dT.data);
if dT.data(samples) - dT.data(samples-30) < precision
    finalT = dT.data(samples);
    timeconstT = 0.63*finalT;
    TC = 1;
    while dT.data(TC) < timeconstT
        TC = TC+1;
    end
    TimeConstant = TC
else
    error('Somebody set up us the bomb. Either lower your precision or use a larger simulation time!')
end
end

```

8.0 Troubleshooting

The following problems were encountered over the course of the summer.

Frost/snow develops on the outside of the radiometer when filling with liquid nitrogen.

The most likely scenario is that the vacuum is not sufficient to isolate the liquid nitrogen jacket from the outside world. Stop filling, attach the vacuum pump and pump the radiometer down again. Once it has gotten back down to an acceptable vacuum level, return to filling. If you are concerned about the vacuum level not staying stable, leave the pump running while you fill and do your tests.

The temperature monitor doesn't seem to be reading the right temperature.

During the testing process, we noticed that the temperature sensor only displayed temperatures as low as 124 K when cooled to liquid nitrogen temperatures. We concluded that the cause of this was the calibration data being off. The temperature sensor is only calibrated to a temperature of approximately 45 K at the factory, and to make it work above that a couple of data points were added at room temperature and at 400 K. Because of the lack of data points, the curve that is produced is off by a significant margin in the liquid nitrogen range. To test whether the sensor is truly at liquid nitrogen temperature, measure the resistance between pins F and G or H and J on the rear plug connection. If the sensor is truly at liquid nitrogen temperatures, the resistance should read approximately 177 Ω .

Liquid nitrogen doesn't stay in the inner chamber, it just spurts back out.

Because there is a lot of mass within the inner chamber, it takes a lot of nitrogen to even cool it down. If you are pouring nitrogen into the inner chamber using one of the ports and a funnel and it keeps spitting back at you, try opening the large port in the very middle of the top of the radiometer. Remove the clamp, O-ring and heat shield, and pour the nitrogen directly into the center. The larger opening will allow more nitrogen to be poured in and make for a faster cooling. **WARNING:** Do not try to reattach the clamp if the edge of the port has frost developing on it. Stop pouring, wait for the frost to dissipate, and only then reattach the clamp.

There is a short between the resistor/sensor wires and the holding structure

The short is caused by the epoxy that is used to connect the pieces together. There are two ways that this could have happened: Either the epoxy is touching the leads from one of the devices as well as the absorber, or the insulation on the wires was burnt away when the epoxy that creates the heat sink between the wires and the holding structure was curing. To fix it, the device/wire that is causing the problem must

be located. If the wire insulation was burnt away, snip out the damaged wire and solder a new one to the required device. If epoxy on a device is causing the short, attempt to scrape off the epoxy causing the problem with a scalpel. If that doesn't work, the device will need to be replaced. These problems are avoidable if one applies the epoxy very carefully and makes sure the temperature of the epoxy stays below 100°C at all times.

The temperature monitor reads "Err 05"

This means that the monitor is not getting the required input to produce sensible output. Check to make sure that the plug connecting the electronics rack to the radiometer is connected well. If it is and the problem persists, then there is a short or a wire break in one of the temperature sensor wires that will have to be fixed by taking the radiometer apart.

The temperature monitor reads "Err 06"

If the temperature monitor reads normally when it is not attached to anything grounded (i.e. a plugged in vacuum pump), but gives this error when grounded, then a ground fault is the likely problem. The most likely cause is a short between the sensor or resistor and the absorber. To fix this, refer to the troubleshooting paragraph on having a short between the wires and the holding structure.

The temperature monitor reads "Err 09".

This is likely happening because the temperature monitor lost power unexpectedly. When it regains power, the monitor does not have the proper calibration curve selected. To set it to the proper calibration curve, do the following:

- Press the select button on the monitor, press the up or down buttons until it reads "Input" and press enter.
- Scroll through the new selections until the monitor reads "ntcrtd" and press enter again.
- Scroll through these new selections until the monitor reads "user" and press enter one more time.
- Finally, choose the units to display the temperature in, and press enter one last time.

The temperature monitor should now be displaying the correct temperature.