

Development and Commissioning of a Large-scale
Rotatable Guarded Hot Plate Apparatus

by

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A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada, 2016

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

A large-scale guarded hot plate apparatus was designed and constructed for measurement of the thermal conductivity of thick insulation specimens and specimens containing layers and/or complex 3D heat flows (i.e. thermal bridges). The apparatus is capable of accepting specimens measuring 4' (1219mm) by 4' (1219mm) and up to 16" (406mm) thick with good accuracy in measurement. Computer models were developed to estimate heat flow errors important for determining the characteristics and limitations of the apparatus. Other sources of error in measurement were also evaluated. Once constructed, the apparatus was validated against a heat flow meter calibrated to better than 1% using a US National Institute of Standards and Technology (NIST) traceable calibration sample. Good agreement was shown between the heat flow meter and the guarded hot plate; <1% deviation in thermal conductivity measurement was observed for a 3" (76mm) thick stonewool specimen and <3.5% deviation in thermal conductivity measurement was observed for a 9" (229mm) thick stonewool specimen. The capability of the guarded hot plate to measure layered specimens with thermal bridges was demonstrated through the measurement of three specimens resembling typical wall assemblies. Measurements from the apparatus were compared against results from computer models and good agreement was found. Errors normally associated with the measurement of non-homogenous specimens in guarded hot plates were not found to be an issue.

Acknowledgments

I would like to greatly thank Prof. John Straube from the Department of Civil and Environmental Engineering at the University of Waterloo for his supervision of my thesis and the staff at RDH Building Science Labs, namely Chris Schumacher, Ryan Billinger, and Aaron Grin, for their assistance with the construction and operation of the guarded hot plate apparatus.

TABLE OF CONTENTS

Author's Declaration.....	ii
Abstract.....	iii
Acknowledgments.....	iv
LIST OF FIGURES	vii
LIST OF TABLES.....	x
LIST OF EQUATIONS	xi
LIST OF APPENDICES.....	xii
1.0 Introduction.....	1
1.1 Research Motive	1
1.2 Research Objectives.....	3
1.3 Scope.....	3
1.4 Approach.....	3
1.5 Design Tools and Limitations.....	4
2.0 Background.....	5
2.1 Theory of Thermal Conductivity and Measurement.....	5
2.2 Measuring Thermal Conductivity	7
2.3 Guarded Hot Plate Apparatus	9
2.3.1 Description.....	9
2.3.2 Standards.....	11
2.3.3 Sources of Error in Measurement	11
2.3.3.1 Unbalance Errors	12
2.3.3.2 Edge Loss Errors	14
2.3.3.3 Errors from Measurement.....	16
2.3.3.4 Contact Resistance Errors.....	18
3.0 Design of the Apparatus.....	20
3.1 Design Considerations	20
3.2 Hot Plate Assembly.....	21
3.3 Cold Plate Assembly.....	31
3.4 Edge Insulation	40
3.4.1 Edge Loss Error Analysis	40
3.4.1.1 Analytical Analysis.....	41
3.4.1.2 Computational Analysis	43

3.4.1.2.1	Models with Adiabatic Conditions at the Top and Bottom of the Edge Insulation.....	43
3.4.1.2.2	Models with Equal Insulation Thickness on the Top, Bottom, and Edge ...	46
3.4.1.2.3	Models with Varying Insulation Thicknesses on the Top, Bottom, and Edge.....	48
3.4.1.2.4	Models with Aerogel as Edge Insulation	49
3.4.1.2.5	Models Comparing Different Meter Plate and Guard Section Widths	50
3.4.1.2.6	The Effect of the Mean Temperature on Edge Loss Error	52
3.4.2	Edge Insulation Design	54
3.5	Apparatus Frame	54
3.6	Controls, Instrumentation, and Operation.....	62
3.6.1	Temperature Measurement	62
3.6.2	Guard Balancing	67
3.6.3	Meter Plate Power Measurement	71
3.6.4	Area Measurement	74
3.6.5	Thickness Measurement.....	75
3.6.6	Cold Plate Operation.....	77
3.6.7	Testing Times.....	77
3.6.8	Temperature Uniformity	77
4.0	Validation of Apparatus	84
4.1	Overview of Validation Testing.....	84
4.2	Heat Flow Meter Testing	85
4.3	Guarded Hot Plate Testing.....	87
4.4	Discussion	89
5.0	Thermal Bridge Testing	91
6.0	Conclusions.....	97
7.0	Recommendations.....	98
	References.....	100

LIST OF FIGURES

Figure 1 – Schematic of the heat flow meter	7
Figure 2 – Heat flow meter.	8
Figure 3 – Double-sided guarded hot plate.....	10
Figure 4 – Guarded hot plate operated in single-sided mode showing error heat flows.	12
Figure 5 – Distortion of the heat flow lines at meter area due to the edges of the specimen being warmer/cooler.....	13
Figure 6 – Heat flux vectors for a specimen with edge losses/gains.	15
Figure 7 – Isotherms for a specimen with edge losses/gains.	16
Figure 8 – Hot plate assembly and naming convention.	22
Figure 9 – Guard gap spacers.....	23
Figure 10 – Model used to determine heat flow across the guard gap.	24
Figure 11 – Taped heater wire on the back of the meter plate and side guards.....	26
Figure 12 – Taped heater wire on the back of the top and bottom guard.	26
Figure 13 – Strain relief connection for the meter plate and side guards.	27
Figure 14 – Heater wire to copper wire connection for the top and bottom guards.	28
Figure 15 – Taped heater wire on the back guard plate.....	29
Figure 16 – Completed hot plate assembly.....	30
Figure 17 – Cold plate network.	32
Figure 18 – Formwork for the pouring of the epoxy.	34
Figure 19 – A detailed view of the Blueskin WP® used to act as formwork for the epoxy.....	34
Figure 20 – Piping network adhered to the plate.	35
Figure 21 – Cured epoxy adhering the piping network to the aluminum plate.	36
Figure 22 – Bar stock screwed in place clamping the copper tubing to the plate.....	37
Figure 23 – A detailed view of the bar stock holding the copper tubing in place.	37
Figure 24 – Mineral wool batt insulation layer on top of the piping.	38
Figure 25 – Polyisocyanurate layers on the cold plate.	39
Figure 26 – Completed cold plate assembly.	40
Figure 27 – A model with adiabatic conditions at the top and bottom of the edge insulation.	44
Figure 28 – Error in thermal conductivity versus R-value of edge insulation.....	45
Figure 29 – Error in thermal conductivity versus specimen thickness.	46

Figure 30 – Typical model with equal insulation on the top, bottom, and edge.....	47
Figure 31 – Error in thermal conductivity versus degree of edge insulation for different mean temperatures.	52
Figure 32 – Error in thermal conductivity versus the difference of the mean temperature from the ambient.....	53
Figure 33 – Conceptual design of the apparatus frame and stand.	55
Figure 34 – East/West cross-section of the guarded hot plate design.....	56
Figure 35 – North/South cross-section of the guarded hot plate design.	57
Figure 36 – Completed apparatus frame on temporary stands with edge insulation panels in the open position.	58
Figure 37 – Completed apparatus frame on temporary stands with edge insulation panels in the closed position.....	59
Figure 38 – Clamps used to hold the edge insulation panels in the closed position.....	60
Figure 39 – Apparatus setup for commissioning.	60
Figure 40 – Pulley system.....	61
Figure 41 – Pulley system attachment to cold plate assembly.....	61
Figure 42 – Thermistor layout on the back guard.....	63
Figure 43 – Thermistor layout on the meter plate and left, right, top, and bottom guards.	64
Figure 44 – Thermistor layout on the cold plate.....	65
Figure 45 – Thermistor leads from the hot plate assembly.....	67
Figure 46 – Control panel and power supplies.	68
Figure 47 – Campbell Scientific software screenshot of the hot plates balanced at steady state.	70
Figure 48 – Meter plate measurement circuit.	72
Figure 49 – Resistors used in the meter plate power measurement circuit.....	73
Figure 50 – Total uncertainty in meter plate power measurement versus total power output.....	73
Figure 51 – Heat flux vectors at the gap under balanced conditions.	74
Figure 52 – Measurement error in thermal conductivity versus specimen thickness.....	76
Figure 53 – Temperature distribution of the meter plate and left, right, top, and bottom guards.	78
Figure 54 – THERM model used to determine the effect of non-isothermal guards.	80
Figure 55 – Temperature distribution of the cold plate.	82
Figure 56 – Test specimen piece with center cut out.....	85

Figure 57 – Cross-section of the thermal bridge specimen with a wood stud.	92
Figure 58 – Temperature distribution along the length of the wood stud.....	95
Figure 59 – Temperature distribution along the length of the steel Z-girt.....	95

LIST OF TABLES

Table 1 – Predicted gap error heat flows.	25
Table 2 – Properties of Epoxies 50-3100RBK resin with catalyst 190	33
Table 3 – Thermal conductivity measurement error determined with an analytical method.	42
Table 4 – Edge loss errors with adiabatic conditions at the top and bottom of the edge insulation	44
Table 5 – Edge loss errors with equal insulation on the top, bottom, and edge.	48
Table 6 – Edge loss errors with varying insulation thicknesses on the top, bottom, and edge.....	49
Table 7 – Edge loss errors using Aerogel as the edge insulation.....	50
Table 8 – Comparison of edge loss errors of two meter plate sizes.	51
Table 9 – Measurement error in thermal conductivity for different specimen thicknesses.....	76
Table 10 – Results from THERM models with isothermal and non-isothermal guards.....	81
Table 11 – Results from the heat flow meter testing.	86
Table 12 – Regression equations for the insulation samples.	86
Table 13 – Tests performed to validate the apparatus.	87
Table 14 – Guarded hot plate testing results for the 3” (76mm) specimen.	88
Table 15 – Guarded hot plate testing results for the 6” (152mm) specimen.	88
Table 16 – Guarded hot plate testing results for the 9” (229mm) specimen.	88
Table 17 – Measured thermal conductivities from the heat flow meter.	93
Table 18 – Thermal bridge testing results with comparison to computer models.	94

LIST OF EQUATIONS

Equation 1 – Jean Fourier’s general heat flow equation.....	5
Equation 2 – General one-dimensional heat flow equation.....	5
Equation 3 – Heat flow equation for building science applications	5
Equation 4 – Thermal conductivity equation	6
Equation 5 – Conductance equation	6
Equation 6 – Propagation of error for variables that are added/subtracted	16
Equation 7 – Propagation of error for variables that are multiplied/divided	17
Equation 8 – Thermal conductivity uncertainty equation	17
Equation 9 – Meter area uncertainty equation.....	17
Equation 10 – Temperature difference uncertainty equation	17
Equation 11 – Woodside’s relationship describing edge heat losses	41
Equation 12 – Formula for e in Woodside’s equation.....	41
Equation 13 – Thermistor temperature formula in terms of resistance	62
Equation 14 – Uncertainty of a mean equation	66

LIST OF APPENDICES

Appendix A – Additional Photos of the Apparatus	105
Appendix B – Resistance Wire Product Details Sheet	120
Appendix C – Resistance Wire Layout Design	122
Appendix D – Thermally Conductive Epoxy Data Sheet	125
Appendix E – VWR 1197P Chiller Specifications	128
Appendix F – Honeywell Thermistor Temperature/Resistance Data	130
Appendix G – Campbell Scientific CR-10X Specifications	133
Appendix H – PID Control Program for the CR-10X	136
Appendix I – Meter Plate Power Measurement Spreadsheet.....	157
Appendix J – Photos from the Validation Testing.....	159
Appendix K – Photos from the Thermal Bridge Testing.....	163

1.0 Introduction

In 2013, 40% of the total energy consumed in the United States was utilized for the heating and cooling of buildings (U.S. Energy Information Administration, 2013). It is critical that accurate values of thermal performance be assigned during design of building enclosure assemblies to ensure comfort, energy efficiency, and conservation of resources. Due to changing codes and an increasing demand for more energy efficient buildings, there is a demand for new testing methods to accurately measure the thermal performance of highly-insulated, thick enclosure assemblies. New testing methods are also needed to allow for quantifying the effects of thermal bridging which is defined as the high relative heat flow through solid materials penetrating the insulating layer. The purpose of this research project was to construct a guarded hot plate apparatus to measure with good accuracy the thermal conductivity of thick insulation specimens and sub-assemblies with thermal bridges.

1.1 Research Motive

Researchers may use a number of techniques and a range of apparatuses to measure the thermal performance of enclosures and materials. The most common apparatus used to measure the thermal conductivity of materials is a heat flow meter. Full-scale enclosure assembly performance is routinely measured by a guarded hot box apparatus. For a research facility that owns both a heat flow meter and a guarded hot box, a guarded hot plate represents an useful middle ground between these two apparatuses as a guarded hot plate allows for the testing of specimens that are too thick for the heat flow meter but too expensive to test in a guarded hot box.

As a result of increasing demands for reducing CO₂ emissions, thicker insulations and better insulating products are required which necessitate the need for testing of thicker specimens (Salmon, 2001). For example, minimum code levels of roof insulation for residential open attics in Ontario is now R-50 hr·ft²·°F/Btu (RSI 8 m²K/W) (Building and Development Branch, Ministry of Municipal Affairs and Housing, 2012) which requires insulation that is at least 12”-16” (305-406mm) thick: beyond the capacity of most heat flow meters and guarded hot plates. Historically, the thermal conductivity of thick insulations was determined by testing the thermal

conductivity of a thinner specimen of the insulation in a heat flow meter and then extrapolating that value to a thicker specimen. This is logical but may not be accurate for all insulations, especially those with highly temperature dependent thermal conductivities such as polyisocyanurate foam (Grin, Schumacher & Smegal, 2014). Some types of thick insulations need to be tested at full thickness due to density and correspondingly thermal conductivity variations (Peavy & Rennex, 1986). Only conduction is directly proportional to the thickness of a specimen (ASTM International, 2004). Thus, for some low-density insulations, the complex mechanism of heat transfer via radiation dominates and is not directly proportional to thickness (Shirtliffe, 1980). This “thickness effect” can lead to an error of several percent in the actual thermal conductivity of a thick, highly thermally resistive insulation specimen (Peavy & Rennex, 1986).

A guarded hot plate has the advantage that it is an absolute method of measuring the thermal conductivity of specimens unlike heat flow meters which are calibrated to a reference standard. This independence from calibration is important as calibration creates limitations and inaccuracies. Specimens similar to the reference specimen used for calibration should only be tested and testing specimens that differ from this reference specimen creates errors (Bomberg & Solvason, 1985). Also, in the calibration of the heat flow meter, unknown errors are included in the calibration constants that in reality are not constant further reducing the accuracy of the thermal conductivity measurement (De Ponte, 1985).

Additionally, a guarded hot plate allows a researcher to measure heat flow through sub-assemblies (layers of different materials, e.g., insulating glazing units) and specimens with two- or three-dimensional heat flow paths such as a thermal bridge. In a guarded hot box test of an enclosure wall, multiple studs or cladding attachments penetrate the thermal layer of the wall and only the overall performance can be determined. An appropriately sized guarded hot plate would be able to test the effect of singular thermal bridges for which experimental data is difficult to obtain.

A guarded hot plate apparatus should ideally allow for the measurement of specimens oriented in a horizontal, sloped, or vertical orientation with heat flow in the same direction and of the same magnitude as expected in a building application. This capability is critical for testing multi-layer

glazing systems and highly air permeable insulations which may allow natural convection. A guarded hot plate apparatus could therefore provide valuable information that could be used by engineers and architects to build more efficient and durable building enclosures as well as progressing the knowledge of how building assemblies function.

1.2 Research Objectives

The objective of the proposed research program is to design, construct, commission, and validate a rotatable guarded hot plate apparatus for measuring the thermal conductivity of thick insulation specimens and complex assemblies. To confirm accuracy, the apparatus will ideally be validated against other test equipment that has been calibrated using reference specimens from the US National Institute of Standards and Technology (NIST).

1.3 Scope

The scope of the research project includes the design, construction, commissioning, and validation of a rotatable guarded hot plate for the purpose of measuring thick building insulations. The capability of the apparatus for measuring thermal bridges penetrating insulation and complex assemblies will also be evaluated.

Future research, outside the scope of this thesis, should investigate multiple types of thermal bridges found in wall assemblies by measurement and comparison with the results of computer models.

1.4 Approach

A literature review of guarded hot plate design, error analysis, and existing commercial products was conducted. After consideration of sources of error and development of design criteria, the guarded hot plate apparatus was first designed. Once designed, the apparatus was constructed in the lab and commissioned, with several steps of validation of individual components during the process. The commissioning process involved preliminary testing whereby the control and measurement techniques were fine-tuned to provide the best measurements. Finally, an

experimental program was developed and executed with the goal of validating the apparatus by comparing the measurements obtained from the apparatus with measurements obtained on the same specimen tested in a heat flow meter. The experimental program provided information on the measurement accuracy for different specimen thicknesses under a variety of temperature conditions including the accuracy of results for thick, low thermal conductivity insulations. Simple measurements of a thermal bridge penetrating insulation were performed to demonstrate the apparatus's capabilities for future testing.

1.5 Design Tools and Limitations

To analyze different sources of error in the guarded hot plate apparatus, thus providing insight on the sizing and testing procedures of the apparatus, THERM 7.3 was used as a design tool to create finite element models describing heat flow through assemblies of materials. THERM 7.3 is free software that allows two-dimensional modelling of heat transfer through building components. It is primarily used for estimation of heat flow through windows and glazing systems (Lawrence Berkeley National Laboratory, 2016).

Computer models can be a useful design tool but it is important to note that they may not be an accurate representation of reality nor are they intended to be. THERM 7.3 is only able to model in two-dimensions and results may therefore be difficult to extrapolate to three-dimensions. For example, for a square guarded hot plate, the models do not give any indication of the error heat flow at the corners where more area exists to increase heat loss. Research has shown that edge heat loss is 10% higher in square guarded hot plates, because of the corners, than in a circular guarded hot plate of similar size (Peavy & Rennex, 1986). Furthermore, assumptions must be made in the models that may not represent reality accurately. For example, contact resistances are not accounted for and homogenous specimens may or may not be perfectly homogenous. Also, it is sometimes difficult to visualize boundary conditions leading to errors in which boundary condition is appropriate to use and whether they are uniform or not in reality (Posey & Dalgliesh, 2005). For example, boundary conditions on specimen models are assumed to have uniform temperatures where guard plates exist but in reality, guard plates are not perfectly uniform. Furthermore, trailing zeros may be truncated in models when they are actually significant (Posey & Dalgliesh, 2005) and in some of the analyses performed in THERM 7.3,

the precision of the model was often close to the recorded values for the heat flow. Thus, it is important to understand the limitations of models when inferring information.

2.0 Background

Background information such as the theory of thermal conductivity and measurement, the devices used to measure the thermal conductivity of materials, and a detailed description of the guarded hot plate are provided in this section.

2.1 Theory of Thermal Conductivity and Measurement

The fundamental law that describes the flow of heat through a material was first defined by Jean Fourier and is given by

$$q = -k \cdot \text{grad } T \quad (1)$$

where q is the heat flux at a point, $\text{grad } T$ is the temperature gradient at a point, and k is the thermal conductivity of the material at a point (Jackson, 1976).

For one-dimensional, steady state heat flow with no internal heat generation and constant thermal conductivity, this equation becomes:

$$q_x = -k \frac{dT}{dx} \quad (2)$$

A more practical way of writing Fourier's law in one-dimension for building science applications is

$$Q = \frac{k}{L} A \Delta T \quad (3)$$

where Q is the heat flow rate in W; k is the average thermal conductivity of the material in W/mK; L is the heat flow path length (the material thickness) in m; A is the cross-

sectional area through which Q flows in m^2 ; and ΔT is the change in temperature across the material in K or $^{\circ}\text{C}$ (Jackson, 1976).

For a solid material, Equation 3 describes the heat flow via conduction through a material and the value of k quantifies its resistance to heat flow. If the material contains voids, the value of k calculated from this equation can also describe the overall resistance of a material, including the effects of heat transfer within the material via radiation and convection but then the thermal conductivity must be referred to as the “apparent” or “effective” thermal conductivity (Zarr, 2001). The apparent thermal conductivity is of most interest for building insulation materials. The thermal conductivity can be calculated by re-arranging Equation 3 as follows:

$$k = \frac{QL}{A\Delta T} \quad (4)$$

If all of the variables on the right-hand side of Equation 4 are known through measurement, the thermal conductivity of a material can be estimated.

The thermal conductance of a layer comprised of one or more materials is sometimes of importance and is characterized as

$$C = \frac{k}{L} \quad (5)$$

where C is the thermal conductance in $\text{W}/\text{m}^2\text{K}$.

The thermal resistance is the reciprocal of the conductance and is reported as an RSI-value in metric units ($\text{m}^2\text{K}/\text{W}$) and an R-value in imperial units ($\text{h}\cdot\text{ft}^2\cdot^{\circ}\text{F}/\text{Btu}$).

Several methods and associated apparatuses are used to measure the thermal conductivity or thermal conductance of materials. These are briefly reviewed next.

2.2 Measuring Thermal Conductivity

Historically, thermal conductivity for building science purposes has been measured using three devices; the heat flow meter, the guarded hot plate, and the guarded hot box (Zarr, 2001). The heat flow meter (HFM) is a comparative method whereby a reference specimen of known thermal conductivity is used to calibrate an apparatus consisting of two unguarded isothermal plates. Once the device is calibrated, the heat flow through specimens that are similar to the reference specimen can be measured and their thermal conductivity recorded (Rennex, 1985). This apparatus typically tests small specimens usually measuring, for example, 0.3m by 0.3m and up to 0.1m thick. The heat flow meter is governed by ASTM Standard C518 “Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus” and measures heat flux via one or more heat flux transducers. A schematic of the heat flow meter is shown in Figure 1.



Figure 1 – Schematic of the heat flow meter (ASTM International, 2015).

A photo of a commercially-available heat flow meter apparatus with a specimen inside is shown in Figure 2.



Figure 2 – Heat flow meter.

The guarded hot plate is similar to a heat flow meter except that it is an absolute method (no calibration specimen is required) and the hot plate is guarded to prevent lateral heat flow which would affect the accuracy of the measurements (ASTM International, 2004). These apparatuses are governed by ASTM Standard C177 “Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus” and are often the same size or larger than heat flow meters.

The guarded or calibrated hot box is an apparatus that creates an environmentally controlled airspace on each side of a specimen and then measures the heat flow across the specimen to determine its conductance (ASTM International, 2011). This apparatus is governed by ASTM Standard C1363 “Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus” and typically tests large specimens

such as entire wall assemblies. The hot box is the most complicated and expensive to operate but it is the most representative of full multi-dimensional assemblies. The hot box is also the least accurate method because of the challenges of flanking losses and air movement. It does not allow users to investigate the influence of specific materials or details directly: two specimens must be built, with and without the detail of interest and the results can then be compared.

2.3 Guarded Hot Plate Apparatus

The guarded hot plate apparatus will be described in detail in this section. How the apparatus functions, the different types of guarded hot plates, the standards that regulate their use, and the sources of error present in measurement will all be considered.

2.3.1 Description

As stated earlier, the guarded hot plate is an apparatus that measures the absolute thermal conductivity of a material. The material being tested is placed between two isothermal plates of differing temperatures, called the hot plate and cold plate, and the heat flow between the plates is measured. The hot plate is separated into multiple pieces so that the centre piece, called the meter plate, is thermally isolated via a gap from the perimeter pieces, called the guards, which are all controlled to the same temperature as the central meter plate. The power from the meter plate is measured and heat flow laterally is prevented by the guards so that heat only flows in one direction, perpendicular to the plates, from the hot plate to the cold plate. Once equilibrium is reached for a particular specimen, heating power, thickness, meter area, and temperature measurements are taken to calculate a thermal conductivity for the specimen using Equation 4.

Guarded hot plates can be operated in either double-sided mode, where two specimens are tested at once on either side of the hot plate, or in single-sided mode, where only one specimen is tested. A double-sided guarded hot plate has long been the gold-standard for measuring material thermal conductivity. A schematic of the guarded hot plate operated in double-sided mode is shown in Figure 3.

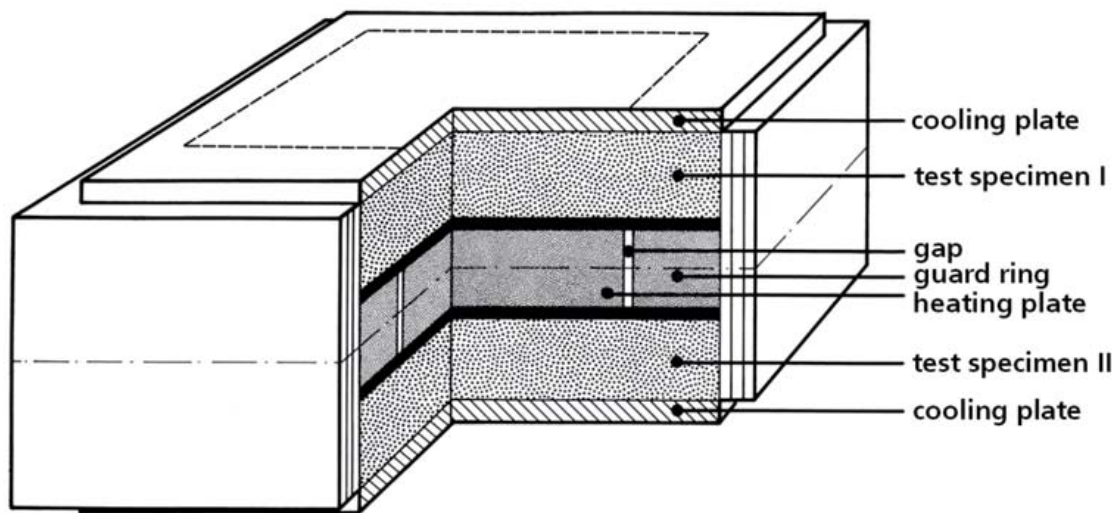


Figure 3 – Double-sided guarded hot plate (Fraunhofer IBP, 2016).

The double-sided mode may be more common but in some situations a single-sided guarded hot plate may be more suitable. In single-sided mode, the lower specimen is replaced with a permanent piece of buffer insulation and the corresponding cold plate is converted to a hot plate acting as a back guard for the meter plate. This back guard is held to the same temperature as the meter plate to prevent heat flow backwards ensuring that heat from the meter plate only flows through the specimen to the cold plate. A single-sided guarded hot plate was chosen for the research project.

Numerous types of guarded hot plate designs are used for testing specific material specimens under specific conditions but the underlying principle of operation is the same. Guarded hot plates may be circular or square in shape and most commercially available products range in size from 0.2m to 0.6m radius/width with special research devices that can accept specimens with a 1.2m to 2.4m radius/width. Generally, it is difficult to build a guarded hot plate that tests a wide variety of specimens at a variety of temperatures with an acceptable level of accuracy (Bomberg & Solvason, 1985). Therefore, unique designs are often made for specific types of applications. For example, “sweating” guarded hot plates exist for the testing of textiles used in clothing. These apparatuses have a porous hot plate which allows the specimen to be subjected to moisture gradients (ASTM International, 2014). Special guarded hot plates also exist for cryogenic

temperatures (Brendeng, 1985), for very high furnace temperatures (National Physical Laboratory, 2016), or for measuring highly thermally conductive materials such as metals (Schlosser, 1958).

2.3.2 Standards

Multiple standards exist that regulate the design, construction, and operation of guarded hot plates but ASTM C177 has achieved international acceptance for being the most accurate (Zarr, 2001). Other standards include ISO8302:1991, BS874 Section 2.1, and DIN 52 612 Part 1 (Salmon, 2001). The ASTM standard guides design and procedure but of course does not provide sufficient design and construction details to construct a guarded hot plate without prior knowledge and experience in heat transfer, temperature measurement, temperature control, and mechanical design. It also does not direct the reader to where this information may be obtained. It only provides general criteria based on experience that has shown to provide guarded hot plates with reliable and reproducible measurements (Jackson, 1976). However, just merely following the standard may not produce a guarded hot plate with a desired level of accuracy (Donaldson, 1962) and some research suggests that the ASTM requirements are not strict enough to reduce errors to an acceptable amount if a high level of accuracy is required (Woodside & Wilson, 1957). The standard can therefore be seen as a useful guide as some seemingly minor requirements in the standard appear to be absolutely necessary (Jackson, 1976).

2.3.3 Sources of Error in Measurement

Multiple sources of error exist in the guarded hot plate apparatus and a large contributor to the overall error in measurement of thermal conductivity is the error heat flow. Figure 4 shows a cross-section of a guarded hot plate operated in single-sided mode with the error heat flows (Q) labelled.

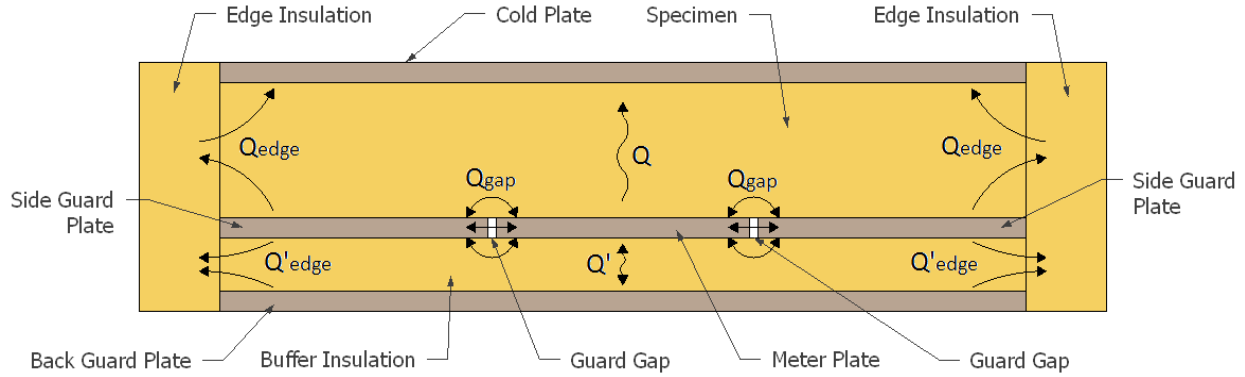


Figure 4 – Guarded hot plate operated in single-sided mode showing error heat flows.

These error heat flows will be described in this section. Also described in this section are other sources of error such as errors from measurement (power, temperature, area, and specimen thickness) and contact resistance errors.

2.3.3.1 Unbalance Errors

The purpose of the gap is to thermally isolate the meter plate from the rest of the guards in the case that the guards and meter plate are not at the same temperature. Ideally, the guards would be balanced to the exact same temperature as the meter plate. However, the guards and meter plate can only practically be balanced to within the accuracy of temperature measurement of each plate. Therefore, a certain level of unbalance will always exist and a gap ensures that the error heat flow to/from the meter plate to the guard is minimized. The distortion in heat flow at the meter area due to an unbalanced guard section is shown in Figure 5.

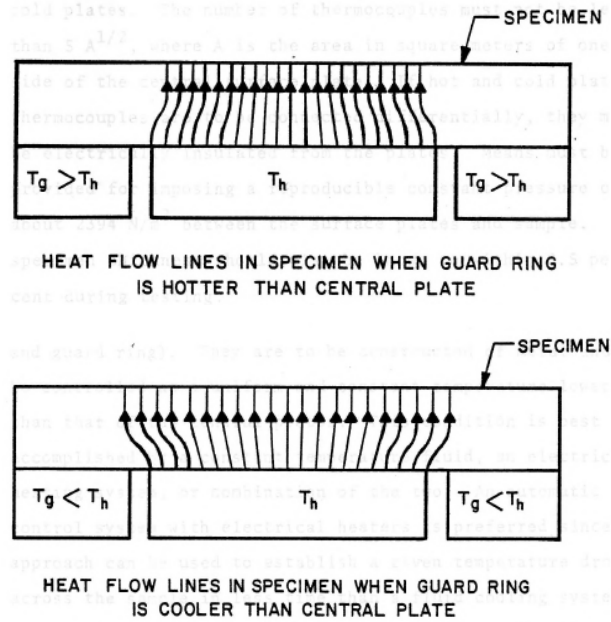


Figure 5 – Distortion of the heat flow lines at meter area due to the edges of the specimen being warmer/cooler (Jackson, 1976).

When the guard plate temperature is higher than the meter plate temperature, heat flow from the guard section enters the meter area and the area that the supplied meter plate heat actually flows through is smaller than accounted for causing an underestimation in the thermal conductivity.

Correspondingly, when the guard plate temperature is lower than the meter plate temperature of the specimen, heat flow from meter section leaves the meter area and the area that the meter plate heat actually flows through is larger than accounted for causing an overestimation in the thermal conductivity (Woodside & Wilson, 1957). Larger errors result when the guard plate is cooler than the meter plate than when the guard plate is hotter than the meter plate by the same amount. This occurs because the edge heat loss in the specimen occurs in the same direction as heat losses from the meter plate when the guard plate is cooler. It is possible to counteract this error by making the guard section hotter by a small amount such as 0.5°C , although this is not typically done (Woodside & Wilson, 1957). Obviously, the larger the imbalance, the larger the error in thermal conductivity measurement and research has shown that a high degree of balance is required in guarded hot plates for accurate measurements (Siu & Bulik, 1981).

Heat travels across the gap via conduction, convection, and radiation but it also conducted around the gap through the specimen and back insulation (De Ponte & Di Filippo, 1974). This

heat flow through the specimen and back insulation causes a distortion in the unidirectional heat flow in the specimen near the gap (Woodside & Wilson, 1957). For larger gaps, this distortion can be significant (Hahn, 1971). Larger gaps thermally isolate the meter plate better thus reducing the amount of error heat flow but as the gap size increases, the uncertainty in the meter area also increases. Furthermore, for lower conductivity and thicker specimens, the error heat flow across the gap increases as more heat will flow from the meter plate under the same degree of unbalance. The error heat flow across the gap is also proportional to the temperature difference across the specimen with less heat flow across the gap resulting from a greater temperature difference across the specimen (Woodside & Wilson, 1957). It should be noted that thinner plates (Donaldson, 1962) and gaps with low-emissivity surfaces (Woodside & Wilson, 1957) will have lower heat flows across the gap. Based on the level of accuracy that can be achieved in balancing the temperatures of the guards to the meter plate, an optimum guard gap can be determined (De Ponte, 1985). However, it should be borne in mind that the characteristics of the gap or even its presence are unimportant if the difference in temperature between the guard and the plate approaches zero.

2.3.3.2 Edge Loss Errors

In the guarded hot plate apparatus, the goal is to create steady-state heat flow perpendicular to the meter plate for accurate estimation of the thermal conductivity of a specimen. However, if appropriate measures are not taken, error heat flow may occur through the sides of the specimen since the edges of the specimens are not at the same temperature as the plates. Theoretically, tests should be conducted at an ambient temperature equal to the mean temperature of the hot and cold plates so that the edge heat loss on the hot side is equal to the edge heat gain on the cold side along the edges of the specimen (Donaldson, 1962; Peavy & Rennex, 1986). This will be shown in Section 3.4.1.2.6 “The Effect of the Mean Temperature on Edge Loss Error”. However, in practice, others have stated that for minimum edge loss errors, an ambient temperature slightly higher than the mean temperature should be targeted by the operator (Orr, 1967; Rennex, 1985). Unfortunately, testing at an ambient temperature equal to the mean temperature of the plates is not always feasible.

The purpose of the guard section is to prevent these edge losses/gains from distorting the unidirectional heat flow in the meter area. However, for thick specimens the edge losses dominate the error (Rennex, 1985), and hence a very large guard width would be required. It is therefore easier to add edge insulation to protect the edge of the specimen from the ambient temperatures when testing thicker specimens.

If the specimen edge temperature is higher than the mean temperature of the hot and cold plates, this causes a similar effect as when the guard section is at a higher temperature since the part of the specimen near its edge is warmer. The same applies if the specimen edge temperature is lower than the mean temperature of the plates; the temperature of the specimen in the guard section is lower than expected. Figure 6 shows heat flux vectors from a computer model created using THERM 7.3 illustrating the edge losses and gains on a cross-section of a specimen with no edge insulation.

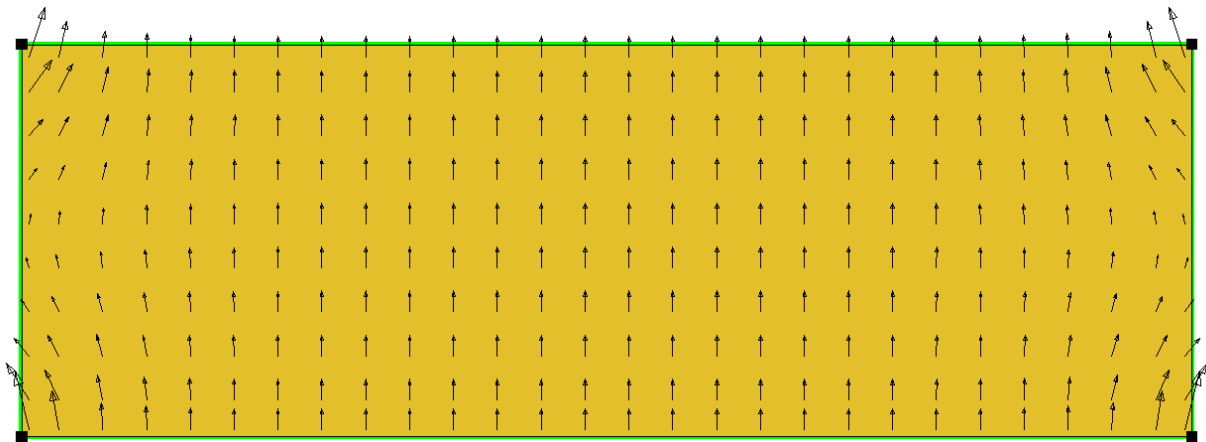


Figure 6 – Heat flux vectors for a specimen with edge losses/gains.

In Figure 6, the bottom is the hot side and the top is the cold side. The edge temperature is set equal to the mean temperature of the top and bottom, and the arrows represent the direction of heat flow. This figure shows that the heat is only flowing vertically and perpendicularly to the plates from the bottom to the top in the middle portion of the specimen. These middle conditions are ideal for measuring the thermal conductivity of the specimen. Another way to view whether heat flow from the bottom to top is unidirectional is with isotherms. Figure 7 presents the same

model as Figure 6 but with isotherms (lines perpendicular to heat flux) in °C instead of flux vectors.

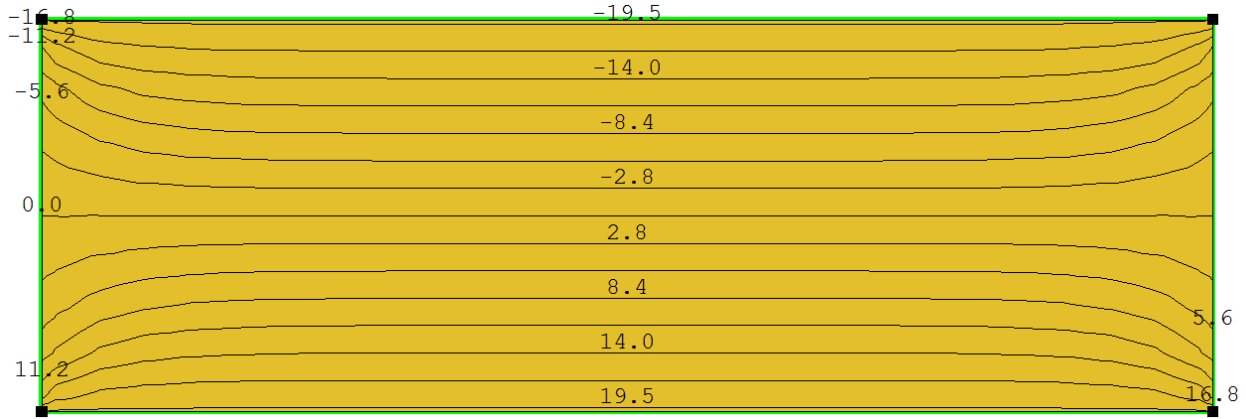


Figure 7 – Isotherms for a specimen with edge losses/gains.

Isotherms are lines of constant temperature and unidirectional heat flow is represented when the isotherms are perfectly parallel with the top and bottom edges. As said before, edge insulation and side guards help to increase the area in the middle of the specimen that approaches unidirectional heat flow necessary for an accurate measurement of thermal conductivity.

2.3.3.3 Errors from Measurement

Even if edge heat losses can be held at zero and the assumption of unidirectional heat flow is true, there would still be an error in the measured thermal conductivity that results from the uncertainty of the measured variables in Equation 4, namely, the power, temperature, area, and specimen thickness. The issue is further compounded as the variables in the conduction equation are multiplied and divided by each other so errors in individual variables become compounded. The propagation of error can be calculated for a variable x_i with uncertainty $u(x_i)$ as follows (Reilly, 1992):

$$u(x_1 \pm x_2 \pm \dots \pm x_n) = \{[u(x_1)]^2 + [u(x_2)]^2 + \dots + [u(x_n)]^2\}^{1/2} \quad (6)$$

If multiple variables are divided or multiplied by each other, the associated resulting error becomes (Reilly, 1992):

$$u\left(x_1 \frac{\times}{\div} x_2 \frac{\times}{\div} \dots \frac{\times}{\div} x_n\right) = \left(x_1 \frac{\times}{\div} x_2 \frac{\times}{\div} \dots \frac{\times}{\div} x_n\right) \left[\sum_{i=1}^n \left(\frac{u(x_i)}{x_i}\right)^2\right]^{1/2} \quad (7)$$

Using Equations 6 and 7, the uncertainty in k , Δk , can be calculated as

$$\Delta k = \frac{QL}{A\Delta T} \left[\left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta\Delta T}{\Delta T}\right)^2 \right]^{1/2} \quad (8)$$

where Q , L , A , and ΔT are as stated earlier; ΔQ is the uncertainty in measured power input; ΔL is the uncertainty in thickness measurement; ΔA is the uncertainty in the meter area; and $\Delta\Delta T$ is the uncertainty in the measured temperature difference.

The meter area is calculated by multiplying the width and length and therefore, the uncertainty, ΔA , is calculated using

$$\Delta A = w_1 w_2 \left[\left(\frac{\Delta w_1}{w_1}\right)^2 + \left(\frac{\Delta w_2}{w_2}\right)^2 \right]^{1/2} \quad (9)$$

where w_1 and w_2 are the width and length of the meter area, and Δw_1 and Δw_2 are the corresponding uncertainties.

In this case, the meter area is square so these lengths and uncertainties should be roughly equal. The measured temperature difference across the specimen, ΔT , is calculated by subtracting the cold plate temperature from the hot plate temperature. As such, the uncertainty in the measured temperature difference, $\Delta\Delta T$, is given by

$$\Delta\Delta T = \left(\Delta T_h^2 + \Delta T_c^2\right)^{1/2} \quad (10)$$

where ΔT_h is the uncertainty in the hot plate temperature measurement and ΔT_c is the uncertainty in the cold plate measurement.

2.3.3.4 Contact Resistance Errors

Ideally, only the thermal conductivity of the specimen between the plates would be measured. However, a contact resistance exists between the specimen and the plates. This contact resistance causes an error in the measured thermal conductivity which becomes more significant for higher thermal conductivity specimens (Tleoubaev & Brzezinski, 2007). One experimenter found that for a 1" (25.4mm) thick brass specimen tested in a guarded hot plate, the temperature difference across the interface of the specimen and each plate was twice that of across the specimen itself (Schlosser, 1958). This is due to the fact that materials that appear to be in intimate contact are only really contacting a small amount on a microscopic level (Reams & Spry, 1957).

To reduce the effect of this contact resistance, ASTM C177 suggests applying a proper clamping pressure of the specimen and plate stack to reduce air voids and to paint the plate surfaces in contact with the specimen with a high emissivity coating. Fortunately, most building materials have a moderate to high emissivity (Fronapfel & Bradley, 2006) which provides a good radiation exchange with the plates reducing contact resistances. Plate emissivity is most important for specimens that rely heavily on radiation as a primary mode of heat transfer such as low-density insulations (Salmon, 2001).

Another method for reducing contact resistances is placing a thin sheet of relatively high thermal conductivity material with good conforming properties (Schlosser, 1958; Salmon, 2001). This sheet can be rubber, plastic, cork, or foam for example. This sheet helps fill in the air gaps that form when the specimens or plates are not perfectly flat on a micro and macro level. The thermal resistance of these sheets must be measured and subtracted from any result, which increases the uncertainty slightly.

The guarded hot plate constructed as part of this research is intended to be used for thick insulation specimens with relatively low conductivity so contact resistances are less of a concern. For example, the thermal conductivity of brass is around 109 W/mK, whereas building insulation products have a conductivity over three orders of magnitude less, typically, 0.035 to 0.16 W/mK (The Engineering Toolbox, 2016).

It should be noted that contact resistances also occur between layers in a specimen. In the case of a layered specimen resembling a wall assembly with a thermal bridge, contact resistances exist between the sheathing layers and thermal bridge, decreasing the effect of the thermal bridge.

3.0 Design of the Apparatus

In this section, the design and construction of the apparatus are presented. Considerable detail is provided in the form of pictures and drawings so that others may reproduce the apparatus or parts thereof. Additional photos of the construction and of the final apparatus can be found in Appendix A.

3.1 Design Considerations

To allow for the measurement of complex building assembly specimens and thick insulations, it was decided that the apparatus should accommodate specimens up to 4' by 4' (1219mm by 1219mm) with a maximum thickness of 16" (406mm) and with a total conductance of between 0.1 and 2.0 W/m²K. This would allow for testing of specimens ranging from thick insulations (min. $C = 0.1 \text{ W/m}^2\text{K}$) to insulated glazing units (max. $C = 2 \text{ W/m}^2\text{K}$). The cooling capabilities of the cold plate were chosen to allow cold side temperatures of between -20°C and 40°C while the heating capabilities of the hot plate were chosen to allow hot side temperatures between 20°C and 60°C. These temperature ranges could be extended to below -40°C for special situations by the use of additional cooling equipment. Temperatures higher than 70°C would have required the use of more expensive and less desirable polymers for adhesives and was deemed to be of limited use for building science research applications.

A square apparatus was chosen as it is easier to construct and specimens can be more easily made. Square guarded hot plates account for more than half of all of the conventional guarded hot plates designs for this reason (Hahn, 1971). The apparatus was chosen to operate in single-sided mode as the result from a single-unique specimen was desired, not the average of two slightly different specimens provided by a double-sided device.

The apparatus was made to be rotatable through 180 degrees to allow for the testing of flat roof, sloped roof, and wall specimens at any arbitrary angle. Testing at different angles more accurately reflects real building conditions as the thermal conductivity of some specimens may change in different orientations due to the buoyancy effect of convection.

Another design consideration was that the apparatus must be portable (easily movable within a lab setting) and easy to use without extensive training. As such, it was designed to fit on a stand with wheels to allow for movement through standard doorways. Given that the specimens would in some cases be heavy, given their large size, easy access to the specimen stack was desirable to allow for installation and removal of the specimen. Durability was also an important attribute as the apparatus is anticipated to be used frequently and for a long period of time. As such, durable materials were chosen and potential wear surfaces were protected. Finally, to protect the apparatus in case of the hot plates overheating due to hardware, software, or user error, insulations and materials with relatively high melting points were used. The guarded hot plate was assembled in four stages: the hot plate assembly, the cold plate assembly, the edge insulation and frame, and the controls and instrumentation. The details of each, including the design analysis conducted to meet the performance targets, follow.

3.2 Hot Plate Assembly

The hot plate assembly consists of two layers of insulation and two levels of plates. Figure 8 shows the hot plate assembly and naming convention. The naming convention for the hot plates is based on a vertical orientation of the specimen.

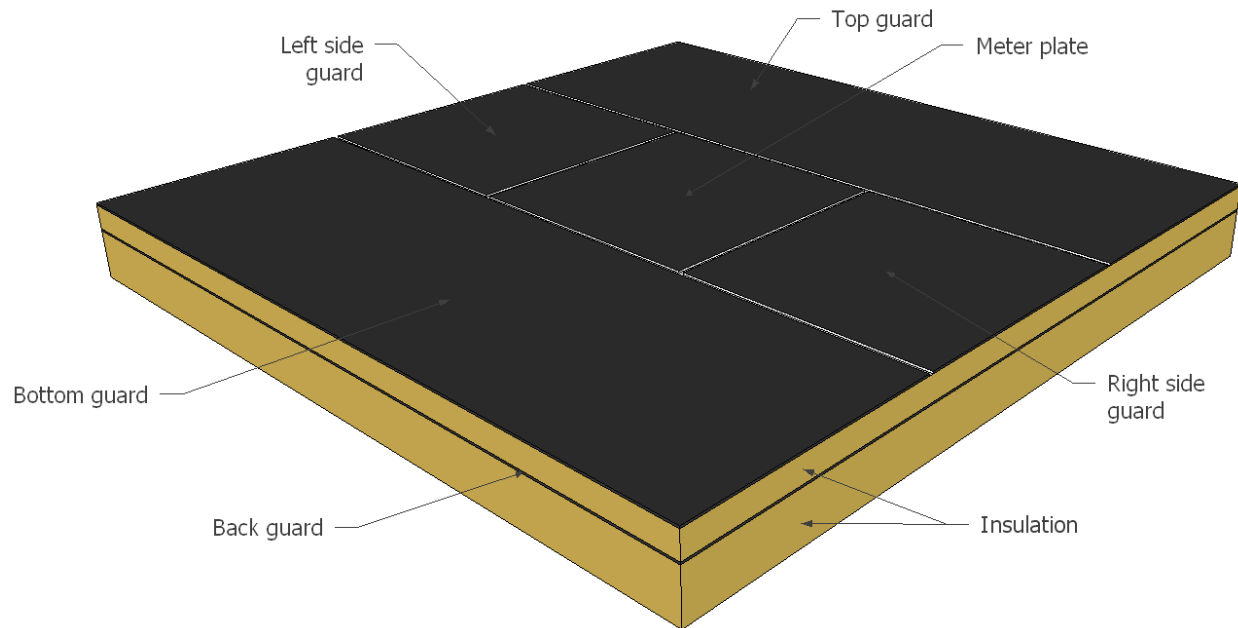


Figure 8 – Hot plate assembly and naming convention.

The hot plates were chosen to be electrically heated only to allow for a simple, accurate power measurement. This choice limited the temperature of the hot plate assembly to ambient temperature and above. This was not felt to be a significant limitation for the application. Each of the hot plates was constructed by taping a high-resistance heating wire to the back of 1/8” (3.175mm) thick aluminum T6061 plates. The aluminum plates have very high thermal conductivity to ensure very small temperature gradients throughout the plates. The plates are heated by sending current through the high resistance wire. Different gauges of Omega brand Nickel-Chromium heater wire were used. Product detail sheets for this wire can be found in Appendix B. The heater wire gauge used for each plate was selected based on the power supply voltage to generate sufficient power for the specimens envisaged and the maximum spacing required to create uniform plate temperatures. THERM 7.3 was used to determine acceptable spacing limits and calculations in Excel were undertaken to find the appropriate gauge. These calculations can be found in Appendix C.

The two plate levels in the assembly are made to be 1/16” (1.59mm) smaller than 4’ by 4’ (1219.2mm by 1219.2mm) to avoid conflicting with the edge insulation. The meter plate and side guards are made to be identical so that they may be interchanged and all measure 15 15/16”

by 15 15/16" (404.8mm by 404.8mm). A further discussion on the sizing of the meter plate is presented in Section 3.4.1 "Edge Loss Error Analysis" as the meter plate size relates to the amount of edge heat loss error. The top and bottom guards are also identical and measure 15 15/16" by 47 15/16" (404.8mm by 1217.6mm). The sizing of these plates was also based on the error analysis presented in Section 3.4.1. The meter plate, side guards, bottom guard, and top guard are arranged on the same level and are separated by a 1/16" (1.59mm) gap between all of the plates. Excellent control of the plate temperatures was expected so a very small gap was used to reduce uncertainty in meter area and unidirectional heat flow distortion. A smaller gap could have been chosen but a 1/16" (1.59mm) gap was selected as it is a convenient size and easy to inspect by eye. The gap is maintained by eight PVC spacers. The spacers measure 1/16" (1.59mm) wide by 3/16" (4.76mm) long by 1/8" (3.175mm) high and are taped to the guard plates with thin strips of clear packing tape. The spacers are shown in Figure 9.



Figure 9 – Guard gap spacers.

The spacers are also placed between the guard plates to maintain a 1/16" (1.59mm) gap between them. The gap between the guards is not typical in most guarded hot plate designs and ideally, there would be no gap between the guards. This gap serves no purpose in this design and is just a result of the plate geometries which allows the side guards to be interchanged with the meter plate.

The amount of heat flow across the gap under different amounts of unbalance was quantified using THERM 7.3 modelling software. An example of the model used to analyze the error heat flow across the gap is shown in Figure 10.

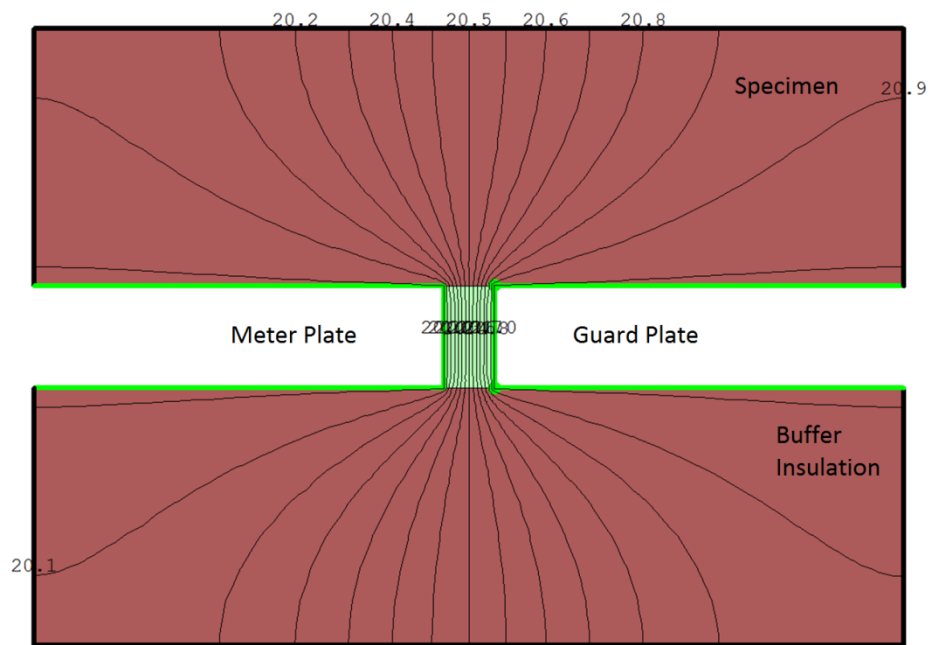


Figure 10 – Model used to determine heat flow across the guard gap.

In Figure 10, the guard plate is made to be 1°C warmer than the meter plate and the resulting temperature isotherms are plotted on the model in the figure. The results of the two-dimensional analysis are presented in Table 1 for a ΔT of 60°C across the specimen.

Table 1 – Predicted gap error heat flows.

Specimen	Meter Plate Power (W)	Amount of Unbalance (°C)	Q_{error} (W)	% of Meter Plate Power
400mm thick rigid mineral wool board C=0.1W/m ² K	1	1	0.1031	10.313%
	1	0.5	0.0516	5.157%
	1	0.1	0.0103	1.031%
	1	0.05	0.0052	0.516%
	1	0.01	0.0010	0.103%
50mm thick rigid mineral wool board C=0.8W/m ² K	8	1	0.1031	1.289%
	8	0.5	0.0516	0.645%
	8	0.1	0.0103	0.129%
	8	0.05	0.0052	0.064%
	8	0.01	0.0010	0.013%
Glazing unit with C=2.0W/m ² K	20	1	0.1031	0.516%
	20	0.5	0.0516	0.258%
	20	0.1	0.0103	0.052%
	20	0.05	0.0052	0.026%
	20	0.01	0.0010	0.005%

These results demonstrate that even for a very low heat flow specimen (400mm of mineral wool), maintaining the guard and meter plate temperatures to within 0.01°C of one another will only generate about a 0.1% error in heat flow. Less insulated specimens will have much less error. Analytic methods for determining gap unbalance errors also exist (Donaldson, 1960; Woodside & Wilson, 1957) but are much more labourious and would likely provide similar results for unbalance errors as the two-dimensional finite-element modeling.

The meter plate, side guards, bottom guard, and top guard all had the same heater wire spacing (34mm) and were adhered with Owens Corning JointSealR® foam joint tape. A piece of 1/2” (12.7mm) wide 3M Scotch® tape was placed between the wire and the plate to electrically insulate the wire from the plate. The meter plate and side guards used 30 gauge wire and the top

and bottom guards used 20 gauge wire. Figure 11 shows the meter plate and side guards and Figure 12 shows the top and bottom guards.



Figure 11 – Taped heater wire on the back of the meter plate and side guards.



Figure 12 – Taped heater wire on the back of the top and bottom guard.

The pattern of the heater wires ensured that heater wire is continuous along the guard gap surrounding the meter plate as required by ASTM C177 Clause 6.4.1. The distance between the wire and the edge of the plate is half of the spacing between the wires.

These plates were connected to power supplies and relays using 18 gauge copper wire that was twisted and soldered in place. Shrink wrap was applied over the connection to electrically insulate it. Due to the small diameter of the 30 gauge wire used for the meter plate and side guards, a strain relief was provided at the connection to ensure the connection did not break. Figure 13 shows this connection.

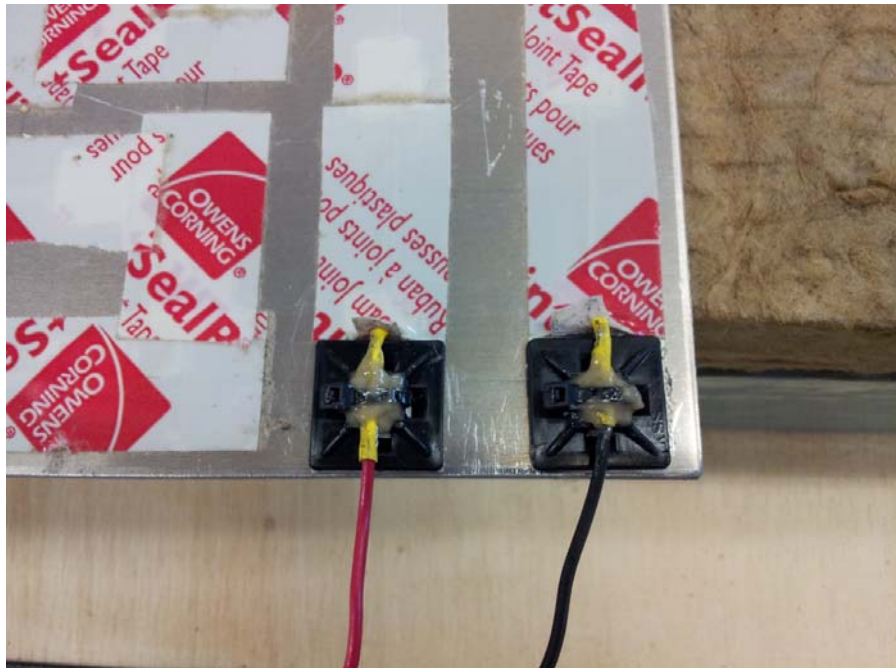


Figure 13 – Strain relief connection for the meter plate and side guards.

Figure 13 shows the strain relief connection which consists of a cable tie mount with LePage PL Premium® polyurethane construction adhesive. For the top and bottom guards, the wire was large enough that breaking it was not as much of a concern so the connection was just taped down with DOW Weathermate® construction tape. Figure 14 shows the connection detail for the top and bottom guards.

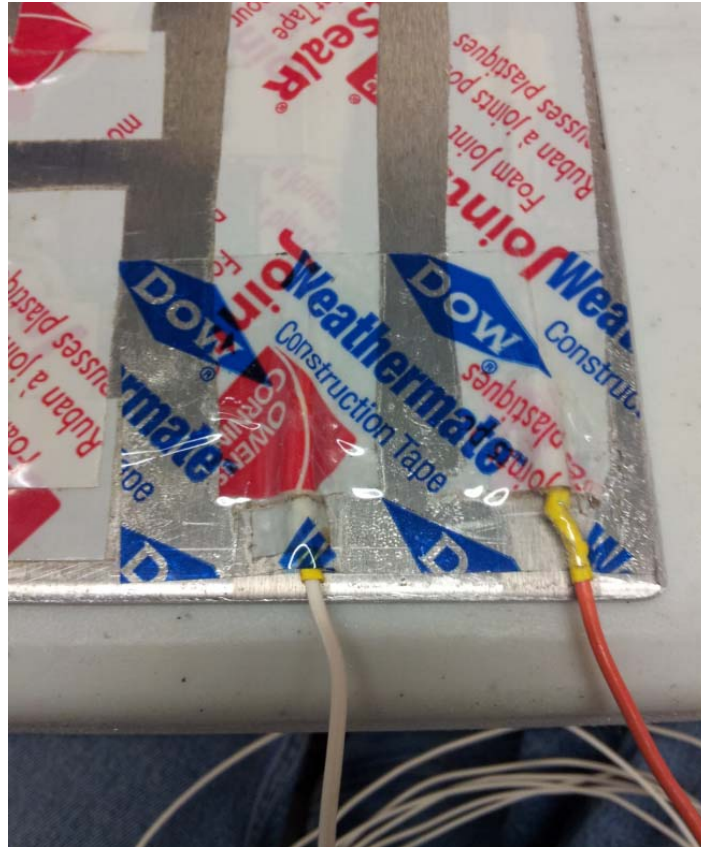


Figure 14 – Heater wire to copper wire connection for the top and bottom guards.

The back guard was constructed in a similar fashion and measured $47 \frac{15}{16}$ " by $47 \frac{15}{16}$ " (1217.6mm by 1217.6mm). The temperature uniformity of the back guard was less critical so the spacing was increased to reduce the labour required to construct this larger plate. A spacing of 50.8mm and 18 gauge heater wire was therefore used. ZIP System stretch flashing tape was used to adhere the wire to the back guard plate instead of Owens Corning JointSealR® foam joint tape because a stronger tape was required to hold the thicker wire down. A $\frac{1}{2}$ " (12.7mm) strip of 3M Scotch® tape was again used on the wire to electrically insulate the wire from the aluminum plate. Figure 15 shows the heater wire taped to the back guard plate.



Figure 15 – Taped heater wire on the back guard plate.

The back guard was connected to the power supplies and relays in the same way as the top and bottom guards. All of the connection locations for the plates were located at the edge of the hot plate assembly with the exception of the meter plate. The wires for the meter plate were run through the insulation between the back guard and meter plate and then along the top of the back guard to the edge of the hot plate assembly.

The insulation in the hot plate assembly was chosen to be rigid mineral wool insulation due to its high temperature resistance. In case of a controller malfunction or relay contacts sticking, the hot plates could become very hot but the mineral wool would not be damaged or melt. The insulation between the back guard and the meter plate, side guards, top guard and bottom guard only acts to buffer the meter plate from the back guard by increasing temperature uniformity and by creating a more stable temperature at the back of the meter plate when the back guard power is cycled on and off. High-density ROXUL Rockboard 80 with a thickness of 1.5" (38.1mm) and a thermal conductivity of 0.037 W/mK at 24°C (ROXUL, 2016) was used for the insulation between the plates at the meter plate level and the back guard. The insulation behind the back guard only serves to reduce the amount of heat loss to the surrounding air decreasing the load on the back

guard power supply. The insulation behind the back guard was chosen to be ROXUL Toprock DD with the less dense side touching the plate. The thickness of this insulation is 3" (76.2mm) and has a thermal conductivity of 0.037 W/mK at 24°C (ROXUL, 2016). The completed hot plate assembly is shown in Figure 16.



Figure 16 – Completed hot plate assembly.

For personnel safety reasons, the hot plates were intended to be operated with low voltage power supplies. All of the hot plates were therefore designed with a heater resistance that would allow a 48V power supply to be used for all anticipated heating power conditions. During the commissioning process, two 48V power supplies and three 40V bench top power supplies were used. One power supply was allocated to each plate with the exception of the side guards which together were operated using a single 48V power supply. Another 48V power supply was used to supply the back guard plate. Both of the 48V power supplies were adjustable between 36V and 60V. The three 40V power supplies were adjustable between 0V and 40V and were allocated to the top guard, bottom guard, and meter plate.

In case of hardware, software, or user error an emergency fail-safe system was implemented to prevent overheating of the hot plate assembly. The shutoff system consists of a bimetallic switch installed in the hot plate assembly that turns off power to the power supplies supplying the hot plates in case of an overheating event. The bimetallic switch is normally closed and opens when it reaches $65^{\circ}\text{C} \pm 5^{\circ}\text{C}$.

3.3 Cold Plate Assembly

The cold plate's function is to provide a stable, cold surface over the entire specimen area as uniformly as possible between the temperatures of -20°C and 40°C. To achieve these requirements, a re-circulating bath chiller that pumps chilled fluid through a copper pipe network attached to the back of a thick aluminum plate was used. These types of units are widely available in laboratories and have appropriately sized cooling capacities (more than the Peltier devices commonly used for small systems). Although the bath used does not have the capacity to cool well below -20°C, other models can be used or liquid nitrogen cooling can be implemented for special projects that require lower temperatures. In addition to cooling, the chiller is capable of providing heating to the re-circulating bath allowing cold plate temperatures well above ambient (e.g., the cold plate can be operated at 30°C when the hot plate is at 60°C).

Aluminum T6061 was again used due to its high thermal conductivity to ensure uniform temperature distributions across the plate. Due to the more labourious task of bending copper tubing as compared to heater wire, the spacing of the copper tubing is larger than the spacing of the heater wire on the heater plates. This larger spacing was accommodated by selecting a thicker plate to create equivalent temperature uniformity. A 1/4" (6.35mm) thick plate measuring 47 15/16" by 47 15/16" (1217.6mm by 1217.6mm) was used. The plate was again made to be slightly smaller than 4' by 4' (1219.2mm by 1219.2mm) to avoid conflicting with the edge insulation. With this plate thickness, a copper tubing spacing of 50-75mm on-centre was predicted by models created in THERM 7.3 to create a variation in temperature across the plate of less than 0.1°C under most testing conditions.

The copper piping network attached to the back of the cold plate consisted of two manifolds of 3/4" (19.05mm) diameter L-type copper pipe connected by six pieces of 3/8" (9.5mm) diameter soft annealed copper tubing bent into an "S" shape. The copper pipe network prior to attachment to the aluminum plate is shown in Figure 17.



Figure 17 – Cold plate network.

The 3/8" (9.5mm) diameter copper "S" shaped pieces were brazed to the manifolds pieces via reducers and tee fittings. The lengths of 3/8" (9.5mm) copper tubing within and between the "S" pieces were spaced at a distance of 68mm on-centre.

The copper pipe network was adhered to the plate using a thermally conductive adhesive and mechanical restraint. The main purpose of the adhesive was to provide good thermal contact by filling in gaps between the aluminum plate and the copper pipes. Epoxies Etc. 50-3100RBK® with Catalyst 190 was used and provided a good mix of cost versus performance for this application. Properties of this two-part epoxy are shown in Table 2 and the entire technical data sheet can be found in Appendix D.

Table 2 – Properties of Epoxies 50-3100RBK resin with catalyst 190 (Epoxies Etc., 2016).

Characteristic	Value
Thermal conductivity (W/mK)	2.16
Tensile strength (MPa)	60.7
Compressive strength (MPa)	103.4
Hardness (Shore D)	90
Coefficient of expansion (°C)	30×10^{-6}
Operating temperature range (°C)	-60 to +205
Working time (min.)	45
Cure time @ 25°C (hours)	24-48

Due to the cost of the epoxy, only enough was ordered to provide a ~1.5mm thick layer just around the copper pipes. Therefore, a form was needed to control where the epoxy would be poured. A layer of approximately 1.5mm thick Blueskin WP® was placed on the backside of the cold plate and was peeled away where the copper pipes would be adhered. A 1.5cm thick strip was peeled away where the 3/8” (9.5mm) diameter copper tubing would be placed and 1/4” (6.35mm) thick weather stripping was used to make forms where the pipe fittings of the manifolds would be adhered. All areas where the epoxy was to be placed were cleaned and roughened using sandpaper. Figure 18 and Figure 19 shows the Blueskin WP® and weather stripping acting as formwork prior to pouring the epoxy.

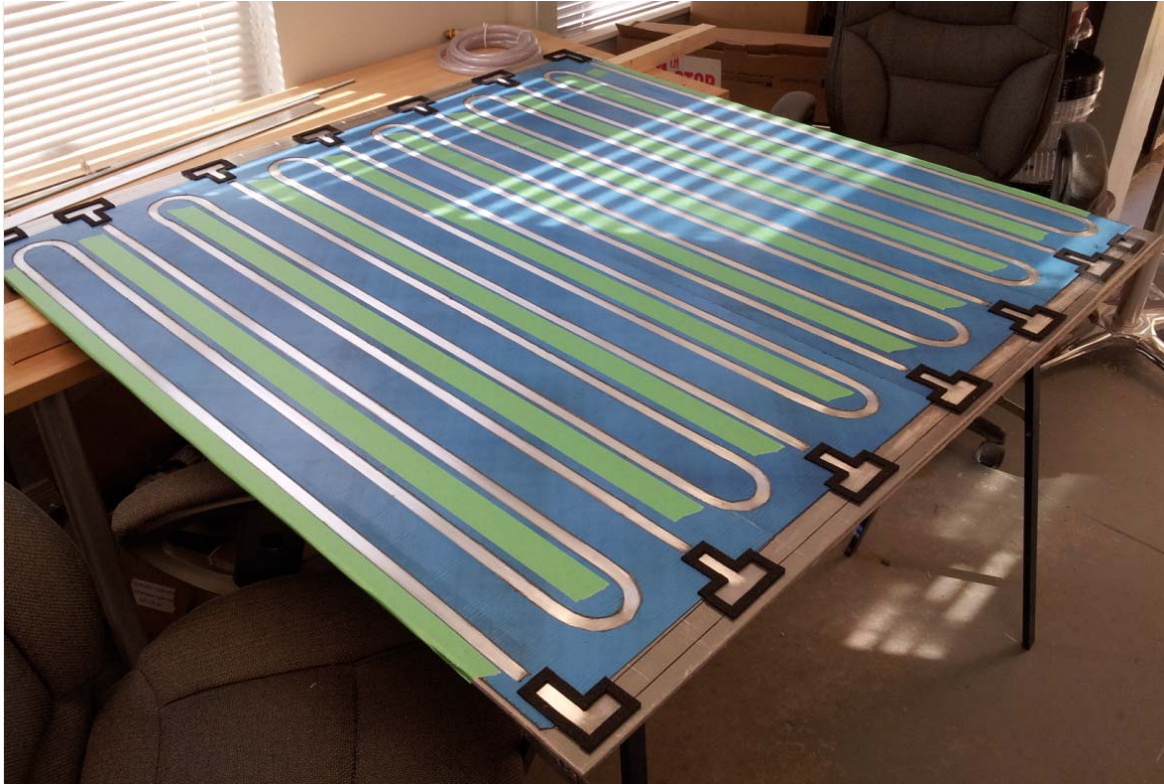


Figure 18 – Formwork for the pouring of the epoxy.



Figure 19 – A detailed view of the Blueskin WP® used to act as formwork for the epoxy.

The green tape in Figure 18 is painter's tape and was used to cover up the holes in the plate that were drilled and tapped for screws that would subsequently be used to apply mechanical restraint. The epoxy was poured onto the plate and distributed across the plate using a flat piece of plastic so that epoxy filled the places where Blueskin WP® was peeled away and nowhere else leaving a 1.5mm thick layer of epoxy below the tubing. The areas around the fittings bounded by the weather stripping were filled separately and then the piping network was placed on top. Approximately 500kg of weight was placed on top of the piping network and plate while the epoxy cured to ensure the piping laid directly against the plate. Figure 20 and Figure 21 show the piping network adhered to the cold plate after the adhesive cured.

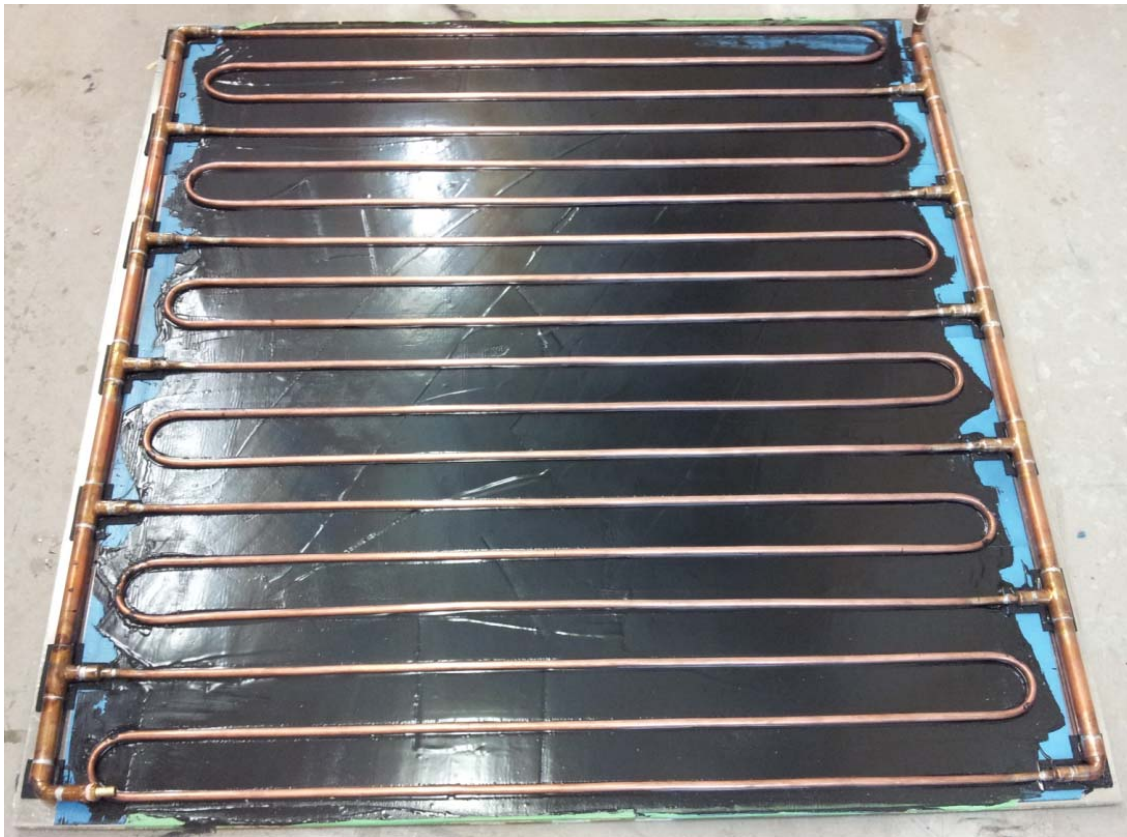


Figure 20 – Piping network adhered to the plate.



Figure 21 – Cured epoxy adhering the piping network to the aluminum plate.

To mechanically hold the piping network tight to the plate, 1/8" (3.175mm) thick by 1.5" (38.1mm) wide aluminum T6061 bar stock was screwed to the plate using 3/4" (19.05mm) long #8 machine screws threaded into the cold plate. The bar stock used to clamp the copper tubing to the plate is shown in Figure 22 and Figure 23.



Figure 22 – Bar stock screwed in place clamping the copper tubing to the plate.



Figure 23 – A detailed view of the bar stock holding the copper tubing in place.

Figure 22 and Figure 23 also show the 1/4" (6.35mm) diameter threaded rods attached to the bar stock with a nuts on both sides. These rods were also used to hold the insulation onto the back side of the plate. A 1" (25.4mm) thick piece of flexible mineral wool batt insulation was placed on top of the piping and then 4 layers of 3/4" (19.05mm) polyisocyanurate was added. The purpose of this insulation is to reduce heat losses from the cold plate to the environment decreasing the load on the chiller and increasing temperature uniformity of the cold plate. The mineral wool batt insulation layer was used to fill in gaps and provide protection to the cold plate insulation in case of the hot plates overheating with a highly conductive specimen. This layer is shown in Figure 24.

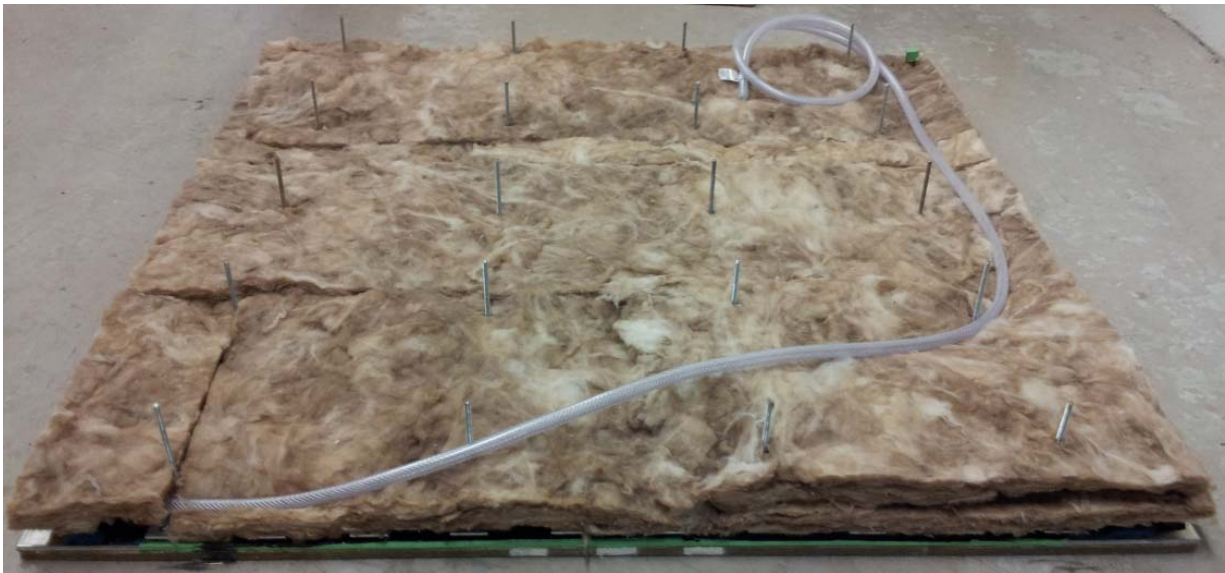


Figure 24 – Mineral wool batt insulation layer on top of the piping.

Polyisocyanurate is used as the main insulating layer for the cold plate because it is lightweight and has a relatively low thermal conductivity as compared to other commonly used insulations. The polyisocyanurate is also faced with a thin sheet of aluminum which stops vapour diffusion through the insulation that could cause condensation on the backside of the cold plate. Figure 25 shows the polyisocyanurate layers installed on the cold plate.



Figure 25 – Polyisocyanurate layers on the cold plate.

A slot was cut in the second layer (from the bottom) of polyisocyanurate to run vinyl tubing from the outlet of one of the manifolds to the other corner so that the inlet and outlets for the cold plate were at one location. To hold the insulation in place, 1x3” (19x64mm) wood furring strips were fastened via the threaded rods. Blueskin WP® was placed under the furring strips to act as an air and vapour diffusion sealant around the holes created by the threaded rods. Voids around the edges of the cold plate assembly were filled with pieces of mineral wool batt insulation and then the edges of the assembly were wrapped with tape for air tightness. The holes where the vinyl tubing protruded were filled with a polyurethane-based spray foam and then further sealed with tape. Lengths of 1x2” (19x38mm) wood strips were attached to the furring strips to act as handles for the cold plate. The finished cold plate is shown in Figure 26.

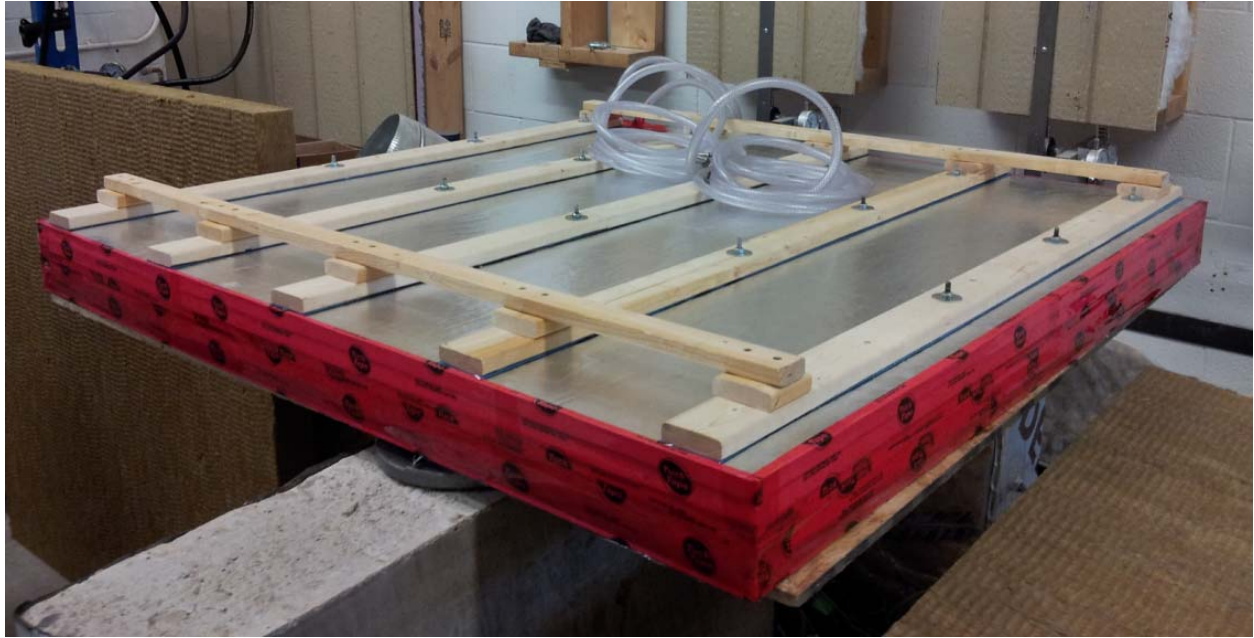


Figure 26 – Completed cold plate assembly.

A VWR 1197P chiller was used to pump chilled fluid through the copper piping network thus cooling the cold plate. Specifications for this chiller model are provided in Appendix E. The chiller supplies a constant temperature fluid through the copper tubing. Supply and return lines from the chiller to the plate were insulated with R 5 hr·ft²·°F/Btu (RSI 0.88 m²K/W) open cell flexible foam pipe insulation to reduce the load on the chiller and to control condensation.

3.4 Edge Insulation

Edge insulation is an important part of the guarded hot plate as it helps guard the entire specimen and plate stack from ambient temperatures. An analysis of its importance and the design of the edge insulation used are presented in this section.

3.4.1 Edge Loss Error Analysis

As part of the design process for the apparatus, the amount of edge insulation required had to be determined. Two analyses were performed to investigate the importance of the edge insulation and determine the thickness required.

3.4.1.1 Analytical Analysis

Multiple analytical analyses exist for determination of edge heat losses in the guarded hot plate apparatus (De Ponte & Di Fillippo, 1974) with the most notable being the analysis performed by Woodside (1957). His analysis is one of the simpler analytic methods but appears to agree well with more complicated methods (Bankvall, 1973). Using his method, the error in thermal conductivity measurement due to edge heat losses is given by (Woodside, 1957)

$$\left(\frac{k_{true}}{k}\right)^{1/2} = \frac{\pi \cdot x/L}{e \cdot \ln\left(\frac{\cosh\left(\frac{\pi(g+x)}{L}\right) + 1}{\cosh\left(\frac{\pi g}{L}\right) + 1}\right) + (1-e) \cdot \ln\left(\frac{\cosh\left(\frac{\pi(g+x)}{L}\right) - 1}{\cosh\left(\frac{\pi g}{L}\right) - 1}\right)} \quad (11)$$

where k is the measured thermal conductivity of the specimen in W/mK; k_{true} is the true thermal conductivity of the specimen in W/mK; g is the guard width starting from the gap centreline in m; L is the specimen thickness in m; x is the side length of the metering section from the centre of the meter plate to the gap centreline in m; and e is dimensionless and defined as

$$e = \frac{T_{edge} - T_c}{T_h - T_c} \quad (12)$$

where T_{edge} is the surface temperature at the edges of the specimen in K (no edge insulation is used); T_c is the temperature of the cold plate in K; and T_h is the temperature of the hot plate in K.

Using Woodside's relationship, Table 3 was constructed to present the effects of different meter area sizes and specimen thicknesses.

Table 3 – Thermal conductivity measurement error determined with an analytical method.

Specimen Thickness	Meter Area Width						
	4" (102mm)	6" (152mm)	8" (203mm)	10" (254mm)	12" (305mm)	14" (356mm)	16" (406mm)
4" (102mm)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
6" (152mm)	0.00%	0.00%	0.01%	0.01%	0.01%	0.02%	0.03%
8" (203mm)	0.05%	0.06%	0.08%	0.10%	0.13%	0.18%	0.24%
10" (254mm)	0.28%	0.33%	0.40%	0.49%	0.60%	0.75%	0.93%
12" (305mm)	0.88%	1.02%	1.20%	1.40%	1.65%	1.96%	2.33%
14" (356mm)	2.02%	2.28%	2.60%	2.96%	3.39%	3.89%	4.47%
16" (406mm)	3.73%	4.14%	4.62%	5.16%	5.78%	6.48%	7.28%
18" (457mm)	5.97%	6.54%	7.18%	7.90%	8.69%	9.58%	10.57%
20" (508mm)	8.65%	9.37%	10.16%	11.03%	11.98%	13.02%	14.16%

The values presented in Table 3 represent the percent difference of k from k_{true} and were calculated based on a cold plate temperature of -20°C , a hot plate temperature of 20°C , and an ambient (edge) temperature of 20°C with no edge insulation. These temperature conditions yield an e value of 1 which represents the worst case scenario. It should be noted that no value for k was assumed as only the ratio of k_{true} to k was calculated. Thus, in this analysis, the errors will be the same independent of the k value of the specimen. Table 3 shows that edge heat loss errors can be significant and that they drastically increase with increasing specimen thickness. It also shows that the meter area size has a smaller impact on the edge loss error than specimen thickness and therefore a larger meter area (16"/406.4mm square) was chosen to allow for testing a greater area of specimen. This size of meter plate is also important for testing of thermal bridges such as steel studs which are often spaced at 16" (406.4mm) on-centre. This method is insightful but it does not allow one to determine the edge losses when edge insulation is used and the corresponding benefits. Therefore, THERM 7.3 was used to further quantify edge heat loss effects as described in the following section.

3.4.1.2 Computational Analysis

Numerous models were developed using THERM 7.3 to illustrate the effect of changing certain factors on the error in measured thermal conductivity due to edge heat loss only. Due to the limitations of the program, only simple models of the guarded hot plate apparatus could be created. For all of the models, a 16" (406.4mm) square meter plate, 16" (406.4mm) wide guard plate without a gap, and a total specimen size of 48" by 48" (1219.2mm by 1219.2mm) were assumed. The material of the specimen in all of the models was low-density mineral fiber insulation with a "true" thermal conductivity of 0.042 W/mK. This material was also used for the edge insulation unless otherwise noted. The hot plate is always situated at the bottom and the cold plate always at the top of the specimen to simulate a roof in a cold climate. In cross-section, only half of the apparatus is shown due to symmetry. The cut-line at the middle of the apparatus is represented as an adiabatic boundary (no heat loss/gain) and is shown in each model on the left side. Unless otherwise noted, the ambient temperature is 20°C, the hot plate temperature is 20°C, and the cold plate temperature is -20°C. There was no unbalance between the guard plates and meter plate in any of the models in this section.

3.4.1.2.1 Models with Adiabatic Conditions at the Top and Bottom of the Edge Insulation

In these models, the top and bottom edges of the edge insulation are made adiabatic. These are the simplest and most generic models created. However, they provide valuable information about the edge loss errors. Figure 27 shows a typical model of this type with temperature isotherms.

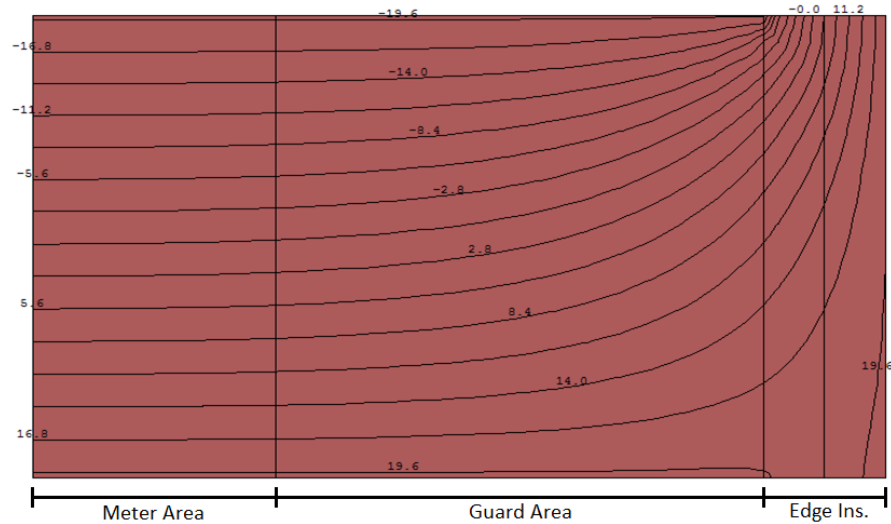


Figure 27 – A model with adiabatic conditions at the top and bottom of the edge insulation.

Three specimen thicknesses were evaluated and the results of the models are shown in Table 4.

Table 4 – Edge loss errors with adiabatic conditions at the top and bottom of the edge insulation.

Specimen Thickness	Edge Ins. Thickness	Edge Ins. R-value (ft ² ·°F·h/Btu)	U (W/m ² ·K)	k (W/m·K)	% Error in k
8" (203mm)	0" (0mm)	0	0.2064	0.04194	0.14%
8" (203mm)	2" (51mm)	6.9	0.2065	0.04196	0.09%
8" (203mm)	4" (102mm)	13.7	0.2065	0.04196	0.09%
8" (203mm)	6" (152mm)	20.6	0.2066	0.04198	0.04%
12" (305mm)	0" (0mm)	0	0.1359	0.04142	1.38%
12" (305mm)	2" (51mm)	6.9	0.1366	0.04164	0.87%
12" (305mm)	4" (102mm)	13.7	0.1369	0.04173	0.65%
12" (305mm)	6" (152mm)	20.6	0.1371	0.04179	0.50%
16" (406mm)	0" (0mm)	0	0.0982	0.03991	4.98%
16" (406mm)	2" (51mm)	6.9	0.0997	0.04052	3.53%
16" (406mm)	4" (102mm)	13.7	0.1006	0.04088	2.66%
16" (406mm)	6" (152mm)	20.6	0.1012	0.04113	2.08%
16" (406mm)	8" (203mm)	27.5	0.1016	0.04129	1.69%

The results from Table 4 are plotted in Figure 28.

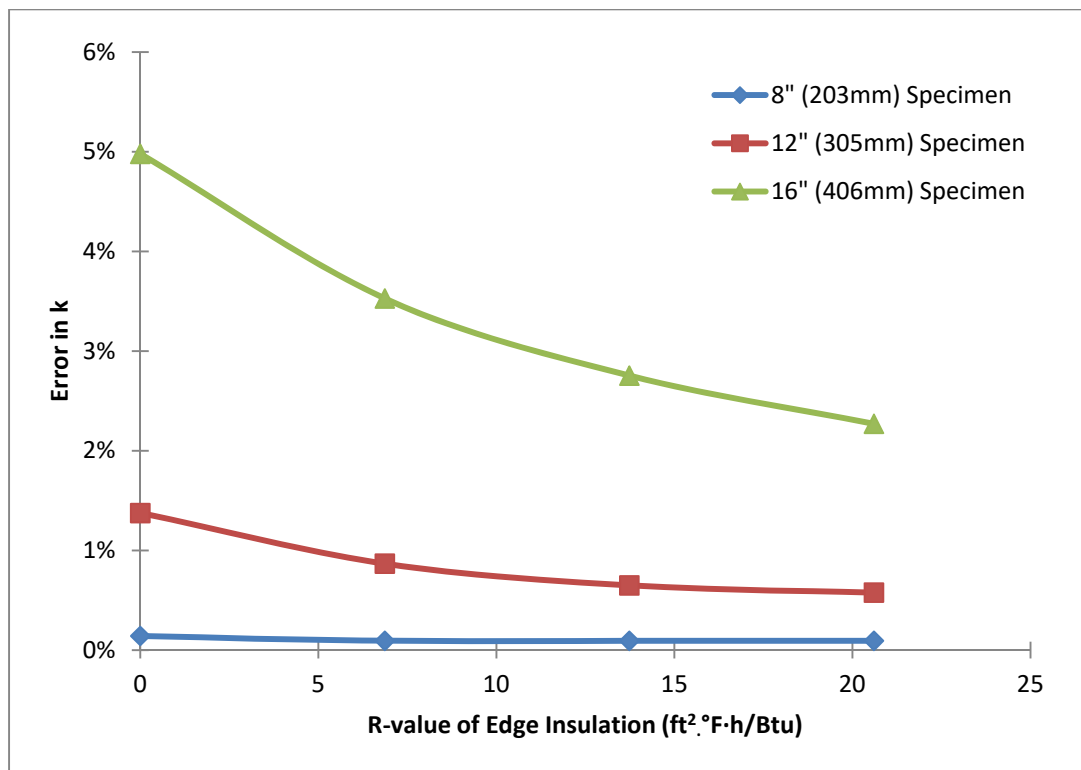


Figure 28 – Error in thermal conductivity versus R-value of edge insulation.

Figure 28 shows that increasing the R-value of edge insulation greatly decreases the measured error in thermal conductivity for well-insulated thick specimens. It also shows that thicker specimens have significantly larger errors and that edge heat losses are important even for moderate thickness specimens. This observation agrees with published research (Bankvall, 1973) and is more clearly illustrated in Figure 29.

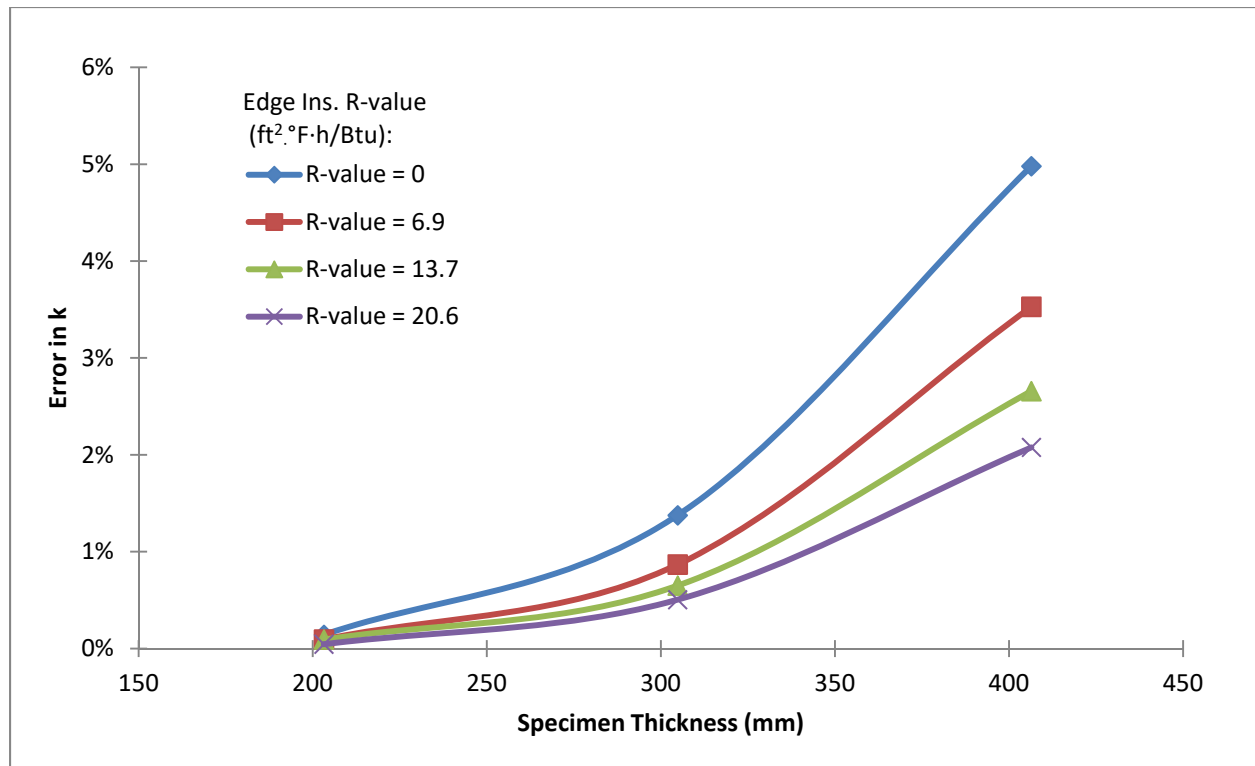


Figure 29 – Error in thermal conductivity versus specimen thickness.

3.4.1.2.2 Models with Equal Insulation Thickness on the Top, Bottom, and Edge

If in these models, for example, 50mm of edge insulation is used, the insulation is extended 50mm above the cold plate and 50mm below the hot plate. The top, bottom, and right edge of the edge insulation in the models are set to ambient conditions. The left edges above the cold plate and below the hot plate are set to adiabatic conditions. The idea of this exercise was to create a more realistic model and relate it to the findings in the previous section. Figure 30 shows a typical model of this type with temperature isotherms.

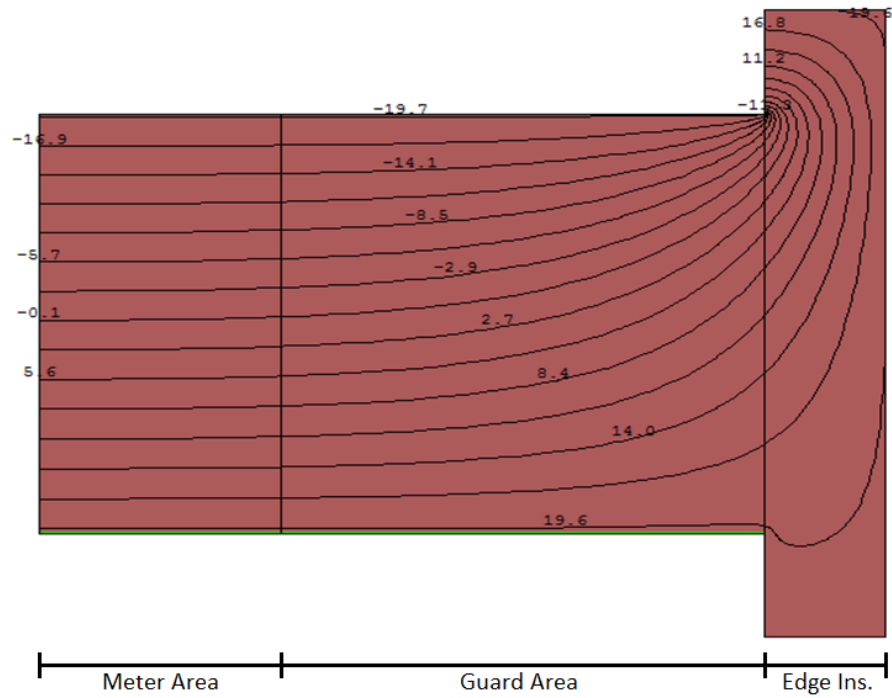


Figure 30 – Typical model with equal insulation on the top, bottom, and edge.

Comparing Figure 30 with the model in Figure 27 (which assumed adiabatic conditions at the top and bottom of the edge insulation), the isotherms appear to be very similar. The results for the model in Figure 30 are shown in Table 5.

Table 5 – Edge loss errors with equal insulation on the top, bottom, and edge.

Specimen Thickness	Edge Ins. Thickness	Edge Ins. R-value (ft²·°F·h/Btu)	U (W/m²·K)	k (W/m·K)	% Error in k
8" (203mm)	0" (0mm)	0	0.2064	0.041940	0.14%
8" (203mm)	2" (51mm)	6.9	0.2065	0.041961	0.09%
8" (203mm)	4" (102mm)	13.7	0.2065	0.041961	0.09%
8" (203mm)	6" (152mm)	20.6	0.2065	0.041961	0.09%
12" (305mm)	0" (0mm)	0	0.1359	0.041422	1.38%
12" (305mm)	2" (51mm)	6.9	0.1366	0.041636	0.87%
12" (305mm)	4" (102mm)	13.7	0.1369	0.041727	0.65%
12" (305mm)	6" (152mm)	20.6	0.1370	0.041758	0.58%
16" (406mm)	0" (0mm)	0	0.0982	0.039908	4.98%
16" (406mm)	2" (51mm)	6.9	0.0997	0.040518	3.53%
16" (406mm)	4" (102mm)	13.7	0.1005	0.040843	2.75%
16" (406mm)	6" (152mm)	20.6	0.1010	0.041046	2.27%
16" (406mm)	8" (203mm)	27.5	0.1013	0.041168	1.98%
16" (406mm)	10" (254mm)	34.3	0.1015	0.041250	1.79%

Comparing this table with Table 4, the values are very similar suggesting that the models in Section 3.4.1.2.1 “Models with Adiabatic Conditions at the Top and Bottom of the Edge Insulation” are realistic enough and more complicated models may not give appreciably more accurate results.

3.4.1.2.3 Models with Varying Insulation Thicknesses on the Top, Bottom, and Edge

This section is an expansion on the previous section. Only two models were evaluated to determine the degree to which the thickness of edge insulation above the cold plate and below the hot plate impacts the error. The results are shown in Table 6.

Table 6 – Edge loss errors with varying insulation thicknesses on the top, bottom, and edge.

Specimen Thickness	Edge Ins. Thickness	Edge Ins. R-value (ft²·°F·h/Btu)	Ins. Below Hot Plate	Ins. Above Cold Plate	U (W/m²·K)	k (W/m·K)	% Error in k
16" (406mm)	2" (51mm)	6.9	6" (152mm)	6" (152mm)	0.0997	0.040518	3.53%
16" (406mm)	6" (152mm)	20.6	2" (51mm)	2" (51mm)	0.1009	0.041006	2.37%

The first model in Table 6 (first row) has more insulation thickness on the top and bottom of the edge insulation when compared to the models in Section 3.4.1.2.2 “Models with Equal Insulation Thickness on the Top, Bottom, and Edge” and the second model (second row in Table 6) has less. Comparing the first model with the corresponding model in Section 3.4.1.2.2, the same error is measured. This is also the same error as in Section 3.4.1.2.1 “Models with Adiabatic Conditions at the Top and Bottom of the Edge Insulation”. The second model gives an error of 2.37%. Comparing this with an error of 2.27% from the corresponding model in Section 3.4.1.2.2 with three times the amount of insulation on the top/bottom, it can be concluded that reducing the amount of insulation on the top/bottom has a negligible effect. The corresponding model in Section 3.4.1.2.1 with adiabatic edges has an error of 2.08% which is similar enough to the aforementioned findings to conclude that models in Section 3.4.1.2.1 are good representations of reality for a model even with varying amounts of edge insulation above the cold plate and below the hot plate.

3.4.1.2.4 Models with Aerogel as Edge Insulation

For these models, Aerogel was used as the edge insulation material with adiabatic conditions at the top and bottom of the edge insulation similar to in Section 3.4.1.2.1. Aerogel is a silica gel formed by supercritical extraction which results in a porous open cell solid insulation with a very low thermal conductivity of about 0.0147 W/mK (Bardy, Mollendorf & Pendergast, 2007). This material was evaluated to determine if lower conductivity edge insulation would be beneficial in reducing the edge insulation thickness to reduce the overall bulkiness of the apparatus and whether there may be any additional reduction in error due to smaller thickness edge insulation. The results of the models are shown in Table 7.

Table 7 – Edge loss errors using Aerogel as the edge insulation.

Specimen Thickness	Edge Ins. Thickness	Edge Ins. R-value (ft²·°F·h/Btu)	U (W/m²·K)	k (W/m·K)	% Error in k
12" (305mm)	1" (25mm) Aerogel	9.8	0.1367	0.041666	0.79%
12" (305mm)	2" (51mm) Aerogel	19.6	0.1370	0.041758	0.58%
12" (305mm)	3" (76mm) Aerogel	29.4	0.1372	0.041819	0.43%
16" (406mm)	2.857" (73mm) Roxul	9.8	0.1002	0.040721	3.04%
16" (406mm)	1" (25mm) Aerogel	9.8	0.1000	0.040640	3.24%
16" (406mm)	2" (51mm) Aerogel	19.6	0.1009	0.041006	2.37%
16" (406mm)	3" (76mm) Aerogel	29.4	0.1014	0.041209	1.88%

As expected, a lower thickness of Aerogel is required for a certain level of edge loss error when compared to the low-density mineral fiber insulation. Based on a ratio of thermal conductivities, the R-value of 2.857" (72.3mm) of low-density mineral fiber insulation is equivalent to 1" (25.4mm) of Aerogel. A low-density mineral fiber insulation of this thickness was modelled to see if the same error would be yielded (fourth row in Table 7). For the 16" (406.4mm) thick specimen, there was only a 0.2% difference in error when comparing equal resistances of the two materials. Therefore, it can be concluded that according to the models, a low thickness, low conductivity material will give a similar error to a higher thickness, higher conductivity material of equal R-value when used as edge insulation and there is no substantial extra benefit from thickness effects for edge insulation.

3.4.1.2.5 Models Comparing Different Meter Plate and Guard Section Widths

The findings from the analysis of the meter plate size presented in Section 3.4.1.1 “Analytical Analysis” showed that a smaller meter plate resulted in less edge loss error. However, a smaller meter plate also reduces the spatial size of the meter area which is important for measuring non-

homogenous specimens. The effect of a smaller meter plate must be evaluated and weighed in comparison to other methods of error reduction such as edge insulation. An 11.3" (285.9mm) square meter plate was compared against the 16" (406.4mm) square meter plate. An 11.3" (285.9mm) square meter plate was chosen for comparison since this size is half of the area of the 16" (406.4mm) square meter plate. If the meter plate could be split into two concentric areas, a more flexible apparatus could be built. If the reduction in error was found to be significant, the heat input from the smaller inside plate could solely be measured as the meter plate heat flux when testing thick insulation specimens. For the 11.3" (285.9mm) square meter plate, a width of 18.4" (466.7mm) was left as the guard section width to keep the specimen size to 48" by 48" (1219mm by 1219mm). The results of the models are shown in Table 8.

Table 8 – Comparison of edge loss errors of two meter plate sizes.

Specimen Thickness	Edge Ins. Thickness	Edge Ins. R-value (ft ² ·°F·h/Btu)	U (W/m ² ·K)	k (W/m·K)	Comparison	
					11.3" (286mm) % Error in k	16" (406mm) % Error in k
12" (305mm)	0" (0mm)	0	0.1364	0.041575	1.01%	1.38%
12" (305mm)	2" (51mm)	6.9	0.1369	0.041727	0.65%	0.87%
12" (305mm)	4" (102mm)	13.7	0.1372	0.041819	0.43%	0.65%
16" (406mm)	0" (0mm)	0	0.0991	0.040274	4.11%	4.98%
16" (406mm)	2" (51mm)	6.9	0.1003	0.040762	2.95%	3.53%
16" (406mm)	4" (102mm)	13.7	0.1011	0.041087	2.17%	2.66%
16" (406mm)	6" (152mm)	20.6	0.1015	0.041250	1.79%	2.08%

The results in Table 8 show that a reduction in edge loss error occurs for a smaller plate size but the error reduction is not as significant as when edge insulation is added. The reduction in error is equivalent to adding 1-2" (25.4-50.1mm) of edge insulation which is much easier to

implement than a separate meter plate control circuit. For this reason, a 16'' (406.4mm) square meter plate was selected to be the most reasonable choice.

3.4.1.2.6 The Effect of the Mean Temperature on Edge Loss Error

The mean temperature of the specimen is calculated as the average of the cold plate and hot plate temperatures and is known to have a large influence on the edge loss errors (Bode, 1985; Dubois & Lebeau, 2013; Eguchi, 1985; Peavy & Rennex, 1986). Models were developed to quantify the effect and the results are plotted in Figure 31.

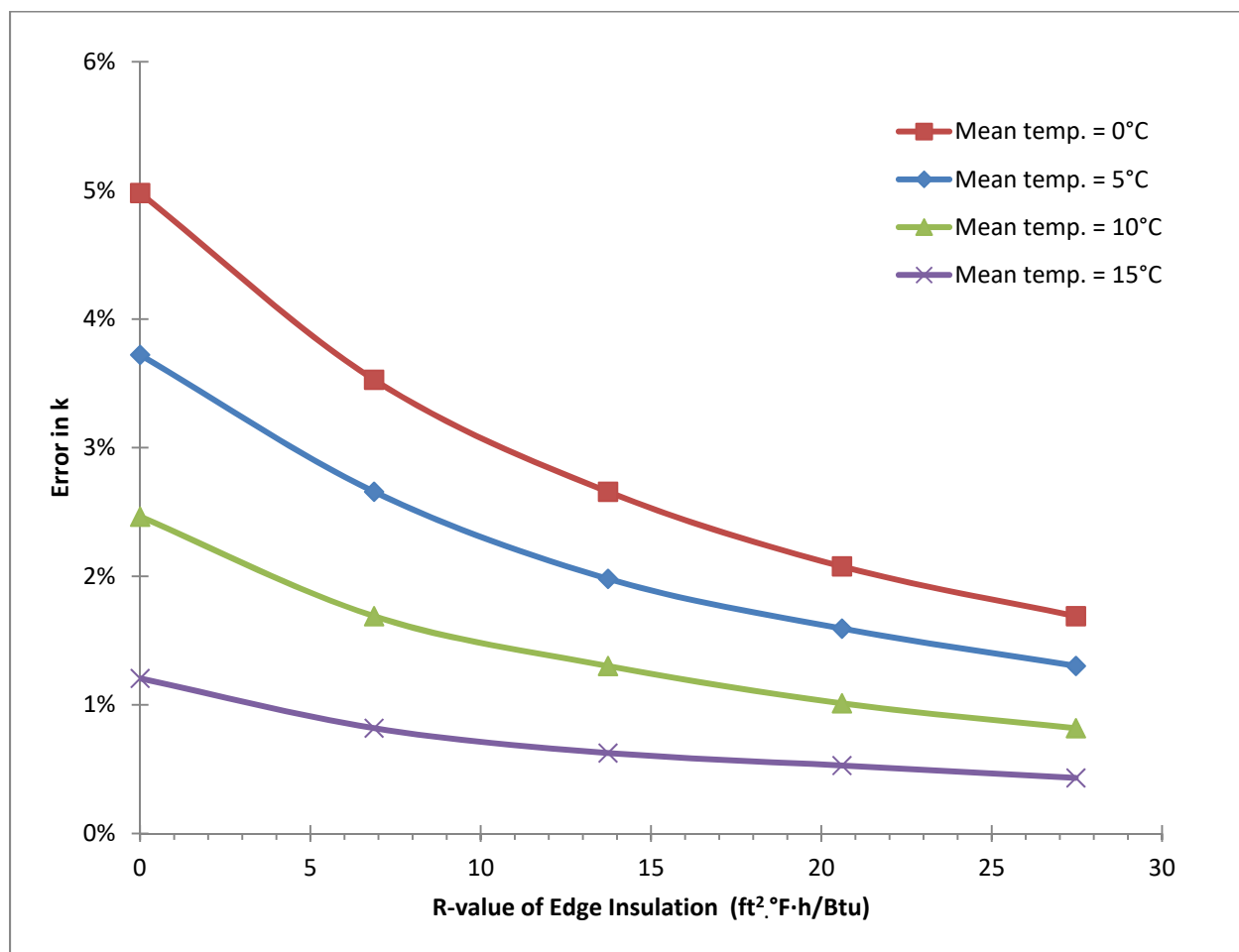


Figure 31 – Error in thermal conductivity versus degree of edge insulation for different mean temperatures.

In these models, the ambient temperature is kept at 20°C, the difference in temperature between the plates is kept to 40°C, and the specimen thickness is 16" (406mm). Figure 31 shows that as the mean temperature approaches the ambient temperature, the error significantly decreases. To determine the relationship between mean temperature and error, Figure 32 was constructed using the same data as Figure 31.

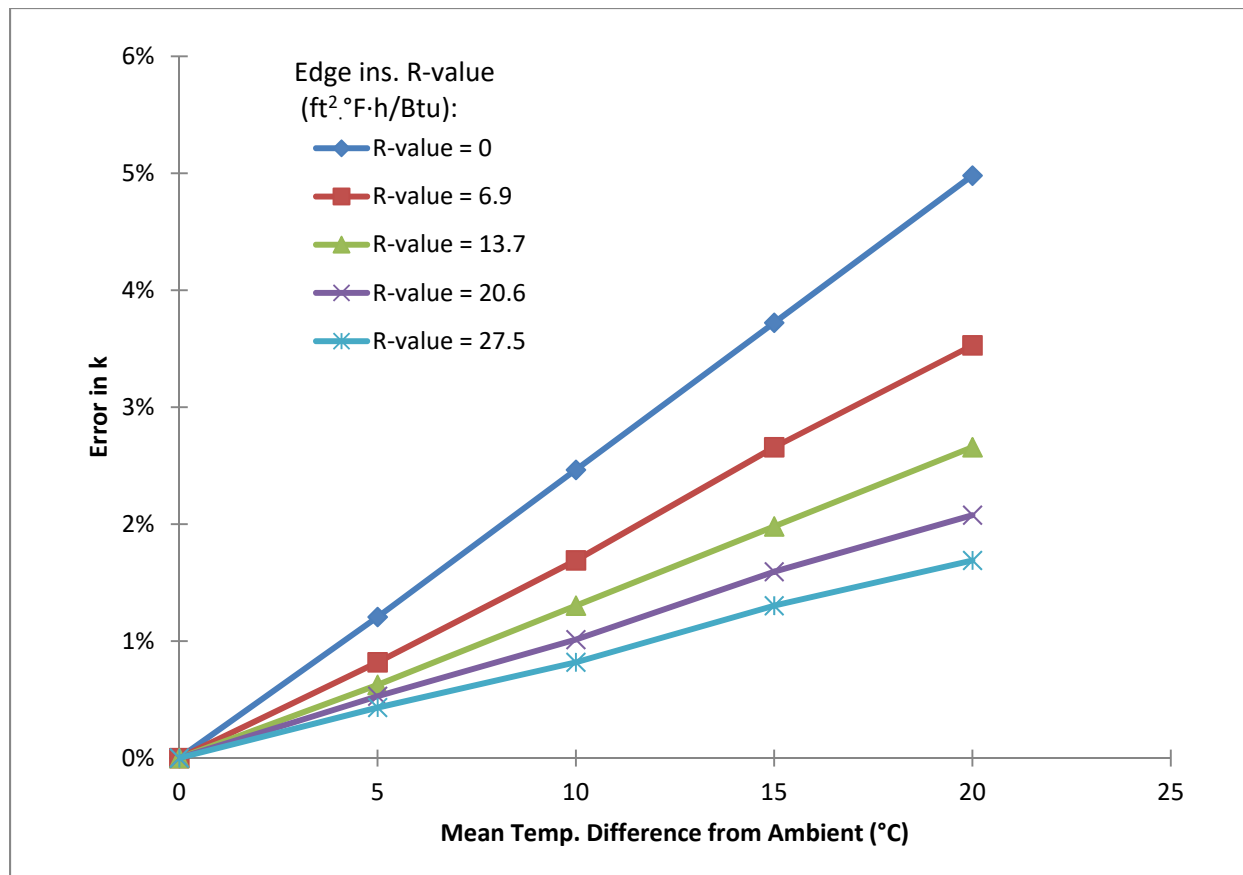


Figure 32 – Error in thermal conductivity versus the difference of the mean temperature from the ambient.

Figure 32 shows roughly that a linear relationship exists between the error in thermal conductivity due to edge losses and the difference of the mean temperature from the ambient. It also shows that when the mean temperature is equal to the ambient temperature, there is theoretically no error since the heat gain above the mid-height of the specimen and the heat loss below the mid-height of the specimen are equivalent. As stated earlier, in practice, the smallest error is more likely to be achieved if the ambient temperature is maintained to slightly above the

mean temperature (Rennex, 1985; Orr, 1967). Furthermore, it should be noted that the ambient temperature to create minimum errors is a function of specimen thickness, specimen thermal conductivity, and the degree of edge insulation (ASTM International, 2004).

3.4.2 Edge Insulation Design

ASTM C177 provides a method to help determine if a certain degree of edge insulation is adequate but no basis for the origin of this criterion is given (Jackson, 1976). The equation given in the standard also suggests a level of edge insulation that is very conservative (Woodside, 1957). Based on the analytical and computational analyses, a design using 3" (76.2mm) of mineral fibre insulation as edge insulation was chosen as appropriate for reducing errors to an acceptable level. This is a convenient size as mineral fibre insulation often comes in 3" (76.2mm) thick boards that are easy to work with. Mineral fibre insulation is also relatively inexpensive and is resistant to high temperatures which is important in case of hardware or software malfunction that would cause the hot plates to overheat. Aerogel is more difficult to work with and more expensive than mineral fiber insulation so it was not chosen as the material for the edge insulation.

The product chosen for the edge insulation was 3" (76.2mm) thick boards of ROXUL Comfortboard CIS. This product has an R-value per inch of $4.3 \text{ hr}\cdot\text{ft}^2\cdot\text{F}/\text{Btu}$ (RSI value per 25.4mm of $0.74 \text{ m}^2\text{K}/\text{W}$) which gives a total R-value of $12.9 \text{ hr}\cdot\text{ft}^2\cdot\text{F}/\text{Btu}$ (RSI of $2.22 \text{ m}^2\text{K}/\text{W}$) (ROXUL Inc., 2016). This product is rigid and fairly durable but surface protection was still necessary to protect it from mechanical abrasion. Therefore, the edge insulation was wrapped with Delta Sd-FLEXX adhered with 3M Super 77 spray adhesive. Delta Sd-FLEXX is a thin, strong nylon membrane that is thin enough to not thermally obstruct the role of the edge insulation but strong enough to greatly increase the insulation's durability.

3.5 Apparatus Frame

A frame is required to hold all of the components together and to allow the completed guarded hot plate assembly to rotate from horizontal to vertical orientations. Figure 33 shows the conceptual design of the apparatus frame and stand.

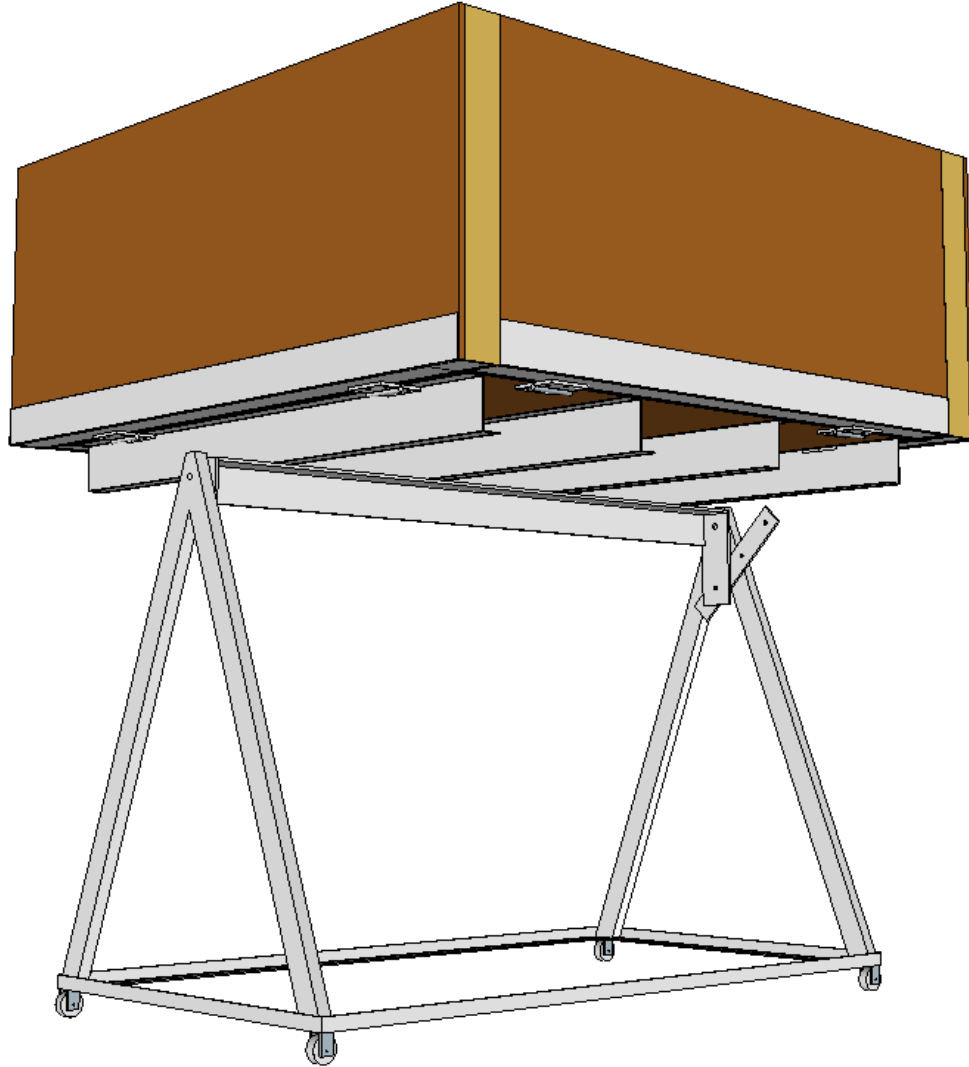


Figure 33 – Conceptual design of the apparatus frame and stand.

The hot plates assembly rests on a plywood base supported by steel Z-girts and the edge insulation around the sides of the hot plate assembly swing up and down on hinges to allow easy insertion and removal of the specimen. The edge insulation is adhered to ½" (12.7mm) plywood which was chosen as a stiff, strong, and easily worked panel material. Figure 34 and Figure 35 show the cross-sectional design of the guarded hot plate frame.

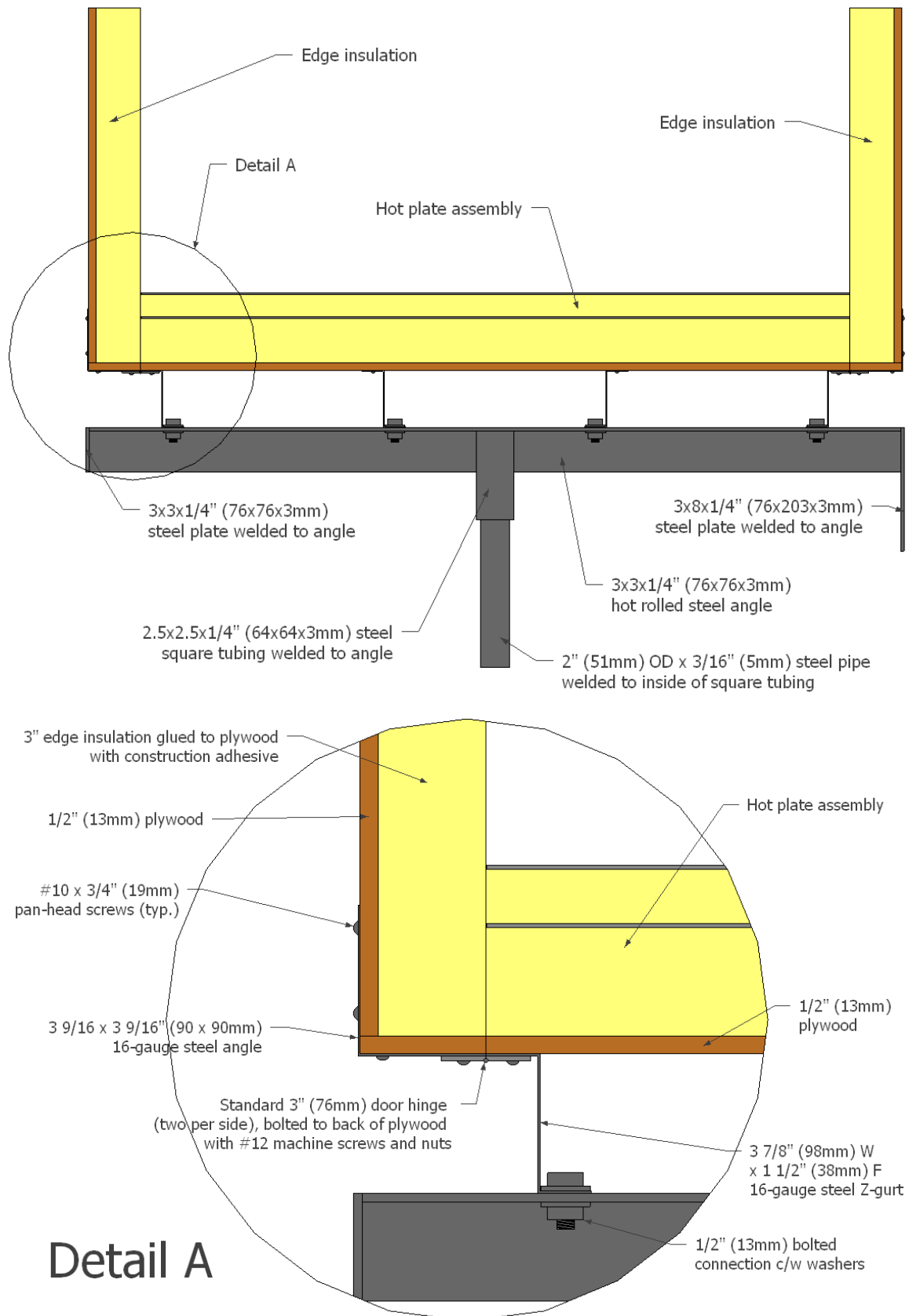
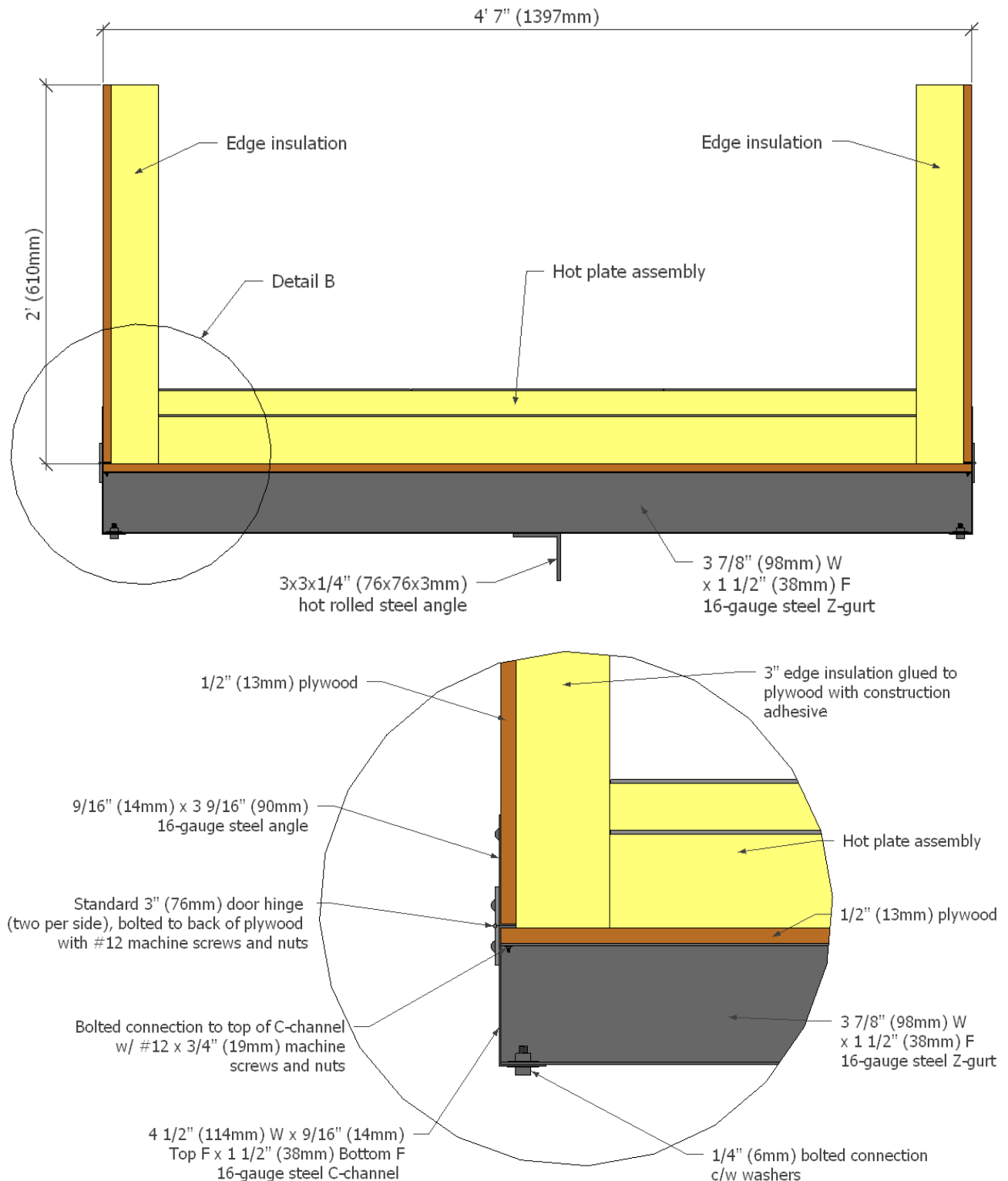


Figure 34 – East/West cross-section of the guarded hot plate design.



Detail B

Figure 35 – North/South cross-section of the guarded hot plate design.

The 3x3x1/4" (76x76x3mm) steel angle shown in Figure 34 and Figure 35 was designed to attach to a steel tube frame via bolts through the 1/4" (3mm) end plates. This angle acts as the pivot point for the apparatus that would allow it to rotate to different orientations on the steel tube frame. The 2" (51mm) steel pipe shown in Figure 36 allows standard weights to be attached to counterbalance the weight of the apparatus. The completed apparatus frame on temporary stands is shown in Figure 36 and Figure 37.



Figure 36 – Completed apparatus frame on temporary stands with edge insulation panels in the open position.

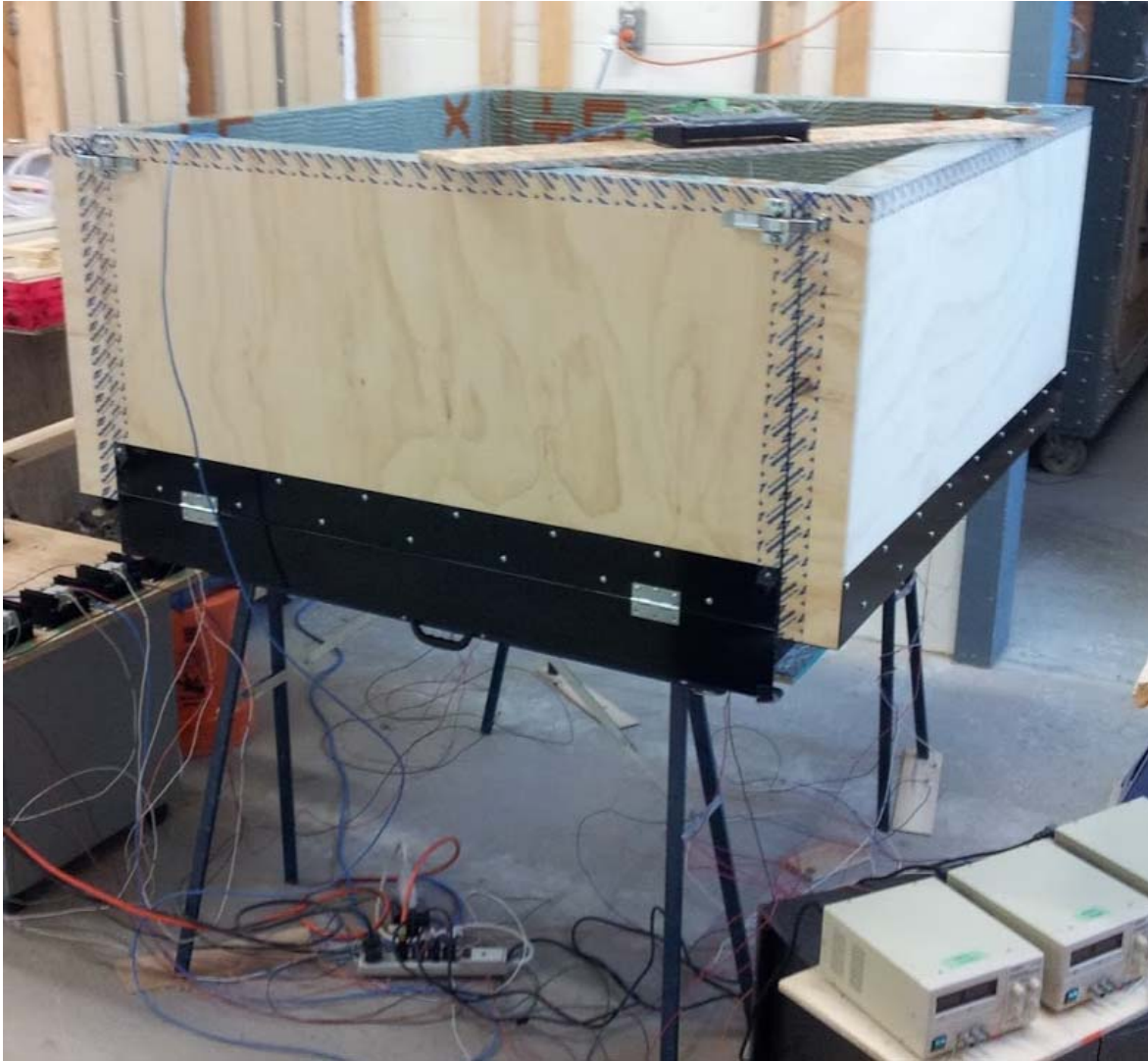


Figure 37 – Completed apparatus frame on temporary stands with edge insulation panels in the closed position.

The tape shown in Figure 37 around the edges of the edge insulation panels (not shown in Figure 36) was applied to adhere the edges of the Delta Sd-FLEXX membrane to the plywood. The edge insulation panels stay in the closed position via spring clamps in each corner (Figure 38).



Figure 38 – Clamps used to hold the edge insulation panels in the closed position.

Due to time constraints, a steel frame on wheels for which the apparatus would rotate on was chosen to be constructed at a later date. For the commissioning process, the apparatus frame was mounted on a table as shown in Figure 39.

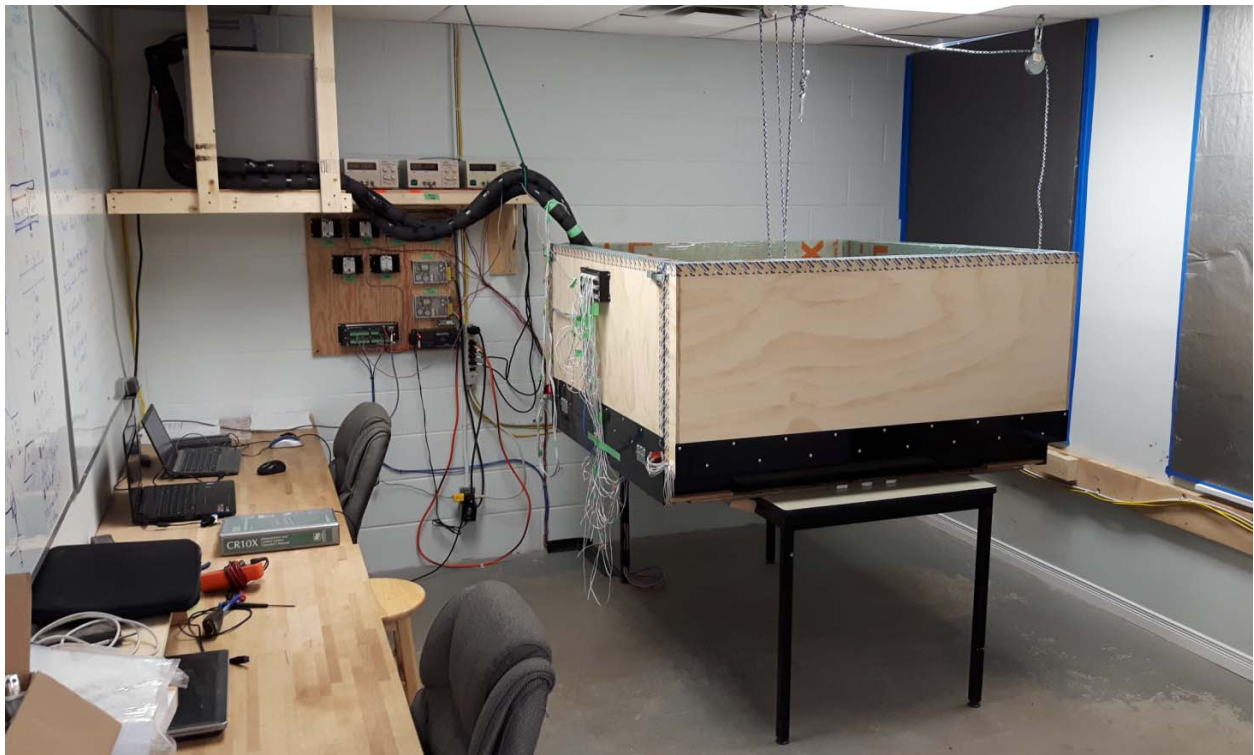


Figure 39 – Apparatus setup for commissioning.

The semi-permanent setup shown in Figure 39 also includes a shelf for the chiller unit and power supplies shown in the top left corner of the figure. A pulley system was assembled to allow the heavy cold plate assembly to be lifted by one person. Figure 40 and Figure 41 show this pulley system.



Figure 40 – Pulley system.

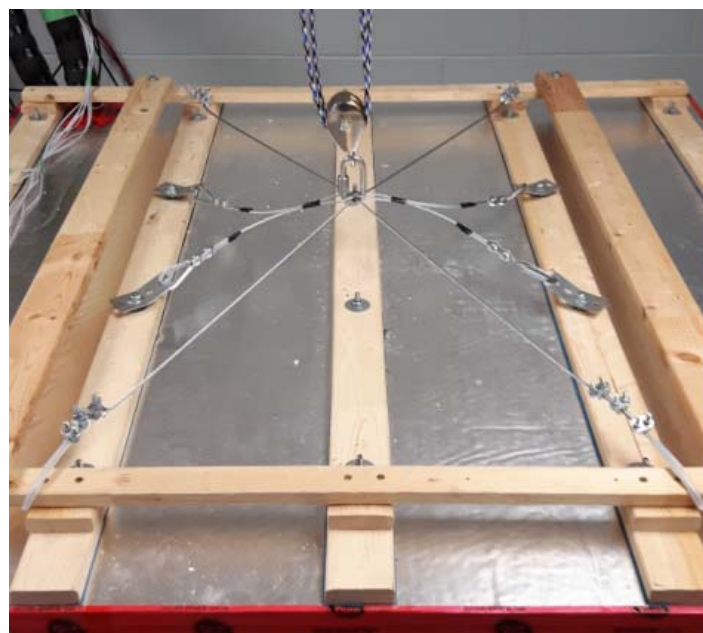


Figure 41 – Pulley system attachment to cold plate assembly.

Redundancy was incorporated into the pulley system to ensure safe operation.

3.6 Controls, Instrumentation, and Operation

In this section, details about the control, instrumentation, and operation strategies for the guarded hot plate are described. Preliminary tests were performed on a 3” (76mm) thick rigid mineral wool insulation specimen to implement and refine the controls. The preliminary tests also provided insight on some of the characteristics of the apparatus such as testing times and the temperature uniformity of the plates.

3.6.1 Temperature Measurement

Honeywell Unicurve 192-103LET-A01 thermistors were used to determine the temperature at different locations throughout the guarded hot plate apparatus. A thermistor’s resistance changes significantly in a predictable manner in response to temperature. The level of precision is determined by the level of precision by which the resistance can be measured. These sensors are sold with an interchangeable accuracy of $\pm 0.2^{\circ}\text{C}$ (Honeywell Sensing and Control, 2016) but can be calibrated in a lab against a known standard for better accuracy.

The relationship between a thermistor’s resistance and the temperature it senses is generally given as a table of values provided by the manufacturer. The data provided for the Honeywell thermistors (attached in Appendix F) was plotted in Microsoft Excel and a relationship was fitted. This fitted relationship has a coefficient of determination of 0.9999998 over the applicable temperature range and is given by

$$T = -0.09446(\ln(R))^3 + 4.16558(\ln(R))^2 - 75.5248\ln(R) + 441.037 \quad (13)$$

where T is the temperature in $^{\circ}\text{C}$ and R is the resistance in Ω .

In the guarded hot plate apparatus, it is essential to know the temperatures of the plates and the distribution of temperature across each plate. Therefore, 45 thermistors were installed in the layouts shown in Figure 43, Figure 42, and Figure 44.

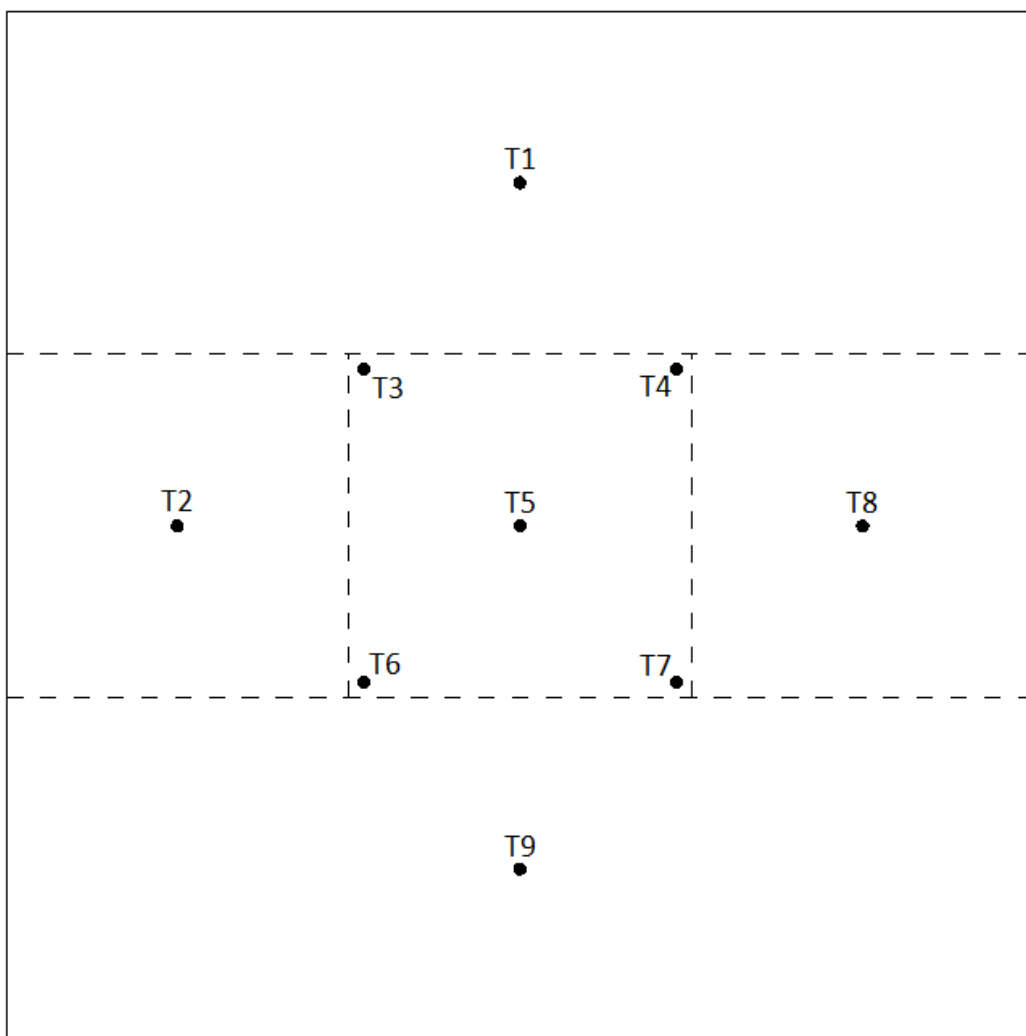


Figure 42 – Thermistor layout on the back guard.

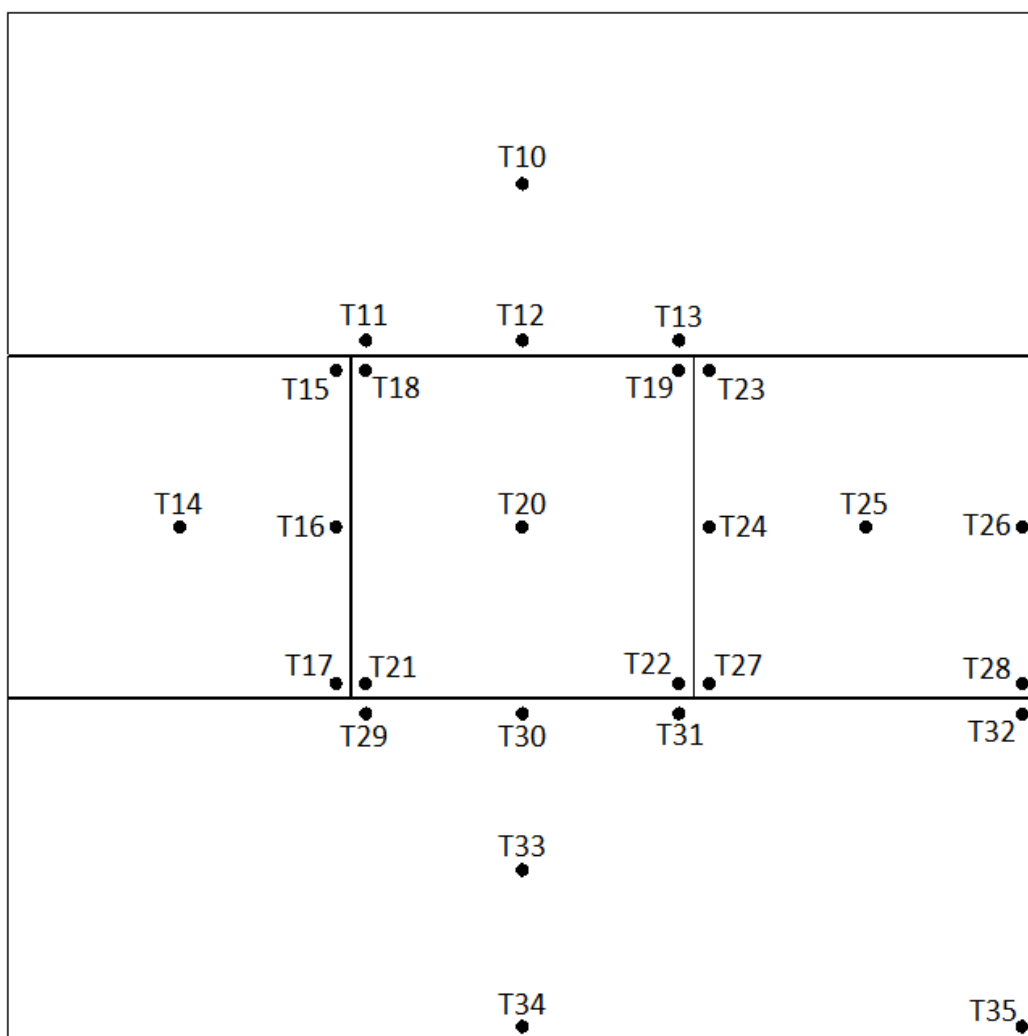


Figure 43 – Thermistor layout on the meter plate and left, right, top, and bottom guards.

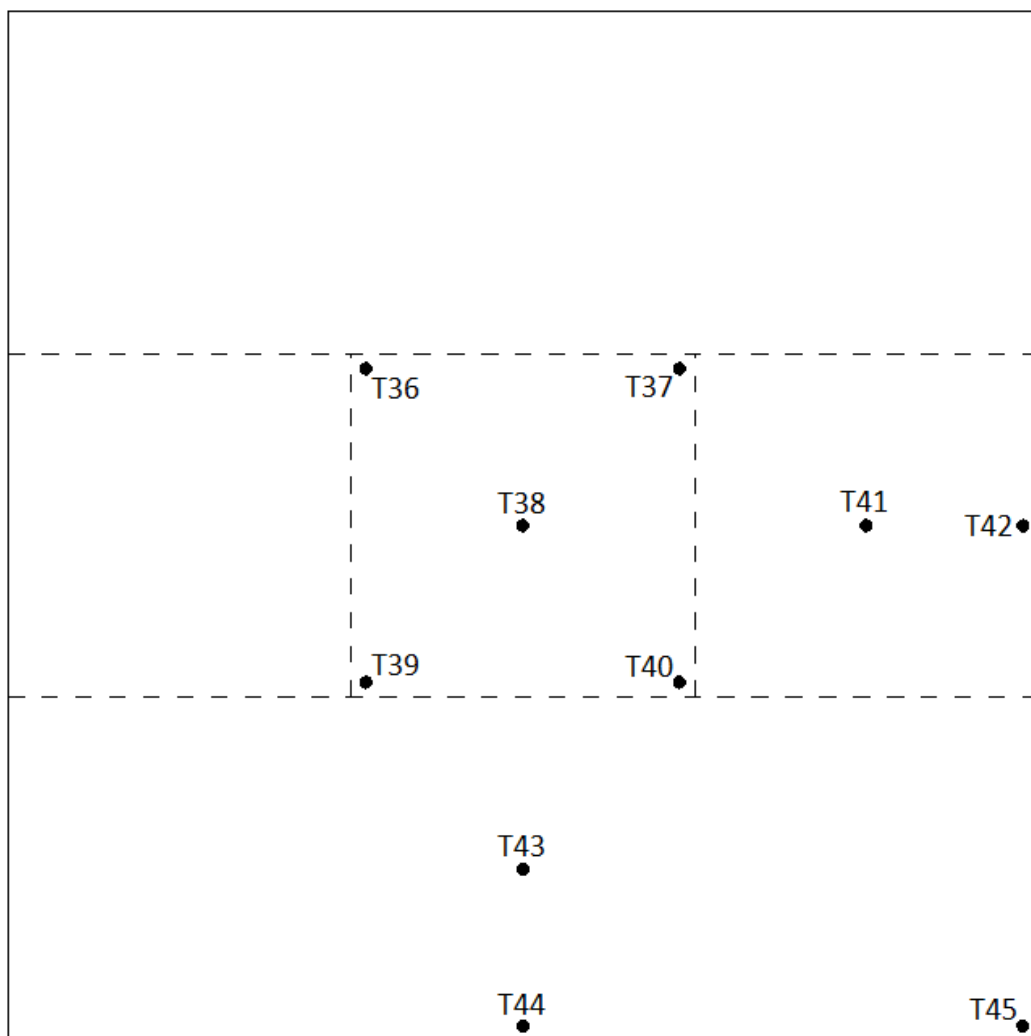


Figure 44 – Thermistor layout on the cold plate.

The average of thermistors T18 to T22 on the meter plate and the average of thermistors T36 to T40 on the cold plate were defined as the hot side and cold side temperatures, respectively, for use in the thermal conductivity calculation (Equation 4). Using multiple thermistors to represent each plate temperature increases the accuracy to which the temperature is known as the $\pm 0.2^\circ\text{C}$ uncertainty is reduced. The uncertainty of a mean is given by (Department of Physics & Astronomy, University of Pennsylvania, 2016)

$$\Delta x_{avg} = \frac{\sigma}{\sqrt{n}} \quad (14)$$

where Δx_{avg} is the uncertainty in the mean value of x ; σ is the uncertainty in x ; and n is the number of samples included in the average.

Using this equation, the accuracy to which the temperature of the cold and hot plates are known is $\pm 0.09^\circ\text{C}$. From Equation 8, this is equivalent to an error in thermal conductivity measurement of $\pm 0.28\%$.

Thermistors were fixed to the specimen side of the plates using a piece of foil tape over the sensor area and masking tape on the wire leads. Due to the number of thermistors used in the hot plate assembly, the thermistor leads had to be taped together into a “ribbon” so as not to form large bumps around the edge insulation. This also served to organize the large number of leads coming out of the hot plate assembly and apparatus frame. Figure 45 shows the thermistor leads taped together to form an orderly “ribbon” along the edge of the hot plate assembly.

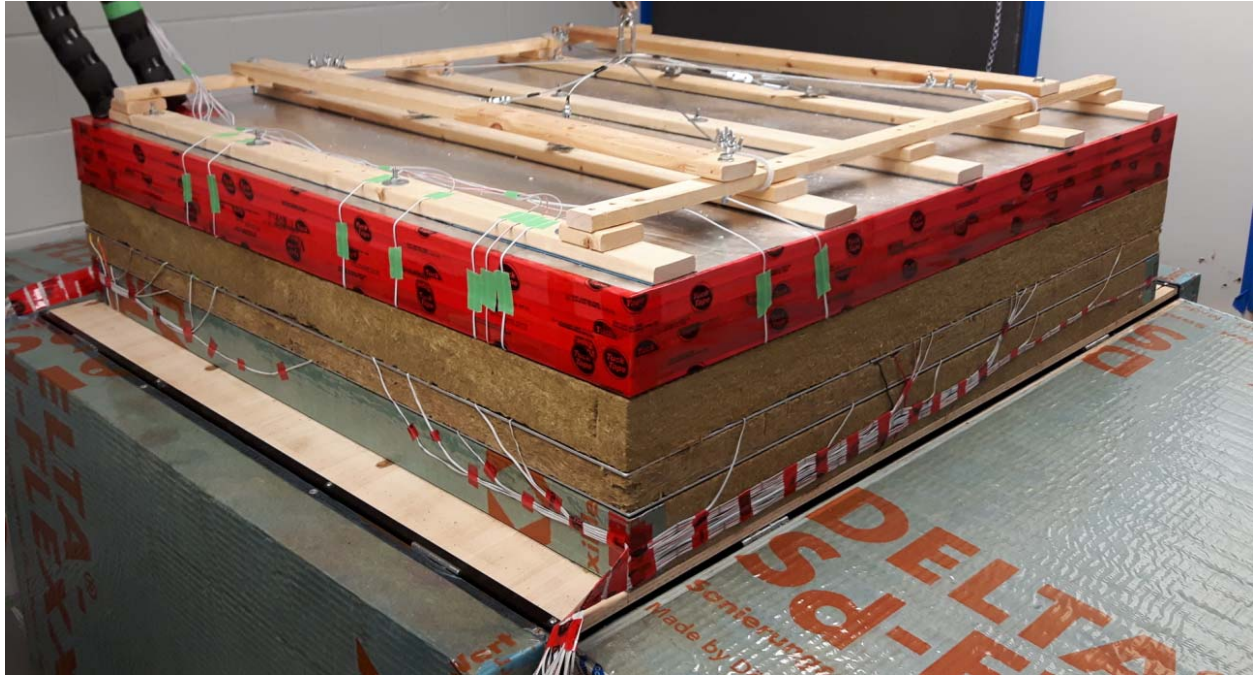


Figure 45 – Thermistor leads from the hot plate assembly.

Also shown in Figure 45 are the cold plate thermistor leads which were taped up along the side and top of the cold plate.

A Campbell Scientific CR-10X measurement and control datalogger (see Appendix G for specifications) in combination with a multiplexer was used to record the resistances of all of the thermistors once every 20 seconds. The resistances were converted to temperatures using Equation 13 to provide temperature data every 20 seconds. The CR-10X was also used to control the temperature of the hot plates.

3.6.2 Guard Balancing

To prevent unplanned heat flow from the meter plate in a one-sided guarded hot plate, the guard plates in the hot plate assembly must all be controlled to the same temperature as the meter plate. A Proportional Integral Derivative (PID) control logic program was written for the CR-10X datalogger to accomplish this in the guarded hot plate constructed. The code for the program is provided in Appendix H. The plate temperatures are controlled by turning on solid state relays for a specified length of time in a 20 second cycle (i.e. Pulse Width Modulation is used with a 20

second cycle and varying pulse widths). These relays are connected in series with the power supplies for the plates providing power and correspondingly heat to the plates when the relays are on. When the relays are off, no power or heat is supplied to the plates. Figure 46 shows the control board consisting of the relays, CR-10X, and two of the power supplies. Also shown in the figure are the three bench top power supplies not attached to the control board.

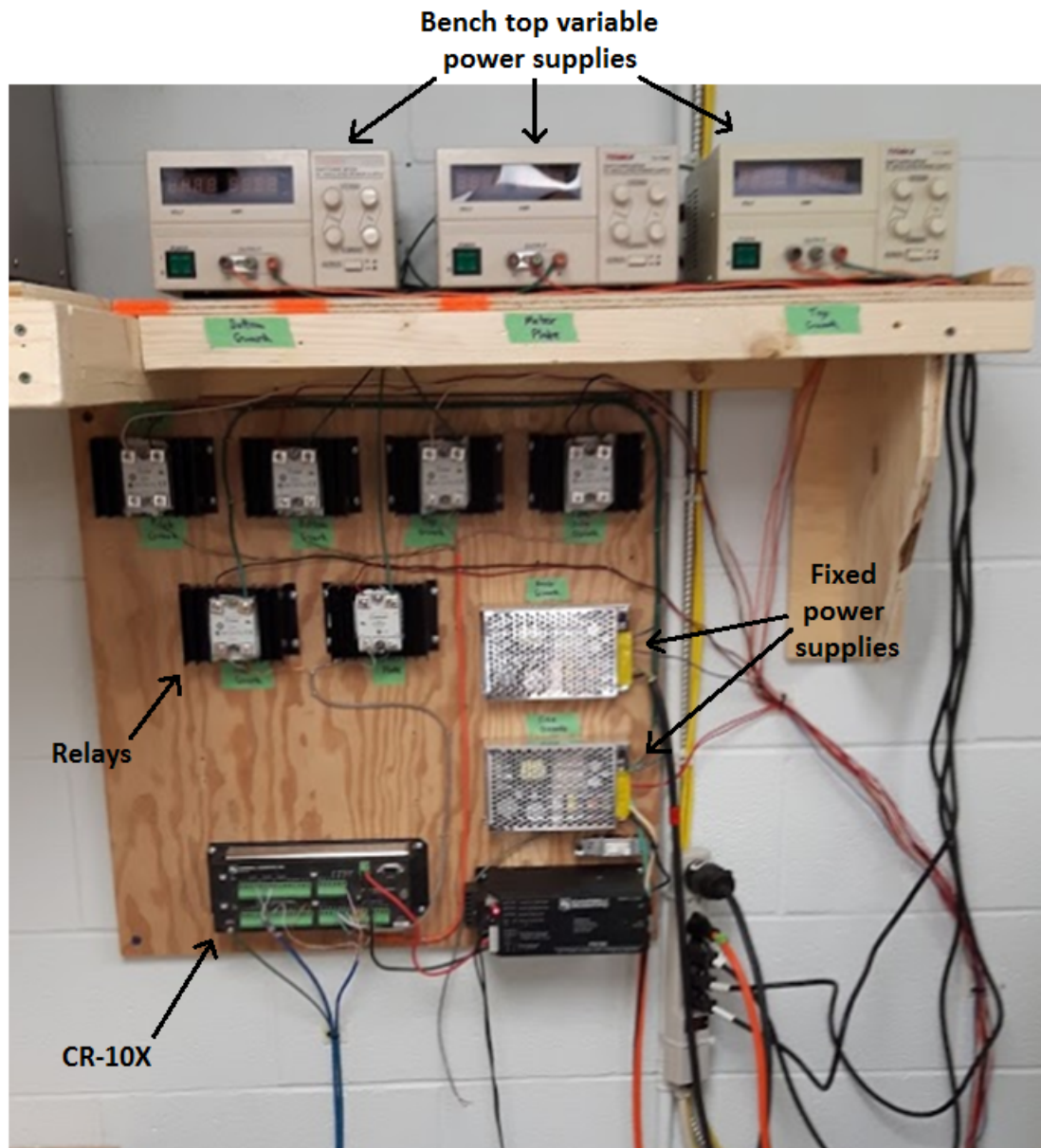
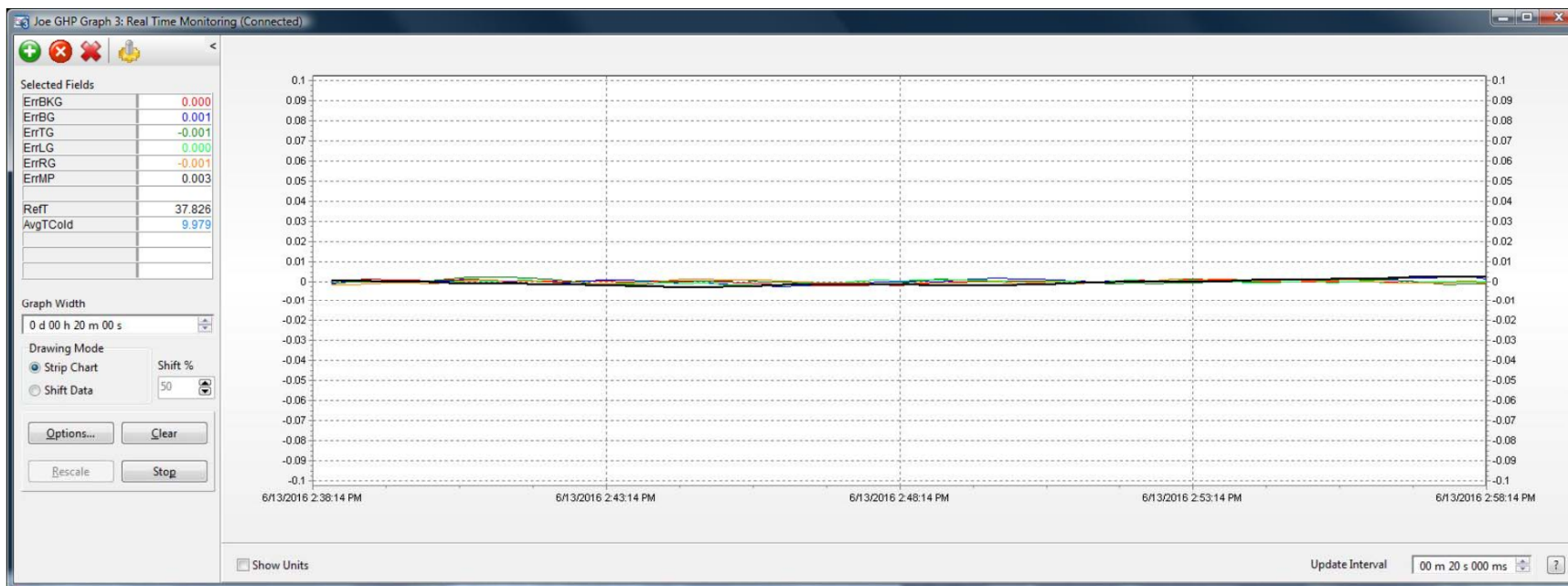


Figure 46 – Control panel and power supplies.

For every 20 second cycle, temperatures are measured and control demands are calculated for each plate. Approximately the first 6 seconds of the 20 second cycle is used for temperature measurement and control calculations. During this period, all relays are closed and no power is delivered to any of the plates. The remaining 14 seconds are used to execute control demands represented as “on” times for each of the relays. These “on” times are calculated using PID controller theory to ensure overshoots and undershoots are minimal. During preliminary testing, the PID coefficients were tuned to ensure steady state conditions are as stable as possible. The power supplies were operated at a constant voltage since good control was achieved just by varying the “on” time of the relays. All of the plates were operated at a voltage of 40V except for the back guard which was operated at 60V. The back guard was operated at 60V because it was relatively slow to warm up due to its size. Figure 47 is a screenshot of the Campbell Scientific software displaying the hot plates balanced at steady state.



Legend: ErrBKG = back guard temp. – meter plate temp., ErrBG = bottom guard temp. – meter plate temp., ErrTG = top guard temp. – meter plate temp., ErrLG = left guard temp. – meter plate temp., ErrRG = right guard temp. – meter plate temp., ErrMP = meter plate temp. – setpoint temperature, RefT = meter plate temp., AvgTCold = cold plate temp. in meter area

Figure 47 – Campbell Scientific software screenshot of the hot plates balanced at steady state.

In Figure 47, the variables plotted are the errors from the temperatures of the guards as compared to the meter plate and the meter plate as compared to the setpoint temperature for a hot plate temperature of 37.82°C and a cold plate temperature of 9.98°C. The figure shows that very tight control of the hot plate temperatures is accomplished for steady state at these testing temperatures. For lower hot plate temperature setpoints, the variability is even less, whereas for higher hot plate temperature setpoints, the variability with time was found to increase (but remains less than $\pm 0.01^\circ\text{C}$). Given the results of the gap error heat flow analysis presented in Table 1, an unbalance of 0.01°C results in a very small error heat loss.

The meter plate was programmed so that the average of thermistors T18 to T22 would attempt to reach the setpoint temperature for the hot side. The back guard was programmed so that the average of the thermistors T36 to T40 would attempt to reach the meter plate average of thermistors T18 to T22. The top, bottom, left, and right guards were programmed so that the averages of the thermistors on either side of the guard gap around the meter plate were balanced to ensure minimal heat flow across the gap. For example, this meant that the average of thermistors T11 to T13 on the top guard was balanced to follow the average of thermistors T18 and T19 at the top of the meter plate.

3.6.3 Meter Plate Power Measurement

The meter plate power is measured by measuring the current flow through and the voltage drop across the heater wire on the meter plate and multiplying these two values together to calculate the power. However, the current and voltage can be more accurately measured through measuring reference resistors placed in series and in parallel with the heater wire. These resistors and heater wire are arranged in a circuit shown in Figure 48.

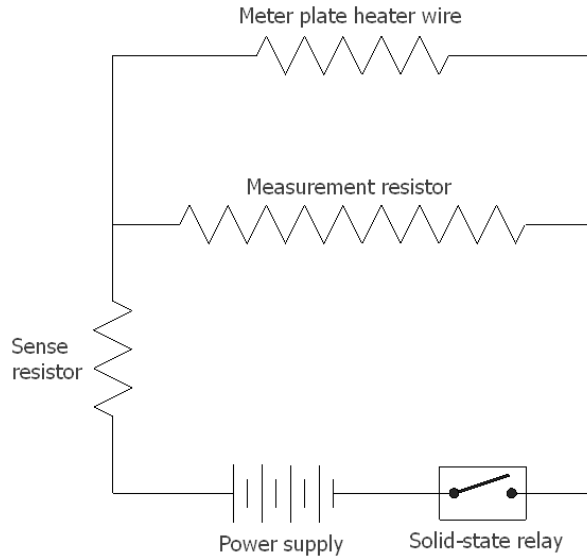


Figure 48 – Meter plate measurement circuit.

The measurement resistor shown in Figure 48 is placed in parallel with the heater wire so that it will have the same voltage drop as the heater wire. This resistor is chosen to have a very high resistance relative to the heater wire so that a negligible amount of current will flow through it. The sense resistor is used to measure the current through the heater wire and is chosen to have a low resistance so the voltage drop across it is negligible. Through the use of precision resistors for both the measurement and sense resistors, the resistance of each resistor is known with very good accuracy. This allows the meter plate power to be measured with a high degree of accuracy.

Twenty $10\text{ k}\Omega$ 0.1% precision resistors connected in series ($200\text{ k}\Omega$ total) were used as the measurement resistor and five $1\ \Omega$ 0.1% precision resistors connected in parallel ($0.2\text{ k}\Omega$ total) were used as the sense resistor. A photo of these resistors is shown in Figure 49. In this figure, the measurement resistors are brown and shown along the top of the figure. The sense resistors are white and shown in the centre of the figure.

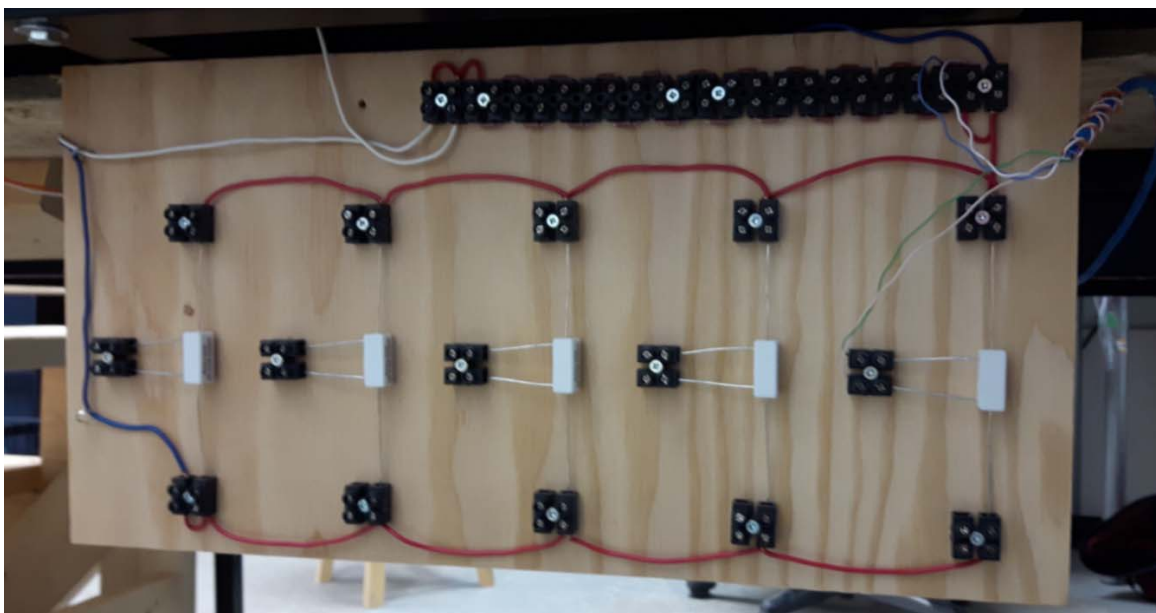


Figure 49 – Resistors used in the meter plate power measurement circuit.

Standard 18-gauge copper wire connected all of the components in the circuit and contributed negligible resistance to the circuit for the currents involved. With this circuit and the voltage sensing capabilities at different ranges of the CR-10X, Figure 50 was constructed showing the uncertainty in measured meter plate power at different power levels.

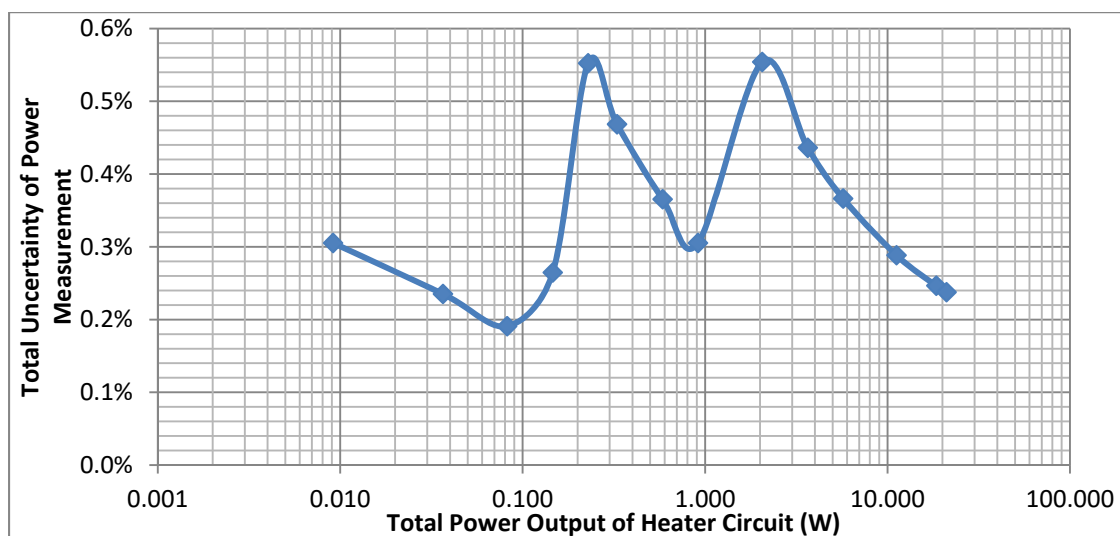


Figure 50 – Total uncertainty in meter plate power measurement versus total power output.

The Microsoft Excel spreadsheet used to construct Figure 50 is provided in Appendix I. The error in thermal conductivity measurement is directly proportional to the total uncertainty in power measurement.

3.6.4 Area Measurement

At first glance, it would be logical to use the meter plate dimensions as the meter area but research has shown that more accurate possibilities exist. ASTM C177 recommends using the meter area measured to the middle of the guard gap but this may not be appropriate for all specimens. Research suggests that the meter area for thin, less thermally resistive specimens approaches the meter plate dimensions whereas the meter area for thick, more thermally resistive specimens approaches the mid gap area (Dubois & Lebeau, 2013). The uncertainty in the meter area is due to the fact that the gap does not provide heat in the same way as the plates and that the temperature imbalance along the gap is not uniform for a square apparatus (De Ponte, 1985). Figure 51 was created in THERM 7.3 to show the heat flux vectors in the gap under perfectly balanced conditions.

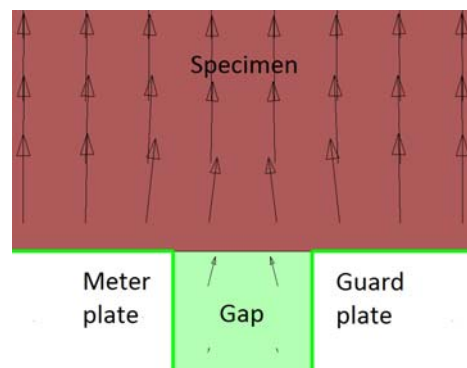


Figure 51 – Heat flux vectors at the gap under balanced conditions.

As Figure 51 shows, even under perfectly balanced conditions a distortion in the heat flow will occur which agrees with research (Pham & Smith, 1986). Heat from the meter plate and guard plate must flow into the part of the specimen above the gap and this is why it cannot be assumed that the meter plate itself defines the meter area.

Fortunately, the meter area error is always positive causing an overestimation in thermal conductivity (Donaldson, 1962) and has upper and lower bounds giving a maximum error which is quite small due to the small size of the gap (De Ponte, 1985). For simplicity and since most specimens tested were thick, low thermal conductivity materials, a meter area measured to the middle of the gap was used. The meter area was measured using a ruler with an estimated accuracy of $\pm 0.5\text{mm}$. This accuracy combined with the meter area uncertainty gives a maximum possible error in thermal conductivity measurement of 0.45%, calculated using Equation (9, with a more probable error of $\pm 0.17\%$ for most specimens.

3.6.5 Thickness Measurement

Measurement of the specimen thickness was made using a ruler along the specimen's edge with an estimated accuracy of $\pm 0.5\text{mm}$. The plates are assumed to be relatively flat and hence contribute little uncertainty in the thickness measurement. As the thickness of the specimen increases, the error associated with the thickness measurement decreases. To quantify the effect, Table 9 and Figure 52 were constructed using Equation 8 assuming zero uncertainty in the other variables and a thickness measurement accuracy of $\pm 0.5\text{mm}$.

Table 9 – Measurement error in thermal conductivity for different specimen thicknesses.

L (in)	L (mm)	% Error in k
0	0	0.000%
1	25.4	1.969%
2	50.8	0.984%
3	76.2	0.656%
4	101.6	0.492%
6	152.4	0.328%
8	203.2	0.246%
10	254	0.197%
12	304.8	0.164%
14	355.6	0.141%
16	406.4	0.123%
18	457.2	0.109%
20	508	0.098%

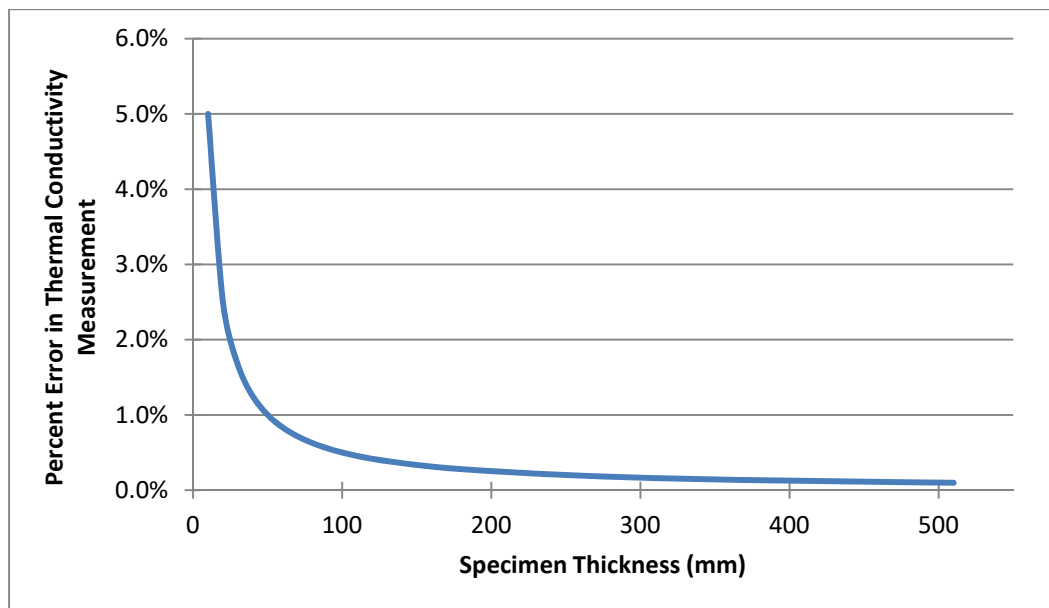


Figure 52 - Measurement error in thermal conductivity versus specimen thickness.

3.6.6 Cold Plate Operation

The cold plate temperature was adjusted by manually adjusting the chiller bath temperature from which a constant temperature fluid was pumped through the cold plate. The chiller bath temperature required to achieve a certain plate temperature was guessed and then the system was left to equilibrate. This meant that obtaining a specific cold temperature was difficult but stability at the resulting temperature was excellent. Through preliminary testing, it was found that the chiller bath temperature had to be set to between 0°C and 2°C lower than the desired cold plate setpoint temperature for cold plate temperature below ambient. This was not seen as a serious issue. The bath can also be equipped with an optional external temperature probe to control the temperature more precisely, if desired.

3.6.7 Testing Times

It was observed that the hot plate assembly required about two hours to get to a maximum temperature of 60°C and the cold plate assembly required about four hours to get to a temperature of -15°C. The hot and cold plate temperatures reached a steady state condition fairly quickly so equilibrium was considered to be reached when the power settled at a value with no noticeable trends upwards or downwards. Time to equilibrium was dependent on the specimen being tested but ranged between 10 and 72 hours. Thick, low thermal conductivity specimens with high thermal mass required the longest to bring to equilibrium.

3.6.8 Temperature Uniformity

Even though the aluminum T6061 plates have a very high thermal conductivity, it was anticipated that some temperature gradients would occur in the hot and cold plates. The thickness of the plates was designed to be thick enough so that temperature gradients between the heating wires on the hot plates and the copper tubes on the cold plate would be negligible. It was also hoped that this thickness would be sufficient to ensure minimal deviations in plate temperatures at the edges of the specimen. From the preliminary tests, the temperature uniformity was evaluated by observing the values of the 45 thermistors attached to the hot and cold plates. The temperature deviation from the middle across the plates would be the worst when they are the

furthest from ambient as at these temperatures there is a larger heat loss/gain to the environment. Therefore, for the hot plate, the most deviation would occur at the highest testing temperatures and for the cold plate, the most deviation would be at the lowest testing temperatures. Figure 53 shows the temperature distribution of the hot plates at the meter plate level for a high testing temperature. Values shown in the figure are average surface temperatures in degrees Celsius at steady state.

56.98						
57.24		57.25	57.01			
57.26	57.24		57.10		57.03	
57.25	57.23	57.26		57.21	56.97	56.71
57.26	57.26	57.24		57.26	56.48	
57.22		57.27	57.26			56.64
57.22						
56.71		56.17				

Figure 53 – Temperature distribution of the meter plate and left, right, top, and bottom guards.

From comparing the temperatures on the meter plate in Figure 53, it is obvious that there is some inherent variation in the data. This was anticipated as the thermistors have a claimed accuracy of $\pm 0.2^{\circ}\text{C}$ from the manufacturer. In addition, some of this variation could occur due to the presence of a contact resistance between the thermistor and the plate which might differ for each thermistor causing a positive or negative bias. The thermistors in the centre of each plate in Figure 53 are located halfway in between the heating wires and all other thermistors are located on the heating wire which is taped to the other side of the plates. When comparing the centre of plate thermistors with the other thermistors, it is very unlikely that there are temperature gradients between the heating wires. If a variation does exist, it would be very small and undetectable due to the variation between thermistors. The variation in the back guard was similar to the variations observed at the meter plate level shown in Figure 53 but is considered less critical as it is not directly influencing the specimen.

It is also apparent in Figure 53 that the temperatures drop closer to the edge of the specimen with the worst temperature drop in the corners. At these high temperatures, the temperature drops by approximately 0.5°C at the edges and 1.0°C at the corners. These deviations are specimen dependent and decrease for lower conductivity specimens. Even though these temperature drops are considerable, it is assumed to not have a large error on the measurement since the temperatures within the meter area do not drop. However, the error produced from this deviation in guard temperature should be checked as the guarding capabilities may be compromised. Models were therefore created in THERM 7.3 and an example of one of these models is shown in Figure 54.

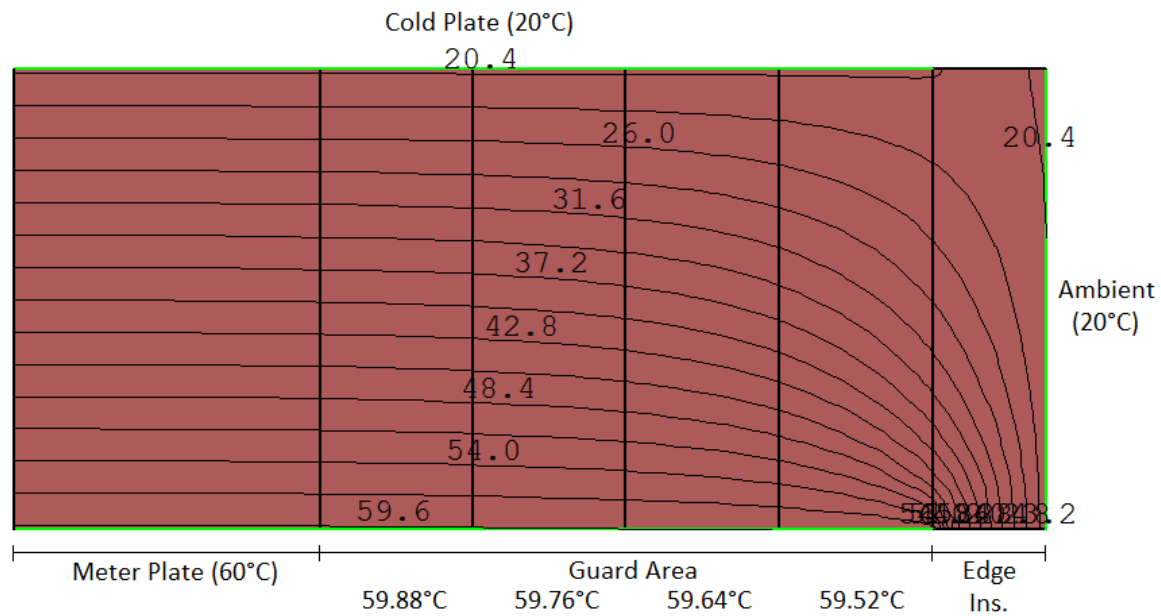


Figure 54 – THERM model used to determine the effect of non-isothermal guards.

In these models, the cold plate was held uniformly at 20°C, the ambient temperature was 20°C, and the edge insulation was 3” (76mm) of low-density mineral fiber insulation with adiabatic conditions at the top and bottom of the edge insulation similar to the models in Section 3.4.1.2.1 “Models with Adiabatic Conditions at the Top and Bottom of the Edge Insulation”. The specimens were also modelled as low-density mineral fiber insulation. The meter plate was set to be 60°C and the guard area was divided into four sections of decreasing temperature from the meter plate as shown in Figure 54. The boundary condition on the left side of the model is adiabatic similar to the previous models presented. The results of the models are shown in Table 10.

Table 10 – Results from THERM models with isothermal and non-isothermal guards.

Model Type	Specimen Thickness	U (W/m ² ·K)	k (W/m·K)	% Error in k	Increase in Error
Isothermal	4" (102mm)	0.4130	0.04196	0.09%	-
	8" (203mm)	0.2065	0.04196	0.09%	-
	12" (305mm)	0.1368	0.04170	0.72%	-
	16" (406mm)	0.1002	0.04072	3.04%	-
Non-isothermal	4" (102mm)	0.4129	0.04195	0.12%	0.02%
	8" (203mm)	0.2063	0.04192	0.19%	0.10%
	12" (305mm)	0.1366	0.04164	0.87%	0.15%
	16" (406mm)	0.1000	0.04064	3.24%	0.19%

From Table 10, it is observed that guards that deviate in temperature from the meter plate due to edge heat losses do not contribute a large error in the thermal conductivity measurement. Thus, the deviation in plate temperatures towards the edges of the apparatus is deemed to be acceptable.

Figure 55 shows the temperature distribution of the cold plate at a very cold testing temperature which represents the worst case scenario for edge heat gains. Again, values shown in the figure are average surface temperatures in degrees Celsius at steady state.

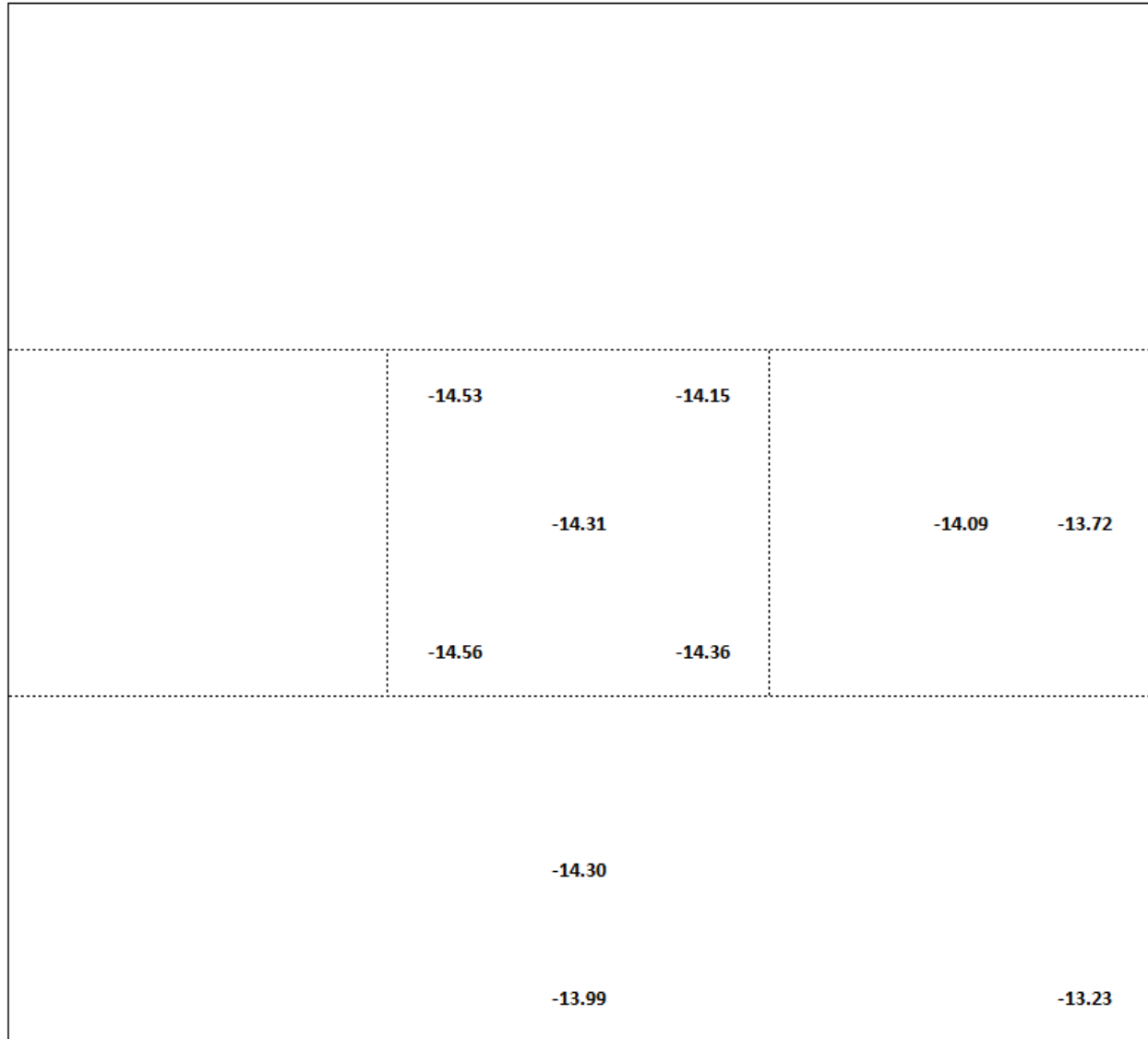


Figure 55 – Temperature distribution of the cold plate.

Figure 55 shows a similar deviation in temperature from the centre when compared to the hot plate temperatures in Figure 53. The temperature deviation between the cooling tubes is difficult to determine but appears to not be an issue. For example, the temperature at the centre of the meter area is in the middle between two cooling tubes whereas the other temperatures in the meter area are very close to the cooling tubes, yet there appears to be no noticeable difference. A larger concern was the temperature difference across the entire plate from left side to right side. As a result of the pattern of the copper piping network that cools the cold plate, chilled fluid flows in one direction from the left side to the right side. It would be expected that there would

be a temperature drop in the incoming and outgoing fluid corresponding to a change in the plate surface temperatures from left to right side. This appears to be the case in Figure 55 but it is difficult to know for sure because of the $\pm 0.2^{\circ}\text{C}$ variation in accuracy of the thermistors. It should be noted that this is a worst case scenario and variations on the cold plate are far less dramatic at higher temperatures (10°C and above).

4.0 Validation of Apparatus

It is important not only that the apparatus functions as intended but that the results are credible. The credibility of the guarded hot plate must therefore be tested against another device known to be credible. As such, an experimental testing program was set up to test and compare multiple specimens in the guarded hot plate and in a heat flow meter calibrated using NIST traceable reference samples.

4.1 Overview of Validation Testing

A 3" (76mm), 6" (152mm), and 9" (229mm) thick specimen comprised of layers of 3" (76mm) thick nominal 64 kg/m³ stonewool (Roxul Toprock DD) were tested at different temperature conditions and then compared in both the guarded hot plate and heat flow meter. The 6" (152mm) and 9" (229mm) specimens were created by stacking two and three layers, respectively, on top of one another. All of the specimens were created from the same three pieces of the stonewool insulation measuring 4' (1219mm) square and with the denser side facing the cold plate. As these specimens are too large to test in the heat flow meter apparatus, 12" by 12" (305mm by 305mm) sections were cut from the center of each piece and tested individually in the heat flow meter as per ASTM C518. One of these stonewool layers with the center cut out is shown in Figure 56.



Figure 56 – Test specimen piece with center cut out.

Each piece was cut with a slight angle along its edge to allow the center cut out to be removed and re-installed easily. Photos from the validation testing can be found in Appendix J.

4.2 Heat Flow Meter Testing

A heat flow meter calibrated to better than 1% against a NIST calibration sample was used to measure the thermal conductivity of the 12” by 12” (305mm by 305mm) centre sections of each insulation layer used to make the test specimens. The results are presented in Table 11.

Table 11 – Results from the heat flow meter testing.

Insulation Sample No.	Hot Plate Temperature (°C)	Cold Plate Temperature (°C)	Mean Temperature (°C)	Measured k (W/mK)
1	10.01	-17.78	-3.885	0.03601
	18.32	-9.38	4.47	0.03707
	37.82	10.01	23.915	0.03903
	29.42	57.22	43.32	0.04125
2	10.01	-17.78	-3.885	0.03618
	18.32	-9.38	4.47	0.03742
	37.82	10.01	23.915	0.03963
	57.22	29.42	43.32	0.04147
3	10.01	-17.79	-3.89	0.03605
	18.32	-9.37	4.475	0.03719
	37.82	10.01	23.915	0.03934
	57.23	29.42	43.325	0.04128

Testing temperatures were selected as per ASTM C1058 “Standard Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation”. Linear regression can be applied to the data in Table 11 to find the best-fitting straight line giving a correlation between mean temperature and measured thermal conductivity. The equation of each regression line is shown in Table 12.

Table 12 – Regression equations for the insulation samples.

Insulation Sample No.	Regression Line Equation	Coefficient of Determination (R^2)
1	$k = 0.0001 \cdot T_m + 0.0365$	0.9989
2	$k = 0.0001 \cdot T_m + 0.0368$	0.9939
3	$k = 0.0001 \cdot T_m + 0.0366$	0.9973

Where
 k is the predicted thermal conductivity of the insulation sample
 T_m is the mean temperature of the insulation sample

Using the equations presented in Table 12, a thermal conductivity can be predicted for each of the specimens tested in the guarded hot plate if the temperature between each layer in the specimens is known. For this reason, a thermistor was placed in the centre of each specimen in-between each layer. Once the conductivity of each layer was known, the RSI of each layer was calculated and added together to represent an RSI for the entire specimen. This RSI was then converted to a predicted thermal conductivity for the entire specimen to be compared with the thermal conductivity measured by the guarded hot plate.

4.3 Guarded Hot Plate Testing

Table 13 outlines the tests performed in the guarded hot plate to validate the apparatus.

Table 13 – Tests performed to validate the apparatus.

Test No.	Specimen Thickness	Cold Plate Temperature (°C)	Hot Plate Temperature (°C)
1A	3" (76mm)	-14.38	23.32
1B	3" (76mm)	10.01	37.82
1C	3" (76mm)	57.22	29.42
2A	6" (152mm)	10.01	37.82
2B	6" (152mm)	57.22	29.42
3A	9" (229mm)	10.01	37.82
3B	9" (229mm)	57.22	29.42

The 3" (76mm) specimen was created using sample 1, the 6" (152mm) specimen was created using samples 1 and 2, and the 9" (229mm) specimen was created using samples 1, 2, and 3. The test temperatures selected closely matched the heat flow meter test temperatures to ensure consistency in the validation process. Test 1A is intended to mimic the heat flow meter test of -9°/18°C but control of the hot plate below room temperature (~23°C) is not possible since it is only electrically heated. Therefore, for this test, 5°C was added to the hot plate temperature and 5°C was subtracted from the cold plate temperature to yield the same mean temperature as the heat flow meter test.

Table 14 shows the testing results on the 3” (76mm) specimen with comparison to the heat flow meter results.

Table 14 – Guarded hot plate testing results for the 3” (76mm) specimen.

Test No.	Cold Plate Temp. (°C)	Hot Plate Temp. (°C)	Meter Plate Power (W)	Predicted k from HFM (W/mK)	Measured k (W/mK)	Difference	% Difference from Predicted
1A	-14.382	23.320	3.0071	0.03695	0.03658	-0.00036	-0.98%
1B	10.021	37.820	2.3549	0.03889	0.03886	-0.00004	-0.09%
1C	29.430	57.220	2.4615	0.04083	0.04063	-0.00021	-0.50%

Table 15 shows the testing results on the 6” (152mm) specimen with comparison to the heat flow meter results.

Table 15 – Guarded hot plate testing results for the 6” (152mm) specimen.

Test No.	Cold Plate Temp. (°C)	Hot Plate Temp. (°C)	Meter Plate Power (W)	Predicted k from HFM (W/mK)	Measured k (W/mK)	Difference	% Difference from Predicted
2A	9.980	37.820	1.1994	0.03904	0.03978	0.00074	1.89%
2B	29.431	57.220	1.2648	0.04099	0.04202	0.00103	2.52%

Table 16 shows the testing results on the 9” (229mm) specimen with comparison to the heat flow meter results.

Table 16 – Guarded hot plate testing results for the 9” (229mm) specimen.

Test No.	Cold Plate Temp. (°C)	Hot Plate Temp. (°C)	Meter Plate Power (W)	Predicted k from HFM (W/mK)	Measured k (W/mK)	Difference	% Difference from Predicted
3A	9.937	37.820	0.80717	0.03903	0.03971	0.00068	1.75%
3B	29.444	57.220	0.85765	0.04097	0.04236	0.00139	3.39%

4.4 Discussion

From the results in Table 14, Table 15, and Table 16, it can be concluded that good agreement is observed between the guarded hot plate and the heat flow meter calibrated using a NIST reference sample. It is difficult to know how accurate the guarded hot plate was as the heat flow meter is calibrated to measure within a 1-2% accuracy of the absolute thermal conductivity. Thus, perfect agreement with the heat flow meter is promising but the guarded hot plate may still have an error of 1-2% from the true value.

As previously discussed, errors in measured thermal conductivity vary based on a number of factors. For these tests, the meter area measurement, temperature measurement, and unbalance errors are all small and approximately constant. The error in thermal conductivity measurement caused by the meter area measurement is about $\pm 0.17\%$, the error caused by temperature measurement is about $\pm 0.28\%$, and the error attributed to the heat flow loss/gain due to unbalance is between ± 0.01 and $\pm 0.1\%$. Other errors that affect accuracy are meter plate power measurement errors, contact resistance errors, edge heat loss errors and errors due to uncertainty in the thickness measurement. The error caused by meter plate power measurement is between $\pm 0.3\%$ and $\pm 0.5\%$ and contact resistance errors are assumed to be negligible due to the high thermally resistive specimens tested. According to the analyses presented earlier, the error associated with edge losses should be small for all of the specimens with a maximum error for the 9" (229mm) specimen of about $\pm 0.1\%$. The error in thermal conductivity measurement caused by the uncertainty in thickness measurement ranges from 0.66% for the 3" (76mm) specimen to 0.22% for the 9" (229mm) specimen. Thus, if excellent agreement is shown with the heat flow meter, the guarded hot plate could have been measuring very close to the true thermal conductivity of the specimen as these errors sum up to about $\pm 1.5\%$ which is around the accuracy of the heat flow meter.

However, the thickness measurement was found to be the most influential as the measurement of this variable was the most ambiguous. For example, a 1mm change in the thickness used for test 1B could change the agreement from 0.09% to 1.23%. Thickness measurement was ambiguous for several reasons:

- Thickness measurements were only taken along the edge of the specimen while the cold plate was installed. Ideally, measurements would be taken in the meter area but this was not practical in this situation.
- The plate surfaces were not perfectly flat and plate edges (where the measurements were taken) were slightly bent as a result of being sheared instead of cut.
- The specimens were not a uniform thickness throughout and did not compress uniformly.
- Thermistors were mounted on the surface of the plates that contacted the specimens. This caused bumps and it was unsure how much the thermistors compressed into the specimen.
- The top, bottom, and side guards did not sit perfectly flush with the meter plate. It was unclear how flush the plates would be as a result of the thermistors possibly pushing unevenly on the plates when compressed during testing.

The strategy that was settled upon as being most appropriate for the specimens tested was to measure along the edge of the specimen from between the hot plate and cold plate at multiple locations in the middle 16" (406mm) of each side length. These measurements were averaged and then the thickness of a thermistor was subtracted to yield the final thickness to be used in the thermal conductivity measurement. The thickness of a thermistor was subtracted because it was assumed that half the thickness of each thermistor compressed into the specimen on both sides.

When comparing the results from each specimen, it is observed that the error appears to be greater for the thicker specimens and for mean temperatures that deviate far from ambient. It is thought that the error increased due to thickness as the accuracy uncertainty associated with the heat flow meter is compounded as more layers of insulation are added to produce each specimen. Errors should increase as the mean temperature deviates further from ambient but as mentioned previously, these errors should be very small and would not explain the large decrease in agreement shown in the 6" (152mm) and 9" (229mm) specimens when tested at 29°C/57°C as compared to the 10°C/38°C tests.

5.0 Thermal Bridge Testing

Guarded hot plates are not typically designed to test specimens that are non-homogenous such as specimens containing thermal bridges. Non-homogenous specimens mean non-uniform heat flow which is traditionally avoided in guarded hot plate apparatuses. Non-uniform heat flow means that specimen temperatures at the surface of the plates are not uniform causing the task of accurate temperature measurement to be difficult (Larson, 1985). Ideally, thermistors would be placed at the locations of average hot or cold side temperature but this is very difficult to implement due to the complexity of three-dimensional thermal bridges. It also means that a unique thermistor layout would be required for each specimen containing a thermal bridge. To create isothermal conditions at the surface of the plates, layers of insulation could be added to both sides of the specimens to smooth out temperature non-uniformities due to thermal bridges. These pieces of insulation could be tested separately and their resistance subtracted from the total result to yield the thermal conductivity of the part of the specimen with the thermal bridge. This procedure, however, would be less representative of a thermal bridge in-situ. Non-uniform heat flow also means that edge loss/gain errors may be increased as heat leaves/enters the meter area via the higher thermal conductivity material within the specimen. For example, if a 48" (1219mm) long steel member was added to a specimen, heat could enter/leave the meter area through the steel member causing more edge heat loss/gain errors. This increased error can be controlled by making the thermal bridge layers smaller than the overall specimen size with an insulation guard bordering the thermal bridge to make up the total specimen size. One researcher suggests that the thermal bridge specimen should be created to be the size of the meter area with the guard sections composed solely of insulation of equivalent thickness (Salmon, 2001). This approach indeed reduces edge losses but does not provide a useful measurement of a thermal bridge since the heat flow at the boundaries of the meter area are not consistent with the heat flow in the middle of the meter area. A better solution would be to extend the thermal bridges outside of the meter area to ensure as uniform heat flow conditions as possible within the meter area but not too far such that edge loss errors become a concern.

Keeping the above considerations in mind, two thermal bridges were tested to demonstrate the ability of the constructed guarded hot plate to measure specimens with thermal bridges. The specimens replicate a wall section with gypsum board on the interior, plywood on the exterior,

and insulation in the stud cavity. Three specimens were tested: an assembly with a wood stud, an assembly with a steel Z-girt, and an assembly without any thermal bridge penetrating the main insulating layer. Photos of these specimens can be found in Appendix K. Figure 57 shows the wood stud specimen in cross-section.

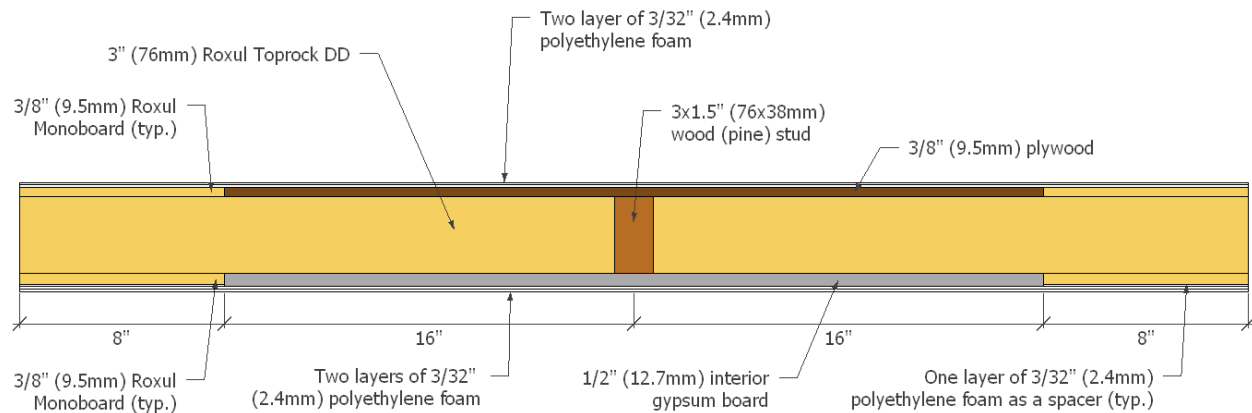


Figure 57 – Cross-section of the thermal bridge specimen with a wood stud.

The gypsum board and plywood measured 32" (813mm) square and the wood stud was 32" (813mm) long. This created a 32" (813mm) square specimen surrounded with 8" (406mm) of guard insulation. The wood stud was cut down to 3"x1.5" (76mm x 38mm) so that it could be placed within the first insulation sample from the validation testing. The layers of polyethylene foam on the top and bottom of the specimen were meant to act as surface films of equivalent resistance. Two layers of the 3/32" (2.4mm) polyethylene foam have an equivalent R-value of 0.58 hr·ft²·°F/Btu (RSI of 0.1 m²K/W) (Roberts Consolidated Industries Inc., 2016) which is close to air film resistances encountered in practice (Straube & Burnett, 2005). These foam layers were added to more accurately represent real-world conditions but they also greatly help to increase the temperature uniformity of the plates near the stud. It was thought that even this small amount of foam would be sufficient to create acceptably uniform temperature conditions at the plate surfaces.

The steel Z-girt specimen was identical to the wood stud specimen but incorporated a 20-gauge Z-girt (3" (76mm) web and 1.5" (38mm) flanges) in place of the wood stud. A steel Z-girt was used instead of a steel stud because it is easier to implement without air voids. The pieces of the

insulation removed due to installation of the wood stud were re-installed with the Z-girt so there were minimal air voids.

The materials used in the both of the aforementioned tests were measured as a separate test without the wood stud or steel Z-girt penetrating the main insulation layer. Pieces of the insulation removed due to the thermal bridges were re-installed to form a uniform insulation layer.

Due to the concern of edge heat losses/gains from the thermal bridge, plywood, and gypsum board outside of the meter area, testing temperatures were selected such that the mean temperature of the specimen was close to ambient. Thus, a hot plate temperature of 37.82°C and a cold plate temperature of 10.01°C were selected for testing of all three specimens as per ASTM C1058.

For comparison of the measured results to computational analyses, the three tests specimens were modelled in THERM 7.3 and their total thermal conductivity was calculated. These computed values were compared to the measured results to demonstrate the accuracy of the constructed apparatus in measuring thermal bridges and to draw conclusions on the inaccuracy of modelling software. To create a representative model, the materials in the specimens were measured in the heat flow meter to provide accurate values for the thermal conductivities for the materials in the models. The thermal conductivities of the materials in the model are shown in Table 17.

Table 17 – Measured thermal conductivities from the heat flow meter.

Material	k (W/mK)
Bottom polyethylene foam layer	0.0437
Top polyethylene foam layer	0.0382
Gypsum board	0.1465
Plywood	0.0874
Wood stud	0.1351

The thermal conductivities of the materials shown in Table 17 are temperature dependent and the thermal conductivity of each material was reported based on the average temperature it experiences during the guarded hot plate testing. Hence, two thermal conductivities were reported for the polyethylene layers for each side of the specimens. The thermal conductivity of the steel Z-girt could not be measured and was assumed to be 50 W/mK. The specimens used to measure the thermal conductivity of the foam, gypsum board, and plywood in the heat flow meter consisted of multiple layers of each material for better measurement. The wood stud was measured in the heat flow meter but gluing multiple studs together to form a block of wood.

The results from the guarded hot plate tests and the predicted thermal conductivities for the specimens from THERM 7.3 are presented in Table 18.

Table 18 – Thermal bridge testing results with comparison to computer models.

Specimen	Measured Meter Plate Power (W)	Predicted k from THERM (W/mK)	Measured k (W/mK)	Difference	% Difference from Predicted
Assembly w/ no thermal bridge	1.963	0.0453	0.0457	0.0005	1.06%
Assembly w/ wood stud	2.285	0.0520	0.0534	0.0014	2.60%
Assembly w/ steel Z-girt	2.894	0.0693	0.0674	-0.0019	-2.73%

From Table 18, it is shown that good agreement is observed between the measured thermal conductivity and the predicted thermal conductivity. The measured thermal conductivity for the specimen without a thermal bridge was closest to the predicted value which was anticipated as it has no thermal bridge. The thermal bridge creates an additional uncertainty since it is a major contributor to heat flow through the specimen meaning that the degree to which it's measured thermal conductivity is known is important. Furthermore, in comparison to the other layers in the specimens, the thermal bridge is most affected by contact resistances which are unknown but as previously discussed, more influential for higher conductivity materials. The measured thermal conductivity of the assembly with the steel Z-girt deviated the most from the predicted value and deviated more from the assembly with no thermal bridge than the wood stud assembly. The

measured thermal conductivity for the steel Z-girt specimen was also less than predicted. This observation was anticipated as the steel Z-girt was more influenced by contact resistances than the wood stud and the presence of contact resistances against the steel Z-girt would cause an underestimation in the thermal conductivity.

The results presented in Table 18 show promise in the constructed guarded hot plates ability to measure layered specimens with thermal bridges but associated errors unique to these kinds of specimens have not yet been evaluated. As previously discussed, edge loss errors and temperature non-uniformity of the plates are of a concern when testing specimens with thermal bridges. Hence, thermistors were placed at multiple locations within the assemblies to provide information on whether edge heat loss errors would be a concern with the proposed 32” (813mm) assembly within the specimen. Thermistors were placed on both sides of the gypsum board and plywood layers at the middle and ends of the thermal bridges. Figure 58 and Figure 59 show the thermistor locations and average temperatures in degrees Celsius along the length of the wood stud and steel Z-girt, respectively.

<i>Cold side</i>				
	11.94	12.53	PE foam	11.97
Stonewool	Plywood			Stonewool
Stonewool	15.39	15.64	Wood stud	15.44
	32.09	31.38		31.37
Stonewool	Gypsum board			Stonewool
	35.27	35.73	PE foam	35.92
<i>Hot side</i>				

Figure 58 – Temperature distribution along the length of the wood stud.

<i>Cold side</i>				
	13.52	13.74	PE foam	13.30
Stonewool	Plywood			Stonewool
Stonewool	23.01	22.38	Steel Z-girt	22.30
	26.97	26.14		25.86
Stonewool	Gypsum board			Stonewool
	33.58	34.86	PE foam	35.85
<i>Hot side</i>				

Figure 59 – Temperature distribution along the length of the steel Z-girt.

Figure 58 and Figure 59 show that the temperatures at either end of the 32" (813mm) square assembly along the thermal bridge are similar to the temperatures in the middle. The average deviation in temperature from the centre of assembly to the edges is 0.15°C for the wood stud and -0.02°C for the steel Z-girt. This average deviation is considered acceptable and edge loss errors are therefore deemed to be insignificant.

The average values of the thermistors on the hot plates and cold plate did not appear to differentiate from the patterns described in Section 3.6.8 "Temperature Uniformity". No noticeable deviations in temperature could be distinguished on the plates in the locations near the wood stud or steel Z-girt. It is therefore deemed that the two layers of polyethylene foam on either side of the assembly were adequate in creating uniform plate temperatures for these specimens and testing conditions.

6.0 Conclusions

A large-scale guarded hot plate was designed for the measurement of thick insulation specimens and specimens containing layers and/or thermal bridges. The design was based on a literature review and several analyses estimating the sources of error in measurement. Computational analyses were performed to quantify the effect of unbalance errors and edge heat loss errors using THERM 7.3 heat modelling software. Once designed, the apparatus was constructed in the lab and preliminary testing was performed to determine the characteristics and testing procedures. Measurement techniques and control operation were refined during this stage to yield the most accurate measurement. Based on the analysis of the sources of errors, the anticipated measurement accuracy of the guarded hot plate constructed is approximately 1.5% for moderate thickness, homogenous specimens.

Validation of the apparatus was subsequently performed using three stonewool specimens ranging from 3" (76mm) to 9" (229mm) in thickness. The thermal conductivity of the layers of these specimens was measured in a heat flow meter calibrated to better than 1% against a NIST calibration sample. These measurements were compared to the measurements in the guarded hot plate and good agreement was shown; <1% deviation in thermal conductivity for the 3" (76mm) specimen and <3.5% deviation in thermal conductivity for the 9" (229mm) specimen were observed.

The ability of the constructed guarded hot plate to measure specimens containing layers and/or thermal bridges was demonstrated by testing three specimens resembling a typical wall assembly. The three specimens were modelled in THERM 7.3 to find a predicted equivalent thermal conductivity and the measurements from the guarded hot plate were compared. Good agreement was observed between the measured and predicted thermal conductivities for the three specimens. The largest deviation from predicted was observed for the specimen containing a steel Z-girt. The deviation can be explained by the negation of contact resistances in the models and the fact that contact resistances are more influential for higher conductivity materials. Edge loss errors and temperature non-uniformity of the plates were not found to be an issue which verified the capability of the constructed guarded hot plate in measuring layered specimens with thermal bridges.

7.0 Recommendations

Several recommendations are proposed as a result of insight following completion of the preliminary tests. Firstly, the non-uniformity in temperature of the guard plates due to edge losses was analyzed and deemed to only contribute a small error. However, it is possible to eliminate this error through a different guard design. Additional heater wire could be added along the edges of the guards to create a higher heater density near the edges. The plates could also be reconstructed to have an increasingly smaller spacing near the edges of the plates to increase the heater density thus decreasing the temperature drop in the guard plates near the edges of the specimen. Secondly, precise control of the hot plates was achieved but the accuracy of these thermistor measurements was poor in comparison. Ideally the thermistors would be individually calibrated for very accurate results but a more time efficient option would be to test all of the thermistors against a reference resistor and the thermistors that read excessively high or low could be tossed away leaving only the more accurate thermistors to be used. Another issue was that the thermistors could have a bias introduced by the contact resistance between the plates and the thermistor. This could be remedied by adhering the thermistors in a different way. If the thermistor layout is not intended to be changed, holes could be drilled in the plate and the thermistors could be threaded through the hole from the back of the plate. Thermally conductive adhesive could then be used to create good thermal contact between the thermistor and the plate. This would also cause the plate surfaces in contact with the specimen to be flatter. The layout of the thermistors could also be improved. Research suggests that temperature along the guard gap is not uniform since more heat loss occurs at the corners of the meter area (De Ponte & Di Fillippo, 1974). Therefore, thermistors used to balance the plates should be placed at the location along the gap where the average of this temperature gradient along the gap exists (Xaman, Lira & Arce, 2008). Some research even proposes an optimum balancing sensor location (De Ponte, 1985; De Ponte & Di Fillippo, 1974).

Another concern was the temperature uniformity of the plates between the heating wires and between the cooling tubes. Further testing should be done with a new thermistor arrangement that better senses any difference in temperature that might exist between the wires or cooling tubes. If the temperature uniformity of the plates needs to be improved, an aluminum face plate

could be glued to the plates to increase their thickness which should decrease temperature variations. Another option would be to glue a thin piece of plastic to the plate surface and then another thin aluminum plate to the existing plates. The plastic is relatively thermally insulating and would cause heat variations to decrease while introducing very little thermal mass to the apparatus.

The temperature drop across the cold plate from one side to the other should be investigated since it is known that the fluid entering the right and leaving the left side differs in temperature. The preliminary testing showed that this may be an issue although it is unlikely to be significant.

For thin, high thermally conductive specimens, the contact resistance between the specimen and the plates may be significant. The plate surfaces in contact with the specimen should therefore be painted flat black as per ASTM C177 Clause 6.3.2.3 increasing the emissivity and correspondingly the heat exchange at the surface of the plates.

Additionally, further testing should be done on very thick specimens (up to 16" (406mm) thick) and different types of thermal bridges to better determine the capabilities and limitations of the constructed apparatus. If edge losses are found to be too large, extra edge insulation can be added to the outside of the side panels or extra heater plates could be installed on the side panels to control the edge temperature of the specimens to the mean testing temperature.

When measurement of specimens on an angle or in a vertical orientation becomes necessary, the steel stand that allows the apparatus to rotate should be constructed. This stand should also allow the apparatus to be rolled to different areas within the lab and to fit through standard man doors.

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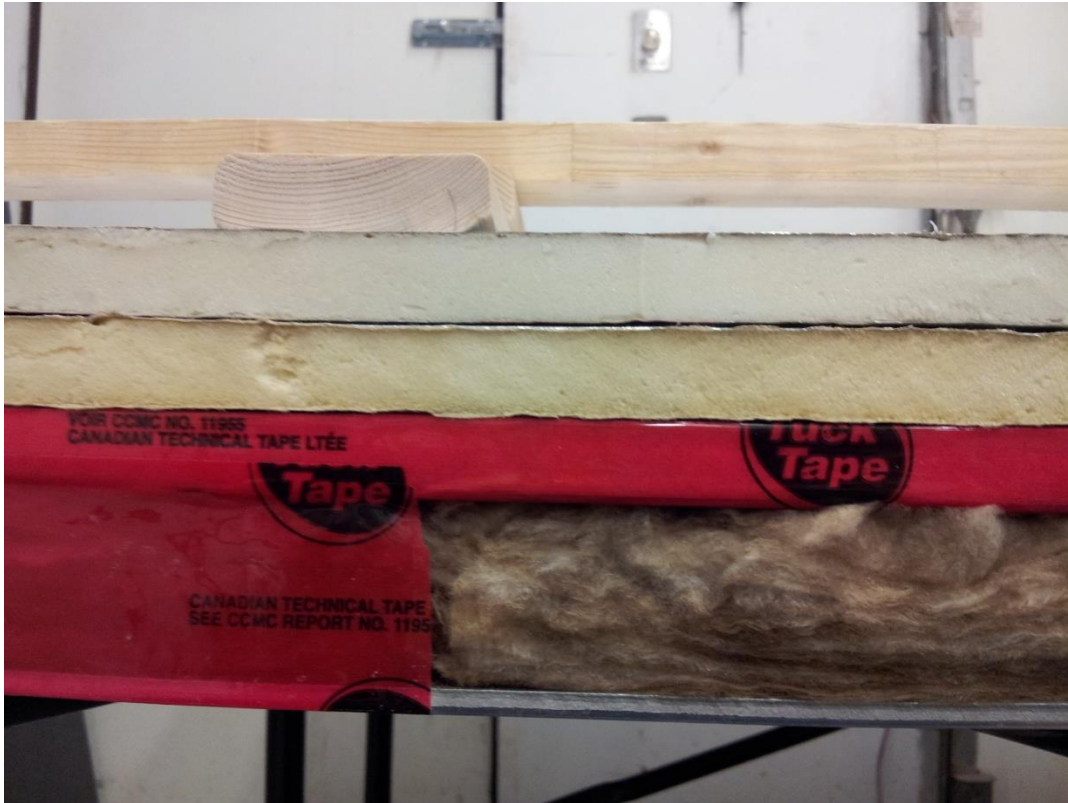
Appendix A – Additional Photos of the Apparatus



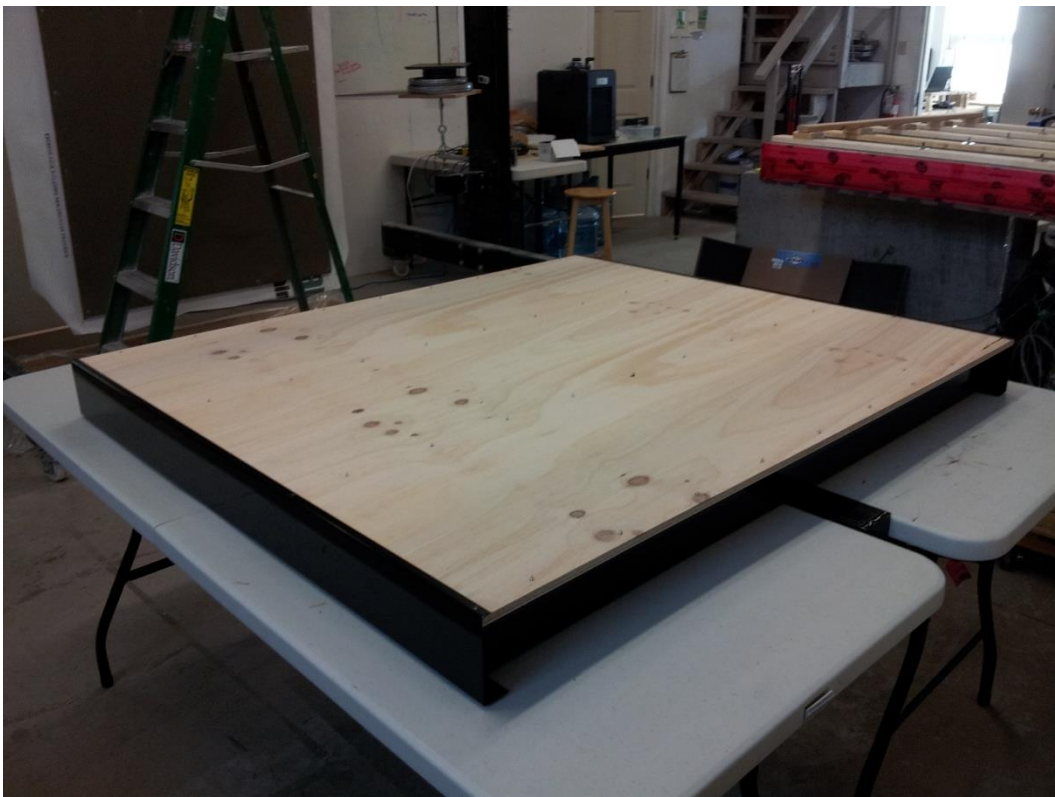
Weight applied over the cold plate and copper tubing during the curing of the thermally conductive epoxy.



The inlet and outlet tubes coming out of the cold plate assembly.



The edge of the cold plate assembly while under construction.



The base of the apparatus frame.



The underside of the base of the apparatus frame.



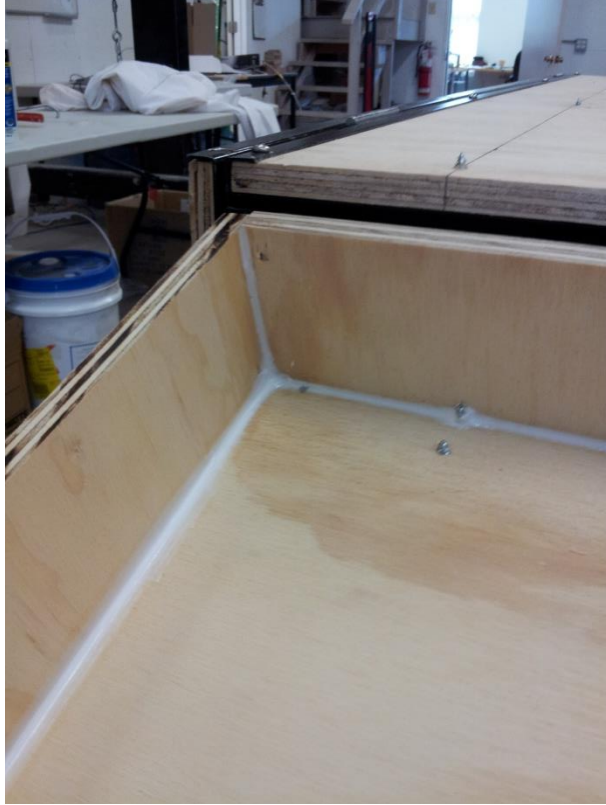
The apparatus frame with hinged side panels.



Side panel prior to edge insulation installation.



Side panel prior to edge insulation installation. Screws used to construct the side panel protrude through the plywood to help keep the insulation fixed.



Edge insulation panels lined with silicone at the edges to avoid air leakage into the panels.



Side panels with adhesive applied just prior to edge insulation installation.



Installation of the edge insulation.



Installation of the edge insulation.



Detailed view of where the hot plate assembly will sit on the apparatus base. Protruding screws near the edges were ground down to avoid damaging the edge of the hot plate assembly. Screws in the middle were left to prevent the assembly from sliding around on the base.



Edge insulation installed.



Detailed view of the edge insulation installed on the side panels.



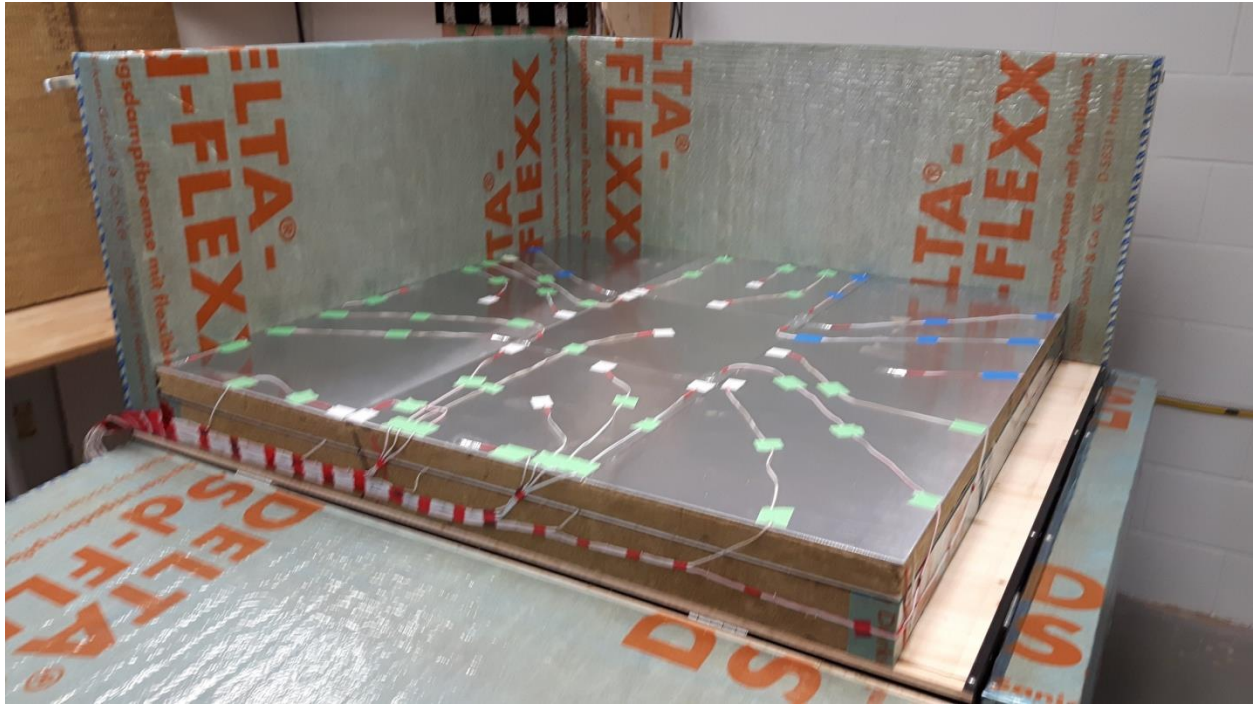
Back guard and back insulation installed on the apparatus frame. The hot plate assembly is not glued together or adhered to the frame.



Meter plate and the top, bottom, left, and right guards upside down to show the heater wire pattern.



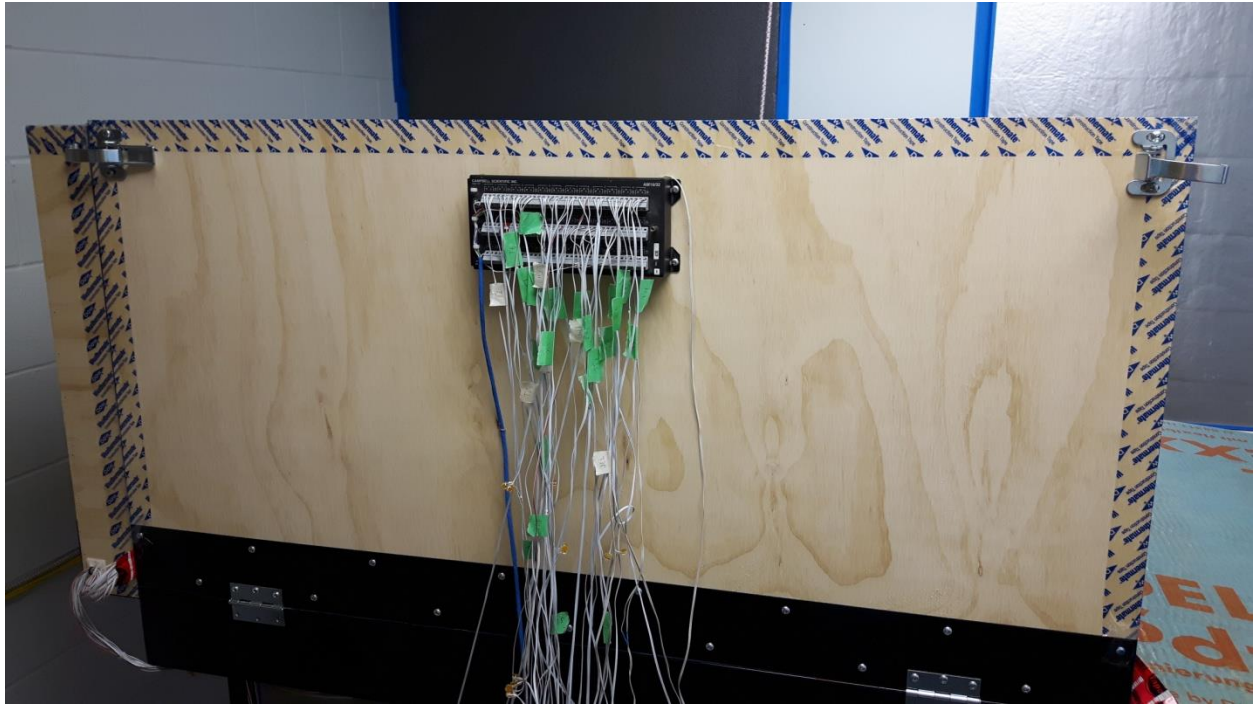
Meter plate and other guards being installed (shown upside down to show heater wire pattern).



Thermistors on the hot plate assembly.



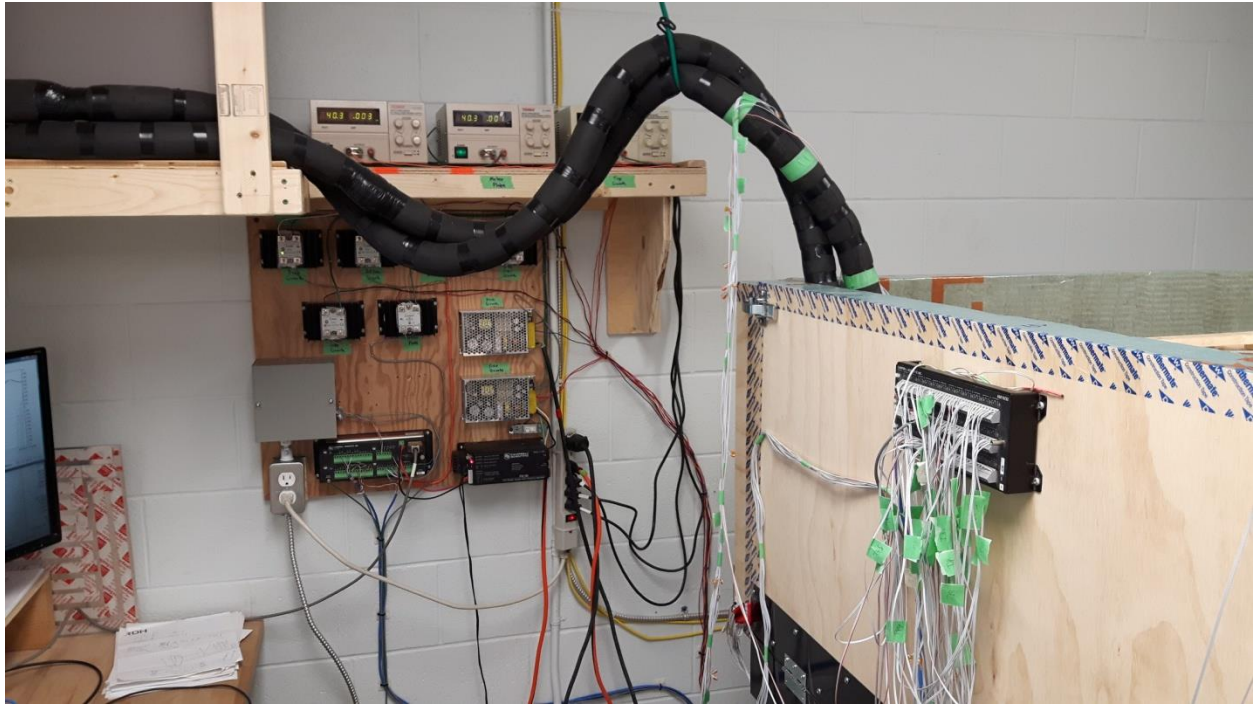
Thermistors on the cold plate assembly.



Multiplexer which connects all of the of thermistors.



Thermistors from the hot plate assembly coming out of the apparatus in-between the edge insulation.



Control circuitry and power supplies.



Plumbing attached to the cold plate at the back of the chiller. Valves can be opened in two arrangements: one that isolates the chiller and one that allows fluid to flow to the cold plate.



Plumbing at the back of the chiller insulated to prevent heat gain.



Bi-metallic switch installed in the hot plate assembly that opens if the assembly gets too hot unexpectedly.



Control circuitry connected to the bi-metallic switch that turns off power to the power supplies in case of an overheating event. The electrical box contains two relays and a switch (red button). One relay turns off the AC outlet below the box to which all of the power supplies attach and the other relay provides the logic behind the system which turns the AC relay on/off. If an overheating event occurs, the power will be shut off until the button switch is pressed.

Appendix B – Resistance Wire Product Details Sheet

Reference:

Omega Engineering Inc. (2016). *Resistance Heating Wire, Nickel-Chromium Alloy, 80% Nickel/ 20% Chromium*. Retrieved September 20, 2015 from <http://www.omega.com/pptst/NI80.html>

Resistance Heating Wire

Nickel-Chromium Alloy

60% Nickel/16% Chromium (Balance Iron)

- ✓ Used to Make Straight or Helical Coil Resistance Heaters
- ✓ Quick Heating, Long Life
- ✓ High Temperature, 1000°C (1850°F)
- ✓ Corrosion Resistant
- ✓ Convenient 15 m (50') and 60 m (200') Spools



Nickel-Chrome 60 is the world's standard of comparison in the electrical trade for metallic resistance wire. It is an alloy of 60% nickel and 16% chromium, and is the accepted material for heating devices operating up to 1000°C (1850°F). This encompasses most pluggable power cord domestic heating appliances and those heating units of medium temperatures which do not require the unsurpassed quality of NI/CR-80/20, the 80-20 alloy.

In addition to being commonly used in electrical heating, Nickel-Chrome 60 is used extensively in industrial

applications for rheostats and resistance units. It makes for compact units capable of withstanding severe overloads and short circuits without damage or circuit impairment.

The excellent corrosion resistance of Nickel-Chrome 60 makes it very useful for purposes other than electrical heating. Acid dipping baskets, cyanide hardening and pickling containers, filter cloth, wire mesh, bolts and nuts are a few representative uses.

Specifications

Composition: 60% Ni, 16% Cr, balance Fe

Specific Resistance: 675 Ω per circular mil-foot at 68°F (20°C); see table below for multiplication factors to obtain resistance at other temperatures

Specific Gravity: 8.25

Density: 0.298 lb/in³

Melting Point: Approx 1350°C (2450°F)

Nominal Coefficient of

Linear Expansion:

0.00017 (20 to 1000°C)

Tensile Strength (lb/in²)

at 20°C (68°F):

Soft Annealed: 95,000

Nominal Temperature Coefficient of Resistance:

0.00015 $\Omega/\Omega/^\circ\text{C}$ (20 to 500°C)

Factor by Which Resistance at Room Temperature Is to Be Multiplied to Obtain Resistance at Indicated Temperatures
(These figures are given as a basis for engineering calculations and represent average material as supplied.)

Temp °C	20	93	204	315	427	538	649	760	871°C
Temp °F	68	200	400	600	800	1000	1200	1400	1600°F
Factor	1.000	1.019	1.044	1.070	1.092	1.108	1.112	1.118	1.13

To Order Visit omega.com/ni60 for Pricing and Details

AWG	Dia. mm (inch)	Ω per ft @ 20°C (68°F)	Current Temperature Characteristics* °C (°F)						Model No.
			425 (800)	550 (1000)	650 (1200)	750 (1400)	875 (1600)	1100 (2000)	
18	1.0 (0.040)	0.4219	7.90	9.75	11.96	14.51	17.37	23.08	NI60-040-(t)
20	0.81 (0.032)	0.6592	5.92	7.25	8.86	10.69	12.72	16.87	NI60-032-(t)
22	0.64 (0.0253)	1.055	4.44	5.40	6.56	7.87	11.63	12.33	NI60-025-(t)
24	0.51 (0.0201)	1.671	3.32	4.01	4.86	5.80	6.82	9.01	NI60-020-(t)
26	0.40 (0.0159)	2.670	2.52	3.00	3.61	4.31	5.06	6.63	NI60-015-(t)
28	0.32 (0.0126)	4.252	1.90	2.28	2.73	3.23	3.77	4.88	NI60-012-(t)
30	0.25 (0.010)	6.750	1.43	1.74	2.06	2.43	2.81	3.59	NI60-010-(t)

* Showing approximate amperes necessary to produce a given temperature, applying only to a straight wire stretched horizontally in free air.

† Specify desired length in feet: "50" or "200". **Note:** This wire is **not** intended for use in making thermocouple elements.

Ordering Example: NI60-010-200 is a 60 m (200') spool of 30 gage bare 60% nickel/16% chromium alloy heating wire.

Note: Published prices are based on market value at time of printing and are subject to change due to Nickel surcharges, Chromium and precious-metal market fluctuations.

Appendix C – Resistance Wire Layout Design

Meter plate and side guard plates

Power (W)	Voltage (V)	Amps (A)	Resistance (Ω)
20	47.958	0.42	115.0
5	23.979	0.21	115.0
1.25	11.990	0.10	115.0
0.22	4.996	0.04	115.0

Need Q of 0.16 to 19.9 W

Power (W)	Voltage (V)	Amps (A)	Resistance (Ω)
20	48.0	0.42	115.0
15	41.5	0.36	115.0
10	33.9	0.29	115.0
5	24.0	0.21	115.0
2.5	17.0	0.15	115.0
1	10.7	0.09	115.0
0.5	7.6	0.07	115.0
0.25	5.4	0.05	115.0
0.15	4.2	0.04	115.0

Top/bottom guard plates

Power (W)	Voltage (V)	Amps (A)	Resistance (Ω)
60	47.958	1.25	38.3
15	23.979	0.63	38.3
3.75	11.990	0.31	38.3
0.65	4.996	0.13	38.3

Need Q range of 0.5 to 59.3 W

Power (W)	Voltage (V)	Amps (A)	Resistance (Ω)
60	48.0	1.25	38.3
50	43.8	1.14	38.3
40	39.2	1.02	38.3
30	33.9	0.88	38.3
20	27.7	0.72	38.3
10	19.6	0.51	38.3
5	13.8	0.36	38.3
2.5	9.8	0.26	38.3
0.6	4.8	0.13	38.3

Back guard plate

Power (W)	Voltage (V)	Amps (A)	Resistance (Ω)
60	47.958	1.25	38.3
15	23.979	0.63	38.3
3.75	11.990	0.31	38.3
0.65	4.996	0.13	38.3

Need Q range of 0 to 58.5 W

Power (W)	Voltage (V)	Amps (A)	Resistance (Ω)
40	48.0	0.83	38.3
30	33.9	0.88	38.3
20	27.7	0.72	38.3
10	19.6	0.51	38.3
5	13.8	0.36	38.3
2.5	9.8	0.26	38.3
1.5	7.6	0.20	38.3
1	6.2	0.16	38.3
0.5	4.4	0.11	38.3

		Meter plate spacing and corresponding resistance (Ω)			
AWG	Ω per ft	0.75"	1"	1.25"	1.5"
18	0.4219	11.35	9.06	6.82	5.71
20	0.6592	17.74	14.15	10.66	8.92
22	1.055	28.39	22.65	17.05	14.28
24	1.671	44.97	35.87	27.01	22.62
26	2.670	71.85	57.31	43.16	36.15
28	4.252	114.42	91.27	68.73	57.57
30	6.750	181.64	144.89	109.11	91.39

Need
115.0 Ω

		Side guard spacing and corresponding resistance (Ω)			
AWG	Ω per ft	1"	1.25"	1.5"	2"
18	0.4219	8.90	6.68	5.58	4.36
20	0.6592	13.91	10.44	8.71	6.81
22	1.055	22.27	16.70	13.95	10.90
24	1.671	35.27	26.45	22.09	17.27
26	2.670	56.35	42.27	35.30	27.59
28	4.252	89.74	67.31	56.21	43.94
30	6.750	142.46	106.86	89.23	69.76

Need
115.0 Ω

		Top/bottom guard spacing and corresponding resistance (Ω)			
AWG	Ω per ft	1"	1.25"	1.5"	2"
18	0.4219	26.80	20.15	17.78	13.26
20	0.6592	41.87	31.48	27.78	20.71
22	1.055	67.02	50.38	44.45	33.15
24	1.671	106.14	79.79	70.41	52.50
26	2.670	169.60	127.49	112.50	83.89
28	4.252	270.09	203.03	179.16	133.59
30	6.750	428.77	322.31	284.42	212.07

Need
38.3 Ω

		Back guard spacing and corresponding resistance (Ω)			
AWG	Ω per ft	1"	1.25"	1.5"	2"
18	0.4219	80.80	60.65	53.78	40.26
20	0.6592	126.25	94.76	84.03	62.90
22	1.055	202.06	151.66	134.48	100.67
24	1.671	320.03	240.21	213.00	159.44
26	2.670	511.36	383.81	340.34	254.77
28	4.252	814.35	611.22	542.00	405.72
30	6.750	1292.77	970.31	860.42	644.07

Need
38.3 Ω

Wire spacing	Meter plate heater wire length (ft)
0.75"	26.9101517
1"	21.4655058
1.25"	16.1650983
1.5"	13.538875

Wire spacing	Side guard heater wire length (ft)	Top/bottom guard heater wire length (ft)	Back guard heater wire length (ft)
1"	21.10484	63.5216775	191.521678
1.25"	15.8306842	47.74976667	143.749767
1.5"	13.2198717	42.136555	127.469888
2"	10.3345933	31.41809833	95.4180983

Appendix D – Thermally Conductive Epoxy Data Sheet

Reference:

Epoxies Etc. (2016). *50-3100 – High Thermal K Heat Transfer Epoxy Resin*. Retrieved February 19, 2016 from https://www.epoxies.com/_resources/common/userfiles/file/50-3100R.pdf

50-3100

HIGH THERMAL K HEAT TRANSFER EPOXY RESIN

DESCRIPTION:

50-3100 is designed for the fastest and most continuous high heat transfer. 50-3100 measures several times faster heat dissipation than other commercially available types. The most important breakthrough is the handling of 50-3100. This system can be easily mixed and poured to form a dimensionally stable heat transfer package.

Typical applications include encapsulation of power supplies, transformers, coils, insulators, protective covering for chips, temperature probes, etc...

CHOICE OF CURING AGENTS:

CATALYST 190: Room temperature curing with a 45 minute pot life. Tough and rigid at all temperatures up to 150°C.

CATALYST 150: Room temperature curing with a 30 minute pot life. Low viscosity and easy handling properties. Excellent adhesion. Has a service temperature up to 150C (300°F). Will soften slightly above 121°C (250°F).

CATALYST 30: Heat curing with a pot life of 4 hours. Low viscosity with excellent handling properties. Excellent thermal and mechanical shock. Recommended for higher operating temperature applications.

TYPICAL SPECIFICATIONS:

Viscosity @ 25°C, cps, Resin	180,000
Viscosity @ 25°C (Cat.190) cps	32,000
Viscosity @ 25°C (Cat.150) cps	6,000
Viscosity @ 25°C (Cat.30) cps	29,000
Specific Gravity, 25°C/25°C, Resin	2.0
Hardness, Shore D	90
Linear Shrinkage, in./in.	.003
Tensile Strength, psi	8,800
Compressive Strength, psi	15,000
Operating Temp. Range, °C	-60 to +205
Coefficient of Expansion, °C	30×10^{-6}
Dielectric Strength, V/mil	485
Dielectric Constant at 60 Hz	6.4
Volume Resistivity, ohm-cm	1.5×10^{15}
Dissipation Factor, 60 Hz	.015
Heat Distortion, °C	120
Thermal Conductivity, W/m- °K	2.16

INSTRUCTIONS FOR USE:

A. WITH CATALYST 190

1. By weight, thoroughly mix 5 parts Catalyst 190 to 100 parts 50-3100 resin.
2. Degas and pour, cure at room temperature for 24 hours @ 25°C ambient or for 2 hours at 66°C (155°F).

B. WITH CATALYST 30 (Recommended for higher operating temperature and physical property applications):

1. By weight, thoroughly mix 9 parts Catalyst 30 to 100 parts 50-3100 resin.
2. Degas and pour, cure according to one of the following recommended cure schedules:
 - a) 85°C (185°F) 3-4 hours
 - b) 100°C (212°F) 2-3 hours

For optimum performance, an additional 2 hours @ 365°F (185°C) is recommended.

C. WITH CATALYST 150

1. By weight, thoroughly mix 12 parts Catalyst 150 to 100 parts 50-3100 resin.
2. Degas and pour, cure for 24 hours at room temperature or for 2 hours at 66°C (155°F).

IMPORTANT:

EPOXIES, ETC. MAKES NO EXPRESS OR IMPLIED WARRANTIES OR MERCHANTABILITY, FITNESS OR OTHERWISE WITH RESPECT TO ITS PRODUCTS. The information in this brochure is based on data obtained by our own research and is considered reliable. However, no warranty is expressed or implied regarding the accuracy of these data, the results to be obtained from the use thereof, or that any such use will not infringe any patent. The properties given are typical values and are not intended for use in preparing specifications. This information is furnished upon the condition that the person receiving it shall make his own tests to determine the suitability thereof for his particular purpose.

05/14

Appendix E – VWR 1197P Chiller Specifications

Reference:

VWR International Inc. (2002). *VWR Circulators and Chillers*. Retrieved January 25, 2016 from http://edge.rit.edu/edge/P13621/public/VWR_Circulators_Chillers_Manual.pdf

VWR Signature Refrigerated/Heating Circulating Baths, 13 Liter, Extra-Low Temperature Control

- Powerful Cooling to -45°C
- Ample Reservoir For Sample Immersion
- Enlarged Access Opening

The 1197P & 1196D circulators provide extended cooling down to a temperature of -45°C with a large 13 liter reservoir. With this extra-low capability and removal of 900 Watts @ 20°C, these circulators cover a wide range of applications.

The unique refrigeration system and energy managing controllers are up to 50% more energy efficient than traditional systems. This technology saves energy by delivering the precise amount of refrigerant for a given heat load.

Refrigeration can be used at high temperatures to cool the bath quickly. Both models feature a 5-speed adjustable pressure/suction pump, excellent stability, redundant over-temperature and low-liquid level protection.

Programmable Model 1197P. This model has a wide temperature range and high stability. Additional features include time/temperature programming and remote probe capability. RS-232 interface and software for PC programming are standard. LabVIEW™ drivers and Excel macros offer even greater programming and data logging convenience.

Digital Model 1196D. The digital controller offers great performance and is your ideal choice when remote probe, time/temperature programming and communication software are not required. Perfect for applications on a budget.

Controllers described on pages 4-5. Accessories listed on page 26.

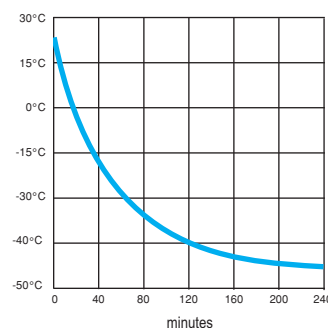


Ideal For: Low Temperature Calibration • Low Temperature Reactions • Cell Freezing
Cloud & Pour Point Testing • Distillation Condensers • General Laboratory Cooling
Rotary Evaporators • Spectrophotometers • Viscosity Studies

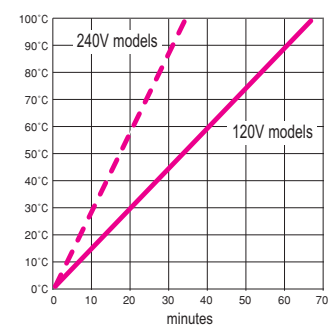
Specifications	Model 1197P	Model 1196D
Temperature Range / Stability	-45°C to 200°C / ±0.01°C	
Controller / RS-232	Programmable / Yes	Digital / Yes
Readout / Accuracy	Graphics LCD, °C or °F / ±0.25°C	
Reservoir Capacity	13 liters	
Cooling Capacity	900 Watts @ +20°C, 825 Watts @ 0°C, 200 Watts @ -30°C	
Heater	1100 Watt (120V models), 2200 Watt (240V models)	
Pressure Flow Rate	5-speed (Duplex Pump), 11 to 24 liters/min.	
Suction Flow Rate	5-speed, 8 to 18 liters/min.	
Safety Cutoffs	Adjustable Over-Temperature & Low-Liquid Cutoff	
Working Access, L x W x D	6 x 11 x 5-1/2 in. / 15.2 x 28 x 14 cm	
Overall Dimensions, L x W x H	17 x 15-1/2 x 24-3/4 in. / 43 x 39.4 x 63 cm	
Pump Inlet & Outlet	1/4 in. FPT Rear Discharge	
Shipping Weight	148 lbs. / 67 kg	
Cat. No. (120V, 60Hz, 12Amps)	13271-118 \$3985	13271-114 \$3265
Cat. No. (240V, 50Hz, 6Amps)	13271-120 \$4010	13271-116 \$3280

Note: Cooling capacity, Watts x 3.41 = BTUs/hr. Performance specifications determined at ambient temperature of 20°C/68°F. For 50Hz units, derate cooling capacity by 17%.

Cooling



Heating



Appendix F – Honeywell Thermistor Temperature/Resistance Data

Reference:

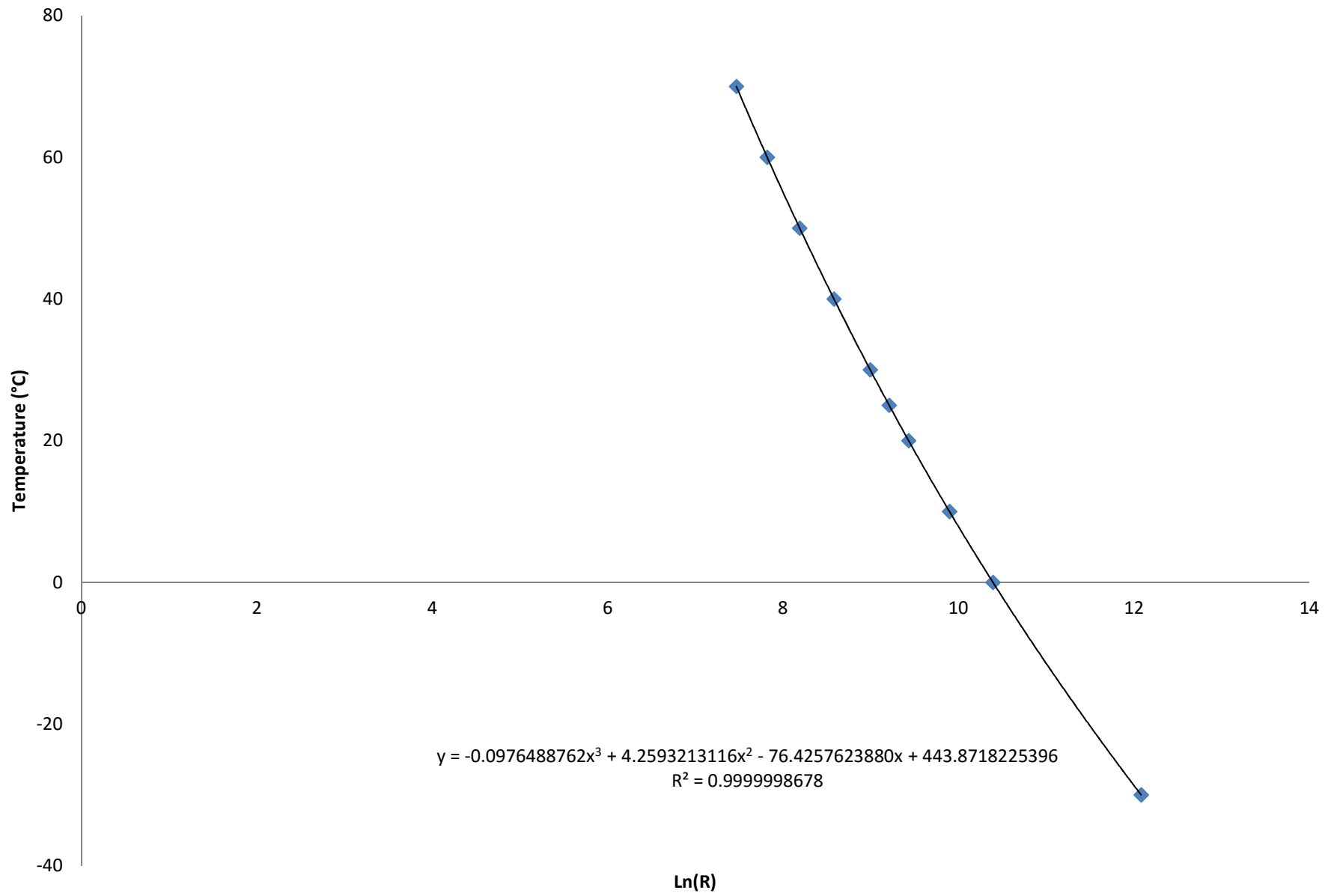
Honeywell Sensing and Control. (2016). *Discrete Thermistors – 192-103LET-A01*. Retrieved May 10, 2016 from <http://sensing.honeywell.com/192-103LET-A01-Discrete-Thermistors>

Honeywell Unicurve 192-103LET-A01

Resistance at 25°C	10,000 Ohm
Tolerance	±0,2 °C [0.36 °F]
Accuracy	0 °C to 70 °C [32 °F to 158 °F]
Operating Temperature	-60 °C to 150 °C [-76 °F to 302 °F]
Diameter	2,413 mm [0.095 in]
Termination Material	32 Gauge tinned copper, alloy 180
Lead Length	38,1 mm [1.50 in]
Time Constant in Air	15.0 s
Dissipation Constant	0,75 m/W°C

°F	°C	R-T Curve Coefficient	Alpha Temp. Coefficient	Resistance Deviation
-76	-60	140.5	7.7	6.6
-58	-50	67.01	7.2	5.6
-40	-40	33.65	6.7	4.7
-22	-30	17.7	6.2	3.8
-4	-20	9.707	5.8	3
14	-10	5.533	5.5	2.2
32	0	3.265	5.1	1.5
50	10	1.99	4.8	0.8
68	20	1.249	4.5	0.2
77	25	1	4.4	0
86	30	0.8057	4.3	0.4
104	40	0.5327	4	1
122	50	0.3603	3.8	1.5
140	60	0.2488	3.6	2
158	70	0.1752	3.4	2.5
176	80	0.1258	3.3	3
194	90	0.09177	3.1	3.4
212	100	0.068	2.9	3.8
230	110	0.05112	2.8	4.2
248	120	0.03893	2.7	4.6
257	125	0.03417	2.6	4.7
266	130	0.03009	2.5	4.9
284	140	0.02348	2.4	5.3
302	150	0.01853	2.3	5.5
320	160	0.01479	2.2	5.8
356	180	0.00968	2	6.5
392	200	0.006559	1.8	7
428	220	0.004581	1.6	7.4
464	240	0.003286	1.5	7.8
500	260	0.002415	1.3	8.3
538	280	0.001814	1.1	8.6
572	300	0.00139	1	8.9

T vs. ln(R)



Appendix G – Campbell Scientific CR-10X Specifications

Reference:

Campbell Scientific Inc. (2006). *CR10X*. Retrieved July 28, 2016 from <https://www.campbellsci.ca/cr10x>

System Description

The CR10X consists of a Measurement and Control Module and a detachable Wiring Panel. The Mean Time Between Failures (MTBF) for the CR10X is over 180 years. Standard operating range is -25° to +50°C; an optional extended range of -55° to +85°C is available.

6 Differential (12 single-ended) Analog Inputs

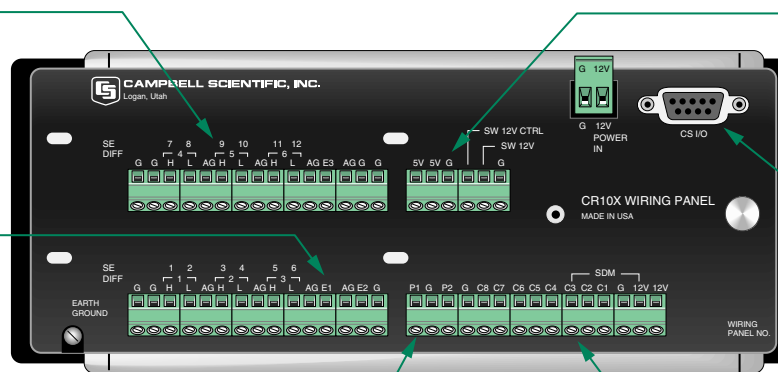
for measuring voltage levels on five software selectable voltage ranges.

3 Switched Excitation Channels

for precision excitation of sensors or short-term actuation of external devices. Excitation is programmable over a ± 2500 mV range.

2 Pulse Counting Channels

for switch closures, high frequency pulses, or low level ac measurement.



Power and Ground Connections for 12 V external batteries or peripherals or for 5 V peripherals. Switched 12 V terminal is controlled by any digital output.

9-Pin CS I/O Port for connection of data storage, retrieval, and telecommunications peripherals.

8 Digital Inputs/Outputs for output control, sensing status, and reading SDM peripherals or SDI-12 sensors.

Measurement and Control Module

The module measures sensors, drives direct communications and telecommunications, reduces data, controls external devices, and stores data and programs in on-board, non-volatile storage. The electronics are RF shielded and glitch protected by the sealed, stainless steel canister. A battery-backed clock assures accurate timekeeping. The module can simultaneously provide measurement and communication functions.

The CR10X contains a comprehensive set of processing, math, and program control instructions to build a datalogger program. The maximum rate the CR10X can execute its program is 64 times per second. (The maximum rate a single input can be measured is 750 samples per second.) Data and programs are stored either in non-volatile Flash memory or battery-backed SRAM. The standard memory stores 62,000 data points. Optional versions store up to one million data points.

Datalogger Operating Systems

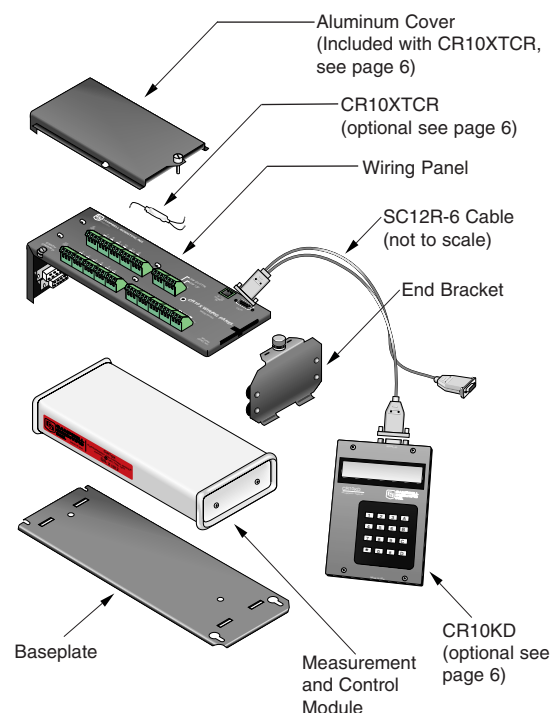
Options for the CR10X Operating System (OS) include array-based, table, Pakbus, Modbus, and ALERT. The array-based OS stores arrays of data at specified intervals or when a measured condition has been met. Two final storage areas are provided for storing the arrays. Table OS groups similar data in separate tables. Pakbus OS enables the CR10X to communicate with CR200-series dataloggers that are in the same network. Pakbus OS stores data in the same format as the table OS. The Modbus OS allows the CR10X to interface with SCADA or MMI software, and ALERT OS allows the CR10X to be used in an ALERT system. Operating System is specified at time of CR10X purchase but can be changed easily if application needs change.

SC12 and SC12R-6 Cables

The SC12 is a two-foot cable that connects communication devices to the CR10X's 9-pin serial port. The SC12 is shipped with most of our communication devices, including our phone modems, satellite transmitters, and keyboard display. The SC12R-6 is a six-foot cable that is purchased separately.

Wiring Panel

The Wiring Panel includes screw terminals for sensor connections and a 9-pin CS I/O port. An end bracket attaches the Wiring Panel to the Control Module and to an enclosure-mounted or free-standing baseplate. The Control Module easily disconnects from the Wiring Panel allowing field replacement without rewiring the sensors. Gas tubes on the wiring panel provide rugged electrostatic discharge protection.



CR10X Specifications

Electrical specifications are valid over a -25° to +50°C range unless otherwise specified; non-condensing environment required. To maintain electrical specifications, Campbell Scientific recommends recalibrating dataloggers every two years.

PROGRAM EXECUTION RATE

Program is synchronized with real-time up to 64 Hz. One channel can be measured at this rate with uninterrupted data transfer. Burst measurements up to 750 Hz are possible over short intervals.

ANALOG INPUTS

NUMBER OF CHANNELS: 6 differential or 12 single-ended, individually configured. Channel expansion provided by AM16/32 or AM416 Relay Multiplexers and AM25T Thermocouple Multiplexers.

ACCURACY: $\pm 0.1\%$ of FSR (-25° to 50°C);
 $\pm 0.05\%$ of FSR (0° to 40°C);
e.g., $\pm 0.1\%$ FSR = ± 5.0 mV for ± 2500 mV range

RANGE AND RESOLUTION:

Full Scale Input Range (mV)	Resolution (μ V) Differential	Resolution (μ V) Single-Ended
± 2500	333	666
± 250	33.3	66.6
± 25	3.33	6.66
± 7.5	1.00	2.00
± 2.5	0.33	0.66

INPUT SAMPLE RATES: Includes the measurement time and conversion to engineering units. The fast and slow measurements integrate the signal for 0.25 and 2.72 ms, respectively. Differential measurements incorporate two integrations with reversed input polarities to reduce thermal offset and common mode errors.

Fast single-ended voltage:	2.6 ms
Fast differential voltage:	4.2 ms
Slow single-ended voltage:	5.1 ms
Slow differential voltage:	9.2 ms
Differential with 60 Hz rejection:	25.9 ms
Fast differential thermocouple:	8.6 ms

INPUT NOISE VOLTAGE (for ± 2.5 mV range):
Fast differential: 0.82 μ V rms
Slow differential: 0.25 μ V rms
Differential with 60 Hz rejection: 0.18 μ V rms

COMMON MODE RANGE: ± 2.5 V

DC COMMON MODE REJECTION: >140 dB

NORMAL MODE REJECTION: 70 dB (60 Hz with slow differential measurement)

INPUT CURRENT: ± 9 nA maximum

INPUT RESISTANCE: 20 Gohms typical

ANALOG OUTPUTS

DESCRIPTION: 3 switched, active only during measurement, one at a time.

RANGE: ± 2.5 V

RESOLUTION: 0.67 mV

ACCURACY: ± 5 mV; ± 2.5 mV (0° to 40°C)

CURRENT SOURCING: 25 mA

CURRENT SINKING: 25 mA

FREQUENCY SWEEP FUNCTION: The switched outputs provide a programmable swept frequency, 0 to 2.5 V square wave for exciting vibrating wire transducers.

RESISTANCE MEASUREMENTS

MEASUREMENT TYPES: The CR10X provides ratiometric bridge measurements of 4- and 6-wire full bridge, and 2-, 3-, and 4-wire half bridges. Precise dual polarity excitation using any of the switched outputs eliminates dc errors. Conductivity measurements use a dual polarity 0.75 ms excitation to minimize polarization errors.

ACCURACY: $\pm 0.02\%$ of FSR plus bridge resistor error.

PERIOD AVERAGING MEASUREMENTS

The average period for a single cycle is determined by measuring the duration of a specified number of cycles. Any of the 12 single-ended analog input channels can be used. Signal attenuation and ac coupling are typically required.

INPUT FREQUENCY RANGE:

Signal peak-to-peak ¹ Min.	Max.	Min. Pulse w.	Max Freq. ²
500 mV	5.0 V	2.5 μ s	200 kHz
10 mV	2.0 V	10 μ s	50 kHz
5 mV	2.0 V	62 μ s	8 kHz
2 mV	2.0 V	100 μ s	5 kHz

¹Signals centered around datalogger ground

²Assuming 50% duty cycle

RESOLUTION: 35 ns divided by the number of cycles measured

ACCURACY: $\pm 0.01\%$ of reading (number of cycles ≥ 100)
 $\pm 0.03\%$ of reading (number of cycles <100)

TIME REQUIRED FOR MEASUREMENT: Signal period times the number of cycles measured plus 1.5 cycles + 2 ms

PULSE COUNTERS

NUMBER OF PULSE COUNTER CHANNELS: 2 eight-bit or 1 sixteen-bit; software selectable as switch closure, high frequency pulse, and low level ac.

MAXIMUM COUNT RATE: 16 kHz, eight-bit counter; 400 kHz, sixteen-bit counter. Channels are scanned at 8 or 64 Hz (software selectable).

SWITCH CLOSURE MODE

Minimum Switch Closed Time: 5 ms
Minimum Switch Open Time: 6 ms
Maximum Bounce Time: 1 ms open without being counted

HIGH FREQUENCY PULSE MODE

Minimum Pulse Width: 1.2 μ s
Maximum Input Frequency: 400 kHz
Voltage Thresholds: Count upon transition from below 1.5 V to above 3.5 V at low frequencies. Larger input transitions are required at high frequencies because of input filter with 1.2 μ s time constant. Signals up to 400 kHz will be counted if centered around ± 2.5 V with deviations $\leq \pm 2.5$ V for ≤ 1.2 μ s.
Maximum Input Voltage: ± 20 V

LOW LEVEL AC MODE

(Typical of magnetic pulse flow transducers or other low voltage, sine wave outputs.)

Input Hysteresis: 14 mV

Maximum ac Input Voltage: ± 20 V

Minimum ac Input Voltage:

(Sine wave mV RMS)	Range (Hz)
20	1.0 to 1000
200	0.5 to 10,000
1000	0.3 to 16,000

DIGITAL I/O PORTS

8 ports, software selectable as binary inputs or control outputs. 3 ports can be configured to count switch closures up to 40 Hz.

OUTPUT VOLTAGES (no load): high 5.0 V ± 0.1 V;
low < 0.1 V

OUTPUT RESISTANCE: 500 ohms

INPUT STATE: high 3.0 to 5.5 V; low -0.5 to 0.8 V

INPUT RESISTANCE: 100 kohms

SDI-12 INTERFACE STANDARD

Digital I/O Ports C1-C8 support SDI-12 asynchronous communication; up to ten SDI-12 sensors can be connected to each port. Meets SDI-12 Standard version 1.2 for datalogger and sensor modes.

CR10XTCR THERMOCOUPLE REFERENCE

POLYNOMIAL LINEARIZATION ERROR: Typically $\pm 0.5^\circ\text{C}$ (-35° to +50°C), $\pm 0.1^\circ\text{C}$ (-24° to +45°C).

INTERCHANGEABILITY ERROR: Typically $\pm 0.2^\circ\text{C}$ (0° to +60°C) increasing to $\pm 0.4^\circ\text{C}$ (at -35°C).

CE COMPLIANCE (as of 09/01)

STANDARD(S) TO WHICH CONFORMITY IS DECLARED:

EN55022: 1995 and IEC61326:2002

EMI and ESD PROTECTION

IMMUNITY: Meets or exceeds following standards:
ESD: per IEC 1000-4-2; ± 8 kV air, ± 4 kV contact discharge

RF: per IEC 1000-4-3; 3 V/m, 80-1000 MHz

EFT: per IEC 1000-4-4; 1 kV power, 500 V I/O

Surge: per IEC 1000-4-5; 1 kV power and I/O

Conducted: per IEC 1000-4-6; 3 V 150 kHz-80 MHz

Emissions and immunity performance criteria available on request.

CPU AND INTERFACE

PROCESSOR: Hitachi 6303

PROGRAM STORAGE: Up to 16 kbytes for active program; additional 16 kbytes for alternate programs. Operating system stored in 128 kbytes Flash memory.

DATA STORAGE: 128 kbytes SRAM standard (approximately 60,000 data values). Additional 2 Mbytes Flash available as an option.

OPTIONAL KEYBOARD DISPLAY: 8-digit LCD (0.5" digits)

PERIPHERAL INTERFACE: 9 pin D-type connector for keyboard display, storage module, modem, printer, card storage module, and RS-232 adapter.

BAUD RATES: Selectable at 300, 1200, 9600 and 76,800 bps for synchronous devices. ASCII communication protocol is one start bit, one stop bit, eight data bits (no parity).

CLOCK ACCURACY: ± 1 minute per month

SYSTEM POWER REQUIREMENTS

VOLTAGE: 9.6 to 16 Vdc

TYPICAL CURRENT DRAIN: 1.3 mA quiescent, 13 mA during processing, and 46 mA during analog measurement.

BATTERIES: Any 12 V battery can be connected as a primary power source. Several power supply options are available from Campbell Scientific. The Model CR2430 lithium battery for clock and SRAM backup has a capacity of 270 mAh.

PHYSICAL SPECIFICATIONS

SIZE: 7.8" x 3.5" x 1.5" - Measurement & Control Module; 9" x 3.5" x 2.9" - with CR10WP Wiring Panel. Additional clearance required for serial cable and sensor leads.

WEIGHT: 2 lbs

WARRANTY

Three years against defects in materials and workmanship.

We recommend that you confirm system configuration and critical specifications with Campbell Scientific before purchase.



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Printed April 2006

Appendix H – PID Control Program for the CR-10X

```

;{CR10X}

*Table 1 Program
  01: 20          Execution Interval (seconds)

;=====Initialization of Variables=====

1:  If Flag/Port (P91)
  1: 21          Do if Flag 1 is Low
  2: 30          Then Do

;*****
;*****Constant Variables*****

      SetPoint = 37.82
      CycleT = 20

;(SetPoint in degrees Celsius and CycleT in seconds)

      ErrMAX = 0.15
      ErrMin = -0.15
      Timeout = CycleT - 0.375

2:  Do (P86)
  1: 11          Set Flag 1 High

      KpBKGc = 1
      KiBKGc = 0.005
      KdBKGc = 0

      KpBGc = 1
      KiBGc = 0.005
      KdBGc = 0

      KpTGc = 1
      KiTGc = 0.005
      KdTGc = 0

      KpLGc = 1
      KiLGc = 0.005
      KdLGc = 0

      KpRGc = 1
      KiRGc = 0.005
      KdRGc = 0

      KpMPc = 1
      KiMPc = 0.005
      KdMPc = 0

      KpBKGf = 0.2
      KiBKGf = 0.001
      KdBKGf = 2

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        KpBGf = 0.2
        KiBGf = 0.001
        KdBGf = 2

        KpTGf = 0.2
        KiTGf = 0.001
        KdTGf = 2

        KpLGf = 0.2
        KiLGf = 0.001
        KdLGf = 2

        KpRGf = 0.2
        KiRGf = 0.001
        KdRGf = 2

        KpMPf = 0.2
        KiMPf = 0.001
        KdMPf = 2

3:  End (P95)

SP_Thresh = SetPoint - 1

4:  If (X<=>Y) (P88)
    1: 99      X Loc [ RefT      ]
    2: 4        <
    3: 16      Y Loc [ SP_Thresh ]
    4: 30      Then Do

        IntBKG = 0.25
        IntBG = 0.25
        IntTG = 0.25
        IntLG = 0.25
        IntRG = 0.25
        IntMP = 0.25

5:  End (P95)

;*****
;*****

;=== =====End of Initialization=====

6:  Timer (P26)
    1: 0000      Reset Timer

;=====Start of MUX=====

        ;Turn
7:  Do (P86)
    1: 47      Set Port 7 High

;First 4 sets measure Temperature

```

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;Begin Outer Loop through 1 set of 32 nputs (H) inputs

8:  Beginning of Loop (P87)
  1: 0000      Delay
  2: 13        Loop Count

      ;++++MOVE TO NEXT SET+++++++
  9: Do (P86)
    1: 78      Pulse Port 8

      ;----HONEYWELL UNICURVE (R) THERMISTOR on MUXsT A & B----
      ;Read V across 10000 Ohm fixed resistor in 1/2 bridge with 100K
thermistor

  10: Excite-Delay (SE) (P4)
    1: 4      Repts
    2: 20      Auto 60 Hz Rejection Range (Delay must be
zero) (OS>1.09)
    3: 3      SE Channel
    4: 1      Excite all reps w/Exchan 1
    5: 0      Delay (units 0.01 sec)
    6: 2500    mV Excitation
    7: 18      Loc [ Therm_1 ]
    8: 1.0     Mult
    9: 0.0     Offset

;Thermistor temperatures calculated from three measurements to reduce
noise

  11: Beginning of Loop (P87)
    1: 0000      Delay
    2: 4         Loop Count

      ;Move Therm_1, calculate thermistor resistance
  12: Z=X (P31)
    1: 18      -- X Loc [ Therm_1 ]
    2: 28      Z Loc [ ThermVMux ]

  13: Z=X (P31)
    1: 18      -- X Loc [ Therm_1 ]
    2: 29      Z Loc [ ThermRMux ]

ThermRMux=100000/(2500/ThermVMux-1)

;Calculate natural log of resistance
  14: Z=LN(X) (P40)
    1: 29      X Loc [ ThermRMux ]
    2: 30      Z Loc [ LnThrmMux ]

      ;Calculate temp from curve fit  $F(x) = -0.09446x^3 + 4.16558x^2 - 75.5248x + 441.037$ 
  15: Polynomial (P55)
    1: 1      Repts
    2: 30      X Loc [ LnThrmMux ]

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3: 31      F(X) Loc [ ThermTMux ]
4: 441.037 C0
5: -75.5248 C1
6: 4.16558 C2
7: -0.09446 C3
8: 0.0      C4
9: 0.0      C5

;Move temperature to temporary storage locations
16:  Z=X (P31)
1: 31      X Loc [ ThermTMux ]
2: 32      -- Z Loc [ Temp_1 ]

;End Loop
17:  End (P95)

18:  Step Loop Index (P90)
1: 4      Step

;Move temperatures from MUX T's to final storage locations
19:  Block Move (P54)
1: 4      No. of Values
2: 32      First Source Loc [ Temp_1 ]
3: 1      Source Step
4: 34      -- First Destination Loc [ T_1 ]
5: 1      Destination Step

;End Outer Loop for 1 sets of inputs
20:  End (P95)

;Turn off Mux T's
21:  Do (P86)
1: 57      Set Port 7 Low

;=====End of MUX=====

;=====Temperature and Error Calculations=====

;Calculate averages for references

AvgTCold = (T_36 + T_37 + T_38 + T_39 + T_40) / 5

AVG_BG = (T_29 + T_30 + T_31) / 3
Tref_B = (T_21 + T_22) / 2

AVG_RG = (T_23 + T_24 + T_27) / 3
Tref_R = (T_19 + T_22) / 2

AVG_LG = (T_15 + T_16 + T_17) / 3
Tref_L = (T_18 + T_21) / 2

AVG_TG = (T_11 + T_12 + T_13) / 3
Tref_T = (T_18 + T_19) / 2

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AVG_BKG = (T_3 + T_4 + T_5 + T_6 + T_7) / 5

RefT = (T_18 + T_19 + T_20 + T_21 + T_22) / 5

;Save old control errors

PrevErrLG = ErrLG
PrevErrRG = ErrRG
PrevErrBG = ErrBG
PrevErrTG = ErrTG
PrevErrBK = ErrBKG
PrevErrMP = ErrMP

;Apply Low Pass Filters to reduce noise

22:  If Flag/Port (P91)
1: 15      Do if Flag 5 is High
2: 30      Then Do

      23:  Low Pass Filter (P58)
          1: 1      Reps
          2: 102     Sample Loc [ AVG_LG      ]
          3: 237     Loc [ AVG_LGF      ]
          4: 0.15     Weighting Factor

      24:  Low Pass Filter (P58)
          1: 1      Reps
          2: 103     Sample Loc [ AVG_RG      ]
          3: 238     Loc [ AVG_RGF      ]
          4: 0.15     Weighting Factor

      25:  Low Pass Filter (P58)
          1: 1      Reps
          2: 104     Sample Loc [ AVG_BG      ]
          3: 239     Loc [ AVG_BGF      ]
          4: 0.15     Weighting Factor

      26:  Low Pass Filter (P58)
          1: 1      Reps
          2: 105     Sample Loc [ AVG_TG      ]
          3: 240     Loc [ AVG_TGF      ]
          4: 0.15     Weighting Factor

      27:  Low Pass Filter (P58)
          1: 1      Reps
          2: 106     Sample Loc [ AVG_BKG      ]
          3: 241     Loc [ AVG_BKGF      ]
          4: 0.15     Weighting Factor

      28:  Low Pass Filter (P58)
          1: 1      Reps
          2: 108     Sample Loc [ Tref_L      ]
          3: 242     Loc [ Tref_LF      ]
          4: 0.15     Weighting Factor

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29:  Low Pass Filter (P58)
    1: 1          Reps
    2: 109        Sample Loc [ Tref_R      ]
    3: 243        Loc [ Tref_RF      ]
    4: 0.15       Weighting Factor

30:  Low Pass Filter (P58)
    1: 1          Reps
    2: 110        Sample Loc [ Tref_B      ]
    3: 244        Loc [ Tref_BF      ]
    4: 0.15       Weighting Factor

31:  Low Pass Filter (P58)
    1: 1          Reps
    2: 111        Sample Loc [ Tref_T      ]
    3: 245        Loc [ Tref_TF      ]
    4: 0.15       Weighting Factor

32:  Low Pass Filter (P58)
    1: 1          Reps
    2: 99         Sample Loc [ RefT       ]
    3: 246        Loc [ RefTF        ]
    4: 0.15       Weighting Factor

;Calculate new control errors

ErrLG = AVG_LGF - Tref_LF
ErrRG = AVG_RGF - Tref_RF
ErrBG = AVG_BGF - Tref_BF
ErrTG = AVG_TGF - Tref_TF
ErrBKG = AVG_BKGF - RefTF
ErrMP = RefTF - SetPoint

Flag5 = 1

33:  Else (P94)

ErrLG = AVG_LG - Tref_L
ErrRG = AVG_RG - Tref_R
ErrBG = AVG_BG - Tref_B
ErrTG = AVG_TG - Tref_T
ErrBKG = AVG_BKG - RefT
ErrMP = RefT - SetPoint

Flag5 = 0

34:  End (P95)

;=====Running Averages=====

35:  Running Average (P52)
    1: 1          Reps
    2: 99         First Source Loc [ RefT       ]
    3: 247        First Destination Loc [ RefT_RA   ]

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4: 15          Number of Values in Avg Window

36:  Running Average (P52)
1: 1           Reps
2: 100         First Source Loc [ AvgTCold  ]
3: 248         First Destination Loc [ TCold_RA  ]
4: 15          Number of Values in Avg Window

37:  Running Average (P52)
1: 1           Reps
2: 225         First Source Loc [ Power       ]
3: 249         First Destination Loc [ Power_RA  ]
4: 15          Number of Values in Avg Window

;===== =====Calculations for control demands=====

;=====Coefficients=====

38:  If Flag/Port (P91)
1: 24          Do if Flag 4 is Low
2: 30          Then Do

        KpBKG = KpBKGc
        KiBKG = KiBKGc
        KdBKG = KdBKGc

        KpBG  = KpBGc
        KiBG  = KiBGc
        KdBG  = KdBGc

        KpTG  = KpTGc
        KiTG  = KiTGc
        KdTG  = KdTGc

        KpLG  = KpLGc
        KiLG  = KiLGc
        KdLG  = KdLGc

        KpRG  = KpRGc
        KiRG  = KiRGc
        KdRG  = KdRGc

        KpMP  = KpMPc
        KiMP  = KiMPc
        KdMP  = KdMPc

        Flag4 = 0

39:  Else (P94)

        KpBKG = KpBKGf
        KiBKG = KiBKGf
        KdBKG = KdBKGf

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KpBG = KpBGf
KiBG = KiBGf
KdBG = KdBGf

KpTG = KpTGf
KiTG = KiTGf
KdTG = KdTGf

KpLG = KpLGf
KiLG = KiLGf
KdLG = KdLGf

KpRG = KpRGf
KiRG = KiRGf
KdRG = KdRGf

KpMP = KpMPf
KiMP = KiMPf
KdMP = KdMPf

Flag4 = 1

40: End (P95)

;=====

TonMAX = (Timeout - TmuxEnd) / CycleT

;=====SSR1 - Back Guard=====

41: Z=ABS(X) (P43)
1: 124      X Loc [ ErrBKG      ]
2: 131      Z Loc [ ABSErrBKG ]

42: If (X<=>Y) (P88)
1: 131      X Loc [ ABSErrBKG ]
2: 4        <
3: 13      Y Loc [ ErrMAX      ]
4: 30      Then Do

PropBKG = -KpBKG * ErrBKG
IntBKG = IntBKG - KiBKG * ErrBKG * CycleT
DerBKG = KdBKG * (PrevErrBK - ErrBKG) / CycleT

TonBKG = PropBKG + IntBKG + DerBKG

43: If (X<=>Y) (P88)
1: 176      X Loc [ TonBKG      ]
2: 3        >=
3: 15      Y Loc [ TonMAX      ]
4: 30      Then Do

TonBKG = TonMAX

```

```

44: End (P95)

45: Else (P94)

46: If (X<=>Y) (P88)
  1: 124      X Loc [ ErrBKG      ]
  2: 3        >=
  3: 13       Y Loc [ ErrMAX      ]
  4: 30       Then Do

      TonBKG = 0

47: End (P95)

48: If (X<=>Y) (P88)
  1: 124      X Loc [ ErrBKG      ]
  2: 4        <
  3: 14       Y Loc [ ErrMIN      ]
  4: 30       Then Do

      TonBKG = 1

49: End (P95)

50: End (P95)

;=====SSR2 - Bottom Guard=====

51: Z=ABS(X) (P43)
  1: 122      X Loc [ ErrBG       ]
  2: 129      Z Loc [ ABSErrBG    ]

52: If (X<=>Y) (P88)
  1: 129      X Loc [ ABSErrBG    ]
  2: 4        <
  3: 13       Y Loc [ ErrMAX      ]
  4: 30       Then Do

      PropBG = -KpBG * ErrBG
      IntBG = IntBG - KiBG * ErrBG * CycleT
      DerBG = KdBG * (PrevErrBG - ErrBG) / CycleT

      TonBG = PropBG + IntBG + DerBG

53: If (X<=>Y) (P88)
  1: 177      X Loc [ TonBG       ]
  2: 3        >=
  3: 15       Y Loc [ TonMAX      ]
  4: 30       Then Do

      TonBG = TonMAX

54: End (P95)

```

```

55: Else (P94)

    56: If (X<=>Y) (P88)
        1: 122      X Loc [ ErrBG      ]
        2: 3        >=
        3: 13       Y Loc [ ErrMAX     ]
        4: 30       Then Do

            TonBG = 0

    57: End (P95)

    58: If (X<=>Y) (P88)
        1: 122      X Loc [ ErrBG      ]
        2: 4        <
        3: 14       Y Loc [ ErrMIN     ]
        4: 30       Then Do

            TonBG = 1

    59: End (P95)

60: End (P95)

;=====SSR3 - Top Guard=====

61: Z=ABS(X) (P43)
    1: 123      X Loc [ ErrTG      ]
    2: 130      Z Loc [ ABSErrTG   ]

62: If (X<=>Y) (P88)
    1: 130      X Loc [ ABSErrTG   ]
    2: 4        <
    3: 13       Y Loc [ ErrMAX     ]
    4: 30       Then Do

        PropTG = -KpTG * ErrTG
        IntTG = IntTG - KiTG * ErrTG * CycleT
        DerTG = KdTG * (PrevErrTG - ErrTG) / CycleT

        TonTG = PropTG + IntTG + DerTG

    63: If (X<=>Y) (P88)
        1: 178      X Loc [ TonTG      ]
        2: 3        >=
        3: 15       Y Loc [ TonMAX     ]
        4: 30       Then Do

            TonTG = TonMAX

    64: End (P95)

65: Else (P94)

```

```

66:  If (X<=>Y) (P88)
    1: 123      X Loc [ ErrTG      ]
    2: 3        >=
    3: 13       Y Loc [ ErrMAX     ]
    4: 30       Then Do

        TonTG = 0

67:  End (P95)

68:  If (X<=>Y) (P88)
    1: 123      X Loc [ ErrTG      ]
    2: 4        <
    3: 14       Y Loc [ ErrMIN     ]
    4: 30       Then Do

        TonTG = 1

69:  End (P95)

70:  End (P95)

;=====SSR4 - Left Guard=====

71:  Z=ABS(X) (P43)
    1: 120      X Loc [ ErrLG      ]
    2: 127      Z Loc [ ABSErrLG   ]

72:  If (X<=>Y) (P88)
    1: 127      X Loc [ ABSErrLG   ]
    2: 4        <
    3: 13       Y Loc [ ErrMAX     ]
    4: 30       Then Do

        PropLG = -KpLG * ErrLG
        IntLG = IntLG - KiLG * ErrLG * CycleT
        DerLG = KdLG * (PrevErrLG - ErrLG) / CycleT

        TonLG = PropLG + IntLG + DerLG

73:  If (X<=>Y) (P88)
    1: 179      X Loc [ TonLG      ]
    2: 3        >=
    3: 15       Y Loc [ TonMAX     ]
    4: 30       Then Do

        TonLG = TonMAX

74:  End (P95)

75:  Else (P94)

76:  If (X<=>Y) (P88)
    1: 120      X Loc [ ErrLG      ]

```

```

2: 3      >=
3: 13     Y Loc [ ErrMAX      ]
4: 30     Then Do

      TonLG = 0

77: End (P95)

78: If (X<=>Y) (P88)
1: 120    X Loc [ ErrLG      ]
2: 4      <
3: 14     Y Loc [ ErrMIN     ]
4: 30     Then Do

      TonLG = 1

79: End (P95)

80: End (P95)

;=====SSR5 - Right Guard=====

81: Z=ABS(X) (P43)
1: 121    X Loc [ ErrRG      ]
2: 128    Z Loc [ ABSErrRG   ]

82: If (X<=>Y) (P88)
1: 128    X Loc [ ABSErrRG   ]
2: 4      <
3: 13     Y Loc [ ErrMAX     ]
4: 30     Then Do

      PropRG = -KpRG * ErrRG
      IntrRG = IntrRG - KiRG * ErrRG * CycleT
      DerRG = KdRG * (PrevErrRG - ErrRG) / CycleT

      TonRG = PropRG + IntrRG + DerRG

83: If (X<=>Y) (P88)
1: 180    X Loc [ TonRG      ]
2: 3      >=
3: 15     Y Loc [ TonMAX     ]
4: 30     Then Do

      TonRG = TonMAX

84: End (P95)

85: Else (P94)

86: If (X<=>Y) (P88)
1: 121    X Loc [ ErrRG      ]
2: 3      >=
3: 13     Y Loc [ ErrMAX     ]

```

```

4: 30          Then Do

    TonRG = 0

87:  End (P95)

88:  If (X<=>Y) (P88)
1: 121      X Loc [ ErrRG      ]
2: 4        <
3: 14      Y Loc [ ErrMIN      ]
4: 30      Then Do

    TonRG = 1

89:  End (P95)

90:  End (P95)

;=====SSR6 - Meter Plate=====

91:  Z=ABS(X) (P43)
1: 125      X Loc [ ErrMP      ]
2: 132      Z Loc [ ABSErrMP   ]

92:  If (X<=>Y) (P88)
1: 132      X Loc [ ABSErrMP   ]
2: 4        <
3: 13      Y Loc [ ErrMAX      ]
4: 30      Then Do

    PropMP = -KpMP * ErrMP
    IntMP = IntMP - KiMP * ErrMP * CycleT
    DerMP = KdMP * (PrevErrMP - ErrMP) / CycleT

    TonMP = PropMP + IntMP + DerMP

    Frac = TonMP * CycleT / 0.125

93:  Z=INT(X) (P45)
1: 231      X Loc [ Frac      ]
2: 232      Z Loc [ Int      ]

    TonMPint = Int * 0.125
    TonMPrem = ((TonMP * CycleT) - TonMPint) * 100 + 0.5

94:  Z=INT(X) (P45)
1: 233      X Loc [ TonMPrem   ]
2: 234      Z Loc [ TonMPpuls  ]

    TonMP = TonMPint / CycleT

95:  If (X<=>Y) (P88)
1: 181      X Loc [ TonMP      ]
2: 3        >=

```

```

3: 15      Y Loc [ TonMAX      ]
4: 30      Then Do

      TonMP = TonMAX

96:  End (P95)

97:  Else (P94)

      TonMPpuls = 0

98:  If (X<=>Y) (P88)
1: 125      X Loc [ ErrMP      ]
2: 3        >=
3: 13      Y Loc [ ErrMAX      ]
4: 30      Then Do

      TonMP = 0

99:  End (P95)

100: If (X<=>Y) (P88)
1: 125      X Loc [ ErrMP      ]
2: 4        <
3: 14      Y Loc [ ErrMIN      ]
4: 30      Then Do

      TonMP = 1
      TrunMP = CycleT

101: End (P95)

102: End (P95)

;=====

TstartMP = 0
TstopMP = 0

RP = MPV * MPV * Power / InstPower

103: Z=SQRT(X) (P39)
1: 220      X Loc [ RP          ]
2: 221      Z Loc [ SQRTRP      ]

MinVtag = CycleT / Tcontrol * SQRTRP

104: Do (P86)
1: 22      Set Flag 2 Low

;=====End of calculations=====

;=====Data collect=====

```

```

105:  If time is (P92)
      1: 0000      Minutes (Seconds --) into a
      2: 5         Interval (same units as above)
      3: 10        Set Output Flag High (Flag 0)

106:  Set Active Storage Area (P80)^9092
      1: 1         Final Storage Area 1
      2: 1         Array ID

107:  Real Time (P77)^10512
      1: 1221      Year,Day,Hour/Minute,Seconds (midnight = 2400)

108:  Sample (P70)^26141
      1: 1         Reps
      2: 11        Loc [ SetPoint  ]

109:  Resolution (P78)
      1: 1         High Resolution

110:  Average (P71)^7172
      1: 1         Reps
      2: 99        Loc [ RefT      ]

111:  Standard Deviation (P82)^14657
      1: 1         Reps
      2: 99        Sample Loc [ RefT      ]

112:  Average (P71)^28653
      1: 1         Reps
      2: 100       Loc [ AvgTCold  ]

113:  Standard Deviation (P82)^2344
      1: 1         Reps
      2: 100       Sample Loc [ AvgTCold  ]

114:  Average (P71)^6046
      1: 1         Reps
      2: 225       Loc [ Power     ]

115:  Standard Deviation (P82)^18660
      1: 1         Reps
      2: 225       Sample Loc [ Power     ]

116:  Average (P71)^24218
      1: 1         Reps
      2: 120       Loc [ ErrLG     ]

117:  Standard Deviation (P82)^3246
      1: 1         Reps
      2: 120       Sample Loc [ ErrLG     ]

118:  Average (P71)^21834
      1: 1         Reps
      2: 121       Loc [ ErrRG     ]

```

```

119: Standard Deviation (P82)^11352
    1: 1      Reps
    2: 121    Sample Loc [ ErrRG      ]

120: Average (P71)^10917
    1: 1      Reps
    2: 123    Loc [ ErrTG      ]

121: Standard Deviation (P82)^22934
    1: 1      Reps
    2: 123    Sample Loc [ ErrTG      ]

122: Average (P71)^6815
    1: 1      Reps
    2: 122    Loc [ ErrBG      ]

123: Standard Deviation (P82)^10690
    1: 1      Reps
    2: 122    Sample Loc [ ErrBG      ]

124: Average (P71)^28125
    1: 1      Reps
    2: 124    Loc [ ErrBKG     ]

125: Standard Deviation (P82)^17927
    1: 1      Reps
    2: 124    Sample Loc [ ErrBKG     ]

126: Sample (P70)^24620
    1: 1      Reps
    2: 255    Loc [ Flag4      ]

127: Sample (P70)^17907
    1: 1      Reps
    2: 256    Loc [ Flag5      ]

;=====

128: Average (P71)^29186
    1: 52     Reps
    2: 34     Loc [ T_1        ]

129: Standard Deviation (P82)^15692
    1: 52     Reps
    2: 34     Sample Loc [ T_1        ]

;=====

130: Do (P86)
    1: 23     Set Flag 3 Low

;*****
*Table 2 Program
    02: 0.125      Execution Interval (seconds)

```

```

;*****
;=====Beginning of Control Loop=====

1:  If Flag/Port (P91)
1: 23      Do if Flag 3 is Low
2: 30      Then Do

        2:  Timer (P26)
        1: 2      Loc [ TmuxEnd  ]

        3:  Do (P86)
        1: 13      Set Flag 3 High

4:  End (P95)

5:  Timer (P26)
1: 3      Loc [ Tread  ]

6:  If (X<=>Y) (P88)
1: 8      X Loc [ Timeout  ]
2: 3      >=
3: 3      Y Loc [ Tread  ]
4: 30     Then Do

        Tcontrol = Tread - TmuxEnd

        Percent = Tcontrol / CycleT

;=====START SSR CONTROL=====

;=====SSR6 - Meter Plate=====

7:  If (X<=>Y) (P88)
1: 9      X Loc [ Percent  ]
2: 3      >=
3: 181    Y Loc [ TonMP    ]
4: 30     Then Do

        8:  If Flag/Port (P91)
        1: 46      Do if Port 6 is High
        2: 30      Then Do

                9:  Do (P86)
                1: 56      Set Port 6 Low

                10: Timer (P26)
                1: 6      Loc [ TstopMP  ]

        11: End (P95)

12: Else (P94)

        13: If Flag/Port (P91)
        1: 56      Do if Port 6 is Low

```

```

2: 30          Then Do

14:  Do (P86)
1: 46          Set Port 6 High

15:  Timer (P26)
1: 7           Loc [ TstartMP ]

16:  End (P95)

;Take Voltage reading from current sense resistor
17:  Volt (Diff) (P2)
1: 1           Reps
2: 24          250 mV 60 Hz Rejection Range
3: 4           DIFF Channel
4: 223         Loc [ MPI          ]
5: 0.005       Multiplier
6: 0.0         Offset

;Take Voltage reading from voltage divider resistor
18:  Volt (Diff) (P2)
1: 1           Reps
2: 25          2500 mV 60 Hz Rejection Range
3: 5           DIFF Channel
4: 224         Loc [ MPV          ]
5: 0.02        Multiplier
6: 0.0         Offset

InstPower = MPV * MPI

19:  End (P95)

;=====SSR1 - Back Guard=====

20:  If (X<=>Y) (P88)
1: 9           X Loc [ Percent    ]
2: 3           >=
3: 176         Y Loc [ TonBKG     ]
4: 30          Then Do

21:  Do (P86)
1: 51          Set Port 1 Low

22:  Else (P94)

23:  Do (P86)
1: 41          Set Port 1 High

24:  End (P95)

;=====SSR2 - Bottom Guard=====

25:  If (X<=>Y) (P88)
1: 9           X Loc [ Percent    ]

```

```

2: 3          >=
3: 177        Y Loc [ TonBG      ]
4: 30         Then Do

        26: Do (P86)
          1: 52          Set Port 2 Low

27: Else (P94)

        28: Do (P86)
          1: 42          Set Port 2 High

29: End (P95)

;=====SSR3 - Top Guard=====

30: If (X<=>Y) (P88)
  1: 9          X Loc [ Percent   ]
  2: 3          >=
  3: 178        Y Loc [ TonTG     ]
  4: 30         Then Do

        31: Do (P86)
          1: 53          Set Port 3 Low

32: Else (P94)

        33: Do (P86)
          1: 43          Set Port 3 High

34: End (P95)

;=====SSR4 - Left Guard=====

35: If (X<=>Y) (P88)
  1: 9          X Loc [ Percent   ]
  2: 3          >=
  3: 179        Y Loc [ TonLG     ]
  4: 30         Then Do

        36: Do (P86)
          1: 54          Set Port 4 Low

37: Else (P94)

        38: Do (P86)
          1: 44          Set Port 4 High

39: End (P95)

;=====SSR5 - Right Guard=====

40: If (X<=>Y) (P88)
  1: 9          X Loc [ Percent   ]

```

```

2: 3          >=
3: 180        Y Loc [ TonRG      ]
4: 30         Then Do

        41: Do (P86)
          1: 55          Set Port 5 Low

42: Else (P94)

        43: Do (P86)
          1: 45          Set Port 5 High

44: End (P95)

;=====END SSR CONTROL=====

45: Else (P94)

        46: If Flag/Port (P91)
          1: 56          Do if Port 6 is Low
          2: 30          Then Do

            TrunMP = TstopMP - TstartMP + (TonMPpuls / 100)

        47: End (P95)

        48: If Flag/Port (P91)
          1: 22          Do if Flag 2 is Low
          2: 30          Then Do

            Power = InstPower * TrunMP / CycleT

            TotPower = TotPower + Power
            TotCycles = TotCycles + 1
            AvgPower = TotPower / TotCycles

        49: Pulse Port w/Duration (P21)
          1: 6           Port
          2: 234         Pulse Length Loc [ TonMPpuls ]

        50: Do (P86)
          1: 12          Set Flag 2 High

        51: End (P95)

52: End (P95)

;=====End of Control Loop=====

*Table 3 Subroutines

End Program
139

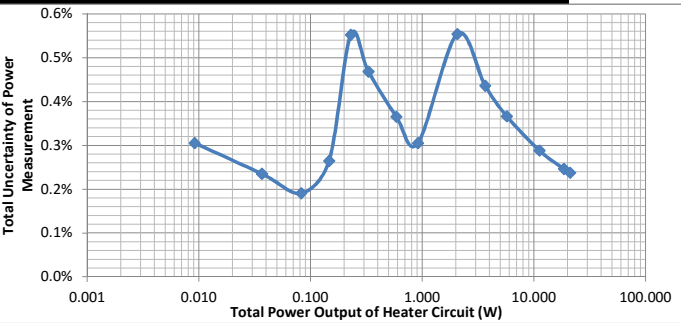
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Appendix I – Meter Plate Power Measurement Spreadsheet

Uncertainty Analysis for DC Heater Measurement Circuit

Resistor Network Details	Measurement Resistors	Heater Resistors	Sense Resistors
Number of Resistor Banks, B (No.)	1	1	5
Number of Resistors / Bank, S (No.)	20	1	1
Resistor Value, R (Ohms)	10,000	109.11	1
Tolerance	0.10%	0.10%	0.10%
Tolerance, wR (Ohms)	10	0.10911	0.001
Equiv resistance of Bank, R_{B_equiv} (Ohms)	200,000	109.11	1
Tolerance of Bank, wR (Ohms)	44.7	0.109	0.001
Equiv resistance of Network, R_{N_equiv} (Ohms)	200,000	109.11	0.20
Tolerance of Network, wR (Ohms)	44.7	0.109	0.000089
Equiv resistance of Network, R_{N_equiv} (Ohms)	109.051	0.20	
Total Resistance (Ohms)	109.251		

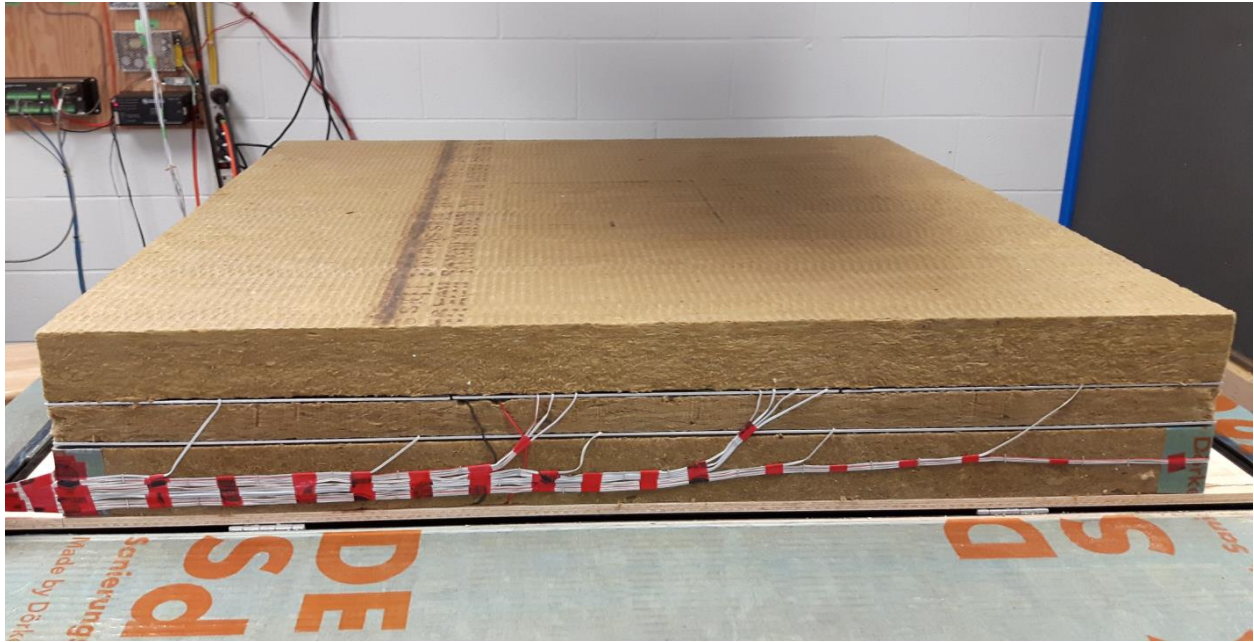
CR10x Uncertainty on DF & SE volts			
Range	DF Offset	SE Offset	
2.5	2.5	0.001250	0.001250
0.25	0.2275	0.000125	0.000125
0.025	0.02275	0.000013	0.000013
0.0075	0.006825	0.000004	0.000004
0.0025	0.002275	0.000001	0.000001
0.0025	0.002275	0.000001	0.000001
For 0 to 40C uncertainty = 0.05% FSR			



Measured & Calculated Values															
Voltage (Volts)	V _{supply}	1	2	3	4	5	6	8	10	15	20	25	35	45	48
	V _{sense} Net	0.002	0.004	0.005	0.007	0.009	0.011	0.015	0.018	0.027	0.037	0.046	0.064	0.082	0.088
	V _{sense}	0.002	0.004	0.005	0.007	0.009	0.011	0.015	0.018	0.027	0.037	0.046	0.064	0.082	0.088
	V _{meas/hr} Net	0.998	1.996	2.995	3.993	4.991	5.989	7.985	9.982	14.973	19.963	24.954	34.936	44.918	47.912
	V _{meas} Net	0.998	1.996	2.995	3.993	4.991	5.989	7.985	9.982	14.973	19.963	24.954	34.936	44.918	47.912
	V _{meas}	0.050	0.100	0.150	0.200	0.250	0.299	0.399	0.499	0.749	0.998	1.248	1.747	2.246	2.396
	V _{htr}	0.998	1.996	2.995	3.993	4.991	5.989	7.985	9.982	14.973	19.963	24.954	34.936	44.918	47.912
Current (Amps)	I _{supply}	0.009	0.018	0.027	0.037	0.046	0.055	0.073	0.092	0.137	0.183	0.229	0.320	0.412	0.439
	I _{sense} Net	0.009	0.018	0.027	0.037	0.046	0.055	0.073	0.092	0.137	0.183	0.229	0.320	0.412	0.439
	I _{sense}	0.002	0.004	0.005	0.007	0.009	0.011	0.015	0.018	0.027	0.037	0.046	0.064	0.082	0.088
	I _{meas/hr} Net	0.009	0.018	0.027	0.037	0.046	0.055	0.073	0.092	0.137	0.183	0.229	0.320	0.412	0.439
	I _{meas} Net	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	I _{meas}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	I _{htr}	0.009	0.018	0.027	0.037	0.046	0.055	0.073	0.091	0.137	0.183	0.229	0.320	0.412	0.439
Power (Watts)	P _{supply}	0.009	0.037	0.082	0.146	0.229	0.330	0.586	0.915	2.059	3.661	5.721	11.213	18.535	21.089
	P _{sense} Net	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.004	0.007	0.010	0.021	0.034	0.039
	P _{sense}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.004	0.007	0.008
	P _{meas/hr} Net	0.009	0.037	0.082	0.146	0.228	0.329	0.585	0.914	2.056	3.655	5.710	11.192	18.501	21.051
	P _{meas} Net	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.003	0.006	0.010	0.011
	P _{meas}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001
	P _{htr}	0.009	0.037	0.082	0.146	0.228	0.329	0.584	0.913	2.055	3.653	5.707	11.186	18.491	21.039

Uncertainty															
Voltage	wVsense	0.000002	0.000006	0.000007	0.000017	0.000018	0.000019	0.000021	0.000023	0.000141	0.000147	0.000152	0.000163	0.000174	0.000178
	wVmeas	0.000126	0.000128	0.000129	0.000131	0.001257	0.001259	0.001262	0.001265	0.001272	0.001280	0.001287	0.001302	0.001317	0.001322
	wVhtr	0.002729	0.003277	0.004015	0.004858	0.025664	0.025917	0.026533	0.027289	0.029716	0.032768	0.036288	0.044272	0.053035	0.055761
Current	wIsense	1.2435E-05	3.08404E-05	3.73051E-05	8.60402E-05	9.22588E-05	9.8561E-05	0.0001136	0.00012435	0.000710039	0.000739386	0.000769138	0.000829683	0.000891379	0.000910078
	wIhtr	1.2435E-05	3.08404E-05	3.73051E-05	8.60402E-05	9.22588E-05	9.8561E-05	0.0001136	0.00012435	0.000710039	0.000739386	0.000769138	0.000829683	0.000891379	0.000910078
Power	wP	0.000028	0.000086	0.000157	0.000387	0.001261	0.001540	0.002136	0.002788	0.011386	0.015932	0.020911	0.032266	0.045604	0.050008
%	wP%	0.31%	0.24%	0.19%	0.26%	0.55%	0.47%	0.37%	0.31%	0.55%	0.44%	0.37%	0.29%	0.25%	0.24%

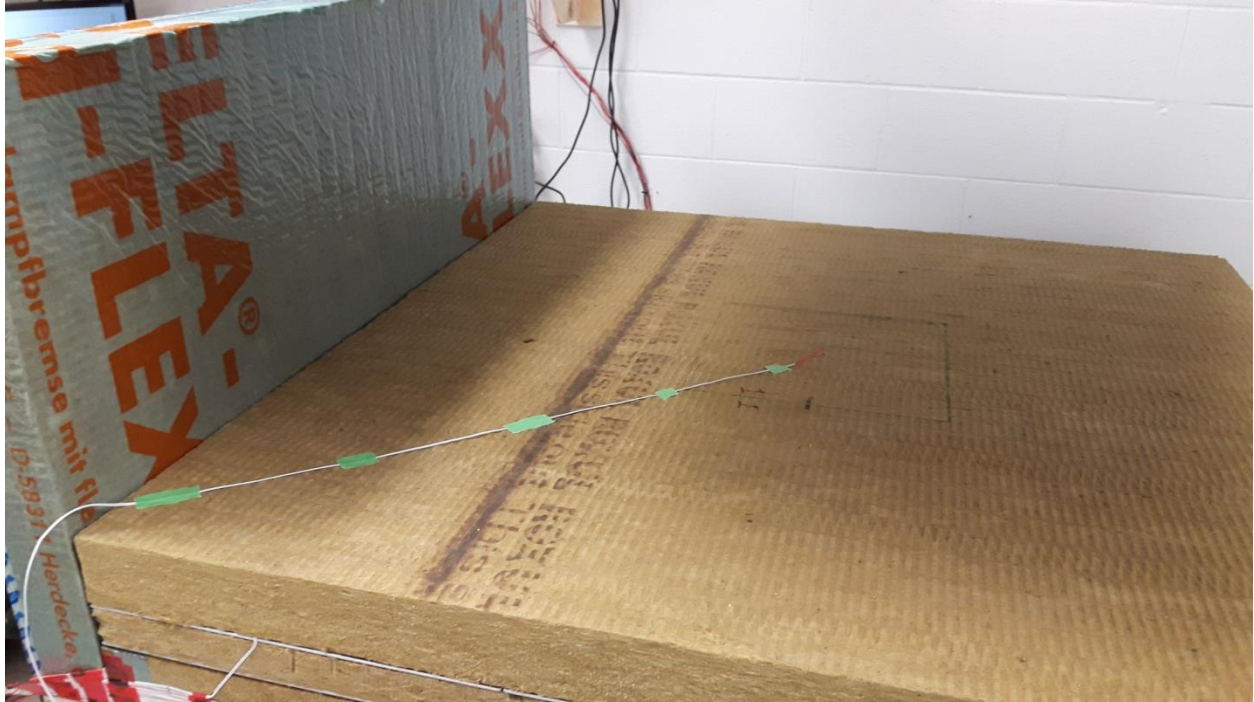
Appendix J – Photos from the Validation Testing



The 3" (76mm) specimen used for validation testing.



The 3" (76mm) specimen used for validation testing with the cold plate on top.



Thermistor placed in the centre of the specimen between the first and second layer of the 6" (152mm) specimen used for validation testing.



The 6" (152mm) specimen used for validation testing.



The 9" (229mm) specimen used for validation testing.

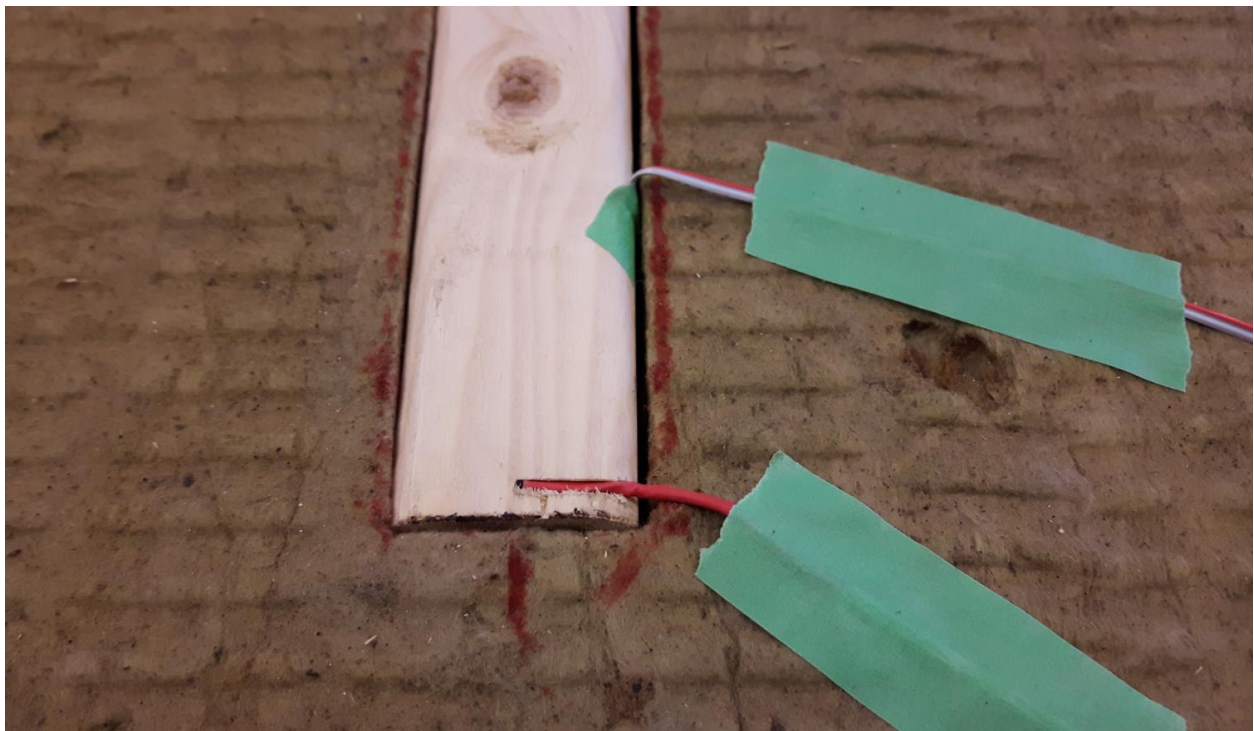


The 9" (229mm) specimen used for validation testing with the cold plate on top.

Appendix K – Photos from the Thermal Bridge Testing



Wood stud installed in the first insulation sample used in the validation testing.



Detailed view of the thermistors on the wood stud. In three locations, one thermistor is placed on each side of the wood stud.



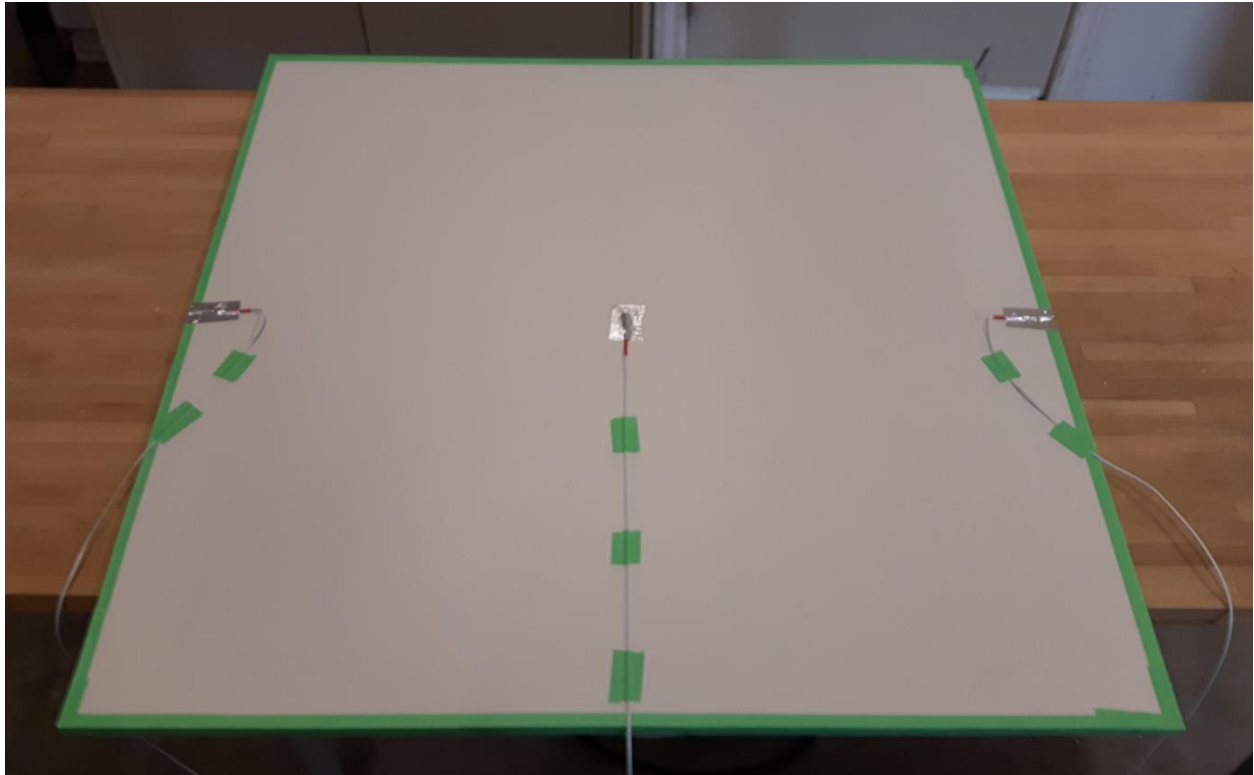
Bottom layers of foam representing a surface film in the thermal bridge testing.



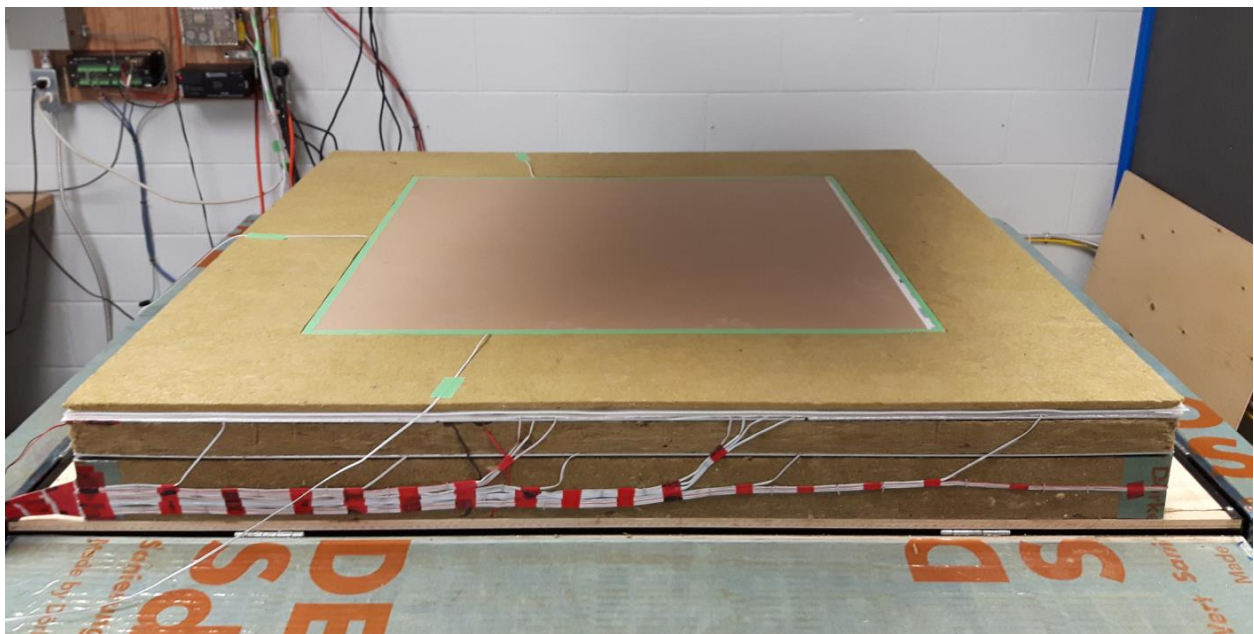
Roxul Monoboard® layer acting as a guard around the inner gypsum board layer (not yet installed).



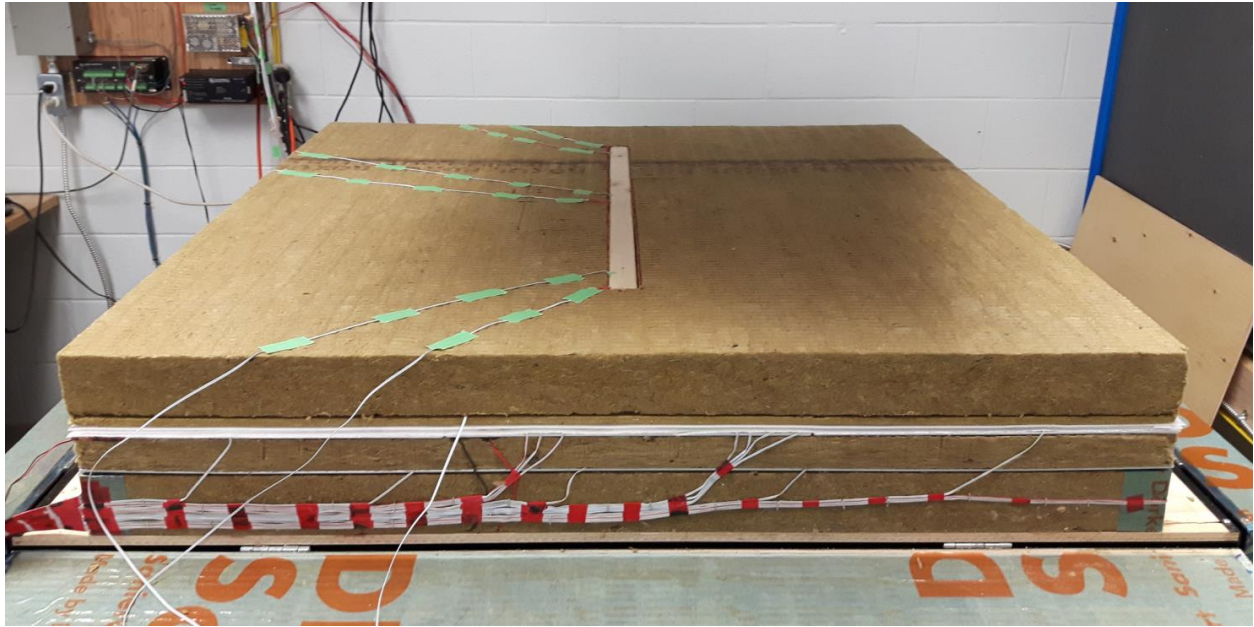
Detailed view of the Roxul Monoboard® layer and foam layers beneath.



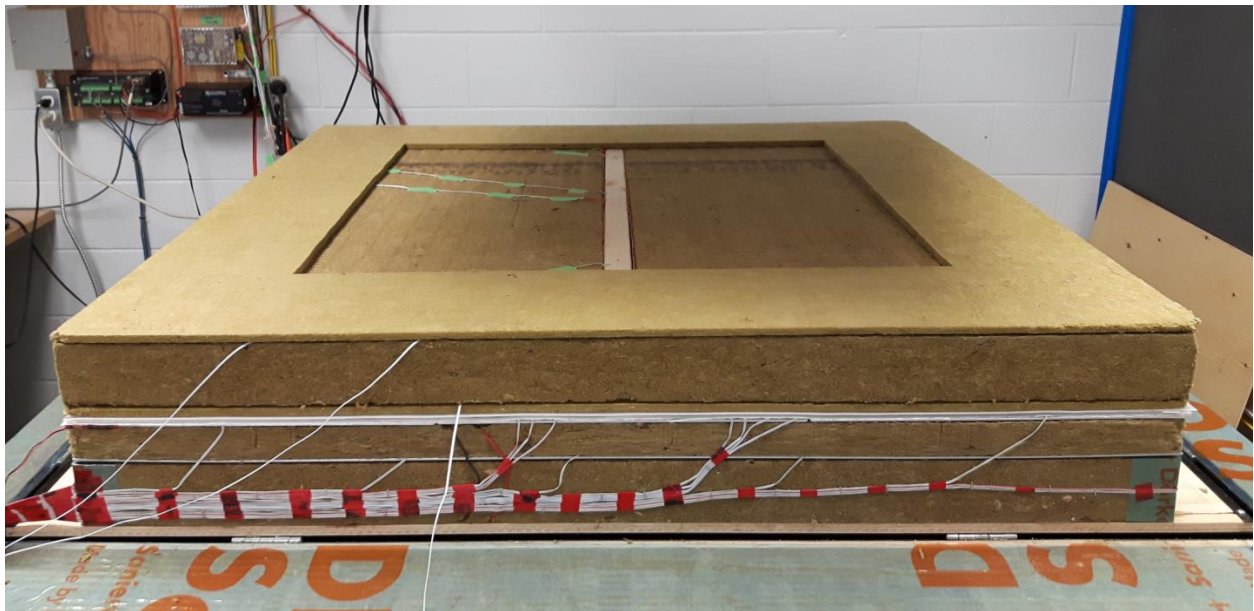
Gypsum board with three thermistors installed. Thermistors are installed in three locations along the stud on the opposite side of the gypsum board.



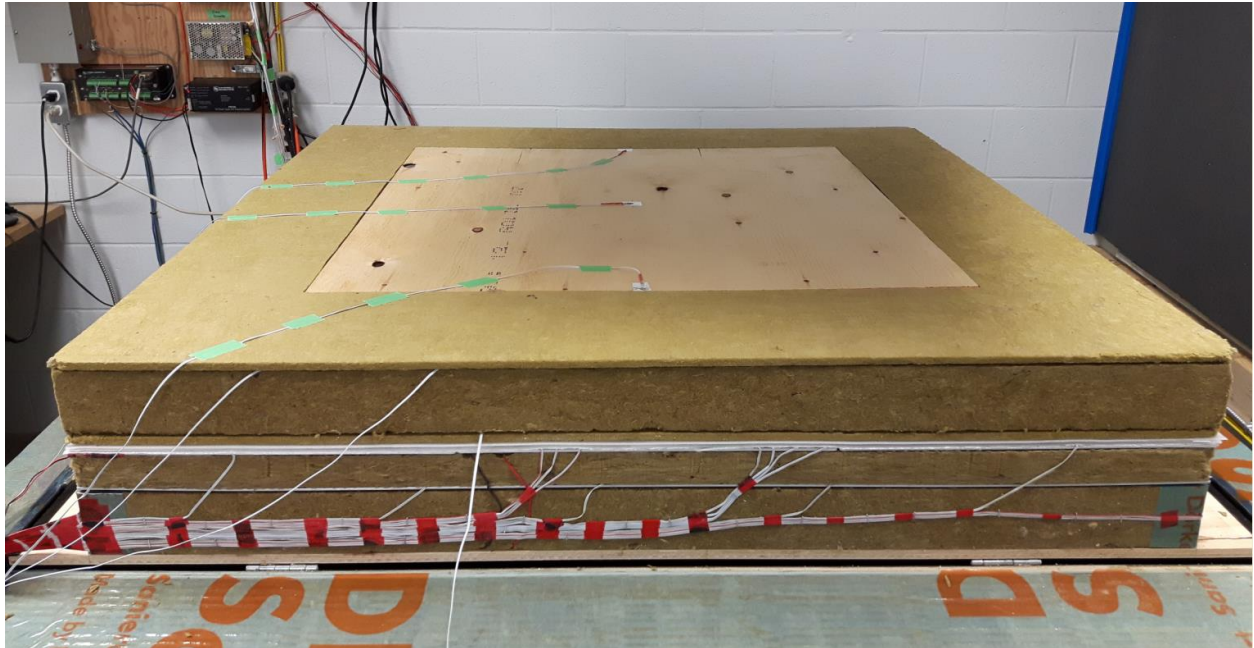
Gypsum board layer installed in the Roxul Monoboard® layer.



Insulation sample with wood stud in the specimen stack.



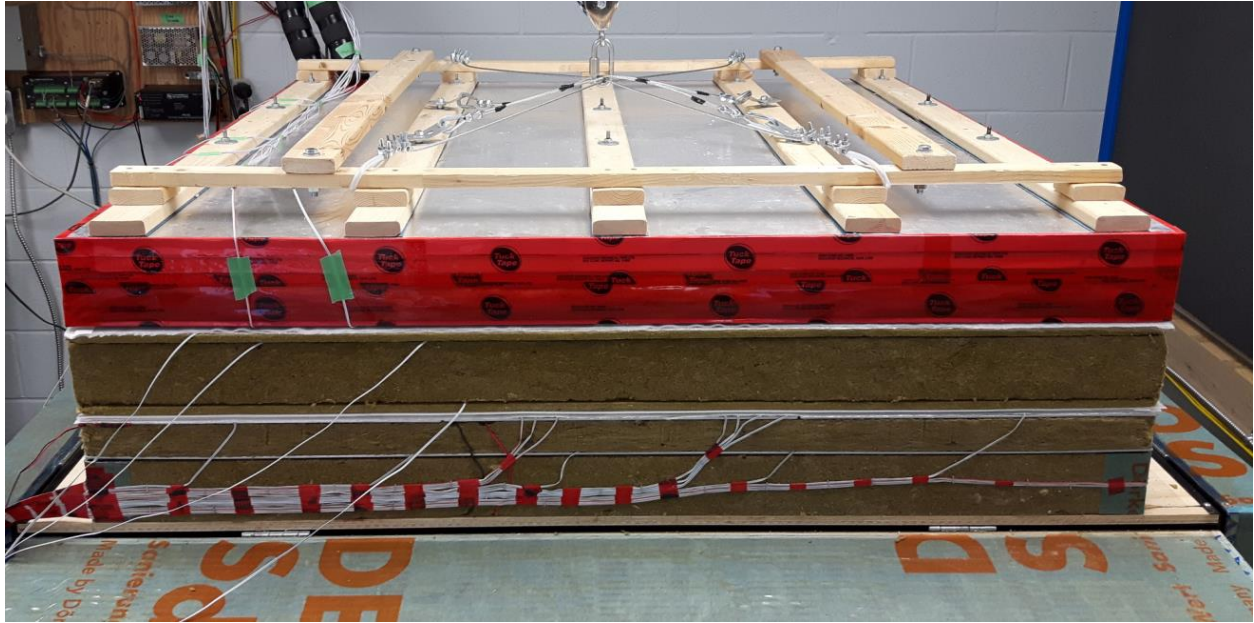
Roxul Monoboard® layer acting as a guard around the inner plywood layer (not yet installed).



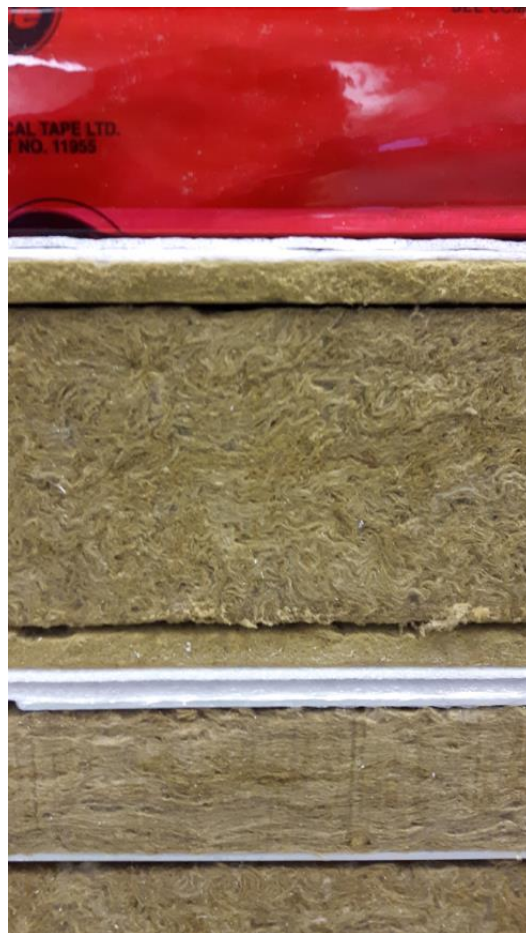
Plywood layer installed within the Roxul MonoBoard® layer.



Top layers of foam representing a surface film in the thermal bridge testing.



Wood stud assembly with cold plate on top.



Detailed view of the edge of the specimen stack.



Steel Z-girt used in the thermal bridge testing. Thermistors are attached to the Z-girt in a similar pattern as the wood stud.



Detailed view of the steel Z-girt.



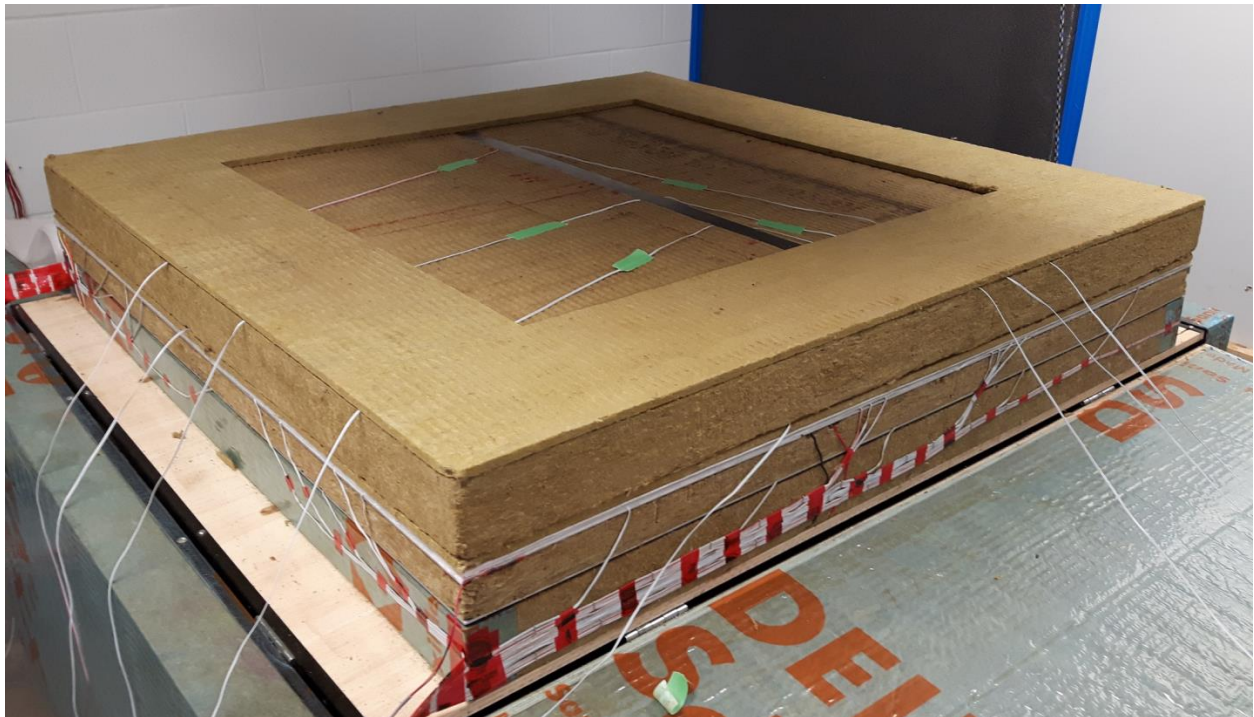
Steel Z-girt installed in the first insulation sample from the validation testing.



Detailed view of the Z-girt in the insulation.



Steel Z-girt and insulation in the specimen stack.



Roxul Monoboard® layer added to the steel Z-girt assembly.