

Artificial Anisotropy for Transverse Thermoelectric Heat Flux Sensing

by
Rebekah Ann Derryberry

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Dr. Scott Huxtable, Advisor

Dr. Thomas Diller, Committee Member

Dr. Mark Paul, Committee Member

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Abstract

Thermoelectric phenomenon describes the relationship between the flow of heat and electricity. Two main categories encompassed in thermoelectric theory are the Seebeck and Peltier effects. The Seebeck effect is the generation of a voltage in a device that consists of two different materials in the presence of a temperature gradient, while the Peltier effect is the generation of a temperature gradient across a device of two different materials in the presence of an electrical current. This project focuses on the first of these two phenomena, where the Seebeck effect is used in a novel heat flux sensor that is transverse in nature. Transverse thermoelectric devices are characterized by their anisotropy, meaning that a temperature gradient generated across a device will be perpendicular to the flow of electricity through the device. This orthogonal arrangement allows for the manipulation of material properties, device arrangement, and construction methods for device optimization.

This project characterizes the heat flux sensing capabilities of an artificially anisotropic transverse thermoelectric device via experimental and theoretical methods. The device tested is constructed out of bismuth telluride and titanium grade 5. Bismuth telluride is a standard thermoelectric material, while the titanium is used because of its high melting point and good electrical conductivity. The device is constructed by alternating rectangular pieces of these two materials. These pieces are bonded together at a given angle to simulate anisotropy. Several devices are constructed in a range of angles from 59° to 88°. These devices are each tested in a vacuum chamber where a heater heats one side of the device. This heat flux into the device creates a temperature gradient across the device and the device generates a voltage perpendicular to this temperature gradient. Steady state data are collected for both the temperature difference between the two sides of the device and the voltage generated by the device. This procedure is repeated on each device for a range of heat fluxes from 0 to 2.6 W/cm². This range generates voltage signals up to 14341 μV for an angle of 59°. Data collected are then used to generate a linear trend line that describes the devices response to a given heat flux. These experimental results are compared to theoretical predictions using thermoelectric theory. The results indicate that the device does exhibit transverse thermoelectric characteristics and the experimental data follow the predicted trends. This thesis documents the process of constructing, testing, and analyzing this device.

Table of Contents

Abstract	ii
Table of Contents	iii
List of Figures	v
List of Tables	viii
1 Introduction and Literature Review	1
1.1 Motivation	1
1.2 History of Thermoelectrics	1
1.3 Thermoelectric Theory	3
1.3.1 Seebeck Effect	4
1.3.2 Peltier Effect	7
1.3.3 Kelvin and Thomson Relationships	8
1.3.4 Thermodynamic Efficiency	8
1.3.5 Intrinsic and Artificial Anisotropy	9
1.4 Summary of Project and Outline of Thesis	10
2 Materials and Experimental Methods	11
2.1 Material Selection	11
2.2 Device Construction	12
2.3 Experimental Setup	14
2.3.1 Vacuum Setup	16
2.3.2 Bulk Material Testing Setup	16
2.3.3 Device Testing	17
2.3.4 Variable Length Testing	17
2.3.5 Experimental Data Analysis	18
2.4 Summary	18
3 Results	19
3.1 Titanium Grade 5 Bulk Material Testing	19
3.2 Early Testing	20
3.3 Theoretical Values	21
3.3.1 Material Properties	21
3.3.2 Governing Equations	21
3.3.3 Characterization of Device Geometry	23
3.4 Time Constant	24
3.5 Experimental Results	25

3.5.1	Description of Devices Tested.....	26
3.5.2	Voltage Signals	26
3.5.3	Sensitivity	29
3.5.4	Temperature Gradients.....	30
3.5.5	Effective Seebeck Value	31
3.6	Comparison of Theoretical and Experimental Data	32
3.6.1	Sources of Error in Theoretical Calculations	35
3.7	Length Comparison Testing.....	37
3.7.1	Length Comparison Testing: Voltage Signals.....	37
3.7.2	Length Comparison Data: Error Sources	39
4	Conclusions and Recommendations.....	40
4.1	Summary of Results and Analysis.....	40
4.2	Recommendations	41
4.3	Conclusions	42
	References	43
	Appendix A. LabView Program Documentation	45
	Appendix B. Titanium Material Test Raw Data.....	58
	Appendix C. Pictures of Device.....	59
	Appendix D. Heat Flux Sensing Data	62
	Vita.....	94

List of Figures

Figure 1.1. Diagram of the Seebeck effect, where a circuit of two dissimilar materials, A and B, generates a voltage when subject to a temperature gradient	4
Figure 1.2. Simple tetragonal lattice structure [14]	5
Figure 1.3. Transverse thermoelectric effect material orientation.....	5
Figure 1.4. Traditional thermoelectric device orientation for $\alpha=0^\circ$ or 90°	5
Figure 1.5. Peltier heat diagram, where a current between two differing materials, A and B, causes heat to be generated or absorbed at the junctions of the two materials.....	7
Figure 1.6. Two methods of creating anisotropy in a thermoelectric device (a) growing a n intrinsically anisotropic material on a miscut substrate and (b) layering two dissimilar materials at an angle [13]	9
Figure 2.1. Diagram of device layering technique.....	12
Figure 2.2. Diagram of device constructed at an angle of α with the surface normal and c-axis shown	12
Figure 2.3. Detailed view of junctions made of indium film and flux between bismuth telluride and titanium pieces.....	12
Figure 2.4. Heater setup used to prepare assembled device in order to bond pieces together and melt away any excess flux.....	13
Figure 2.5. Experimental testing setup for device including ceramic plates and connections for the two thermocouples and voltage leads.....	14
Figure 2.6. Control panel for LabView master program used to collect data, average data over a time period, and to determine whether or not steady state has been achieved	15
Figure 2.7. Vacuum pump and chamber used during testing	16
Figure 2.8. Titanium material testing setup used to find the Seebeck coefficient of the bulk material.....	16
Figure 2.9. Experimental mounting of thermoelectric device on an aluminum heat sink with cartridge heater on top of device.....	17
Figure 3.1. Titanium Grade 5 Seebeck Testing Results with a linear best fit line and a trend line that has an intercept of zero	19
Figure 3.2. Comparison of voltage signals generated for a single device under atmospheric and vacuum conditions	20
Figure 3.3. Length of device as a function of angle of inclination and thickness of pieces.....	23
Figure 3.4. Theoretical voltage signals generated by an 11 piece device at heat flux levels from 4 to 14 W/cm^2	24
Figure 3.5. Voltage and ΔT signals generate over a period of one hour.....	25
Figure 3.6. Summary of voltage signal generated for all devices tested versus heat flux generated by heater	26
Figure 3.7. Comparison of slopes calculated by the methods of a least squares fit and a linear fit through the origin, “volt-ref” refers to the least squares fit and “volt-ref w/zero” refers to linear fit that passes through the origin.....	27
Figure 3.8. Percent difference between least squares fit data and linear fit crossing through the origin for each of the devices.....	28
Figure 3.9. Summary of temperature gradients produced within devices for a given heat flux...	30
Figure 3.10. Summary of temperature gradient and voltage data for each device tested	31
Figure 3.11. Comparison of experimental and theoretical sensitivity	32
Figure 3.12. Comparison of experimental and theoretical effective Seebeck	34

Figure 3.13. Effects on sensitivity of changing the Seebeck and thermal conductivities of bismuth telluride by +/- 10% from their nominal values	36
Figure 3.14. Effects on sensitivity of changing the Seebeck and electrical conductivities by +/- 10% from their nominal values.....	37
Figure 3.15. Summary of voltage signals produced by various length devices for a range of heat flux values and least squares linear trend lines.....	38
Figure 3.16. Comparison of experimental and predicted values of sensitivity for a 68° device at various lengths with the standard deviation of the experimental values shown as error bars.....	39
Figure 4.1. Comparison of experimental and predicted results for effective Seebeck of device at various angles with a ‘Positive Shift’ indicating a 10% increase in S-Bi ₂ Te ₃ , 10% decrease in σ -Bi ₂ Te ₃ , and a 10% increase in σ -Ti; ‘Negative Shift’ indicating a 10% decrease in S-Bi ₂ Te ₃ , 10% increase in σ -Bi ₂ Te ₃ , and a 10% decrease in σ -Ti	40
Figure 4.2. Example of regularly shaped device with smooth edges and simple geometry	42
Figure C.1. Picture of device 5 with $\alpha=65^\circ$	59
Figure C.2. Picture of device 6 with $\alpha=59^\circ$	59
Figure C.3. Picture of device 7 with $\alpha=75^\circ$	60
Figure C.4. Picture of device 8 with $\alpha=79^\circ$	60
Figure C.5. Picture of device 9 with $\alpha=73^\circ$	60
Figure C.6. Picture of device 10 with $\alpha=70^\circ$	61
Figure C.7. Picture of device 11 with $\alpha=88^\circ$	61
Figure C.8. Picture of device 12 with $\alpha=68^\circ$	61
Figure D.1. Device 5: voltage signal generated vs. heat flux	63
Figure D.2. Device 5: delta T generated vs. heat flux.....	64
Figure D.3. Device 5: delta T generated vs. voltage signal generated.....	64
Figure D.4. Device 6: voltage signal generated vs. heat flux	66
Figure D.5. Device 6: delta T generated vs. heat flux.....	66
Figure D.6. Device 6: delta T generated vs. voltage signal generated.....	67
Figure D.7. Device 7: voltage signal generated vs. heat flux	69
Figure D.8. Device 7: delta T generated vs. heat flux.....	69
Figure D.9. Device 7: delta T generated vs. voltage signal generated.....	70
Figure D.10. Device 8: voltage signal generated vs. heat flux	72
Figure D.11. Device 8: delta T generated vs. heat flux.....	72
Figure D.12. Device 8: delta T generated vs. voltage signal generated.....	73
Figure D.13. Device 9: voltage signal generated vs. heat flux	75
Figure D.14. Device 9: delta T generated vs. heat flux.....	75
Figure D.15. Device 9: delta T generated vs. voltage signal generated.....	76
Figure D.16. Device 10: voltage signal generated vs. heat flux	77
Figure D.17. Device 10: delta T generated vs. heat flux.....	77
Figure D.18. Device 10: delta T generated vs. voltage signal generated.....	78
Figure D.19. Device 11: voltage signal generated vs. heat flux	80
Figure D.20. Device 11: delta T generated vs. heat flux.....	80
Figure D.21. Device 11: delta T generated vs. voltage signal generated.....	81
Figure D.22. Device 12/A: voltage signal generated vs. heat flux	83
Figure D.23. Device 12/A: delta T generated vs. heat flux	83
Figure D.24. Device 12/A: delta T generated vs. voltage signal generated	84
Figure D.25. Device B: voltage signal generated vs. heat flux	86
Figure D.26. Device B: delta T generated vs. heat flux.....	86
Figure D.27. Device B: delta T generated vs. voltage signal generated	87

Figure D.28. Device C: voltage signal generated vs. heat flux	89
Figure D.29. Device C: delta T generated vs. heat flux.....	89
Figure D.30. Device C: delta T generated vs. voltage signal generated	90
Figure D.31. Device D: voltage signal generated vs. heat flux	92
Figure D.32. Device D: delta T generated vs. heat flux.....	92
Figure D.33. Device D: delta T generated vs. voltage signal generated	93

List of Tables

Table 2.1. Material properties of bismuth telluride and titanium grade 5.....	11
Table 3.1. Material properties of bismuth telluride and titanium grade 5 used in theoretical calculations	21
Table 3.2. Summary of number, angle, length, and area for each 11 piece device tested	26
Table 3.3. Slopes and intercepts for least squares linear fits of voltage and heat flux data.....	28
Table 3.4. Average experimental sensitivity of devices.....	29
Table 3.5. Comparison of sensitivity values found by averaging experimental data and finding slope of linear best fit line	29
Table 3.6. Comparison of predicted and measure values of sensitivity	32
Table 3.7. Comparison of predicted and measure values of sensitivity	33
Table 3.8. Comparison of predicted and measure values of sensitivity	34
Table 3.9. Effects of changing material properties on the predicted sensitivity and effective Seebeck.....	35
Table 3.10. Name, number of pieces, length, and area for devices used in length comparison testing	37
Table 3.11. Percent difference between measured and theoretical sensitivity for 68° device of various lengths	39
Table B.1. Titanium material testing raw data	58
Table D.1. Device 5 Raw Data	62
Table D.2. Device 6 raw data	65
Table D.3. Device 7 raw data	68
Table D.4. Device 8 raw data	71
Table D.5. Device 9 raw data	74
Table D.6. Device 10 raw data	76
Table D.7. Device 11 raw data	79
Table D.8. Device 12/A raw data.....	82
Table D.9. Device B raw data.....	85
Table D.10. Device C raw data.....	88
Table D.11. Device D raw data.....	91

1 Introduction and Literature Review

1.1 Motivation

Thermal management in industrial, residential, and commercial applications has become very common place. Temperature measurement is done in most applications, but its counterpart, the measurement of heat flux is not utilized nearly as much. Temperature is fundamental, whereas heat flux is a derived quantity, but often times it is more important to quantify heat flux than temperatures. Determining how and where thermal energy is used is key to being able to optimize thermal machinery, therefore making heat flux sensors an essential component to any system where there is heat transfer involved [1]. This project explores the use of an artificially transverse thermoelectric device for heat flux sensing. A transverse thermoelectric device has an advantage over traditional heat flux sensors in that it can be made extremely thin to generate fast response times and still have an appreciable signal. Whereas traditional heat flux sensors have a signal that is proportional to the thickness of the sensor, therefore a larger signal sacrifices response time [2]. This project gives considerations to the current state of thermoelectric devices and materials, develops and tests a prototype under various operating conditions, calculates experimental averages, and compares experimental results to predictions made by theory. Chapter 1 contains the history of thermoelectric devices and the theory behind thermoelectricity. Chapter 2 discusses the methods used to select the materials utilized, device construction, experimental setup, and testing methods. Chapter 3 covers the results of the experimental testing and the theoretical predictions. Chapter 4 discusses the implications of the project and makes suggestions for further work that can be done to improve the device and understanding of thermoelectrics in general.

1.2 History of Thermoelectrics

The long history of thermoelectrics can be broken up into three periods of development. The first period began in 1823 when Thomas Seebeck conducted an experiment that is the basis for thermoelectric generators. Seebeck produced an electromotive force by heating a junction between two dissimilar metals that formed a closed loop. Seebeck mistakenly connected it to his ideas about the earth's magnetism causing a temperature difference between the poles. In reality, he had discovered the thermoelectric effect [3]. In 1834, Jean C.A. Peltier discovered the opposite effect by passing a current through a series of conductors, thus producing a temperature

gradient. Unfortunately, Peltier did not relate his discovery to the one made by Seebeck 12 years earlier [3, 4]. A couple years later in 1838, Lenz concluded that the direction of the current flow between two dissimilar conductors determined whether heat was absorbed or generated [5]. Lord Kelvin determined a relationship between the Seebeck and Peltier coefficients in 1851 [6]. After this discovery, research on thermoelectricity was primarily pursued at Leningrad University in Russia.

At Leningrad, Altenrich created theories of thermoelectric generation and refrigeration in 1909 and 1911, respectively. He also concluded that good thermoelectric materials would have a large Seebeck coefficient (S), low thermal conductivity (k), and high electrical conductivity (σ). Altenrich proposed that a figure of merit, Z , shown in Equation 1.1, be used as a measure of the quality of a thermoelectric device [7].

$$Z = \frac{S^2 \sigma}{k} \quad \text{Eq 1.1}$$

The figure of merit can also be written as a non-dimensional figure of merit ZT as shown in Equation 1.2, where T is the absolute temperature.

$$ZT = \frac{S^2 \sigma}{k} T \quad \text{Eq 1.2}$$

Altenrich's conclusion highlighted the difficulty in finding an effective thermoelectric material because metals generally have small Seebeck coefficients less than or equal to $10 \mu\text{V/K}$ and their electrical and thermal conductivity cannot be varied independently. This all changed in the 1930s when synthetic semiconductors were created that had Seebeck coefficients greater than $100 \mu\text{V/K}$ [3].

These new materials caused resurgence in the interest of thermoelectrics. In 1947, Telkes made a power generator with 5% efficiency [8]. In 1954, Goldsmid and Douglas demonstrated that cooling from ambient temperatures to below 0°C was possible with thermoelectrics [9]. Ioffe showed in 1956 that the ratio of thermal to electrical conductivity could be decreased by adding an amorphous element or compound into a material [10]. In 1959, Zener predicted thermoelectric materials would produce cooling with performances equal to those of compression cycle machines using Freon and produce electricity on the level of steam turbines and alternators [4]. This grand prediction spurred over 100 companies to become active in thermoelectrics [4]. Zener's predictions failed to come to fruition because of the much faster development and higher efficiency of compression cycle machines using Freon and electricity.

Lately, there has been a renewed interest in thermoelectrics because of the development of nanoscale materials and testing methods. Today, thermoelectrics come in a wide range of sizes, uses, and materials. Over 100 companies are not developing them anymore, but they do have a special niche market where the advantages of thermoelectrics outweigh their poor efficiency levels [4].

For very small cooling applications (less than 50 W), such as those in electronics, thermoelectrics are ideal because they have no moving parts, require no maintenance, and provide sufficient cooling. These small devices have not changed considerably over the past 20 years, but the techniques used to manufacture them have improved [9]. Commercial equipment also incorporates thermoelectric coolers for spot cooling. Up to 50 Watts of cooling is provided by thermoelectrics in devices like dew point meters, blood analyzers, and temperature control systems [9]. A common way an everyday consumer uses a thermoelectric device is in a portable picnic cooler. This kind of cooler runs on a standard car battery, generates around 20 Watts of cooling power, and can produce ice if it is not too hot outside [12]. On a larger scale, a thermoelectric system has been in use as an air conditioner for the French Railways since 1981 [13]. In general though, between 50 and 1000 W, thermoelectrics are always more costly and less efficient than vapor compression cycles. For these large systems, a thermoelectric device will only be useful when one of the following is important: redundancy and reliability, flexibility of operation, transient mode, and/or quietness and safety. Thermoelectrics typically consist of subunits, so if one or two subunits fail, they can be short-circuited without losing the operation of the entire unit. As cooling power is reduced, the coefficient of performance for a thermoelectric device increases, unlike compression cycles where the coefficient of performance decrease as cooling power is reduced. Thermoelectric devices have little thermal inertia, so the device reaches steady state much faster than a standard compression cycle. As said before, thermoelectrics have no moving parts and no thermal compression fluid that could be considered a health hazard, so they are quiet and safe to use [9]. Additionally, thermoelectrics have the advantage of being able to heat or cool, so they are ideal for applications that involve temperature control.

1.3 Thermoelectric Theory

Thermoelectric phenomenon describes the relationship between the flow of heat and electricity. These are the Seebeck effect, the Peltier effect, and the Thomson effect which are

described in the following sections. The thermoelectric properties of a material are measurable and are bulk properties of a given material just like electrical or thermal conductivity. The Seebeck, Peltier, and Thomson relations are commonly used to characterize materials that exhibit thermoelectric properties. [13]

1.3.1 Seebeck Effect

The Seebeck effect is when a circuit of two dissimilar materials that are subject to a temperature gradient generates a voltage as shown in Figure 1.1.

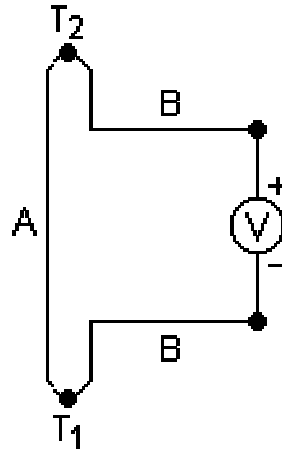


Figure 1.1. Diagram of the Seebeck effect, where a circuit of two dissimilar materials, A and B, generates a voltage when subject to a temperature gradient

For small temperature gradients the voltage, E , is proportional to the temperature gradient as shown in Equation 1.3.

$$E = S \cdot \Delta T \quad \text{Eq 1.3}$$

The Seebeck coefficient, S , is dependent upon the properties of the material being used and is given by Equation 1.4 for a material that has a tetragonal geometry [3, 21].

$$S = \begin{pmatrix} S_{\parallel} \cos^2 \alpha + S_{\perp} \sin^2 \alpha & 0 & (S_{\parallel} - S_{\perp}) \frac{\sin(2\alpha)}{2} \\ 0 & S_{\parallel} & 0 \\ (S_{\parallel} - S_{\perp}) \frac{\sin(2\alpha)}{2} & 0 & S_{\parallel} \sin^2 \alpha + S_{\perp} \cos^2 \alpha \end{pmatrix} \quad \text{Eq 1.4}$$

Tetragonal geometry results from stretching a cubic lattice along one of its vectors, resulting in a rectangular prism as shown in Figure 1.2 [14].

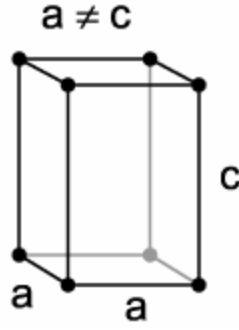


Figure 1.2. Simple tetragonal lattice structure [14]

$S_{\parallel}$ and $S_{\perp}$ in Equation 1.4 are the “in-plane” and “out-of-plane” Seebeck values, respectively. The angle between the surface normal and the c-axis, as shown in Figure 1.3, is represented by α .

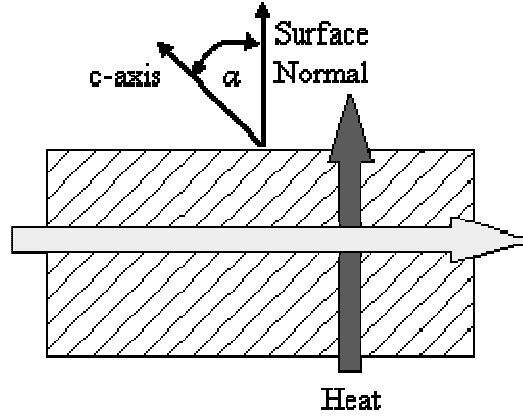


Figure 1.3. Transverse thermoelectric effect material orientation

In traditional thermoelectric devices, the c-axis is most often parallel ($\alpha = 0^\circ$) or perpendicular ($\alpha = 90^\circ$) to the surface normal. A material with $\alpha = 0^\circ$ is shown in Figure 1.4. For this device, the off-diagonal terms in the Seebeck tensor become zero (shown in Equation 1.5) and the current and heat flow are parallel to one another.

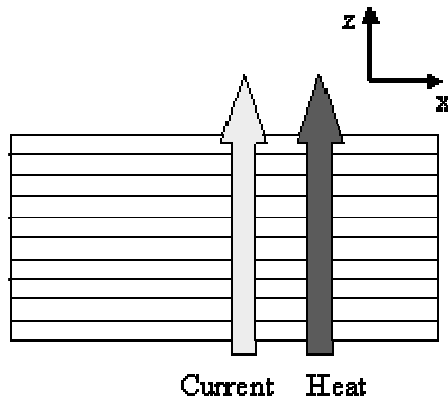


Figure 1.4. Traditional thermoelectric device orientation for $\alpha=0^\circ$ or 90°

$$S = \begin{pmatrix} S_{\parallel} & 0 & 0 \\ 0 & S_{\parallel} & 0 \\ 0 & 0 & S_{\perp} \end{pmatrix} \quad \text{Eq 1.5}$$

If a material is oriented with α at an angle to the surface normal as shown in Figure 1.5, the current and heat flow are perpendicular to one another, this is called a transverse thermoelectric device. For a transverse thermoelectric device the voltage signal in the z -direction becomes Equation 1.6.

$$E = \frac{1}{2} \sin(2\alpha) (S_{\parallel} - S_{\perp}) \nabla_z T \quad \text{Eq 1.6}$$

The orthogonal nature of the heat and electrical current flow opens the door for a new class of thermoelectrics where there is more freedom to optimize material properties, layout, and fabrication of the devices [2]. In order for a device to be effective in the transverse orientation, the in- and out-of-plane Seebeck coefficients ($S_{\parallel}$ and $S_{\perp}$) must be significantly different. Meaning, the material must be strongly anisotropic. This anisotropy causes the heat and current to flow perpendicular to one another as shown in Figure 1.5. This perpendicularity of heat and current flow is particularly useful for heat flux sensors. Commercial heat flux sensors frequently have signals that are proportional to thickness, and the thicker the device the slower the time response, resulting in a slow response time for an appreciable signal. If a transverse thermoelectric device is connected to a heat sink, the heat flux going into the device is that shown in Equation 1.7, where k_{zz} is thermal conductivity along the z -axis shown in Equation 1.8 [22].

$$q'' = \frac{P}{A} = (\nabla_z T) k_{zz} \quad \text{Eq 1.7}$$

$$k_{zz} = k_{\parallel} \sin^2 \alpha + k_{\perp} \cos^2 \alpha \quad \text{Eq 1.8}$$

The effective value k_{zz} is based on the in- and out-of-plane thermal conductivities. For a traditional thermoelectric device, k_{zz} would be reduced to $k_{\parallel}$. Since the heat flux is proportional to area, ultimately, the voltage signal (V_x) produced by a transverse thermoelectric device is proportional to the length of the device as shown in Equation 1.9.

$$V_x = \frac{1}{2} (S_{\parallel} - S_{\perp}) \frac{\sin(2\alpha) q''}{k_{\parallel} \sin^2 \alpha + k_{\perp} \cos^2 \alpha} l \quad \text{Eq 1.9}$$

This means a transverse thermoelectric device can be made extremely thin and can achieve very fast response times and still have an appreciable signal.

1.3.2 Peltier Effect

The Peltier effect occurs when an electric current that passes from one material to another causes heat to be absorbed or generated in the junction regions, depending on the flow of the current as demonstrated in Figure 1.5.

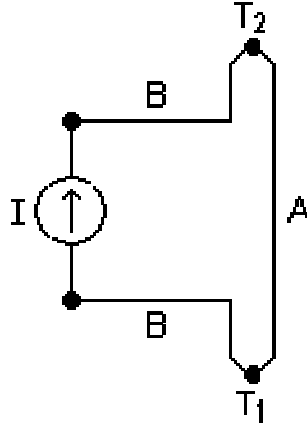


Figure 1.5. Peltier heat diagram, where a current between two differing materials, A and B, causes heat to be generated or absorbed at the junctions of the two materials

The current drives heat from one junction to the other, resulting in thermoelectric cooling. This cooling is very different from Joule heating, which occurs in all conductors (except superconductors). Peltier heat is linear with current density, but Joule heat follows the square of current; Peltier heat can be positive or negative, depending on the direction of current, but Joule heat is always positive; Peltier heat is reversible, but Joule heat is irreversible [13]. Peltier heat is given by Equation 1.10, where $\dot{Q}$ is the rate of heat absorption, Π is the reversible Peltier heat developed per unit per unit electric current, and I is the current.

$$\dot{Q} = \Pi * I \quad \text{Eq 1.10}$$

Peltier heat additionally depends on the common temperature at the junction of the two conductors. Despite the fact that the Peltier heat is either evolved or absorbed at the junction between the two conductors, it does not have anything to do with the properties of the junction itself. Peltier heat is just a function of the two materials that form the junction, where each of the two materials makes its own contribution to the Peltier heat. This individual effect can be

observed if a conductor were joined with a superconductor (which makes no contribution to Peltier heat).

1.3.3 Kelvin and Thomson Relationships

The Thomson relations draw the conclusion that there is an additional thermoelectric effect beyond Peltier and Seebeck. This leads to an equation that states if an electric current density (J_x) is passing through an individual conductor in the presence of a temperature gradient (dT/dx), and the net heat generated is given by Equation 1.11.

$$\dot{Q} = \frac{J_x^2}{\sigma} - \mu J_x \frac{dT}{dx} \quad \text{Eq 1.11}$$

The first term in Equation 1.11 is the irreversible Joule heat and the second term is the thermoelectric heat. The Thomson heat is represented by μ . Equation 1.11 is the fundamental equation of thermoelectricity. Additionally, the Kelvin relationships were developed to correlate all of the thermoelectric properties together as shown in Equations 1.12 and 1.13.

$$\mu = T \frac{dS}{dT} \quad \text{Eq 1.12}$$

$$\Pi = TS \quad \text{Eq 1.13}$$

In these equations, S is the Seebeck coefficient, T is the temperature, and Π is the Peltier heat. These relationships show how to create a complete set of knowledge on the thermoelectric properties of a conductor based upon the Seebeck coefficient [13].

1.3.4 Thermodynamic Efficiency

Thermodynamic efficiency of a power generating thermoelectric device without contact resistance is given by Equation 1.14, where P_o is the electrical power generated as shown in Equation 1.15 and Q_h is heat added to the system as shown in Equation 1.16.

$$\eta_t = \frac{\hat{P}_o}{\hat{Q}_h} \quad \text{Eq 1.14}$$

$$\hat{P}_o = nP_o \quad \text{Eq 1.15}$$

$$\hat{Q}_h = nQ_h \quad \text{Eq 1.16}$$

In these equations, n is the number of components in the thermoelectric device. Ultimately, the efficiency is calculated using Equation 1.17, where μ is a dimensionless quantity given by Equations 1.18 and 1.19. R is the electrical resistance of the device, Z is the figure of merit, η_c is

the Carnot efficiency shown in Equation 1.20, and T_h is the temperature of the hot side of the device [3].

$$\eta_t = \frac{\mu\eta_c}{[(\mu+1)^2/ZT_h + (\mu+1) - \eta_c/2]} \quad \text{Eq 1.17}$$

$$\mu = \frac{R_o}{R} \quad \text{Eq 1.18}$$

$$R_o = \frac{P_o}{I^2} = \frac{\text{Electrical Power Out}}{\text{Current}} \quad \text{Eq 1.19}$$

$$\eta_c = \frac{\Delta T}{T_h} \quad \text{Eq 1.20}$$

1.3.5 Intrinsic and Artificial Anisotropy

To get the off diagonal terms of the Seebeck tensor in Equation 1.4 to be nonzero, the material being used in a thermoelectric device must be anisotropic. There are two methods of achieving anisotropy within a device. One way is that a device can be made of a single material that is intrinsically anisotropic, such as growing single-crystal bismuth, $\text{YBa}_2\text{Cu}_3\text{O}_{7-8}$, or some other anisotropic material on a miscut substrate so the c-axis is angled away from the surface normal. Alternatively, a device can be constructed by alternating layers of materials with different thermoelectric properties and cutting the device at an angle [13]. These two methods are shown in Figure 1.6.

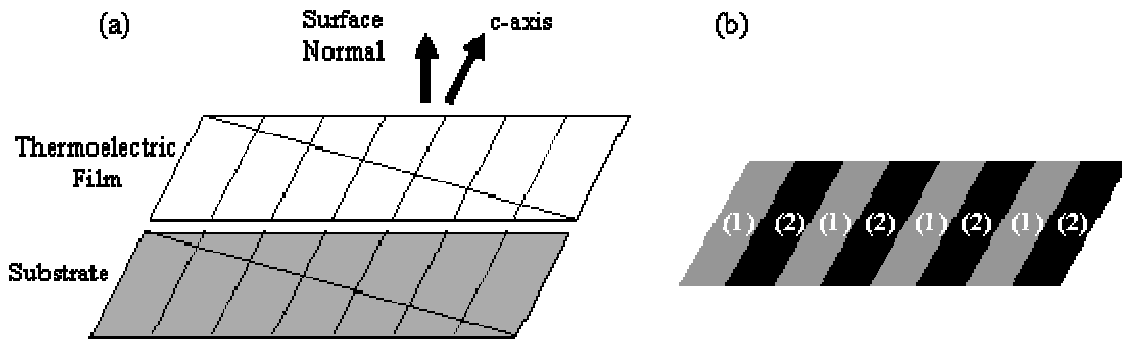


Figure 1.6. Two methods of creating anisotropy in a thermoelectric device (a) growing an intrinsically anisotropic material on a miscut substrate and (b) layering two dissimilar materials at an angle [13]

An intrinsically anisotropic device as shown in Figure 1.6a is typically a thin film device that can have a very quick response time and can be easily mass-produced. The artificially anisotropic device shown in Figure 1.6b can be considered as a single anisotropic material if the length of the device is much larger than the thickness of each individual layer [15]. Since the artificially anisotropic device must be constructed on a layer-by-layer basis, it would prove to be more

difficult to mass-produce, but it has advantages for laboratory testing. The layered device is easier to construct because it does not require the use of a clean room and it can be cut and assembled by hand due to the larger nature of the components. The only difficulty in using a layered device lies in the junctions between each of the layers; the material used to make the connections cannot contribute significantly to the performance of the device to ensure accurate results.

1.4 Summary of Project and Outline of Thesis

This project focuses on developing, testing, and evaluating the effectiveness of an artificially anisotropic thermoelectric device used for heat flux sensing. In Chapter 2, considerations during device development, device construction, experimental methods, and analysis steps are discussed. Chapter 3 discusses and compares the experimental results and theoretical performance calculations as well as discussing potential sources of error. Chapter 4 summarizes the findings of the experiment and makes suggestions for future work.

2 Materials and Experimental Methods

This chapter describes the basis for the materials chosen for the thermoelectric device, the construction of the device, the testing procedures, and the analysis methods used.

2.1 Material Selection

For a thermoelectric device that is constructed of two materials to generate a voltage signal, the materials must have different thermal and electrical conductivities [16]. The chief parameters that govern the performance of a thermoelectric device are the Seebeck coefficient S , the electrical conductivity σ , and the thermal conductivity k . Ideal materials for a thermoelectric device will have high electrical conductivity, high Seebeck coefficient, and low thermal conductivity.

A proven thermoelectric material, p-type bismuth telluride (Bi_2Te_3), which has a ZT of 1.13 [17], was chosen for the first material. It has been shown that a combination of a semiconductor (bismuth telluride) and a metal in a thermoelectric device create an effective contrast of properties and work well in transverse applications; therefore, metals with high electrical conductivities and melting points above the operating temperatures of the device were considered for the second component of the device. Originally, aluminum was selected because of its high melting point (650 °C) and low electrical resistivity (3×10^{-6} ohm-cm.), but ultimately only a very small signal could be produced from a device made from aluminum due to its high thermal conductivity (220 W/m-K) [18]. Based on this information, it was decided that the best metal to use would be one with a very low thermal conductivity. Ultimately, Titanium Grade 5 (purchased from McMaster-Carr) was selected as the second material. The properties of bismuth telluride and titanium grade 5 are shown in Table 2.1.

Table 2.1. Material properties of bismuth telluride and titanium grade 5

	Seebeck Coefficient ($\mu\text{V/K}$)	Electrical Resistivity ($1/\Omega\cdot\text{m}$)	Thermal Conductivity (W/m-K)	Melting Point ($^\circ\text{C}$)
p-type Bismuth Telluride [19]	250	2.11×10^5	1.5	585
Titanium Grade 5 [20]	3.9*	5.62×10^5	6.7	1660

*from experimental testing described in 2.4.1

2.2 Device Construction

The device tested consists of alternating pieces of bismuth telluride and titanium. Individual pieces are cut to dimensions of 1.35 mm x 7.91 mm x 5.35 mm using a Buehler Isomet Low Speed Saw. The main device tested is 11 pieces in length with 6 pieces of bismuth telluride and 5 pieces of titanium as shown in Figure 2.1.

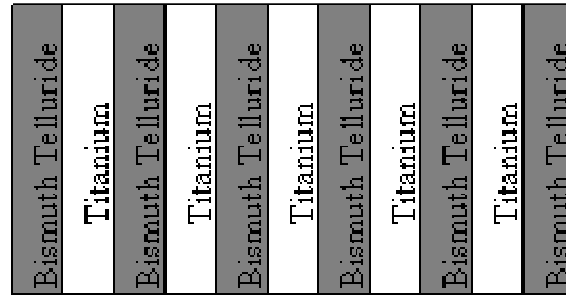


Figure 2.1. Diagram of device layering technique

Figure 2.2 shows how the pieces are assembled at an angle from the vertical orientation to achieve anisotropy.

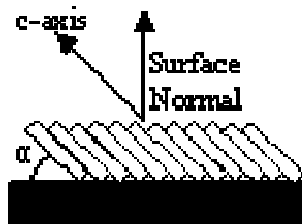


Figure 2.2. Diagram of device constructed at an angle of α with the surface normal and c-axis shown

The pieces are bonded together using indium film and flux, from the Indium Corporation of America. A detailed view of the junctions made within the device is shown in Figure 2.3.

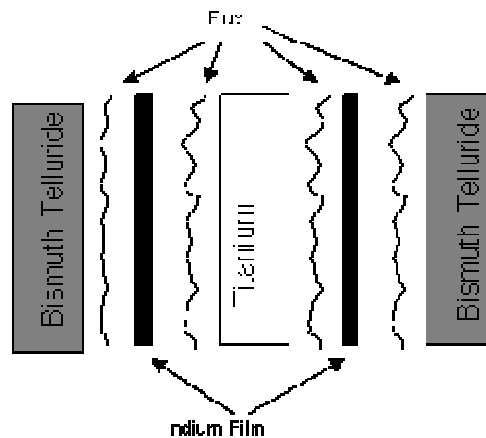


Figure 2.3. Detailed view of junctions made of indium film and flux between bismuth telluride and titanium pieces

The device is assembled with all components at room temperature on a ceramic plate with a piece of foam that is used to keep the desired angle. The assembly is then placed on a cartridge heater and heated as shown in Figure 2.4.

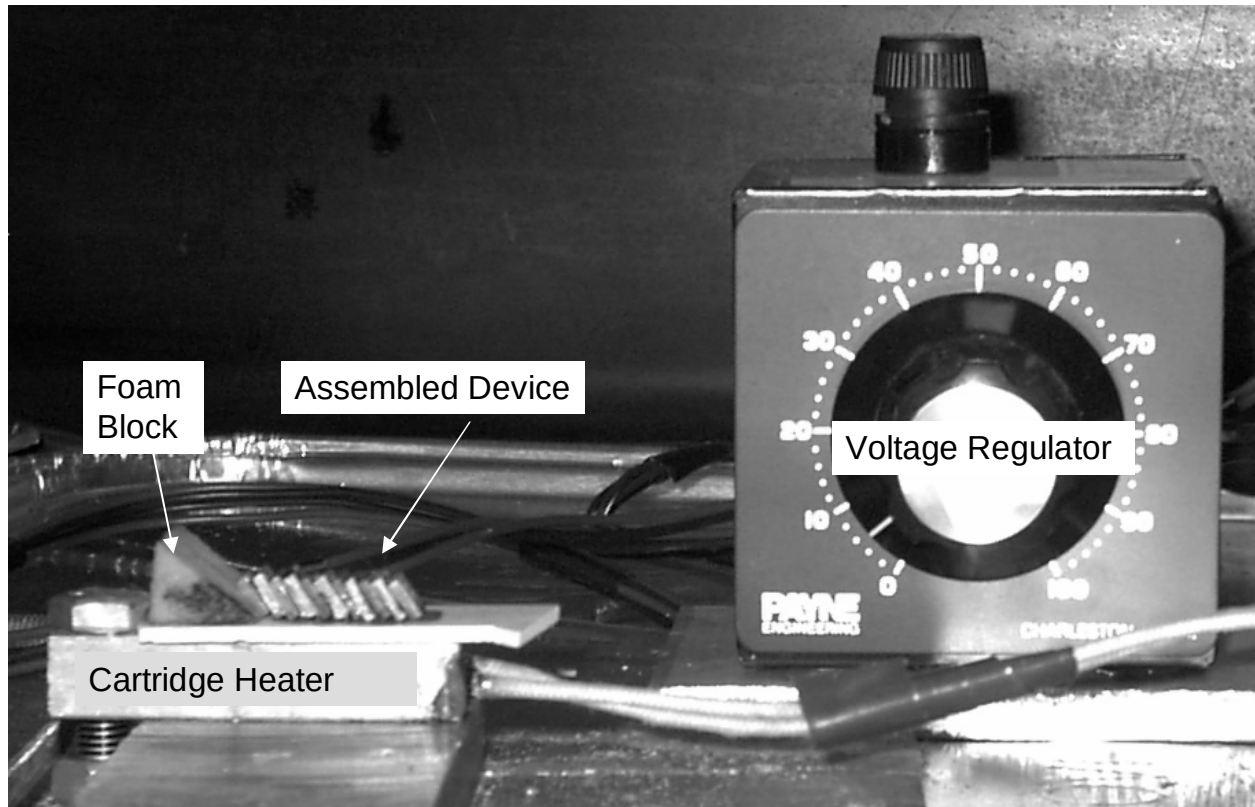


Figure 2.4. Heater setup used to prepare assembled device in order to bond pieces together and melt away any excess flux

Heating continues until the indium film becomes liquid and the flux boils away. While heating, light pressure is applied to the ends of the device to ensure good compression of the pieces and low resistivity throughout the device. Once the indium film is thoroughly melted, the device is removed from the cartridge heater and allowed to cool to room temperature.

After cooling, the device is connected to two thermocouples to measure temperature gradients in the vertical direction, two wires to measure voltage, and is capped on top and bottom by ceramic plates as shown in Figure 2.5.

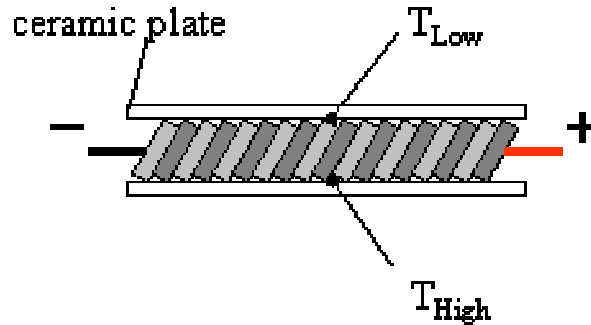


Figure 2.5. Experimental testing setup for device including ceramic plates and connections for the two thermocouples and voltage leads

The junctions between the ceramic plates and the device are connected using Omegatherm[®] “201” High Temperature-High Thermal Conductivity Heat Paste or using a Gap Pad from Bergquist Company. The thermocouples are type K and the voltage connections are standard 20 gauge wire. Electrical connections are made using SPI[®] High Purity Silver Paint. The ceramic plates are necessary to ensure good thermal conduction to and from the device and the heat sink or heat source. The ceramic plates used are boron nitride; boron nitride was selected because of its high thermal conductivity (30 W/m-K), low electrical conductivity, and current use in commercial thermoelectric coolers.

2.3 Experimental Setup

Experiments were conducted in order to determine the voltage and temperature response to different heat flux levels generated by the cartridge heater. The object being tested is heated at a given power level until it reaches steady state. Voltage and temperature data are then collected. This procedure is repeated at various heater power levels until a trend emerges. LabView is the controller and data collector for all testing. Documentation of the programming is shown in Appendix A. The front control panel of the program can be seen in Figure 2.6.

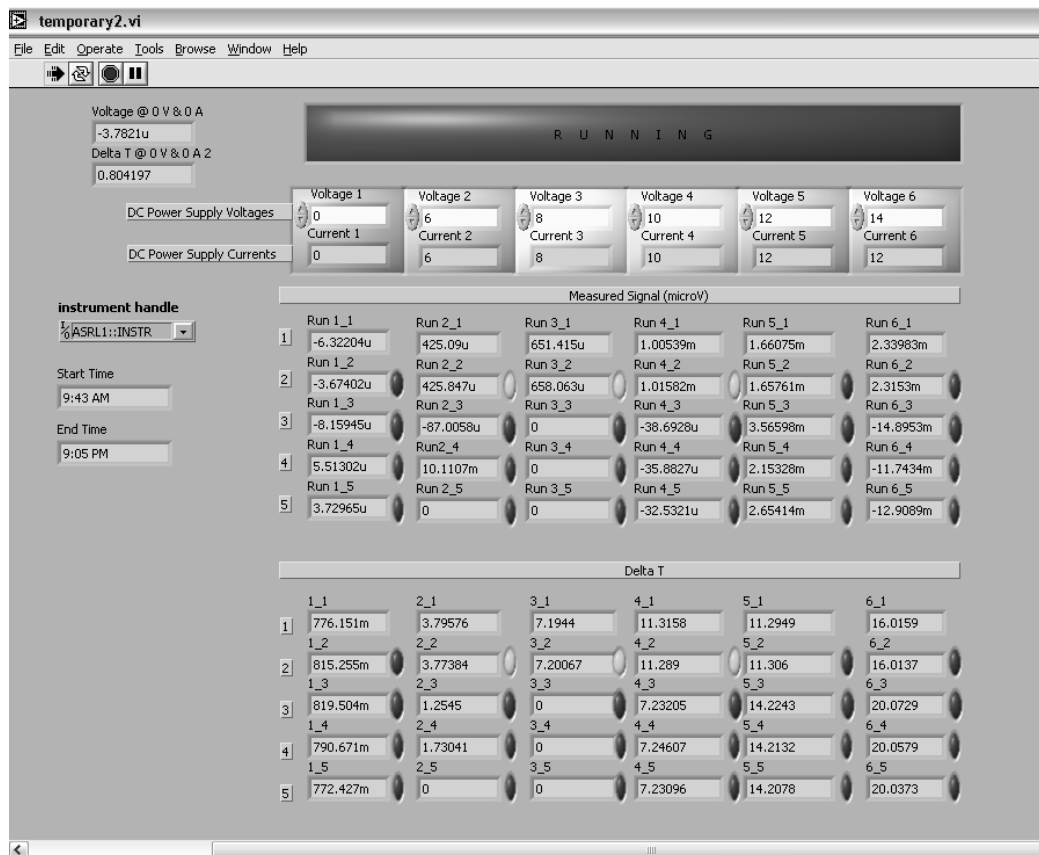


Figure 2.6. Control panel for LabView master program used to collect data, average data over a time period, and to determine whether or not steady state has been achieved

From this front panel, the user can select the port that the DC power supply is connected to and the desired voltage levels that they want to test. Additionally, the user can see where in the cycle the program is operating. An illuminated voltage block means that the user inputted voltage level has been set, a green light illuminated next to a delta T or voltage value indicates the steady state data. A file collects the time, temperature, and voltage data. Shown below is a general outline of the iterative process used by this program:

- 1) Initiate Testing, take baseline Temperature and Voltage data for 30 seconds, find averages
- 2) Set Voltage of Cartridge Heater to Voltage Level 1
- 3) Wait 1 hour
- 4) Take sample data for 30 seconds
- 5) Wait 10 minutes
- 6) Take sample data for 30 seconds
- 7) Compare data to that collected in previous step
 - a) If less than 2% different, return to step 2 and repeat at next voltage level
 - *Once all voltage levels have been completed go to step 8
 - b) If more than 2% different, return to step 5
- 8) Set Voltage of Cartridge Heater to 0 V

2.3.1 Vacuum Setup

The majority of testing is conducted under vacuum conditions using a vacuum chamber from Abbess Instruments and a Pfeiffer vacuum. Vacuum conditions are ideal for testing a thermoelectric device because it ensures that the majority of the heat generated by the heater passes through the thermoelectric device by minimizing the amount of convection. The operating pressure of the vacuum chamber is around 4.5×10^{-3} Torr, which is low enough to assume that all heat losses from convection are eliminated. A picture of the vacuum pump and chamber can be seen below in Figure 2.7.

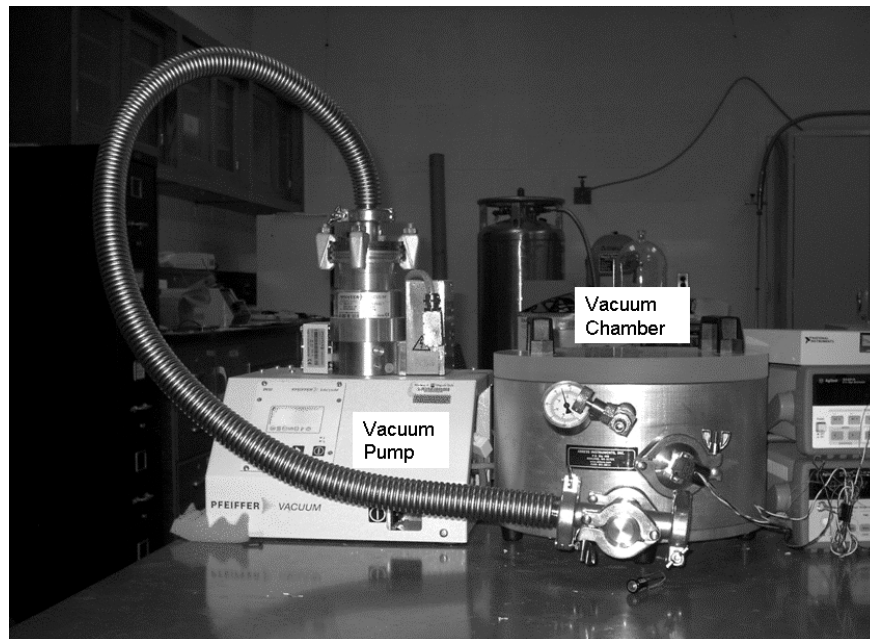


Figure 2.7. Vacuum pump and chamber used during testing

2.3.2 Bulk Material Testing Setup

In order to determine the Seebeck coefficient of the titanium, a test setup as shown in Figure 2.8 was devised.

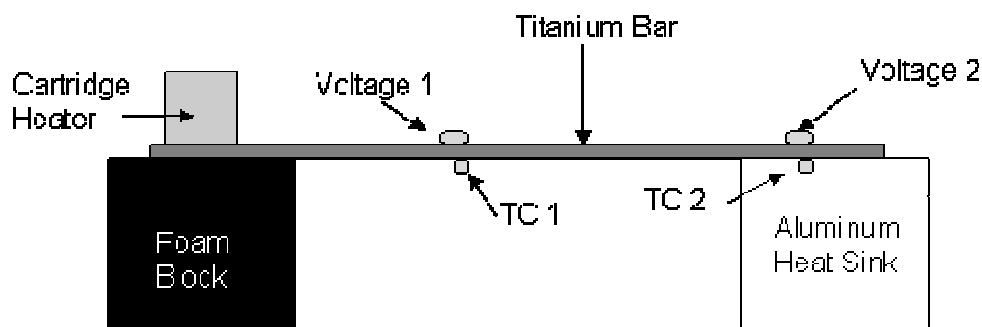


Figure 2.8. Titanium material testing setup used to find the Seebeck coefficient of the bulk material

The thermocouples are attached using Bergquist Gap Pad[®] HC1000 and the voltage leads are connected with silver paint to ensure good electrical contact. The LabView program is then used to collect differences in temperature and voltage. These results, presented in Chapter 3, are then used to calculate the Seebeck coefficient of the bulk material sample.

2.3.3 Device Testing

The device described in Section 2.2 and pictured in Figure 2.5 is tested by mounting it on an aluminum heat sink and attaching a cartridge heater to the top of it as shown in Figure 2.9.

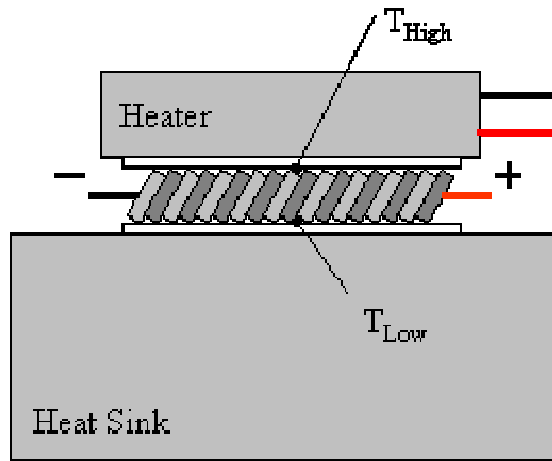


Figure 2.9. Experimental mounting of thermoelectric device on an aluminum heat sink with cartridge heater on top of device

Once the device is mounted, it is heated overnight with the upper temperature around 80 °C to ensure the silver paint used for the voltage connections is fully cured. Once the device returns to room temperature, the LabView program described above is used to collect data on temperature and voltage levels for various heater power levels. Multiple data sets are collected for each angle being tested to verify device performance.

2.3.4 Variable Length Testing

The voltage signal generated by a transverse thermoelectric device is directly proportional to the length of the device as shown in Equation 1.9. Because of this, devices with less than 11 elements at a uniform angle are tested to demonstrate this theory. This is done by first testing the device at its maximum length of 11 elements using the methods described in Section 2.3.3. Then, a given number of pieces are removed with tweezers and acetone, and the device is retested at the new length. This method ensures that the device does not undergo any changes in angle and that the irregularities between the connections of the elements remain

constant. This test can provide further evidence that the device constructed exhibits thermoelectric behavior.

2.3.5 Experimental Data Analysis

All temperature and voltage data collected using the LabView program are entered into an Excel spreadsheet. Within the spreadsheet, a reference voltage level (the offset voltage signal produced with a heat flux of zero) is subtracted from all the voltage levels collected during a given test run. Also, sensitivity (the ratio of the voltage signal to the heat flux) is calculated. Heat flux is found using Equation 2.1, where A is the contact area between the device and the heater, V is the voltage set by the user, and I is the current generated from the power supply.

$$q'' = \frac{I * V}{A} \quad \text{Eq 2.1}$$

Along with these calculations, graphs of the voltage signal and temperature gradients versus heat flux are generated. A line is fitted to the voltage data in order to characterize the response of the device to different heat fluxes.

2.4 Summary

In summary, the materials chosen for use in the multi-layered device are bismuth telluride, for its well-proven thermoelectric characteristics, and titanium grade 5 for its good electrical conductivity and low thermal conductivity. Various devices are constructed by alternating layers of thin pieces of these materials at an angle from perpendicular. Each device's voltage and temperature response due to a given heat flux applied to one side of the device are determined experimentally using a LabView program. These data are recorded and analyzed. The tests conducted include the bulk material, devices with the same number of elements but different angles, and devices with the same angle but a different number of elements.

3 Results

This chapter contains an overview of the data collected during testing of the bulk material, devices constructed at various angles, and various length devices at the same angle as described in Chapter 2. Additionally, calculations involved in predicting the voltage response and sensitivity of the device based upon the properties of the materials are shown. Comparisons between experimental findings and theoretical predictions are made. Finally, uncertainty and sources of error in the experimental measurements are discussed.

3.1 Titanium Grade 5 Bulk Material Testing

Titanium Grade 5 is tested according to the methods in Section 2.3.2 in order to determine the Seebeck coefficient of the bulk material. This is necessary because no published value of the Seebeck coefficient is available for the titanium alloy. Figure 3.1 shows a summary of the data collected on five different trial runs. This plot shows the voltage produced for a given temperature gradient. The raw data are shown in Appendix B.

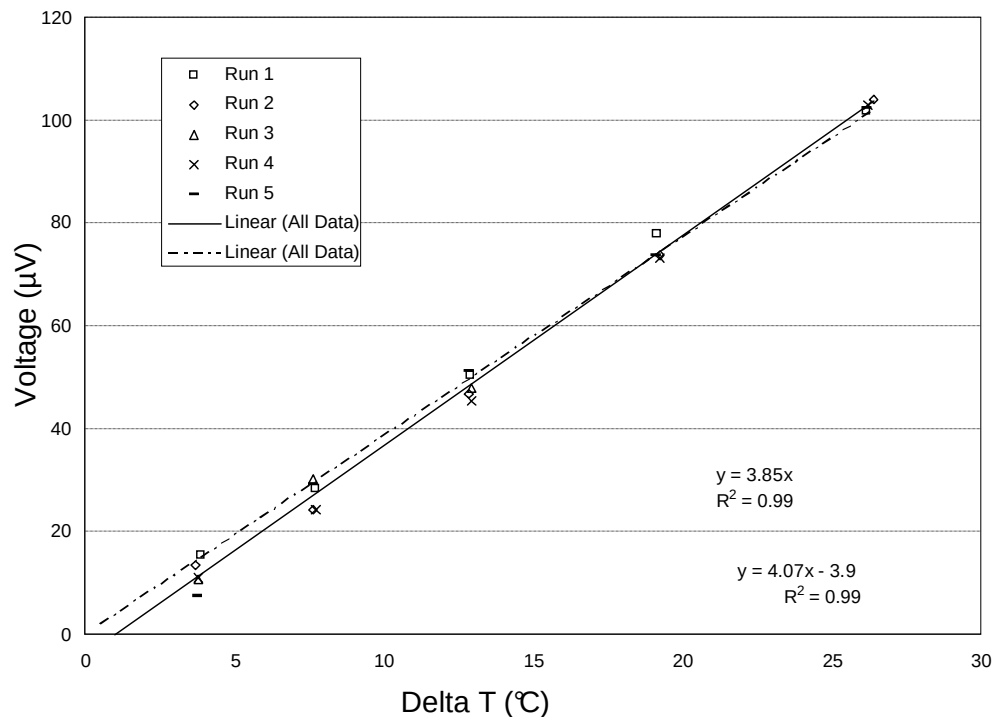


Figure 3.1. Titanium Grade 5 Seebeck Testing Results with a linear best fit line and a trend line that has an intercept of zero

For the data collected, two different linear fits are calculated. One is the least squares linear fit shown in Equation 3.1 and the second is a linear fit that passes through the origin as shown in Equation 3.2.

$$\text{Voltage} = 4.07 * \Delta T - 3.90 \quad \text{Eq 3.1}$$

$$\text{Voltage} = 3.85 * \Delta T \quad \text{Eq 3.2}$$

The slope of each of these equations represents the experimental Seebeck coefficient. Since the voltage should be zero for any given material with a temperature gradient of zero, the slope from Equation 3.2 is used as the Seebeck coefficient for titanium in all calculations. This Seebeck value is relative to copper. The Seebeck coefficient generated in testing falls within the range of pure metals ($<10\mu\text{V/K}$), so this value is reasonable.

3.2 Early Testing

In order to determine the necessity of conducting tests in vacuum, one device is tested both under atmospheric and vacuum conditions. The results of these tests are shown in Figure 3.2. The plot shows the voltage signal produced for a given heat flux coming from the cartridge heater.

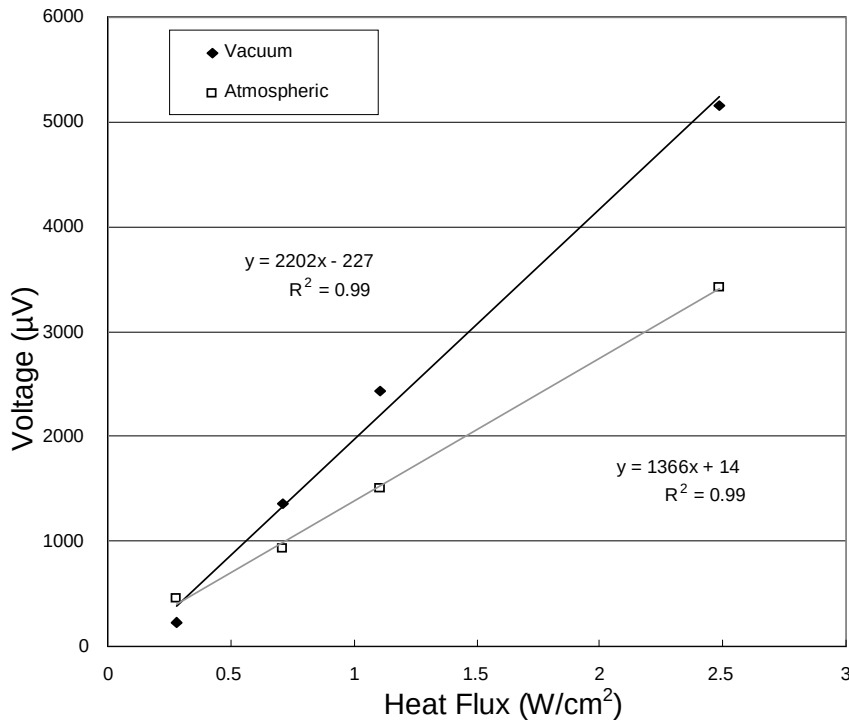


Figure 3.2. Comparison of voltage signals generated for a single device under atmospheric and vacuum conditions

As shown in Figure 3.2, there is an appreciable difference between the data generated under atmospheric and vacuum conditions. In vacuum, the device has a slope that is 61% greater than under atmospheric pressure. This basic test confirms that under atmospheric conditions, the device losses heat through convection to the surrounding air, thus invalidating the assumption that all heat generated by the cartridge heater goes through the device.

3.3 Theoretical Values

Predictions of the performance of the device are generated using the methods described in the papers by Zahner [21] and Fischer [22]. These predictions are used to evaluate the experimental data generated, and they are summarized in the following section.

3.3.1 Material Properties

Properties of the materials used to calculate the theoretical model are shown in Table 3.1. The Seebeck coefficient, S , electrical resistivity, σ , thermal conductivity, k , and thermal resistivity, R , are shown.

Table 3.1. Material properties of bismuth telluride and titanium grade 5 used in theoretical calculations

	Bismuth Telluride	Titanium Grade 5
S ($\mu\text{V/K}$)	250	3.9
σ ($1/\Omega\text{-m}$)	2.11×10^5	5.62×10^5
k (W/m-K)	1.5	6.7
$R = 1/k$	0.67	0.15

The Seebeck coefficient for titanium is that found in the bulk material testing. The electrical and thermal resistivities are from the published values from McMaster-Carr. The bismuth telluride values all come from the CRC Handbook of Thermoelectrics [3].

3.3.2 Governing Equations

The Seebeck effect is described by the tensor equation shown in Equation 3.3, where S is the Seebeck tensor shown in Equation 3.4.

$$\mathbf{E} = \mathbf{S} \cdot \Delta T \quad \text{Eq 3.3}$$

$$S = \begin{pmatrix} S_{\parallel} \cos^2 \alpha + S_{\perp} \sin^2 \alpha & 0 & (S_{\parallel} - S_{\perp}) \frac{\sin(2\alpha)}{2} \\ 0 & S_{\parallel} & 0 \\ (S_{\parallel} - S_{\perp}) \frac{\sin(2\alpha)}{2} & 0 & S_{\parallel} \sin^2 \alpha + S_{\perp} \cos^2 \alpha \end{pmatrix} \quad \text{Eq 3.4}$$

If there is a temperature gradient along the z-axis, the electric field generated along the x-axis is shown in Equation 3.5.

$$E = \frac{1}{2} \sin(2\alpha) (S_{\parallel} - S_{\perp}) \nabla_z T \quad \text{Eq 3.5}$$

$S_{\parallel}$ and $S_{\perp}$ represent the “in-plane” and “out-of-plane” Seebeck values respectively. These values are obtained using Equations 3.6 and 3.7.

$$S_{\parallel} = \frac{\sigma_{Bi_2Te_3} S_{Bi_2Te_3} + d\sigma_{Ti} S_{Ti}}{\sigma_{Bi_2Te_3} + d\sigma_{Ti}} \quad \text{Eq 3.6}$$

$$S_{\perp} = \frac{R_{Bi_2Te_3} S_{Bi_2Te_3} + dR_{Ti} S_{Ti}}{R_{Bi_2Te_3} + dR_{Ti}} \quad \text{Eq 3.7}$$

The ratio of the number of pieces of titanium to the number of pieces of bismuth telluride is indicated by d, assuming that the thicknesses of the titanium and bismuth telluride pieces are equal. For the majority of devices constructed, the ratio d is 5/6. Using the material properties shown in Table 3.1, $S_{\parallel}$ is 80.32 $\mu\text{V/K}$ and $S_{\perp}$ is 211.30 $\mu\text{V/K}$.

Since the device is connected to a heat sink, power P over an area A generates a heat flux that is proportional to temperature gradient via Equation 3.8. For experimental calculations, it is assumed that all of the heat generated by the heater goes directly into the device, so the heat flux can be found by multiplying together the voltage and current supplied to the heater and dividing by the contact area as shown in Equation 3.9.

$$q'' = \frac{P}{A} = (\nabla_z T) k_{zz} \quad \text{Eq 3.8}$$

$$q'' = \frac{P}{A} = \frac{I * V}{A} \quad \text{Eq 3.9}$$

In Equation 3.8, k_{zz} is the thermal conductivity along z, given by Equation 3.10.

$$k_{zz} = k_{\parallel} \sin^2 \alpha + k_{\perp} \cos^2 \alpha \quad \text{Eq 3.10}$$

The effective values for the thermal conductivity of the device, $k_{\parallel}$ and $k_{\perp}$, are given in Equations 3.11 and 3.12.

$$k_{\parallel} = \frac{k_{Bi_2Te_3} + dk_{Ti}}{k_{Bi_2Te_3} + dk_{Ti}} \quad \text{Eq 3.11}$$

$$k_{\perp} = \frac{k_{Bi_2Te_3} k_{Ti} (1 + d)}{k_{Bi_2Te_3} + dk_{Ti}} \quad \text{Eq 3.12}$$

Using the material properties in Table 3.1, $k_{\parallel}$ is 3.86 W/m-K and $k_{\perp}$ is 2.60 W/m-K. Theoretical voltage is calculated using Equation 3.13, where l is the length of the device and α is the angle of the device.

$$V_x = \frac{1}{2}(S_{\parallel} - S_{\perp}) \frac{\sin(2\alpha)q''}{k_{\parallel} \sin^2 \alpha + k_{\perp} \cos^2 \alpha} l \quad \text{Eq 3.13}$$

The theoretical effective Seebeck value can be found using Equation 3.13.

$$\frac{V_x}{\nabla_z T} = \frac{1}{2}(S_{\parallel} - S_{\perp}) \sin(2\alpha) \quad \text{Eq 3.14}$$

3.3.3 Characterization of Device Geometry

The length of the device is calculated using Equation 3.15, where n is the number of pieces and t is the thickness of the layer (assuming each layer has the same thickness) as represented in Figure 3.3.

$$l = \frac{n \cdot t}{\sin \alpha} \quad \text{Eq 3.15}$$

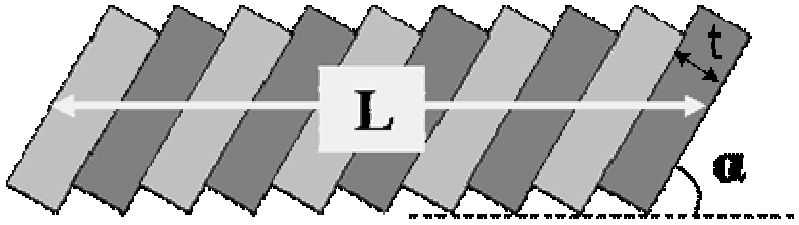


Figure 3.3. Length of device as a function of angle of inclination and thickness of pieces

The angle of the device is found by measuring the angles in a photograph of the device. Pictures of all the devices are shown in Appendix C. The area of the device that is subject to the heat flux from the heater is calculated by Equation 3.16 where w is the width of the device.

$$area = \frac{n \cdot t \cdot w}{\sin \alpha} \quad \text{Eq 3.16}$$

The devices vary from 4 to 11 pieces in length, with a piece thickness of 0.135 cm, and width of 0.791 cm. The majority of testing utilizes a device consisting of 11 pieces.

Figure 3.4 shows the predicted voltage levels for various heat fluxes at angles from 45° to 90°. These angles are of interest for an artificially anisotropic transverse thermoelectric device because they are feasible construction angles. Angles approaching zero are not plausible because little contact would be made between the pieces.

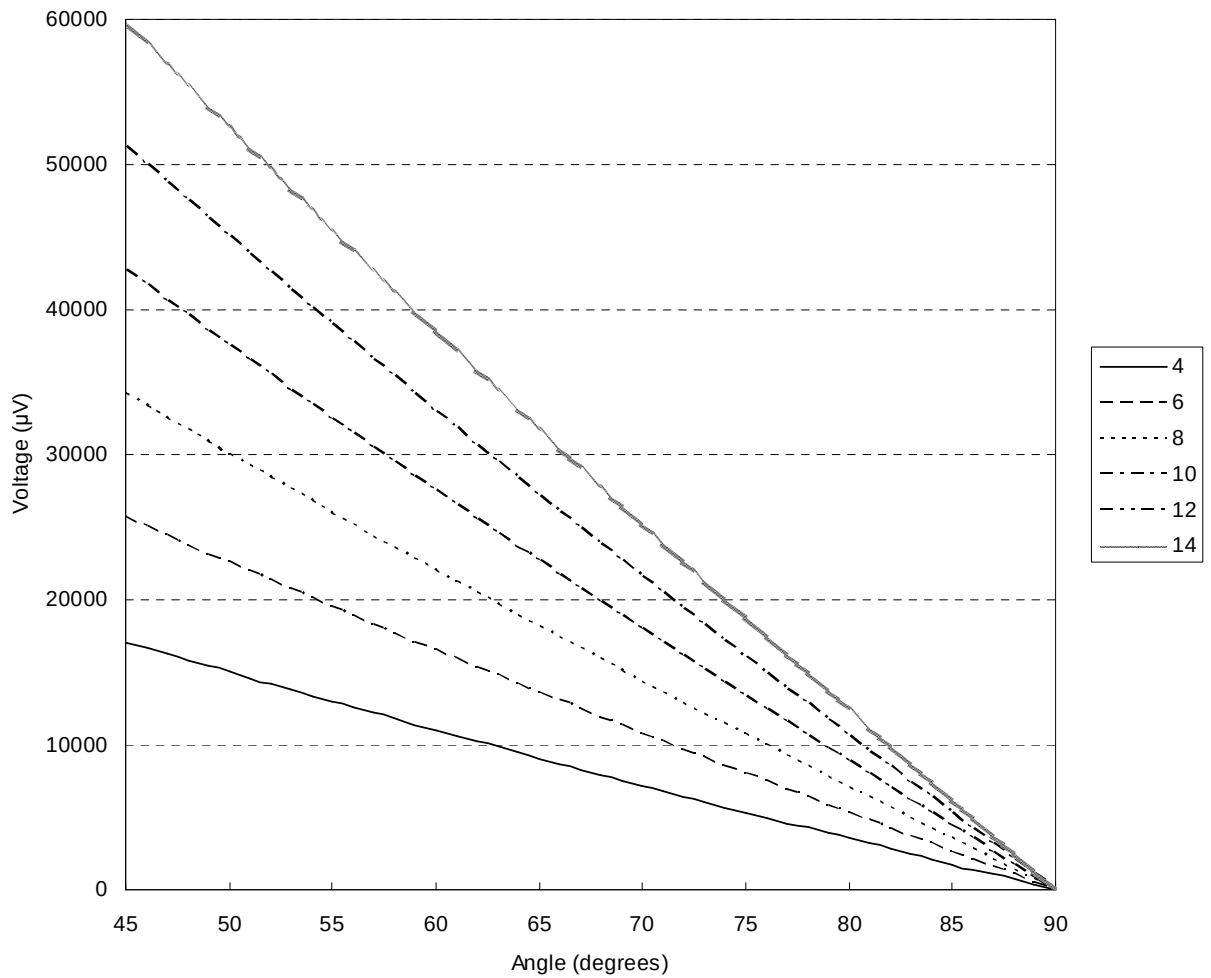


Figure 3.4. Theoretical voltage signals generated by an 11 piece device at heat flux levels from 4 to 14 W/cm²

As expected, the voltage signals generated are greatest approaching 45° and fall to zero at an angle of 90° for all heat flux values.

3.4 Time Constant

Testing was originally conducted with only a 30-minute dwell time at a given heater power level. This early data was very scattered and somewhat unrepeatable. Thus, a test was done to determine the time constant of the device in order to see if adequate time was being allowed for the device to reach steady state. Figure 3.5 shows the results from this test.

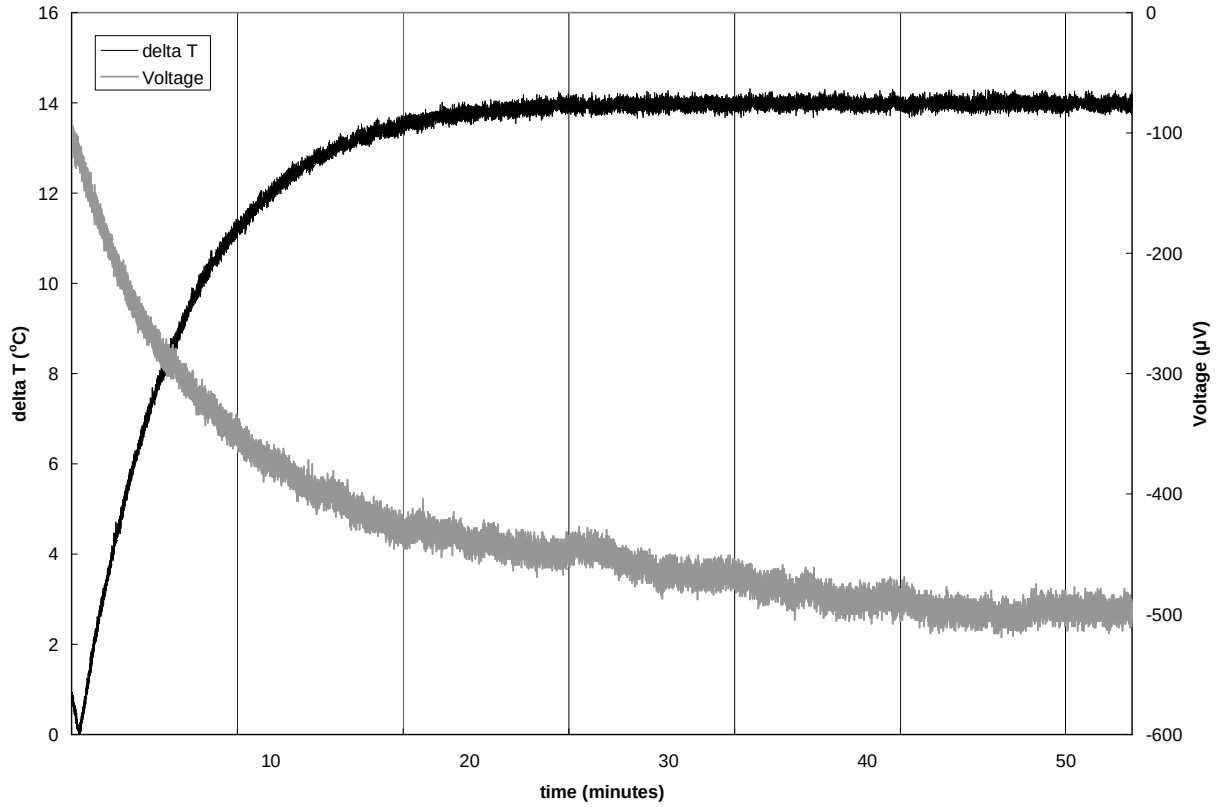


Figure 3.5. Voltage and delta T signals generate over a period of one hour

Shown in Figure 3.5 is the voltage signal and temperature gradient generated by the device over a period of about an hour. The temperature gradient of the device reaches steady state much sooner (~20 minutes) than the voltage signal of the device (~50 minutes). This could be due to the fact that the temperature is measured in the center of the device, and the center most likely reaches steady state quicker than the edges of the device. Also, this steady state temperature could be deceptive because the temperature gradient could be remaining constant but the actual upper and lower temperatures could still be varying. Because of this information, it was determined that thirty minutes was not sufficient time for the whole length of the device to reach steady state, so the dwell time was increased to 60 minutes for all subsequent testing.

3.5 Experimental Results

This section provides an overview of all the full-length devices tested including the pertinent dimensions, angles, voltages, and sensitivities. Detailed data for each device tested in both tabular and graphical form are shown in Appendix D.

3.5.1 Description of Devices Tested

A summary of the angles, effective areas, and lengths of all 11 piece devices tested are shown below in Table 3.2.

Table 3.2. Summary of number, angle, length, and area for each 11 piece device tested

Device Number	Angle	Length (cm)	Area (cm ²)
5	65°	1.64	1.30
6	59°	1.74	1.37
7	75°	1.54	1.22
8	79°	1.52	1.20
9	73°	1.56	1.23
10	70°	1.59	1.25
11	88°	1.49	1.18
12	68°	1.61	1.27

Devices 1-4 are not shown in this table because they were tested using the shorter dwell time described in Section 3.4, making the data not very repeatable. Therefore, these devices have been eliminated from consideration. Pictures of devices 5-12 can be seen in Appendix C.

3.5.2 Voltage Signals

A summary of the voltage signals generated by the devices for different heater power levels are shown in Figure 3.6.

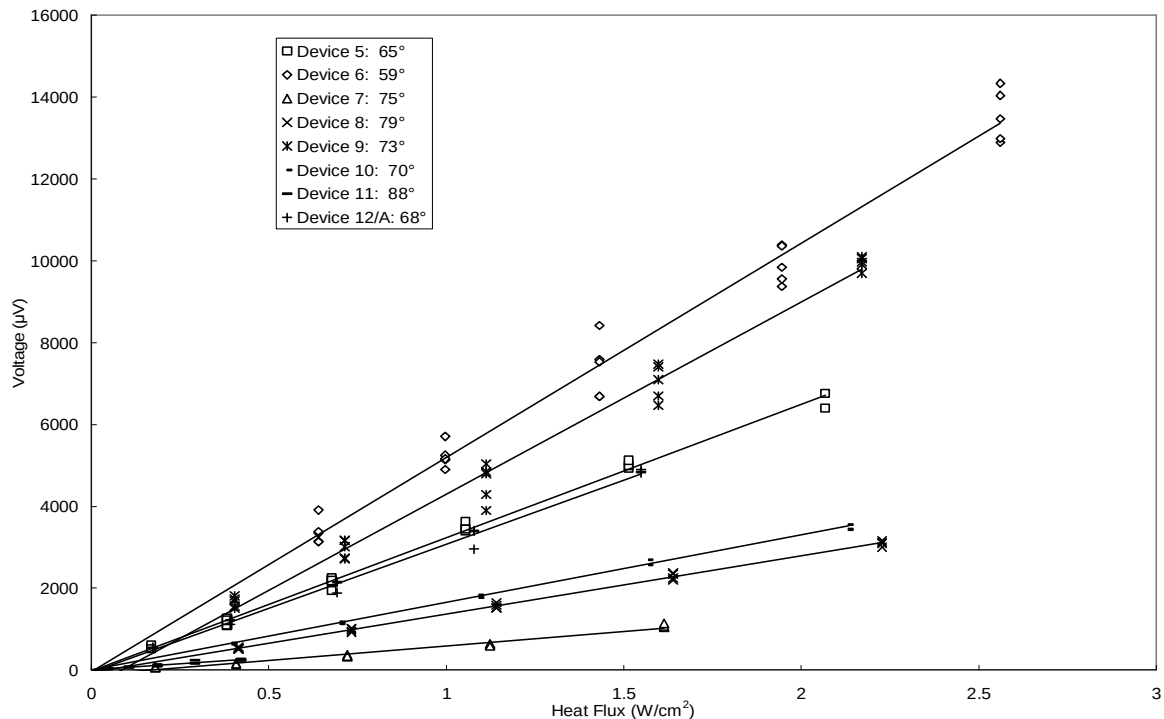


Figure 3.6. Summary of voltage signal generated for all devices tested versus heat flux generated by heater

Detailed graphs of each device and the numerical data are shown in Appendix D. Figure 3.6 shows that the data is repeatable and follows a linear trend. Two different methods are used to calculate a linear fit for the data collected: a least squares linear fit or a linear fit that passes through the origin. A comparison of the slopes generated for these two methods is shown in Figure 3.7.

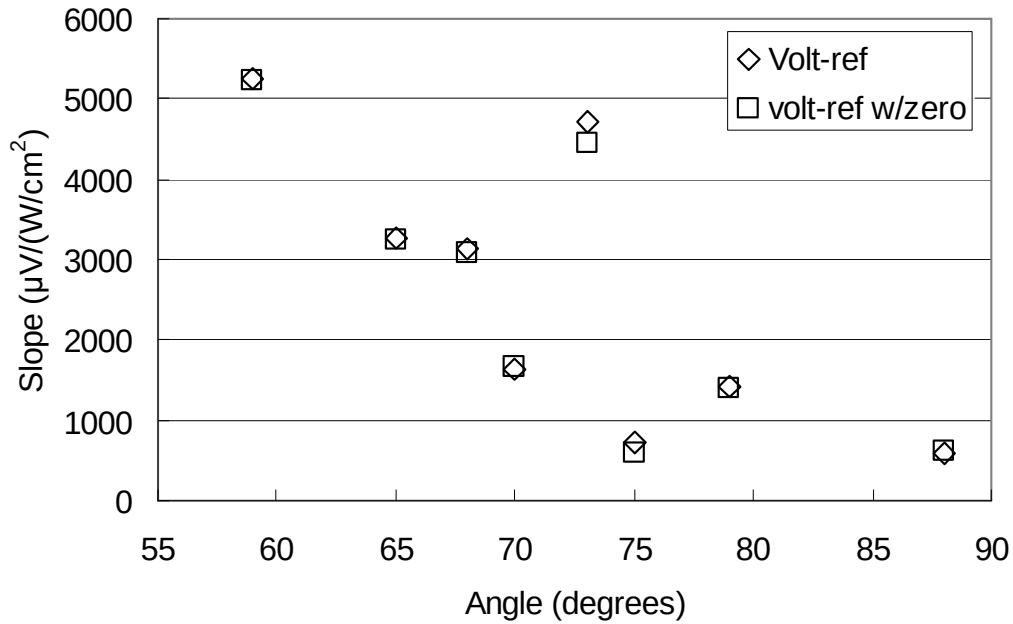


Figure 3.7. Comparison of slopes calculated by the methods of a least squares fit and a linear fit through the origin, “volt-ref” refers to the least squares fit and “volt-ref w/zero” refers to linear fit that passes through the origin

The two methods shown in Figure 3.7 generate relatively similar sensitivities or slopes for each of the given devices. The other consideration with these two methods is how the intercept affects the results. To demonstrate the effects of the intercept, the difference in voltage signals generated via the two methods is shown in Figure 3.8 for a range of heat fluxes.

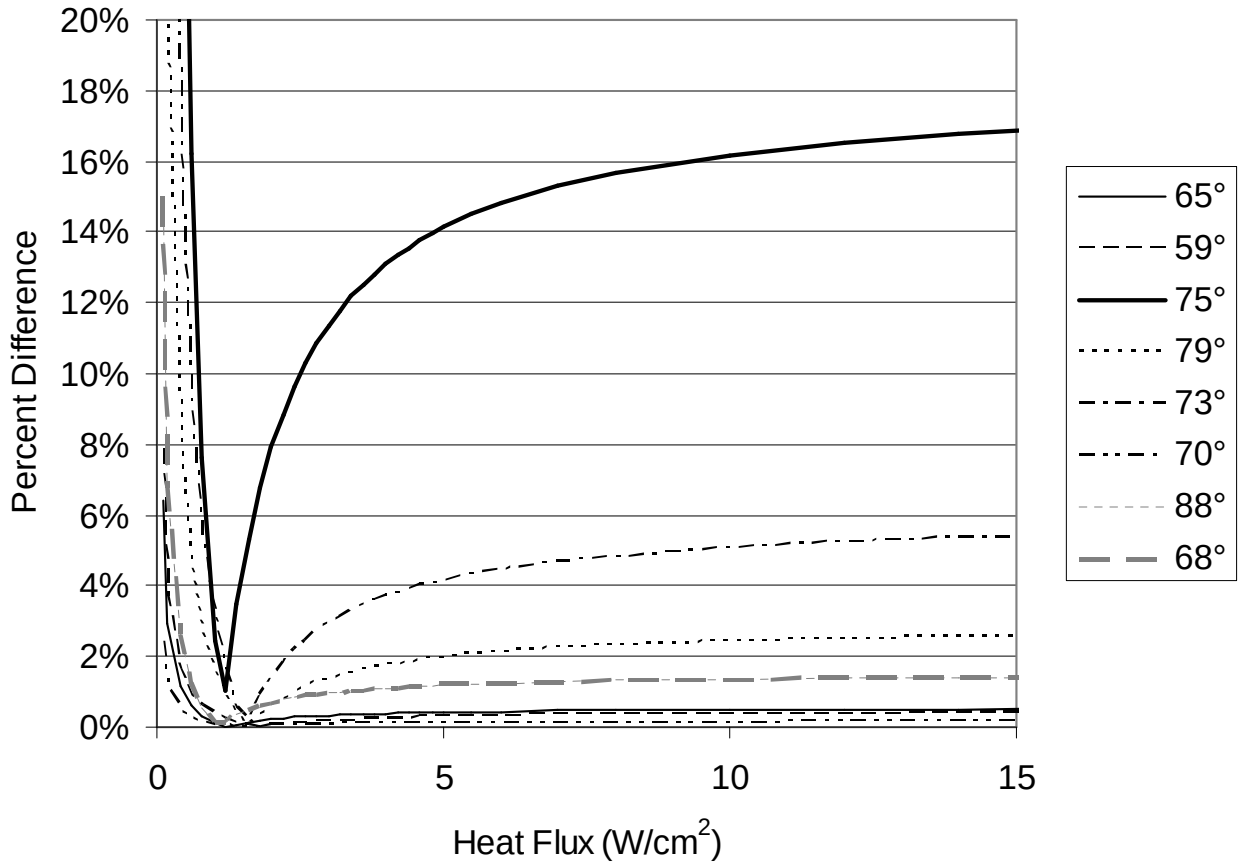


Figure 3.8. Percent difference between least squares fit data and linear fit crossing through the origin for each of the devices

This graph shows that there is only an appreciable difference between the values generated at extremely low heat flux levels, where noise interferes with the small signal, and for device 9, which is the 75° line in Figure 3.8. Due to these elements, for all future calculations, the linear fit used is the least squares fit where the slopes and intercepts for each of the devices are shown below in Table 3.3.

Table 3.3. Slopes and intercepts for least squares linear fits of voltage and heat flux data

Device	Slope	Intercept	Angle
5	3260	-22.55	65°
6	5237	-43.51	59°
7	712	-124.52	75°
8	1423	-62.31	79°
9	4702	-406.49	73°
10	1647	4.33	70°
11	591	3.59	88°
12	3126	-50.95	68°

Since all of the least squares linear fits generate an offset, this indicates that there is some voltage signal for zero heat flux. True thermoelectric devices should generate no voltage with zero heat flux. This offset that is observed could be caused by noise generated within the system, electrical potentials between the connections within the device, or potentials generated at the junctions of the wiring that is used to collect the data. For most of the devices, the offset is less than 5% of the slope (except for devices 7 and 9, which have offsets of 17.5% and 8.6% respectively), so the offset does not significantly affect the linear trends.

3.5.3 Sensitivity

Sensitivity is the ratio of the voltage signal generated to the heat flux. The sensitivity of the device is one value for all heat flux levels. The sensitivity can be calculated either by finding the average and the standard deviation of all experimental data for a given device or by finding the slope of the best fit line. Average sensitivities for each device are shown below in Table 3.4.

Table 3.4. Average experimental sensitivity of devices

Device	Average Sensitivity	Standard Deviation	Angle
5	3214	181	65°
6	5214	352	59°
7	485	126	75°
8	1350	66	80°
9	4270	337	73°
10	1648	39	70°
11	602	79	88°
12	3053	155	68°

Ideally, the sensitivities in Table 3.4 should be the same as the slope values in Table 3.3. The percent difference between these values is shown in Table 3.5.

Table 3.5. Comparison of sensitivity values found by averaging experimental data and finding slope of linear best fit line

Device	Average Sensitivity	Sensitivity from best fit line	Percent Difference
5	3214	3260	1.4%
6	5214	5237	0.4%
7	485	712	46.8%
8	1350	1423	5.4%
9	4270	4702	10.1%
10	1648	1647	0.06%
11	602	591	1.8%
12	3053	3126	2.4%

For the majority of the devices, the difference between the two values is less than 6%, but for devices 7 and 9, the two methods for calculating sensitivity are 46.8% and 10.1% different. This variance is mainly due to the large offset for these data sets. All sensitivity values presented from here on out in this paper are the average sensitivities shown in Table 3.4.

3.5.4 Temperature Gradients

Temperature gradients generated within all the devices for a given heat flux are shown in Figure 3.9. Detailed graphs for each device are shown in Appendix D. This chart demonstrates that the devices reached a steady state temperature gradient for each data point collected because of the linearity and repeatability within the data sets.

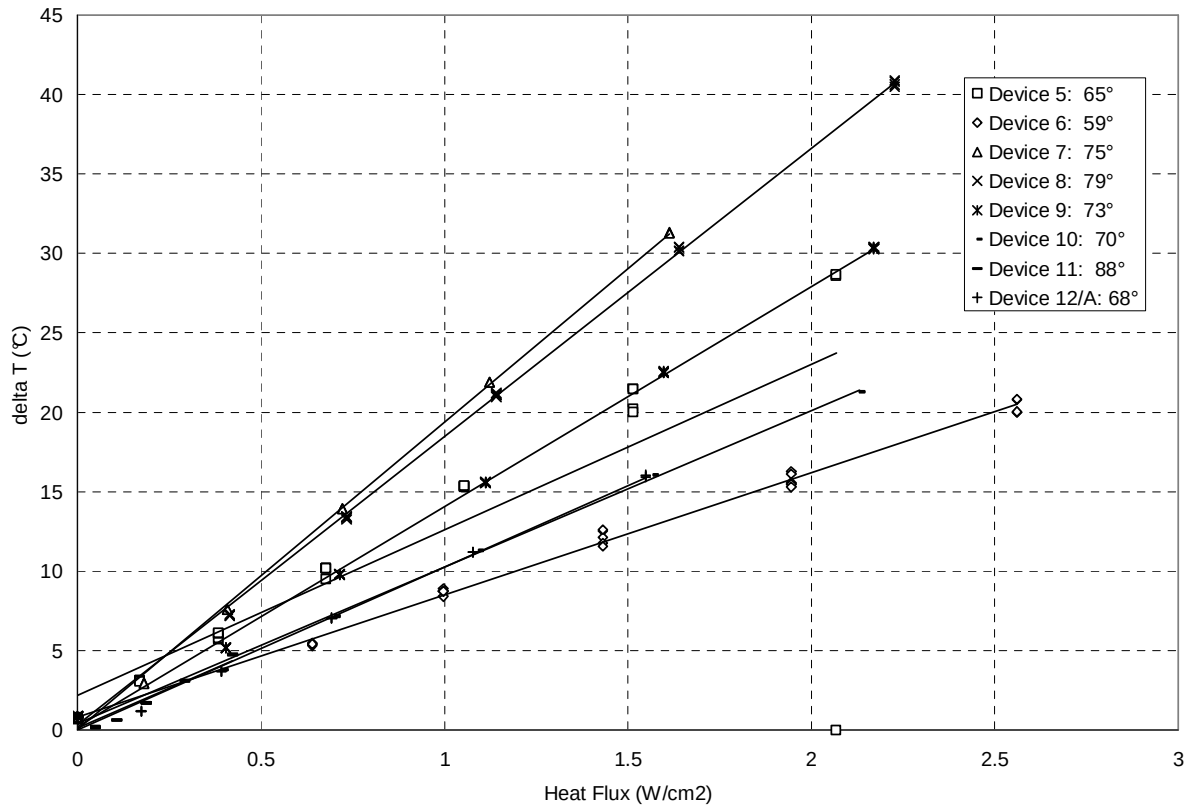


Figure 3.9. Summary of temperature gradients produced within devices for a given heat flux

It is possible to calculate heat flux using temperature gradient information using Equation 3.15, where k is the thermal conductivity, dT is the temperature gradient, and dx is the height of the device.

$$q'' = -k \frac{dT}{dx} \quad \text{Eq 3.15}$$

Since the temperature gradient is only measured in the center of the device, this method of calculating heat flux is not very reliable because there could be variability across the length of the device.

3.5.5 Effective Seebeck Value

The effective Seebeck value relates temperature and voltage signal together. It is found by plotting the voltage signals versus the temperature gradient generated for each device tested. A summary of these data sets can be seen below in Figure 3.10. Individual plots for each of the devices are shown in Appendix D.

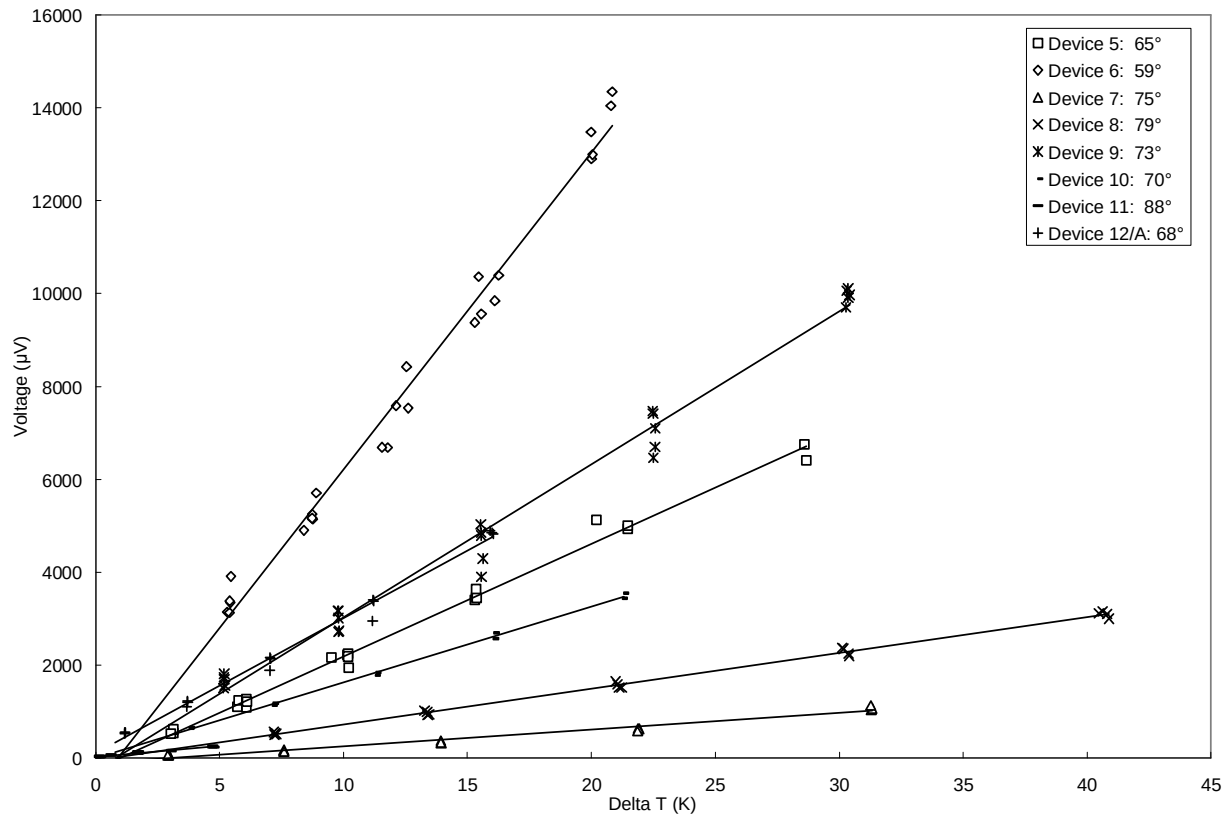


Figure 3.10. Summary of temperature gradient and voltage data for each device tested

Table 3.6 shows a summary of the effective Seebeck values for each of the devices. Values are the slopes found by fitting a line to the data that passed through the origin, similar to the material testing for titanium.

Table 3.6. Comparison of predicted and measure values of sensitivity

Device	Effective Seebeck ($\mu\text{V}/\text{K}$)	Angle
5	228.3	65°
6	640.8	59°
7	31.1	75°
8	75.4	80°
9	317.3	73°
10	163.3	70°
11	54.9	88°
12	299.7	68°

Table 3.6 demonstrates that for an angle closer to 90° , the Seebeck value decreases and for those angles closer to 45° , the Seebeck value increases. This is reasonable because the effective Seebeck equation shown in Equation 3.14 is dependent upon the sine of the angle.

3.6 Comparison of Theoretical and Experimental Data

In order to judge the effectiveness of the testing method and the construction of the device, a comparison of the theoretical values presented in Section 3.3 to the experimental values is performed for device sensitivity. Predicted and experimental values of sensitivity are shown in Figure 3.11, where the experimental values are the averages discussed in Section 3.5.3.

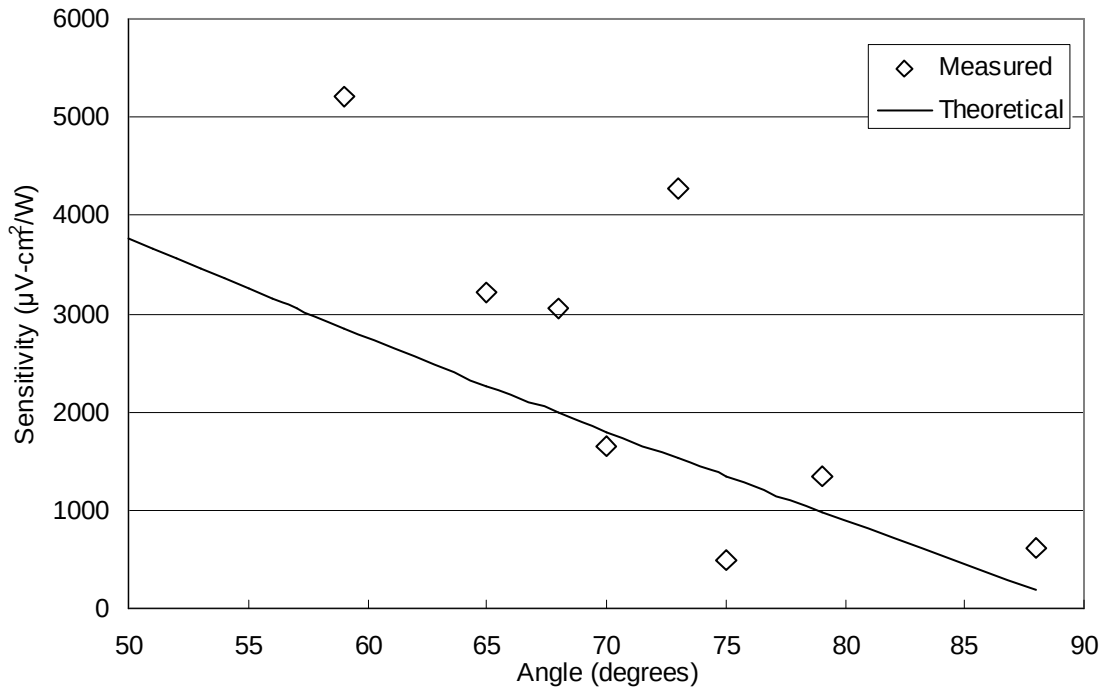


Figure 3.11. Comparison of experimental and theoretical sensitivity

Figure 3.11 demonstrates that the devices tested exhibits thermoelectric properties and are in general agreement with the predicted values. Table 3.7 shows the percent error between the measured and predicted sensitivities.

Table 3.7. Comparison of predicted and measure values of sensitivity

Device	Angle	Predicted Sensitivity ($\mu\text{V}\cdot\text{cm}^2/\text{W}$)	Measured Sensitivity ($\mu\text{V}\cdot\text{cm}^2/\text{W}$)	Percent Error
5	65	2268	3214	83%
6	59	2849	5214	42%
7	75	1337	485	54%
8	79	976	1350	8%
9	73	1520	4270	181%
10	70	1797	1648	64%
11	88	176	602	38%
12	68	1984	3053	242%

The largest deviances from the predicted model are for 68° (device 12) and 73° (device 9), for both of these points, the experimental value is roughly double the predicted value. Device 9 had a large offset in its linear fit and had a larger variance between its average sensitivity and the slope sensitivity. Because of these things, it seems that device 9 (73°) is an outlier and should not be considered part of the representative data from the experiment. Other sources of error could include bad connections within the device or poor electrical connections for measurement.

Figure 3.12 compares the theoretical and experimental effective Seebeck values for each of the devices. This comparison provides further insight into how closely this device is following the theoretical model. The percent differences between the theoretical and experimental effective Seebeck values are shown in Table 3.8.

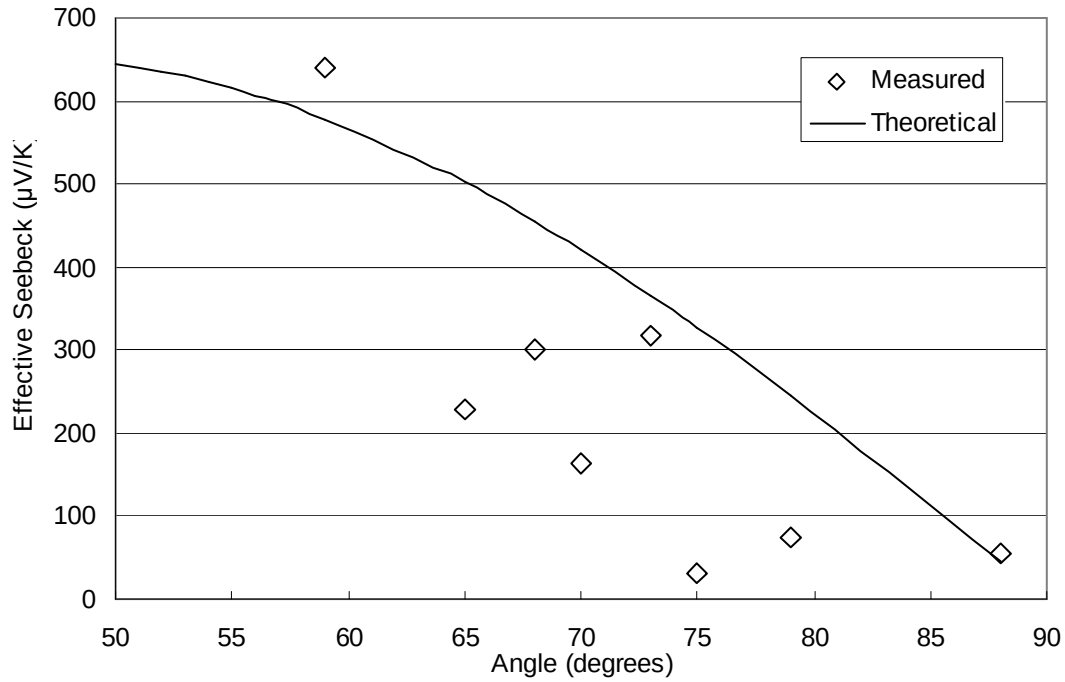


Figure 3.12. Comparison of experimental and theoretical effective Seebeck

Table 3.8. Comparison of predicted and measure values of sensitivity

Device	Angle	Predicted Effective Seebeck (μV/K)	Measured Effective Seebeck (μV/K)	Percent Error
5	65	501.7	228.3	54%
6	59	578.2	640.8	11%
7	75	327.4	31.1	91%
8	79	245.3	75.4	69%
9	73	366.2	317.3	13%
10	70	420.9	163.3	61%
11	88	45.7	54.9	20%
12	68	454.9	299.7	34%

The experimental effective Seebeck values are much closer to the theoretical values than the sensitivity values shown in Figure 3.11 and Table 3.7. This shows that perhaps the method of calculating heat flux does not entirely capture all of the heat transfer mechanisms that are occurring within the system. It should be noted that the highest deviances for the effective Seebeck values occur at 75° (device 7) and 79° (device 8). Device 8 had the smallest deviance in the sensitivity values. Device 7, had a moderate deviation, but it also had a large variance between its sensitivity calculation methods.

3.6.1 Sources of Error in Theoretical Calculations

In order to understand the deviations between the experimental and predicted values for sensitivity, an analysis is performed on the effects of the different material properties on the overall predicted sensitivity of the device. How the predicted sensitivity values change with a given change in material property is shown in Table 3.9.

Table 3.9. Effects of changing material properties on the predicted sensitivity and effective Seebeck

Property	Nominal Value	Change in Predicted Effective Seebeck		Change in Predicted Sensitivity	
		+10%	-10%	+10%	-10%
S-Bi ₂ Te ₃	250 μ V/K	-10.1%	10.2%	-10.1%	10.2%
S-Ti	3.9 μ V/K	0.2%	-0.2%	0.2%	-0.2%
σ -Bi ₂ Te ₃	2.11×10^5 1/ Ω -m	4.0%	-4.1%	3.9%	-4.1%
σ -Ti	5.62×10^5 1/ Ω -m	-3.8%	4.3%	-3.8%	4.3%
k- Bi ₂ Te ₃	1.5 W/m-K	2.4%	-2.6%	6.5%	-7.4%
k-Ti	6.7 W/m-K	-2.3%	2.8%	3.0%	-3.1%

The effective Seebeck and sensitivity values in general have the same sensitivities when it comes to changing the material properties, except for the thermal conductivities. Sensitivity is affected more by changes in thermal conductivity because it appears twice in the equations used to calculate the values, whereas they only appear once in the calculations of effective Seebeck. The predictions for sensitivity are most sensitive to the Seebeck and thermal conductivity of bismuth telluride. A decrease in the Seebeck of bismuth telluride shifts the sensitivity curve away from the origin; a decrease in the thermal conductivity of bismuth telluride shifts the sensitivity curve towards the origin. Outside of material properties, the predicted sensitivities are most affected by changes in the thickness of each layer. Since there is a direct relationship between sensitivity and length, for a 10% increase in thickness, sensitivity decreases by 10%; for a 10% decrease in thickness, sensitivity increases by 10%. This indicates that poor measurement or variance in layer thickness could contribute greatly to deviances between the predicted and measured values of sensitivity. Figure 3.13 shows the affects of altering the Seebeck and thermal conductivity of bismuth telluride has on the sensitivity.

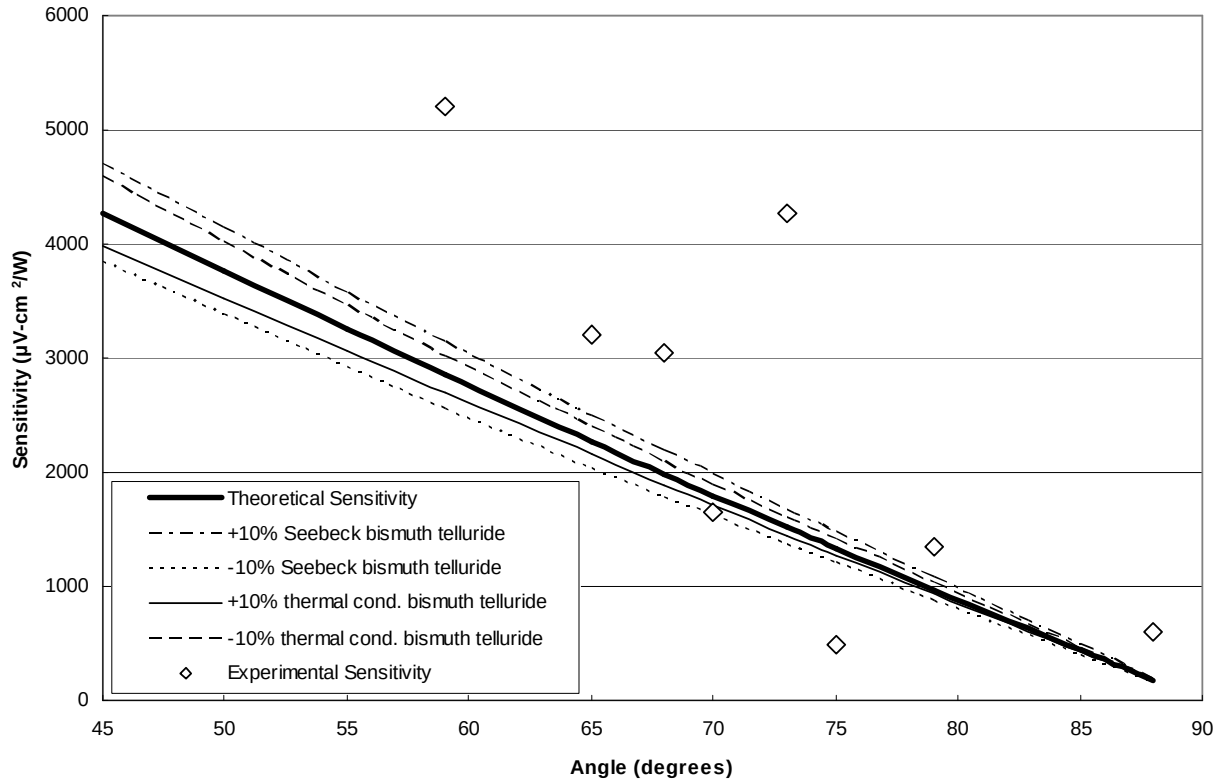


Figure 3.13. Effects on sensitivity of changing the Seebeck and thermal conductivities of bismuth telluride by +/- 10% from their nominal values

Effective Seebeck value, on the other hand, is most sensitive to changes in the Seebeck of bismuth telluride and changes in the electrical conductivity of both materials. A decrease in the electrical conductivity of bismuth telluride causes a decrease in effective Seebeck; a decrease in the electrical conductivity of titanium causes an increase in effective Seebeck. Changes in material properties are cumulative in when these changes are done concurrently. Figure 3.14 shows how altering the Seebeck of bismuth telluride and the electrical conductivities of both materials shift the theoretical effective Seebeck value.

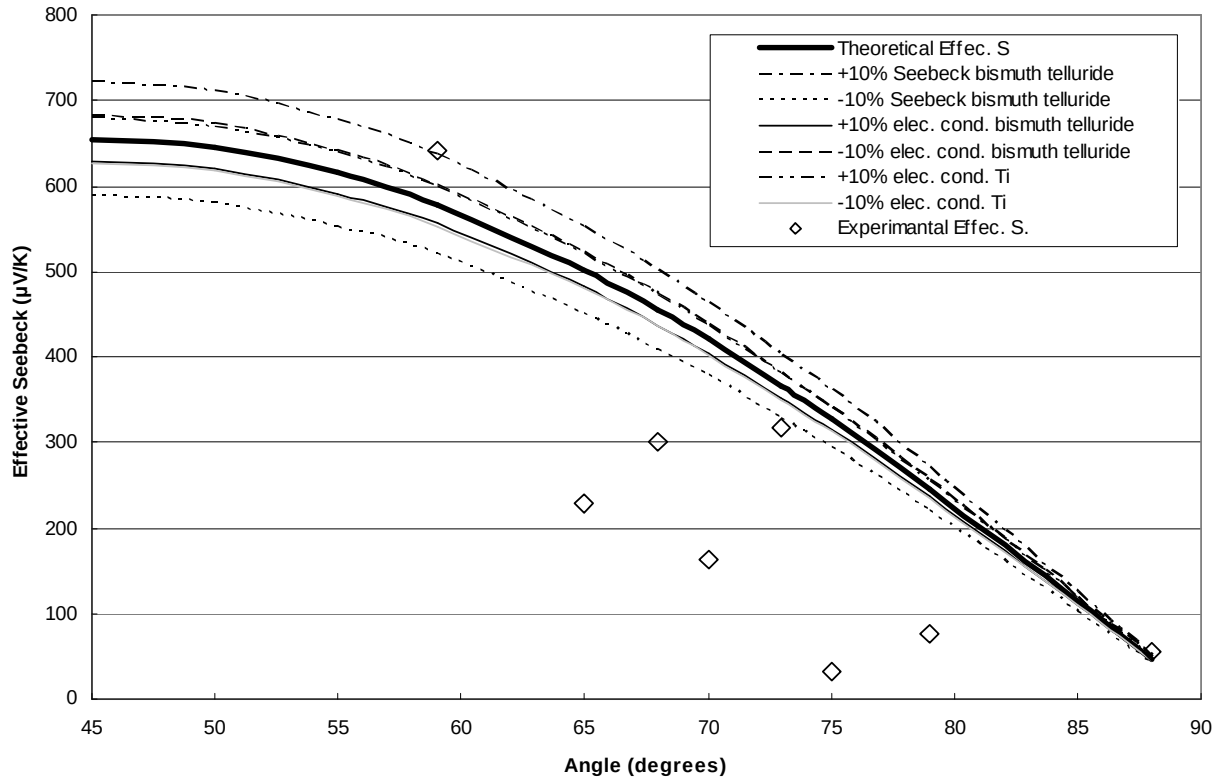


Figure 3.14. Effects on sensitivity of changing the Seebeck and electrical conductivities by +/- 10% from their nominal values

3.7 Length Comparison Testing

For a transverse thermoelectric device, the voltage signal produced is directly proportional to the length of the device as discussed in Section 2.3.4. For this reason, a set of devices with a uniform angle and varying lengths are tested to demonstrate this theory and to confirm that the signal is transverse in origin. The different lengths, number of pieces, and areas for the devices tested are shown in Table 3.10. All of these devices are at an angle of 68°.

Table 3.10. Name, number of pieces, length, and area for devices used in length comparison testing

Device	Number of Pieces	Length (cm)	Area (cm ²)
A	11	1.38	1.27
B	9	1.13	1.04
C	7	0.88	0.81
D	4	0.50	0.46

3.7.1 Length Comparison Testing: Voltage Signals

The voltage produced for each of the devices for a given heat flux is shown in Figure 3.15. The numerical data as well as a plot of the temperature gradients for various heat fluxes is shown in Appendix D.

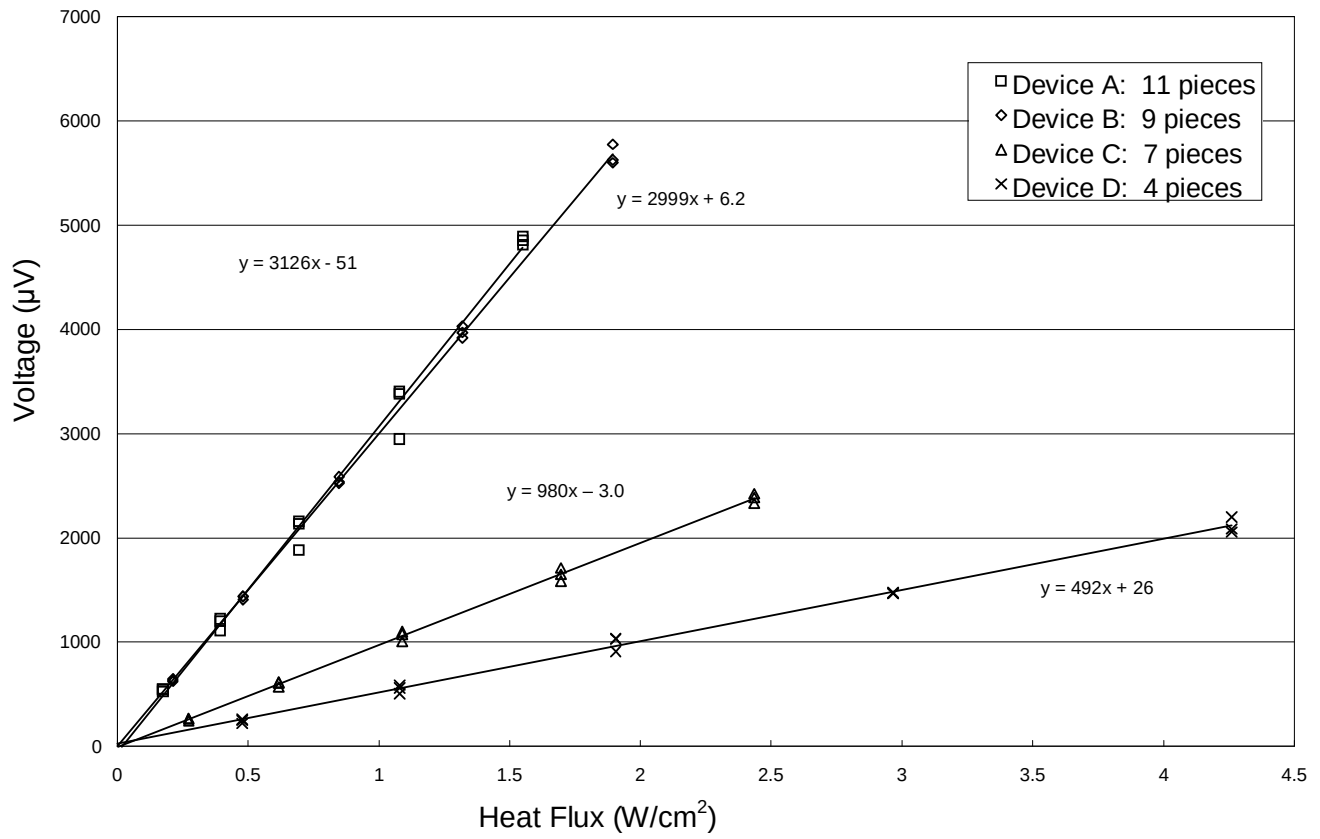


Figure 3.15. Summary of voltage signals produced by various length devices for a range of heat flux values and least squares linear trend lines

Figure 3.16 plots the theoretical and experimental values of sensitivity for the various length devices of the same angle.

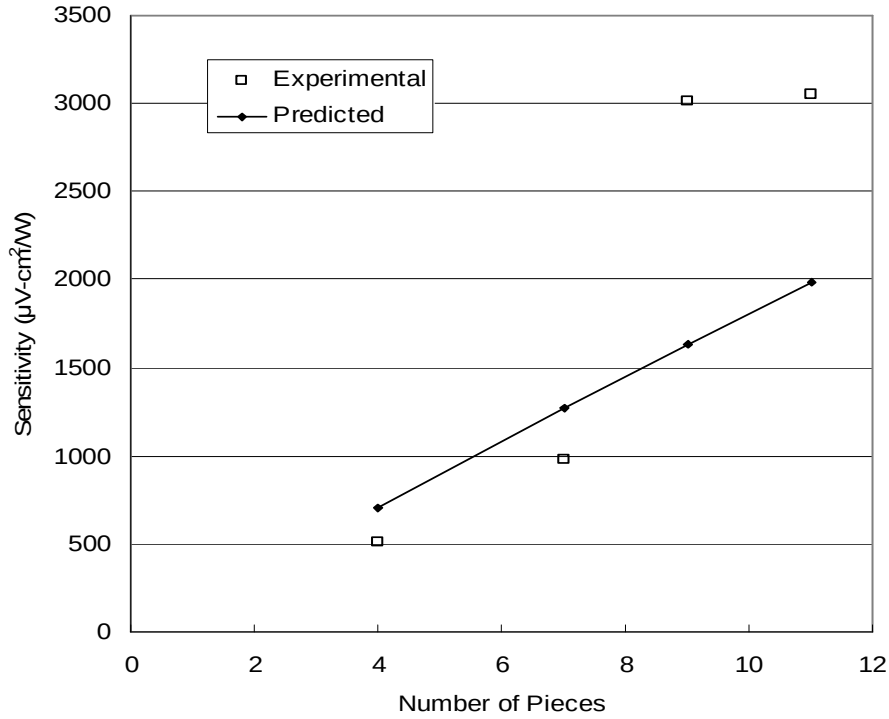


Figure 3.16. Comparison of experimental and predicted values of sensitivity for a 68° device at various lengths with the standard deviation of the experimental values shown as error bars

This plot shows that for this device, the sensitivity is not exactly a linear function of the length, which is due to the fact that area and length are both varying when pieces are removed or added. Table 3.11 shows the difference in the measured value versus the predicted value.

Table 3.11. Percent difference between measured and theoretical sensitivity for 68° device of various lengths

Device	Sensitivity ($\mu\text{V-cm}^2/\text{W}$)		Percent Difference
	Experimental	Theoretical	
A	3053	1984	54 %
B	3007	1630	85 %
C	976	1275	-23 %
D	510	703	-27 %

3.7.2 Length Comparison Data: Error Sources

Errors in this data could be due to poor material property calculations, bad connections within the device, or as in the case with device D, because the end pieces were made out of different materials. Additionally, thermoelectric theory for an artificially intrinsic device like the one constructed is only applicable where the length of the device is much greater than the thickness of the individual pieces, thus it is possible that with the shorter length devices this limit was being exceeded generating inaccurate results.

4 Conclusions and Recommendations

4.1 Summary of Results and Analysis

The thermoelectric device constructed of bismuth telluride and grade 5 titanium underwent extensive testing to demonstrate transverse thermoelectric phenomena as a heat flux sensor. The device was tested by collecting temperature and voltage data for various heater power levels. These data were used to generate a linear trend that characterizes the device's voltage response to a given heat flux. These linear trend lines were then used to compare the experimental data to theoretical calculations of performance. The results followed the general trend of the predicted values. These differences can likely be attributed to several factors: uncertainty of bulk material properties, variability in actual heat flux being applied to device, and creep caused by bonding materials.

Results from experimentation on each of the devices are shown in Appendix D. A summary of the effective Seebeck values found experimentally and calculated theoretically are shown in Figure 4.1.

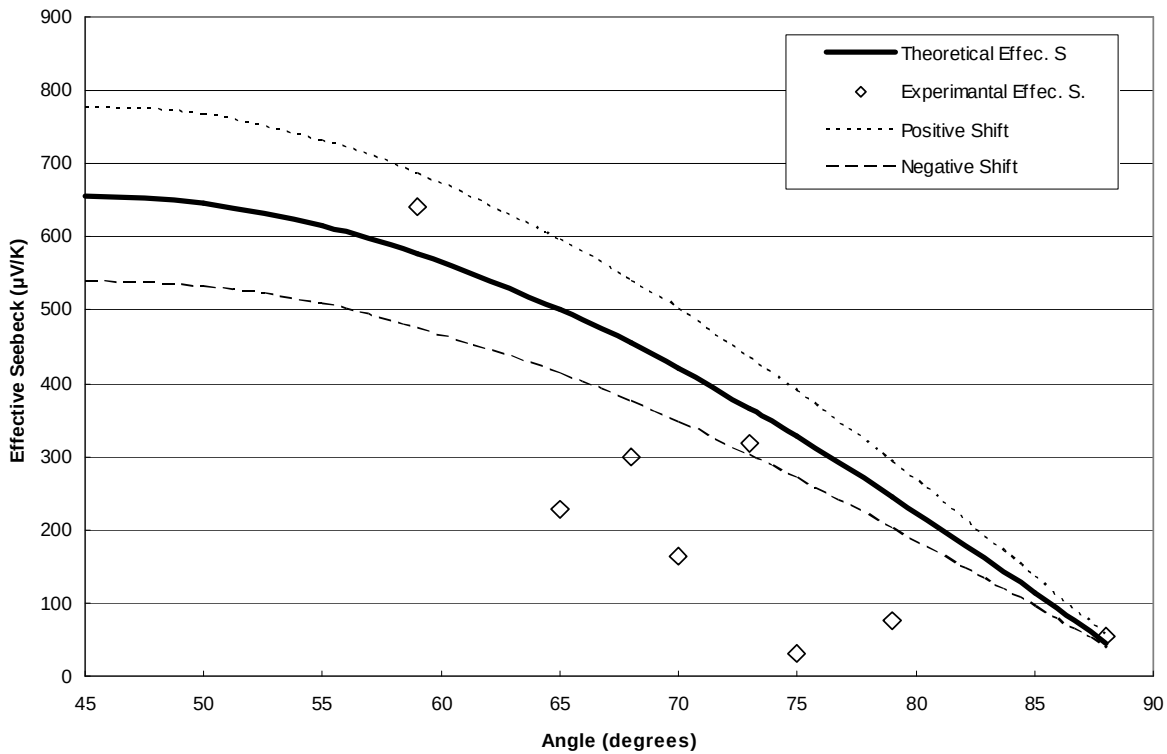


Figure 4.1. Comparison of experimental and predicted results for effective Seebeck of device at various angles with a 'Positive Shift' indicating a 10% increase in S-Bi₂Te₃, 10% decrease in σ-Bi₂Te₃, and a 10% increase in σ-Ti; 'Negative Shift' indicating a 10% decrease in S-Bi₂Te₃, 10% increase in σ-Bi₂Te₃, and a 10% decrease in σ-Ti

The thick line in Figure 4.1 shows the predicted values for the device using the nominal material property values and the diamonds are the experimental averages. This graph also shows the bounds from changing the most influential material properties discussed in Section 3.6.1. The most influential material properties for the effective Seebeck value of the device are the Seebeck coefficient and electrical conductivity of Bi_2Te_3 and the electrical conductivity of Ti. The top line represents a 10% increase in both the Seebeck of Bi_2Te_3 and electrical conductivity of Ti and a 10% decrease in the electrical conductivity of Bi_2Te_3 . The bottom line represents the opposite changes of the top line. Increases in the Seebeck coefficient increase the predicted sensitivity; increases in thermal conductivity decrease the predicted sensitivity. All of these data points were collected under vacuum conditions, so there was negligible convection of heat away from the device.

4.2 Recommendations

As with all experiments, some improvements could be made given the time and desire to delve further into this subject matter.

- Amount of heat flux going into the device has been assumed to be the total heat flux from the heater, but it would be good to be able to compare this assumed value to a measured one to see if this assumption is accurate. This could be done with a calibrated heat flux sensor that could be mounted between the device and the heat source. This is especially important given the inconsistencies between the sensitivity and effective Seebeck values shown in Section 3.6.
- Different device geometries could be explored further, including different layer thicknesses, lengths, and effective areas. This would further expand the knowledge of these devices into more dimensions.
- Materials with different properties could be tested to try to optimize the effective Seebeck value for the overall total device.
- Thinner materials that could be bonded without the intermediary of the indium film could be used to eliminate any sort of interference that this material causes.
- A regularly shaped device could be created so that contact surfaces on all sides are flat and geometry and area calculations would be more straightforward as shown in Figure 4.2.

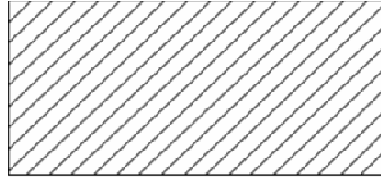


Figure 4.2. Example of regularly shaped device with smooth edges and simple geometry

4.3 Conclusions

This project demonstrates the feasibility of constructing, testing, and analyzing a transverse thermoelectric device within a small-scale laboratory setting. It improves upon methods used by a previous graduate student to create a more consistent and a larger quantity of results [15]. This is done by conducting testing under vacuum conditions to eliminate the heat transfer effects from convection and by completely automating the experimental process using LabView. This automation allows for more tests to be conducted and a greater quantity of data collected with little or no supervision of the experimental process. Furthermore, a different material is used to connect the device to the ceramic cap plates which eliminates any diffusion of thermal paste material into the device. Testing is done for a variety of length devices to demonstrate the theory that voltage signal in a transverse thermoelectric device is proportional to the length of the device. Additionally, this project generates baseline thermoelectric values for titanium grade 5, for which no previous values are available in the literature.

This work shows that the artificially anisotropic thermoelectric device constructed out of bismuth telluride and titanium grade 5 exhibits transverse thermoelectric properties. This is done by finding voltage and sensitivity values for a device with a uniform number of components and a variable angle of inclination and for a device with a uniform angle and a variable length. Data collected follows predicted values within a margin of error for most data points. Voltage signals that can be generated by a device of this nature are at most in the range of a few milli-volts. Higher voltage signals are possible with angles approaching 45°, greater heat flux values, and longer devices. In order to be feasible in a commercial market, this kind of device will need to be thinner for faster response times, have better bonding between material layers, and have a more regular geometry. Additional research could be conducted to examine the many possibilities that are available for thermoelectric device configurations.

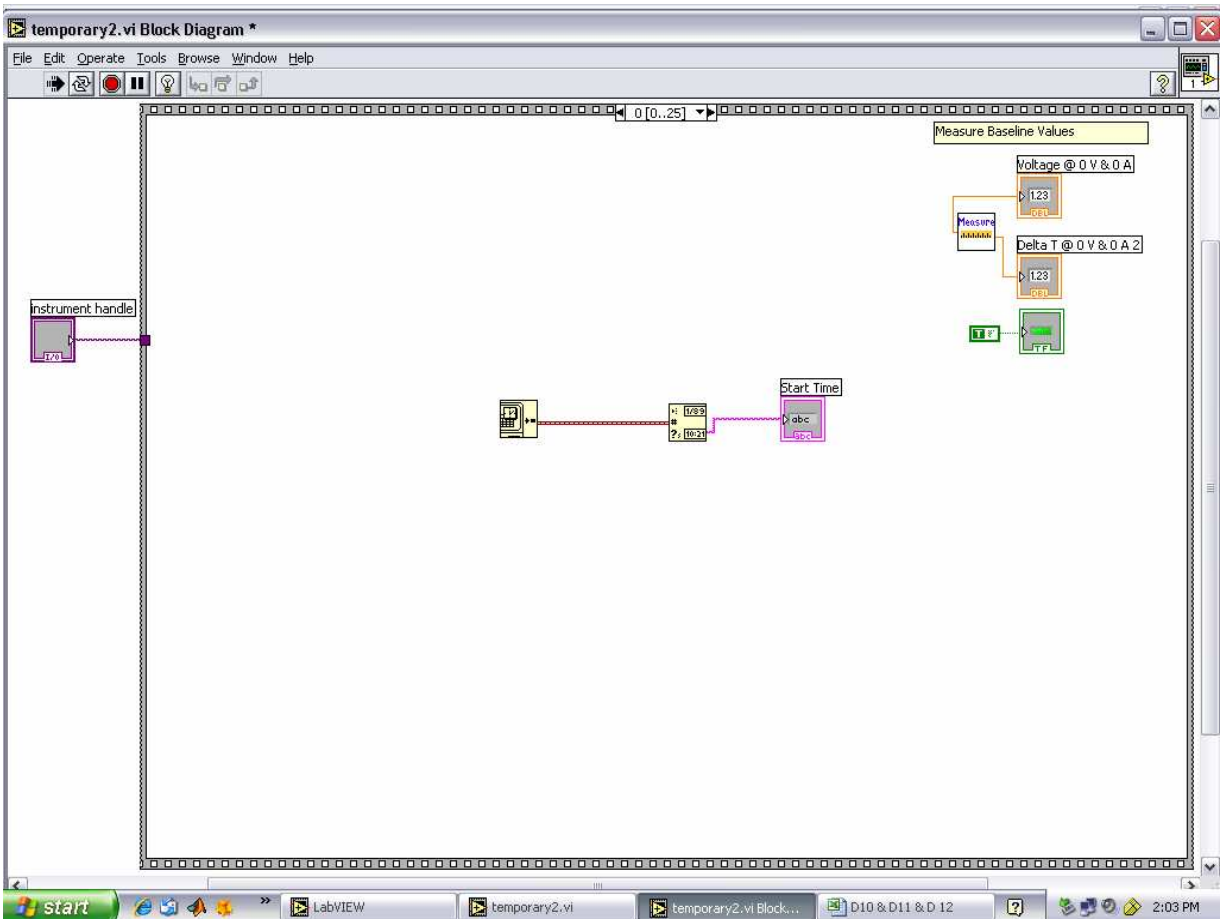
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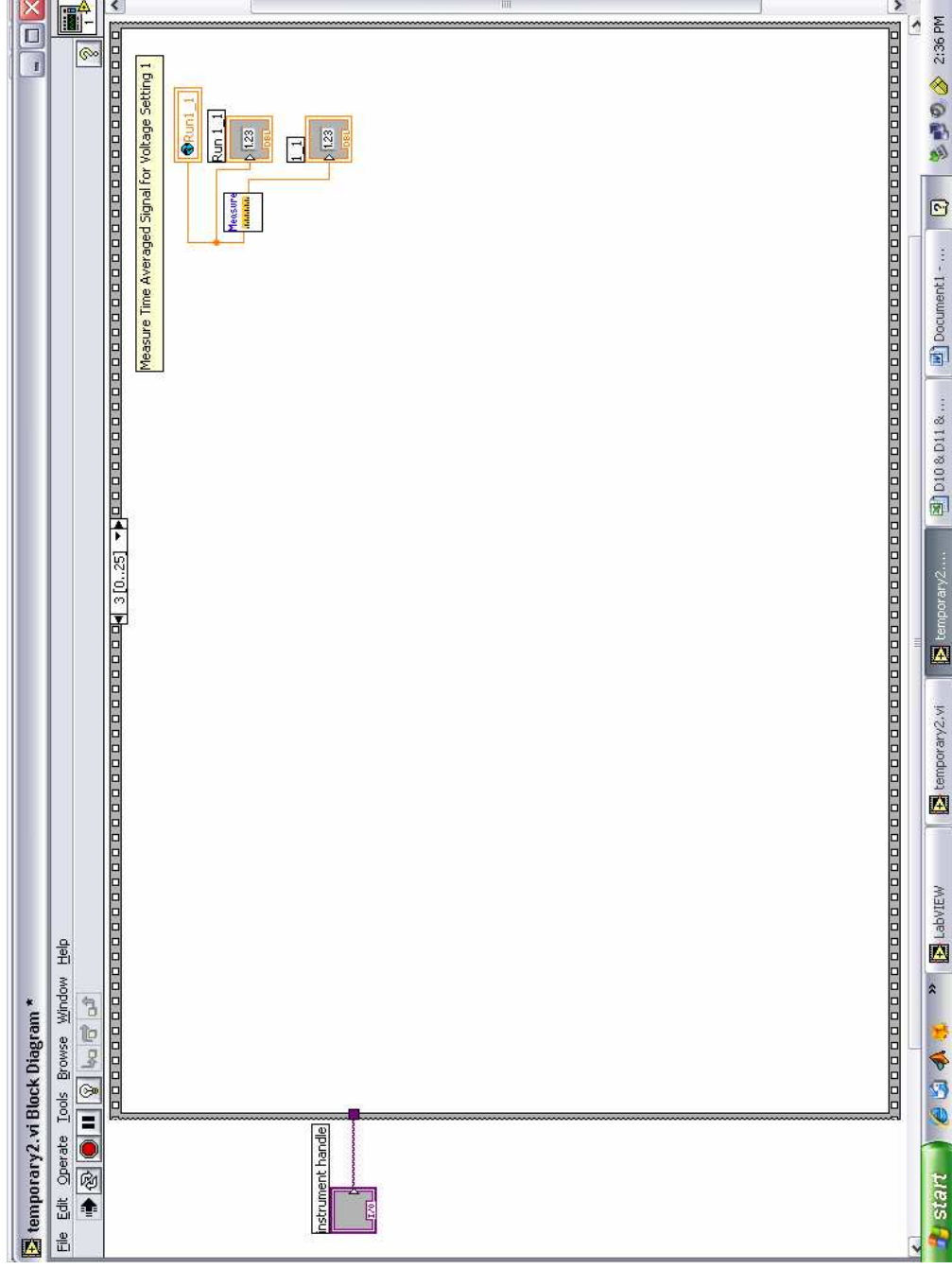
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Appendix A. LabView Program Documentation

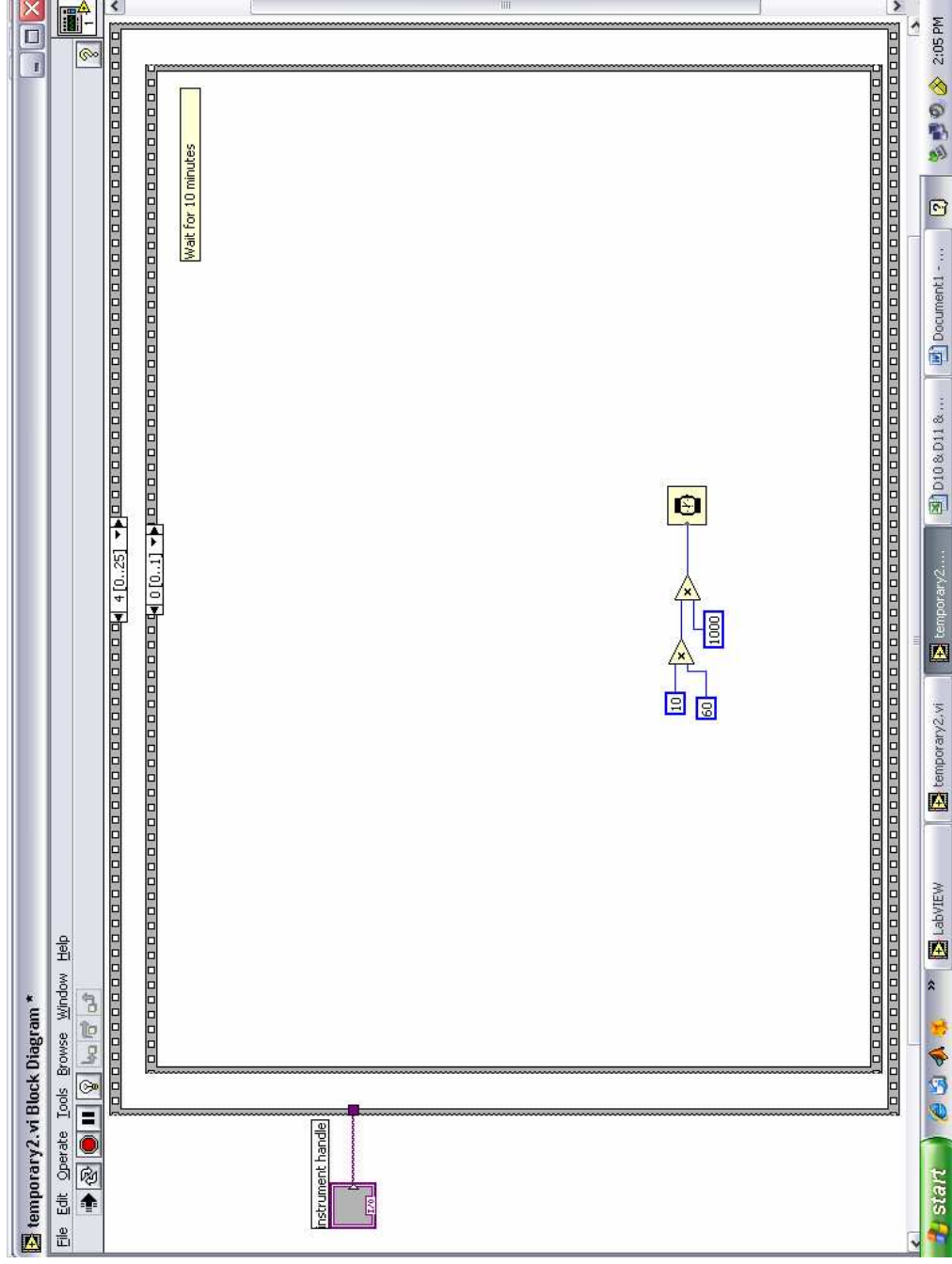
This appendix shows the block diagram of the main LabView program that is used to control the experiments conducted. This first frame shows the initial measurement of temperature and voltage.



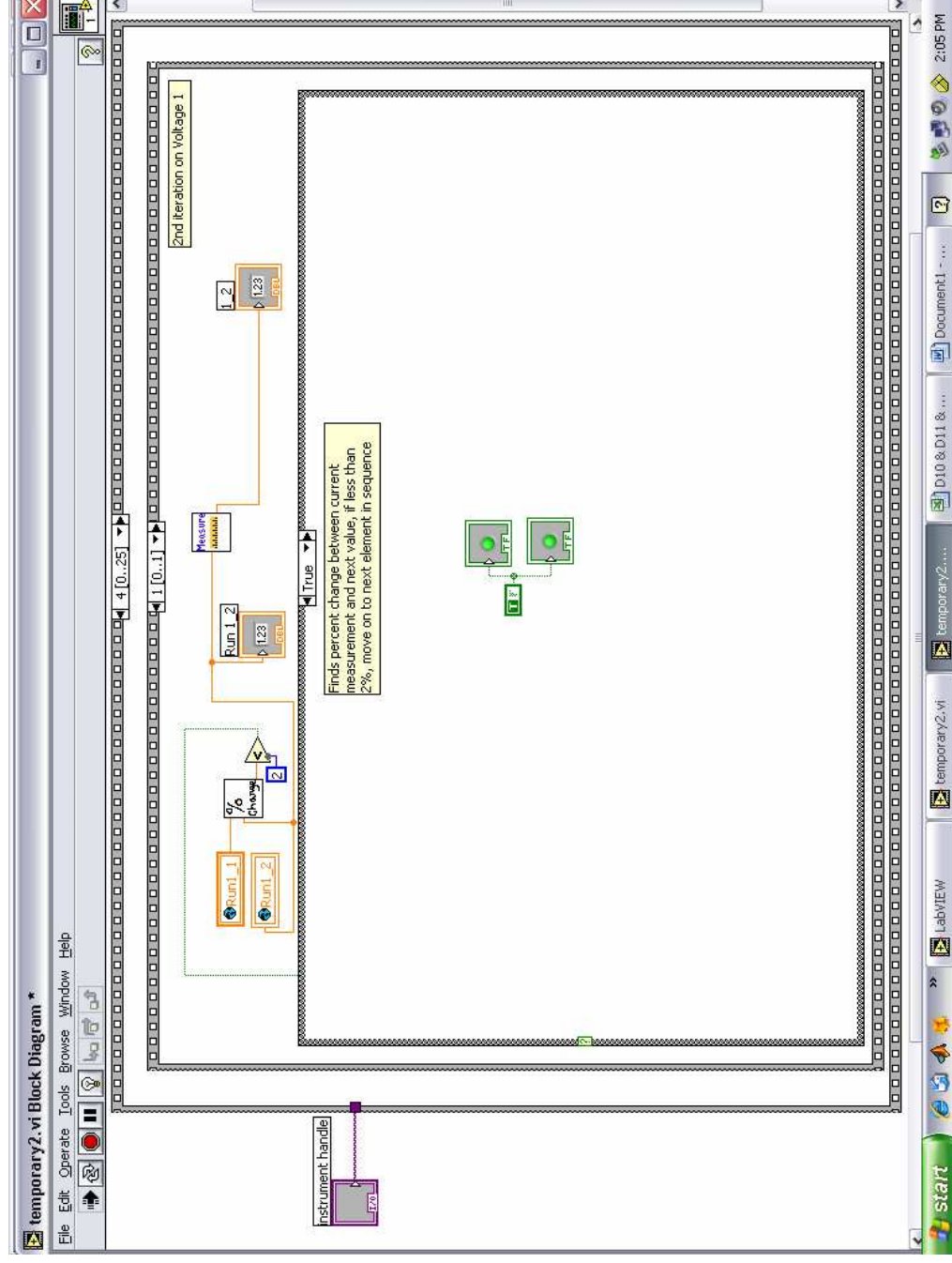
The next frame takes an initial voltage and temperature gradient measurement and displays it for the user to see.



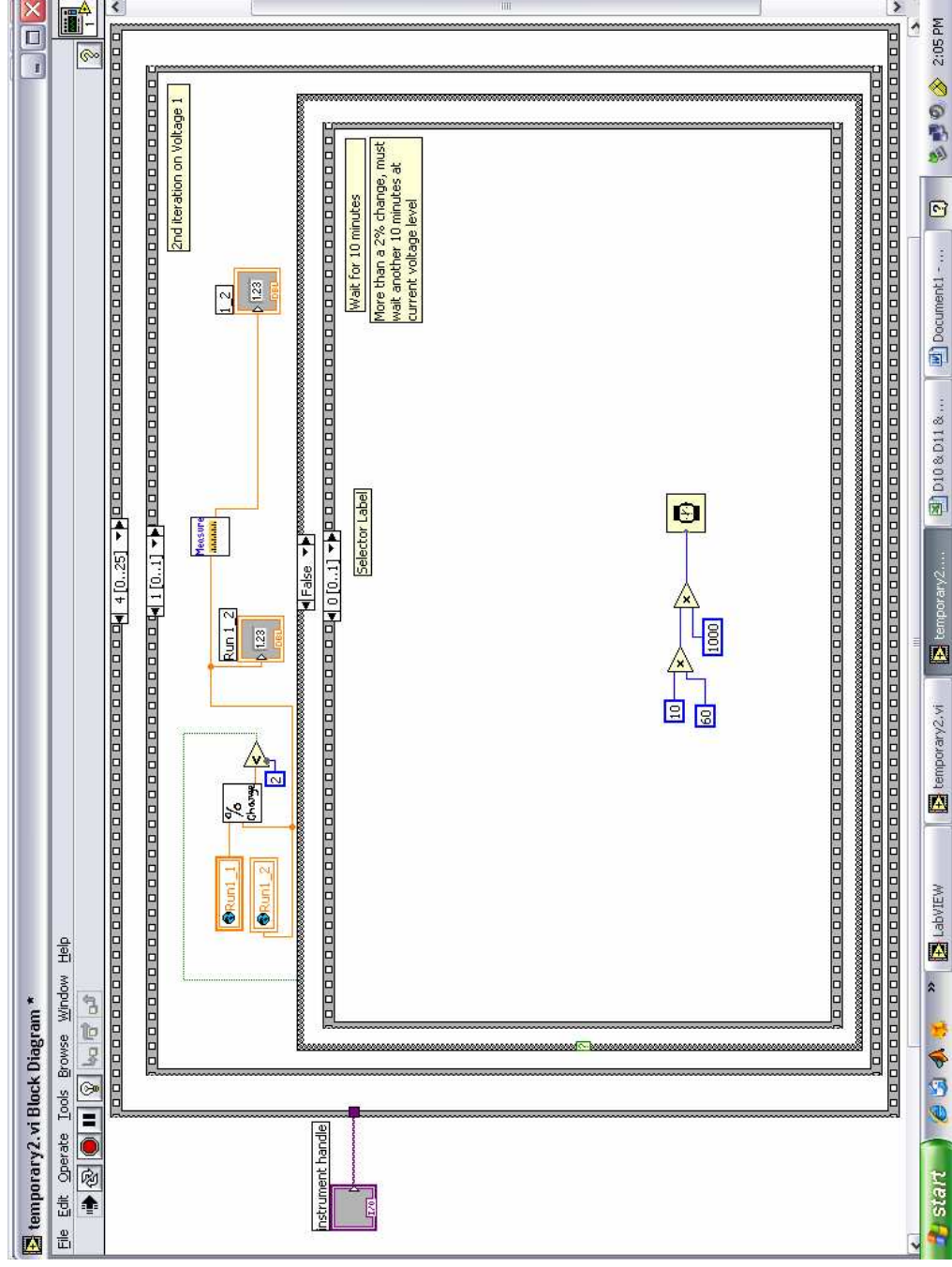
The next frame has the program wait 10 minutes.



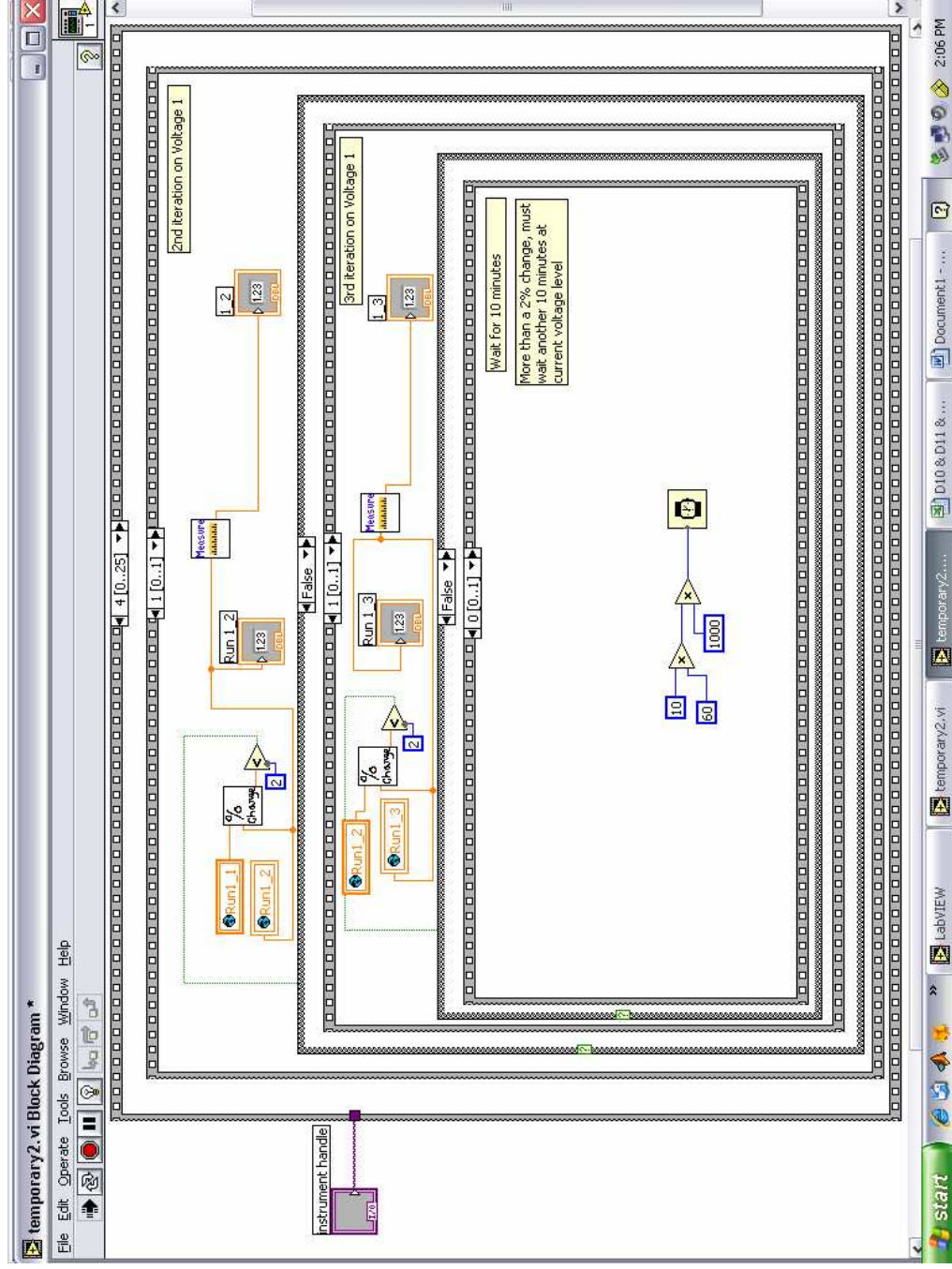
In this frame, a second set of voltage and temperature data is taken and compared with the first set of data. If there is less than a 2% change, the light next to the data is illuminated and the program will return to the solid line and set a new voltage level.



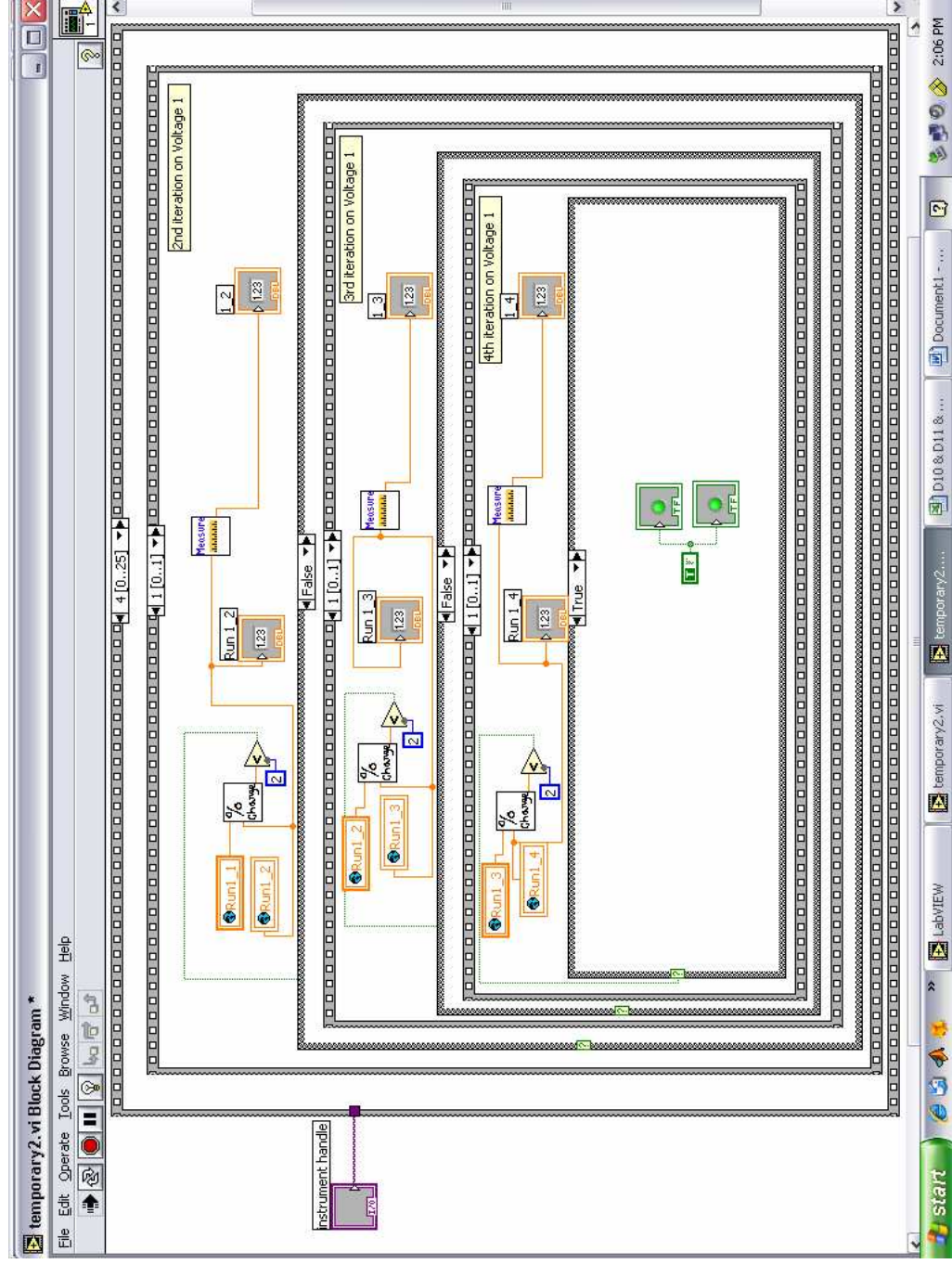
If the percent change is greater than 2%, the program continues to the next slide where it waits another ten minutes.



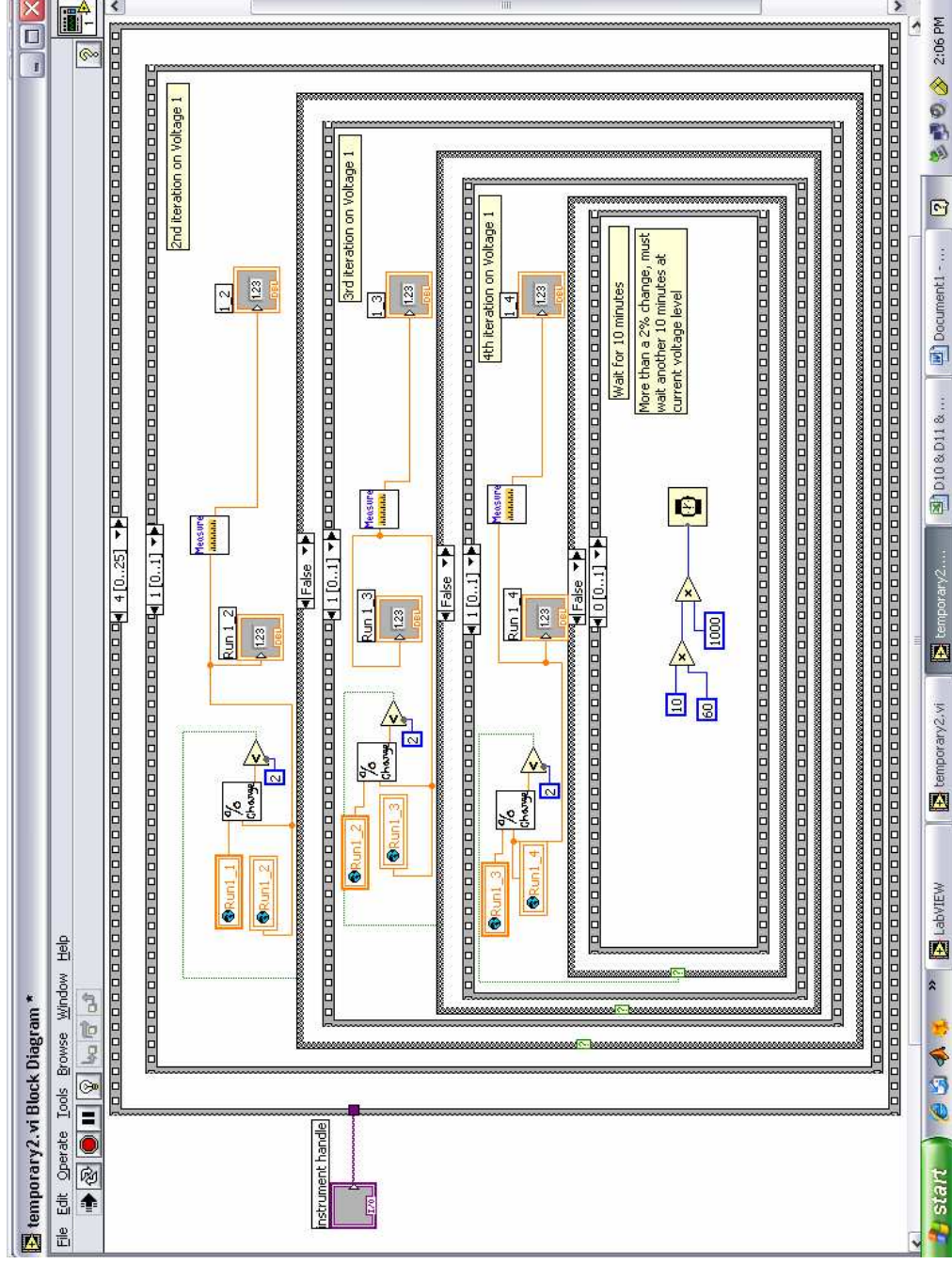
If the requirement is not satisfied, the program continues to the next screen and waits an additional ten minutes.



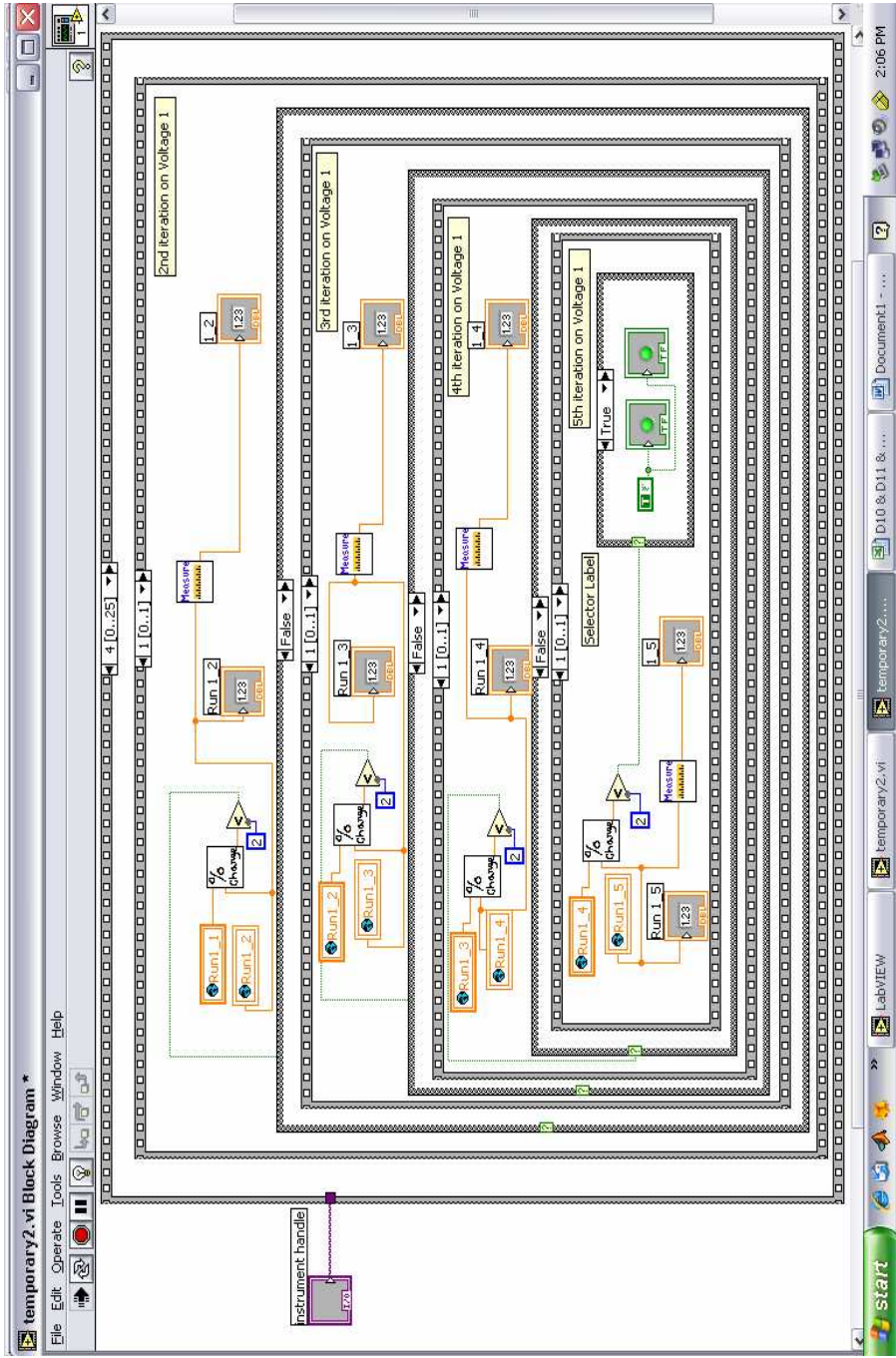
After ten minutes, a fourth data set is taken and compared to the third data set. If less than a 2% change has occurred, the light next to the data is illuminated and the program returns to the solid line and begins sets another voltage level.



If the requirement is not satisfied, the program continues to the next screen and waits an additional ten minutes.

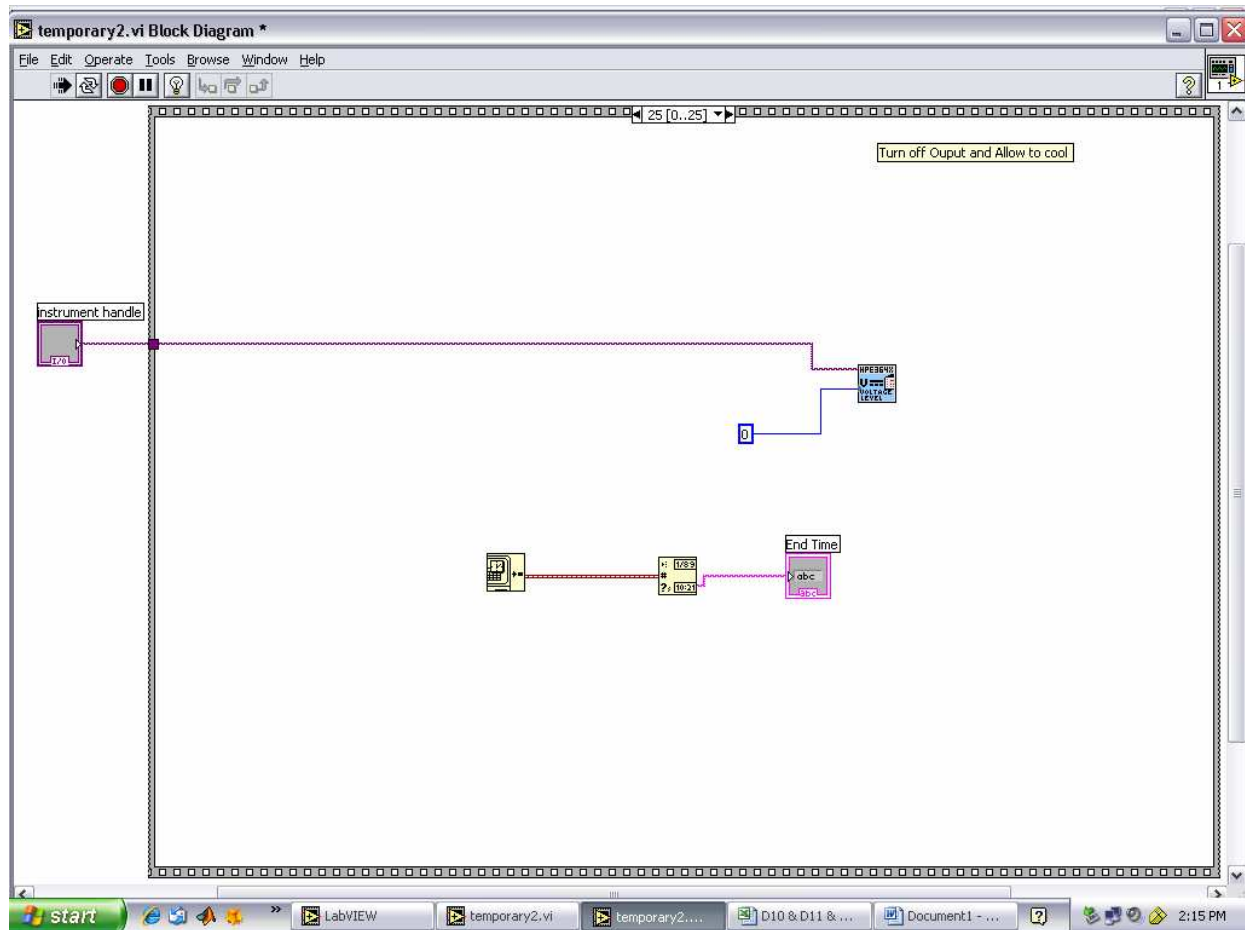


After ten minutes, a fifth and final data set is taken and compared to the fourth data set. If less than a 2% change has occurred, the light next to the data is illuminated and the program returns to the solid line and begins sets another voltage level. If the requirement is not satisfied, the program still returns to the solid line, but no light is illuminated.



This sequence repeats six times for each of the six user inputted voltage levels.

After the completion of the six repetitions, the program continues to the final screen where the power supply is set to zero volts and the device is allowed to cool back down to room temperature.



The data collected in each of the iterations is saved in a text file that can be accessed by the user. A driver from the Agilent Technologies website controls the voltage levels for the Agilent E3644A DC Power Supply. There are several sub-VIs in this program. The block that says “% change” merely calculates the difference between the current voltage level and the previous voltage level measured. The block that says “measure” collects temperature and voltage data for 30 seconds at a rate of 1 Hz and finds the average values. A National Instruments SC-2345 Signal Conditioning Connector Block is used to collect both the temperature and voltage data.

Appendix B. Titanium Material Test Raw Data

This appendix shows the raw data that was collected while conducting testing for the Seebeck coefficient of the Titanium Grade 5 alloy used. Table B.1 shows the measured voltages and temperature gradients for various heater voltage levels. Additionally, the ratio of the voltage signal to the temperature gradient is shown.

Table B.1. Titanium material testing raw data

Heater Voltage	Measured (μV)	delta T ($^{\circ}\text{C}$)	$\mu\text{V/K}$	
0	-105.272	0.79573		Run 1
4	-120.728	3.86801	15.456	
6	-133.589	7.71989	28.317	
8	-155.53	12.8817	50.258	
10	-183.145	19.163	77.873	
12	-206.978	26.1652	101.706	
0	-108.947	0.54425		Run 2
4	-122.349	3.7155	13.402	
6	-133.265	7.65044	24.318	
8	-155.746	12.8483	46.799	
10	-182.605	19.2312	73.658	
12	-213.03	26.4112	104.083	
0	-105.596	0.51227		Run 3
4	-116.458	3.80472	10.862	
6	-135.967	7.63064	30.371	
8	-153.369	12.9154	47.773	
10				
12				
10	-181.578	19.2197	73.226	Run 4
12	-211.409	26.2203	103.057	
0	-108.352	0.82617		
4	-119.485	3.79763	11.133	
6	-132.455	7.74781	24.103	
8	-153.693	12.9366	45.341	
0	-108.676	0.57748		Run 5
4	-116.134	3.75951	7.458	
6	-137.859	7.64688	29.183	
8	-159.854	12.8314	51.178	
10	-182.389	19.0923	73.713	
12	-210.977	26.1573	102.301	

Appendix C. Pictures of Device

This appendix contains the pictures taken of each device tested. These pictures were used to determine the angle of the device, which in turn was used to calculate both the length and area of the device.

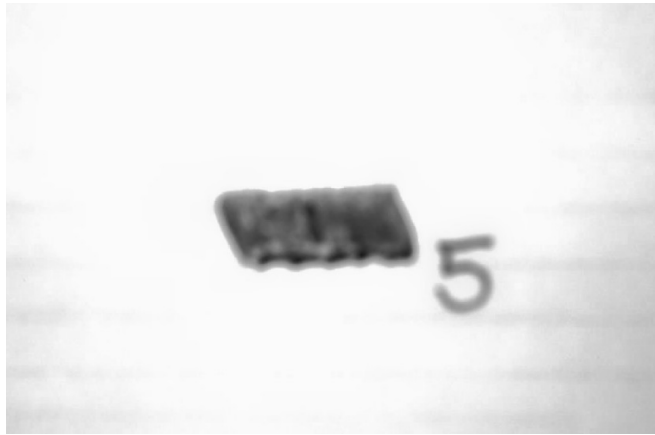


Figure C.1. Picture of device 5 with $\alpha=65^\circ$



Figure C.2. Picture of device 6 with $\alpha=59^\circ$

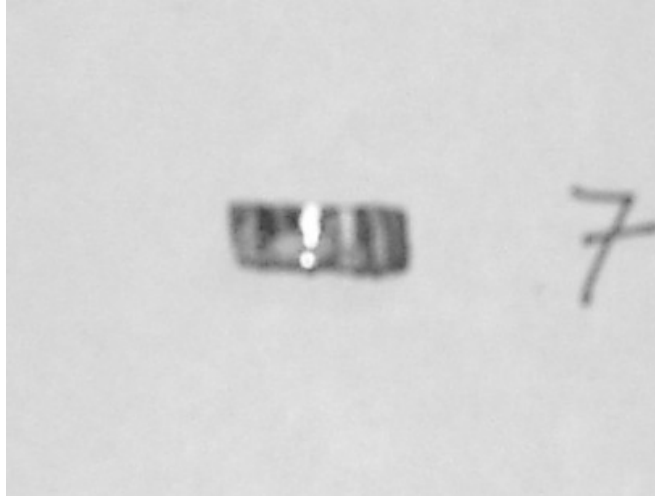


Figure C.3. Picture of device 7 with $\alpha=75^\circ$

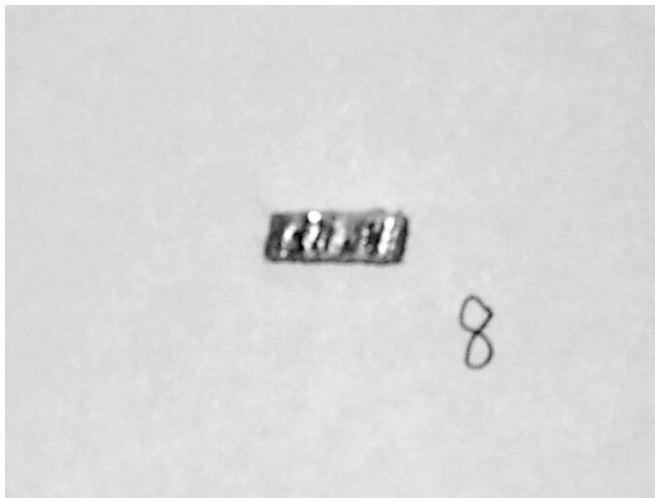


Figure C.4. Picture of device 8 with $\alpha=79^\circ$

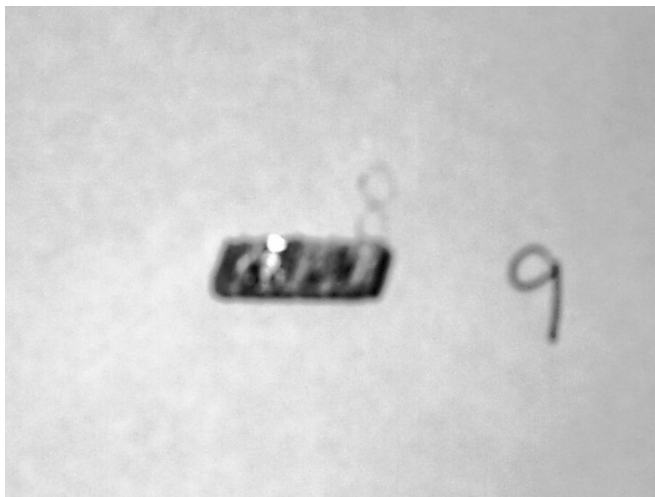


Figure C.5. Picture of device 9 with $\alpha=73^\circ$

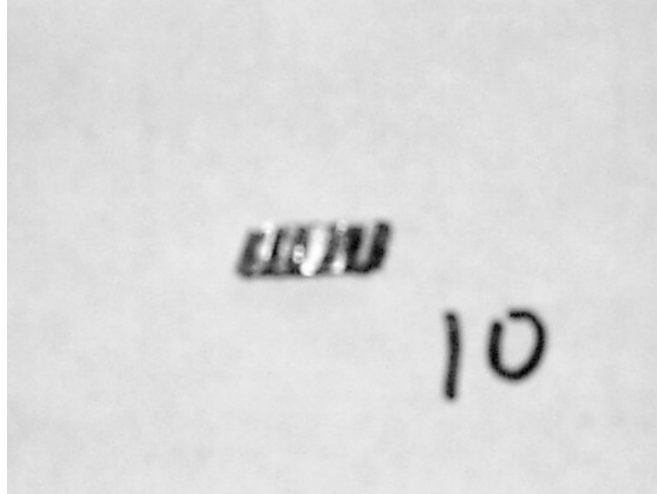


Figure C.6. Picture of device 10 with $\alpha=70^\circ$

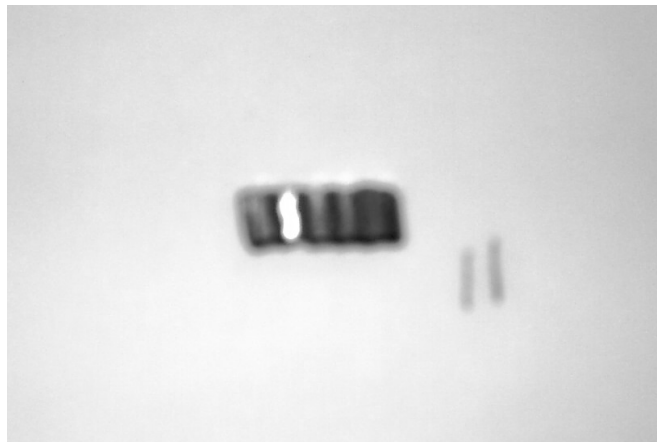


Figure C.7. Picture of device 11 with $\alpha=88^\circ$



Figure C.8. Picture of device 12 with $\alpha=68^\circ$

Appendix D. Heat Flux Sensing Data

This appendix contains the raw data collected for each of the angles tested. This data includes the angle of the device, area of device, voltage and current settings for the heater, power per area based on heater settings and area of the device, measured voltage, temperature gradient, measured voltage less the reference voltage, and sensitivity. There are 11 total tables, one for each device tested. For each device tested, a plot of the measured voltage less the reference voltage versus the heat flux is shown with a least squares linear fit of the data. In addition, a plot of the temperature gradient versus the heat flux is shown for each device to demonstrate the existence of steady state.

Table D.1. Device 5 Raw Data

Device 5: 65° Area1.3000 Angle65						
Voltage	Current	Power	Delta T	Volt Out (μV)	Volt Out-Ref	Sensitivity
0	0	0.0000	0.773974	-96.5171		
10	0.137	1.0538	15.3038	-3495.34	3398.8229	3225.27
12	0.164	1.5138	21.4678	-5023.04	4926.5229	3254.42
0	0	0.0000		didn't reach steady state		
6	0.083	0.3831	6.08627	-1185.18	1088.6629	2841.99
8	0.11	0.6769	10.201	-2040.76	1944.2429	2872.27
0	0	0.0000	0.787304	-120.62		
4	0.055	0.1692	3.13069	-658.926	538.306	3181.01
6	0.083	0.3831	5.72226	-1225.06	1104.44	2883.17
8	0.11	0.6769	10.1714	-2336.1	2215.48	3272.98
10	0.137	1.0538	15.346	-3572.89	3452.27	3275.99
12	0.164	1.5138	21.4747	-5116.1	4995.48	3299.97
14	0.192	2.0676	28.5948	-6877.36	6756.74	3267.88
0	0	0.0000	0.688124	-90.0321		
4	0.055	0.1692	3.12259	-702.969	612.9369	3622.02
6	0.083	0.3831	5.77722	-1323.31	1233.2779	3219.51
8	0.11	0.6769	9.50305	-2254.93	2164.8979	3198.25
12	0.164	1.5138	20.2097	-5213.91	5123.8779	3384.79
0	0	0.0000	0.759589	-93.8691		
14	0.192	2.0676	didn't reach steady state			
10	0.137	1.0538	15.3523	-3722.15	3628.2809	3443.01

8	0.11	0.6769	10.1816	-2339.83	2245.9609	3318.01
6	0.083	0.3831	6.08057	-1361.63	1267.7609	3309.53
4	0.055	0.1692	3.03899	-614.341	520.4719	3075.62
0	0	0.0000	0.743522	-87.222		
6	0.083	0.3831	6.10062	-1300.88	1213.658	3168.29
8	0.11	0.6769	10.1859	-2271.36	2184.138	3226.68
10	0.137	1.0538	15.3716	-3528.04	3440.818	3265.12
12	0.164	1.5138	20.0225	-4346.01		
14	0.192	2.0676	28.6838	-6489.61	6402.388	3096.50
AVG						3213.74
STD DEV						181.43

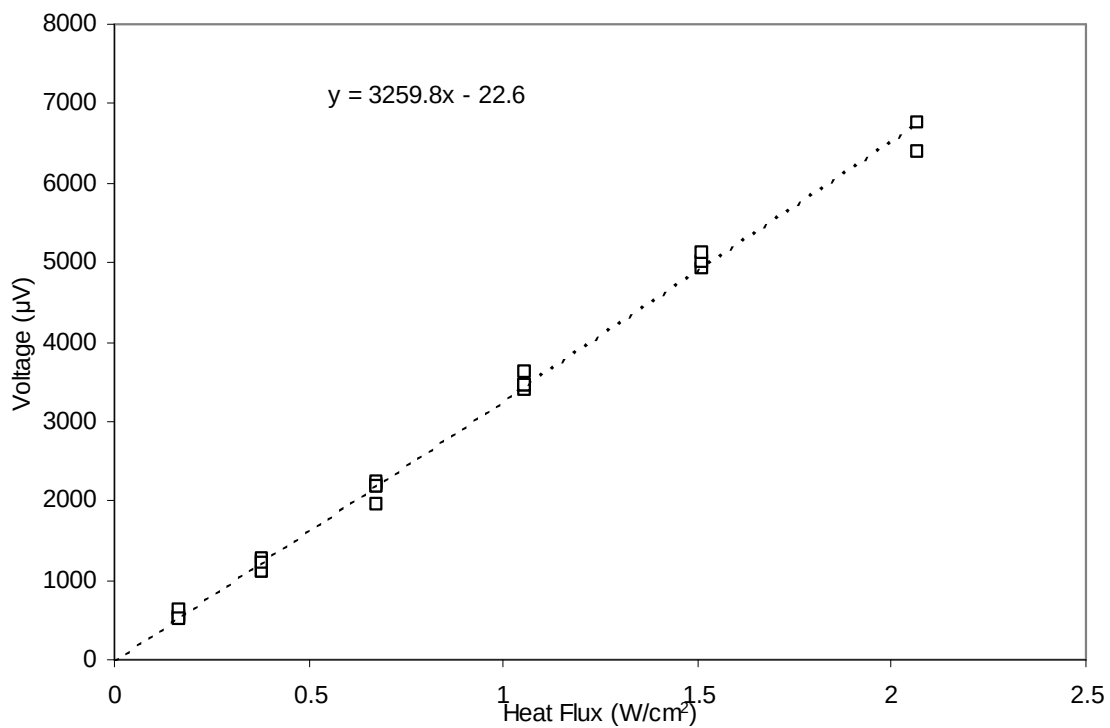


Figure D.1. Device 5: voltage signal generated vs. heat flux

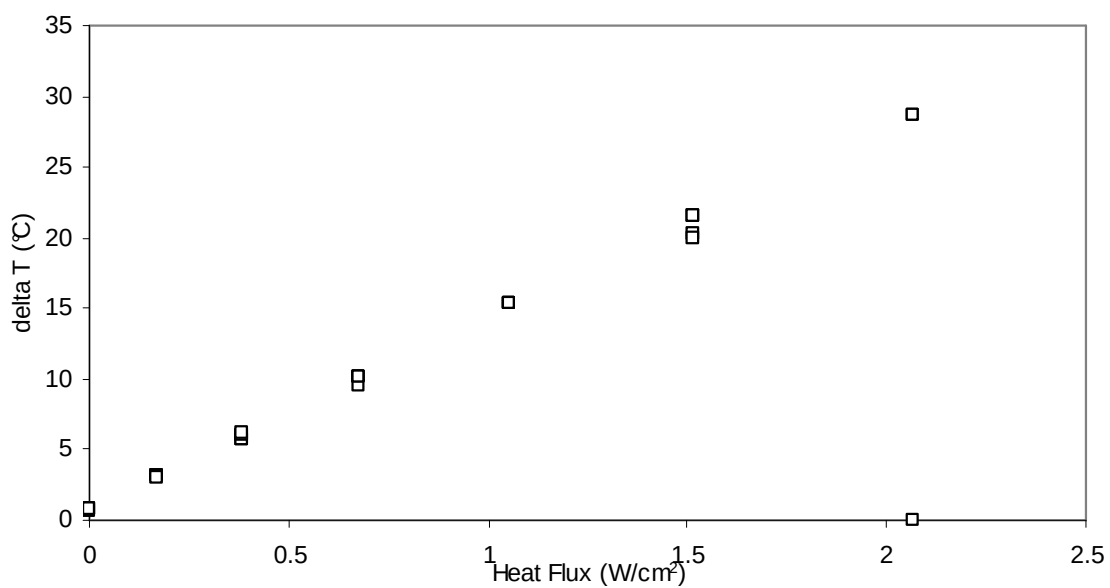


Figure D.2. Device 5: delta T generated vs. heat flux

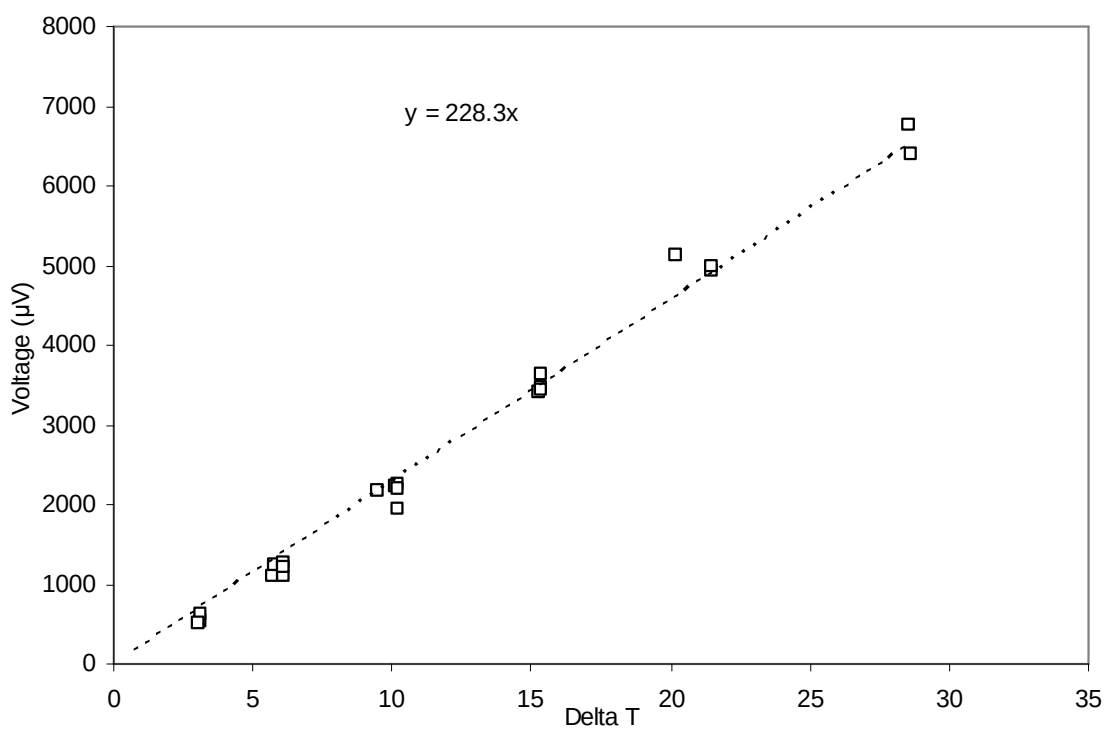


Figure D.3. Device 5: delta T generated vs. voltage signal generated

Table D.2. Device 6 raw data

Device 6: 59°				Area	1.3746	
				Angle	59	
Voltage	Current	Power	Delta T	Volt Out (μV)	Volt Out-Ref	Sensitivity
0	0	0.0000	0.771495	-100.246		
8	0.11	0.6402	5.45915	3808.73	3908.976	6105.88
10	0.137	0.9967	8.8978	5603.39	5703.636	5722.68
12	0.164	1.4317	12.5375	8322.38	8422.626	5882.89
14	0.191	1.9453	16.2612	10287.1	10387.346	5339.63
16	0.22	2.5608	20.7798	13940.8	14041.046	5483.09
0	0	0.0000	0.751147	-108.406		
8	0.11	0.6402	5.42114	3234.97	3343.376	5222.41
10	0.137	0.9967	8.75025	5030.28	5138.686	5155.84
12	0.164	1.4317	12.1114	7475.83	7584.236	5297.31
14	0.191	1.9453	15.5633	9450.12	9558.526	4913.58
16	0.22	2.5608	19.9822	13363.4	13471.806	5260.80
0	0	0.0000	0.779622	-106.623		
8	0.11	0.6402	5.30372	3035.51	3142.133	4908.06
10	0.137	0.9967	8.40423	4794.77	4901.393	4917.76
12	0.164	1.4317	11.7747	6578.62	6685.243	4669.39
14	0.191	1.9453	15.4534	10260.2	10366.823	5329.08
16	0.22	2.5608	20.0025	12784.8	12891.423	5034.15
0	0	0.0000	0.779622	-106.623		
8	0.11	0.6402	5.39163	3026.1	3132.723	4893.36
10	0.137	0.9967	8.73493	5142.53	5249.153	5266.68
12	0.164	1.4317	12.6128	7426.37	7532.993	5261.51
14	0.191	1.9453	16.1064	9738.27	9844.893	5060.78
16	0.22	2.5608	20.8378	14234.7	14341.323	5600.35
0	0	0.0000	0.762151	-112.081		
8	0.11	0.6402	5.40685	3268.42	3380.501	5280.40
10	0.137	0.9967	8.72441	5050.22	5162.301	5179.54
12	0.164	1.4317	11.5542	6578.62	6690.701	4673.20
14	0.191	1.9453	15.2889	9259.89	9371.971	4817.68
16	0.22	2.5608	20.0432	12875.5	12987.581	5071.70
					AVG	5213.91
					STD DEV	351.91

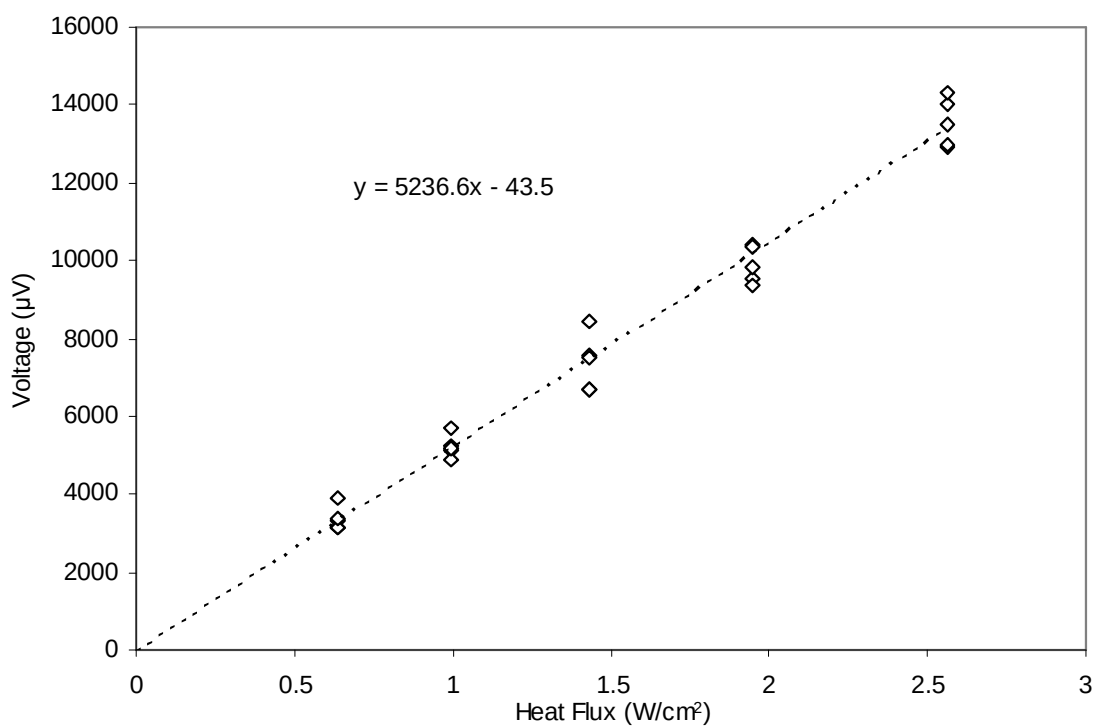


Figure D.4. Device 6: voltage signal generated vs. heat flux

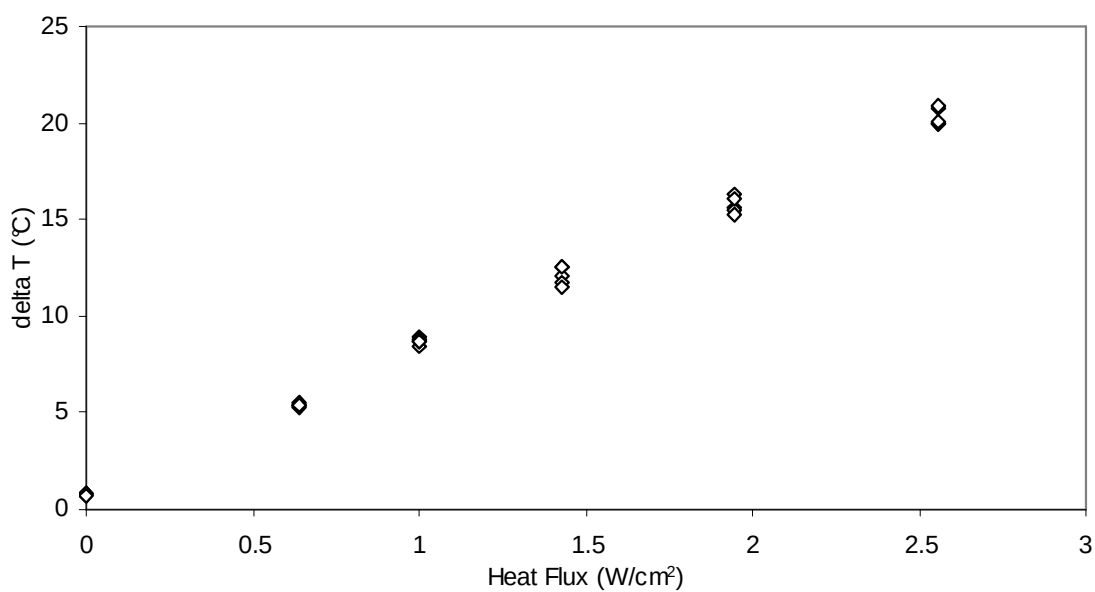


Figure D.5. Device 6: delta T generated vs. heat flux

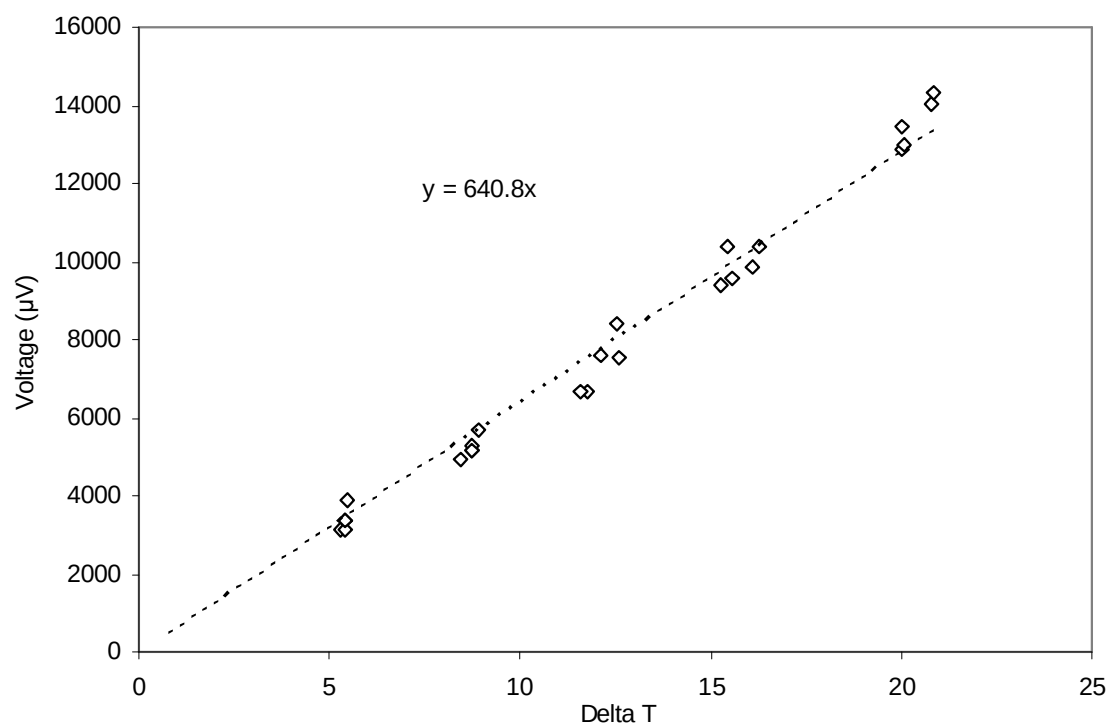


Figure D.6. Device 6: delta T generated vs. voltage signal generated

Table D.3. Device 7 raw data

Device 7: 75°				Area	1.2198	
				Angle	75	
Voltage	Current	Power	Delta T	Volt Out (μV)	Volt Out-Ref	Sensitivity
0	0	0.0000	0.753357	-108.514		
4	0.055	0.1804	2.95237	-185.523	77.009	426.98
6	0.083	0.4083	7.58525	-278.636	170.122	416.70
8	0.11	0.7214	13.9364	-481.238	372.724	516.65
10	0.137	1.1231	21.9197	-735.502	626.988	558.25
12	0.164	1.6134	31.2918	-1151.89	1043.376	646.70
0	0	0.0000	0.823716	-112.513		
4	0.055	0.1804	2.95936	-174.877	62.364	345.78
6	0.083	0.4083	7.5865	-249.995	137.482	336.75
8	0.11	0.7214	13.938	-440.544	328.031	454.70
10	0.137	1.1231	21.8928	-746.743	634.23	564.70
12	0.164	1.6134	31.324	-1180.48	1067.967	661.95
0	0	0.0000	0.821686	-109.217		
4	0.055	0.1804	2.909	-163.853	54.636	302.93
6	0.083	0.4083	7.5958	-248.968	139.751	342.31
8	0.11	0.7214	13.9219	-451.623	342.406	474.62
10	0.137	1.1231	21.8653	-692.593	583.376	519.42
12	0.164	1.6134	31.2724	-1244.79	1135.573	703.85
					AVG	484.82
					ST DEV	126.26

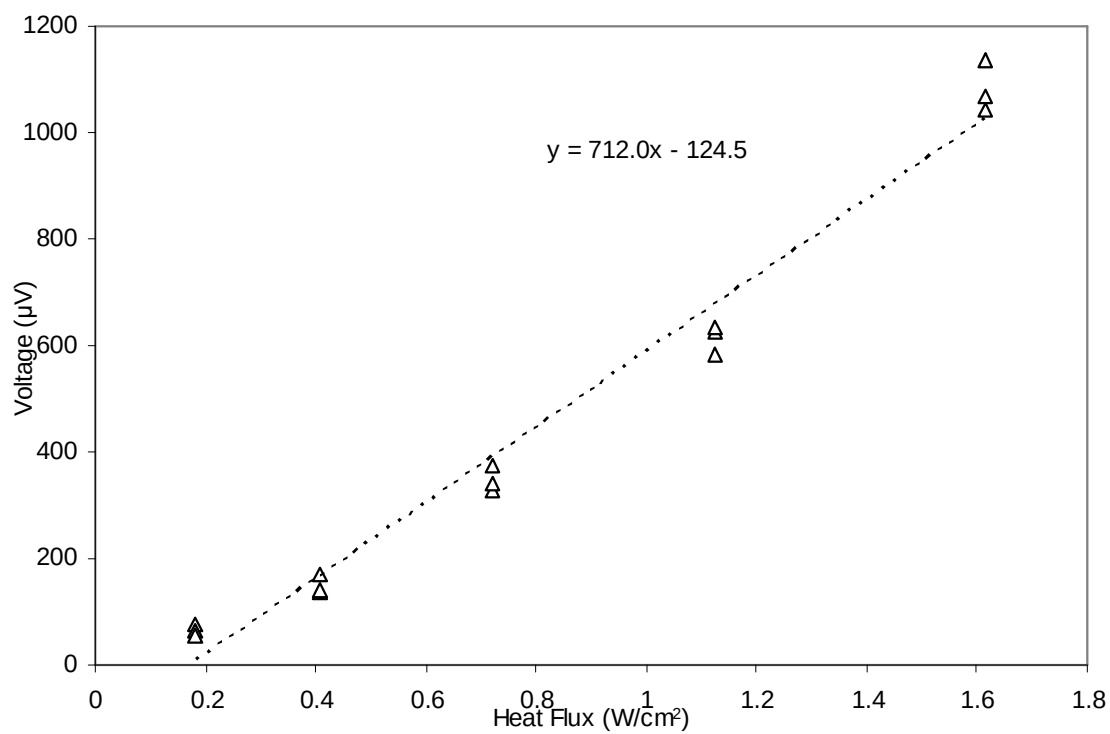


Figure D.7. Device 7: voltage signal generated vs. heat flux

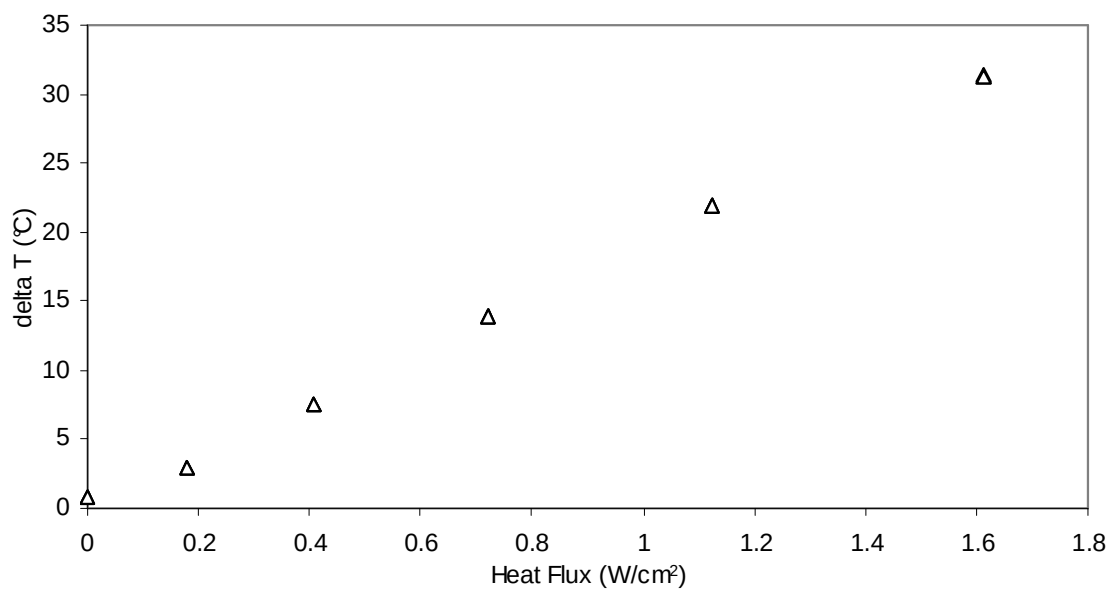


Figure D.8. Device 7: delta T generated vs. heat flux

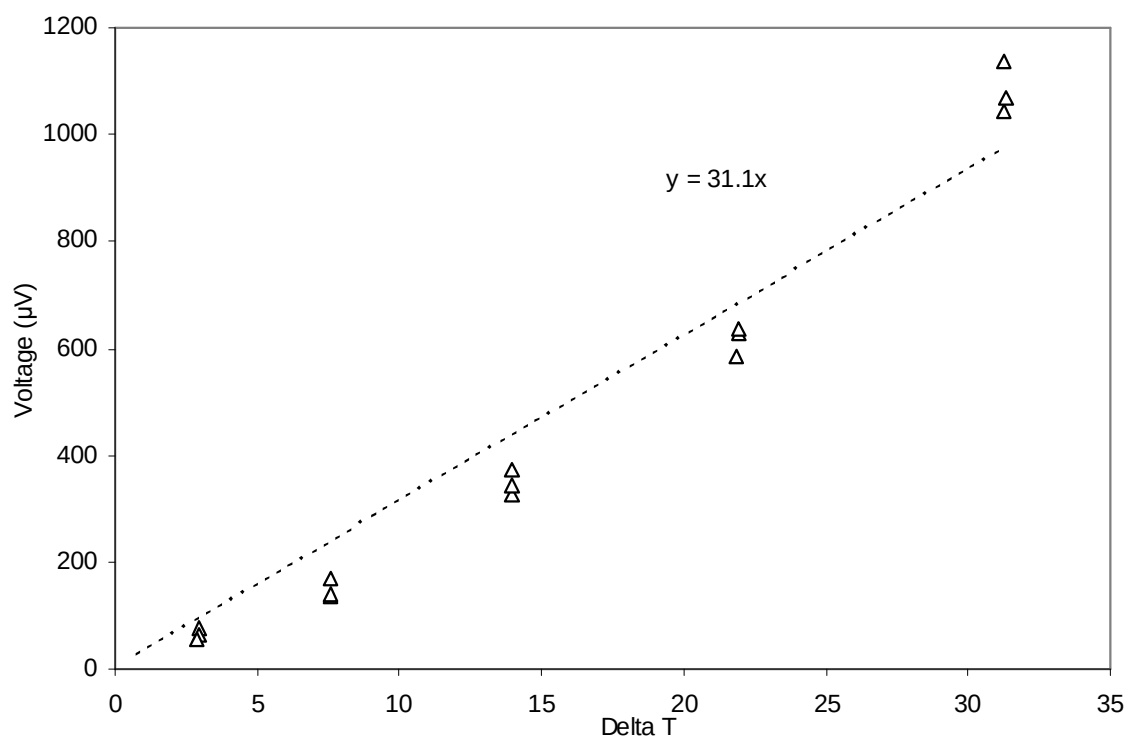


Figure D.9. Device 7: delta T generated vs. voltage signal generated

Table D.4. Device 8 raw data

Device 8: 79°				Area	1.2003	
				Angle	79	
Voltage	Current	Power	Delta T	Volt Out (μV)	Volt Out-Ref	Sensitivity
0	0	0.0000	0.825601	-110.946		
6	0.083	0.4149	7.29631	-628.014	517.068	1246.25
8	0.11	0.7332	13.4475	-1050.62	939.674	1281.69
10	0.137	1.1414	21.2136	-1629.02	1518.074	1330.02
12	0.164	1.6396	30.4013	-2312.05	2201.104	1342.46
14	0.191	2.2278	40.8884	-3108.78	2997.834	1345.65
0	0	0.0000	0.873726	-110.081		
6	0.083	0.4149	7.20446	-614.341	504.26	1215.38
8	0.11	0.7332	13.391	-1034.78	924.699	1261.26
10	0.137	1.1414	21.1211	-1622.97	1512.889	1325.48
12	0.164	1.6396	30.3766	-2354.85	2244.769	1369.10
14	0.191	2.2278	40.7986	-3205.84	3095.759	1389.61
0	0	0.0000	0.838565	-111.162		
6	0.083	0.4149	7.23258	-642.875	531.713	1281.55
8	0.11	0.7332	13.3687	-1103.09	991.928	1352.96
10	0.137	1.1414	21.0512	-1696.09	1584.928	1388.60
12	0.164	1.6396	30.1731	-2459.96	2348.798	1432.54
14	0.191	2.2278	40.6212	-3270.74	3159.578	1418.26
0	0	0.0000	0.832603	-110.298		
6	0.083	0.4149	7.19156	-669.464	559.166	1347.72
8	0.11	0.7332	13.2672	-1131.41	1021.112	1392.77
10	0.137	1.1414	20.9755	-1754.61	1644.312	1440.62
12	0.164	1.6396	30.12	-2480.93	2370.632	1445.86
14	0.191	2.2278	40.4818	-3228.7	3118.402	1399.77
					AVG	1350.38
					STD DEV	66.41

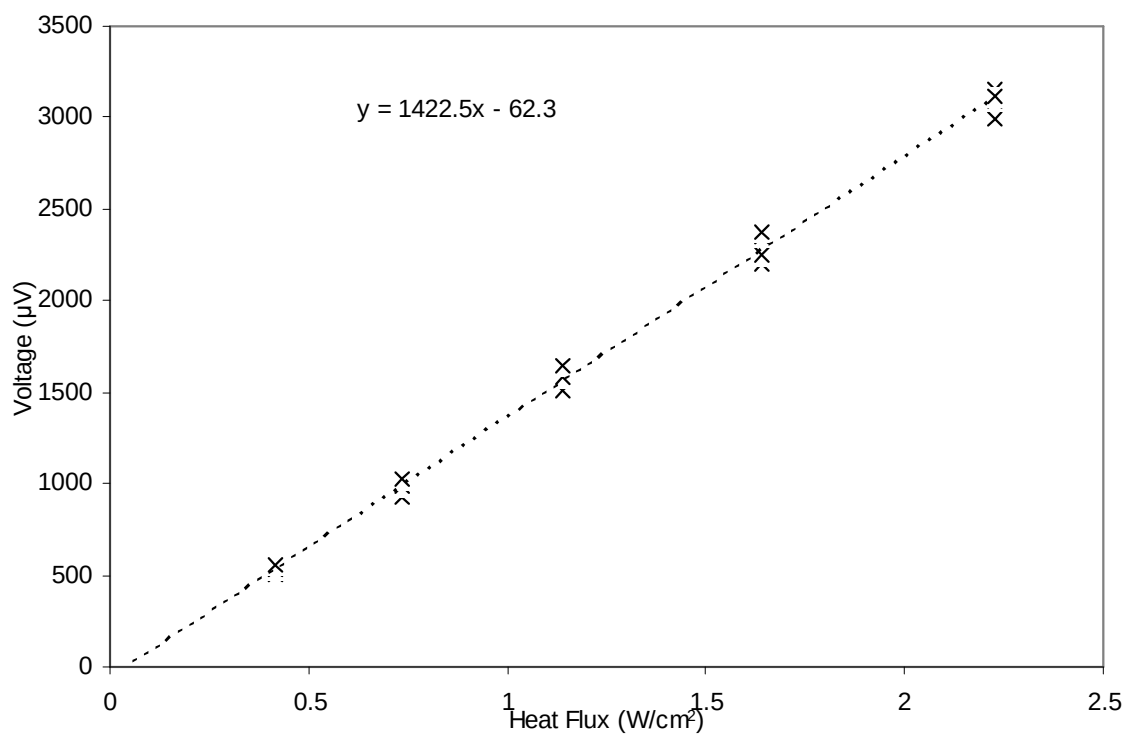


Figure D.10. Device 8: voltage signal generated vs. heat flux

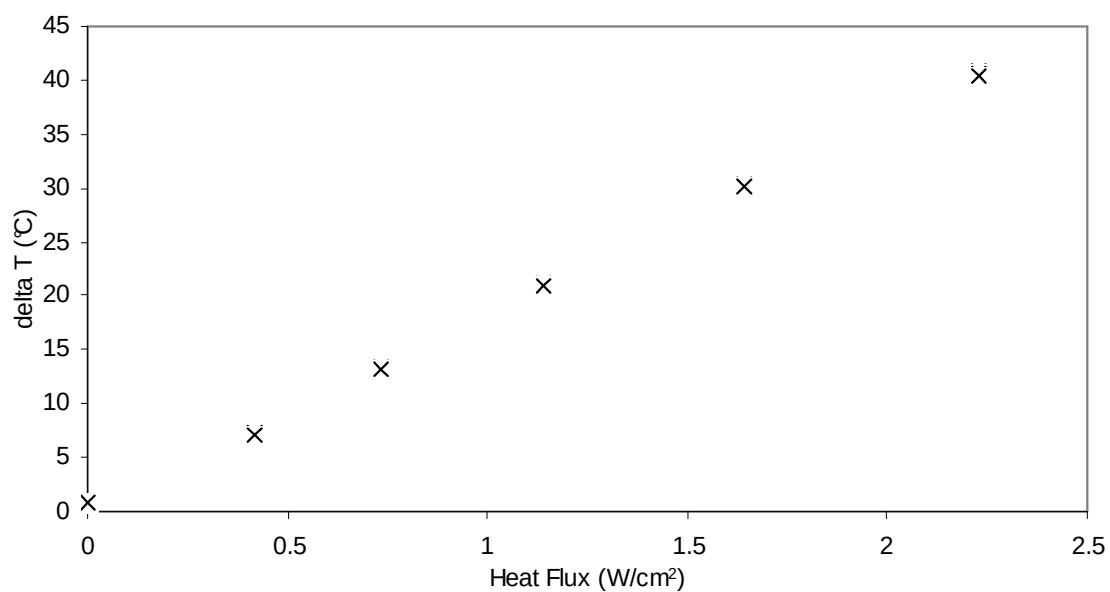


Figure D.11. Device 8: delta T generated vs. heat flux

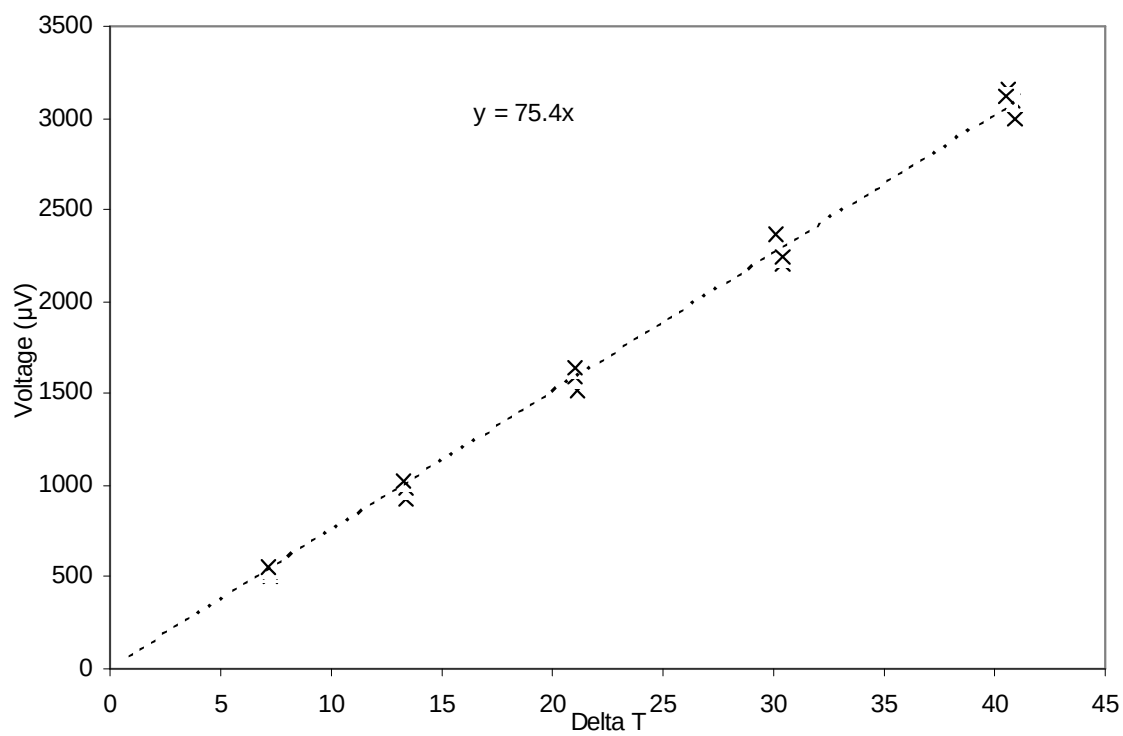


Figure D.12. Device 8: delta T generated vs. voltage signal generated

Table D.5. Device 9 raw data

Device 9: 73°						
			Area	1.2321		
			Angle	73		
Voltage	Current	Power	Delta T	Volt Out (μV)	Volt Out-Ref	Sensitivity
0	0	0.0000	0.8323	-119.863		
6	0.083	0.4042	5.1575	1385.62	1505.483	3724.64
8	0.11	0.7142	9.7972	2595.72	2715.583	3802.05
10	0.137	1.1119	15.567	3777.22	3897.083	3504.75
12	0.164	1.5973	22.499	6347.49	6467.353	4048.92
14	0.191	2.1703	30.282	9579.98	9699.843	4469.31
0	0	0.0000	0.8534	-112.784		
6	0.083	0.4042	5.1634	1625.51	1738.294	4300.62
8	0.11	0.7142	9.7916	3053.07	3165.854	4432.47
10	0.137	1.1119	15.542	4919.07	5031.854	4525.28
12	0.164	1.5973	22.489	7294.4	7407.184	4637.30
14	0.191	2.1703	30.307	9947.3	10060.084	4635.30
0	0	0.0000	0.8466	-104.029		
6	0.083	0.4042	5.2069	1451.93	1555.959	3849.52
8	0.11	0.7142	9.8219	2632.73	2736.759	3831.70
10	0.137	1.1119	15.62	4186.91	4290.939	3858.95
12	0.164	1.5973	22.567	6593.54	6697.569	4193.05
14	0.191	2.1703	30.419	9863.97	9967.999	4592.87
0	0	0.0000	0.8083	-105.704		
6	0.083	0.4042	5.1781	1589.2	1694.904	4193.27
8	0.11	0.7142	9.7961	2908.13	3013.834	4219.63
10	0.137	1.1119	15.56	4686.63	4792.334	4309.87
12	0.164	1.5973	22.474	7366.87	7472.574	4678.24
14	0.191	2.1703	30.356	9801.28	9906.984	4564.76
0	0	0.0000	0.8583	-117.701		
6	0.083	0.4042	5.1797	1693.71	1811.411	4481.52
8	0.11	0.7142	9.771	3049.99	3167.691	4435.04
10	0.137	1.1119	15.556	4729.7	4847.401	4359.39
12	0.164	1.5973	22.582	6979.02	7096.721	4442.94
14	0.191	2.1703	30.356	9984	10101.701	4654.47
					AVG	4269.83
					STD DEV	336.70

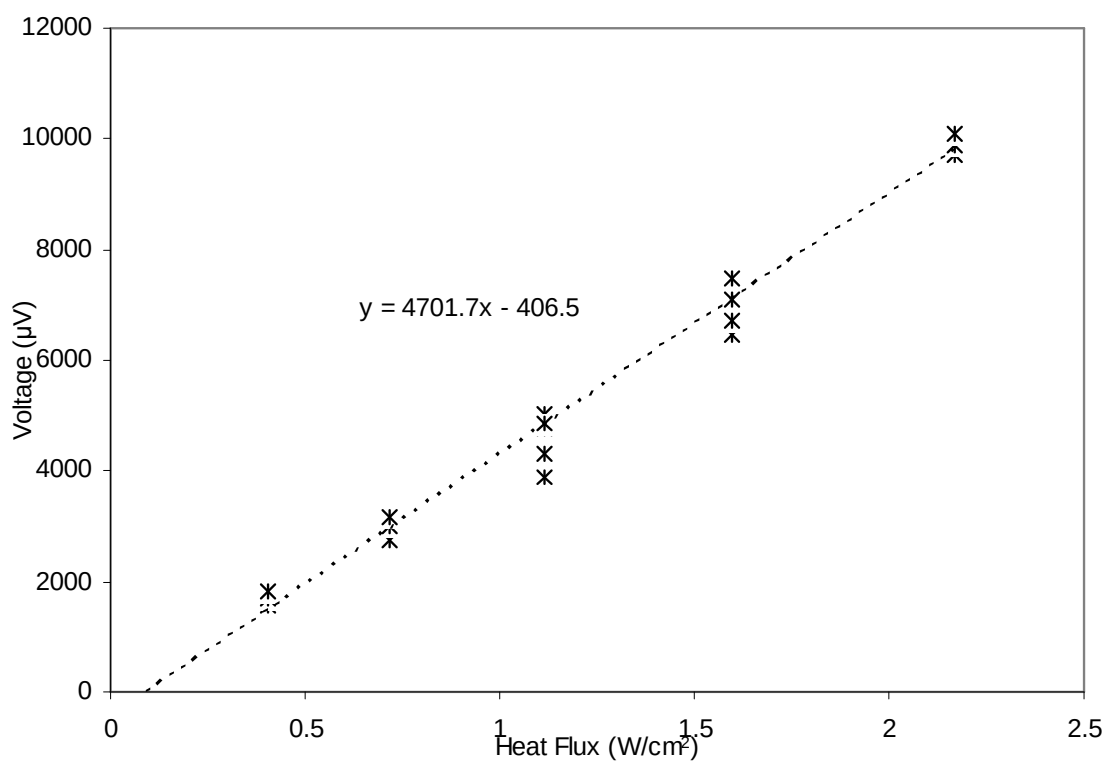


Figure D.13. Device 9: voltage signal generated vs. heat flux

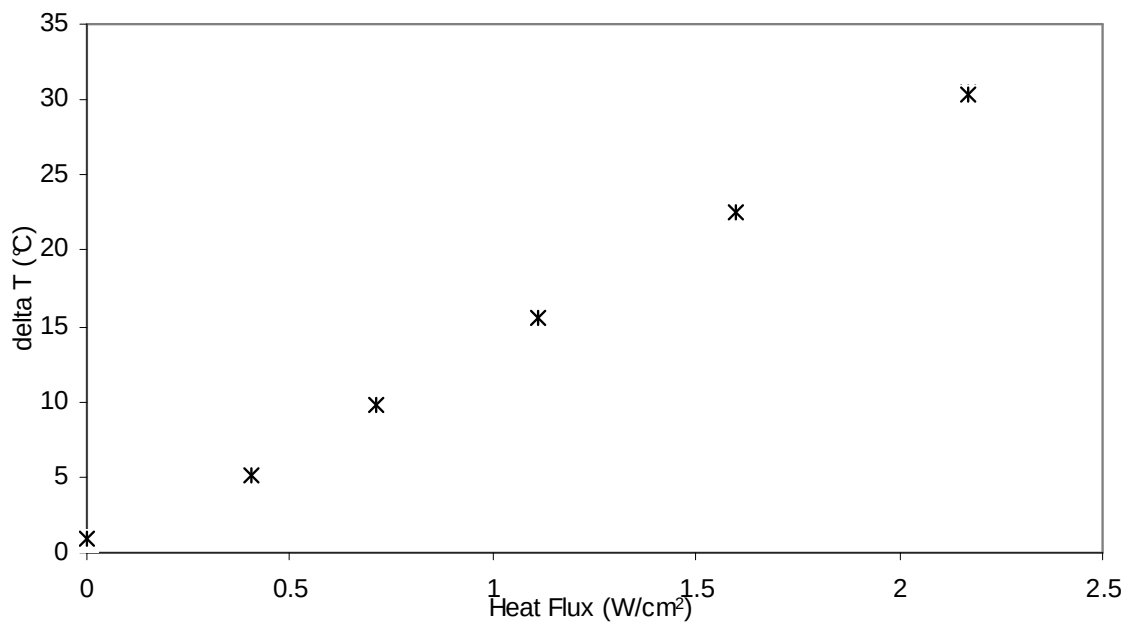


Figure D.14. Device 9: delta T generated vs. heat flux

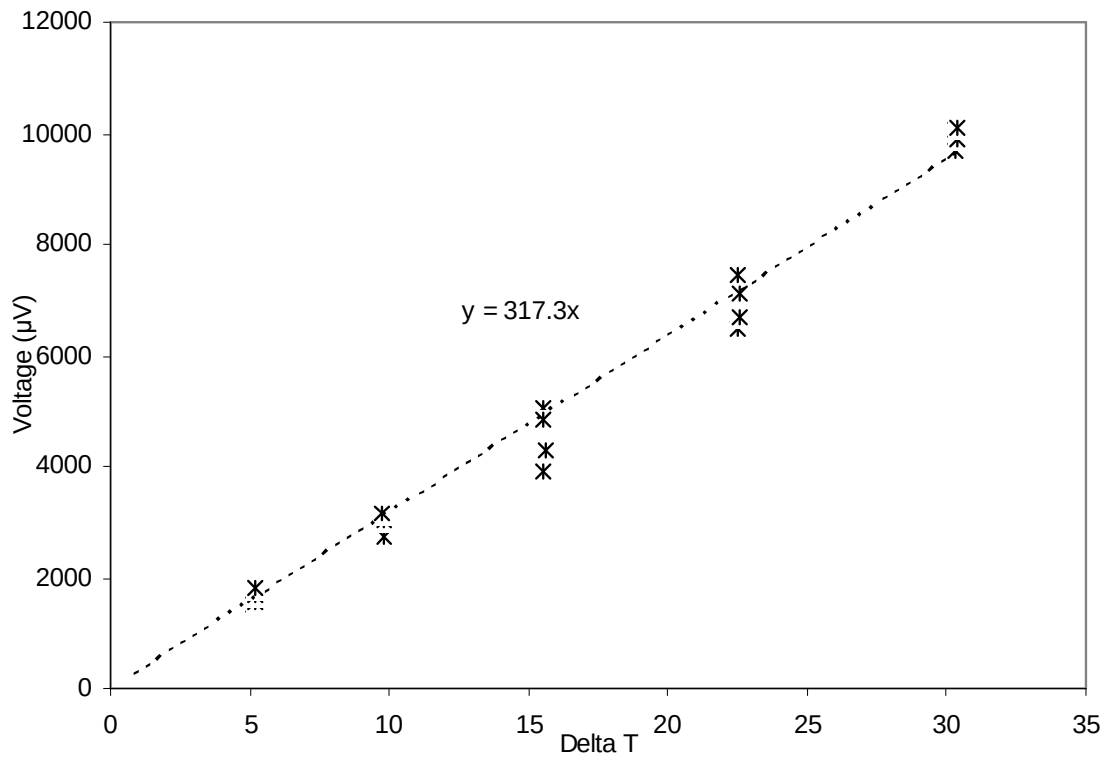


Figure D.15. Device 9: delta T generated vs. voltage signal generated

Table D.6. Device 10 raw data

Device 10: 70°				Area	1.2539	
				Angle	70	
Voltage	Current	Power	Delta T	Volt Out (µV)	Volt Out-Ref	Sensitivity
0	0	0.0000	0.768595	-102.245		
6	0.083	0.3972	3.78158	529.985	632.23	1591.82
8	0.11	0.7018	7.1355	1031.76	1134.005	1615.77
10	0.137	1.0926	11.2911	1673.5	1775.745	1625.20
12	0.164	1.5696	16.0499	2465.64	2567.885	1636.06
14	0.191	2.1326	21.2658	3330.52	3432.765	1609.65
0	0	0.0000	0.791615	-108.568		
6	0.083	0.3972	3.7904	554.627	663.195	1669.78
8	0.11	0.7018	7.17021	1069.86	1178.428	1679.07
10	0.137	1.0926	11.3181	1726.73	1835.298	1679.71
12	0.164	1.5696	16.0772	2581.77	2690.338	1714.07
14	0.191	2.1326	21.304	3437.84	3546.408	1662.94
					AVG	1648.41
					STD DEV	38.53

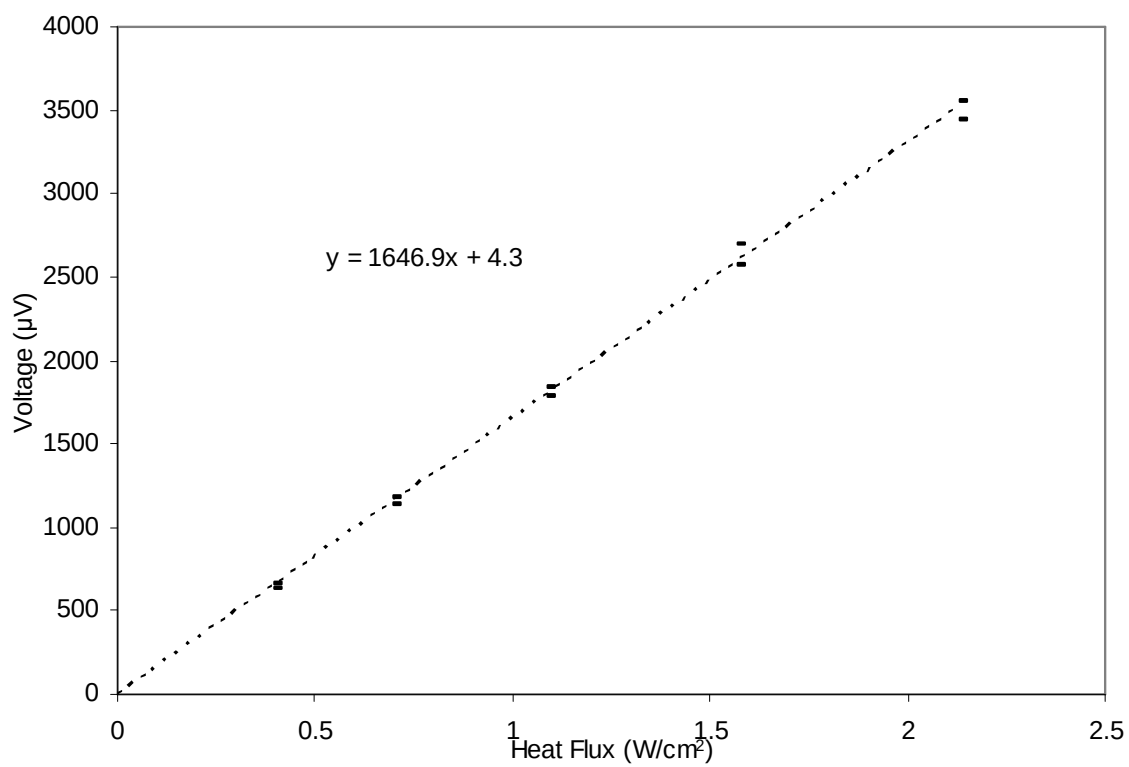


Figure D.16. Device 10: voltage signal generated vs. heat flux

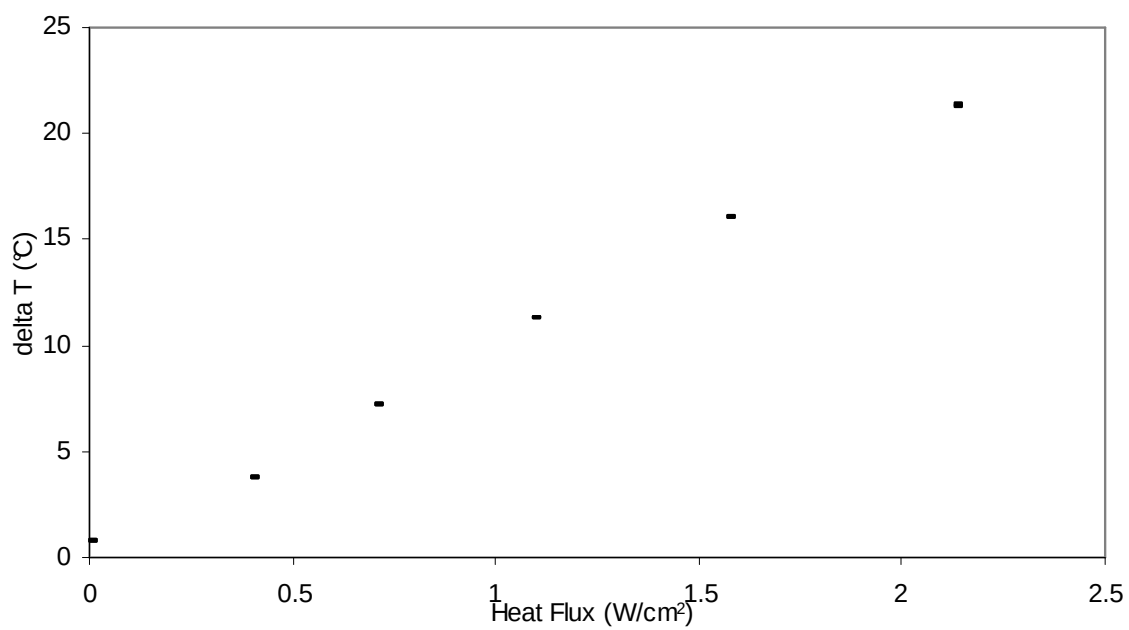


Figure D.17. Device 10: delta T generated vs. heat flux

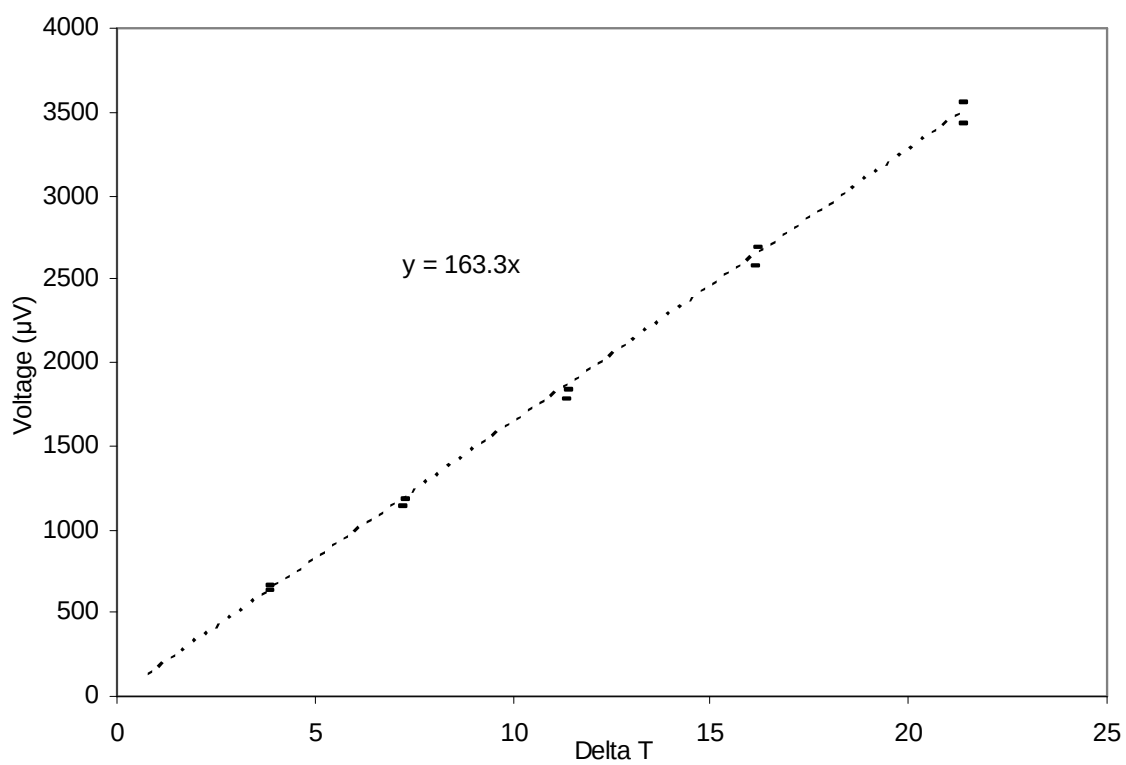


Figure D.18. Device 10: delta T generated vs. voltage signal generated

Table D.7. Device 11 raw data

Device 11: 88°				Area	1.1790	
				Angle	88	
Voltage	Current	Power	Delta T	Volt Out (μ V)	Volt Out- Ref	Sensitivity
0	0	0.00	0.823424	-101.651		
2	0.028	0.05	0.20947	-75.441	26.21	551.79
4	0.055	0.19	1.7	-1.09	100.561	538.90
6	0.083	0.42	4.70483	139.428	241.079	570.73
0	0	0.00	0.82118	-100.57		
2	0.028	0.05	0.159234	-74.5763	25.9937	547.24
4	0.055	0.19	1.69562	-1.174605	99.395395	532.65
6	0.083	0.42	4.76503	132.834	233.404	552.56
5	0.069	0.29	3.05321	56.3119	156.8819	536.11
0	0	0.00	0.796295	-100.354		
2	0.028	0.05	0.159841	-73.09015	27.26385	573.98
3	0.042	0.11	0.611928	-39.4494	60.9046	569.87
4	0.055	0.19	1.68132	9.62016	109.97416	589.34
5	0.069	0.29	3.10642	129.916	230.27	786.89
6	0.083	0.42	4.73331	160.774	261.128	618.19
0	0	0.00	0.838801	-100.624		
2	0.028	0.05	0.168339	-66.6863	33.9377	714.48
4	0.055	0.19	1.68516	32.2095	132.8335	711.84
0	0	0.00	0.775003	-99.5434		
2	0.028	0.05	0.139707	-67.76671	31.77669	668.99
3	0.042	0.11	0.630301	-30.4245	69.1189	646.73
4	0.055	0.19	1.72545	33.9928	133.5362	715.61
					AVG	613.29
					STD DEV	79.23

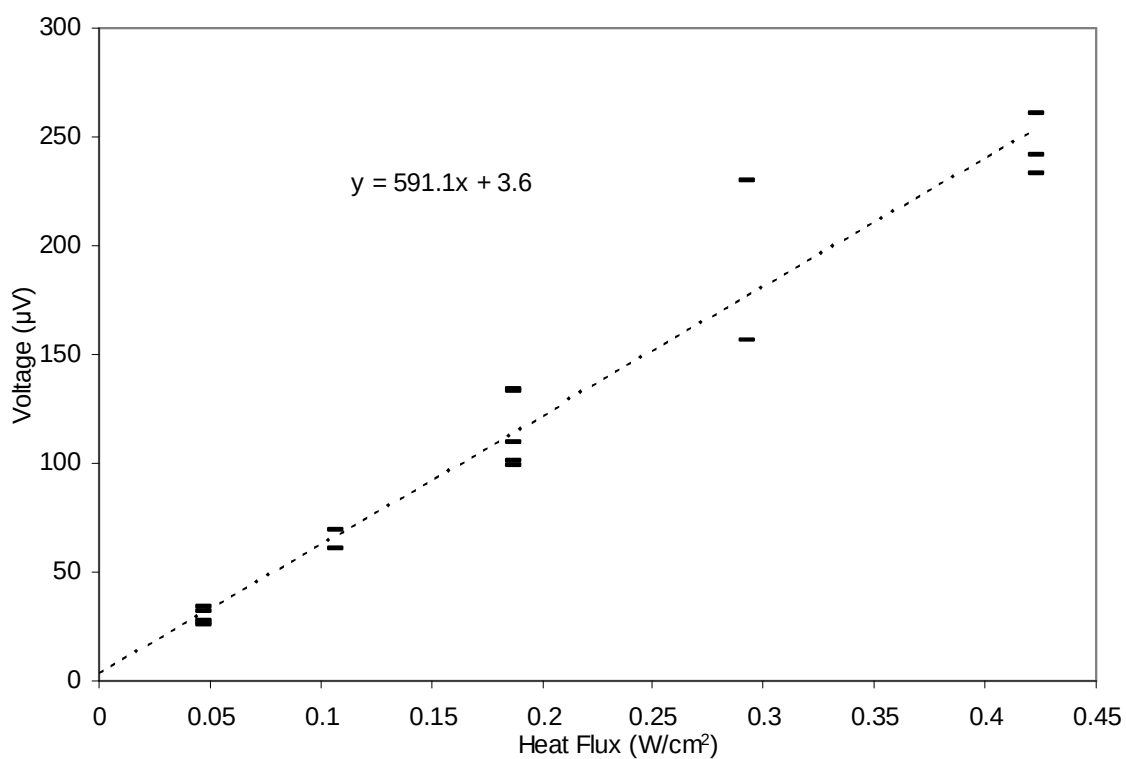


Figure D.19. Device 11: voltage signal generated vs. heat flux

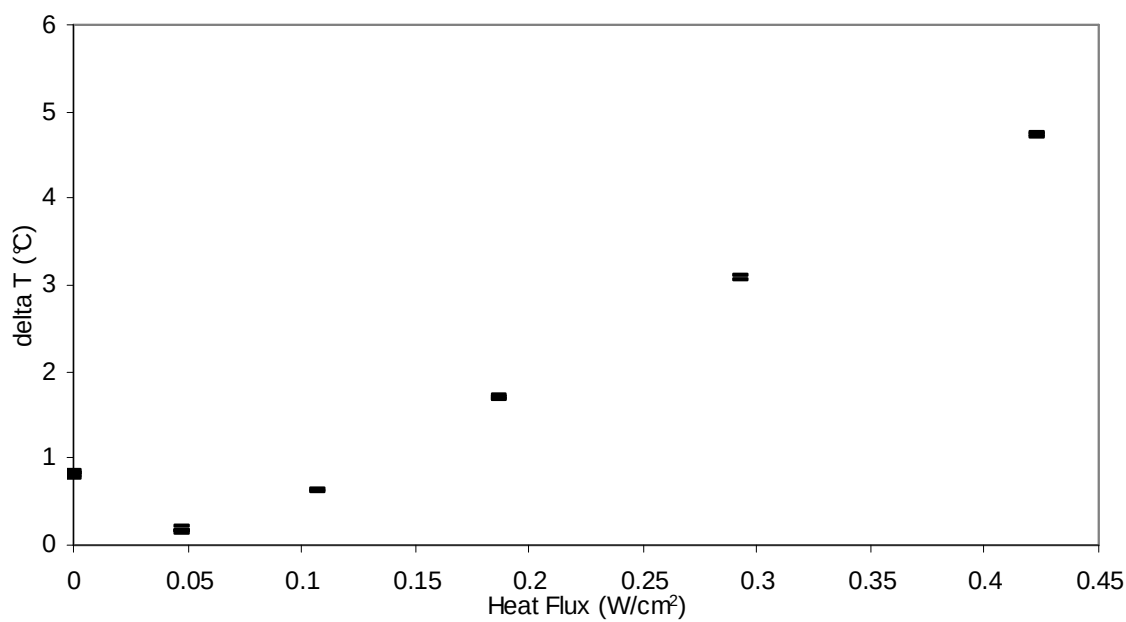


Figure D.20. Device 11: delta T generated vs. heat flux

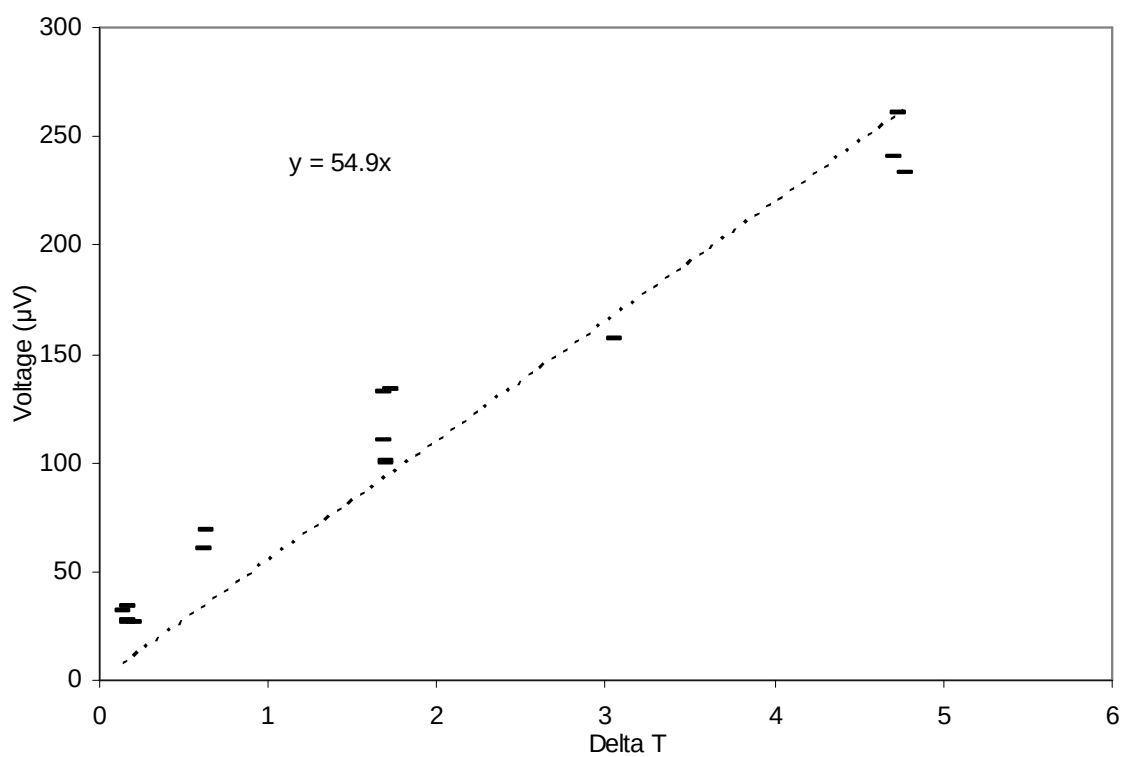


Figure D.21. Device 11: delta T generated vs. voltage signal generated

Table D.8. Device 12/A raw data

Device 12/A: 68°						
				Area	1.2708	
				Angle	68	
				Number	11	
Voltage	Current	Power	Delta T	Volt Out (μ V)	Volt Out- Ref	Sensitivity
0	0	0.0000	0.778968	-120.728		
4	0.055	0.1731	1.17162	-648.928	528.2	3051.01
6	0.083	0.3919	3.70743	-1327.2	1206.472	3078.62
8	0.11	0.6925	7.06276	-2256.23	2135.502	3083.79
10	0.137	1.0781	11.2047	-3502.8	3382.072	3137.11
12	0.164	1.5487	16.0485	-4938.41	4817.682	3110.86
0	0	0.0000	0.815728	-121.214		
4	0.055	0.1731	1.1906	-666.113	544.899	3147.47
6	0.083	0.3919	3.68928	-1346.71	1225.496	3127.16
8	0.11	0.6925	7.03705	-2284.54	2163.326	3123.97
10	0.137	1.0781	11.1891	-3527.22	3406.006	3159.31
12	0.164	1.5487	15.9829	-4975.8	4854.586	3134.69
0	0	0.0000	0.791057	-123.43		
4	0.055	0.1731	1.17126	-675.03	551.6	3186.17
6	0.083	0.3919	3.67476	-1235.66	1112.23	2838.14
8	0.11	0.6925	7.01667	-2007.53	1884.1	2720.75
10	0.137	1.0781	11.1724	-3073.93	2950.5	2736.80
12	0.164	1.5487	15.9211	-5019.96	4896.53	3161.78
					AVG	3053.18
					STD DEV	154.82

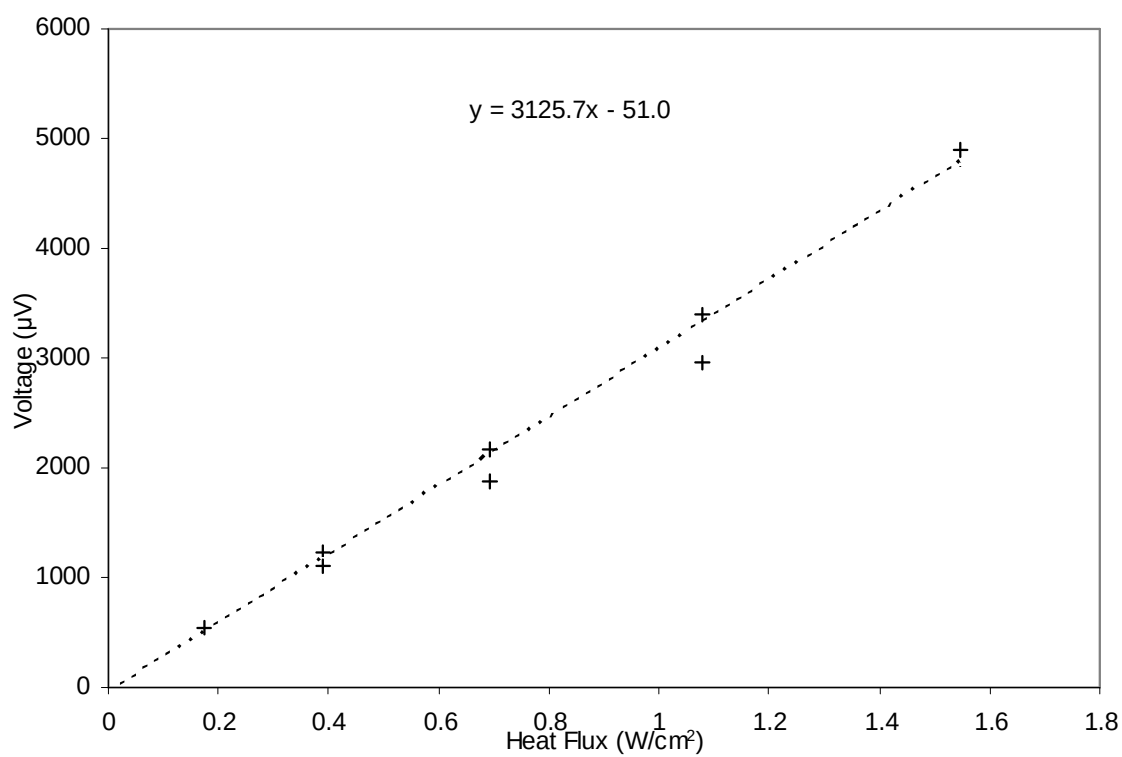


Figure D.22. Device 12/A: voltage signal generated vs. heat flux

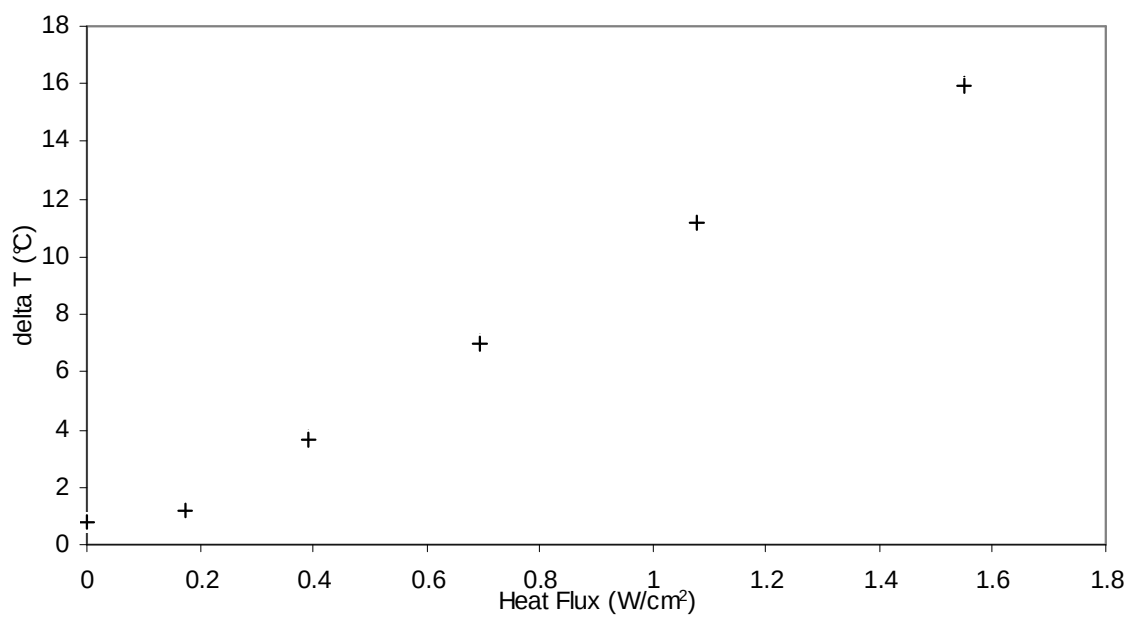


Figure D.23. Device 12/A: delta T generated vs. heat flux

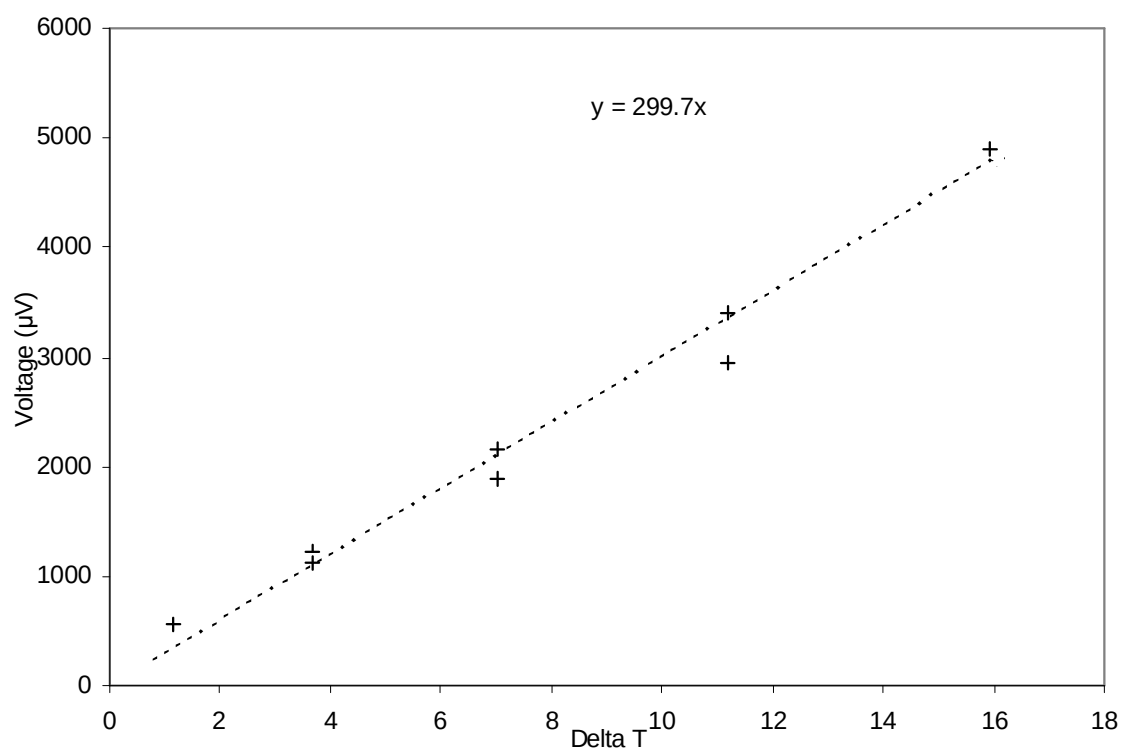


Figure D.24. Device 12/A: delta T generated vs. voltage signal generated

Table D.9. Device B raw data

Device B: 68°				Area	1.0397	
				Angle	68	
				Number	9	
Voltage	Current	Power	Delta T	Volt Out (μ V)	Volt Out- Ref	Sensitivity
0	0	0.0000	0.794328	-94.7337		
4	0.055	0.2116	1.61453	-722.316	627.5823	2965.96
6	0.083	0.4790	4.59034	-1503.97	1409.2363	2942.20
8	0.11	0.8464	8.64928	-2620.9	2526.1663	2984.68
10	0.137	1.3177	13.5825	-4067.85	3973.1163	3015.29
12	0.164	1.8928	19.3803	-5696.07	5601.3363	2959.27
0	0	0.0000	0.814757	-91.2751		
4	0.055	0.2116	1.57143	-730.098	638.8229	3019.09
6	0.083	0.4790	4.55142	-1533.91	1442.6349	3011.93
8	0.11	0.8464	8.55496	-2681.48	2590.2049	3060.34
10	0.137	1.3177	13.528	-4125.9	4034.6249	3061.97
12	0.164	1.8928	19.226	-5868.89	5777.6149	3052.40
0	0	0.0000	0.81127	-92.8423		
4	0.055	0.2116	1.57085	-742.906	650.0637	3072.21
6	0.083	0.4790	4.56367	-1533.26	1440.4177	3007.30
8	0.11	0.8464	8.58253	-2635.27	2542.4277	3003.89
10	0.137	1.3177	13.5603	-4016.35	3923.5077	2977.64
12	0.164	1.8928	19.3103	-5719.68	5626.8377	2972.74
					AVG	3007.13
					STD DEV	40.64

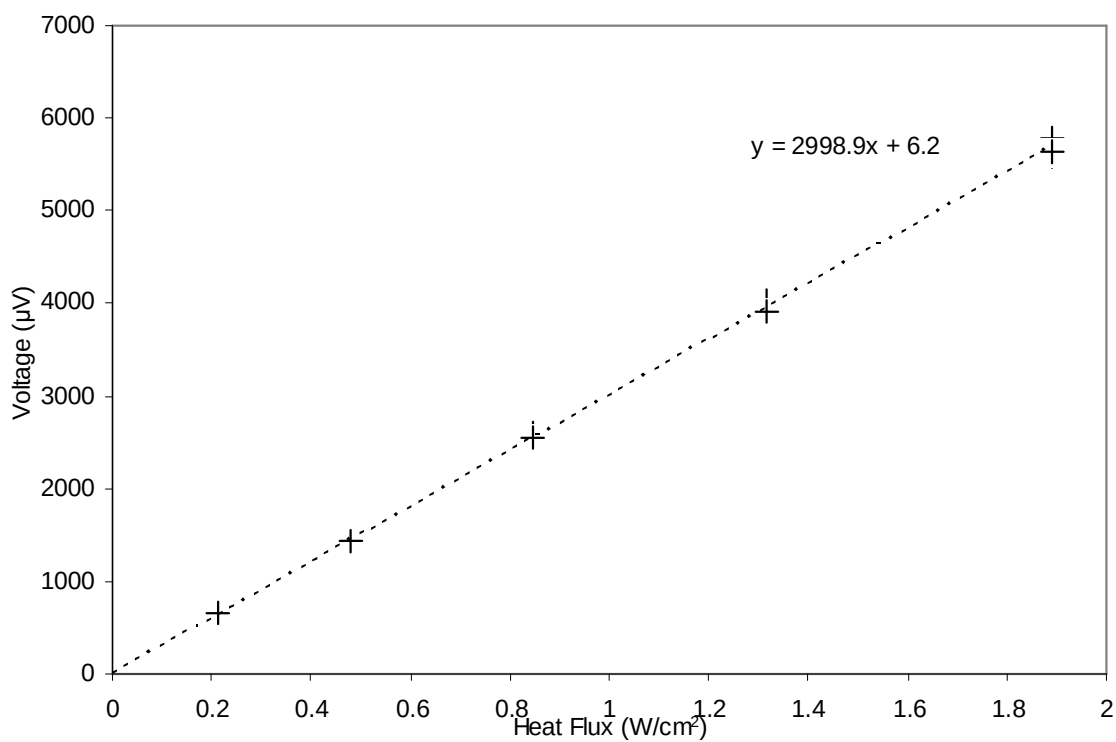


Figure D.25. Device B: voltage signal generated vs. heat flux

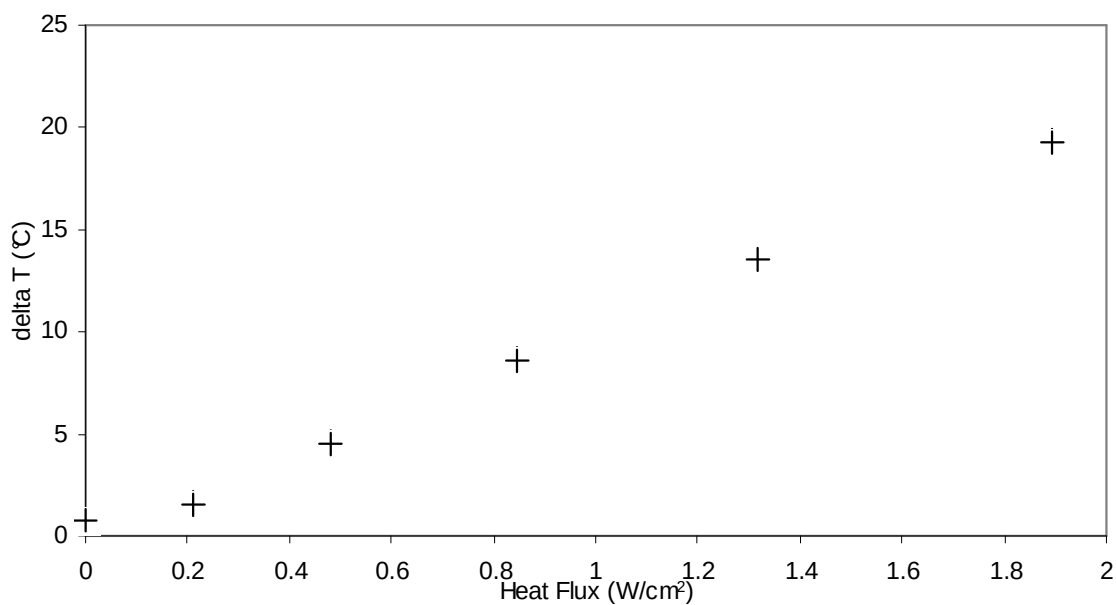


Figure D.26. Device B: delta T generated vs. heat flux

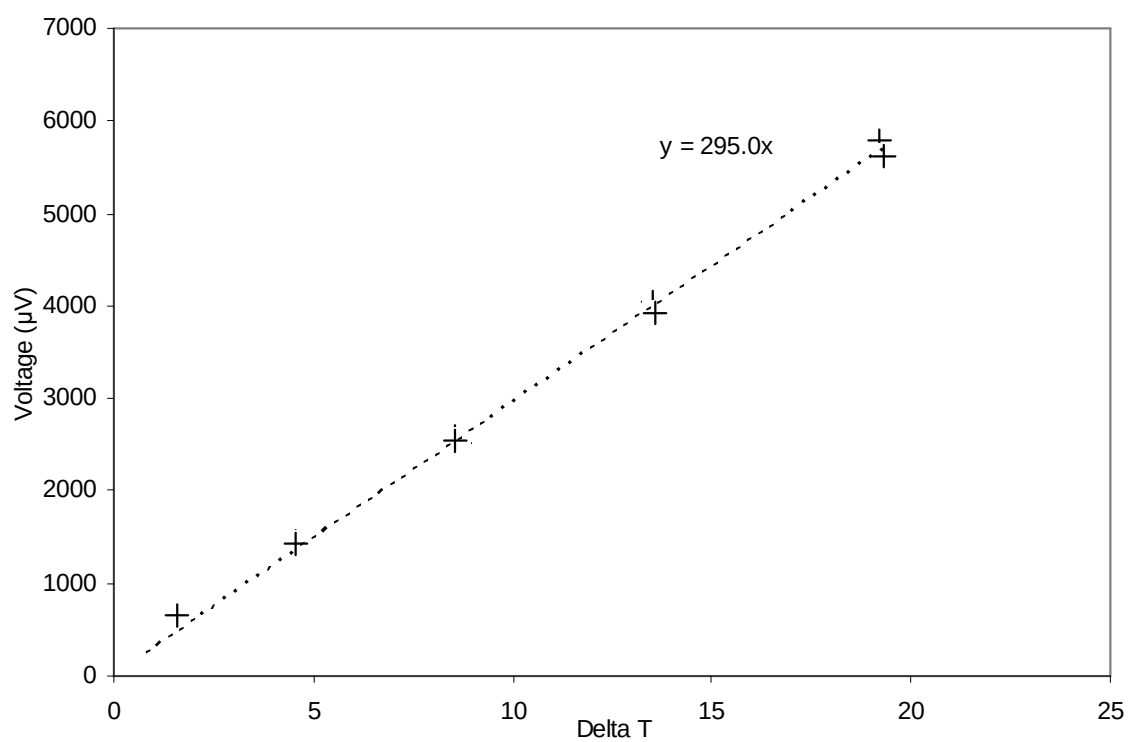


Figure D.27. Device B: delta T generated vs. voltage signal generated

Table D.10. Device C raw data

Device C: 68°						
				Area	0.8087	
				Angle	68	
				Number	7	
Voltage	Current	Power	Delta T	Volt Out (μ V)	Volt Out- Ref	Sensitivity
0	0	0.0000	0.697759	-97.2196		
4	0.055	0.2721	4.24516	153.965	251.1846	923.30
6	0.083	0.6158	8.62567	476.267	573.4866	931.25
8	0.11	1.0882	14.4877	911.895	1009.1146	927.32
10	0.137	1.6941	21.6525	1491.38	1588.5996	937.71
12	0.164	2.4336	29.9061	2237.91	2335.1296	959.53
0	0	0.0000	0.668279	-102.408		
4	0.055	0.2721	4.22012	169.366	271.774	998.98
6	0.083	0.6158	8.56358	514.421	616.829	1001.63
8	0.11	1.0882	14.4208	1001.5	1103.908	1014.43
10	0.137	1.6941	21.5893	1613.08	1715.488	1012.61
12	0.164	2.4336	29.7748	2325.02	2427.428	997.46
0	0	0.0000	0.706085	-96.6792		
4	0.055	0.2721	4.26217	171.258	267.9372	984.88
6	0.083	0.6158	8.61643	517.393	614.0722	997.16
8	0.11	1.0882	14.429	983.446	1080.1252	992.58
10	0.137	1.6941	21.5943	1556.39	1653.0692	975.76
12	0.164	2.4336	29.7898	2292.71	2389.3892	981.83
					AVG	975.76
					STD DEV	31.83

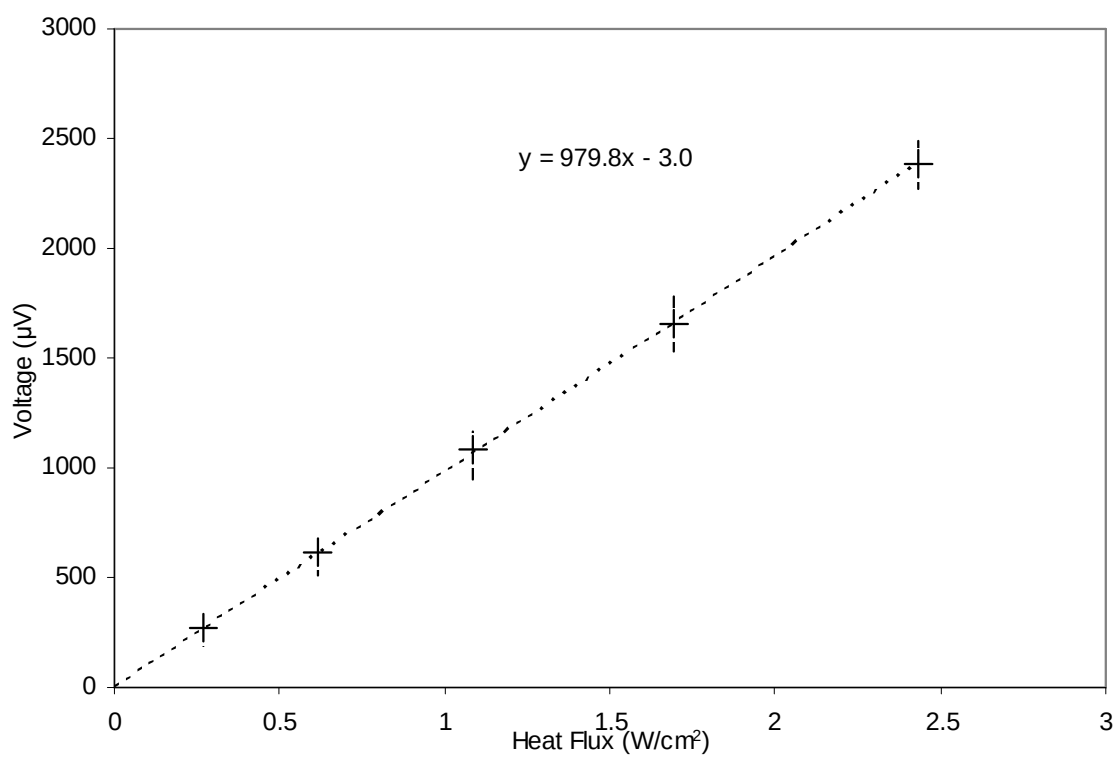


Figure D.28. Device C: voltage signal generated vs. heat flux

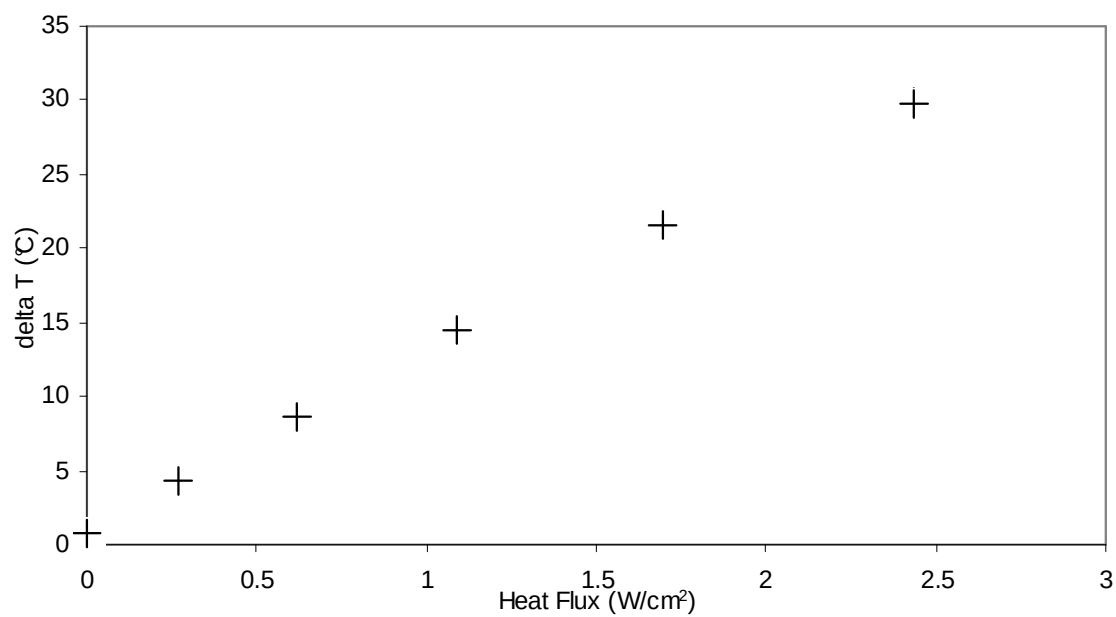


Figure D.29. Device C: delta T generated vs. heat flux

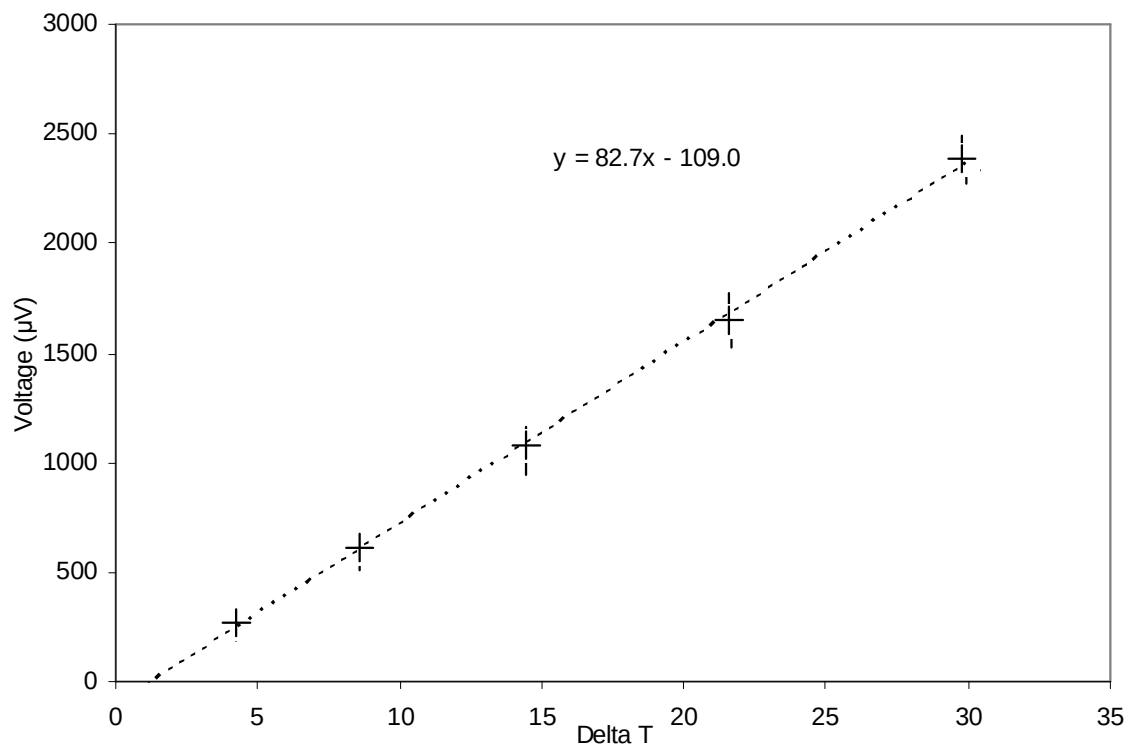


Figure D.30. Device C: delta T generated vs. voltage signal generated

Table D.11. Device D raw data

Device D: 68°						
			Area		0.4621	
			Angle		68	
			Number		4	
Voltage	Current	Power	Delta T	Volt Out (μV)	Volt Out-Ref	Sensitivity
0	0	0.0000	0.748	-102.354		
4	0.055	0.4761	3.7542	-355.429	253.075	531.57
6	0.083	1.0777	7.3488	-666.167	563.813	523.17
8	0.11	1.9044	12.046	-1137.46	1035.106	543.55
10	0.137	2.9647	17.547	-1579.2	1476.846	498.14
12	0.164	4.2588	23.385	-2305.4	2203.046	517.29
0	0	0.0000	0.7005	-92.8963		
4	0.055	0.4761	3.701	-355.213	262.3167	550.98
6	0.083	1.0777	7.3014	-683.406	590.5097	547.94
8	0.11	1.9044	12.036	-1127.19	1034.2937	543.12
10	0.137	2.9647	17.67	-1565.58	1472.6837	496.73
12	0.164	4.2588	23.789	-2181.05	2088.1537	490.31
0	0	0.0000	0.7678	-96.1928		
4	0.055	0.4761	3.7403	-320.302	224.1092	470.73
6	0.083	1.0777	7.3368	-604.722	508.5292	471.87
8	0.11	1.9044	12.048	-1009.87	913.6772	479.78
10	0.137	2.9647	17.637	-1565.9	1469.7072	495.73
12	0.164	4.2588	23.672	-2156.14	2059.9472	483.69
					AVG	509.64
					STD DEV	28.71

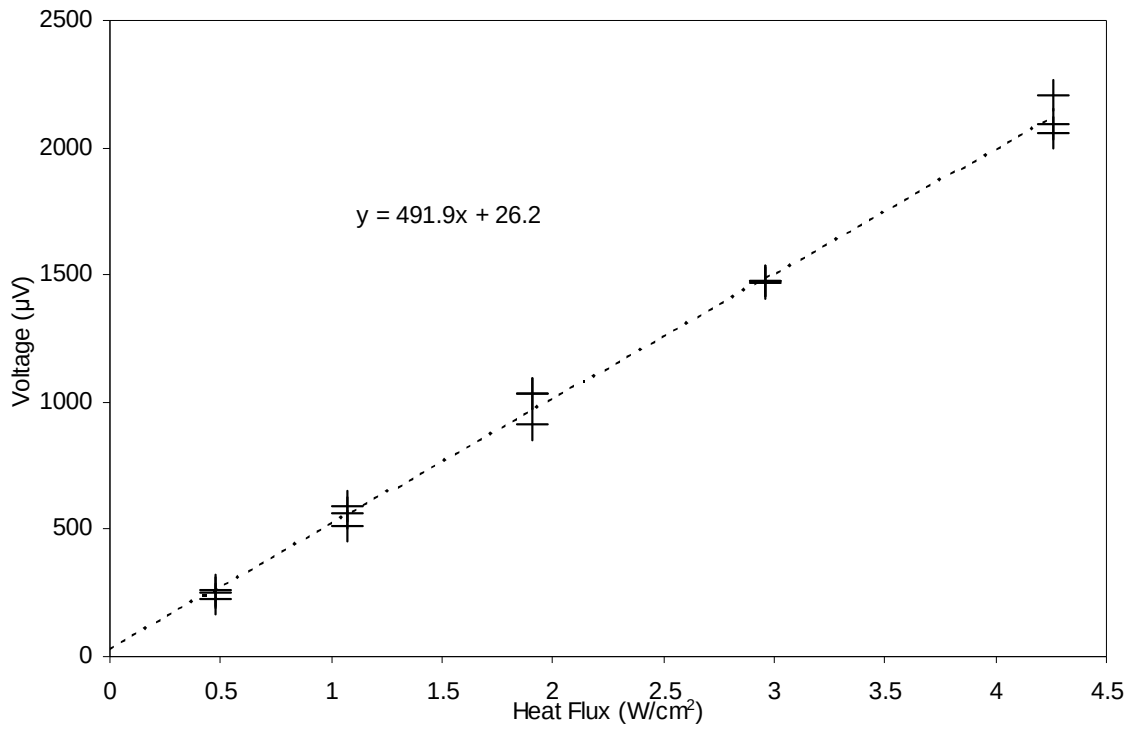


Figure D.31. Device D: voltage signal generated vs. heat flux

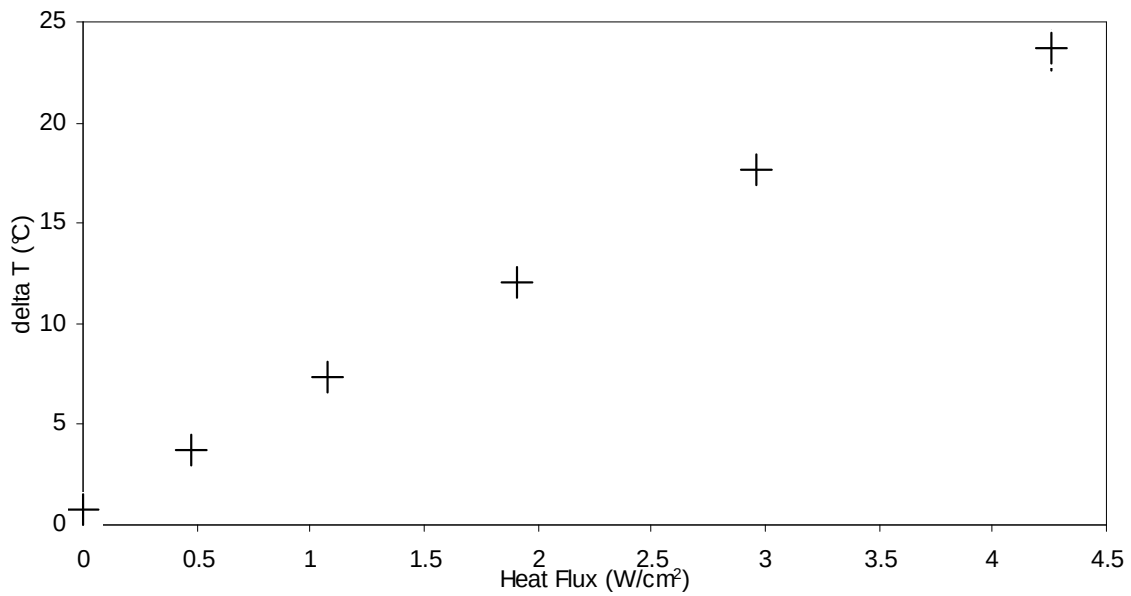


Figure D.32. Device D: delta T generated vs. heat flux

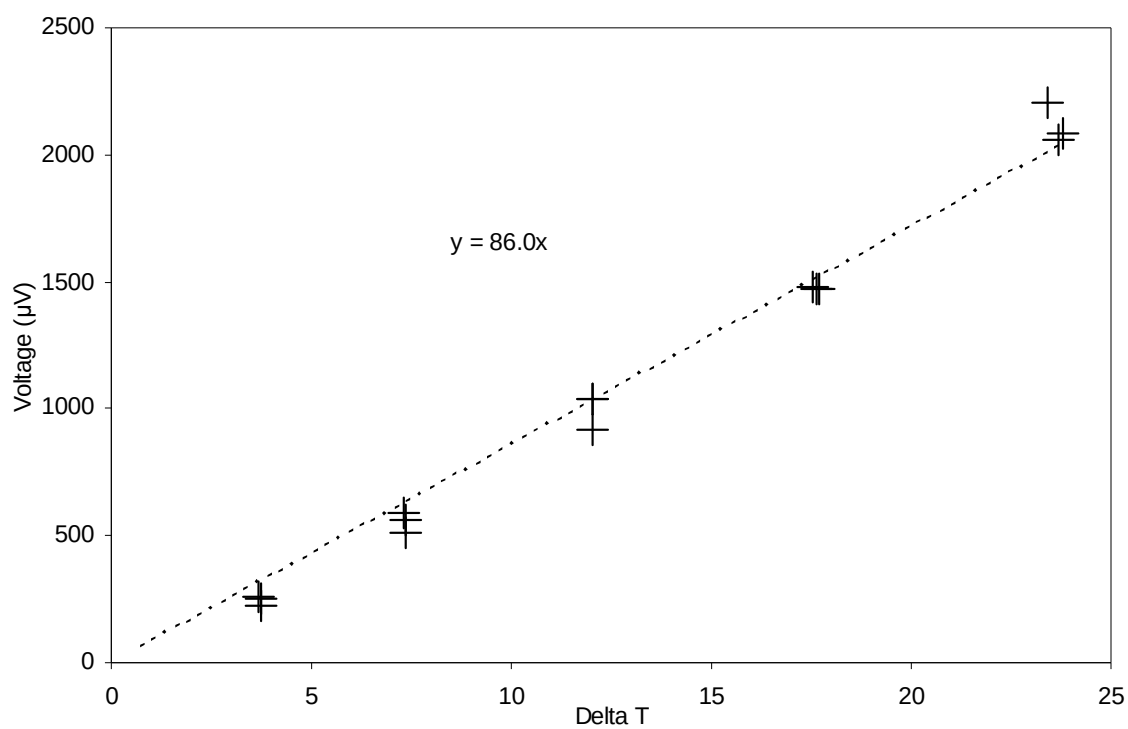


Figure D.33. Device D: delta T generated vs. voltage signal generated

Vita

Rebekah Ann Derryberry was born on May 15, 1983 in Austin, Texas to William and Shirley Derryberry. Rebekah spent her whole childhood in the Austin area where she was an active swimmer and member of the band. Rebekah graduated from Leander High School in 2001 and continued to Trinity University where she studied Engineering Science. After graduating from Trinity in 2005, Rebekah went to Virginia Tech to pursue a graduate degree in Mechanical Engineering. Rebekah worked as a Graduate Research Assistant while working on her thesis under Dr. Scott Huxtable. She defended her Masters thesis during the spring semester of 2007 at Virginia Polytechnic Institute and State University. Rebekah graduated with an M.S. in Mechanical Engineering in 2007. After graduation, Rebekah joined the DuPont Field Engineering program where her first assignment was in the Central Research Department in Wilmington, Delaware.