

UC Davis

UC Davis Electronic Theses and Dissertations

Title

Utilizing a Peltier Module as a Heating Solution to Electronic Assemblies Exposed to Freezing Temperatures

Permalink

<https://escholarship.org/uc/item/72s456cv>

ISBN

9798189225628

Author

Askin, Murat

Publication Date

2026-06-25

Peer reviewed|Thesis/dissertation

Utilizing a Peltier Module as a Heating Solution to Electronic Assemblies Exposed to Freezing Temperatures

By

MURAT ASKIN
THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Mechanical and Aerospace Engineering

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Benjamin Shaw, Chair

Ralph Aldredge

Vinod Narayanan

Committee in Charge

2026

Copyright © 2026 by Murat Askin

Abstract

Utilizing a Peltier Module as a Heating Solution to Electronic Assemblies Exposed to Freezing Temperatures

This thesis explores the use case of a Peltier module as a heating solution to electronic assemblies exposed to temperatures below their operating temperature range. In aerospace applications, electrical systems can be exposed to rapidly changing environments, and Peltier coolers are one of the potential thermal solutions that can keep pace with the dynamic ambient temperature to ensure electrical systems can remain in operation. This work aims to expand the use case of a Peltier module and provide a solution applicable to any electronic assembly attempting to operate in an unsuitable environment. A VNX+, or VITA90, chassis design was used as motivation for the chassis assembly designed in this work, and a Peltier module was selected based on clamshell dimension restrictions, SWaP (size, weight, and power consumption) principles, and hand calculations. The hand calculations were used to build a thermal model in Ansys to visualize a temperature distribution, and resulted in simulated component temperatures falling within 6% of the target -20°C after 180s. Experimental results were within 3% of hand calculations; the selected Peltier module, PCX5.6, successfully heated an electrical subassembly from -50°C to -20°C in 180s. The Peltier modules provided an average total heat flow of 35W into the clamshell subassembly. If a shorter time frame is required, the power supplied to the Peltier module could be increased to reduce the time spent to heat the clamshell to -20°C , as the Peltier module's operating point was slightly below the max coefficient of performance (COP).

Table of contents

Abstract.....	ii
List of Figures.....	iv
List of Tables.....	vi
Acknowledgements.....	vii
I. Introduction	1
II. Theory and Literature Review.....	3
A. What is a Peltier Module and how does it work?	3
B. What are the applications of a Peltier Module?	4
C. What is a clamshell?	4
III. Experimental Approach and Facility.....	6
A. Equipment.....	6
B. Thermal Chamber Considerations	6
C. Raspberry Pi.....	7
D. Raspberry Pi Clamshell.....	8
E. Chassis Assembly	9
F. Peltier Module Selection Process.....	10
G. Experimental Setup.....	17
IV. Simulation (Ansys).....	19
A. Simulation setup and parameters	19
V. Results and Discussion	22
A. Simulation Results	22
B. Experimental Results	24
i. 7.5V Test.....	24
ii. 8V Test.....	28
VI. Conclusions and Recommendations	31
Appendix A: Hand Calculations for Convection Coefficients.....	37
Appendix B: Uncertainty Analysis	40

List of Figures

Figure 1. 19mm module with clamshell (left) and sample VNX+ system (right).....	2
Figure 2. Peltier Module.	3
Figure 3. Example clamshell and circuit board.....	5
Figure 4. Tenney UTC Upright Temperature Chamber.....	7
Figure 5. Raspberry Pi 5.	8
Figure 6. Thermoelectrically regulated clamshell in a harsh, external environment.	8
Figure 7. Isometric view (left) and top view (right) of front clamshell.	9
Figure 8. Isometric view (left) and top view (right) of back clamshell.	9
Figure 9. Exploded view of complete chassis assembly.	10
Figure 10. Peltier effect, Joule heating, and thermal conductivity in a Peltier module.	12
Figure 11. Peltier module placement	14
Figure 12. Interactive data sheet results for PCX5.6.	15
Figure 13. COP and Q_h versus current for PCX5.6.....	16
Figure 14. Wiring diagram for Keithley Data Acquisition/Multimeter System.	18
Figure 15. Prepared front clamshell Ansys geometry.	19
Figure 16. Prepared back clamshell Ansys geometry.....	20
Figure 17. Meshed clamshell assembly.....	20
Figure 18. Boundary conditions for clamshell surfaces.....	21
Figure 19. Heat flux boundary condition for front clamshell.	21
Figure 20. Temperature distribution for clamshell assembly.	22
Figure 21. Temperature distribution for back clamshell.	22
Figure 22. Temperature distribution in front clamshell.....	22
Figure 23. Ansys component temperatures versus time.....	23
Figure 24. Lower, middle, and upper chamber temperature versus time (7.5V).	24
Figure 25. Peltier module hot and cold face temperatures versus time (7.5V).	24
Figure 26. Peltier face temperature difference versus time (7.5V).	25
Figure 27. Peltier voltage versus time (7.5V).	25
Figure 28. Peltier current draw versus time (7.5V).....	26
Figure 29. RP5 component temperatures versus time (7.5V).	26
Figure 30. Peltier power output versus time (7.5V).....	27
Figure 31. Lower, middle, and upper chamber temperature versus time (8V).	28
Figure 32. Peltier module hot and cold face temperatures versus time (8V).	28

Figure 33. Peltier face temperature difference versus time (8V).	29
Figure 34. Peltier voltage versus time (8V).	29
Figure 35. Peltier current draw versus time (8V).....	30
Figure 36. RP5 component temperatures versus time (8V).	30
Figure 37. Peltier power output versus time (8V).....	31
Figure 38. Rectangular Cavity definition [32].	37
Figure 39. DC Voltage table from DAQ6510 datasheet.....	40
Figure 40. DC Current table from DAQ6510 datasheet	41
Figure 41. Temperature table from DAQ6510 datasheet	42

List of Tables

Table 1. Experimental Equipment.....	6
Table 2. Dry air purge thermal chamber settings.	6
Table 3. Values used to calculate $Q = mc\Delta T$	11
Table 4. Peltier module top candidates.	15
Table 5. Datasheet values for PCX5.6, PCX6, and PCX4.	16
Table 6. Keithley DAQ channel allocation for experimental measurement.....	18
Table 7. Peltier energy and power output data (7.5V).	27
Table 8. Peltier energy and power output data (8V).	31
Table 9. Thermophysical properties of air.....	37
Table 10. Top clamshell surface convection coefficient calculation.	38
Table 11. Side clamshell surfaces convection coefficient calculation.	38
Table 12. Back clamshell surface convection coefficient calculation.	38
Table 13. Bottom clamshell surface convection coefficient calculation.	39
Table 14. Voltage uncertainty analysis.....	41
Table 15. Current uncertainty analysis.....	41
Table 16. Temperature uncertainty analysis.....	42
Table 17. Peltier module power output uncertainty analysis	43
Table 18. Peltier module energy output uncertainty analysis.....	44
Table 19. Theoretical input energy uncertainty analysis.....	45

Acknowledgements

First and foremost, I would like to express my gratitude to my advisor, Professor Benjamin D. Shaw, for his patience, guidance, and support throughout the course of this thesis. His insights, knowledge, and encouragement helped me grow as a researcher, and this thesis would not have been possible otherwise. I would also like to thank Professor Ralph Aldredge and Professor Vinod Narayanan for being responsive mentors throughout my time at UC Davis and for serving on my committee. Words cannot express my gratitude.

To my research group members, Bhargav and Mehdi, thank you for your friendship, generosity, and valuable discussions. Thank you to Jerry, Gary, Mehmet, Manny, Kai, Kian, Anthony, and Riley for your consistent support. To my siblings, thank you for believing in me and pushing me to challenge myself. Lastly, thank you to my parents for your sacrifices and giving me a life full of opportunity. To every friend, classmate, and coworker who supported me on this journey, I thank you all from the bottom of my heart.

I. Introduction

Circuit boards are used daily for a variety of applications: starting a car, turning on a heater, using a laptop. These devices do not require a complex thermal solution, as temperatures do not exceed above, or drop below, the printed circuit board's operating temperature range. This range is determined from the individual components on the board, meaning that the component with the narrowest temperature span derives the temperature rating for the entire PCB. In aerospace and defense applications, circuit boards can be exposed to temperatures well outside their operating temperature range [1]. Additionally, defense electronics are subject to a version of MIL-STD, a military standard that is designed to ensure military equipment meets the requirements and specifications for an intended application [2]. These military standards can be quite rigorous, as the application could be intended for extreme hot, dry environments or extreme cold, wet environments. The temperatures that defense electronics will be exposed to, in combination with the temperature requirements defined by the government, call for a complex thermal management system.

When designing a thermal management system, a designer can choose an active or passive thermal management technique. Active thermal management systems utilize "active" elements, or elements that can vary their cooling load dependent on temperature. Examples are fans, heat pipes, and thermoelectric coolers. The advantages of active cooling are that these systems can respond quickly to dynamic temperature loads and provide precise temperature control [3]. Passive thermal management systems utilize "passive" elements, or elements that have no moving parts and require minimal power consumption. Examples are heat sinks, thermal blankets, and radiators. These systems are adequate, low maintenance solutions but are not as powerful as an active cooling system [4]. Cooling of defense electronics utilize active cooling solutions as they allow for the system to keep up with rapid changes in ambient conditions [5]. Some additional examples of active solutions are forced liquid cooling and liquid cooled cold plates [6].

VNX+, also known as VITA 90, is a standard that sets a general design blueprint for military and aerospace embedded computing applications [7]. VNX+ is a newer, more compact, embedded computing standard, and emphasizes the significant reduction in size, weight, and power consumption (SWaP) of a system without sacrificing performance [8]. The VNX+ standard calls for a housing, otherwise known as a clamshell, that sandwiches a circuit board for conduction cooling circuit board components (see Figure 1) [9]. The clamshell is in physical contact with other clamshells in the system, in addition to the external chassis, to increase the thermal mass of the system and enhance heat transfer performance [10].

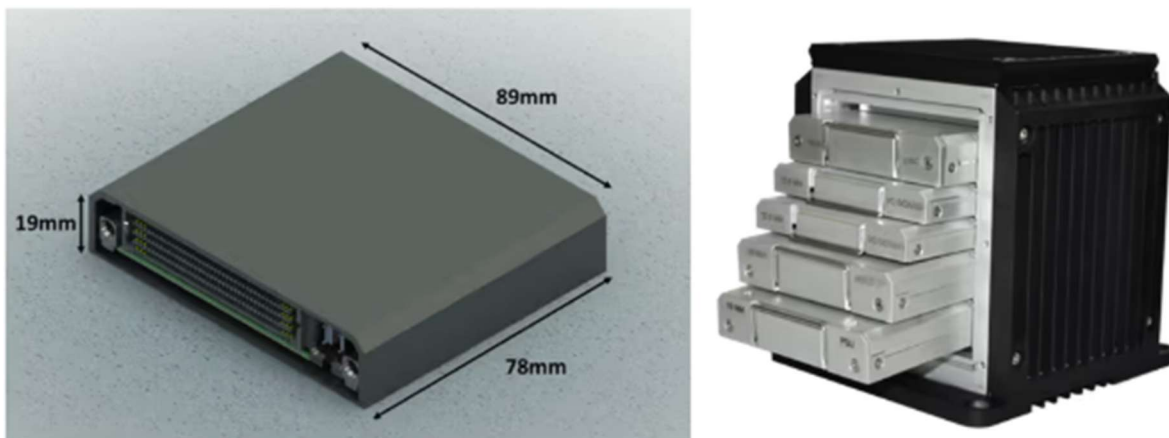


Figure 1. 19mm module with clamshell (left) and sample VNX+ system (right) [10].

The assembly structure of the VNX+ chassis is designed for conduction cooling. However, if this system is exposed to extreme cold environments, the system would have to be heated to remain operable. The caveat in adding a heating solution is that it would have to be incorporated externally, as the interior chassis space is consumed by the clamshells. For example, if the chassis were mounted on a hot plate, the heat would have to first transfer through the chassis walls before reaching the clamshells. A more efficient method would be to penetrate a layer of the chassis assembly and directly apply a heating load to the clamshell stack. Resistive heaters could be used, for example, but doing so compromises the ability to conduction cool the clamshells, as a resistive heater would separate the physical connection between the clamshell stack and chassis walls. A better solution is to utilize Peltier modules. Although this would still separate the physical connection between the clamshell stack and chassis walls, the bidirectional heat pump capability of a Peltier module would allow for the necessary heating load to be applied without

sacrificing the ability to cool the clamshell stack. Utilizing a Peltier module as a cooling solution has been extensively researched [11], [12], [13], [14], [15], [16], [17], including PID controller incorporation for cooling optimization [18], [19], [20], [21]. There is minimal research, however, in using a Peltier module as a heating solution. Therefore, the purpose of this work is to size and implement a Peltier module as a heating solution in a simplified, VITA90 motivated chassis assembly, to expand the use case of a Peltier module as a heater and unlock the ability to combine this work with others to create a complete thermal solution with bidirectional thermal control.

II. Theory and Literature Review

A. What is a Peltier Module and how does it work?

A Peltier module is a thermoelectric device that acts as a heat pump when connected to a power source. The principle behind its functionality is the Peltier effect, where a current flowing through two conductors creates a temperature difference across the conductors [22]. In a physical sense, one side of a Peltier module will heat up, and the other side of the module will cool down. If the polarity of the current is reversed, the hot and cold sides of the Peltier module will switch [23].

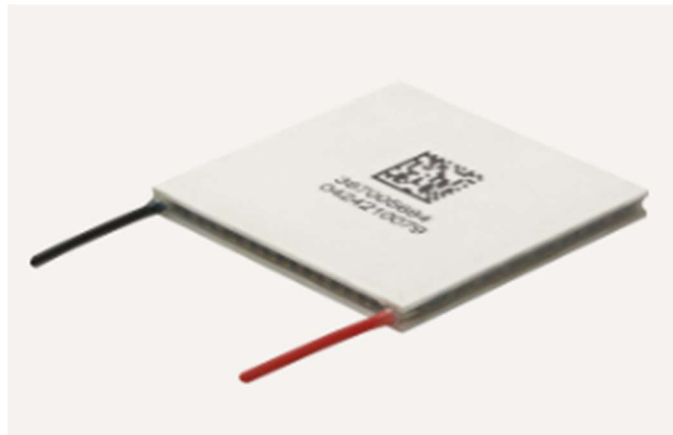


Figure 2. Peltier Module.

B. What are the applications of a Peltier Module?

There are three main applications that the Peltier module is used for: cooling, heating, and power generation. Cooling and heating are the two applications that are relevant to this work. In cooling applications, the cold side of the Peltier module is placed against the heat load, and the hot side of the Peltier module is paired with a cooler to enhance Peltier module performance [24]. For example, a finned heat sink can be attached to the hot side of the module to dissipate the extracted heat to the surroundings [25]. An alternative method is passing cold water over the hot side of the module, directly water cooling it [26]. If the heat from the hot side of the module is not properly dissipated, the Peltier will force itself into thermal runaway [27]. In the context of a Peltier module, thermal runaway means that the module has reached a maximum ΔT between the two faces, but the hot side will continue to rise in temperature because the cooler cannot dissipate the heat faster than the Peltier absorbs it. As a result, the object or medium the Peltier is trying to cool will start to heat up, as the cool side's temperature will rise in tandem with the hot side.

Instead of dissipating the heat to the surroundings, one can utilize the heat absorbed by the Peltier module to heat another object or medium. Novianto and Sujono successfully proved this concept by heating and cooling two water streams by placing a Peltier module between the two working fluids [28]. An important note is that in Novianto and Sujono's experiment, current direction was held constant and the hot and cold sides of the Peltier module were used simultaneously to regulate the different water streams. Cosnier et al. used a thermoelectric module to heat or cool an air stream to create a heat exchanger that avoided using harmful refrigerants [29]. In contrast to the work of Novianto and Sujono, Cosnier et al. would flip the current direction to switch the system between cooling and heating mode, using only one side of the Peltier module to heat and cool the medium.

C. What is a clamshell?

A clamshell is a two-piece enclosure that mechanically surrounds and thermally interfaces with a VNX+ circuit board. The purpose of the clamshell is to increase the thermal capacitance of a

VNX+ system and enhance heat transfer away from circuit board components to decrease their working temperatures during system operation. The clamshell works by transferring heat from the circuit board components to the clamshell via conduction, transferring that absorbed heat into a chassis, then dissipating the transferred heat to the surroundings through convection. 6061-T6 Aluminum is a common choice for clamshell material because of its high thermal conductivity [30] and ease of machinability [31]. The importance of thermal conductivity comes from its directly proportional relationship to heat transfer rate [32], meaning that a clamshell with higher thermal conductivity can more effectively move heat away from the components than a material with low thermal conductivity.

The external dimensions of a clamshell are 78 x 89 x 19mm and are defined by VITA90 standards. The internal dimensions and features are driven by the components on the circuit board and are constructed by projecting the footprint of the component onto the internal clamshell surface, then extruding the footprint area to a height 0.10mm from the component surface. Performing the projecting and extruding process for all components of interest creates a skyline like appearance, hence the clamshell's interior nickname, "the skyline." Figure 3 displays an example clamshell with numbered surfaces correlating to the components the clamshell will touch on a circuit board.

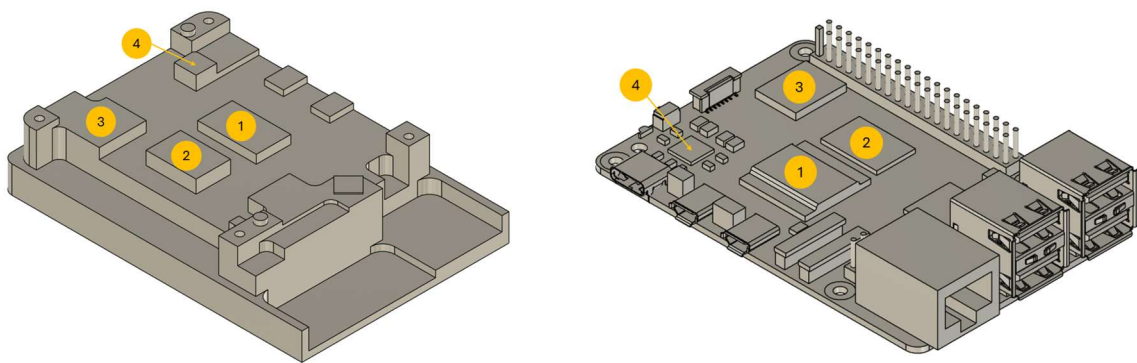


Figure 3. Example clamshell and circuit board.

The 0.10mm gap between the component surfaces and the skyline is intended for a thermal interface material, or TIM. It is important for a TIM to have minimal thermal resistance so that it does not bottleneck the heat transfer process. The two controllable factors regarding thermal resistance are

thermal conductivity and thickness: the higher the thermal conductivity and the thinner the TIM, the lower the thermal resistance [32]. The TIM chosen for this work is a 0.254mm thick thermal pad with a thermal conductivity of $3 \frac{W}{m-K}$. The intentionally undersized gap between the skyline and component surfaces allows compression of the TIM, which mitigates any tolerancing that occurs in the clamshell manufacturing process and ensures absolute contact between the skyline and circuit board components.

III. Experimental Approach and Facility

A. Equipment

Table 1. Experimental Equipment.

Component Name	Serial/Part Number
Raspberry Pi 5 (RP5)	SC1112
Tenney Environmental Upright Thermal Chamber	TUJR-A-F4T
K-Type Thermocouples	CA-Weewooday-4774
Keithley Data Acquisition/Multimeter System	DAQ6510
Keithley Triple Channel DC Power Supply	2230-30-6
Peltier Module	PCX5.6-19-F1N-3030-TA-RT-W6
Thermal Interface Material (TIM)	A16104-01
Kaeser Air Compressor	Aircenter SM 7.5

B. Thermal Chamber Considerations

With temperatures below 0°C, the risk of condensation/frost becomes a concern; a water droplet/snowflake that simultaneously touches two legs of a controller chip could short circuit the board. Therefore, the dry air purge system on the thermal chamber is used to pump dry air into the chamber and eliminate frost from forming. As a trial run, the chamber was set to -68°C and visually verified that there is no frost present in the thermal chamber. The settings for the dry air purge system are listed in Table 2.

Table 2. Dry air purge thermal chamber settings.

Parameter	Numerical Value
Dry air flow rate (Cubic feet per hour)	300 CFPH
Pressure (psi)	80 psi



Figure 4. Tenney UTC Upright Temperature Chamber.

C. Raspberry Pi

For this work, a Raspberry Pi 5 (RP5) is used as a proxy for a VITA90 plug-in module in a traditional VNX+ chassis assembly. The 5 key components to the RP5's functionality are the system-on-chip (SoC), random access memory (RAM), I/O controller, power management integrated circuit (PMIC), and radio module. All are labeled in Figure 5. The SoC contains both the central processing unit (CPU) and the graphics processing unit (GPU). The CPU is the "brains" of the board, and the graphics processing unit (GPU) is responsible for display output. Both processing units work together simultaneously to give the user a smooth experience. The RAM chip is the raspberry pi's memory and is responsible for temporarily storing active data and application instructions. When the RP5 loses power, anything that was not saved to the system will be lost. The I/O controller is responsible for managing output devices like USB, ethernet, and cameras. The PMIC is responsible for taking input power from the USB C port and distributing it to components like the SoC and RAM. Lastly, the radio module is responsible for Bluetooth and Wi-Fi functions [33].

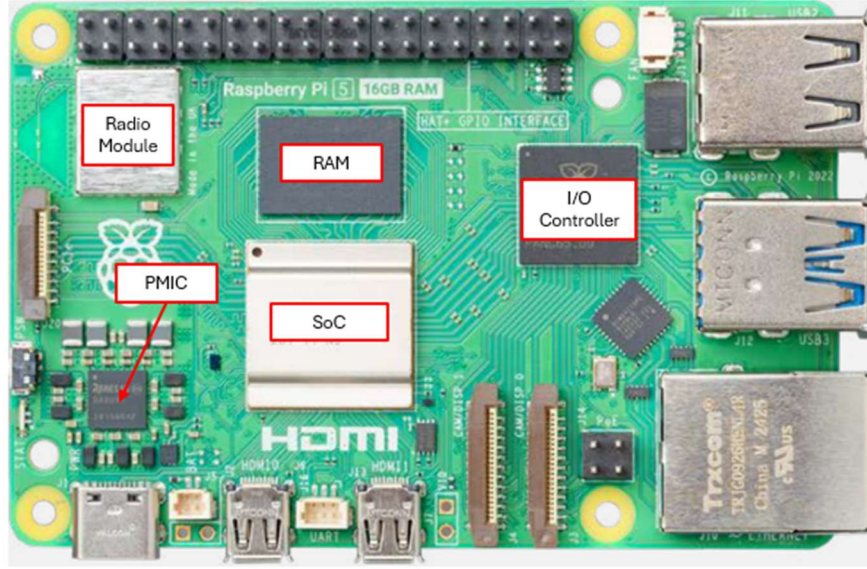


Figure 5. Raspberry Pi 5.

D. Raspberry Pi Clamshell

In this work, the clamshell is not in direct contact with the chassis like in traditional VNX+ systems. Instead, Peltier modules are the only bridge between the clamshell and the chassis. This ensures that the direction of heat transfer can be controlled with the direction of current being pushed through the Peltier modules. Using the modules to vary and control the temperature of the clamshell creates a local environment, separate from the ambient environment, in which the circuit board can operate. Figure 6 illustrates this concept.

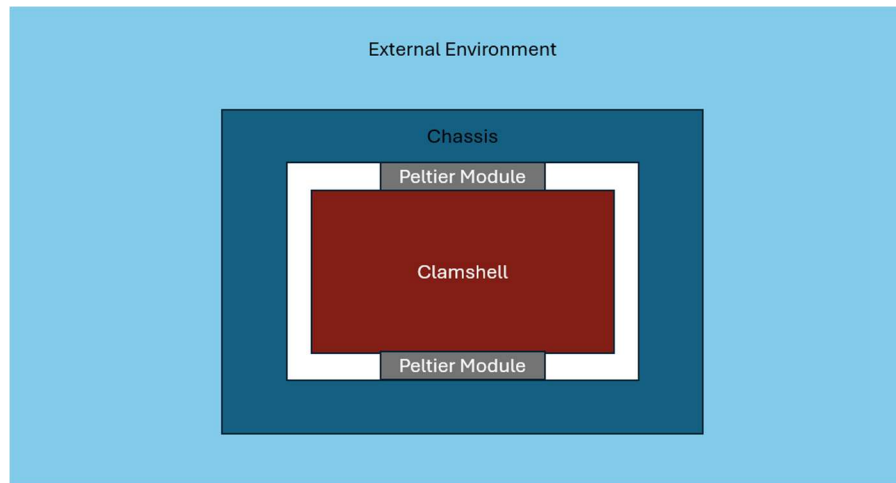


Figure 6. Thermoelectrically regulated clamshell in a harsh, external environment.

The clamshell’s “skyline” is designed to touch the SoC, RAM, I/O controller, radio module, and PMIC. The channels on the front clamshell are intended for thermocouple routing and placement. The back clamshell is not designed to touch any components or host any thermocouples, so its interior remains flat. Figure 7 and Figure 8 show isometric and top views of the front and back clamshell halves.

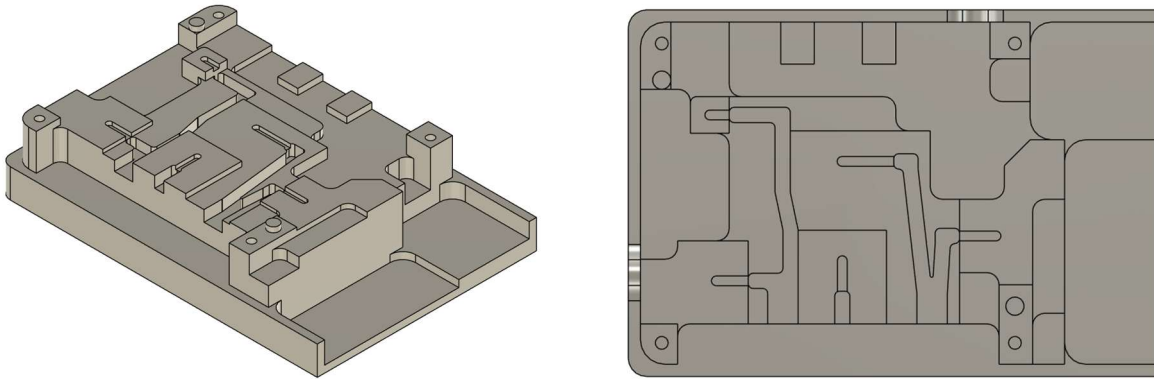


Figure 7. Isometric view (left) and top view (right) of front clamshell.

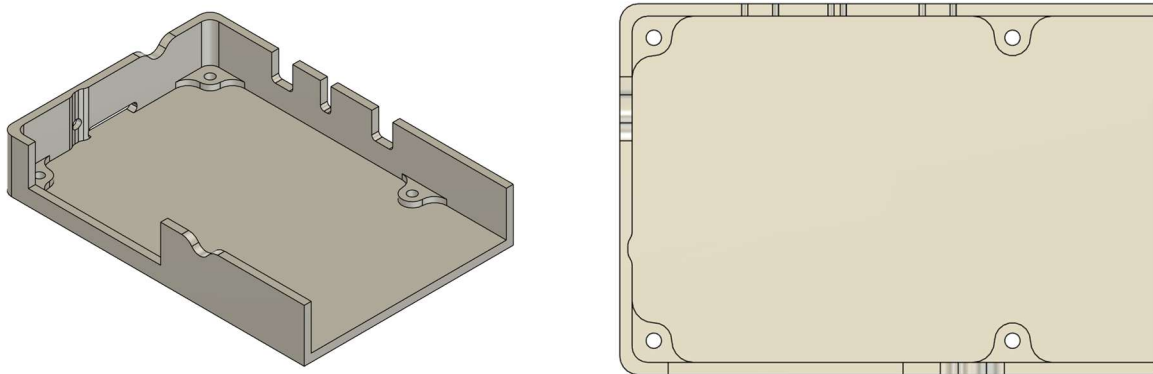


Figure 8. Isometric view (left) and top view (right) of back clamshell.

E. Chassis Assembly

The chassis assembly consists of top and bottom chassis components that sandwich the clamshell between two Peltier modules. The cutouts on the side surface of the back clamshell and the bottom chassis are intended for thermocouple, power, and display cable routing out of the assembly.

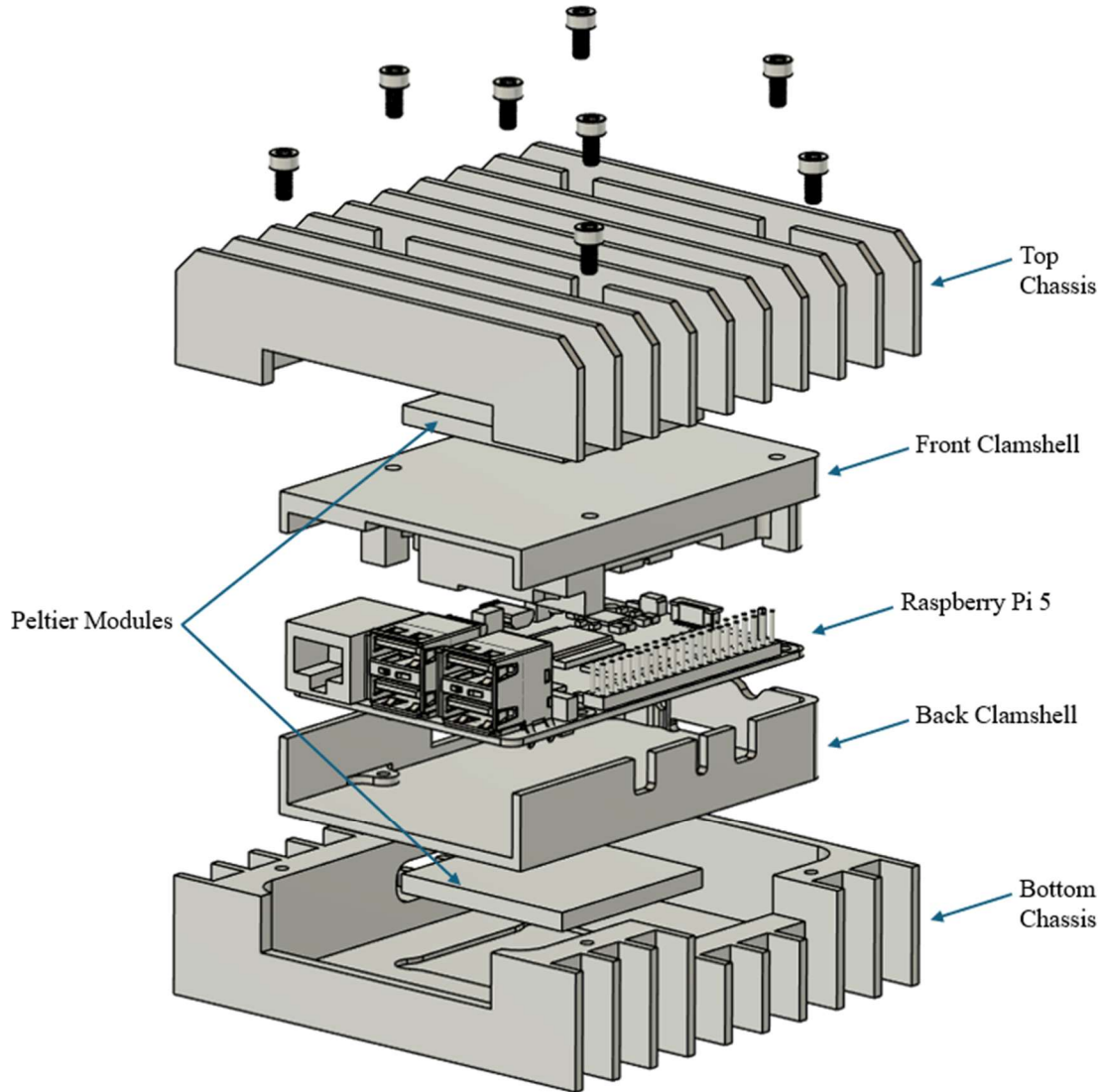


Figure 9. Exploded view of complete chassis assembly.

F. Peltier Module Selection Process

The Peltier module selection process starts with hand calculating the amount of energy needed to heat the clamshell from -50°C to -20°C using $Q = mc\Delta T$. The mass of the clamshell, m , was determined from the modeling software after applying Aluminum 6061 as a material property and the specific heat capacity, c , was graphically evaluated at -35°C using the graphs provided from NIST for 6061-T6 aluminum [30]. Table 3 displays the values for m , c , and Q .

Table 3. Values used to calculate $Q = mc\Delta T$.

Parameter	Numerical Value
Mass (m)	0.209 kg
Specific heat (c)	$897 \frac{J}{kg-K}$
ΔT	30° C
Calculated Energy (Q)	5624 J

To calculate the amount of power the Peltier modules must provide, Q must be divided by the desired time it takes to reach boot temperature. For proprietary reasons, the time constraint is set to 180 seconds, or 3 minutes. There are two Peltier modules being used to heat the clamshell; thus, the target power output of one Peltier module is $\frac{1}{2} \frac{Q}{t}$, or 15.62W. However, the clamshell is also subject to natural convection, meaning that additional power is required from the Peltier module to compensate for the convection heat loss during the heating period. To calculate this, the convection heat transfer equation, $q = hA\Delta T$, must be used. The surface area of the clamshell, A, was determined from the modeling software and the convection coefficient, h, was calculated using Nusselt number correlations for a rectangular enclosure. For calculation simplicity and determining a conservative estimate, it was assumed that the clamshell would start and maintain a temperature of -20°C for the entirety of the 3 minutes. The front face of the clamshell is an opening for the Ethernet and USB connectors on the RP5 and has minimal surface area exposed to the surroundings. Therefore, it was assumed that the losses due to convection from the front face were negligible and were not included in the final Q calculation. Convection coefficients for the top, bottom, left, right, and back surfaces of the clamshell were calculated, and the expected convective heat loss was added to the initial Q calculation. The new target power output of each Peltier module is 17.51W. Reference Appendix A for convective coefficient hand calculations and new target power output calculations.

The vendor for the Peltier modules used was Tark Thermal Solutions (TTS), formerly known as Laird Thermal Systems. TTS has 11 different Peltier module series available dependent on the intended use case. The PowerCycling (PCX) Series was selected as the most applicable for this work, as this series

is specifically engineered for thermal cycle testing [34]. The governing criterion for Peltier module selection were module COP, module thickness, and module length/width.

When sizing a Peltier module, an engineer must understand the governing equations and what metrics to inspect when searching for and comparing Peltier modules [35]:

$$Q_h = \alpha IT_h + \frac{I^2 R}{2} - K(T_h - T_c)$$

$$Q_c = \alpha IT_c - \frac{I^2 R}{2} - K(T_h - T_c)$$

The first term in the heating/cooling output equation describes the Peltier effect, the second term describes the Joule heating effect, and the last term describes conduction from hot to cold face of the Peltier module. Joule heating effect is the energy that internally generates in the module when current passes through the semiconductors. Half of this heat transfers to the hot side, adding to the heating power, and half of this heat transfers to the cold side, taking away from the cooling power [36]. A physical interpretation of Peltier effect, Joule heating, and conduction in a Peltier module is shown in Figure 10.

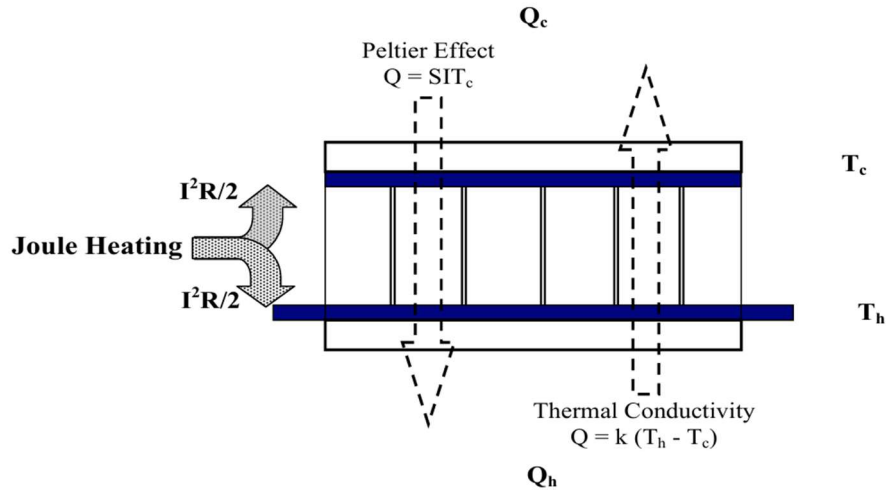


Figure 10. Peltier effect, Joule heating, and thermal conductivity in a Peltier module [35].

In principle, a Peltier module with high Peltier effect relative to low Joule heating effect and thermal conductivity is considered best. The parameter that describes this relationship is the figure of

merit, ZT , a dimensionless quantity that can be used to perform module-to-module comparison to determine the most effective Peltier module. A higher figure of merit indicates a more effective Peltier module [37]:

$$ZT = \frac{\alpha^2 T}{RK}$$

The Seebeck coefficient (α), electrical resistance (R), and thermal conductivity (K) vary from module to module, and their value can either be retrieved via data sheet or calculated using proposed formulas [38]:

$$\alpha = \frac{V_{max}}{T_{h0}}$$

$$R = \frac{(T_{h0} - \Delta T_{max})V_{max}}{T_{h0}I_{max}}$$

$$K = \frac{(T_{h0} - \Delta T_{max})V_{max}I_{max}}{2T_{h0}\Delta T_{max}}$$

The second metric that can be used to perform module-to-module comparison is the coefficient of performance, or COP, and is described as the ratio of cooling capacity, Q_c , to input power, P . COP can also be described as the ratio of heating capacity, Q_h , to input power, if the module is used for heating [39]:

$$COP_{heating} = \frac{Q_h}{P} = \frac{\alpha I T_h + \frac{I^2 R}{2} - K(T_h - T_c)}{\alpha I (T_h - T_c) + I^2 R}$$

$$COP_{cooling} = \frac{Q_c}{P} = \frac{\alpha I T_h - \frac{I^2 R}{2} - K(T_h - T_c)}{\alpha I (T_h - T_c) + I^2 R}$$

TTS provides interactive datasheets that determine COP and required power input based on a desired ΔT between the Peltier module faces, so module-to-module comparison for this work was performed using these interactive data sheets. TTS also allows sorting of Peltier modules via description,

part number, length, width, height, $Q_{c,max}$, ΔT_{max} , I_{max} , V_{max} , max operating temperature, and module resistance.

Module resistance needs to be considered when determining whether the Peltier will be applied in a high voltage, low current design or low voltage, high current design. From Ohm's law, a high voltage, low current design calls for a Peltier module with high resistance, and a low voltage, high current design calls for a Peltier module with low resistance. Since this work is not driven by any government requirements, a high voltage, low current design is chosen. An emphasis will be placed on module thickness to be as minimally additive to the chassis as possible, aligning with the SWaP ideology for VNX+. The Peltier module will be placed between the 4 threaded holes that secure the clamshell to the chassis, as this is where the “meat” of the clamshell is (see Figure 11). More specifically, this places the heat source directly above the key components of the RP5, minimizing the distance heat would have to travel to reach these components. The max dimensions for the Peltier module for this placement are 46 x 50 mm.

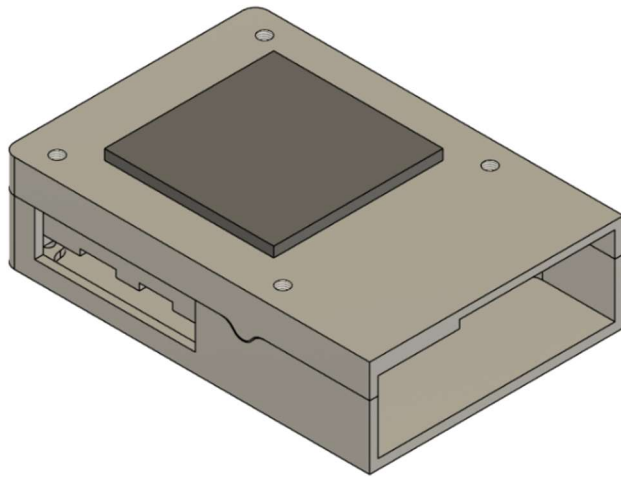


Figure 11. Peltier module placement

To determine a baseline for the PCX series modules, they were first sorted based on thickness to determine the thinnest module, then resorted by resistance to identify the highest resistance module.

PCX8-12-F2-2525-TA-RT-W6 (PCX8) was the thinnest module with a thickness of 2mm, and PCX2-12-

F1-3030-TA-RT-W6 (PCX2) was the module with the most resistance with a value of 5.59Ω . Now that the baseline for both metrics was established, PCX8 was evaluated as a potential candidate; the module's resistance of 1.75Ω falls on the low side compared to the max resistance available and was ruled out despite it being the thinnest option. Additionally, the length and width dimensions of 26.9mm x 24.6mm do not maximize the available clamshell surface area. PCX2 was evaluated next; the module's thickness of 4mm is too thick considering the thinnest module available is 2mm. The module's dimensions of 30mm x 30mm, although still not maximizing available surface area, is an improvement in comparison to PCX8. Since PCX8 and PCX2 were not considered optimal solutions, the modules were re-sorted again by thickness and evaluated based on a combination of their length, width, and resistance. The new baselines are a minimum module resistance of 1.75Ω and a maximum thickness of 4mm. A table listing the top potential candidates is listed in Table 4.

Table 4. Peltier module top candidates.

Module	Length	Width	Height	Resistance
PCX5.6-19-F1N-3030-TA-RT-W6	30mm	30mm	2.4mm	3.8 Ω
PCX6-28-F2-4040-TA-RT-W6	44mm	40mm	3.1mm	5.27 Ω
PCX4-12-F1-3030-TA-RT-W6	30mm	30mm	3.2mm	3.47 Ω

All other modules that were not listed did not have a resistance greater than 1.75Ω , were thicker than 4mm, or broke a length or width constraint. PCX5.6, PCX6, and PCX4, were all compared via Tark Thermal Solutions interactive datasheet.

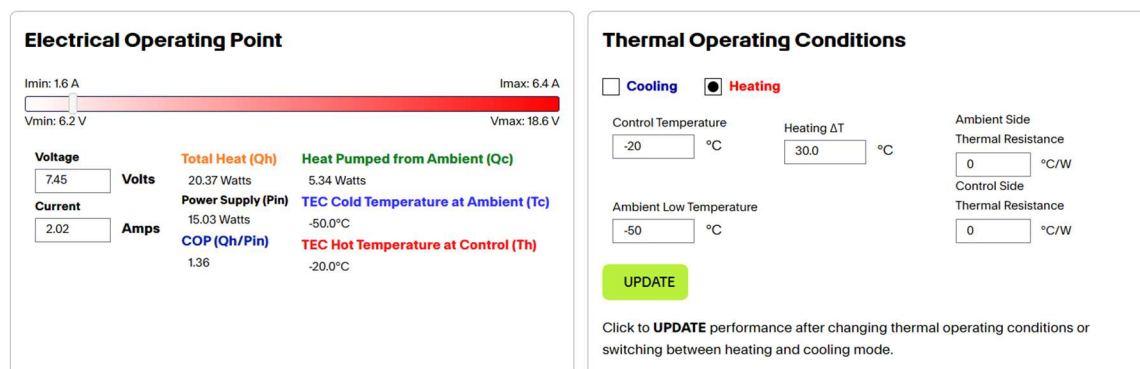


Figure 12. Interactive data sheet results for PCX5.6.

The “Ambient Low Temperature” is set to -50°C , “Control Temperature” is set to -20°C , the resistances are left at the default value of 0, and the slider bar is moved until an output power of approximately 20W is achieved. Table 5 displays the relevant values for each module.

Table 5. Datasheet values for PCX5.6, PCX6, and PCX4.

Module	COP	Output power	Input power	Input Voltage	Input Current
PCX5.6-19-F1N-3030-TA-RT-W6	1.36	20.37W	15.03W	7.45V	2.02A
PCX6-28-F2-4040-TA-RT-W6	1.17	20.37W	17.36W	9.63V	1.80A
PCX4-12-F1-3030-TA-RT-W6	1.49	20.41W	13.66W	6.42V	2.13A

The module chosen for this work is PCX5.6-19-F1N-3030-TA-RT-W6, as it provides a happy medium between thickness, module resistance, and size. However, any one of the three modules listed could have been selected and used for this work. An important note is that the operating point for the PCX5.6 is slightly below the max COP value, meaning that if input power needed to be adjusted to decrease heating time, the PCX5.6 has plenty of capability to do so. Figure 13 shows a screenshot of how COP and Q_h vary with current draw.

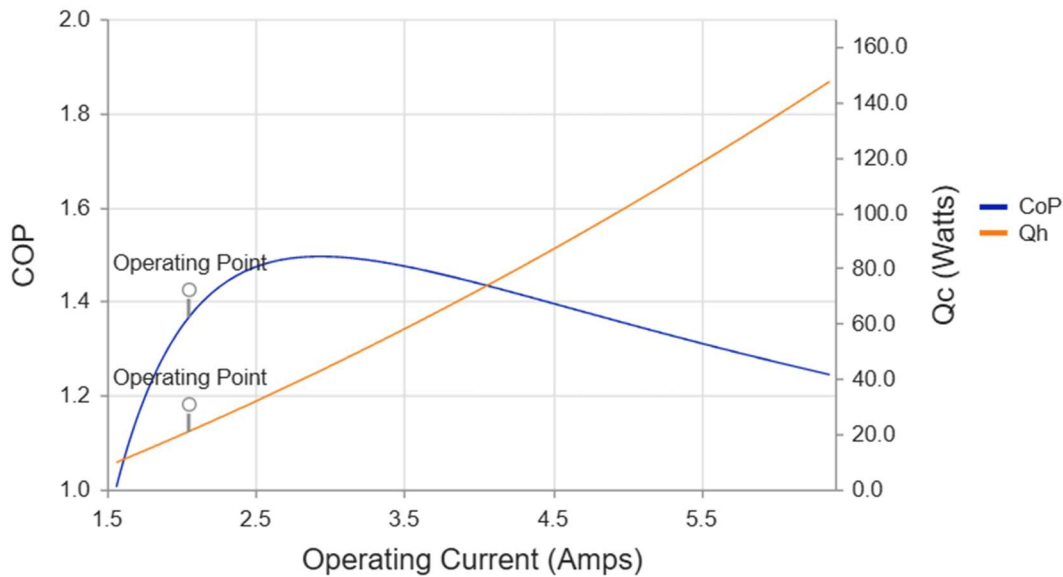


Figure 13. COP and Q_h versus current for PCX5.6

G. Experimental Setup

Verification of the RP5's minimum operating temperature of -20°C was first performed. The RP5 was placed inside the thermal chamber, soaked until the critical components reached -20°C , then attempted to power up. A thermocouple was placed on the SoC, RAM, I/O controller, and PMIC to verify that they had reached the thermal chamber temperature before the power up attempt. The radio module was not monitored due to testing facility restrictions. This process was repeated 5 times with a 100% boot success rate.

Thermocouple probes are routed through the side ports of the thermal chamber to their allocated locations in the clamshell and chassis. In addition to the SoC, RAM, I/O controller, and PMIC, thermocouples were placed on both sides of the top Peltier module to record the hot and cold Peltier face temperatures. Thermocouples were also placed at the bottom, middle, and top of the thermal chamber to capture any temperature gradients. Because the thermocouple probes, mouse/keyboard cables, and power delivery cables are routed through the chamber's side ports, the chamber is not a completely sealed system and will not reach the lowest factory chamber limit of -68°C . Therefore, the chassis assembly was tested at the lowest achievable temperature with the thermal chamber set to -68°C .

The Keithley power supply voltage limit was set to the desired 7.5V output, and the current limit was set to 3A. Voltage draw, current draw, and thermocouple temperatures were recorded every 2 seconds with the DAQ. Figure 14 shows the wiring diagram for the DAQ.

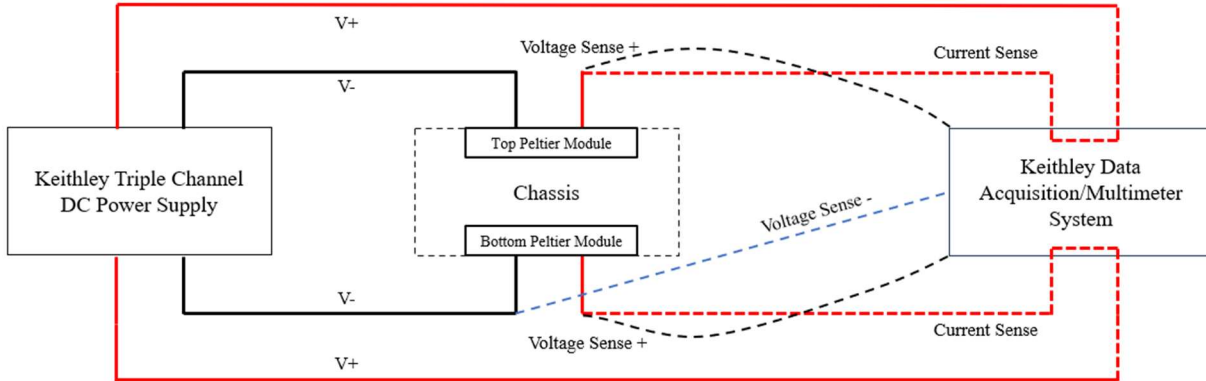


Figure 14. Wiring diagram for Keithley Data Acquisition/Multimeter System.

After the chamber reached its lowest achievable temperature and before the data collection began, the thermal chamber was turned off to eliminate forced airflow through the chamber. This ensured a natural convection environment. Table 6 shows which DAQ channels were utilized for which measurement.

Table 6. Keithley DAQ channel allocation for experimental measurement.

Channel	Parameter measured
1	SoC Temperature (RP5)
2	Front exterior clamshell temperature (hot side Peltier)
5	Thermal Chamber Temperature - Bottom
6	RAM Temperature (RP5)
7	Internal Chassis Temperature (cold side Peltier)
8	I/O Controller Temperature (RP5)
9	Thermal Chamber Temperature - Middle
11	Thermal Chamber Temperature - Top
12	PMIC Temperature (RP5)
19	Top Peltier voltage
20	Bottom Peltier voltage
21	Top Peltier current
22	Bottom Peltier current

IV. Simulation (Ansys)

A. Simulation setup and parameters

ANSYS Student 2026 R1 was used to simulate the temperature distribution of the clamshell, given the calculated convection coefficients and Peltier datasheet power input. The three key components in setting up the successful simulation were geometry preparation, meshing, and initial/boundary conditions. The aim of the simulation is to visualize that the calculated theoretical Peltier power output is sufficient to bring the clamshell temperature to -20°C in 3 minutes. The outer chassis assembly can be excluded from the simulation as the theoretical input power to the clamshell from the Peltier module is known, simplifying the simulation without sacrificing accuracy.

The clamshell was prepared for the simulation by filling all threaded holes and removing thermocouple channels. Not adjusting the clamshell geometry would have resulted in an ultra-fine, complicated mesh that increased simulation time without any added benefit. Figure 15 shows the prepared Ansys geometry.

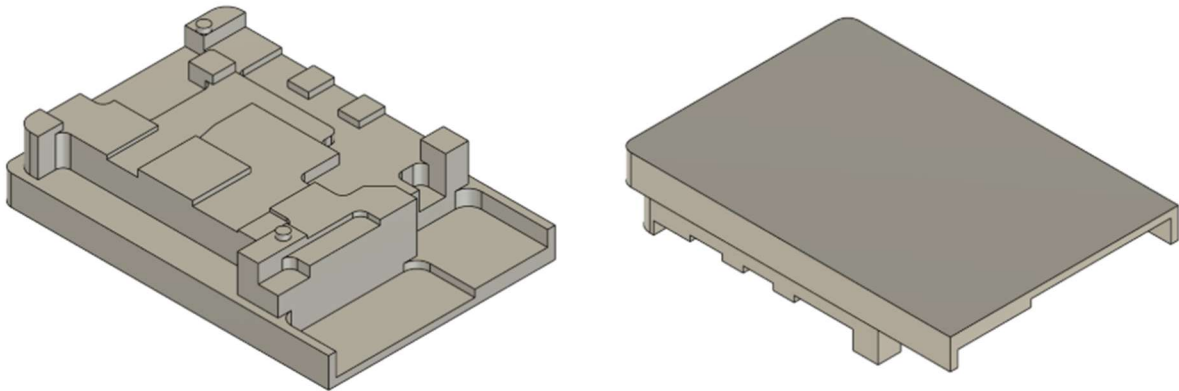


Figure 15. Prepared front clamshell Ansys geometry.

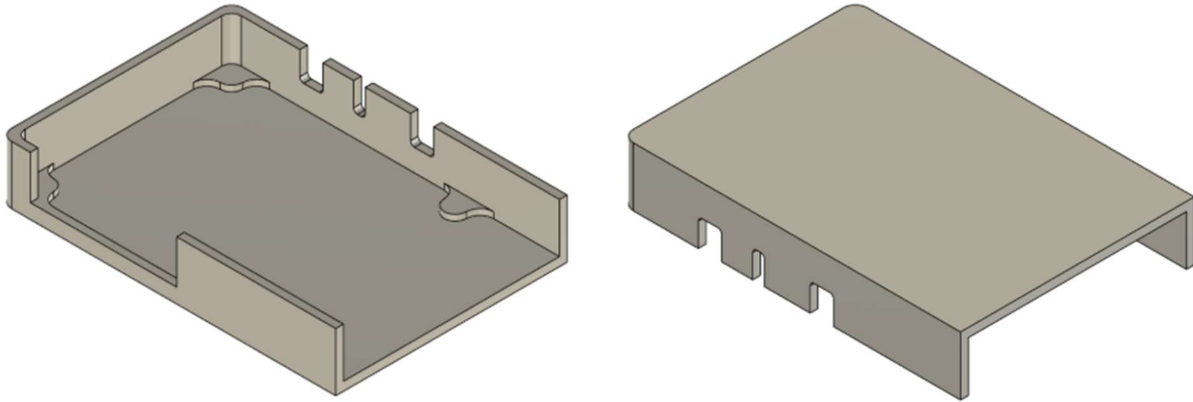


Figure 16. Prepared back clamshell Ansys geometry.

Material properties were added manually through the “Engineering Data” tab, and the values for density ($2700 \frac{kg}{m^3}$), thermal conductivity ($167 \frac{W}{m-K}$), and specific heat for constant pressure ($897 \frac{J}{kg-K}$) were obtained from NIST tables. The meshing method used was a Multizone Hexa element strategy with a Hexa Dominant free mesh type, and a 2.5mm body sizing. Figure 17 shows the meshed clamshell assembly.

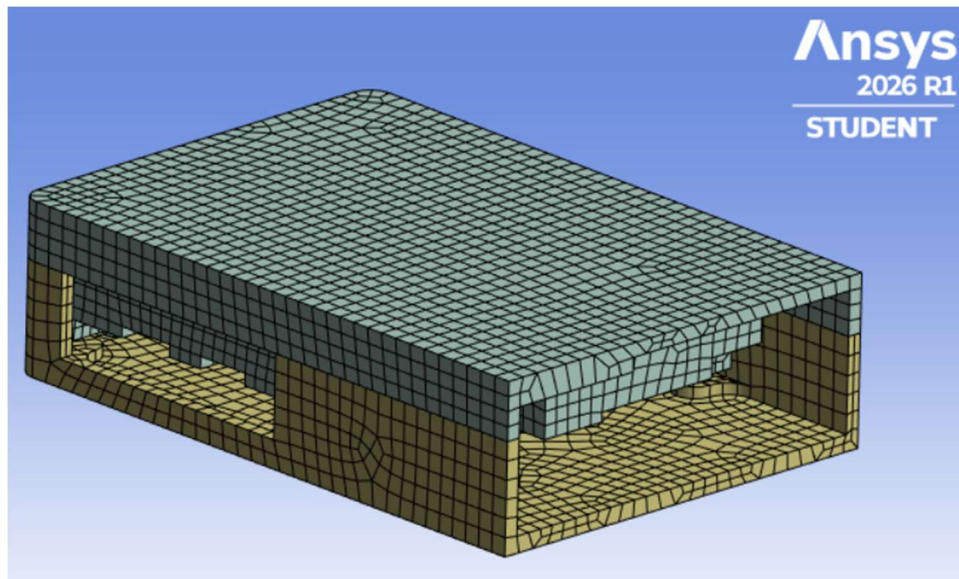


Figure 17. Meshed clamshell assembly. Images used courtesy of ANSYS, Inc.

Using the hand calculations from Appendix A, the convection and heat flux boundary conditions were applied to the appropriate clamshell surfaces. For clarity, the heat flux condition for the back

clamshell and convection conditions for all surfaces are shown in Figure 18, and the heat flux condition for the front clamshell surface is shown in Figure 19.

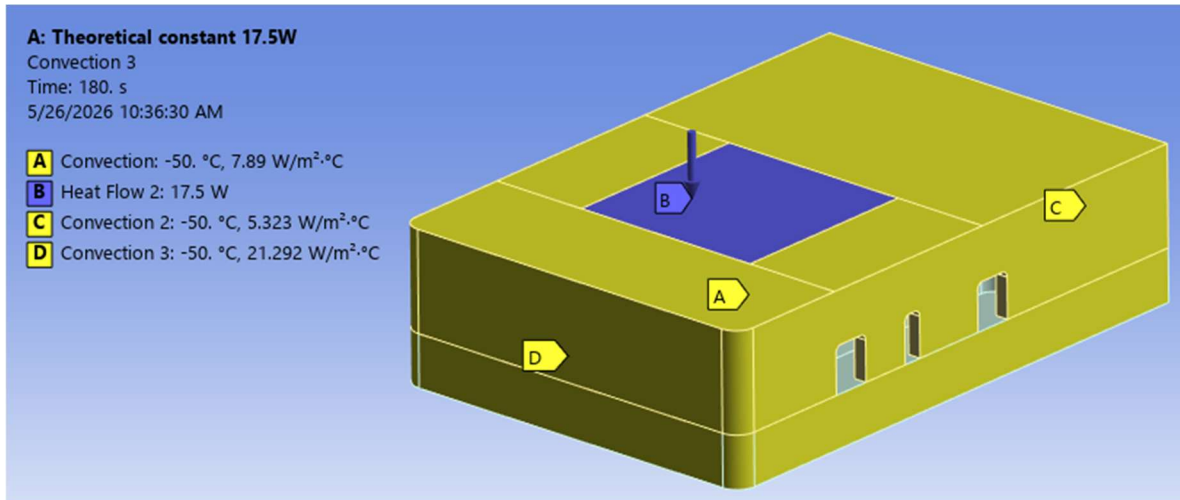


Figure 18. Boundary conditions for clamshell surfaces. Images used courtesy of ANSYS, Inc.

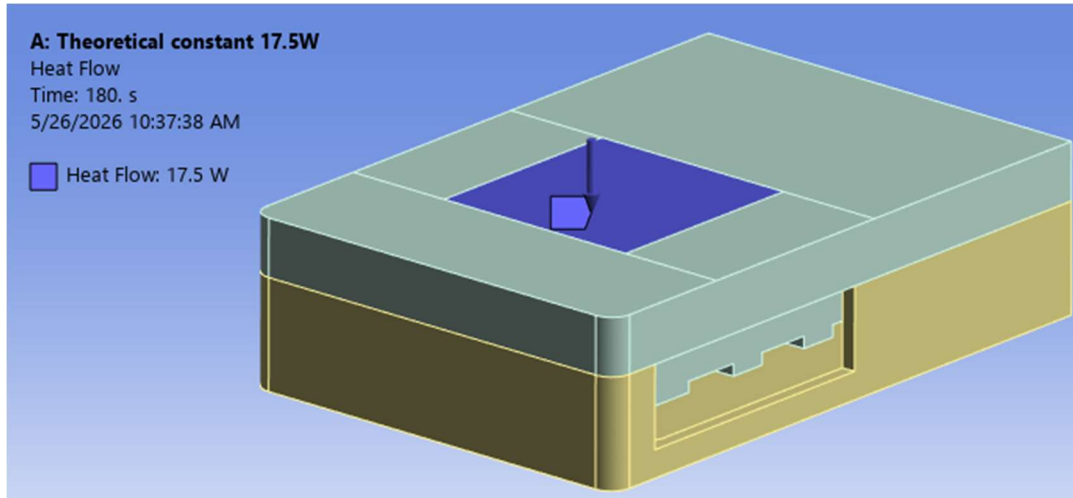


Figure 19. Heat flux boundary condition for front clamshell. Images used courtesy of ANSYS, Inc.

V. Results and Discussion

A. Simulation Results

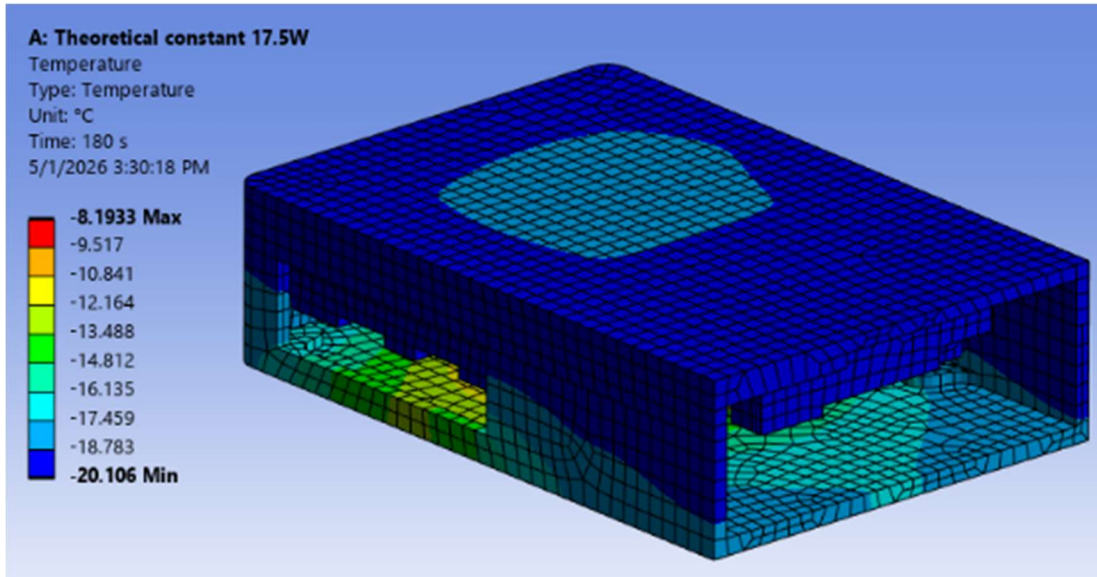


Figure 20. Temperature distribution for clamshell assembly. Images used courtesy of ANSYS, Inc.

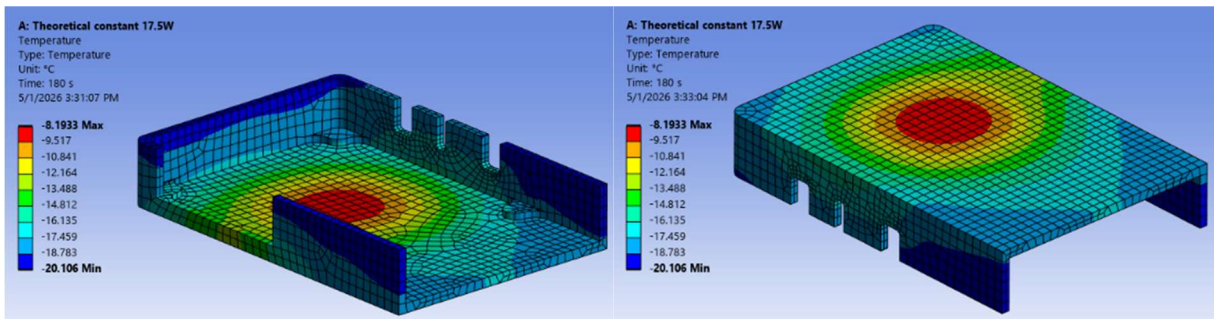


Figure 21. Temperature distribution for back clamshell. Images used courtesy of ANSYS, Inc.

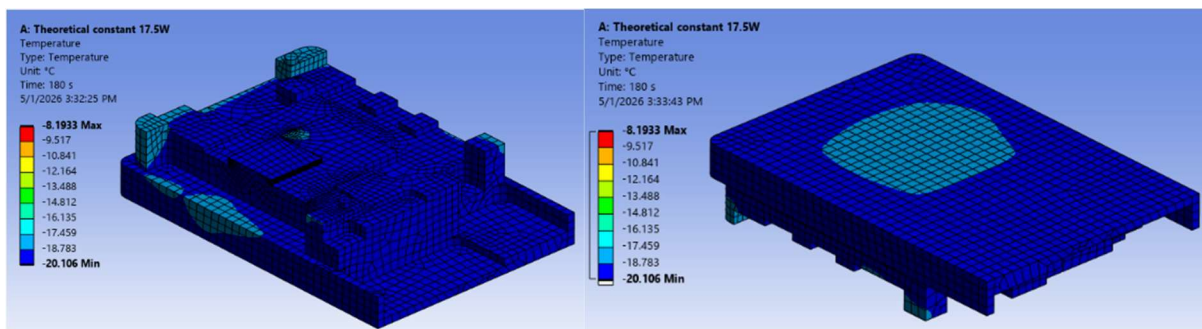


Figure 22. Temperature distribution in front clamshell. Images used courtesy of ANSYS, Inc.

All simulated component temperatures were nearly identical during the heat up process, with final SOM, RAM, I/O Controller, and PMIC temperatures being -18.78°C , -18.82°C , -19.44°C , and -19.01°C . This simulation demonstrates the physical interpretation of what the hand calculations in Appendix A prove. In other words, the chassis assembly exposed to a -50°C environment with each Peltier module pumping 17.5W of power into the clamshell assembly for 180 seconds will yield a real-world temperature distribution similar to the temperature distribution shown in Figures 20, 21, and 22.

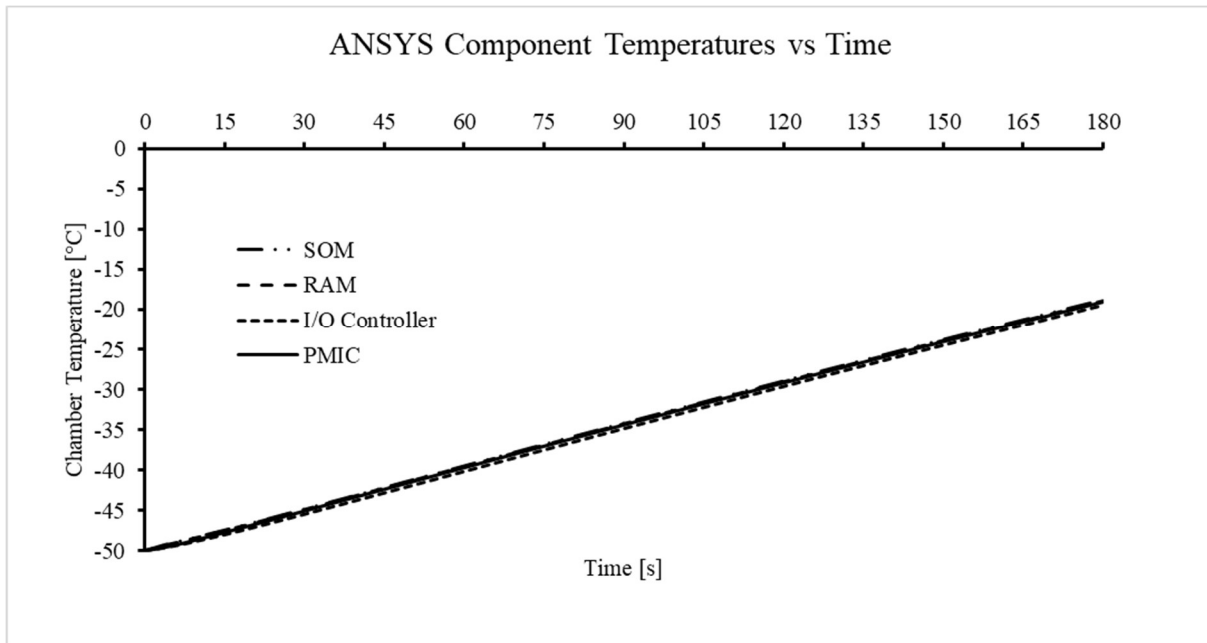


Figure 23. Ansys component temperatures versus time. Data generated using ANSYS Mechanical.

B. Experimental Results

i. 7.5V Test

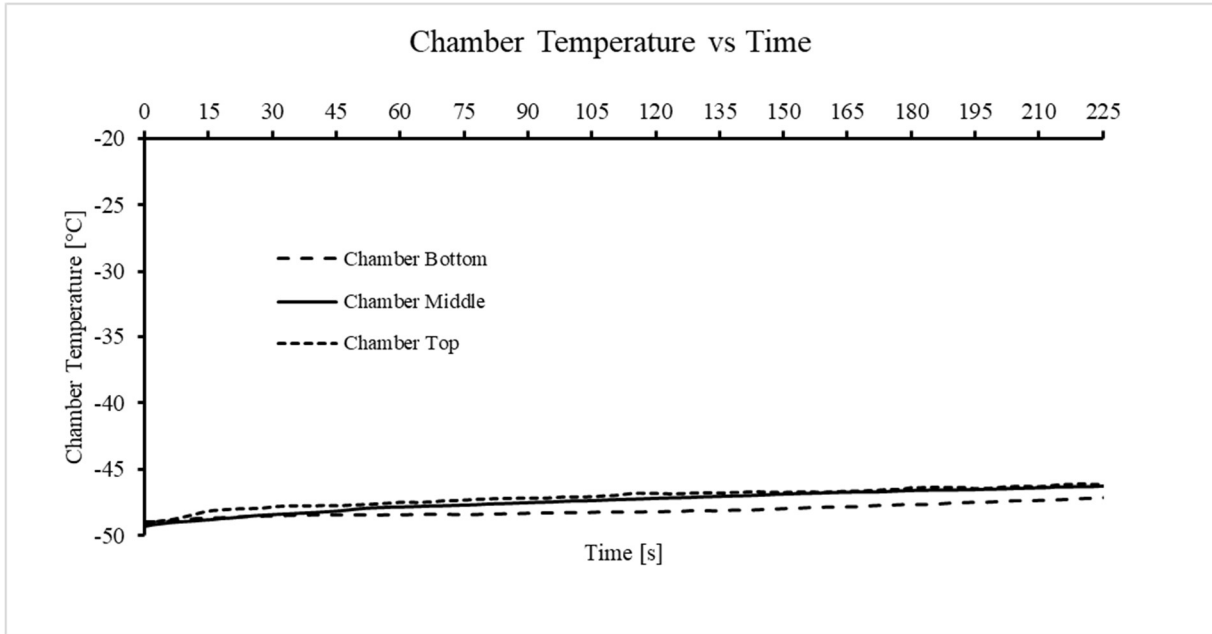


Figure 24. Lower, middle, and upper chamber temperature versus time (7.5V).

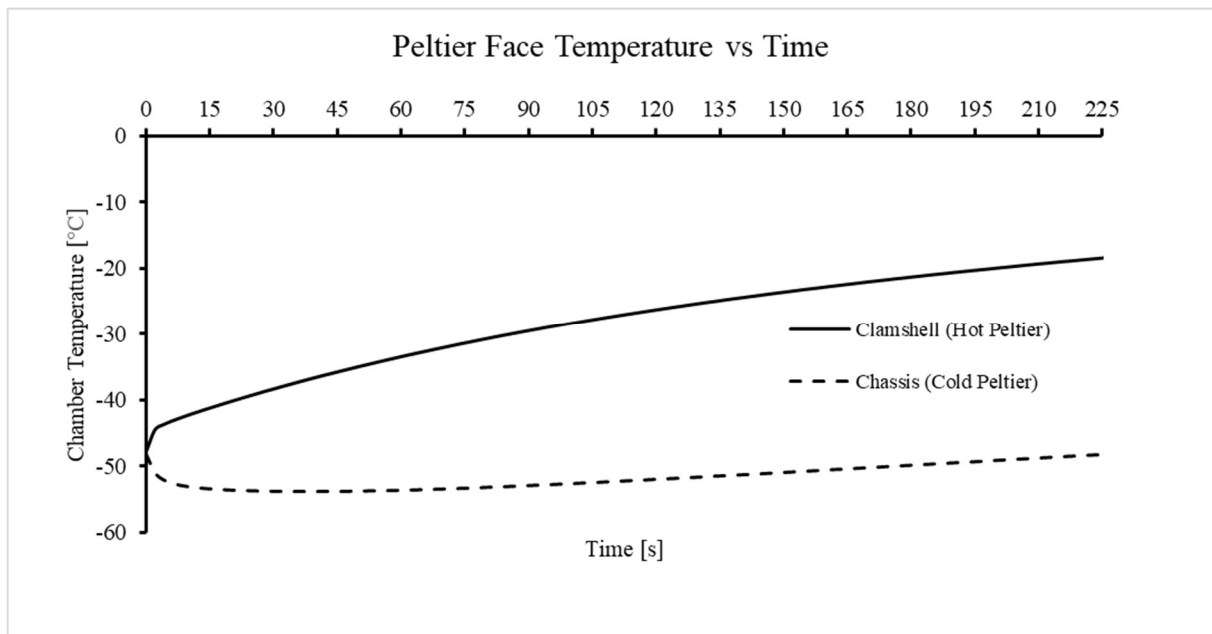


Figure 25. Peltier module hot and cold face temperatures versus time (7.5V).

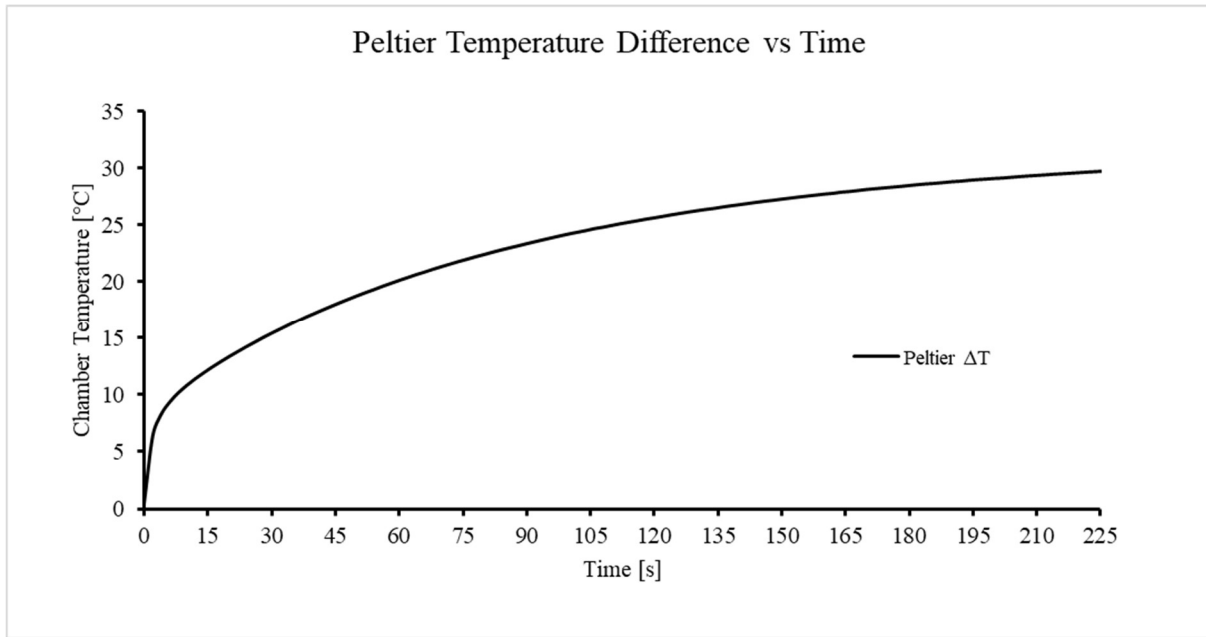


Figure 26. Peltier face temperature difference versus time (7.5V).

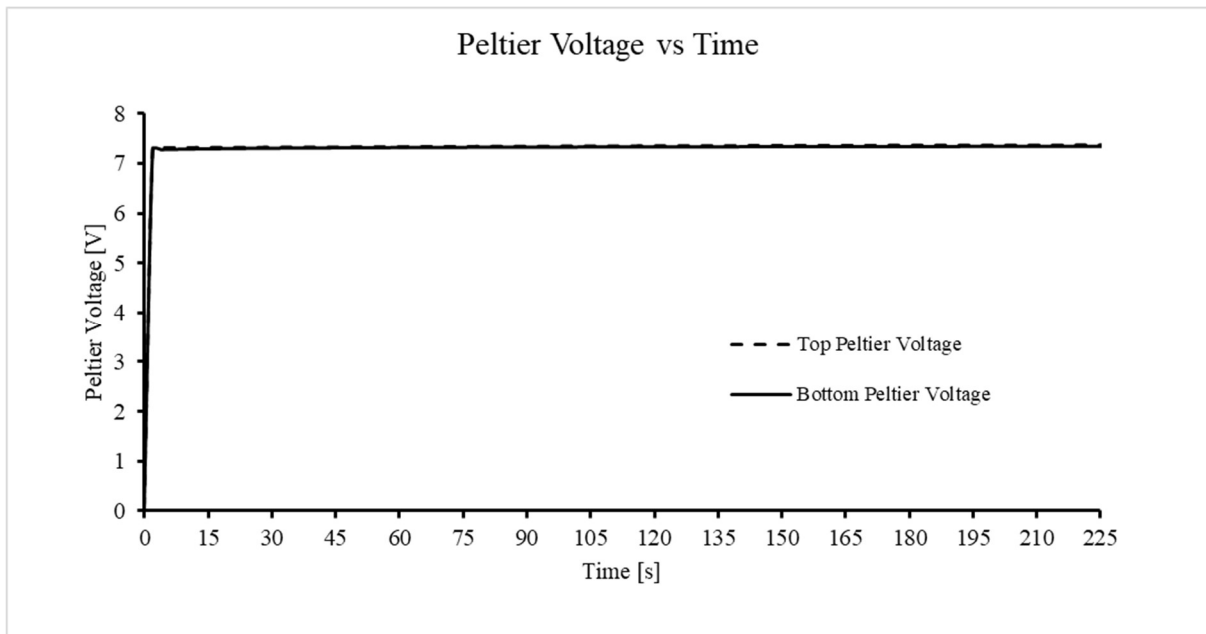


Figure 27. Peltier voltage versus time (7.5V).

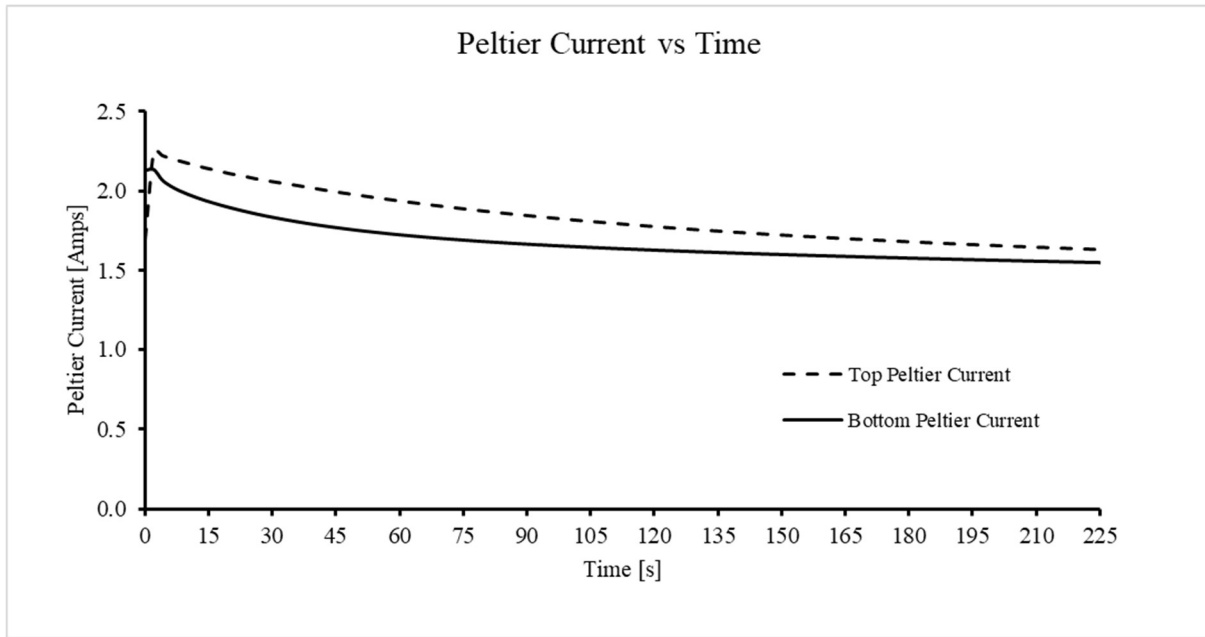


Figure 28. Peltier current draw versus time (7.5V).

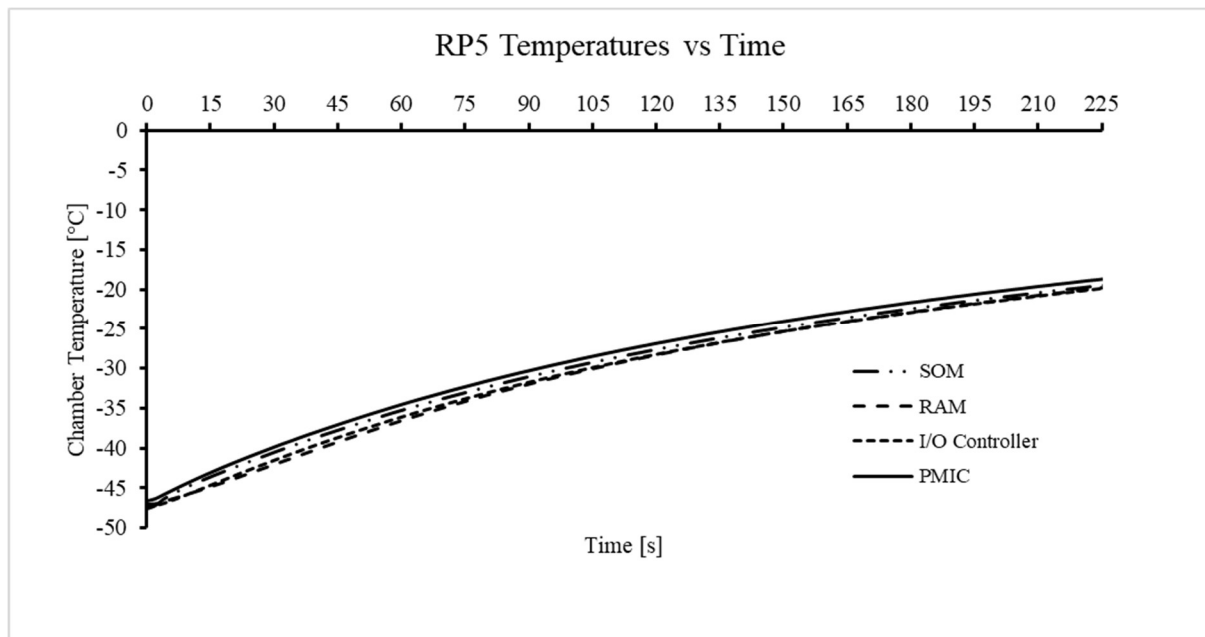


Figure 29. RP5 component temperatures versus time (7.5V).

The 7.5V testing achieved a component temperature of -20°C in approximately 212 seconds, missing the 180 second target. Extracting the Q_h data from the PCX5.6 datasheet, the actual power output of each Peltier module can be analyzed. Table 7 shows the individual energy and power statistics for the

Peltier modules, in addition to the total energy transferred to the system in comparison to theoretical values.

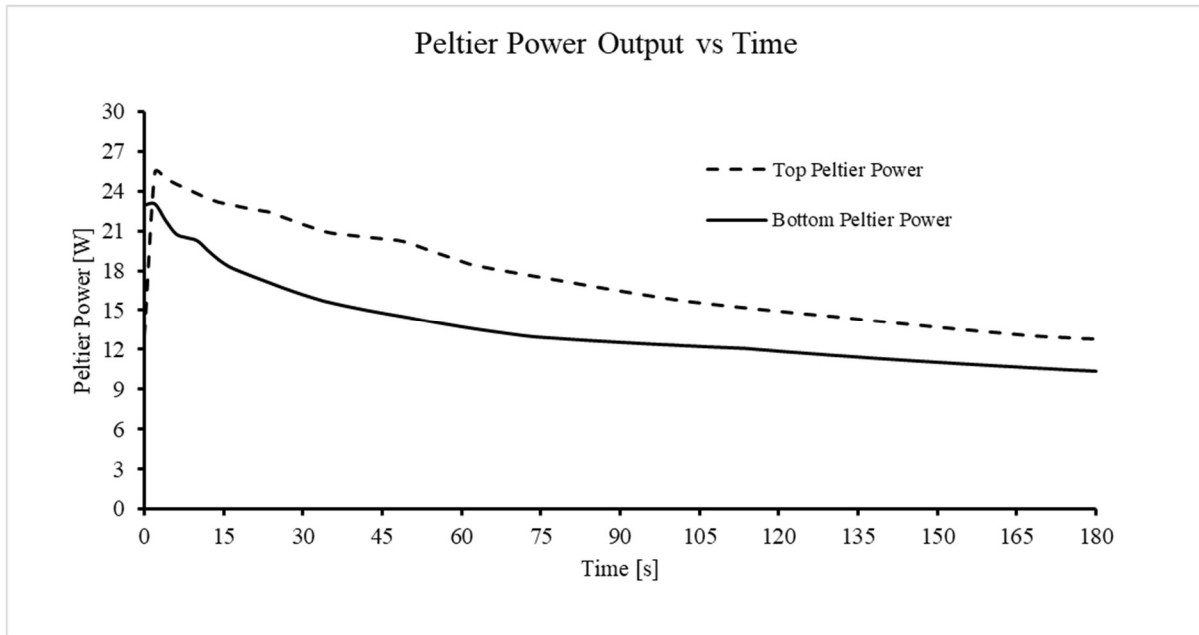


Figure 30. Peltier power output versus time (7.5V).

Table 7. Peltier energy and power output data (7.5V).

	Top Peltier	Bottom Peltier	Combined	Expected	% Difference
Energy	3136.0±16.6J	2470.1±16.6J	5606.1±23.5J	6302±281J	11%
Average Power	17.23±0.87W	13.57±0.87W	15.40±0.62W	17.51±1.56W	12%

The combined energy output of the Peltier modules in 180s is 5606J, with an average power output of 15.4W per module. Both statistics are lower than the target values. This does not imply our hand calculations are incorrect, but that the Peltier modules did not output the expected power based on the datasheet. The difference in power output between the top and bottom Peltier modules relates to the thermal mass of the clamshell half they are connected to. The top Peltier module is connected to the front clamshell, which has a much higher thermal mass than the back clamshell. This means that the top Peltier must pump more heat into the front clamshell to achieve the desired ΔT of 30°C compared to the bottom Peltier, hence the difference in power output between the modules. If the front and back clamshells had similar thermal masses, the current draw and power output of both Peltier modules would be similar. To achieve the 180s target, the input power to the Peltier modules must be increased. The Keithley power

supply voltage limit was increased to 8V, and the current limit was left at 3A, as the datasheet showed increasing voltage from 7.5V to 8V resulted in only a 0.21A increase in current pull.

ii. 8V Test

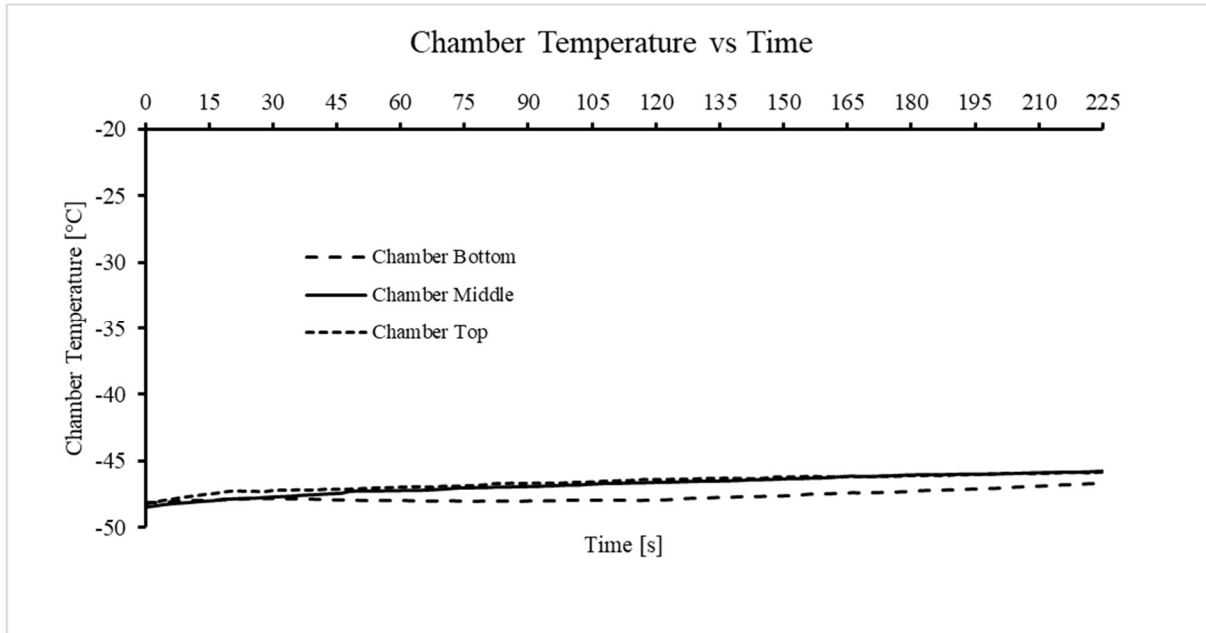


Figure 31. Lower, middle, and upper chamber temperature versus time (8V).

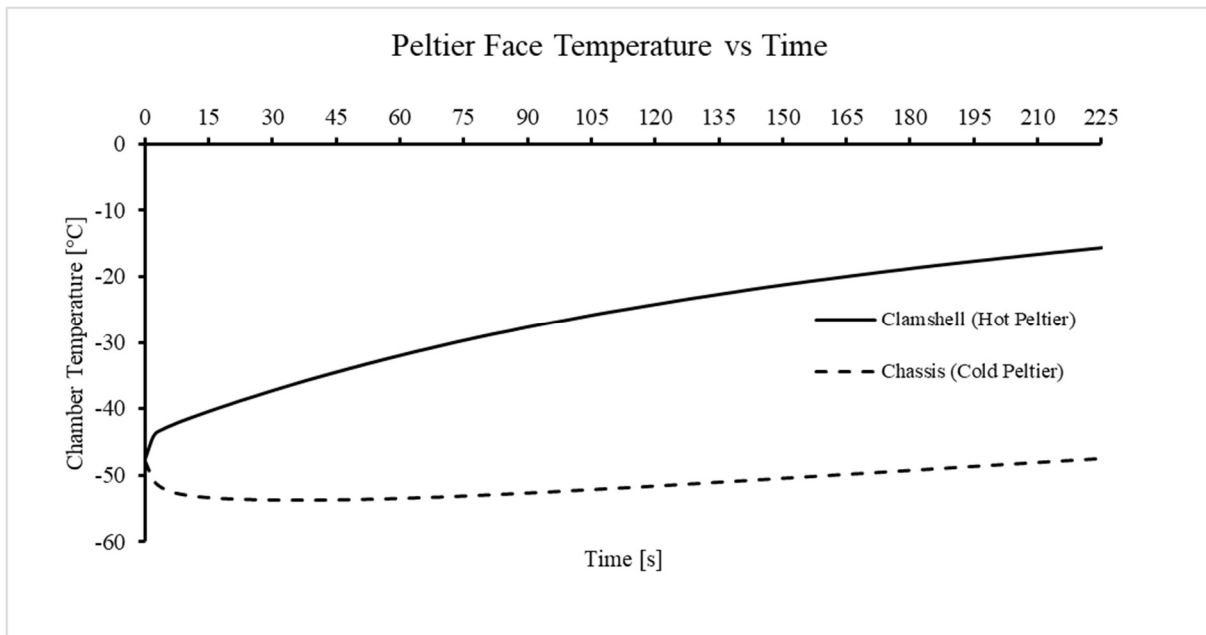


Figure 32. Peltier module hot and cold face temperatures versus time (8V).

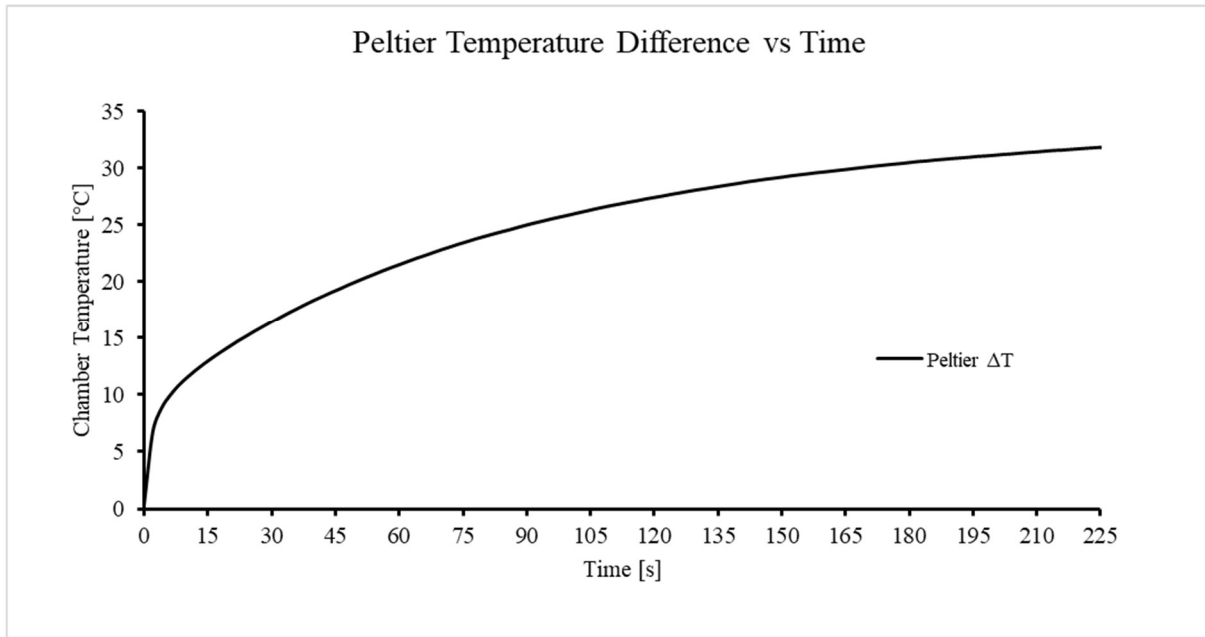


Figure 33. Peltier face temperature difference versus time (8V).

The Peltier module's trend is that of one in thermal runaway, as the temperature difference between the two faces continues to increase after hitting the desired ΔT of 30°C. In a cooling case, thermal runaway would imply poor heat sink design. In this heating case, however, thermal runaway is encouraged, as the goal is to heat up the clamshell within a set time.

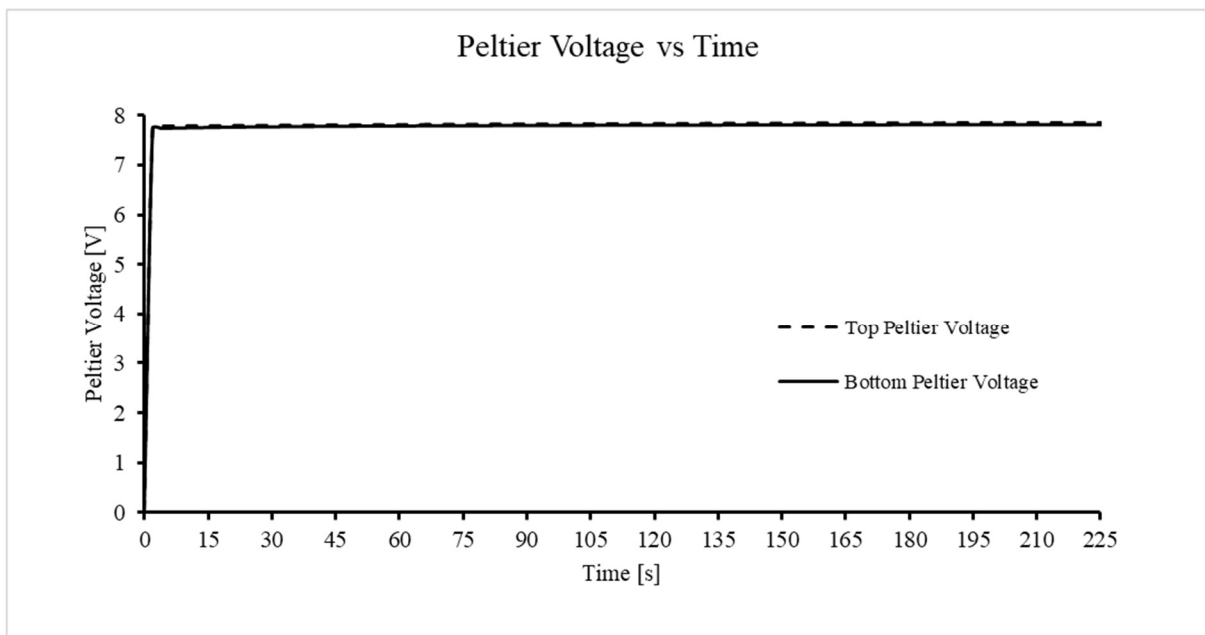


Figure 34. Peltier voltage versus time (8V).

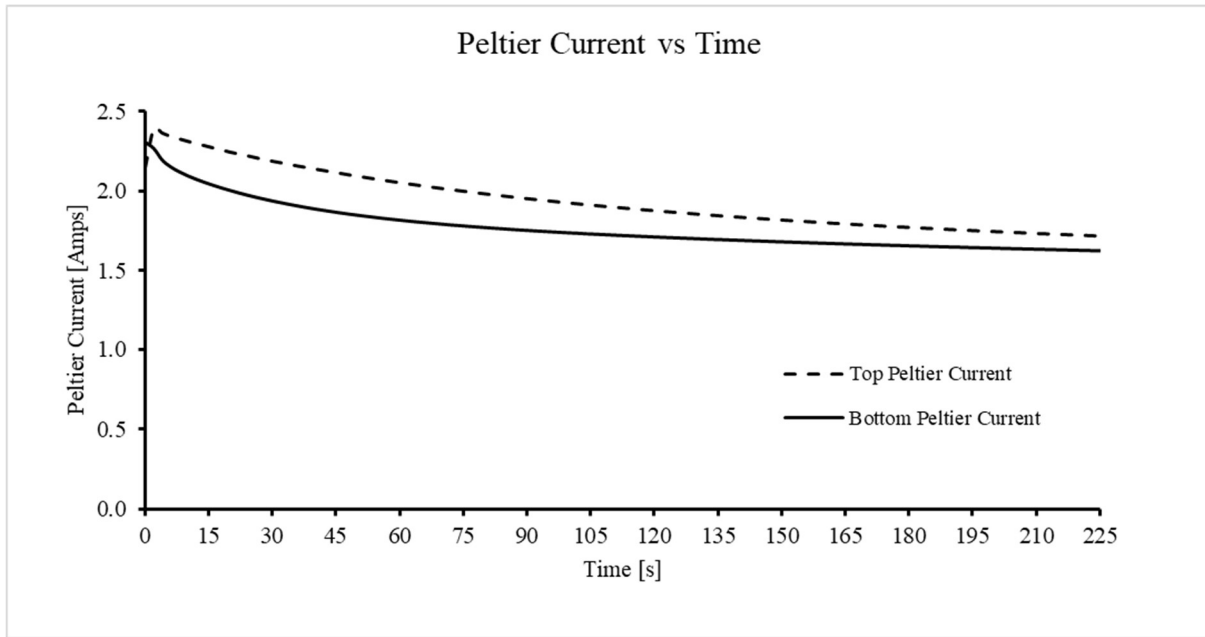


Figure 35. Peltier current draw versus time (8V).

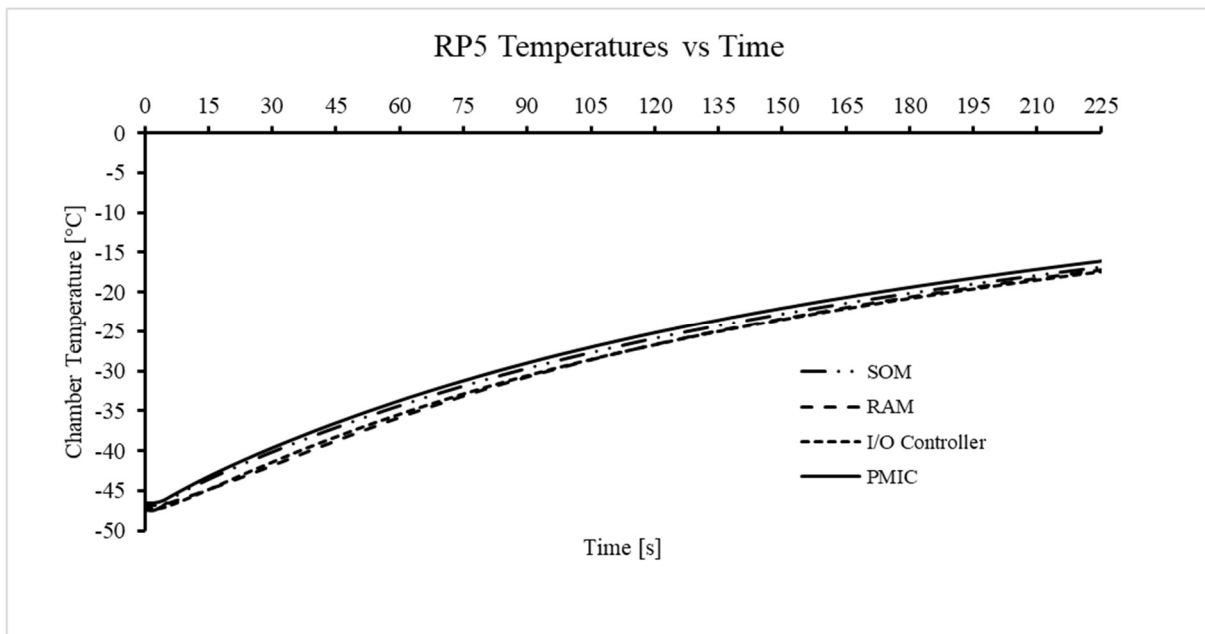


Figure 36. RP5 component temperatures versus time (8V).

Increasing the Peltier voltage to 8V resulted in successfully heating the critical components to -20°C in 180s. Analyzing the power data, the total power input to the clamshell was within 3% of the hand calculations. Table 8 shows the individual energy and power statistics for the Peltier modules, in addition to the total energy transferred to the system in comparison to theoretical values.

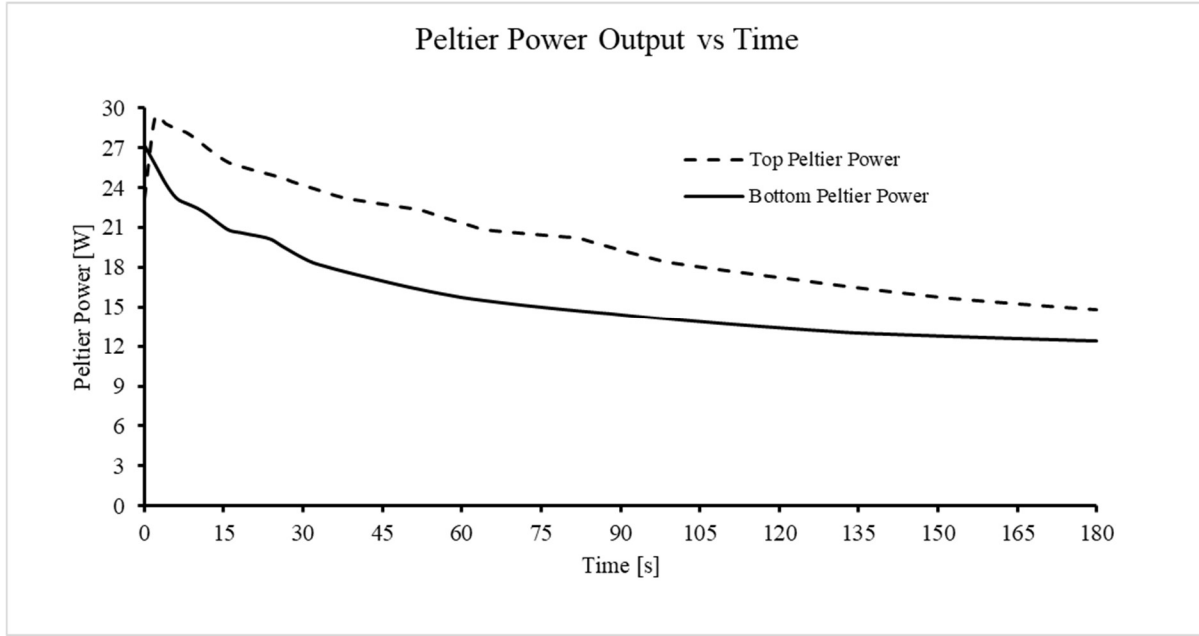


Figure 37. Peltier power output versus time (8V).

Table 8. Peltier energy and power output data (8V).

	Top Peltier	Bottom Peltier	Combined	Expected	% Difference
Total Energy	3620.6±16.6J	2836.5±16.6J	6457.1±23.5J	6302±281J	2.4%
Average Power	19.89±0.87W	15.59±0.87W	17.74±0.62W	17.51±1.56W	1.3%

VI. Conclusions and Recommendations

An effective heating solution for a VNX+ driven chassis assembly was developed and implemented with Peltier modules. This work expanded the use case of a Peltier module as a thermal solution, as thermoelectric coolers are primarily used as evacuating heat from a system instead of pumping heat in. Sizing of the Peltier module is outlined in Section III.F and key design factors and implications are discussed. Hand calculations and simulation results were in alignment with experimental results, implying that the assumptions used in calculating convection coefficients were appropriate and the simulation setup (geometry preparation, meshing methods, and boundary conditions) was adequate. There was a difference between the power output of the top and bottom Peltier modules, as the hot side of the modules were placed against different clamshell halves with different thermal masses. The clamshell was designed to mimic a traditional VITA90 plug-in module clamshell, whilst also adapting to board

geometry, which is why the clamshell halves in this work have differing geometries and properties. If identical behavior of Peltier modules is desired, the modules must be attached to objects of identical thermal mass.

The application of this work could be combined with the work done by Sundayani et al. [18], Jian et al. [19], Chen et al. [20], or Kherkhar et al. [21] to create a complete thermal solution with PID controlled Peltier modules, resulting in the capability of heating or cooling a system dependent on ambient temperature. This could expand operating temperature range for any electrical system in both directions, lowering minimum operating temperature and raising maximum operating temperature. Applying this work directly to a multi-clamshell chassis assembly would involve additional Peltier modules placed between the side walls of the clamshell stack and chassis. This would ensure that the clamshells in the middle of the stack are temperature controlled in similar manner to the top and bottom clamshells.

One limitation of this study is that the power supply feeding the Peltier modules is outside the -50°C environment. Temperature affects both voltage [40] and current [41], thus future work could include feeding power to the Peltier modules with a power supply also exposed to the freezing environment. Furthermore, embedding the power supply within the VNX+ chassis assembly to create an isolated system could also be explored.

References

- [1] “Thermal Management of Defense Electronics.” Qpedia, Oct. 2010.
- [2] Department of Defense, “MIL-STD-1540B.” Department of Defense, Oct. 10, 1982. [Online]. Available: <https://www.vibrationdata.com/tutorials/MilStd1540B.pdf>
- [3] K. Ersoy, “Review of Electronic Cooling and Thermal Management in Space and Aerospace Applications,” in *2024 IEEE 7th International Conference on Knowledge Innovation and Invention*, MDPI, Mar. 2025, p. 42. doi: 10.3390/engproc2025089042.
- [4] H. Liu, C. Yang, and R. Wang, “Passive thermal management of electronic devices,” *Device*, vol. 3, no. 3, p. 100684, Mar. 2025, doi: 10.1016/j.device.2024.100684.
- [5] K. Ersoy, “Review of Electronic Cooling and Thermal Management in Space and Aerospace Applications,” in *2024 IEEE 7th International Conference on Knowledge Innovation and Invention*, MDPI, Mar. 2025, p. 42. doi: 10.3390/engproc2025089042.
- [6] D. C. Price, “A review of selected thermal management solutions for military electronic systems,” *IEEE Trans. Compon. Packag. Technol.*, vol. 26, no. 1, pp. 26–39, Mar. 2003, doi: 10.1109/TCAPT.2003.811464.
- [7] W. Ripley, A. Walker, and M. Adalier, “Introducing VITA 90, the latest rugged small-form-factor module standard - Military Embedded Systems,” *Military Embedded Systems*. Accessed: Apr. 04, 2026. [Online]. Available: <https://militaryembedded.com/unmanned/rugged-computing/introducing-vita-90-the-latest-rugged-small-form-factor-module-standard>
- [8] J. Keller, “VNX+ and small-form-factor SOSA: the next trend in embedded computing,” *Military Aerospace*. Accessed: Mar. 17, 2026. [Online]. Available: <https://www.militaryaerospace.com/computers/article/14290276/embedded-computing-sosa-small-form-factor>
- [9] J. Gipper, “VITA - ANSI and VITA Ratify ANSI/VITA 90 VNX+ Enhanced Small Form Factor System,” *VITA*. Accessed: Apr. 04, 2026. [Online]. Available: <https://www.vita.com/VITA-Announcements/13599937>
- [10] M. Littlefield, “SOSA™ VNX+: Small Form Factor for Ground Vehicle Applications,” presented at the 2024 NDIA Michigan Chapter Ground Vehicle Systems Engineering and Technology Symposium, Novi, Michigan, United States, Aug. 2023, pp. 2024-01–4117. doi: 10.4271/2024-01-4117.
- [11] H. Y. Zhang, Y. C. Mui, and M. Tarin, “Analysis of thermoelectric cooler performance for high power electronic packages,” *Appl. Therm. Eng.*, vol. 30, no. 6–7, pp. 561–568, May 2010, doi: 10.1016/j.applthermaleng.2009.10.020.

- [12]R. Mahajan, Chia-pin Chiu, and G. Chrysler, "Cooling a Microprocessor Chip," *Proc. IEEE*, vol. 94, no. 8, pp. 1476–1486, Aug. 2006, doi: 10.1109/JPROC.2006.879800.
- [13]S. Sharma, V. K. Dwivedi, and S. N. Pandit, "A Review of Thermoelectric Devices for Cooling Applications," *Int. J. Green Energy*, vol. 11, no. 9, pp. 899–909, Oct. 2014, doi: 10.1080/15435075.2013.829778.
- [14]N. A. Sidorenko and Z. M. Dashevsky, "Cryogenic Thermoelectric Cooler for Operating Temperatures below 90 K," *Semiconductors*, vol. 53, no. 6, pp. 752–755, Jun. 2019, doi: 10.1134/S1063782619060216.
- [15]R. Chein and G. Huang, "Thermoelectric cooler application in electronic cooling," *Appl. Therm. Eng.*, vol. 24, no. 14–15, pp. 2207–2217, Oct. 2004, doi: 10.1016/j.applthermaleng.2004.03.001.
- [16]B. Yang, P. Wang, and A. Bar-Cohen, "Mini-Contact Enhanced Thermoelectric Cooling of Hot Spots in High Power Devices," *IEEE Trans. Compon. Packag. Technol.*, vol. 30, no. 3, pp. 432–438, Sep. 2007, doi: 10.1109/TCAPT.2007.898744.
- [17]M. Zebarjadi, "Electronic cooling using thermoelectric devices," *Appl. Phys. Lett.*, vol. 106, no. 20, p. 203506, May 2015, doi: 10.1063/1.4921457.
- [18]Sundayani *et al.*, "PID temperature controlling of thermoelectric based cool box," in *2017 International Conference on Control, Electronics, Renewable Energy and Communications (ICCREC)*, Yogyakarta: IEEE, Sep. 2017, pp. 236–240. doi: 10.1109/ICCEREC.2017.8226671.
- [19]M. Jian, S. Zhu, W. Du, L. Yang, and J. Zhang, "Design of a temperature control system for transient thermal measurement utilizing the backpropagation PID algorithm," *Int. J. Therm. Sci.*, vol. 210, p. 109654, Apr. 2025, doi: 10.1016/j.ijthermalsci.2024.109654.
- [20]Z. Chen, X. Xu, J. Zhang, Y. Yuan, P. Shen, and X. Mou, "High-efficiency adaptive temperature control for thermoelectric system based on the OBPPID strategy," *Energy*, vol. 308, p. 132932, Nov. 2024, doi: 10.1016/j.energy.2024.132932.
- [21]A. Kherkhar, Y. Chiba, A. Tlemçani, and H. Mamur, "Thermal investigation of a thermoelectric cooler based on Arduino and PID control approach," *Case Stud. Therm. Eng.*, vol. 36, p. 102249, Aug. 2022, doi: 10.1016/j.csite.2022.102249.
- [22]A. O. Ochieng, T. F. Megahed, S. Ookawara, and H. Hassan, "Comprehensive review in waste heat recovery in different thermal energy-consuming processes using thermoelectric generators for electrical power generation," *Process Saf. Environ. Prot.*, vol. 162, pp. 134–154, Jun. 2022, doi: 10.1016/j.psep.2022.03.070.
- [23]H. M. Hu, T. S. Ge, Y. J. Dai, and R. Z. Wang, "Experimental study on water-cooled thermoelectric cooler for CPU under severe environment," *Int. J. Refrig.*, vol. 62, pp. 30–38, Feb. 2016, doi: 10.1016/j.ijrefrig.2015.10.015.

- [24]X. Sun *et al.*, “Experimental Research of a Thermoelectric Cooling System Integrated with Gravity Assistant Heat Pipe for Cooling Electronic Devices,” *Energy Procedia*, vol. 105, pp. 4909–4914, May 2017, doi: 10.1016/j.egypro.2017.03.975.
- [25]Y.-W. Chang, C.-C. Chang, M.-T. Ke, and S.-L. Chen, “Thermoelectric air-cooling module for electronic devices,” *Appl. Therm. Eng.*, vol. 29, no. 13, pp. 2731–2737, Sep. 2009, doi: 10.1016/j.applthermaleng.2009.01.004.
- [26]H.-S. Huang, Y.-C. Weng, Y.-W. Chang, S.-L. Chen, and M.-T. Ke, “Thermoelectric water-cooling device applied to electronic equipment,” *Int. Commun. Heat Mass Transf.*, vol. 37, no. 2, pp. 140–146, Feb. 2010, doi: 10.1016/j.icheatmasstransfer.2009.08.012.
- [27]F. L. Tan and S. C. Fok, “Methodology on sizing and selecting thermoelectric cooler from different TEC manufacturers in cooling system design,” *Energy Convers. Manag.*, vol. 49, no. 6, pp. 1715–1723, Jun. 2008, doi: 10.1016/j.enconman.2007.11.001.
- [28]S. Sujono and H. Novianto, “Experimental study on the performance of Peltier TEC12706 as a cooling and heating media,” *J. Polimesin*, vol. 22, no. 6, p. 600, Dec. 2024, doi: 10.30811/jpl.v22i6.5345.
- [29]M. Cosnier, G. Fraisse, and L. Luo, “An experimental and numerical study of a thermoelectric air-cooling and air-heating system,” *Int. J. Refrig.*, vol. 31, no. 6, pp. 1051–1062, Sep. 2008, doi: 10.1016/j.ijrefrig.2007.12.009.
- [30]“Aluminum 6061-T6 (UNS AA96061),” *NIST*, Feb. 2018, Accessed: Apr. 28, 2026. [Online]. Available: <https://www.nist.gov/mml/acmd/aluminum-6061-t6-uns-aa96061>
- [31]A. U. Samuel, A. O. Araoyinbo, R. R. Elewa, and M. B. Biodun, “Effect of Machining of Aluminium Alloys with Emphasis on Aluminium 6061 Alloy – A Review,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1107, no. 1, p. 012157, Apr. 2021, doi: 10.1088/1757-899X/1107/1/012157.
- [32]T. L. Bergman and A. S. Lavine, *Fundamentals of heat and mass transfer*, Eighth edition. Hoboken, NJ: John Wiley & Sons, 2017.
- [33]G. Halfacree, *The official Raspberry Pi beginner’s guide: how to use your new computer*, Fifth edition. Cambridge: Raspberry Pi Press, 2023.
- [34]“PowerCycling PCX Series - Peltier coolers for thermal cycling | Tark Thermal Solutions.” Accessed: Apr. 28, 2026. [Online]. Available: <https://tark-solutions.com/products/thermoelectric-cooler-modules/peltier-thermal-cycling-pcx-series>
- [35]R. N. M. Al-Kaby, “Study of Thermal Performance of Thermoelectric Cooling System,” 2007.
- [36]T. M. Pravinchandra, “Peltier Cooling Module,” Master of Technology, Pandit Deendayal Petroleum University, Mechanical Engineering Department, 2015.

- [37] Sonal Renge, Yashika Barhaiya, Shikhar Pant, Shubham Sharma, and SHRI RAMDEOBABA COLLEGE OF ENGINEERING AND MANAGEMENT, NAGPUR, “A Review on Generation of Electricity using Peltier Module,” *Int. J. Eng. Res.*, vol. V6, no. 01, p. IJERTV6IS010308, Jan. 2017, doi: 10.17577/IJERTV6IS010308.
- [38] Z. Xu, C. Li, H. Zhao, Y. Zheng, and J. Zhang, “Design and performance analysis of hot side heat sink of thermoelectric cooler device based on simulation and experiment,” *Energy Sci. Eng.*, vol. 11, no. 12, pp. 4463–4480, Dec. 2023, doi: 10.1002/ese3.1591.
- [39] W. Zhang *et al.*, “Performance analysis of a thermoelectric cooler based on thermal management,” *Appl. Therm. Eng.*, vol. 265, p. 125655, Apr. 2025, doi: 10.1016/j.applthermaleng.2025.125655.
- [40] P. Löper *et al.*, “Analysis of the Temperature Dependence of the Open-Circuit Voltage,” *Energy Procedia*, vol. 27, pp. 135–142, 2012, doi: 10.1016/j.egypro.2012.07.041.
- [41] A. Yadav, “Effect of Temperature on Electric Current, Magnets and Electromagnet,” *Int. J. Adv. Technol.*, vol. 07, no. 04, 2016, doi: 10.4172/0976-4860.1000167.
- [42] “DAQ6510 Data Acquisition and Logging, Multimeter System Datasheet”.
- [43] “Thermocouple accuracies - Thermocouple Accuracy - Thermocouple Accuracy Comparison Chart.” Accessed: May 25, 2026. [Online]. Available: <https://www.thermocoupleinfo.com/thermocouple-accuracies.htm>

Appendix A: Hand Calculations for Convection Coefficients

All hand calculations and Nusselt number correlations are in reference to section 9.8.1

(Rectangular Cavities) in *Fundamentals in Heat and Mass Transfer* [32]. L, W, and H parameters are following the notation show in Figure 38.

9.8.1 Rectangular Cavities

The rectangular cavity (Figure 9.10) has been studied extensively, and comprehensive reviews of both experimental and theoretical results are available [26, 27]. Two of the opposing walls are maintained at different temperatures ($T_1 > T_2$), while the remaining walls are insulated from the surroundings. The tilt angle τ between the hot and cold surfaces

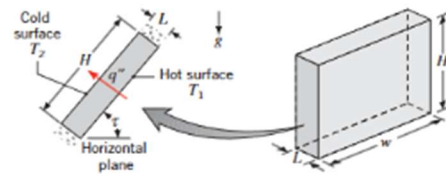


FIGURE 9.10 Free convection in a rectangular cavity.

Figure 38. Rectangular Cavity definition [32].

Table 9. Thermophysical properties of air.

Property/Variable Name	Numerical Value
$T_{surface}$	253K
$T_{surroundings}$	223K
T_{film}	238K
Coefficient of volumetric expansion, β	$0.0042 \frac{1}{K}$
Gravity, g	$9.81 \frac{m}{s^2}$
Kinematic viscosity, ν	$0.000011 \frac{m^2}{s}$
Thermal of linear thermal expansion, α	$0.000015 \frac{m^2}{s}$
Prandtl number, Pr	0.724
Thermal conductivity, k	$0.0213 \frac{W}{m-K}$

Note: The values in Table 9 were interpolated from Table A.4 in *Fundamentals in Heat and Mass Transfer* [32], and air was assumed as an ideal gas for calculation simplicity.

$$Ra = \frac{g\beta(T_{surface} - T_{surroundings})L^3}{\nu\alpha}$$

$$Nu = \frac{hL}{k}$$

Table 10. Top clamshell surface convection coefficient calculation.

Parameter	Numerical Value
L	0.0027 m
W	0.054 m
H	0.084 m
Rayleigh's Number*	159.01
Convection coefficient, h_{top}	$7.89 \frac{W}{m^2 K}$
Surface area, A_{top}	$5.22 * 10^{-3} m^2$

*The critical Rayleigh number for a hot surface underneath a cold surface is 1708. Therefore, Nu = 1.

Table 11. Side clamshell surfaces convection coefficient calculation.

Parameter	Numerical Value
L	0.004 m
W	0.084 m
H	0.023 m
Rayleigh's Number*	517.01
Convection coefficient, h_{side}	$5.32 \frac{W}{m^2 K}$
Surface area (both sides), A_{sides}	$3.33 * 10^{-3} m^2$

*The critical Rayleigh number for vertical, parallel hot and cold surfaces is 1000. Therefore, Nu = 1.

Table 12. Back clamshell surface convection coefficient calculation.

Parameter	Numerical Value
L	0.001 m
W	0.054 m
H	0.023 m
Rayleigh's Number*	8.08
Convection coefficient, h_{back}	$21.29 \frac{W}{m^2 K}$
Surface area, A_{back}	$1.24 * 10^{-3} m^2$

*The critical Rayleigh number for vertical, parallel hot and cold surfaces is 1000. Therefore, Nu = 1.

Table 13. Bottom clamshell surface convection coefficient calculation.

Parameter	Numerical Value
L	0.0027 m
W	0.054 m
H	0.084 m
Convection coefficient*, h_{bottom}	$7.89 \frac{W}{m^2 K}$
Surface area, A_{bottom}	$5.22 * 10^{-3} m^2$

*For a hot surface above a cold surface, heat transfer is exclusively by conduction. Therefore, $Nu = 1$.

New Total Energy Required:

$$q_{total} = q_{noconvection} + q_{top} + q_{sides} + q_{back} + q_{bottom}$$

$$q_{total} = q_{noconvection} + h_{top}A_{top}\Delta T + h_{side}A_{sides}\Delta T + h_{back}A_{back}\Delta T + h_{bottom}A_{bottom}\Delta T$$

$$q_{total} = 31.24W + 1.23W + 0.52W + 0.79W + 1.23W$$

$$q_{total} = 35.01W$$

$$Q_{total} = q_{total} * t = 35.01W * 180s$$

$$Q_{total} = 6302J$$

Appendix B: Uncertainty Analysis

The errors present within the DAQ6510 system are sourced from its datasheet using the provided values and equations, and are considered for voltage, current, and temperature readings [42]. For voltage and current, an additional error introduced through the contact between the alligator clips and exposed wire of the Peltier modules is considered. An additional error considered for temperature is the accuracy error of the thermocouple. The thermocouples used did not have a datasheet that explicitly defined an accuracy error, so a standard limit uncertainty of $\pm 2.2^{\circ}\text{C}$ is assumed [43]. All uncertainties gathered from datasheets are assumed as 95% uncertainty intervals and converted to standard deviations to perform the uncertainty analysis. In other words, the given 95% uncertainty intervals are divided by 2, room sum squared, then multiplied by a coverage factor of 2 to convert back to a 95% uncertainty interval.

Voltage resolution, accuracy and linearity errors are calculated from the DC Voltage table using the 10V range row. For a worst-case accuracy error estimate, a 2-year calibration error is considered in addition to using 10V as the “reading” value. “Temperature Coefficient” is not included as the DAQ6510 was operating in a room temperature environment. Because measurements were taken at 2 second intervals, the noise error is 0. Plug-in 7700 module error of $1\mu\text{V}$ is included. Contact error is assumed as 1mV . All voltage uncertainties considered are listed in Table 14.

DC Voltage

DC Voltage Accuracy $\pm(\%$ of reading + $\%$ of range)

Range	Resolution	Input Impedance	24 Hours $T_{\text{CAL}} \pm 1^{\circ}\text{C}$	90 Days $T_{\text{CAL}} \pm 5^{\circ}\text{C}$	1 Year $T_{\text{CAL}} \pm 5^{\circ}\text{C}$	2 Years $T_{\text{CAL}} \pm 5^{\circ}\text{C}$	Temperature Coefficient
100 mV	100 nV	$>10\text{ G}\Omega$ or $10\text{ M}\Omega \pm 1\%$	$0.0015 + 0.0030$	$0.0025 + 0.0035$	$0.0030 + 0.0035$	$0.0035 + 0.0035$	$0.0001 + 0.0005$
1 V	$1\mu\text{V}$	$>10\text{ G}\Omega$ or $10\text{ M}\Omega \pm 1\%$	$0.0015 + 0.0006$	$0.0020 + 0.0006$	$0.0025 + 0.0006$	$0.0030 + 0.0006$	$0.0001 + 0.0001$
10 V	$10\mu\text{V}$	$>10\text{ G}\Omega$ or $10\text{ M}\Omega \pm 1\%$	$0.0010 + 0.0004$	$0.0020 + 0.0005$	$0.0025 + 0.0005$	$0.0030 + 0.0005$	$0.0001 + 0.0001$
100 V	$100\mu\text{V}$	$10\text{ M}\Omega \pm 1\%$	$0.0015 + 0.0006$	$0.0035 + 0.0006$	$0.0040 + 0.0006$	$0.0050 + 0.0006$	$0.0006 + 0.0001$
1000 V ¹	1 mV	$10\text{ M}\Omega \pm 1\%$	$0.0020 + 0.0006$	$0.0035 + 0.0006$	$0.0040 + 0.0006$	$0.0050 + 0.0006$	$0.0006 + 0.0001$

Figure 39. DC Voltage table from DAQ6510 datasheet

Table 14. Voltage uncertainty analysis

Error Type	Source	95% interval	Standard uncertainty
DAQ Resolution	DAQ6510 Datasheet	10 μ V	5 μ V
DAQ Accuracy	DAQ6510 Datasheet	3.5mV	1.75mV
DAQ Linearity	DAQ6510 Datasheet	10 μ V	5 μ V
DAQ Noise	DAQ6510 Datasheet	0V	0V
DAQ Plug-In Module	DAQ6510 Datasheet	1 μ V	0.5 μ V
Alligator Clip contact error	Conservative estimate	1mV	0.5mV
95% uncertainty interval for voltage, U_V			$\pm 0.0036V$

Current resolution and accuracy errors are calculated from the DC Current table using the 3A range row. For a worst-case accuracy error estimate, a 2-year calibration error is considered in addition to using 3A as the “reading” value. “Temperature Coefficient” is not included as the DAQ6510 was operating in a room temperature environment. Because measurements were taken at 2 second intervals, the noise error is 0. Contact error is assumed as 0.005A. All current uncertainties considered are listed in Table 15.

DC Current

DC Current Accuracy $\pm$ (% of reading + % of range)

Range	Resolution	Burden Voltage	24 Hours $T_{CAL} \pm 1^\circ C$	90 Days $T_{CAL} \pm 5^\circ C$	1 Year $T_{CAL} \pm 5^\circ C$	2 Years $T_{CAL} \pm 5^\circ C$	Temperature Coefficient
10 μA ¹¹	10 pA	< 0.13 V	0.007 + 0.002	0.035 + 0.005	0.045 + 0.005	0.055 + 0.005	0.0030 + 0.0006
100 μA	100 pA	< 0.14 V	0.010 + 0.020	0.035 + 0.005	0.045 + 0.005	0.055 + 0.005	0.0020 + 0.0005
1 mA	1 nA	< 0.17 V	0.007 + 0.006	0.035 + 0.005	0.045 + 0.005	0.055 + 0.005	0.0020 + 0.0005
10 mA	10 nA	< 0.17 V	0.006 + 0.003	0.018 + 0.005	0.020 + 0.005	0.025 + 0.005	0.0015 + 0.0005
20 mA ¹²	10 nA	< 0.05 V	0.010 + 0.150	0.015 + 0.025	0.020 + 0.025	0.025 + 0.025	0.0015 + 0.0025
100 mA	100 nA	< 0.20 V	0.010 + 0.030	0.015 + 0.005	0.020 + 0.005	0.025 + 0.005	0.0015 + 0.0005
1 A	1 mA	< 0.55 V ¹³	0.020 + 0.004	0.030 + 0.005	0.040 + 0.005	0.050 + 0.005	0.0030 + 0.0005
3 A	1 mA	< 1.70 V ¹³	0.030 + 0.004	0.040 + 0.004	0.050 + 0.004	0.060 + 0.004	0.0030 + 0.0005

Figure 40. DC Current table from DAQ6510 datasheet

Table 15. Current uncertainty analysis

Error Type	Source	95% interval	Standard uncertainty
DAQ Resolution	DAQ6510 Datasheet	0.001A	0.0005A
DAQ Accuracy	DAQ6510 Datasheet	0.00192A	0.00096A
DAQ Noise	DAQ6510 Datasheet	0A	0A
Alligator Clip contact error	Conservative estimate	0.005A	0.0025A
95% uncertainty interval for current, U_I			$\pm 0.0054A$

Temperature resolution and accuracy errors are calculated from the “Thermocouple Accuracy” table using the K-type row. For a conservative estimate, the “Internal CJC” column for a 7700 plug-in

module is used. “Temperature Coefficient” is not included as the DAQ6510 was operating in a room temperature environment. All current uncertainties considered are listed in Table 16.

Temperature

Thermocouple Accuracy $\pm^\circ\text{C}$ ¹⁷

Type	Resolution	Range	2 Year Accuracy T _{CAL} ±5°C; all uncertainties in °C						Temperature Coefficient in°C/°C
			Simulated or External CJC			Internal CJC (on module)			
			Front Terminals, 7700, 7702, 7708	7706, 7709, 7710	7701, 7703, 7707	7700, 7708	7706	7710	
J	0.001°C	0 °C to 760 °C	0.20	0.20	0.20	1.00	1.00	1.30	0.03
		-200 °C to < 0 °C	0.20	0.20	0.40	1.50	1.90	3.00	0.03
K	0.001°C	0 °C to 1372 °C	0.20	0.20	0.30	1.00	1.00	1.00	0.03
		-200 °C to < 0 °C	0.30	0.30	0.50	1.70	2.00	2.00	0.03
N	0.001°C	0 °C to 1300 °C	0.20	0.20	0.30	1.00	1.00	1.40	0.03
		-200 °C to < 0 °C	0.50	0.60	0.80	1.80	2.30	3.60	0.03
T	0.001°C	0 °C to 400 °C	0.20	0.20	0.20	1.00	1.00	1.50	0.03
		-200 °C to < 0 °C	0.30	0.30	0.50	1.60	2.00	3.50	0.03
E	0.001°C	0 °C to 1000 °C	0.20	0.20	0.20	1.00	1.00	1.20	0.03
		-200 °C to < 0 °C	0.20	0.30	0.30	1.50	1.80	3.00	0.03
R	0.010 °C	600 °C to 1768 °C	0.40	0.50	0.70	1.00	1.00	1.20	0.03
		0 °C to < 600 °C	0.80	1.00	1.50	1.50	1.60	2.20	0.03
S	0.010 °C	600 °C to 1768 °C	0.40	0.50	0.70	1.00	1.00	1.20	0.03
		0 °C to < 600 °C	0.80	1.00	1.50	1.30	1.60	2.20	0.03
B	0.010 °C	1100 °C to 1820 °C	0.40	0.50	0.80	1.00	1.00	1.00	0.03
		350 °C to < 1100 °C	1.20	1.50	2.20	1.10	1.40	1.50	0.03

Figure 41. Temperature table from DAQ6510 datasheet

Table 16. Temperature uncertainty analysis

Error Type	Source	95% interval	Standard uncertainty
DAQ Resolution	DAQ6510 Datasheet	0.001 $^\circ\text{C}$	0.0005 $^\circ\text{C}$
DAQ Accuracy	DAQ6510 Datasheet	1 $^\circ\text{C}$	0.5 $^\circ\text{C}$
Thermocouple accuracy	Conservative estimate	2.2 $^\circ\text{C}$	1.1 $^\circ\text{C}$
95% uncertainty interval for temperature, U_T			$\pm 2.42^\circ\text{C}$

Power calculations for the Peltier modules are based on extracted data from the Peltier module datasheet graph shown in Figure 13. The formula used to calculate power uncertainty is

$$u_P = \sqrt{\left(\frac{dP}{dI} u_I\right)^2 + u_{dig}^2}$$

where $\frac{dP}{dI}$ is the derivative of the power curve with respect to I (current), u_I is the standard uncertainty of the current, and u_{dig} is the uncertainty from extracting datasheet Q_h values via PlotDigitizer. For a

conservative estimate, $\frac{dP}{dI}$ is calculated based on a simplification that Q_h vs Operating Current is linear (28 W/A). Standard digitization uncertainty, u_{dig} , is estimated based on pixel coverage of the Q_h vs Operating Current graph. Assuming a data point can be accurately selected ± 1 pixel with 95% confidence, and one pixel accounting for 0.86W, the standard uncertainty, u_{dig} , is 0.43W. All power uncertainties considered are listed in Table 17.

Table 17. Peltier module power output uncertainty analysis

Term	Source	95% interval	Standard uncertainty
Current uncertainty	Table 15	0.0054A	0.0027A
PlotDigitizer uncertainty	Conservative estimate	0.86W	0.43W
95% uncertainty interval for power, U_P			$\pm 0.87W$

Note that the uncertainty of PlotDigitizer dominates the $\frac{dP}{dI} u_I$ term, meaning that the linear oversimplification of the power output plot does not play a significant role in the uncertainty. An additional step is necessary to find the uncertainty of the combined, average power output. A Taylor Series uncertainty analysis on $P_{average} = \frac{P_1 + P_2}{2}$ yields

$$U_{P,average} = \frac{U_P}{\sqrt{2}} = \pm 0.62W$$

For energy calculation of each Peltier module, the uncertainty is calculated by root sum squaring the uncertainty of each measurement multiplied by the time step.

$$u_Q = \sqrt{(u_{P,1}\Delta t)^2 + (u_{P,2}\Delta t)^2 + \dots + (u_{P,n}\Delta t)^2}$$

Assuming the uncertainty of power is identical at every 2 second step, the equation simplifies to

$$u_Q = \sqrt{n(u_P\Delta t)^2}$$

where n is the number of measurements. In this work, over a period of 180 seconds, 91 measurements are taken. Power uncertainty and the uncertainty energy interval are listed in Table 18.

Table 18. Peltier module energy output uncertainty analysis

Term	Source	95% interval	Standard uncertainty
Power uncertainty	Table 17	0.87W	0.435W
95% uncertainty interval for energy, U_Q			$\pm 16.6J$

Total energy is calculated by summing the energies of each Peltier module. The uncertainty from applying Taylor Series uncertainty analysis to $E_{total} = E_1 + E_2$ results in a standard energy uncertainty equation of

$$u_{Q,total} = \sqrt{u_{Q,1}^2 + u_{Q,2}^2}$$

Both Peltier modules have the same energy uncertainty, resulting in a 95% uncertainty interval for energy ($U_{Q,total}$) of $\pm 23.5J$.

An uncertainty analysis must be performed for the theoretical calculation of the total energy required, as $Q = mc\Delta T$ was used and convection heat loss assumptions were implemented. Mass is treated as exact since the value was determined via modeling software. However, the specific heat capacity for aluminum, c , was estimated graphically. For convection heat loss, surface area is treated as exact since the value was determined via modeling software, but convection coefficients are estimated from interpolated values and Nusselt number correlations. ΔT is set at an exact theoretical $30^\circ C$ for convection heat loss and $Q = mc\Delta T$ calculations. Taylor Series uncertainty analysis is applied to the following equation:

$$Q = mc\Delta T + h_{top}A_{top}\Delta T + h_{sides}A_{sides}\Delta T + h_{back}A_{back}\Delta T + h_{bot}A_{bot}\Delta T$$

This results in:

$$u_{Q,theoretical}$$

$$= \sqrt{(m\Delta T u_c)^2 + [(u_{h,top}A_{top})^2 + (u_{h,sides}A_{sides})^2 + (u_{h,back}A_{back})^2 + (u_{h,bottom}A_{bottom})^2]\Delta T^2}$$

Table 19 shows all numerical values for calculating theoretical energy uncertainty, in addition to the calculated value of theoretical energy uncertainty. A 5% reading error on $897 \frac{J}{kg-K}$ is assumed for U_c , and a 25% interpolation uncertainty is assumed for all calculated convection values.

Table 19. Theoretical input energy uncertainty analysis

Term	Source	Value
m	Modeling software	0.209kg
ΔT	Experimental setup	30°C
U_c	Conservative estimate	$44.85 \frac{J}{kg-K}$
$U_{h,top}$	$0.25 * h_{top}$	$1.97 \frac{W}{m^2 K}$
$U_{h,sides}$	$0.25 * h_{sides}$	$1.33 \frac{W}{m^2 K}$
$U_{h,back}$	$0.25 * h_{back}$	$5.40 \frac{W}{m^2 K}$
$U_{h,bottom}$	$0.25 * h_{bottom}$	$1.97 \frac{W}{m^2 K}$
A_{top}	Table 10	$5.22 * 10^{-3} m^2$
A_{sides}	Table 11	$3.33 * 10^{-3} m^2$
A_{back}	Table 12	$1.24 * 10^{-3} m^2$
A_{bottom}	Table 13	$5.22 * 10^{-3} m^2$
95% uncertainty interval for theoretical energy, $U_{Q,theoretical}$		$\pm 281 J$

Note that despite assuming a 25% error on convection coefficients, the 5% reading error is the main contributor.

Lastly, the uncertainty of the theoretical power input required from the Peltier modules is performed. Taylor Series uncertainty analysis applied to $P = \frac{Q}{t}$ results in:

$$U_{P,theoretical} = \frac{U_{Q,theoretical}}{t} = \frac{\pm 281 J}{180 s} = \pm 1.56 W$$