

Experimental Evaluation of Innovative Thermal Energy Storage Options for a Hypersonic Non-Airbreathing Vehicle's Internal Loads

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Abstract

Managing the thermal loads inside a non-airbreathing hypersonic vehicle is particularly difficult. The heat generated by the power electronics, avionics, etc. must be removed so that the components do not exceed their maximum temperatures. These vehicles cannot dump the waste heat into fuel or ram air because they carry no fuel and do not have provisions for ram air. This means that the thermal energy resulting from the heat generated must be dumped into an onboard heat sink. Existing solutions to this problem have been passive systems based on solid-liquid phase change materials (PCMs), which store thermal energy as they melt. Since space is at a premium, a heat sink must store a lot of energy per unit volume, while keeping components below their maximum temperature. In this project, three heat sink concepts are tested, i.e., one based on PCMs, a second on thermal to chemical (TTC) energy storage, and a third on a hybrid combination of the first two. For the first, three different PCMs are tested and for the second a single endothermic chemical reaction. The hybrid PCM/TTC concept consists of a single PCM which plays the dual role of PCM and reactant in the endothermic chemical reaction of the TTC energy storage. To enhance heat sink performance, the use of thermoelectric generators (TEGs) and a local coolant loop are investigated. The advantage of the former is that they transform waste heat into usable electricity, reducing the amount of thermal energy that needs to be stored by the heat sink. The advantage of the latter is that it results in a more uniform cooling of the heat source and more uniform heating of the heat sink. Prototypes of each of the heat sink concepts and the coolant loop are designed, built, and tested. Experimental results indicate that all the solutions tested in this project outperform widely used paraffin heat sink technologies on an energy per unit volume basis. Our experiments also show that a local coolant loop is indeed advantageous and that current off-the-shelf thermoelectric generators do not generate enough power to offset the power requirements of the coolant loop. Significant improvements in the ZT factor of the thermoelectric materials used by the TEG would be required.

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General Audience Abstract

All electronics produce waste heat and have a maximum operating temperature above which they fail due to overheating. Heat sinks absorb the waste heat and prevent overheating. Non-airbreathing hypersonic vehicles do not have natural heat sinks like intake air or liquid fuel which are commonly used as heat sinks in airbreathing vehicles. Heat cannot be transferred to the environment due to the high temperatures caused by the friction of hypersonic air travel. This means that all waste heat must be absorbed by an onboard heat sink. Existing heat sinks in non-airbreathing hypersonic vehicles use paraffin based solid-liquid phase change materials (PCMs) which store thermal energy as they melt. Three novel heat sink options are evaluated in this project, hydrated salt PCMs which absorb energy as they melt, a chemical reaction which absorbs heat as it reacts, and a hybrid system which incorporates one of the hydrated salt PCMs as a reactant in the chemical reaction. Because space is at a premium, these options are evaluated by the amount of energy they can absorb (kilojoules) per unit volume (in^3) while keeping the electronics below their maximum temperature. To enhance heat sink performance, the use of thermoelectric generators (TEGs) and a local coolant loop are investigated. The advantage of the former is that they transform waste heat into usable electricity, reducing the amount of thermal energy that needs to be stored by the heat sink. The advantage of the latter is that it results in a more uniform cooling of the electronics and more uniform heating of the heat sink. Prototypes of each of the heat sink concepts and the coolant loop are designed, built, and tested. Experimental results indicate that all the solutions tested in this project outperform widely used paraffin heat sink technologies on an energy per unit volume basis. Our experiments also show that a local coolant loop is indeed advantageous and that current off-the-shelf thermoelectric generators do not generate enough power to offset the power requirements of the coolant loop. Significant improvements in the state of the art of thermoelectric materials would be required for TEGs to generate enough electricity from our waste heat load to power the local coolant loop.

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Chapter 1 Introduction

The research presented in this thesis was funded by a corporate sponsor who wished to find more efficient ways to keep the power electronics, avionics, etc. cool onboard a hypersonic, non-airbreathing vehicle. New methods of thermal management are needed to satisfy the demanding mission requirements of such a vehicle. This thesis research was done in collaboration with another M.S. student, Logan Edwards, who performed most of the modeling and some of the experimental work [1].

1.1 Background

All power electronics and avionics produce waste heat and have a maximum operating temperature above which they begin to fail due to overheating. Thus, all such systems need a thermal management system (TMS) to remove waste heat so as not to exceed their maximum operating temperature. Everyday systems like computers or microwaves dump waste heat into the environment through radiators and fans because the environment is much cooler than the electronics. Unfortunately, electronic and avionics systems onboard non-airbreathing hypersonic vehicles cannot dump waste heat into fuel since there is none and often times using ram air as a heat sink is not an option. This necessitates an onboard heat sink which can absorb and store thermal energy.

Typically, hypersonic aircraft have used fuel or ram air as heat sinks as part of a passive, active, or semi-passive [2] thermal management system (TMS). Active and semi-passive systems generally involve coolant loops, which pump a working fluid. Passive systems involve local heat sinks placed in direct contact with a heat source to absorb heat directly [2]. Historically, hypersonic aircraft have generally use active systems over passive systems.

The NASA/Air Force X-15 [3] is an experimental hypersonic rocket-powered plane from the 50's and 60's that was launched from a carrier airplane midflight . While attached to the airplane, the X-15 would use ram air to cool its electronics. During powered flight, the X-15 employed an active TMS which used nitrogen gas supplied from a cryogenic tank as a heat sink. After absorbing waste heat, the nitrogen gas doubled as the pressurized atmosphere inside the plane. Figure 1.1 [3] shows the schematics for the TMSs used in the plane. This TMS worked for the X-15 but required a large amount of space and weight due to the engineering constraints of storing liquid nitrogen.

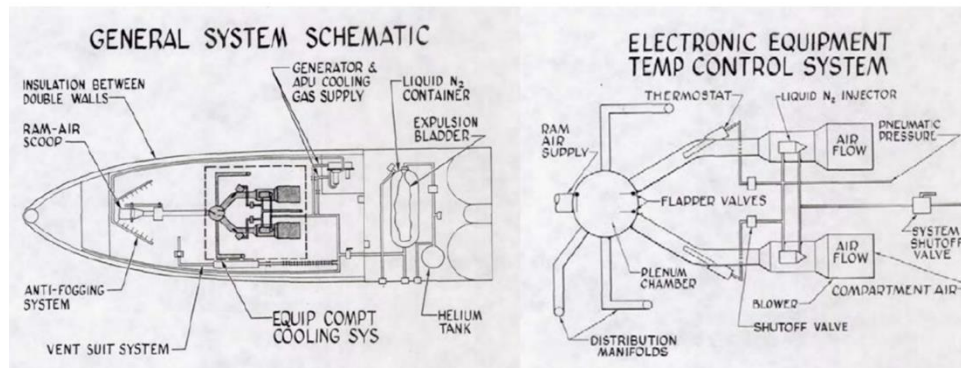


Figure 1.1: General system schematic of the X-15 TMS and the electronics TMS [3].

Edwards [1] also reviewed more recent TMSs for other hypersonic aircraft like the pressurized water-ethylene-glycol system aboard NASA's airbreathing, hydrogen-fueled, hypersonic X-43A and the sublimation system aboard Sierra Nevada Corporation's airbreathing, hypersonic Dream Chaser. A look at all these past TMSs provided much needed context about the cooling of hypersonic aircraft at the outset of our project.

1.2 Problem Specification

An active TMS requires electrical power to pump a working fluid, takes up a large amount of space, and tends to weigh a lot. Since electricity, space, and weight are at a premium in non-airbreathing hypersonic vehicles, our corporate sponsor chose to have us focus on passive TMSs, on local TMS storage schemes in particular.

Since, both weight and volume and in particular volume are important constraints on the use of passive TMSs, the primary measure of performance considered here was how much thermal energy a TMS could absorb per unit volume (i.e., its volumetric energy density), while also keeping the electronics or avionics below some maximum operating temperature. Figure 1.2 shows a basic schematic of a passive local TMS, which is composed of a heat sink material housed inside a box that sits on top of the heat source. The temperature range considered in this research was 40 °C - 85 °C, which is a typical temperature range of operation for power electronics and avionics. In addition, the absorbed heat load requirement was set at 40 W, which is typical of on-board aircraft power electronics and avionics.

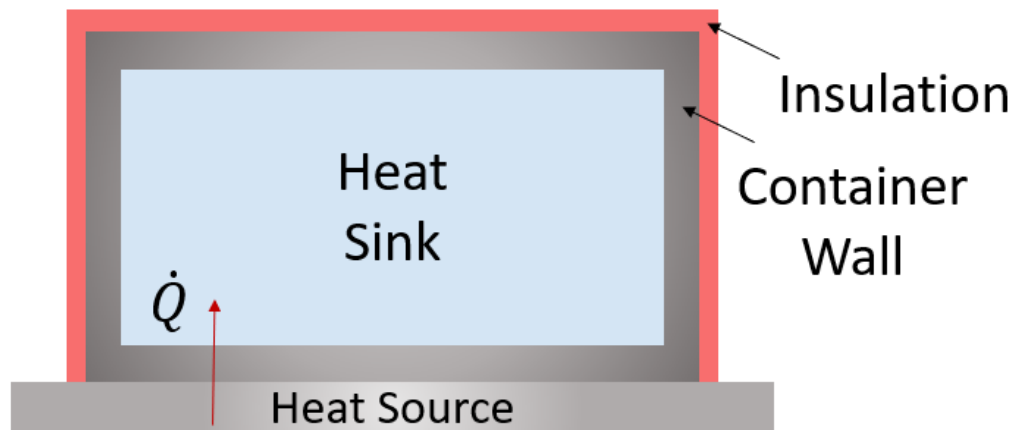


Figure 1.2: Passive TMS heat sink schematic.

The literature review conducted by Edwards [1] look at various heat sink materials to determine which were the most promising based on their calculated volumetric energy density. Two types of heat sink materials were found to be the most promising, namely, solid-liquid phase change materials (PCMs) and endothermic chemical reactions. PCMs store thermal energy both sensibly and via a constant temperature phase change. The latter is useful for keeping any type of electronics below its maximum temperature. Endothermic reactions absorb thermal energy as chemical energy in the products of the reaction.

Based on the analysis by Edwards [1], three PCMs and one chemical reaction were selected for experimentation based on their volumetric energy density values. Upon receiving the PCMs from the manufacturer, it was discovered that one of the PCMs, barium hydroxide octahydrate, was also one of the two reactants in the endothermic reaction that has been selected. This led to the idea of a hybrid system that combines the energy storage of this particular PCM and the endothermic reaction.

Also investigated in this project is the viability of integrating a local low-power coolant loop and/or thermoelectric generator (TEG) with the heat sink TMS. The coolant loop is an active TMS that transfers heat from the bottom of the heat source to the top of the heat sink using very little electricity. The TEG is a solid-state system, which sits in between the heat source and heat sink and transforms a small amount of the heat into usable electricity, which increases the effective energy density of the heat sink and could potentially be used to power the pumps in the coolant loop.

1.3 Thesis Objectives

The goal of this research is to experimentally determine the actual volumetric energy densities of the chosen heat sink materials within the temperature range of interest as well as evaluate the usefulness of an active local coolant loop and a passive TEG. The performance of power electronics and avionics onboard any aircraft are limited by the performance of the TMS, and so improving the performance of the TMS can unlock more performance from the power electronics and, thus, the vehicle as a whole.

To accomplish the stated goal, the first step is to review the literature survey of heat sink materials conducted by Edwards [1]. This includes understanding the theoretical performance of the different materials researched and the ones selected, i.e., 3 PCMs and 1 endothermic chemical reaction [1].

A next step is to conduct a literature review of TEGs to understand how they work and how they can be used beneficially as part of a local TMS storage scheme. Cutting edge thermoelectric materials must be reviewed to understand what the state of the art of the technology currently is and where it is headed. Plotting future efficiency improvements goes hand in hand with determining how TEGs can be incorporated into an existing TMS design so as to be able to benchmark how viable they are now or how much more progress in material design is necessary to make them viable. Various TEG manufacturers must also be contacted to inquire about constructing custom TEGs for our application and/or which off the shelf devices best suit the needs of our TMS design.

A review of existing coolant loop technologies in hypersonic vehicles must also be performed to understand under what conditions they are used and why. The coolant loop must then be designed to transfer the most heat possible with the smallest power possible. This design will be based on prior simulations [4] to determine the smallest pressure drop and, thus, the least power required to circulate the coolant.

The next step is to design a set of prototypes and a test stand to evaluate the selected heat sink materials in the prototypes. The prototypes must be designed to specifications provided by the corporate sponsor to mimic a real-world TMS. A test stand where each prototype can be tested under at least some of the conditions onboard a non-airbreathing hypersonic vehicle must be designed so that the heat fluxes and temperatures throughout the prototype can be measured.

Next, materials and equipment must be ordered and each prototype manufactured and assembled and the test stand constructed. This stage may reveal flaws in the designs and force some redesigns. Once this stage is complete, testing can begin.

The testing step must begin with a design of the test procedures for each prototype. Once these are known, testing on each prototype can be conducted to gather heat flux and temperature data. This data must then be processed to determine the total amount of energy absorbed by each heat sink material. From this data, the volumetric energy density of each material can be computed and used to validate the model predicted found in Edwards [1].

Finally, conclusions will be drawn on which materials perform the best, what are the practical lessons learned on material handling and use, and whether or not the coolant loops and TEGs are viable additions to each TMS. Recommendations will also be made for design improvements, better test procedures, etc.

Chapter 2 Literature Review

Edwards [1] literature review of current heat sink solutions is the starting point for determining the best heat sink solution for our problem specifications. Although TMSs for the power electronics and avionics of non-airbreathing hypersonic vehicles is the focus of this project, thermal solutions for other kinds of electronics are relevant and are considered here. PCMs are a common heat sink type for aircraft and electronics, but not much research has gone into using endothermic reactions for aircraft applications. Coolant loops are also extremely common in aircraft and electronics such as computers, while TEGs have been considered in aircraft for their ability to harvest energy for powering small, low-power sensors in hard-to-reach areas.

2.1 Current Heat Sink Technologies

2.1.1 PCMs

PCMs are used as heat sinks because they can store thermal energy as both latent and sensible energy. Latent energy is the energy that goes into melting a PCM, while sensible energy is the energy that goes towards raising a material's temperature. It should be noted that during phase change, a material's temperature does not change, which is very beneficial for keeping electronics and avionics below specific temperatures.

A review of current PCM implementations in aircraft is found in Reed, von Spakovsky, and Raj [5], Gvozdoch [6], and Burnes, *et al.* [7]. Organic paraffins are a common PCM in applications where temperature range between 0 °C and 100 °C, but an issue that it has is that its thermal conductivity is too low, which results in hotspots and lower heat transfer into the PCM. This is a problem common to most PCMs. To overcome this, highly conductive materials are inserted into PCMs to increase their effective thermal conductivity. Examples of inserted materials are carbon foam [6] and metal or metal oxide nanostructures [8]. As will be seen in the next chapter on prototype design, a simpler solution is used here to increase the effective thermal conductivity.

To down select from every option available, Edwards [1] conducted a thorough search of commercial PCMs. These products are used in a wide variety of industrial applications from cold storage to electronics. Three commercial PCMs were selected based on their high volumetric energy densities within the temperature range of interest in this thesis research. Table 2.1 [1] shows the thermodynamic properties [9] of the three selected PCMs. All three are hydrated salts, HS58 - sodium acetate trihydrate, HS72 - magnesium nitrate hexahydrate, and HS78 - barium hydroxide octahydrate, with melting temperatures of 58 °C, 72 °C, and 78 °C, respectively. It should be noted that each PCM absorbs different proportions of energy in each of the three stages of heating, temperature rise of the solid, phase change, and temperature rise of the liquid. Table 2.2 shows a breakdown of the percentages of each stage for each PCM. Comparing the proportions of energy absorbed by each stage between the three PCMs we can see that HS58 absorbs the most during the temperature rise of liquid, HS72 absorbs the most during the temperature rise of solid, and HS78 absorbs the most during phase change. How much energy goes to which stage of heating greatly affects how each PCM acts during testing. The most “front-loaded” PCM, HS72, can absorb a tremendous amount of energy without even finishing the phase change because so much of the energy absorbed by HS72 goes to the first stage of heating. The implications of a PCM being “front-loaded” or “back-loaded” are explained further in the results section of this thesis.

Table 2.1: Thermodynamic properties [1], [9] and calculated volumetric energy density of the three down selected hydrated salts (HSs).

Material	Initial Temp. (°C)	Phase Change Temp. (°C)	Max. Temp. (°C)	Latent Heat Capacity (kJ/kg)	Density - Solid (kg/m ³)	Density - Liquid (kg/m ³)	Specific Heat Capacity - Solid (kJ/kg °C)	Specific Heat Capacity - Liquid (kJ/kg °C)	Vol. Heat Capacity - Due to Temp. Rise of Solid (kJ/in ³)	Vol. Heat Capacity - Due to Phase Change (kJ/in ³)	Vol. Heat Capacity - Due to Temp. Rise of Liquid (kJ/in ³)	Total (kJ/in ³)
HS58	40	58	85	267	1400	1320	2.40	3.15	0.99	5.95	1.84	8.78
HS72	40	72	85	162	1504	1494	2.30	2.9	1.81	3.98	0.92	6.72
HS78	40	78	85	240	1890	1900	1.46	1.59	1.72	7.45	0.35	9.52

Table 2.2: Percentage breakdown of energy density of each stage of heating [1].

Material	Vol. Heat Capacity - Due to Temp. Rise of Solid (kJ/in ³) / (% of Total)	Vol. Heat Capacity - Due to Phase Change (kJ/in ³) / (% of Total)	Vol. Heat Capacity - Due to Temp. Rise of Liquid (kJ/in ³) / (% of Total)	Total (kJ/in ³)
HS58	0.99 (11.3%)	5.95 (67.7%)	1.84 (21.0%)	8.78
HS72	1.81 (26.9%)	3.98 (59.2%)	0.92 (13.7%)	6.72
HS78	1.72 (18.1%)	7.45 (78.3%)	0.35 (3.6%)	9.52

2.1.2 Thermal-to-Chemical (TTC) Energy Storage

Thermal-to-chemical (TTC) energy storage uses an endothermic chemical reaction as the heat sink. Endothermic reactions absorb thermal energy and store it both as chemical potential in the products of the reaction and in their sensible temperature rise. If an endothermic reaction does not receive enough heat, it slows down or eventually ceases. In the application considered here, heat from the power electronics or avionics provides the thermal energy necessary to complete the reaction. Complete here does not mean that all the reactants became products but instead that the reactants and products exist in thermodynamic equilibrium with each other.

The review of modern heat sink materials revealed little consideration had been made for endothermic reactions in cooling aircraft. A 2014 review of thermochemical energy storage [10] shows that endothermic reactions may have significant advantages compared to PCMs. Higher energy densities per mass and volume as well as lower charging temperatures and less heat loss are possible advantages. Some drawbacks are that chemical reactions are more complicated to use as heat sinks than PCMs. Figure 2.1 [10] shows a breakdown of the volumetric energy densities of common sensible thermal storage materials as well as paraffin wax, which is a PCM and three endothermic chemical reactions. As can be seen, the chemical reactions have much higher volumetric energy densities than the paraffin wax. There are many types of paraffin waxes, which are common to many heat sink applications, including those in hypersonic vehicles. Of course, the volumetric energy density is different for each type and, in fact, the value shown in Figure 2.1 for the paraffin wax is on the high side. Furthermore, as can be deduced from Table 2.1 above, there are higher performing PCMs such as the hydrated salts listed, i.e., the volumetric energy density of the paraffin wax in Figure 2.1 is about 4.71 kJ/in³. In addition, there are higher performing

endothermic reactions as will be seen below. In addition to these reversible endothermic reactions being used as heat sinks, they can also be used in heat pumps in place of vapor compression cycles [10].

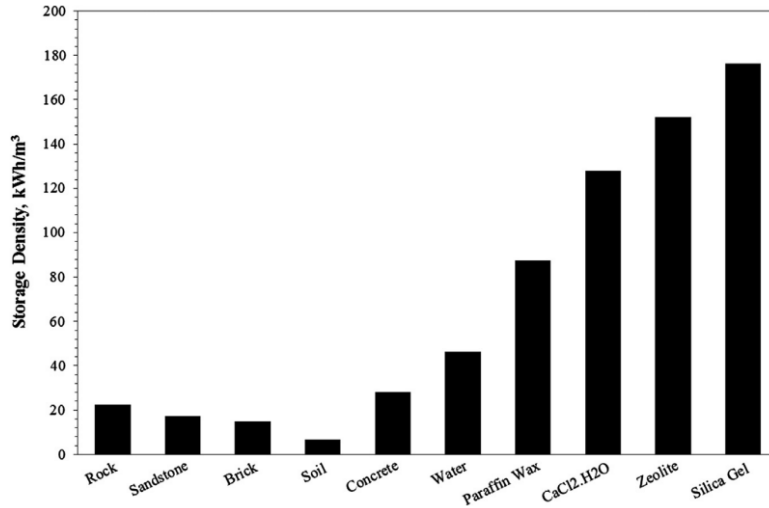


Figure 2.1: Comparison of heat storage densities of different materials [10].

Research has also gone into endothermic reactions for cooling other heat sources. For example, a 1998 study [11] into supersonic civilian aircraft showed that fuel itself has endothermic heat sink potential. Dumping waste heat into the fuel can cause it to crack, which is an endothermic process, and, thus, absorb more energy than just sensibly heating the fuel. Cracked fuel can also have better mixing characteristics, combustion stability, and reduced smoke and NO_x emissions. A 2017 patent [12] describes an endothermic chemical reaction phone case that can be used to cool phones below the ambient, which is very similar to the TTC cooling process considered in the present research. The phone case employs cartridges with partitioned chemicals that can be slotted into the case and the partition removed as needed.

Edwards [1] analyzed eight endothermic reactions that react within a temperature range of 40 °C – 85 °C, the results of which are given in Table 2.3 [1]. The volumetric energy density is calculated in a three-step process. First, the enthalpy of reaction, ΔH_r° , was calculated (or in the case of reactions 5 through 8, found in the literature [18]) using:

$$\Delta H_r^\circ = \sum_i^{pro} \Delta H_{f_i}^\circ \nu_i - \sum_i^{rea} \Delta H_{f_i}^\circ \nu_i \quad (1)$$

where ν_i is the stoichiometric coefficient of the i^{th} constituent and $\Delta H_{f_i}^\circ$ is the enthalpy of formation of the i^{th} constituent. This calculates the energy absorbed by 1 mole of reaction. The next step is to calculate the volume occupied by the reactants of 1 mole of reaction using:

$$V_{rea} = \sum_i^{rea} \frac{M_i \nu_i}{\rho_i} \quad (2)$$

where M_i and ρ_i are the molar mass and density of the i^{th} reactant, respectively. The final step is to simply divide the enthalpy of reaction by the volume occupied by the reactants to arrive at the volumetric energy density of a reaction. This can be written succinctly in one equation as:

$$e_{vol}^{TTC} = \frac{\sum_i^{pro} \Delta H_{f_i}^\circ \nu_i - \sum_i^{rea} \Delta H_{f_i}^\circ \nu_i}{\sum_i^{rea} \frac{M_i \nu_i}{\rho_i}} \quad (3)$$

Edwards [1] did not consider a temperature range for these reactions because the vast majority of the energy absorbed by a TTC system goes into driving the endothermic reaction, not to the sensible heating of the constituents.

It is important to note that all of the products and reactants in these reactions are corrosive to aluminum, except water. This necessitates the use of stainless steel or some kind of coated aluminum to house the materials. Density values for the reactants of reactions 5 to 8 were not found in the literature and, thus, had to be approximated by combining the individual densities of the species making up a given compound, e.g., in reaction 5 the density of $PbCl_2$ and that of NH_3 were combined on a molar basis. These values were then corrected using a correlation developed in [1], which uses the known density values of the reactants in reactions 1 to 4 and those constructed from combining the individual densities of the species making up a given compound. The corrected values for the volume and volumetric energy density for reactions 5 to 8 appear in parentheses. Of the eight reactions considered, 1 and 2 were selected for further study because they had the highest energy densities except for reaction 5. The latter was not chosen because most of the solid ammonia ends up as a gas in the products since in contrast to reactions 1 and 2, there is no water to absorb the ammonia. This makes reaction 5 impractical for the heat sink application considered here because of the higher container volume that would be required. Another important detail is that reactions 4-8 are gas-sorption cycles that absorb thermal energy by dissociating ammonia out of the original reactant. These reactions occur at specified “charging temperatures.”

Table 2.3: Summary of volumetric energy densities for the eight endothermic reactions [1].

#	Ref.	Reaction	ΔH_r° (kJ)	V_{rea} (in ³)	e_{vol}^{TTC} (kJ/in ³)	Charging Temp. (°C)
1	[13], [14]	$2NH_4Cl (s) + Ba(OH)_2 (s) \rightarrow 2NH_3 (aq) + BaCl_2 (aq) + 2H_2O (l)$	66.10	7.061	9.37	-
2	[14], [15]	$[Ba(OH)_2 \cdot 8H_2O] (s) + 2NH_4Cl (s) \rightarrow [BaCl_2 \cdot 2H_2O] (aq) + 2NH_3 (aq) + 8H_2O (l)$	98.66	13.097	7.53	-
3	[14], [16]	$NH_4NO_3 (s) + H_2O (l) \rightarrow NH_4^+ (aq) + NO_3^- (aq) + H_2O (l)$	25.70	3.94	6.52	-
4	[17]	$NH_4Cl \cdot 3 NH_3 (s) \rightarrow NH_4Cl (s) + 3 NH_3 (g)$	29.43	6.81	4.32	48
5	[17]	$PbCl_2 \cdot 8 NH_3 (s) \rightarrow PbCl_2 \cdot 3.25 NH_3 (s) + 4.75 NH_3 (g)$	34.32	6.09 (4.05)*	5.64 (8.48)†	47
6	[17]	$NaBr \cdot 5.25 NH_3 (s) \rightarrow NaBr (s) + 5.25 NH_3 (g)$	35.36	5.778 (5.53)*	6.12 (6.39)†	51
7	[17]	$BaCl_2 \cdot 8 NH_3 (s) \rightarrow BaCl_2 (s) + 8 NH_3 (g)$	38.25	8.08 (6.92)*	4.73 (5.53)†	56
8	[17]	$LiCl \cdot 4 NH_3 (s) \rightarrow LiCl (s) + NH_3 (g)$	36.83	5.57 (6.44)*	6.61 (5.72)†	67

* The values in parenthesis for V_{rea} is based on the corrected density values.

† e_{vol}^{TTC} values in parenthesis account for corrected density values.

Upon receiving the barium hydroxide octahydrate and the ammonium chloride, it was discovered that their powdered forms have much lower densities than the values found in the literature. Thus, Edwards corrected the theoretical energy density value of the TTC system [1] using manually measured density values. Table 2.4 shows a breakdown of how this correction was made. This new, corrected value for the volumetric energy density is what the experimental value will be compared to in the results section. Note that this new value is less than half the initial theoretical value.

Table 2.4: Calculation for correcting the theoretical energy density value of the TTC system.

Reaction 2 [Ba(OH) ₂ *8H ₂ O] (s) + 2NH ₄ Cl (s) → [BaCl ₂ *2H ₂ O] (aq) + 2NH ₃ (aq) + 8H ₂ O (l)						
Constituent	Initial Density	Initial Volume (V _{rea})	Initial Volumetric Energy Density (e _{vol} ^{TTC})	Corrected Density	Corrected Volume (V _{rea})	Corrected Volumetric Energy Density (e _{vol} ^{TTC})
Ba(OH) ₂ *8H ₂ O	2.18 g/cm ³	13.057 in ³	7.53 kJ/in ³	0.948 g/cm ³	27.812 in ³	3.55 kJ/in ³
NH ₄ Cl	1.53 g/cm ³			0.871 g/cm ³		

2.1.3 PCM/TTC Hybrid Energy Storage

Upon receiving shipments of HS78, it was discovered that the PCM is composed of barium hydroxide octahydrate (i.e., Ba(OH)₂*8H₂O), which is one of the reactants in reaction 2. Thus, the idea to combine a PCM and TTC into a hybrid system was considered as a possible third heat sink energy storage option. This idea does not exist in literature so that the only previous work done on this concept was that of Edward's estimation of the volumetric energy density of this particular hybrid system [1]. Table 2.5 [1] shows the pertinent information for calculating the energy density. As can be seen, the volumetric energy density is significantly higher than any of the PCMs or the TTC. The TTC energy density value used here is the initial, uncorrected one. This is because a solidified block of HS78 is about equally dense as the values in the literature for barium hydroxide octahydrate and the purpose of this thesis is to validate, not perfect, the models.

Table 2.5: Volumetric energy density calculation for HS78/Reaction 2 hybrid system [1].

Hybrid System	e _{vol} ^{TTC} (kJ/in ³)	$\frac{V_{PCM}}{V_{rea}}$	Vol. Heat Capacity - Due to Temp. Rise of Solid (kJ/in ³)	Vol. Heat Capacity - Due to Phase Change (kJ/in ³)	e _{vol} ^{Hybrid} (kJ/in ³)
HS78/Reaction 2	7.53	0.705	1.72	7.45	13.99

2.2 Energy Transfer and Conversion Technologies

Also studied in this thesis research are systems that can be integrated with the heat sinks to transfer thermal energy efficiently from the heat source and can offset some of the thermal energy storage by converting thermal energy into usable electricity.

2.2.1 TEGs

TEGs are devices which produce a voltage when a temperature gradient is applied across them [18]. This voltage can be used to generate usable electricity, meaning that TEGs can be used to turn waste heat back into usable electrical energy. In fact, TEGs could conceivably be used to

power the local coolant loop considered in this project. Another attractive feature of the TEGs is that can increase the effective energy density of the heat sink by diverting some of the thermal energy via the production of electricity that would otherwise have to go into the heat sink. Figure 2.2 [1] shows a schematic of how the TEGs would sit in between the heat source and heat sink. TEGs in aircraft have been studied for their ability to generate electricity for wireless sensors in difficult to reach areas, like strain gauges in the fuselage or sensors in seats [19]. One particular configuration placed TEGs in between the skin of a commercial jet, which experiences sub-zero temperatures, and a container of water, which freezes and acts as a PCM to maintain a temperature difference across the TEG [19].

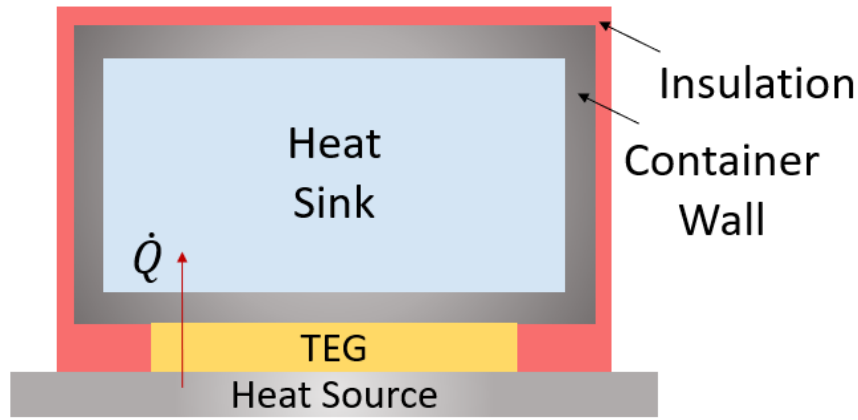


Figure 2.2: Schematic of TEG placed between a heat source and a heat sink [1].

The basis of thermoelectric generation is the Seebeck effect. The Seebeck effect describes the voltage that appears across a conductor when a temperature difference is applied across the conductor. For electricity to flow, two conductors must be connected electrically in series and thermally in parallel. The voltage across the junction is described by [18]

$$V = (S_A - S_B)(T_h - T_c) \quad (4)$$

where S_A and S_B are the Seebeck coefficients of the semi-conductors A and B . The sign of the Seebeck coefficient depends on whether the semi-conductor material has an excess of electrons or an excess of holes, i.e., if the material is negatively or positively doped. This means that maximum voltage occurs when a negatively doped semiconductor is paired with a positively doped semiconductor. The efficiency of a TEG is the percentage of thermal energy in a heat interaction entering the TEG that is transformed into electricity, and is expressed as follows [18]:

$$\eta_{TEG} = \frac{\Delta T}{T_h} \frac{(\sqrt{1 + ZT} - 1)}{(\sqrt{1 + ZT} + \frac{T_c}{T_h})} \quad (5)$$

where ZT is a material property known as the figure of merit and is defined for a thermoelectric material as [18]

$$ZT = \frac{S^2 T}{\rho \kappa} \quad (6)$$

and

$$T = \frac{T_c + T_h}{2} \quad (7)$$

Here κ and ρ are the thermal conductivity and electrical resistivity of the material, respectively, T_c and T_h are the temperatures of the cold and hot junctions, and $\Delta T = T_h - T_c$.

Most commercially available TEGs have materials with ZT values ranging from 0.5 to 0.75, which yield efficiencies of 10% or lower depending on the temperature difference across the device and the thermal resistance between the TEG and the heat sink or heat source. Material scientists are searching for ways to increase the ZT of semi-conductor materials to values above 1. This can be done by increasing the Seebeck coefficient, which increases the voltage generated per degree of temperature difference; increasing the electrical conductivity, which decreases losses due to Joule heating; and/or decreasing the thermal conductivity to create the largest temperature difference possible at a given heat rate.

This has proven to be very difficult because these properties are interdependent. In bulk materials, it is difficult to decrease the thermal conductivity without also decreasing electrical conductivity [20]. Material scientists are trying to circumvent this fact by utilizing novel material structures. A 1993 study [21] found that a 5 Å wide Bi_2Te_3 quantum wire, a structure which confines electrons to one dimensional motion, can achieve a ZT of 14. A 2015 study [22] focused on graphdiyne, a single atom thick 2D lattice of carbon atoms similar to graphene. It was found that positively doped and negatively doped graphdiyne could achieve room temperature ZT values of 3.0 and 4.8, respectively. The caveat to both of these studies is that fabricating such materials at scale is currently very expensive compared to existing TEG manufacturing methods.

2.2.2 Coolant Loops

Coolant loops are very common in hypersonic aircraft. They often run throughout a vehicle picking up heat loads like those caused by the electronics and avionics or air friction on leading edges and dropping the thermal energy off into a heat sink, usually the fuel. NASA's X-43A used a glycol-water coolant system to cool the engine during its boost phase and a water only loop to cool the engine during the free flight phase. The pressure to move the coolant through the loop came from an onboard tank of compressed nitrogen gas [23]. Coolant loops which must transfer large volumes of coolant long distances require substantial power or space and thus are not viable in our corporate sponsor's application.

This research instead focuses on a local coolant loop which opens a second route for heat transfer into the top of the heat sink as shown in Figure 2.3. This second route of heat transfer heats the heat sink material from both sides which decreases the temperature difference between the top and bottom of the material. The local coolant loop also decreases the effective thermal resistance

between the heat source and heat sink which should decrease the temperature difference between the two. Decreasing this temperature difference would help keep the heat source within its temperature limit. The local coolant loop does not require a high flow rate because it merely supplements heat transfer, the water blocks are designed to maximize heat transfer for a minimal pressure drop, and the loop itself is very short. This all means that transferring the coolant through the loop only requires a low-power pump, the power for which should be within the electricity budget on our sponsor's vehicle. A good low-power pump option are piezoelectric pumps because of their low electricity use compared to their relatively high flow rate [24].

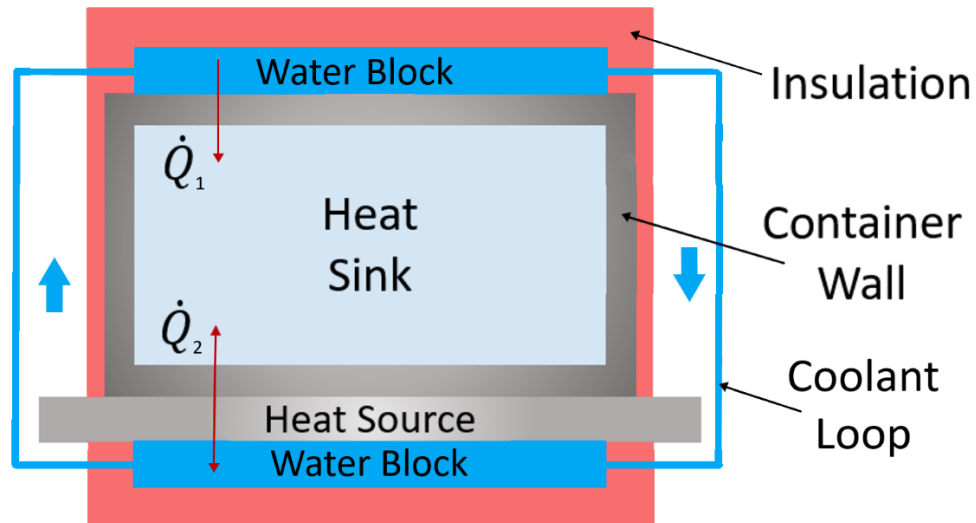


Figure 2.3: Schematic of a local coolant loop [1].

Chapter 3 Experiment Design

To experimentally evaluate the volumetric energy density of the different heat sink concepts proposed, prototypes for each concept and a test stand for evaluating the prototypes were developed. This chapter describes all the components of the prototypes (steel boxes, coolant loop, TEGs, and pressure relief system) and then the components of the test stand (copper block, insertion heaters, insulation, sensors, and data acquisition system). The chapter ends with a description of the test procedures used for each prototype.

3.1 Prototypes

All machining was performed by the mechanical engineering machine shop at Virginia Tech, formerly located in the basement of Randolph Hall, currently located in Goodwin Hall.

3.1.1 PCM Box

Figure 1.2 (shown again here) illustrates the basic setup for testing each prototype, namely, a box containing a heat sink material surrounded by insulation sitting in direct contact with the heat source. We selected 303 stainless steel as the material for the prototype boxes because it is

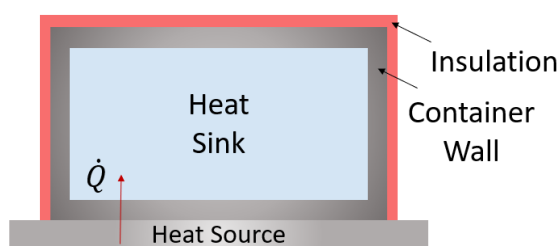


Figure 1.2: Heat sink setup.

chemically stable relative to the selected PCMs and is easily machined. Our corporate sponsor provided us with the dimensions 4" x 8" x 1.5" for the inside of the box. The process for creating each box starts with a 6" x 10" x 2" solid block of steel, which has 1/8" machined off every side, resulting in a 5.75" x 9.75" x 1.75" solid block with 1/4" filleted corners. This step was taken to ensure every surface is as smooth as possible to maximize heat transfer. This solid block then has a 4" x 8" x 1.5" cavity with 1/2" filleted corners machined out. The walls of the steel box are very thick to prevent any deformation.

Next, four pairs of 1/8" NPT (national pipe tapered) threaded holes, which act as thermocouple ports, are drilled into the four sides of the box at 20% and 80% of the 1.5" internal height of the box, measured from the bottom of the cavity. NPT threads were chosen because they seal when tightened as opposed to straight threads which do not. Thermocouples are inserted through compression fittings which thread into these NPT holes. A more detailed explanation of the thermocouples and their fittings is given in Section 3.2.3. The 20% and 80% measurements were chosen so that the temperature near the bottom and top of the PCM can be measured, which is important for characterizing the temperature gradient within the PCM and the local coolant loop's effectiveness (discussed below) at reducing this temperature gradient. The holes drilled into

the short sides are put exactly in the middle, but the holes drilled into the long sides are offset to the left so that they lay $\frac{1}{3}$ of the internal side length from the left side as shown in Figure 3.1. The reason for placing the thermocouples like this is to permit the measurement of temperature along the length of the box. The thermocouples in the short sides measure the temperature near the ends of the box and the thermocouples in the long sides measure the temperature near the middle of the box. Figure 3.2 illustrates how the thermocouples sit inside the box.

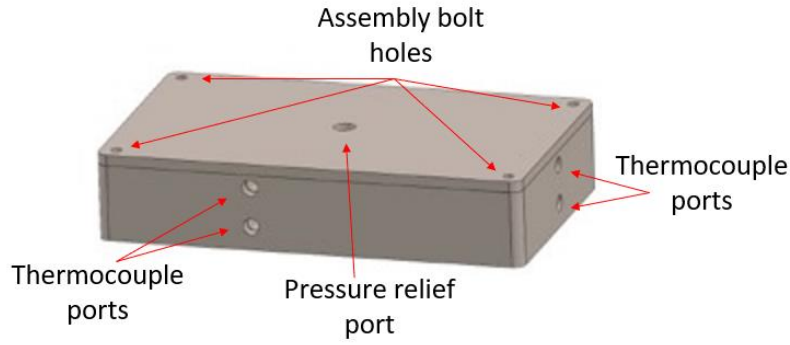


Figure 3.1: Rendering of the stainless steel PCM box and lid.

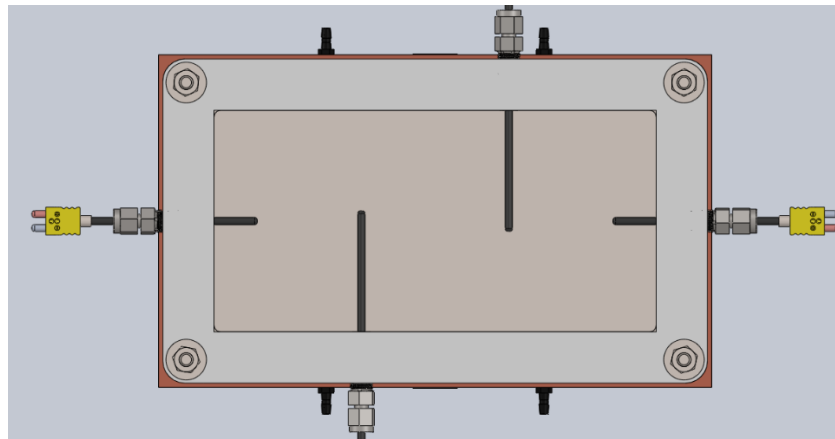


Figure 3.2: Rendering of PCM box to show thermocouples.

Finally, four $\frac{1}{4}$ " through holes were drilled into the corners of the box in a 5" x 9" rectangular pattern as shown in Figure 3.1. An identical pattern is drilled into the box lid, copper block (i.e., the location of the heat source), and aluminum water blocks (i.e., part of the local coolant loop) so that threaded rods can be inserted through the holes to align the components. Nuts are used to compress the components together to decrease thermal contact resistance and seal the PCM box. $\frac{1}{4}$ " bolts are chosen because they are as thin as possible and not risk bending them during assembly. The sizing of this pattern is chosen to place the holes as far from the cavity as possible to reduce stress concentrations.

The lid to the PCM box starts as a 24" x 6" x 0.5" plate of polished 303 stainless steel, which is cut into two 9.75" x 5.75" x 0.25" lids. A 24"-wide plate was used because 20" plates were not available. The lids are made $\frac{1}{4}$ " thick so they are sufficiently strong to resist any deformation. Deformation of the lid would be catastrophic as the seal depends on the lid being flat.

Two of the selected PCMs expand when they melt, which could create high pressure inside the box, possibly causing leaks and forcing material out of the box. To alleviate any pressure build up, a $\frac{1}{4}$ " NPT hole is drilled in the lid of the box to which a pressure relief system is attached, which is described in detail later in this chapter. The pressure relief hole is made with a $\frac{1}{4}$ " diameter instead of a $\frac{1}{8}$ " one so that any PCM material is less likely to get clogged in the hole. The lid is sealed using a gasket cut from pliable, chemically resistant PTFE (polytetrafluoroethylene or more commonly Teflon).

Figure 3.3 shows a PCM test setup without insulation with the assembly bolts and nuts visible. As can be seen, the thermocouple holes are offset to the right of center in Figure 3.3. This was an error during the machining process for this particular box only, which fortunately had no real effects on the final results. Because the insulation was manufactured to precisely fit around the prototype design, the piece that insulates the PCM box had to be flipped upside down when using the botched box. In the end, it did not matter in which direction the thermocouples were offset as long as they were all offset the same amount. The white material between the lid and box is the PTFE gasket. A more detailed view of how the gasket interacts with the box is provided in Figure 3.4.

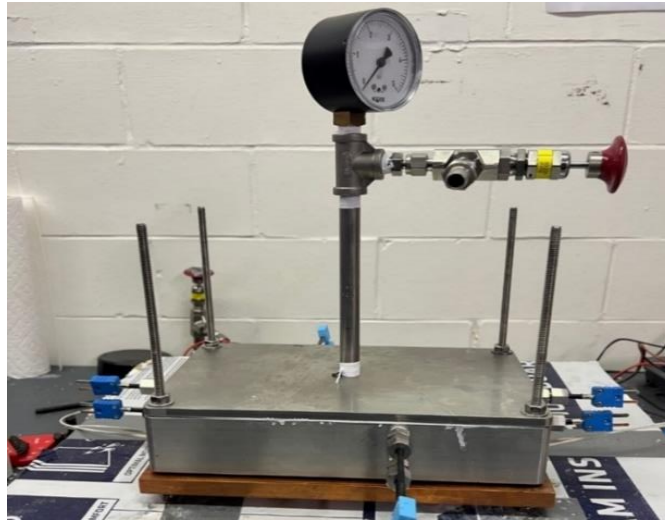


Figure 3.3: PCM setup without insulation.

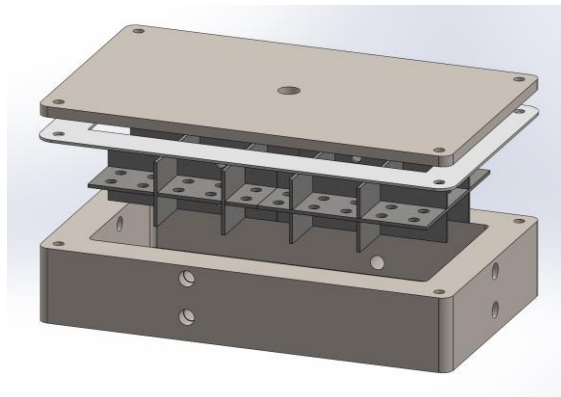


Figure 3.4: Rendering of the PCM box with fin assembly and gasket.

One of the drawbacks of the selected PCMs or PCMs in general is that they have low thermal conductivities. This causes a large temperature gradient within the PCM, which can lead to the heat source, i.e., the copper plate, exceeding the set maximum temperature for the heat source before all the PCM is done phase changing. Taking inspiration from previous PCM applications, it was decided to add a highly conductive material to each PCM to increase its effective thermal conductivity. To do so, aluminum is used because of its high thermal conductivity, ease of machining, and cost effectiveness. An assembly of cut sheet metal parts is designed to spread heat throughout the heat sink. Figure 3.5 shows how the parts fit together and Figure 3.6 shows the full assembly. Detailed engineering drawings are included in the Appendix. The holes in the horizontal plate are to allow for PCM to flow through and the holes on the long top and bottom plates are for the thermocouples to fit through. Once assembled, the fins were shipped to Matrix Coatings Corp. where they were coated with a 0.1” layer of Teflon because aluminum is highly reactive with the selected PCMs. Once coated, the fins are ready to use.

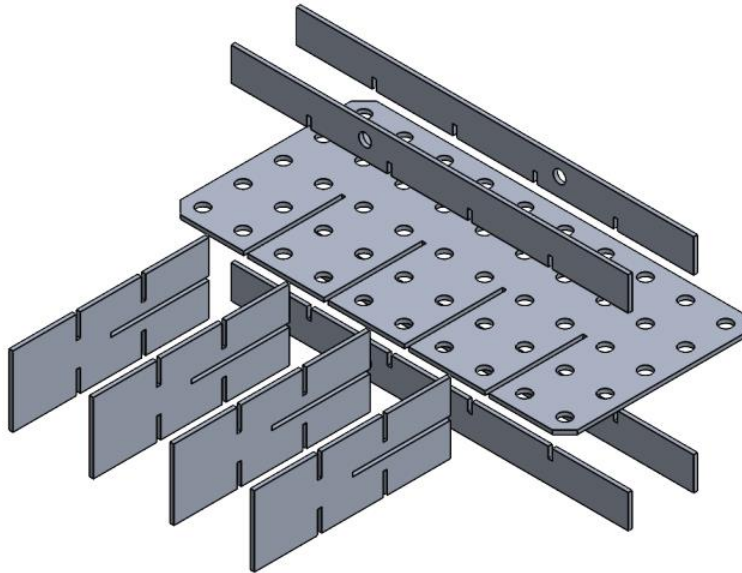


Figure 3.5: Schematic of the disassembled aluminum fins.

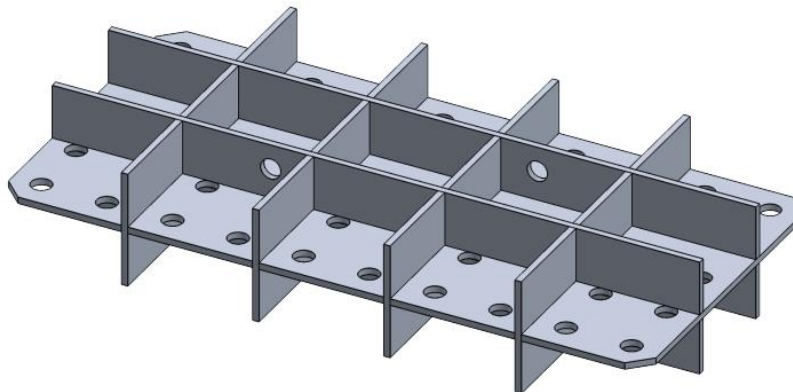


Figure 3.6: Schematic of the assembled aluminum fin assembly.

A simple parallel heat path analysis was conducted to determine how the fins would impact the thermal conductivity. Without the fins, a 4" x 8" x 1.5" volume of HS78 would have a thermal resistance of 2.64 K/W. With the aluminum fins, that value drops to 0.11 K/W. The thermal resistance of the HS78 alone is calculated with

$$R_t = \frac{L}{kA}$$

where L is the thickness (1.5"), k is the thermal conductivity (0.7 W/m K), and A is the area (32 in²). The thermal resistance of the HS78 with fins is calculated with

$$R_t = \left(\left(\frac{L}{k_{PCM}A_{PCM}} \right)^{-1} + \left(\frac{L}{k_{Al}A_{Al}} \right)^{-1} \right)^{-1}$$

where A_{PCM} is the area not occupied by the fins (29.78 in²), A_{Al} is the area occupied by the fins (2.22 in²), k_{PCM} is the thermal conductivity of HS78 (0.7 W/m K), and k_{Al} is the thermal conductivity of the aluminum fins (237 W/m K). This analysis does not factor in the Teflon coating or the horizontal aluminum fin, so it is only a rough estimate.

The procedure for filling the PCM boxes with PCM is as follows. First, the PCM is melted by placing the sealed (to prevent moisture loss) PCM container in a hot water bath set well above the phase change temperature for about 24 hours. Next, the aluminum fins are placed in the empty PCM box and the pressure fittings with thermocouples are threaded into place. Then, the now liquid PCM is poured into the box between the fins and let to cool and solidify. Figure 3.7 shows a PCM box with freshly poured HS58.

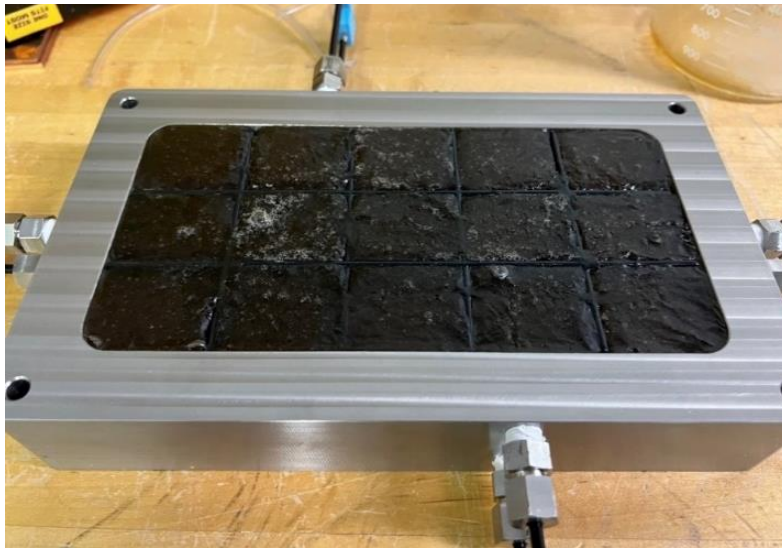


Figure 3.7: Freshly poured HS58.

3.1.2 TTC Box

Two endothermic reactions were selected for testing: reactions 1 and 2 in Table 2.2. Upon initial testing, it was discovered that reaction 1 does not occur spontaneously and requires constant mixing to continue reacting. Reaction 2, on the other hand, occurs spontaneously and does not require constant stirring. Thus, the focus turned exclusively to reaction 2. The design of the TTC box is very similar to the PCM box except for three key differences, its height, its internal Teflon coating, and its lack of fins. The TTC box is also made from 303 stainless steel.

An initial specification from our corporate sponsor was that the heat sink should be able to store 40 W over 2 hr or 288 kJ. Analysis by Edwards [1] reveals that a 4" x 8" x 1.5" volume of the selected reaction cannot absorb 288 kJ without exceeding the maximum temperature set for the heat source (85 °C). Thus, the decision was made to double the internal height of the TTC box to 3" because the energy specification is more important than the volume specification provided by the sponsor. Unfortunately, it was not possible to source stainless steel blocks tall enough to machine the box out of a single piece, so the TTC box is made of two separate parts that are adhered together with a gasket forming epoxy. Figure 3.8 shows a rendering of the TTC box and Figure 3.9 shows a TTC setup without insulation with the black epoxy slightly visible between the two pieces.

The TTC box is made up of three parts: the base, the middle, and the lid. The lid is identical to the lid used with the PCM box. The base of the TTC box is identical to a PCM box except that it only has one thermocouple port positioned at 20% of the 3" internal height of the box measured

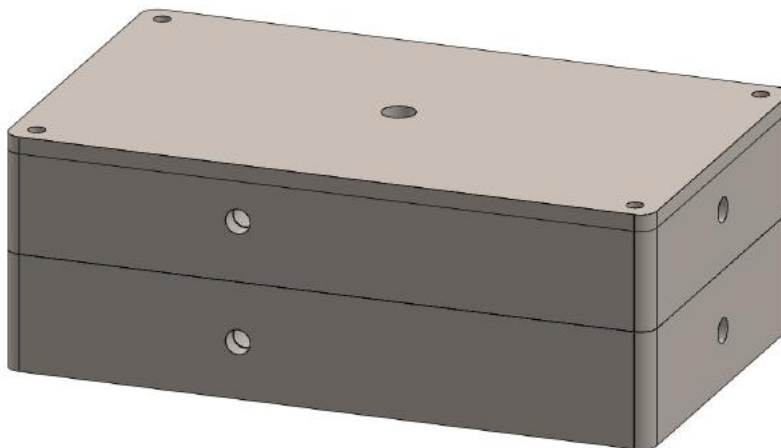


Figure 3.8: Rendering of the TTC box.

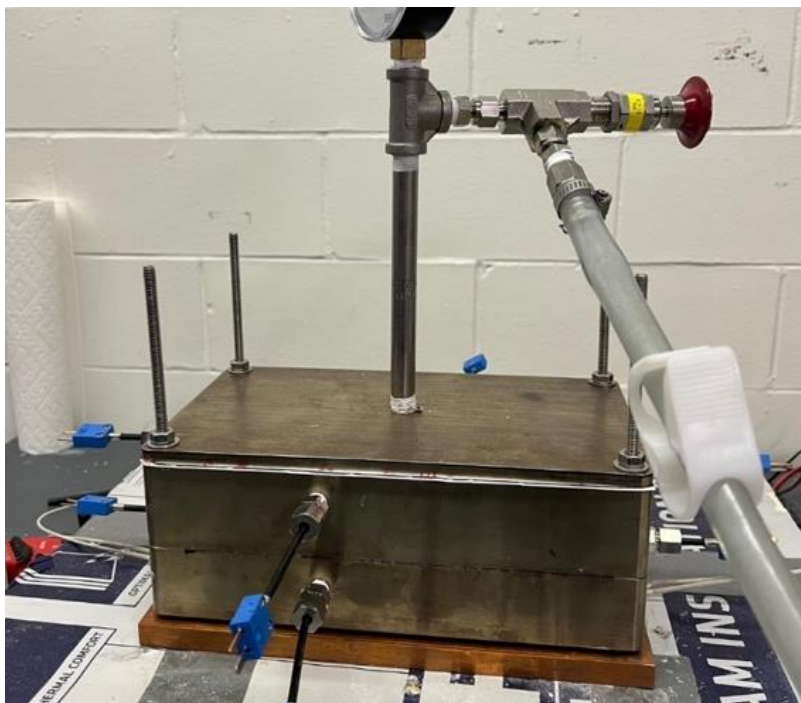


Figure 3.9: TTC setup without the insulation.

from the bottom of the 4" x 8" x 1.5" cavity. This puts the bottom thermocouple port at 0.6" from the base of the cavity instead of 0.3". The middle piece starts as a 6" x 10" x 2" solid steel block and is machined down to a 5.75" x 9.75" x 1.5" solid block, which is 0.25" shorter than the base. The middle piece then has a 4" x 8" cavity machined completely through so it ends up like a ring. One thermocouple port is put into each side at 80% of the 3" internal height measured from the base of the cavity or 0.6" down from the top of the middle piece. The lateral placement of the thermocouple ports in the TTC box is identical to those in the PCM box and they are the same 1/8" NPT holes.

One of the reactants, NH_4Cl , and one of the products, BaCl_2 , are corrosive to stainless steel and thus the inside of the TTC box is coated with Teflon. Figure 3.10 shows a picture of the two TTC box halves and lid with their Teflon coatings applied. The base is in the top right, the middle is in the bottom right, and the lid is on the left. Conductive fins are not used as they would impede the mixing of the chemicals before the test. The procedure for filling the TTC box is as follows. First, the pressure fittings with thermocouples are threaded into place. Next, both reactants are premeasured by weight into separate beakers. Then a thin layer (about 1/10th of the total reactant thickness) of one chemical is poured out into the box followed by a thin layer of the other chemical. This is repeated until both beakers are empty. Once the box is full it is sealed and must immediately be tested because the reaction begins to occur albeit very slowly because of heat transfer from the surroundings to the reactants in the box. If the reaction progresses at all before testing begins, the energy capacity of the TTC prototype will be diminished and the calculated value for the volumetric energy density will be lower than it should be.

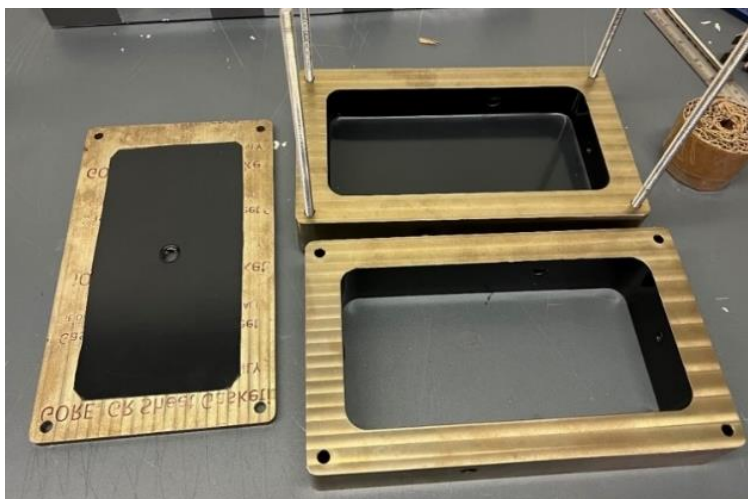


Figure 3.10: Teflon coated TTC box pieces.

Layering as opposed to stirring is a way to mix the chemicals without adding a lot of extra energy that would be difficult if not impossible to measure. Furthermore, there is much more contact surface area between the reactants if they are alternately poured in many thin layers compared to just two layers with a single plane of contact between them. This large surface area of contact between the chemicals helps the reaction occur more readily as energy in a heat interaction is added to the system. Stirring the chemicals together is not an option because it would add energy to the system that could not be measured with the sensors, which would reduce the measured volumetric energy density of the reaction.

3.1.3 Hybrid Box

The hybrid TMS is the result of the realization that the PCM HS78 is the same chemical as one of the reactants in the TTC reaction, namely barium hydroxide octahydrate. The initial idea was to simply pour a layer of liquid HS78 into a TTC box, let it solidify, pour in the amount of ammonium chloride required, seal the box, and test it. With this approach, it was assumed that the reaction would not readily occur between the solid reactants since they were essentially separated except at the interface between the two. However, once the HS78 (barium hydroxide octahydrate) melted, it was assumed the reaction would proceed very readily because the second reactant would be free to mix with the liquid HS78 after which the thermal energy absorbed by the chemical reaction would cause the temperature to drop, resulting in a re-solidification of the HS78. This would repeat in a cycle until all the reactants had reacted, chemical equilibrium had been reached, and any remaining HS78 melted. Knowing when this occurred would be signaled by the temperature of the contents of the box rising above the melting point of the HS78.

The first attempt at a hybrid TTC/PCM test was a failure because the liquid HS78 is denser than the ammonium chloride, causing the ammonium chloride to simply float on top of the liquid HS78 and not mix with it. As a result, it was decided to flip the box upside down once the chemicals had been loaded and the box sealed so that the liquid HS78 would drip down into the ammonium chloride and the reaction occur more readily. To flip the box upside down but still have the pressure relief system at the top required drilling a $\frac{1}{4}$ " NPT hole in the base piece of a TTC box and seal

the lid with a solid $\frac{1}{4}$ " NPT plug. The copper block and heaters are also moved to what is now the top of the hybrid box so that they heat the steel box from the top down so that the HS78 is heated first. A $\frac{3}{8}$ " hole is drilled through the center of the copper block and thin copper plate to make room for the pressure relief system. Figure 3.11 shows a hybrid test setup without insulation with the copper block on top and the pressure relief system connected to the new hole in the base piece of the TTC box. The blue substance on the copper block is corrosion caused by a spill that occurred while the products of the reaction were cleaned out of a TTC box after a test.



Figure 3.11: Hybrid setup without the insulation.

Unlike in the case of the TTC prototype, conductive fins are incorporated into the hybrid box as was done with the PCM prototype but these are constructed in an ad hoc fashion. The horizontal plate in the aluminum fin assembly used with the PCM prototype would impede the flow of the HS78 down into the ammonium chloride so only the vertical fins could be used. However, the aluminum fins could not be disassembled because they are permanently fused due to the Teflon coating. Thus, vertical fins were cut from steel foil. The fins are just rectangles with slits cut into them so they can slot together to create a 3D assembly. A new fin assembly is made prior to each hybrid test because the fins corrode. Corrosion of the steel fins is not a concern because they are thrown out with the spent chemicals after the test. Figure 3.12 shows a hybrid box with just the fins and Figure 3.13 shows a hybrid box with solidified HS78.

The procedure for filling the hybrid box is as follows. First, the correct weight of HS78 is placed in a container, sealed, and heated in a water bath set to 85 °C. Fins are cut out of steel foil and placed in the hybrid box. Once the HS78 is fully melted, it is poured into the box, making sure it is evenly dispersed. The HS78 is allowed to cool and solidify overnight. Once the HS78 has solidified, ammonium chloride is weighed out into a beaker and then poured over the top of the HS78. Like the TTC, the hybrid must be tested immediately after the chemicals are mixed, although the reaction occurs much more slowly because there is only one plane of contact between

the chemicals. To do so, the lid is placed on the box and the box sealed and turned over. The hole for the pressure relief system that has been drilled into the bottom of the box (now the top of the box) is then unplugged and the heat source, i.e., the cooper block and insertion heaters, placed at the top after which the pressure relief system is attached to the top of the box.



Figure 3.12: Steel foil fins inside hybrid box.



Figure 3.13: Solidified HS78 inside of hybrid box with the vertical steel foil fins.

3.1.4 Pressure Relief

Due to the expansion of PCMs during melting and the release of ammonia gas in the TTC reaction, pressure builds inside the box during testing. Since high pressures inside the box may cause material to leak out, a pressure relief system was developed and implemented. The system is very simple and consists of pipe threads in the top of the steel box (or the bottom in the case of the hybrid box) to which a pipe is attached, which extends upward eventually branching to a pressure gauge and an adjustable relief valve. The pressure relief system is visible in Figure 3.3, Figure 3.9, and Figure 3.11.

A pressure test of the PCM box is undertaken to determine where to set the pressure relief valve. If the valve is set at too high a pressure, material may leak out before the valve opens to relieve the pressure. If the valve is set at too low a pressure, it will release more material than necessary, which will skew the energy data measurements because thermal energy is exiting the system carried by a hot gas without being measured.

Teflon tape is applied to every threaded joint to prevent ammonia leaks. The relief valve is connected to a plastic tube which runs through the lab and out a window so that ammonia is ejected outside the lab. Due to the ideal gas law, when the pressure valve opens, the temperature inside the heat sink drops, which can be seen later in the results section. This temperature drop from the pressure relief system can add to the energy density of a TTC or hybrid system, given that whatever system into which it is incorporated has a place to vent the ammonia.

3.1.5 TEGs

As stated in the literature review, the efficiency of a TEG is the percentage of thermal energy entering the TEG that is transformed into electricity and is expressed by Eq. (5) in Chapter 2 [18]. Note that the temperature difference across the TEG greatly impacts the efficiency of the TEG regardless of the ZT factor. Figure 3.14 illustrates the efficiencies that can be expected at different ZT values with the temperatures of interest in this research. Using a cold-side temperature of 60 °C (a reasonable estimate for the temperature at the bottom of the steel box during the HS58's phase change) and sweeping from 60 °C to 85 °C on the hot side, the effects of the hot-side temperature on efficiency for a given cold side temperature can be seen. The 4 ZT line hits an efficiency of 1% with the hot side near 68 °C. The same efficiency can be achieved by the much lower 0.75 ZT value with the hot side at 85 °C. This indicates that temperature difference plays just as large a role in the efficiency of a TEG as the ZT value.

A final point is that it takes 300 mW to power the local coolant loop piezoelectric pumps. For the TEGs to generate that much power from a 40 W heat rate, they need to be 0.75% efficient or more. For a cold-side temperature of 60 °C, this can be achieved with a ZT of 0.75 and a hot-side temperature of 79 °C. With a ZT of 0.5, it is theoretically impossible to achieve the efficiency necessary to power the local coolant loop even with the most generous temperature difference that could be achieved with this test setup. Any temperature difference larger than the ones plotted here would exceed the maximum temperature of the copper block, because the cold side could never be held at any colder a temperature than around the HS58 phase change temperature.

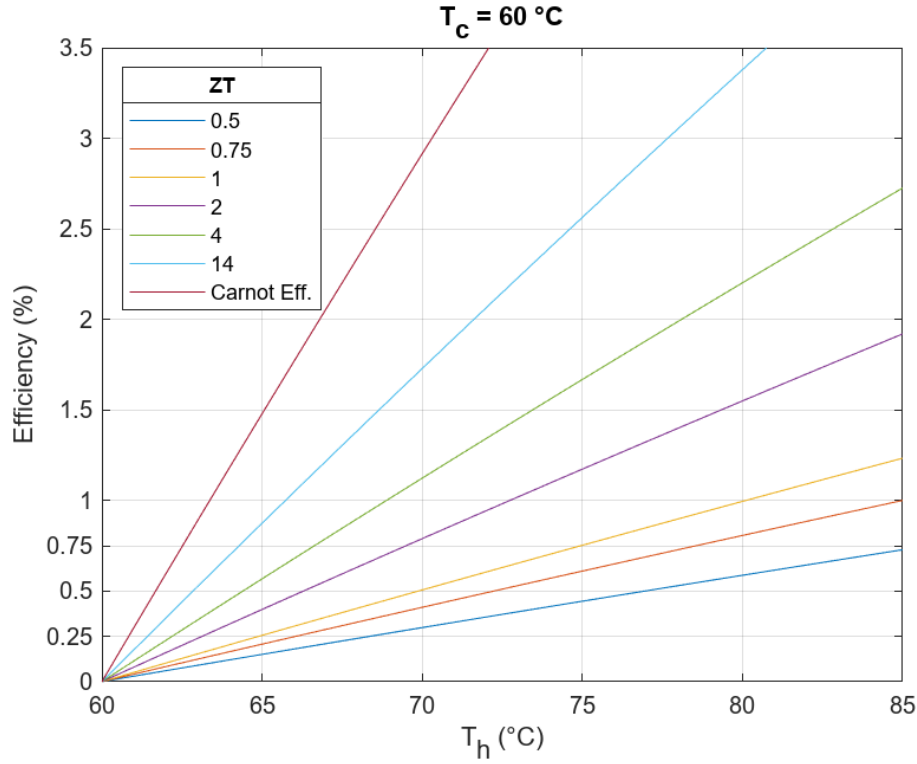


Figure 3.14: TEG efficiency chart

The initial plan for the TEG was to commission a single custom-built TEG to cover the entire 4" x 8" area. 40 W through a 4" x 8" area is a relatively small heat flux, only 1.25 W/in², so the custom TEG would have to have a high thermal resistance to create a large enough temperature difference to achieve the necessary efficiencies. But the larger the temperature difference, the higher the temperature on the hot-side becomes. The cold-side temperature is determined by the heat sink inside the box and cannot be changed. Thus, any added thermal resistance only increases the hot-side temperature. This creates a balancing act where the TEG cannot have too high a thermal resistance lest the maximum temperature of the heat source is exceeded, and it cannot have too low a thermal resistance or else the TEG cannot generate enough power.

In the end, these considerations were irrelevant because a custom designed TEG was too costly. TEGs are extremely complicated devices and setting up the tooling to create a new design is prohibitively expensive. Instead, off-the-shelf TEGs were found that were suitable. Because a 4" x 8" area needs to be covered, and virtually all TEGs are squares, a TEG with either 2" or 4" on a side need to be found. The search was narrowed to a collection of 50 mm (1.97") square thermoelectric modules from Custom Thermoelectric. Their engineers were consulted about which specific model would best suit our temperature range and heat rate, and they recommended the 12711-9L31-06CW thermoelectric module [25]. This module is actually a thermoelectric cooler, but when operating under 100 °C, it can, according to the engineers at Custom Thermoelectric, be used as a TEG just as effectively.

Because the TEGs are 50 mm squares, they can be arranged in a 2 x 4 array to cover the 4" x 8" area. The TEGs are wired in series to maximize voltage and minimize wiring complexity.

Figure 3.15 shows a picture of a TEG array wired in series. Each TEG is connected to the one next to it with twist connectors, leaving a positive and negative lead open from the first and last TEG in the series. These leads connect to the external load whose voltage is measured to calculate the power output by the TEGs.

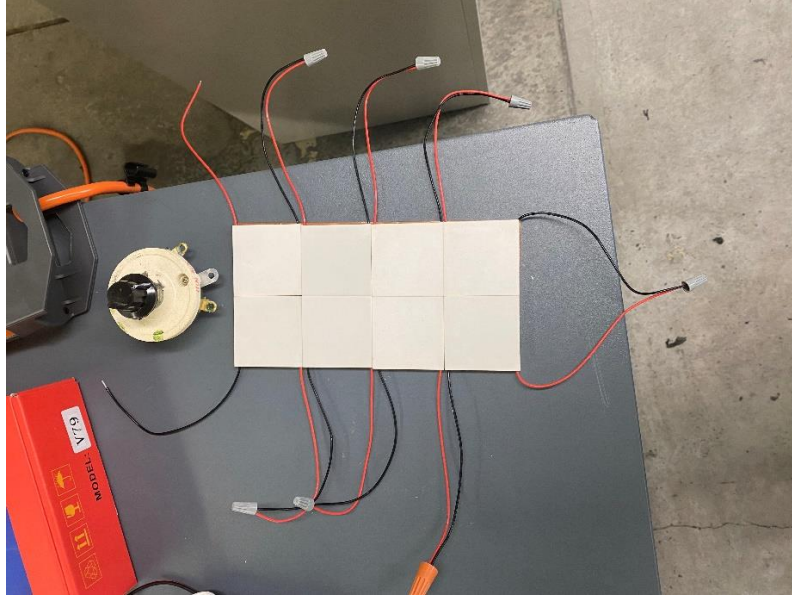


Figure 3.15: TEG array.

The TEG array had an issue in that individual TEGs could move freely and could, thus, shift such that one TEG may lay slightly on top of an adjacent TEG. When the nuts to the prototype assembly were tightened to compress all the components, any TEG not laying perfectly flat could be damaged. Any damage to the internal circuitry of a TEG destroys it because an unbroken electrical circuit is necessary for a TEG's operation. To ensure all the TEGs laid flat, an adhesive thermal pad was placed on top of a thin 4" x 8" copper plate and the TEG array was adhered to this pad. The thin plate would then rest on the copper block, but it was assumed not to add very much to the thermal resistance between the copper and the steel because it is thin copper. This setup ensured that the TEGs would remain perfectly flat and in place.

To find the resistance value for an external load that maximizes power output, a potentiometer must be used to sweep across a range of resistances to find which resistance creates maximum power. To measure the resistance of the potentiometer, it is connected in series with a resistor and the voltage measured across them both in what is known as a voltage divider [26]. Figure 3.16 shows a wiring diagram of a voltage divider where R_1 is the potentiometer and R_2 is the resistor. The resistance for R_1 is calculated via

$$R_1 = R_2 \left(\frac{V_{in}}{V_{out}} - 1 \right) \quad (1)$$

The result of this test is that the resistance that maximizes the power output is 50 Ω , which is slightly more than the sum of the internal resistances of the TEGs.

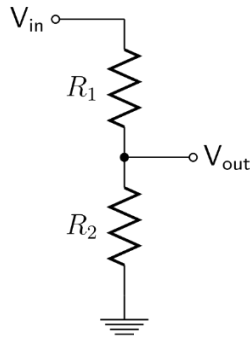


Figure 3.16: Voltage divider [26].

3.1.6 Local Coolant Loop

The local coolant loop consists of two water blocks, eight plastic tubes, eight threaded plastic barbed tube fittings, eight machine screws, two double ended barbed tube fittings, and two pumps. In the case of the PCM and TTC test, one water block is placed under the copper block and the other on top of the steel box. In the hybrid setup, since the copper block is on top, a water block is placed on top of the copper block, and another is placed under the steel box. Initially, two piezoelectric pumps were used controlled by one pump controller supplied by Dolomite Microfluidics because they can each push 20 mL/min using only 300 mW total, including the controller [24]. 20 mL/min was determined to be the minimum flow rate for efficient heat transfer in the water blocks [4]. The pump controller provides a modified sine wave to the pumps, which maximizes flow, so that any ultra-low-power embedded system designed to control piezoelectric pumps in a hypersonic vehicle would need to generate a similarly modified wave.

Each water block consists of two pieces of machined aluminum, a lid which is flat on both sides, and a base which has two cavities machined out for water to flow through. Both pieces started as 6" x 12" tight-tolerance, precision ground aluminum blocks, the lid was 0.25" thick and the base was 0.5" thick. For both pieces, 0.5" fillets were placed on the outside corners, a 0.6" through hole was put in the center for the pressure relief system, and 0.25" through holes were put in all corners for the assembly bolts. The assembly nuts and bolts compress the water block onto the steel and copper which reduces thermal contact resistance, increasing heat transfer. The base is thicker to provide space for the threaded adapters to join the plastic tubes and the cavity in the water block. Figure 3.17 shows a rendering of the two water block pieces. Note the raised features on the long side of the base. That is where the tube adapters thread into the base. The lid fits snugly onto the base and is bolted with four 8-32 socket head screws. The lid has through holes and the base has threaded holes in the middle of each side. The same gasket forming epoxy used with the TTC box is also used to seal the water block pieces together before assembly, as shown in Figure 3.18. The cavity is cut 1/8" deep into the base, leaving 1/8" of aluminum between the water and the outside of the water block. A detailed engineering drawing is given in the Appendix. Our corporate sponsors desired the heat transfer to occur only within a 4" x 8" area, so both cavities together measure about 4" x 8". The two water blocks are connected to each other via plastic tubes, which also connect to pumps to circulate the coolant. The tubes connect to the water blocks through tube fittings, which thread into the side holes tapped into the base of the water block. The two

cavities in each water block are separated in the middle and connect to the corresponding cavity on the other water block as shown in Figure 3.19. Since there are two separate loops, two pumps are needed. Not pictured in Figure 3.19 is the pump controller.

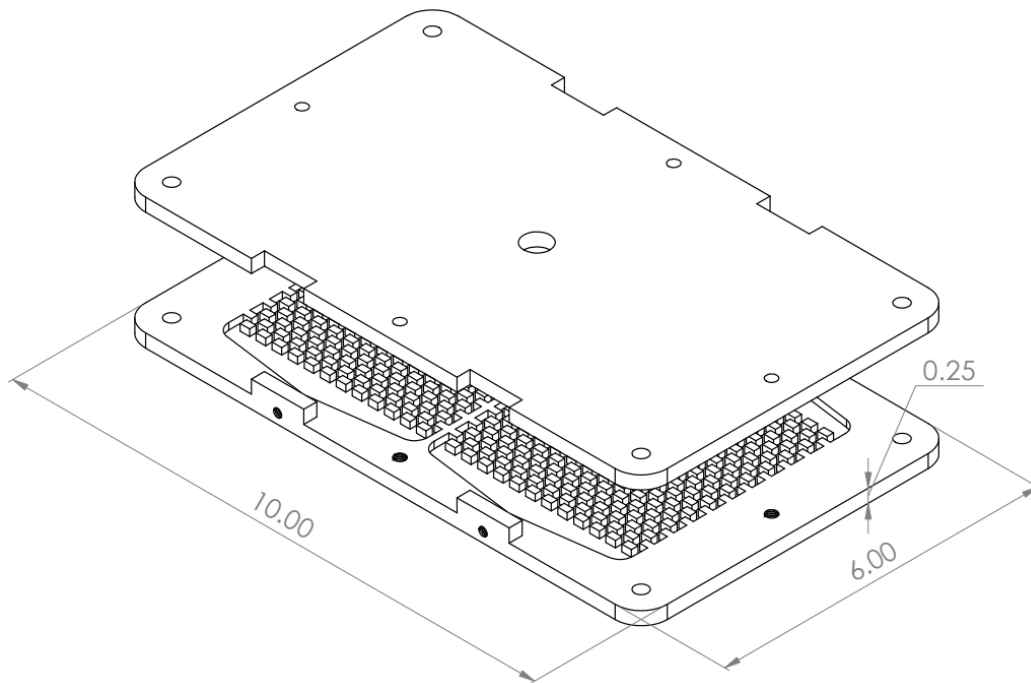


Figure 3.17: Rendering of the water block.

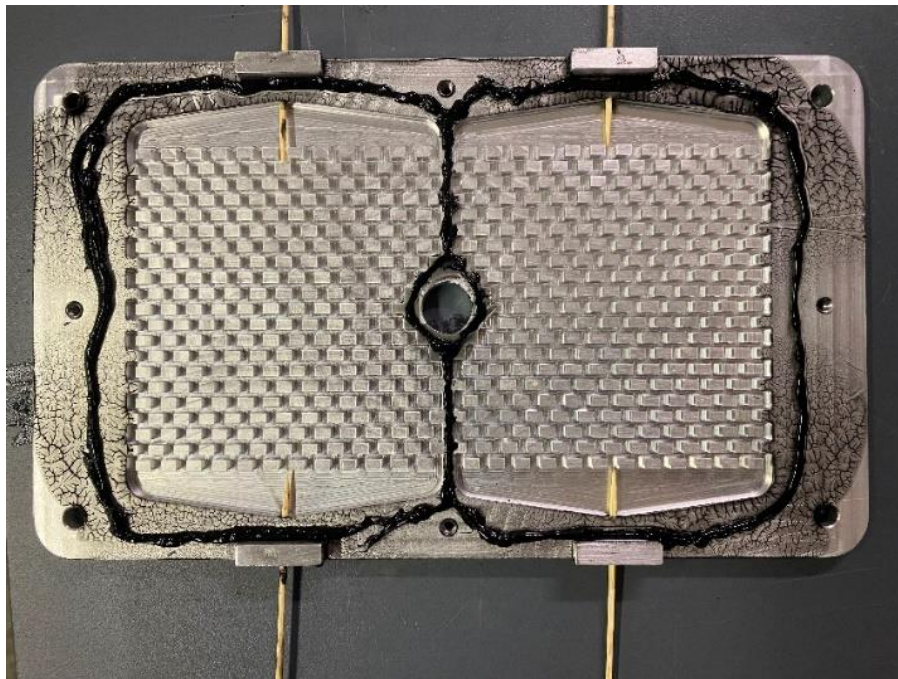


Figure 3.18: Water block base with gasket forming epoxy.



Figure 3.19: Rendering of the local coolant loop with piezoelectric pumps.

A test was run to determine if the TEGs could power the pump controller and pumps. To do this, the TEG array was wired into a buck-boost converter, which boosted the TEG voltage to a constant 5 V. Next, the 5 V power supply cable of the pump controller was cut to reveal the two leads inside, which were wired directly to the buck-boost converter. This setup was able to turn the pump controller on standby, so it at least generated 150 mW, but the controller was unable to power the pumps. In fact, in the attempt to power the piezoelectric pumps, both broke from improperly conditioned electricity. Because the pumps cost so much, it was decided to instead use less expensive peristaltic pumps, which can achieve flow rates as low as the piezoelectric pumps, i.e., flow rates of 20 mL/min. Maintaining the low flow rate is necessary because higher flow rates create better performing water blocks but would not be indicative of the performance achievable with low power pumps, which is a focus of this project. The peristaltic pumps are nowhere near as efficient as the piezoelectric pumps, but that does not matter for testing the effectiveness of the water blocks. Since the peristaltic pumps can be set to the same flow rate, they are nearly identical in regards to the water blocks.

3.2 Test Stand

3.2.1 Insulation

The entire system, i.e., prototype and heat source, must be insulated to prevent heat loss. Any heat transfer that occurs somewhere there is not a sensor cannot be measured and, thus, will affect the accuracy of the energy density calculation. Additionally, on board a hypersonic vehicle, the heat sink would be insulated to prevent heat leaking into other temperature sensitive components. Solimide insulation is chosen for our system due to its extremely low thermal conductivity value of less than 0.046 W/m K and because its manufacturer can make custom shaped pieces of insulation. This is necessary because precisely shaped insulation is needed to fit tightly over the components to reduce heat loss. Figure 3.20 shows a PCM setup with the Solimide insulation. The insulation is made of multiple pieces designed specifically for each component in the test setup. Engineering drawings can be found in the Appendix.

When operating with the coolant loop, the plastic tubes run along the outside of the insulation as they carry water between the blocks. This is to prevent the tubes from coming into

contact with the copper block and melting. To insulate the tubes, fiberglass insulation is taped to the Solimide and the tubes are sandwiched between the two insulations.

To prevent heat loss from the bottom of the system into the table, the entire system rests upon multiple layers of rigid insulation, which is also visible in Figure 3.20. Solimide is too soft to support the weight of the system and would compress to the point of being an ineffective insulator.

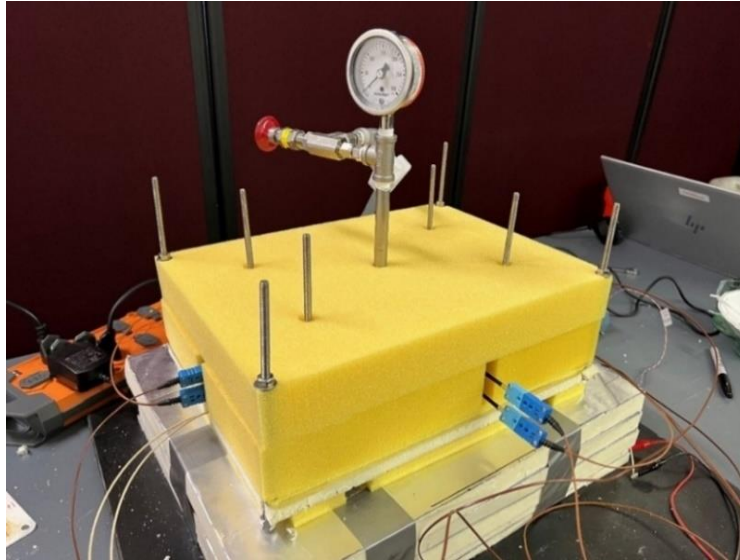


Figure 3.20: PCM setup with Solimide insulation.

3.2.2 Copper block

A copper block with insertion resistance heaters is chosen as the heat source. This is because the substrate on which the real power electronics sits is made of copper and the resistance heaters can control the exact wattage generated in the heat source. The resistance heaters are inserted into holes drilled into the copper block and are connected in parallel to a desktop power supply as shown in Figure 3.21. The power supply makes controlling the exact wattage into the heaters possible.

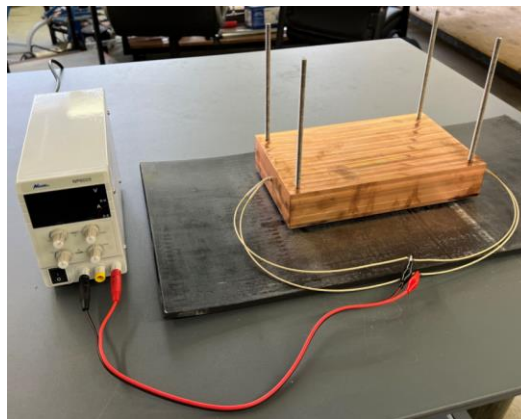


Figure 3.21: Copper block, heaters, and power supply.

The copper block was originally designed to be 10” wide, 6” long, and 2” high as shown in Figure 3.21 but was cut down to 0.5” in height to reduce the thermal mass of the block and better mimic the power electronics substrate. To ensure that the heat transfer occurs primarily within a 4” x 8” area, a thin 4” x 8” copper plate is placed between the copper block and steel box to ensure conduction is primarily limited to that area.

3.2.3 Sensors and Data Acquisition System

Table 3.1 lists all the sensors and data acquisition components used in this thesis research as well as the URL where they can be found. Two new laptops were purchased in lieu of using personal laptops because the data from this project cannot be stored on personal devices due to the export control restrictions on this research.

Two kinds of sensors are used in this project: insertion thermocouples and heat flux sensors with built in thermocouples. The insertion thermocouples are long, thin, PFA coated temperature probes which are used to measure the temperature throughout the heat sink inside the box. Type T thermocouples are used as they are the most accurate thermocouple type within the temperature range of interest here. The PFA coating is to protect the thermocouples from corrosion. Eight of these sensors are used: a top and bottom sensor for each of the four sides of the box. Each thermocouple is inserted through a compression fitting which tightens down to form a permanent, airtight seal around the thermocouple to prevent leaks. Custom built compression fittings were sourced from TC Measurement and Control Inc. because the Teflon coat on the thermocouple makes them 0.145” in diameter, an unusual measurement that does not exist in off-the-shelf compression fittings. The compression fitting then has Teflon tape applied to its threads and is threaded into the thermocouple ports in the steel box. Figure 3.22 shows a 3” thermocouple inserted through a compression fitting. The sensor is sealed in the fitting by first loosening the fitting by twisting the nuts away from each other, inserting the thermocouple to the appropriate length, and then twisting the nuts into each other to tighten the fitting. This process is permanent as it deforms the PFA coating where the fitting seals. 6” and 3” long thermocouples are used with the 6” thermocouples placed into the long sides of the box and the 3” thermocouples placed in the short sides of the box. The thermocouple connects to the DAQ via a wire shown in Figure 3.23 that connects with a female adaptor to the male adaptor at the end of the thermocouple. The ends of the wire are stripped ends, which connect to the screw terminals on the DAQ

Table 3.1: Sensor and data acquisition system component list.

Item	Supplier	Website
USB-2416-4AO (DAQ)	Measurement Computing	mccdaq.com/usb-data-acquisition/USB-2416-Series.aspx
AI-EXP32 (DAQ Expansion Module)	Measurement Computing	mccdaq.com/usb-data-acquisition/USB-2416-Series.aspx
HP ENVY Laptop 17	HP	https://www.hp.com/us-en/shop/pdp/hp-envy-laptop-17-ch2747nr
PHFS-01 Heat Flux Sensor	FluxTeq	https://www.fluxteq.com/phfs-01-heat-flux-sensor

PHFS-09e Large Surface Area Heat Flux Sensor	FluxTeq	https://www.fluxteq.com/phfs-09e-large-area-heat-flux-sensor
Custom Heat Flux Sensor	FluxTeq	https://www.fluxteq.com/products
Type T PFA Coated Thermocouple Probe 1/8" Diameter 3" Long	Evolution Sensors and Controls	https://evosensors.com/collections/t/products/type-t-pfa-coated-thermocouple-probe-1-8-diameter-3-inches-long-with-a-grounded-junction-and-miniature-connector
Type T PFA Coated Thermocouple Probe 1/8" Diameter 6" Long	Evolution Sensors and Controls	https://evosensors.com/collections/t/products/copy-of-type-t-pfa-coated-thermocouple-probe-1-8-diameter-6-inches-long-with-a-grounded-junction-and-miniature-connector
Type T Thermocouple Extension Cable Miniature Female Connector and Stripped Leads	Evolution Sensors and Controls	https://evosensors.com/collections/miniature-female/products/type-t-thermocouple-extension-cable-5ft-long-with-miniature-female-connector-and-stripped-leads
Custom Compression Fitting	TC Measurement and Control Inc.	https://www.tc-inc.com/fittings/compression_fittings.html

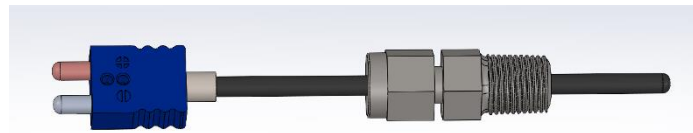


Figure 3.22: 3" Thermocouple with compression fitting.



Figure 3.23: Thermocouple cable with miniature flat pin female connector to stripped ends [27].

The heat flux sensors are thin, flat sensors, which sense the heat flux (W/m^2) and output a voltage that can be used to calculate a heat flux using the sensor's sensitivity value ($\text{V} / (\text{W/m}^2)$). The sensitivity of these sensors changes with temperature, and so a thermocouple is built into each of these sensors to allow the sensitivity value to be corrected and accurate heat flux values calculated. The thermocouples embedded in the heat flux sensors are also type T thermocouples and allow measurement of the temperature of flat surfaces such as the side of the copper block opposite the steel box.

To accurately measure the heat flux flowing through the 4" x 8" area of interest, custom built heat flux sensors were commissioned that measure exactly 4" x 8". These sensors were used whenever possible, but for some tests, they could not be employ. For example, the water block tests cannot use one large sensor to measure the flux out of the water block into the steel box because of the pressure relief system at the top of the box. The hybrid box has a similar issue with the pressure relief system at the interface between the copper and steel. In these cases, multiple smaller, off-the-shelf sensors are used such as, two 3.45" x 3.75" on either side of the pressure relief pipe. Figure 3.24 shows an image of the custom-made sensor. In the early stages of the project, four 1" x 1" sensors were used but later switched to the 3.45" x 3.75" for increased surface area and, thus, increased accuracy.

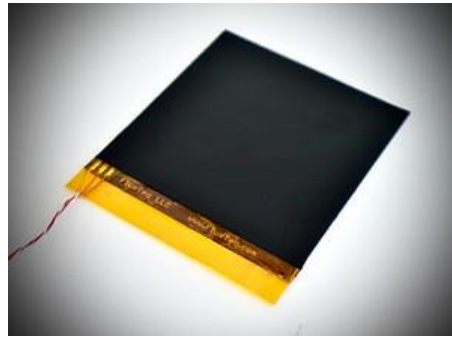


Figure 3.24: PHFS-09e large area heat flux sensor [28].

The wire leads of the sensors are connected to screw terminals on the DAQ. Some tests require more than 16 measurements and so an expansion module is connected, which adds another 16 channels. This DAQ connects via USB to a laptop where data acquisition companion software designed by the DAQ manufacturer is run. From the software, data can be collected and saved to .csv files for processing in MATLAB or Excel. The sample rate is set to 1 Hz for all channels because one watt over one second is one joule.

3.3 Test Procedure

Table 3.2 shows a list of all tests undertaken during this research. Not every material is tested with every possible setup due to time, money, and complexity constraints. For instance, TEGs were not used in the hybrid or TTC setup because the TEGs are very prone to breaking, which requires disassembling the test setup to replace the broken TEG. Disassembling a loaded TTC or hybrid box is dangerous and complicated because the chemicals are in powder form and can very easily spill out of the box, while the PCMs are solid blocks of material and are impossible to spill.

Table 3.2: List of every test permutation.

Heat Sink Material	Auxiliary Systems
HS58	None
	TEGs
	Local coolant loop
	TEGs and local coolant loop
HS72	None
	TEGs and local coolant loop
	Local coolant loop
HS78	None
	TEGs and local coolant loop
	Local coolant loop
TTC	None
Hybrid	None
	Local coolant loop only

HS58 is the only material to be tested with TEGs alone because it was considered the best-case scenario for TEGs alone. PCMs create a temperature difference across the TEGs by keeping one side at a constant temperature during the phase change, but HS72 and HS78 change phase at such a high temperature that the copper would exceed its maximum temperature long before the phase temperature is reached due to the temperature difference caused by the thermal resistance of the TEGs. The local coolant loop and TEGs are tested with all of the PCMs because the local coolant loops were predicted to reduce hotspots and help HS72 and HS78 melt completely before the copper exceeds its maximum temperature. The hybrid is tested with water blocks but not the TTC because the hybrid is just a better version of the TTC. The hybrid utilizes the exact same chemical reaction as the TTC but with a solid block of barium hydroxide octahydrate instead of layers of powdered barium hydroxide octahydrate.

It is imperative to make sure all the sensors readings make sense upon starting a test. Thermocouples should initially read room temperature and heat flux sensors should initially read zero, or close to it. Once heating is started, the heat flux sensors are checked to make sure their values are reasonable (1-10 W/in²). The labels on the thermocouple channels should also be checked, the bottom thermocouples should read hotter than the top in the PCM/TTC tests and opposite in the hybrid test. If any sensor is broken it must be replaced before the test continues,

3.3.1 PCM Alone Test Procedure

1. Fill the PCM box according to the procedure in section 3.1:
 - a. First, the PCM is melted by placing the sealed (to prevent moisture loss) PCM container in a hot water bath set well above the phase change temperature for about 24 hours. Next the aluminum fins are placed in the empty PCM box and the pressure fittings with thermocouples are threaded into place. Then, the now liquid PCM is poured into the box over and between the fins and let to cool and solidify.
2. Insert the four assembly bolts through the corner holes in the copper block and place it on the rigid insulation so the head of the bolts are flat against the insulation (Figure 3.21).
3. Insert the heaters into the copper block.
4. Place the 4" x 8" copper plate on top of the block.
5. Place a 4" x 8" heat flux sensor on top of the copper plate.
6. Align the PCM box's corner holes with the assembly bolts and slide it down onto the heat flux sensor. Do likewise with the PTFE gasket and box lid.
7. Place washers on the bolts and tighten the nuts down as hard as possible (Figure 3.3).
8. Place the insulation pieces around their respective components, starting with the copper block, then the PCM box, and finishing with the top piece (Figure 3.20).
9. Insert the assembly bolts through insulation corner holes, apply washer and nuts, tighten gently (Figure 3.20).
10. Apply Teflon tape to the end of the pipe on the pressure relief system, thread the pipe into the hole in the PCM box lid.
11. Connect the female ends of the thermocouple extension cables to the male ends of the thermocouples sticking out from the PCM box.
12. Connect the thermocouple extension cable wire leads to the screw terminals on the DAQ.
 - a. It is important to properly label the channels to know which channel is which thermocouple.
13. Connect the heat flux sensor wire leads to the screw terminals on the DAQ.
14. Connect the DAQ to the laptop, open the DAQ software, and start recording data.
 - a. Make sure the sample rate is 1 Hz.
 - b. Make sure the range on each channel is big enough to capture the entire expected signal but not too big, or the resolution becomes too large.
15. Connect the heaters to the power supply.
16. Turn on the power supply and set the desired wattage.
17. Let the test run until the PCM has completely melted.
 - a. You will know the PCM has finished melting when all the internal temperatures exceed the phase change temperature.
18. Once finished, save the data to a .csv, turn off the power supply, and remove the insulation from the sides of the system. (The top insulation cannot be removed while the pressure relief system is in place).
19. Let the entire system cool overnight. Once cool, it is safe to disassemble.
 - a. DO NOT open the PCM box while the PCM is still hot, all three PCMs are highly toxic.

3.3.2 TTC Alone Test Procedure

1. Insert the four assembly bolts through the corner holes in the copper block and place it on the rigid insulation so the head of the bolts are flat against the insulation (Figure 3.21).
2. Insert the heaters into the copper block.
3. Place the 4" x 8" copper plate on top of the block.
4. Place a 4" x 8" heat flux sensor on top of the copper plate.
5. Align the empty TTC box's corner holes with the assembly bolts and slide it down onto the heat flux sensor.
6. Fill the TTC box according to the procedure in section 3.2:
 - a. First, the pressure fittings with thermocouples are threaded into place. Next, both reactants are premeasured by weight into separate beakers. Then a thin layer (about 1/10th of the total reactant thickness) of one chemical is poured out into the box followed by a thin layer of the other chemical. This is repeated until both beakers are empty.
7. Slide the PTFE gasket onto the assembly bolts onto the TTC box, do likewise with the lid.
8. Place washers on the bolts and tighten the nuts down as hard as possible (Figure 3.9).
9. Place the insulation pieces around their respective components, starting with the copper block, then the TTC box, and finishing with the top piece (Figure 3.20).
10. Insert the assembly bolts through insulation corner holes, apply washer and nuts, tighten gently (Figure 3.20).
11. Apply Teflon tape to the end of the pipe on the pressure relief system, thread the pipe into the hole in the TTC box lid.
12. Connect the female ends of the thermocouple extension cables to the male ends of the thermocouples sticking out from the TTC box.
13. Connect the thermocouple extension cable wire leads to the screw terminals on the DAQ.
 - a. It is important to properly label the channels to know which channel is which thermocouple.
14. Connect the heat flux sensor wire leads to the screw terminals on the DAQ.
15. Connect the DAQ to the laptop, open the DAQ software, and start recording data.
 - a. Make sure the sample rate is 1 Hz.
 - b. Make sure the range on each channel is big enough to capture the entire expected signal but not too big, or the resolution becomes too large.
16. Connect the heaters to the power supply.
17. Turn on the power supply and set the desired wattage.
18. Let the test run until the copper block exceeds its maximum temperature.
19. Once finished, save the data to a .csv, turn off the power supply, and remove the insulation from the sides of the system. (The top insulation cannot be removed while the pressure relief system is in place).
20. Let the entire system cool overnight. Once cool, it is safe to disassemble.
 - a. DO NOT open the TTC box while it is hot, it is full of pressurized, hot ammonia gas and highly toxic solid products dissolved in water.

3.3.3 Hybrid Alone Test Procedure

1. Insert the four assembly bolts through the corner holes in the copper block and place it on a table so the heads of the bolts lay flat against the table (Figure 3.21).
2. Place the 4" x 8" copper plate on top of the block making sure the hole in the middle of the plate and block are aligned.
3. Place two 3.45" x 3.75" heat flux sensors on the copper plate, placing one on each side of the hole in the middle.
 - a. Make sure the area where the wire leads attach to the sensor are hanging just off the side of the plate, so they aren't crushed.
 - b. Make sure not to cover the hole as the sensors will be damaged by the NPT plug in the hybrid box.
4. Align the hybrid box's corner holes with the assembly bolts and slide it down onto the heat flux sensor. The NPT plug in the pressure relief hole should slot into the hole in the middle of the copper block.
5. Fill the hybrid box according to the procedure in section 3.3:
 - a. First, the correct weight of HS78 is placed in a container, sealed, and heated in a water bath set to 85 °C. Fins are cut out of steel foil and placed in the hybrid box. Once the HS78 is fully melted, it is poured into the box, making sure it is evenly dispersed. The HS78 is allowed to cool and solidify overnight. Once the HS78 has solidified, ammonium chloride is weighed out into a beaker and then poured over the top of the HS78.
6. Slide the PTFE gasket onto the assembly bolts onto the TTC box, do likewise with the lid.
7. Place washers on the bolts and tighten the nuts down as hard as possible (Figure 3.9).
8. Pick up the entire assembly and flip it upside down. Place the entire system onto the rigid insulation, letting the assembly bolts pierce into the insulation so that the lid of the box touches the insulation.
 - a. This step is very physically difficult due to the weight of the box, a partner is recommended.
 - b. It should look like Figure 3.26 once this step is complete. Note that the setup in that figure uses 4 small sensor, not 2 medium sensors.
9. Insert the heaters into the copper block.
10. Place the insulation pieces around their respective components, then the hybrid box, then the copper block, and finishing with the top piece (Figure 3.20).
11. Insert the assembly bolts through insulation corner holes, apply washer and nuts, tighten gently (Figure 3.20).
12. Apply Teflon tape to the end of the pipe on the pressure relief system, thread the pipe into the hole drilled into the base of the hybrid box (bottom of the TTC box).
13. Connect the female ends of the thermocouple extension cables to the male ends of the thermocouples sticking out from the TTC box.
14. Connect the thermocouple extension cable wire leads to the screw terminals on the DAQ.
 - a. It is important to properly label the channels to know which channel is which thermocouple.
15. Connect the heat flux sensor wire leads to the screw terminals on the DAQ.

16. Connect the DAQ to the laptop, open the DAQ software, and start recording data.
 - a. Make sure the sample rate is 1 Hz.
 - b. Make sure the range on each channel is big enough to capture the entire expected signal but not too big, or the resolution becomes too large.
17. Connect the heaters to the power supply.
18. Turn on the power supply and set the desired wattage.
19. Let the test run until all the thermocouples exceed 78 °C by at least a few degrees and the copper block has exceeded its maximum temperature.
20. Once finished, save the data to a .csv, turn off the power supply, and remove the insulation from the sides of the system. (The top insulation cannot be removed while the pressure relief system is in place).
21. Let the entire system cool overnight. Once cool, it is safe to disassemble.
 - a. DO NOT open the hybrid box while it is hot, it is full of pressurized, hot ammonia gas and highly toxic solid products dissolved in water.

3.3.4 PCM with TEGs Test Procedure

1. Fill the PCM box according to the procedure in section 3.1:
 - a. First, the PCM is melted by placing the sealed (to prevent moisture loss) PCM container in a hot water bath set well above the phase change temperature for about 24 hours. Next the aluminum fins are placed in the empty PCM box and the pressure fittings with thermocouples are threaded into place. Then, the now liquid PCM is poured into the box over and between the fins and let to cool and solidify.
2. Insert the four assembly bolts through the corner holes in the copper block and place it on the rigid insulation so the head of the bolts are flat against the insulation (Figure 3.21).
3. Insert the heaters into the copper block.
4. Place the 4" x 8" copper plate on top of the block.
5. Place a 4" x 8" heat flux sensor on top of the copper plate.
6. Apply the adhesive thermal pad onto the heat flux sensor.
7. Place the TEGs in a 2 x 4 array with the leads facing out (Figure 3.15).
8. Wire the TEGs in series, leaving the positive and negative leads of the first and last TEG open. Connect these leads via alligator clips to a 50 Ω resistor.
9. Wire two stripped wires into a DAQ terminal and connect them via alligator clips to each end of the resistor to measure the voltage output by the TEGs.
10. Place a second 4" x 8" heat flux sensor on top of the TEG array.
11. Align the PCM box's corner holes with the assembly bolts and slide it down onto the heat flux sensor. Do likewise with the PTFE gasket and box lid.
12. Place washers on the bolts and tighten the nuts down as hard as possible (Figure 3.3).
13. Place the insulation pieces around their respective components, starting with the copper block, then the PCM box, and finishing with the top piece (Figure 3.20).
14. Insert the assembly bolts through insulation corner holes, apply washer and nuts, tighten gently (Figure 3.20).
15. Apply Teflon tape to the end of the pipe on the pressure relief system, thread the pipe into the hole in the PCM box lid.

16. Connect the female ends of the thermocouple extension cables to the male ends of the thermocouples sticking out from the PCM box.
17. Connect the thermocouple extension cable wire leads to the screw terminals on the DAQ.
 - a. It is important to properly label the channels to know which channel is which thermocouple.
18. Connect the heat flux sensor wire leads to the screw terminals on the DAQ.
19. Connect the DAQ to the laptop, open the DAQ software, and start recording data.
 - a. Make sure the sample rate is 1 Hz.
 - b. Make sure the range on each channel is big enough to capture the entire expected signal but not too big, or the resolution becomes too large.
20. Connect the heaters to the power supply.
21. Turn on the power supply and set the desired wattage.
22. Let the test run until the PCM has completely melted.
 - a. You will know the PCM has finished melting when all the internal temperatures exceed the phase change temperature.
23. Once finished, save the data to a .csv, turn off the power supply, and remove the insulation from the sides of the system. (The top insulation cannot be removed while the pressure relief system is in place).
24. Let the entire system cool overnight. Once cool, it is safe to disassemble.
 - a. DO NOT open the PCM box while the PCM is still hot, all three PCMs are highly toxic.

3.3.5 PCM with Local Coolant Loops Test Procedure

1. Fill the PCM box according to the procedure in section 3.1:
 - a. First, the PCM is melted by placing the sealed (to prevent moisture loss) PCM container in a hot water bath set well above the phase change temperature for about 24 hours. Next the aluminum fins are placed in the empty PCM box and the pressure fittings with thermocouples are threaded into place. Then, the now liquid PCM is poured into the box over and between the fins and let to cool and solidify.
2. Insert the four assembly bolts through the corner holes in the first aluminum water block and place it on the rigid insulation so the head of the bolts are flat against the insulation (Figure 3.21, except with a water block not the copper block). Make sure the heads on the machine screws of the water block are facing down.
3. Align the copper block's corner holes with the assembly bolts and slide it down onto the aluminum water block.
4. Insert the heaters into the copper block.
5. Place the 4" x 8" copper plate on top of the block.
6. Place a 4" x 8" heat flux sensor on top of the copper plate.
7. Align the PCM box's corner holes with the assembly bolts and slide it down onto the heat flux sensor. Do likewise with the PTFE gasket and box lid.
8. Place two 3.45" x 3.75" heat flux sensors on the PCM box lid.
 - a. Make sure the area where the wire leads attach to the sensor are hanging just off the side of the plate, so they aren't crushed.

9. Align the second water block's corner holes with the assembly bolts and slide it down onto the heat flux sensor. Make sure the heads of the machine screws of the water block are facing up.
10. Place washers on the bolts and tighten the nuts down as hard as possible (Figure 3.3).
11. Place the insulation pieces around their respective components, starting with the bottom water block, then the copper block, the PCM box, the top water block, and finishing with the top piece (Figure 3.20).
12. Insert the assembly bolts through insulation corner holes, apply washer and nuts, tighten gently (Figure 3.20).
13. Apply Teflon tape to the end of the pipe on the pressure relief system, thread the pipe into the hole in the PCM box lid.
14. Connect the tubes for each coolant loop as follows, referring to Figure 3.19:
 - a. First, connect a tube from the pump output to the close connection on the bottom water block. Then, connect a tube from the far connection on the bottom water block to the far connection on the top water block. Then, connect a tube to the close connection on the top water block and place it into a beaker full of water. Then, connect a tube to the input of the pump and place it in the same beaker. Turn on the pump and wait until the loop fills with water. Once the loop is full of water, place a double ended barbed tube adapter onto one of the tubes in the beaker, hold both tubes under water and connect them under water. This creates a closed loop without the need for a reservoir. Repeat this process for the other loop, i.e. the other cavity in the water block.
15. Place wrap insulation around the tubes.
16. Connect the female ends of the thermocouple extension cables to the male ends of the thermocouples sticking out from the PCM box.
17. Connect the thermocouple extension cable wire leads to the screw terminals on the DAQ.
 - a. It is important to properly label the channels to know which channel is which thermocouple.
18. Connect the heat flux sensor wire leads to the screw terminals on the DAQ.
19. Connect the DAQ to the laptop, open the DAQ software, and start recording data.
 - a. Make sure the sample rate is 1 Hz.
 - b. Make sure the range on each channel is big enough to capture the entire expected signal but not too big, or the resolution becomes too large.
20. Connect the heaters to the power supply.
21. Turn on the power supply and set the desired wattage.
22. Let the test run until the PCM has completely melted.
 - a. You will know the PCM has finished melting when all the internal temperatures exceed the phase change temperature.
23. Once finished, save the data to a .csv, turn off the power supply, and remove the insulation from the sides of the system. (The top insulation cannot be removed while the pressure relief system is in place).
24. Let the entire system cool overnight. Once cool, it is safe to disassemble.
 - a. DO NOT open the PCM box while the PCM is still hot, these PCMs are highly toxic.

3.3.6 Hybrid with Local Coolant Loops Test Procedure

1. Insert the four assembly bolts through the corner holes in the first aluminum water block and place it on the rigid insulation so the head of the bolts are flat against the insulation (Figure 3.21, except with a water block not the copper block). Make sure the heads on the machine screws of the water block are facing down.
2. Align the copper block's corner holes with the assembly bolts and slide it down onto the aluminum water block.
3. Place the 4" x 8" copper plate on top of the block making sure the hole in the middle of the plate and block are aligned.
4. Place two 3.45" x 3.75" heat flux sensors on the copper plate, placing one on each side of the hole in the middle.
 - a. Make sure the area where the wire leads attach to the sensor are hanging just off the side of the plate, so they aren't crushed.
 - b. Make sure not to cover the hole as the sensors will be damaged by the NPT plug in the hybrid box.
5. Align the hybrid box's corner holes with the assembly bolts and slide it down onto the heat flux sensor. The NPT plug in the pressure relief hole should slot into the hole in the middle of the copper block.
6. Fill the hybrid box according to the procedure in section 3.3:
 - a. First, the correct weight of HS78 is placed in a container, sealed, and heated in a water bath set to 85 °C. Fins are cut out of steel foil and placed in the hybrid box. Once the HS78 is fully melted, it is poured into the box, making sure it is evenly dispersed. The HS78 is allowed to cool and solidify overnight. Once the HS78 has solidified, ammonium chloride is weighed out into a beaker and then poured over the top of the HS78.
7. Slide the PTFE gasket onto the assembly bolts onto the TTC box, do likewise with the lid.
8. Place two 3.45" x 3.75" heat flux sensors on the PCM box lid.
 - a. Make sure the area where the wire leads attach to the sensor are hanging just off the side of the plate, so they aren't crushed.
9. Align the second water block's corner holes with the assembly bolts and slide it down onto the heat flux sensor. Make sure the heads of the machine screws of the water block are facing up.
10. Place washers on the bolts and tighten the nuts down as hard as possible (Figure 3.9).
11. Pick up the entire assembly and flip it upside down. Place the entire system onto the rigid insulation, letting the assembly bolts pierce into the insulation so that the lid of the box touches the insulation.
 - a. This step is very physically difficult due to the weight of the box, a partner is recommended.
 - b. It should look like Figure 3.26 once this step is complete. Note that the setup in that figure uses 4 small sensor, not 2 medium sensors.
12. Insert the heaters into the copper block.

13. Place the insulation pieces around their respective components, then the hybrid box, then the copper block, and finishing with the top piece (Figure 3.20).
14. Insert the assembly bolts through insulation corner holes, apply washer and nuts, tighten gently (Figure 3.20).
15. Apply Teflon tape to the end of the pipe on the pressure relief system, thread the pipe into the hole drilled into the base of the hybrid box (bottom of the TTC box).
16. Connect the tubes for each coolant loop as follows, referring to Figure 3.19:
 - a. First, connect a tube from the pump output to the close connection on the bottom water block. Then, connect a tube from the far connection on the bottom water block to the far connection on the top water block. Then, connect a tube to the close connection on the top water block and place it into a beaker full of water. Then, connect a tube to the input of the pump and place it in the same beaker. Turn on the pump and wait until the loop fills with water. Once the loop is full of water, place a double ended barbed tube adapter onto one of the tubes in the beaker, hold both tubes under water and connect them under water. This creates a closed loop without the need for a reservoir. Repeat this process for the other loop, i.e. the other cavity in the water block.
17. Place wrap insulation around the tubes.
18. Connect the female ends of the thermocouple extension cables to the male ends of the thermocouples sticking out from the TTC box.
19. Connect the thermocouple extension cable wire leads to the screw terminals on the DAQ.
 - a. It is important to properly label the channels to know which channel is which thermocouple.
20. Connect the heat flux sensor wire leads to the screw terminals on the DAQ.
21. Connect the DAQ to the laptop, open the DAQ software, and start recording data.
 - a. Make sure the sample rate is 1 Hz.
 - b. Make sure the range on each channel is big enough to capture the entire expected signal but not too big, or the resolution becomes too large.
22. Connect the heaters to the power supply.
23. Turn on the power supply and set the desired wattage.
24. Let the test run until all the thermocouples exceed 78 °C by at least a few degrees and the copper block has exceeded its maximum temperature.
25. Once finished, save the data to a .csv, turn off the power supply, and remove the insulation from the sides of the system. (The top insulation cannot be removed while the pressure relief system is in place).
26. Let the entire system cool overnight. Once cool, it is safe to disassemble.
 - a. DO NOT open the hybrid box while it is hot, it is full of pressurized, hot ammonia gas and highly toxic solid products dissolved in water.

3.3.6 PCM with Local Coolant Loops and TEGs Test Procedure

1. Fill the PCM box according to the procedure in section 3.1:
 - a. First, the PCM is melted by placing the sealed (to prevent moisture loss) PCM container in a hot water bath set well above the phase change temperature for about 24 hours. Next the aluminum fins are placed in the empty PCM box and the pressure fittings with thermocouples are threaded into place. Then, the now liquid PCM is poured into the box over and between the fins and let to cool and solidify.
2. Insert the four assembly bolts through the corner holes in the first aluminum water block and place it on the rigid insulation so the head of the bolts are flat against the insulation (Figure 3.21, except with a water block not the copper block). Make sure the heads on the machine screws of the water block are facing down.
3. Align the copper block's corner holes with the assembly bolts and slide it down onto the aluminum water block.
4. Insert the heaters into the copper block.
5. Place the 4" x 8" copper plate on top of the block.
6. Place a 4" x 8" heat flux sensor on top of the copper plate.
7. Apply the adhesive thermal pad onto the heat flux sensor.
8. Place the TEGs in a 2 x 4 array with the leads facing out (Figure 3.15).
9. Wire the TEGs in series, leaving the positive and negative leads of the first and last TEG open. Connect these leads via alligator clips to a 50 Ω resistor.
10. Wire two stripped wires into a DAQ terminal and connect them via alligator clips to each end of the resistor to measure the voltage output by the TEGs.
11. Place a second 4" x 8" heat flux sensor on top of the TEG array.
12. Place a 4" x 8" heat flux sensor on top of the copper plate.
13. Align the PCM box's corner holes with the assembly bolts and slide it down onto the heat flux sensor. Do likewise with the PTFE gasket and box lid.
14. Place two 3.45" x 3.75" heat flux sensors on the PCM box lid.
 - a. Make sure the area where the wire leads attach to the sensor are hanging just off the side of the plate, so they aren't crushed.
15. Align the second water block's corner holes with the assembly bolts and slide it down onto the heat flux sensor. Make sure the heads of the machine screws of the water block are facing up.
16. Place washers on the bolts and tighten the nuts down as hard as possible (Figure 3.3).
17. Place the insulation pieces around their respective components, starting with the bottom water block, then the copper block, the PCM box, the top water block, and finishing with the top piece (Figure 3.20).
18. Insert the assembly bolts through insulation corner holes, apply washer and nuts, tighten gently (Figure 3.20).
19. Apply Teflon tape to the end of the pipe on the pressure relief system, thread the pipe into the hole in the PCM box lid.
20. Connect the tubes for each coolant loop as follows, referring to Figure 3.19:
 - a. First, connect a tube from the pump output to the close connection on the bottom water block. Then, connect a tube from the far connection on the bottom water block

- to the far connection on the top water block. Then, connect a tube to the close connection on the top water block and place it into a beaker full of water. Then, connect a tube to the input of the pump and place it in the same beaker. Turn on the pump and wait until the loop fills with water. Once the loop is full of water, place a double ended barbed tube adapter onto one of the tubes in the beaker, hold both tubes under water and connect them under water. This creates a closed loop without the need for a reservoir. Repeat this process for the other loop, i.e. the other cavity in the water block.
21. Place wrap insulation around the tubes.
 22. Connect the female ends of the thermocouple extension cables to the male ends of the thermocouples sticking out from the PCM box.
 23. Connect the thermocouple extension cable wire leads to the screw terminals on the DAQ.
 - a. It is important to properly label the channels to know which channel is which thermocouple.
 24. Connect the heat flux sensor wire leads to the screw terminals on the DAQ.
 25. Connect the DAQ to the laptop, open the DAQ software, and start recording data.
 - a. Make sure the sample rate is 1 Hz.
 - b. Make sure the range on each channel is big enough to capture the entire expected signal but not too big, or the resolution becomes too large.
 26. Connect the heaters to the power supply.
 27. Turn on the power supply and set the desired wattage.
 28. Let the test run until the PCM has completely melted.
 - a. You will know the PCM has finished melting when all the internal temperatures exceed the phase change temperature.
 29. Once finished, save the data to a .csv, turn off the power supply, and remove the insulation from the sides of the system. (The top insulation cannot be removed while the pressure relief system is in place).
 30. Let the entire system cool overnight. Once cool, it is safe to disassemble.
 - a. DO NOT open the PCM box while the PCM is still hot, these PCMs are highly toxic.

3.3.2 Control Test

Our corporate sponsor wanted to test the heat sink materials with 40 W over the course of 2 hours (288 kJ), but it was discovered that a tremendous amount of energy was being stored by the steel box or dissipated to the environment, and so it was necessary to supply much more than 40 W to ensure 40 W entered the heat sink material alone. This led to the development of a control test of an empty steel box stuffed full of insulation as shown in Figure 3.25 where the heat flux that entered the steel box was measured while heating the copper block at 40 W. The insulation and pressure relief were incorporated as in a normal test with the only difference being the lack of heat sink material. It was determined that about 21.5 kJ entered the PCM box, and 29 kJ entered the TTC box, resulting in 30 W and 40 W respectively when applied over 2 hours. This meant that PCM and TTC tests had to be conducted at 70 W and 80 W, respectively, to ensure that 40 W entered the heat sink material.

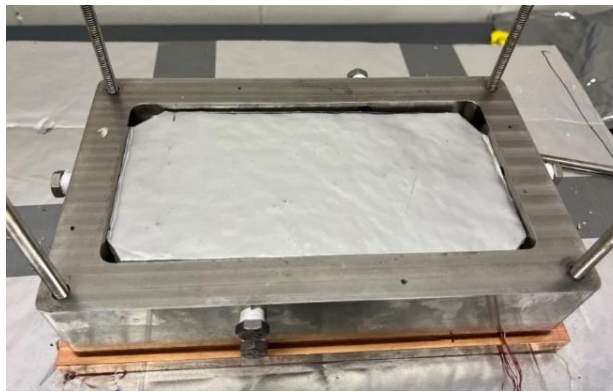


Figure 3.25: PCM box stuffed with insulation for control test.

Another reason for the control test was to allow us to determine how much energy enters the heat sink material alone. By adding up the total energy that enters a steel box filled with heat sink material and subtracting the energy that enters that steel box during the control test, it was possible to determine how much energy entered the heat sink material alone. This necessitated running a second round of control tests at 70 and 80 W for the PCM and TTC boxes, respectively. The hybrid box was also given a control test at 80 W because it is the same mass as the TTC box. The hybrid control test was conducted with an upside down TTC box, like the regular hybrid test, as shown in Figure 3.26.



Figure 3.26: Hybrid control test setup without insulation

Chapter 4 Results

4.1 Data Analysis Methods

Volumetric energy density (kJ/in^3) is the metric by which we decide to judge each heat sink material. The energy is calculated by measuring the heat flux (W/m^2) entering the steel box, multiplying that flux by the area of heat transfer ($4'' \times 8''$) to get heat rate (W), and summing that heat rate over time to get the energy (J). The energy is divided by the volume of the material in the box to arrive at the volumetric energy density. In the case of the local coolant loop, the heat rate on both sides of the box is calculated and then added together for the total heat rate. For the TEG system, the heat rate reading from the sensor in between the TEGs and steel box is used.

Because the temperature range of interest is 40°C - 85°C , only the heat rates in the period where the side of the copper block that interfaces with the steel box is in this temperature range are summed. The side that interfaces with the steel is the top of the copper block, except in the case of the hybrid test. In the TEG test, the copper interfaces with the steel through the TEGs, and the temperature is still measured at the surface of the copper. Table 4.1 gives a demonstration of what this looks like in a spreadsheet. Each row is 1 second and the data is made up for the purpose of illustration.

Table 4.1: Example spreadsheet to demonstrate energy summation within the given temperature range.

Time (s)	Copper Interface Temp ($^\circ\text{C}$)	Heat Rate (W)	Energy (J)
1000	39.8	40	0
1001	39.9	40	0
1002	40.0	40	0
1003	40.1	40	40
1004	40.2	40	80
--	---	---	--
9000	84.8	40	17960
9001	84.9	40	18000
9002	85.0	40	18040
9003	85.1	40	18040

Although the volumetric energy density is the metric by which a heat sink's performance is judged, its performance is also characterized through the temperature range. This can be achieved with a graph of energy on the y-axis and temperature on the x-axis as will be shown below.

As explained in Section 3.13, the energy that enters the material alone can be determined by subtracting the energy that entered the steel during the control test from the total energy. However, to create a graph, the control energy must be subtracted from every point in our data series. Unfortunately, there are a different number of data points in every test, so not every regular

data point can be matched up with a control data point for subtraction. Instead, a vector of evenly spaced numbers from 0 to the steel's energy is created with the exact same number of data points as the test data from which the subtraction must occur. This simplifying assumption is accurate since the control test did have a relatively constant heat rate as shown in Figure 4.1 where the heat rate into a PCM box is plotted during the 70 W control test.

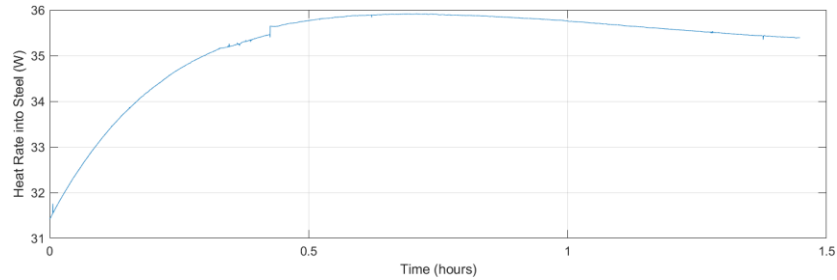


Figure 4.1: Heat rate into the PCM box during a control test with the heaters supplying 70 W.

4.2 PCMs Alone

The first set of tests conducted were the PCM tests without the local coolant loops or TEGs. Figure 4.2, Figure 4.3, and Figure 4.4 show plots of the temperature at the copper interface as well as the mean of the four lower (20%) and four upper (80%) thermocouple sets compared to the energy absorbed by the PCM alone. Note how the slope of each graph flattens as the temperature inside the PCM reaches the phase change temperature. Also note that the HS58 finishes melting the but HS72 and HS78 do not. HS58 finishes melting because both sets of thermocouples far exceeded the melting point of this PCM, and the slopes of the temperature lines become steep at the end again. This is because the phase change has completed, and only sensible heating of the liquid products is occurring. For HS72, only the bottom set of thermocouples exceed the melting point, meaning that only some of it has melted. For HS78, neither set of thermocouples exceeds the melting point. Thus, most of the HS78 did not melt.

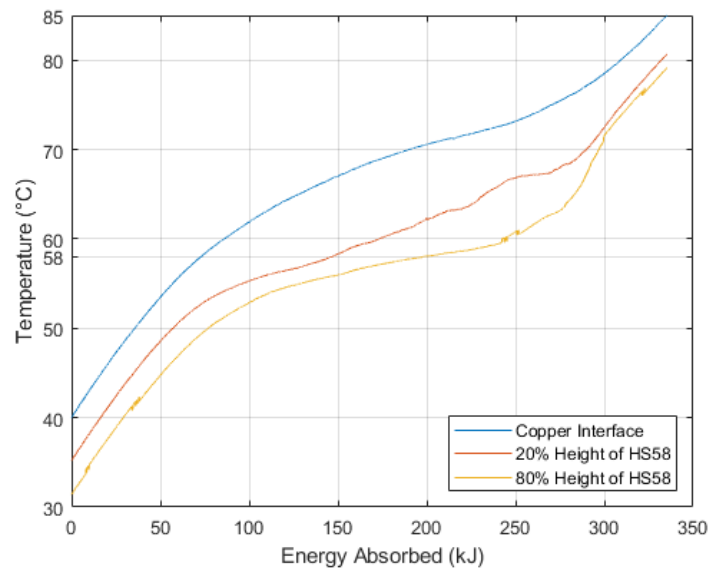


Figure 4.2: Temperature versus energy absorbed for the HS58 alone.

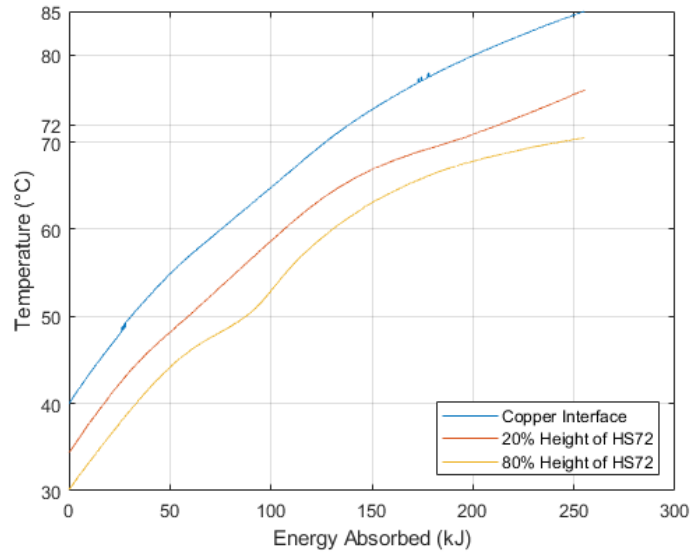


Figure 4.3: Temperature versus energy absorbed, HS72 alone.

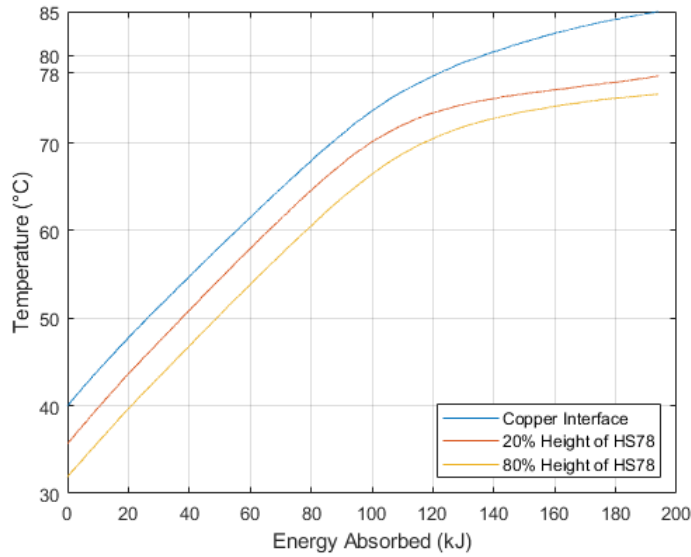


Figure 4.4: Temperature versus energy absorbed, HS78 alone.

Table 4.2 shows the experimentally derived volumetric energy densities of the three PCMs without the local coolant loops or TEGs. HS58 is by far the best PCM without the coolant loops or TEGs, which makes sense as it is the only one to fully change phase. The energy column in Table 4.2 refers to the energy entering just the material. The control energy has already been subtracted out. Also included in the table are the theoretical energy densities as calculated by Edwards [1] and the percent difference using the theoretical as the “actual” value.

One should note that HS72 performed about the same relative to its theoretical performance as the HS58 despite the HS58 fully melting and the HS72 only partially melting. This can be explained by referring back to Table 2.2 and seeing that the HS72 absorbs a larger proportion of its total energy in the first stage of heating, i.e., with the temperature rise of the solid, than the

HS58. By the time the phase change starts, HS72 has already absorbed 26.9% of its total energy while HS58 has only absorbed 11.3% of its total. HS72 stores relatively little energy in phase change compared to HS58 and HS78, which is why it performs so well despite not even finishing its phase change. HS78 absorbs the most during its phase change as a proportion of the total compared to HS58 and HS72, which is why it performs so poorly compared to the theoretical when it is unable to finish its phase change.

The reason the HS72 and HS78 cannot finish their phase change is due to the thermal resistance between the copper and the material inside the box. The contact resistance between the copper and the steel plus the resistance of the steel create a large temperature difference between the material at the bottom of the PCM box and the top of the copper. So even though the PCM inside the box is being held constant at the phase change temperature, the copper can still increase in temperature due to the thermal resistance between the PCM and copper. The expectation is that the local coolant loop will be able to more uniformly transfer the thermal energy from the copper block to the PCM and, thus, help the PCM complete its phase change before the copper exceeds the maximum temperature.

A reason why the experimental value for the energy density of the HS58 is less than its theoretical value could be that the amount of energy that the steel box absorbs was overestimated. It is likely that the control test overestimates the amount of energy absorbed by the box during a test because the PCM provides an easier path for the heat to take. This means that more energy is absorbed into the steel box during the control test than the regular tests and thus the experimental energy density values are lower than expected.

Table 4.2: Volumetric energy density of each PCM compared to its theoretical value.

Material	Energy (kJ)	Volume (in ³)	Experimental Density (kJ/in ³)	Theoretical Density (kJ/in ³)	Percent Difference
HS58	335.34	48	6.99	8.78	-20.4 %
HS72	255.29	48	5.32	6.72	-20.8 %
HS78	194.12	48	4.04	9.52	-57.5 %

4.2 TTC Alone

According to analysis by Edwards [1], the theoretical volumetric energy density value of the TTC system has to be corrected to account for the powder form of the chemicals being less dense than what is stated in the literature. The experimental value is compared to this corrected theoretical value, not the original, uncorrected value. Also, the TTC box is not filled all the way so that only 88 in³ of reactants are poured into the box, not the full 96 in³. The experimental value exceeds the theoretical, which could be because the energy that the steel box absorbs in the control test is underestimated or the energy that enters the steel box during the real test is overestimated.

Table 4.3: Volumetric energy density of the TTC system compared to the theoretical value.

Material	Energy (kJ)	Volume (in ³)	Experimental Density (kJ/in ³)	Theoretical Density (kJ/in ³)	Percent Difference
TTC	366.96	88	4.17	3.55	+17.5 %

Figure 4.5 shows the temperature at the copper interface as well as the mean of the lower (20%) and upper (80%) thermocouple sets compared to the energy absorbed by the TTC alone. The sudden drop in temperature near the end is due to the pressure relief valve opening, which cools off the system. Also note how the temperatures inside the TTC box are incredibly low at the start. The upper set is well below room temperature. This is due to the large temperature drop created by the endothermic reaction at the very start, which can be seen in Figure 4.6. Note the sudden drop in temperature around the 6 min mark in Figure 4.6. This occurred because the assembly nuts had not been tightened all the way, and then when they were at the 6 min mark, the steel and copper were brought into better contact, reducing the thermal resistance and increasing the heat flow from the copper into the steel and as a result reducing the copper's temperature. Because the heaters output a constant heat rate into the copper, decreasing the thermal resistance in a direction out of the copper will increase the heat that flows in that direction.

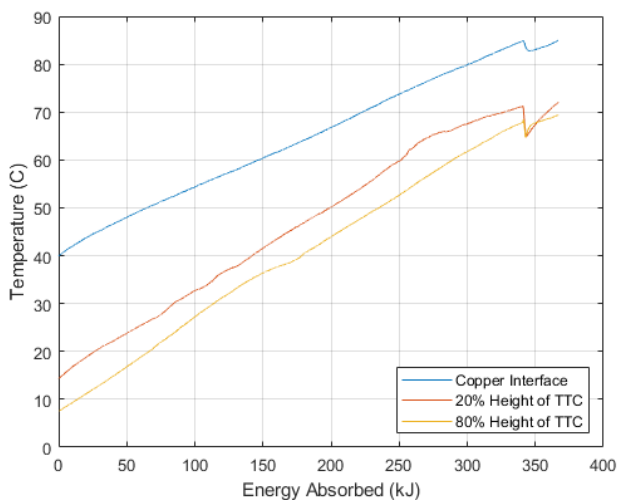


Figure 4.5: Temperature versus energy absorbed for the TTC alone.

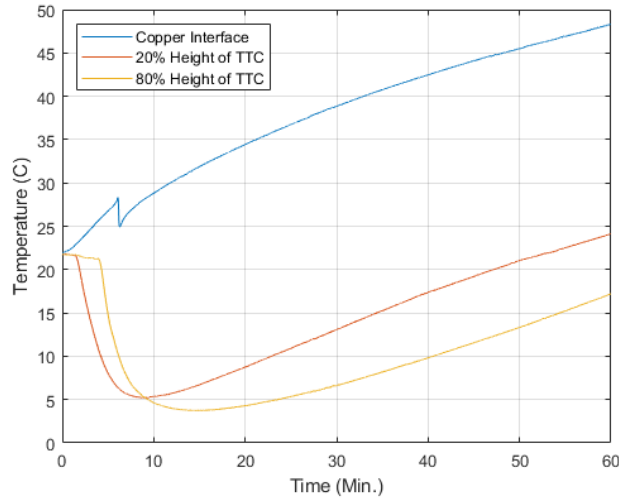


Figure 4.6: Temperature versus time for the TTC alone in the first hour.

4.3 Hybrid Alone

The results of the hybrid test are shown in Table 4.4. In its initial test, the hybrid system performed very poorly compared to its predicted theoretical performance. This is because the HS78 barely melted before the copper exceeded its maximum temperature. A major problem with this configuration is that the side of the HS78 that is closer to the copper melts first and this is the side that is the farthest from the ammonium chloride. This means that the small amount of HS78 that initially melts will never be in contact with the ammonium chloride and, thus, no reaction with the melted HS78 occurs. The only reaction that may occur and that only minimally is at the interface of the solid HS78 and the ammonium chloride.

Figure 4.7 shows a plot of the copper interface temperature versus energy absorbed by the hybrid system as well as the mean temperature at 20% and 80% of the height of the hybrid box. Note that the 20% height temperatures are lower than the 80% height temperatures, which is the opposite of the case for every other test (i.e., PCM, TTC, and initial hybrid). This is because the hybrid box for this test is flipped and the copper heats the steel box from above. The 80% height temperature begins to plateau as it nears 78 °C as in the HS78 PCM test, while the 20% height temperature does not. This is because the 20% height thermocouples sit within the ammonium chloride, which does not phase change. Also worth noting is that the temperature differences between the copper and the HS78 as well as the temperature difference between the 20% and 80% thermocouples is larger than in the HS78 PCM test. Because the copper heats from the top down, whenever the first bit of HS78 melts and falls away from the ceiling of the box, an air gap forms between the material and the ceiling of the hybrid box. This air gap greatly increases the thermal resistance between the copper and the heat sink material, increasing the temperature difference and leading to the copper exceeding its maximum temperature before the phase change can finish.

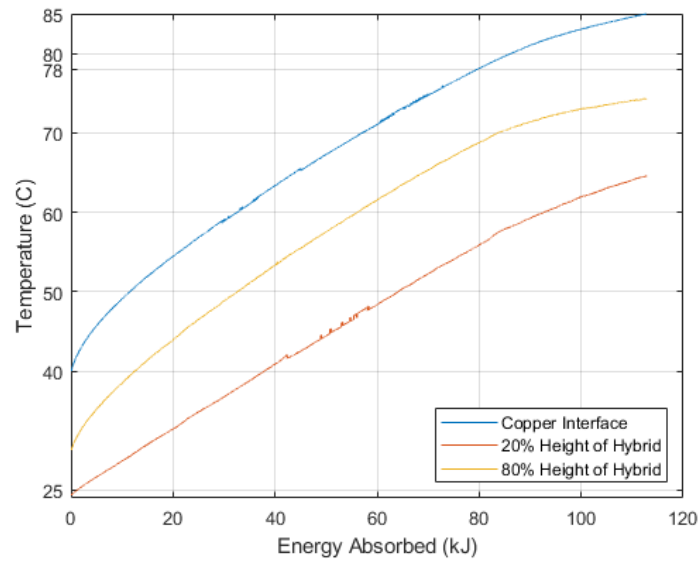


Figure 4.7: Temperature versus energy absorbed for the initial hybrid configuration alone.

Table 4.4: Volumetric energy density of the hybrid system compared to the theoretical value.

Material	Energy (kJ)	Volume (in ³)	Experimental Density (kJ/in ³)	Theoretical Density (kJ/in ³)	Percent Difference
Hybrid	112.88	96	1.18	13.99	-91.7 %

4.4 Local Coolant Loops

Table 4.5 shows the theoretical volumetric energy density, experimental energy density without the local coolant loops, experimental energy density with the local coolant loops, and the percentage difference between the experimental and theoretical values for both of the test permutations. Note that the HS78 and the hybrid both come much closer to their theoretical performance with the local coolant loops.

It may appear that HS58 and HS72 performed worse with the local coolant loops, but this is not necessarily the case. Unfortunately, the sensor arrangement used in the local coolant loop tests for HS58, HS72, and HS78 severely undermeasured the amount of thermal energy entering the steel box from the water block. Four 1" x 1" sensors were placed underneath the water block to measure the heat flow into the steel box, but the sensors were placed in areas where relatively little heat flux (W/m^2) was occurring because they could not be placed towards the middle of the block since that would crush the leads extending from the sensors. In fact, a couple of the sensors were damaged because initially they were placed towards the center of the block. Unfortunately, as a result of this, the volumetric energy density values for the PCM with the local coolant loops tests are lower than the actual value of the energy absorbed by the PCMs in those tests. It is important to note that the hybrid test with the local coolant loops used a different, much more accurate sensor arrangement. Instead of four 1" x 1" sensors, two 3.45" x 3.75" sensors were used, covering a much larger proportion of the area of heat transfer and, thus, providing a more realistic value for the heat flux and the energy absorbed.

Table 4.5: Experimental volumetric energy density values compared to the theoretical with and without the local coolant loops.

Material	Theoretical Volumetric Energy Density (kJ/in ³)	Experimental Volumetric Energy Density without the Local Coolant Loops (kJ/in ³)	Percent Difference Without the Local Coolant Loops	Experimental Density with the Local Coolant Loops (kJ/in ³)	Percent Difference with the Local Coolant Loops
HS58	8.78	6.99	-20.4 %	6.74	-23.2 %
HS72	6.72	5.32	-20.9 %	5.13	-23.7 %
HS78	9.52	4.04	-57.5 %	7.93	-16.7 %
Hybrid	13.99	1.18	-91.7 %	11.47	-18.0 %

Temperature versus energy absorbed graphs comparing each PCM test with and without the local coolant loops are shown in Figure 4.8, Figure 4.9, and Figure 4.10. The internal temperature curve in each of these figures represents an average of all 8 of the internal thermocouples. This was done so as not to crowd the figure.

Figure 4.8 shows that the average internal temperature in both tests far exceeded the phase change temperature for HS58 and, thus, all the material finished changing phase. Thus, the HS58 does not really benefit from the local coolant loops because the HS58 is able to fully change phase even without them. Any benefit would be to the heat source, which could be cooled more uniformly.

Looking only at the data presented in Table 4.5, it may seem that HS72 also does not benefit from the local coolant loops. However, it, in fact, does. Figure 4.9 shows that in both tests with and without the local coolant loops, the average internal temperature of HS72 is able to exceed the phase change temperature, but only with the local coolant loops does the temperature rapidly spike at the end, which indicates that all the material has finished changing phase. This means that even though the calculated volumetric energy density values are lower, HS72 did benefit from incorporating the local coolant loops.

Figure 4.10 shows that HS78 absorbs far more energy with the local coolant loops than without, even with the inaccurate sensor arrangement in the local coolant loops test. Also, the average internal temperature reaches the phase change temperature with the local coolant loops but not without them, meaning that the local coolant loops are absolutely necessary for an HS78 based TMS to function in the temperature range considered here.

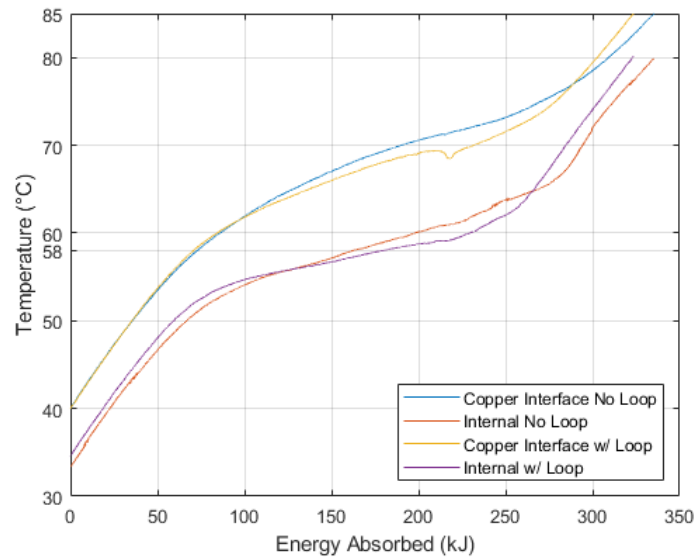


Figure 4.8: Temperature versus energy absorbed by the HS58 with and without the local coolant loops.

Figure 4.11 shows temperature against energy absorbed graph for the hybrid test with the local coolant loops. This graph was generated in Excel instead of MATLAB because the copper temperature exceeded 85 °C multiple times due to pump failures and it was easier to manipulate the data manually in Excel than automatically in MATLAB. Peristaltic pumps were used in this test, which quickly degraded due to the high temperature of the water. Whenever a pump degraded

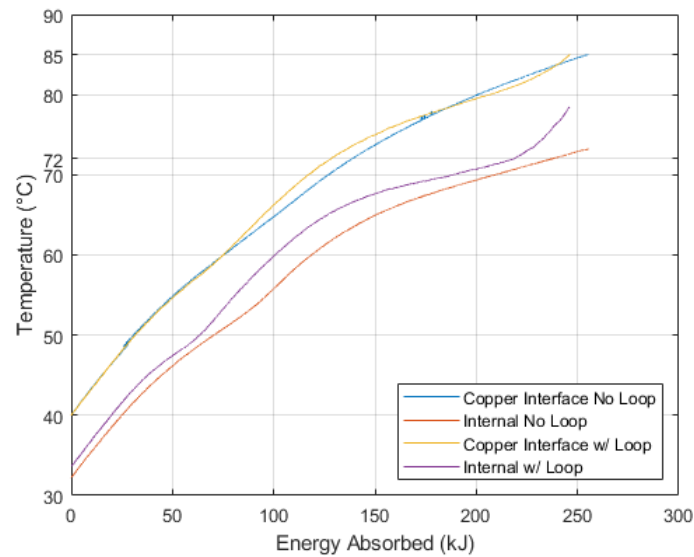


Figure 4.9: Temperature versus energy absorbed by the HS72 with and without the local coolant loops.

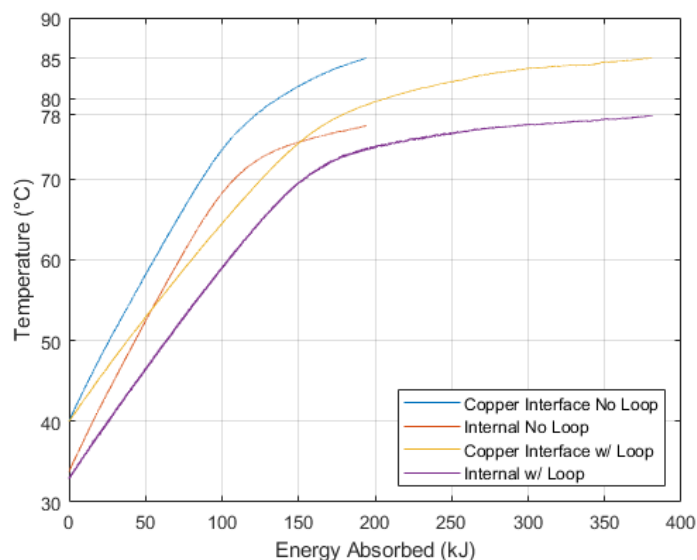


Figure 4.10: Temperature versus energy absorbed by the HS78 with and without the local coolant loops.

too much, it would stop pumping water, and the copper temperature would quickly spike. One can see pump failures at about 900 kJ, 1150 kJ, and 1400 kJ in this figure. The large drops in temperature around 500 kJ and 900 kJ were due to the use of a chemical fume hood. The fume hood created a fast flow of air, which increased the heat loss from the pressure relief system due to convection. This happened during the hybrid tests because the copper block is on top of the steel box, and so heat is able to pass very easily from the copper block to the pressure relief system. Thus, any increase in the heat loss through the pressure relief system quickly translates into a temperature drop in the copper. Once this was discovered, the fume hood was no longer used. Note that the top thermocouples have a higher temperature most of the time than the bottom thermocouples, which is the opposite as in every other test (i.e., PCM, TTC, and initial hybrid). This is because the copper heats the steel from above and so the material at the top heats up first.

Note the large temperature drop inside the box around the 1200 kJ point. This is likely caused by a large amount of the endothermic reaction occurring all at once and by the fact that the temperature of the copper remains relatively constant during this time. Temperature drops occur inside the box around 500 kJ and 900 kJ as well, but this is due to the fume hoods as seen in the corresponding temperature drop in the copper. Like HS78, the hybrid test requires the use of local coolant loops to be viable within the temperature range of interest due to the high phase change temperature of HS78.

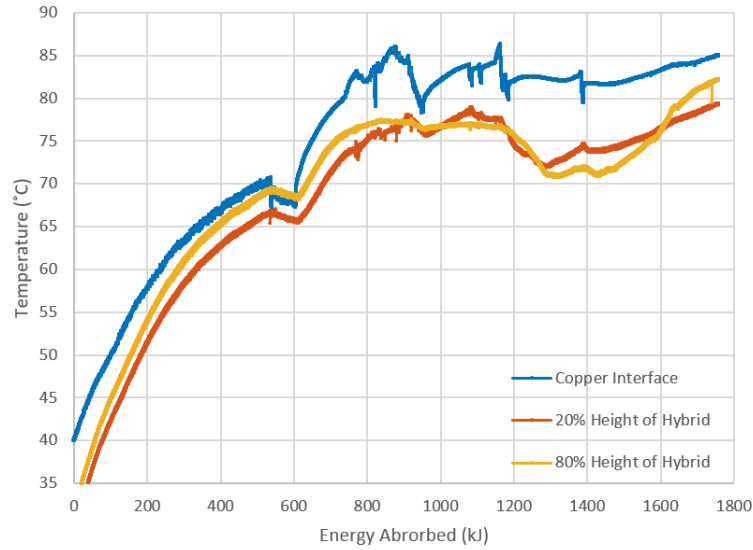


Figure 4.11: Temperature versus energy absorbed by the hybrid with the local coolant loops.

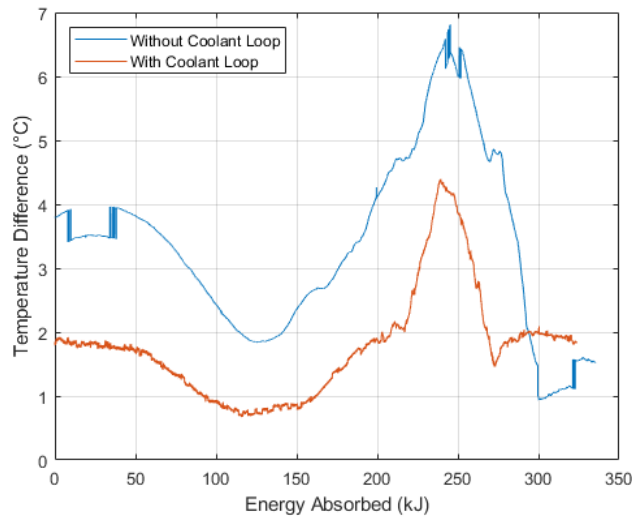


Figure 4.12: Temperature difference between the top and bottom thermocouples for the HS58 with and without the local coolant loops.

One of the main benefits of the local coolant loop is that it reduces the temperature gradient within a PCM. **Error! Reference source not found.**, Figure 4.13, and Figure 4.14 show the temperature difference between the bottom four thermocouples and the top four thermocouples in each PCM test with and without the local coolant loops. Note how the temperature difference is far smaller in every single local coolant loop test. One can conclude then that the local coolant loops are very effective at evening out the temperature within the heat sink material. This is also evidenced by the massive temperature difference in the hybrid test without the local coolant loops (Figure 4.7) and the relatively small temperature difference in the hybrid test with the local coolant loops (Figure 4.11).

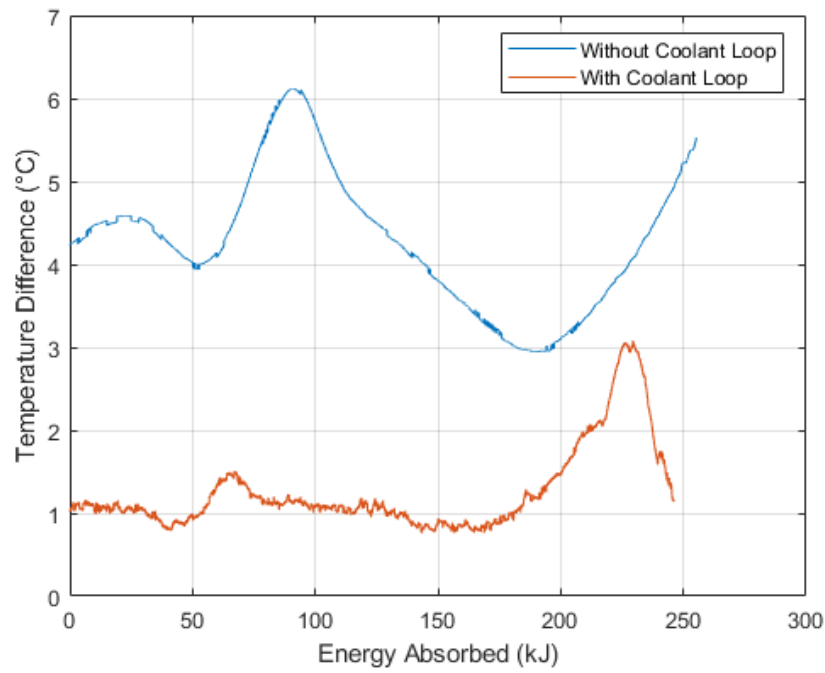


Figure 4.13: Temperature difference between the top and bottom thermocouples for the HS72 with and without the local coolant loops.

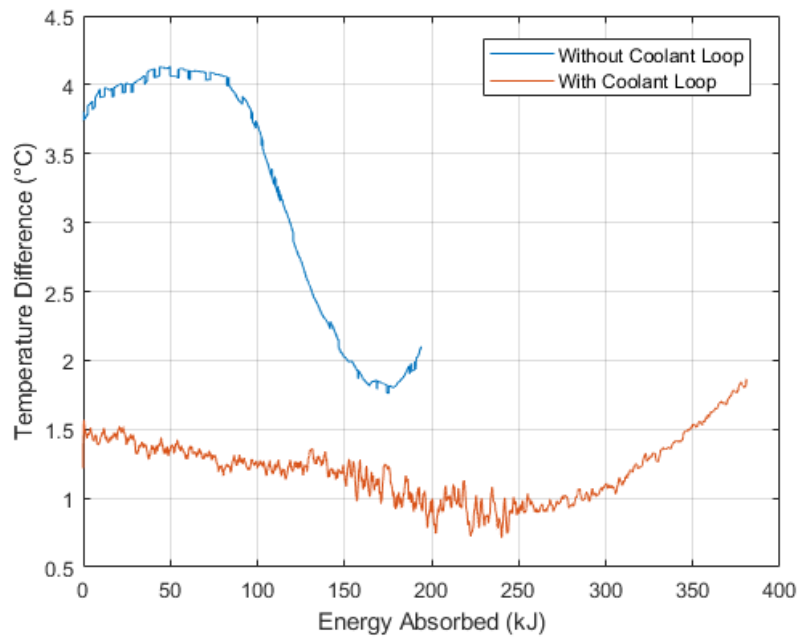


Figure 4.14: Temperature difference between the top and bottom thermocouples for the HS78 with and without the local coolant loops.

4.5 TEGs

For the TEG tests, a heat flux sensor is put on both sides of the TEG array to measure the heat flux into and out of the TEGs as well as the temperature on each side of the array. Initially, it was hoped that a difference between the heat entering the TEGs and the heat leaving the TEGs, could be measured, but our heat flux sensors are not precise enough to measure the relatively small difference. A much higher heat rate would be necessary for the sensors to be able to tell a difference. Higher precision heat flux sensors exist but are even more expensive than the custom ones that were used.

A control test with TEGs between a PCM box and the copper was conducted in order to subtract this amount from the total energy measured going into a PCM box with the PCM inside. Figure 4.15 shows a temperature versus energy absorbed graph of HS58. Note how the lines move into the negative at first. This is because the control has a higher heat rate when the copper is 40 °C. Figure 4.16 shows the heat rate of the control test with TEGs and the HS58 test with TEGs. Also plotted in that figure is the average value that is subtracted from all of the HS58 test data. Note that the control and HS58 lines only have the same length because they are plotted against temperature and not time. The control test and HS58 test took different amounts of time which is why the average is created and subtracted from the test data. The 48 in³ of HS58 with TEGs absorbed 41.3 kJ, which results in a volumetric energy density of 0.86 kJ/in³ and is -90.2% of the theoretical volumetric energy density of HS58. The reason so little energy is absorbed is that the TEGs increase the thermal resistance between the copper and steel. This added resistance increases the temperature difference between the copper and the steel so that the copper exceeds its maximum temperature before the HS58 can begin its phase change. The copper exceeding 85 °C before the phase change is the same reason the HS78 and the hybrid prototypes without the local coolant loops performed so poorly.

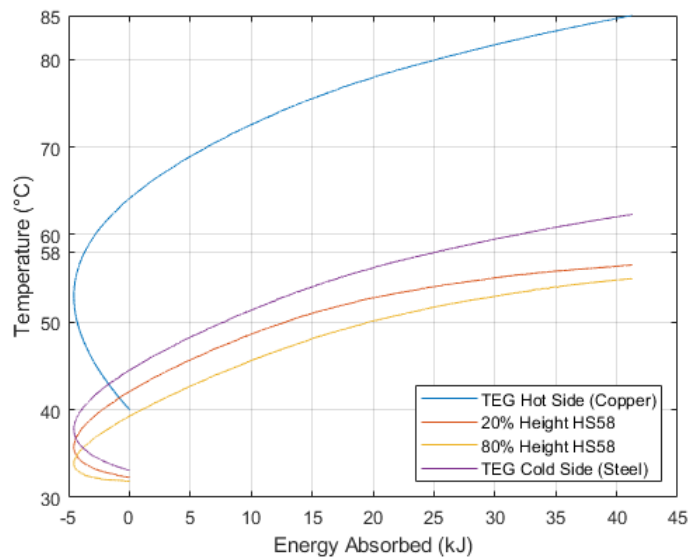


Figure 4.15: Temperature against energy absorbed by the HS58 with the TEGs.

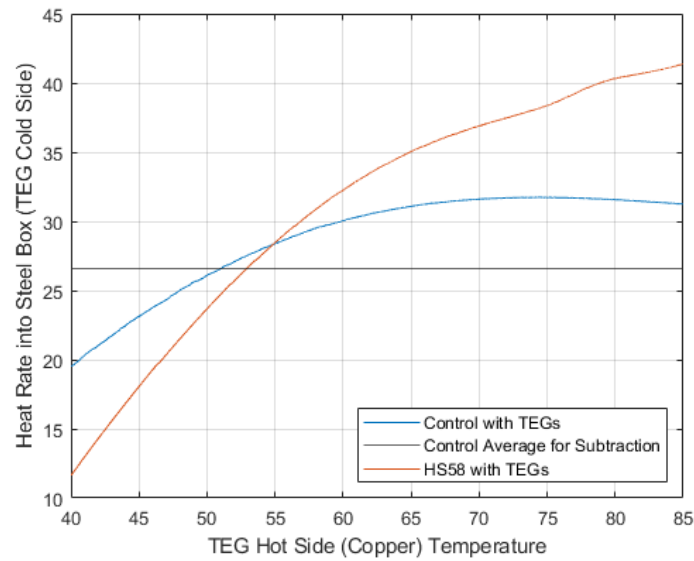


Figure 4.16: Heat rate of the control and HS58 test with the TEGs.

Figure 4.17 shows the power output of the TEG array using a 50 Ω resistor and the temperature difference across the TEGs. A single Dolomite piezoelectric pump requires 76 mW to operate, meaning this TEG array did generate enough power for at least 1 piezoelectric pump. If an ultra-low-power embedded system were developed to control the pumps, then one could theoretically control and power a pump just from the power generated by this TEG array.

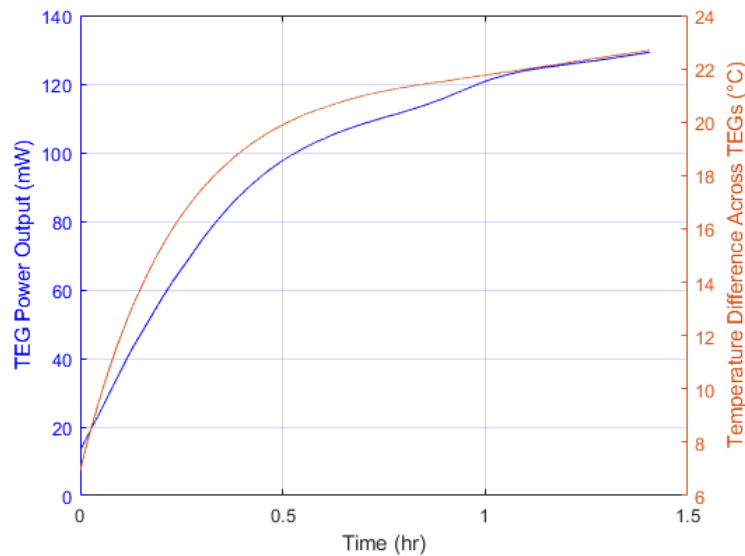


Figure 4.17: TEG power output versus time for the HS58 with TEGs.

Figure 4.18, Figure 4.19, and Figure 4.20 show the output voltage, TEG efficiency, and ZT value of the TEG array plotted against the temperature difference across the TEG array. The output voltage is measured across the 50 Ω . The output voltage is a straight line because the voltage generated across a TEG is linearly dependent on the temperature difference across it as expressed

in Eq. (4). With a $50\ \Omega$ load, the TEGs generate $0.11\ \text{V}/^\circ\text{C}$ temperature difference. A higher resistance increases this value up to a point and a lower resistance decreases the value to zero at $0\ \Omega$. Figure 4.19 shows a straight line for the efficiency as well. The TEG efficiency is linearly related to the temperature difference just like the voltage as expressed in equation 5. The ZT value of the TEGs is back calculated from the measured efficiency and hot- and cold-side temperatures using Eq. (5). One can see that the ZT values calculated here are very low, less than $1/10^{\text{th}}$ the reported ZT values of the commercial materials. The ZT is very low possibly because of the thermal resistance between the heat flux sensors and the TEGs, which would cause the heat flux sensors to record a higher temperature difference than what actually exists across the semiconductor material inside the TEG. If the temperature difference is increased but everything else held constant, then the calculated ZT value would necessarily be lower.

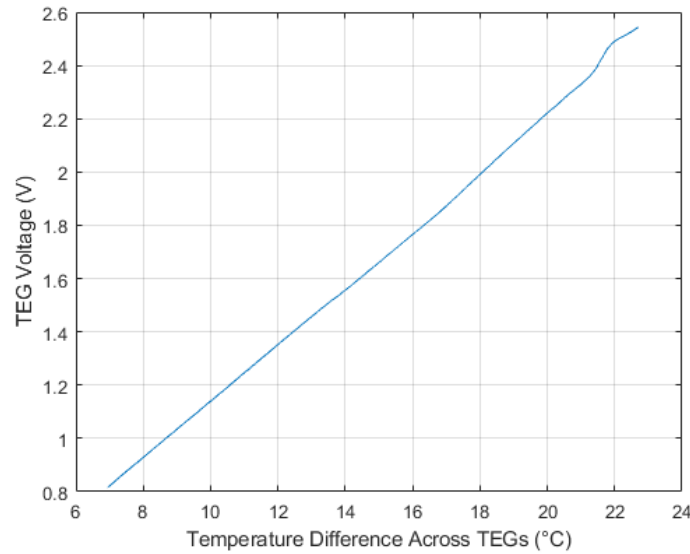


Figure 4.18: TEG output voltage against the TEG temperature difference.

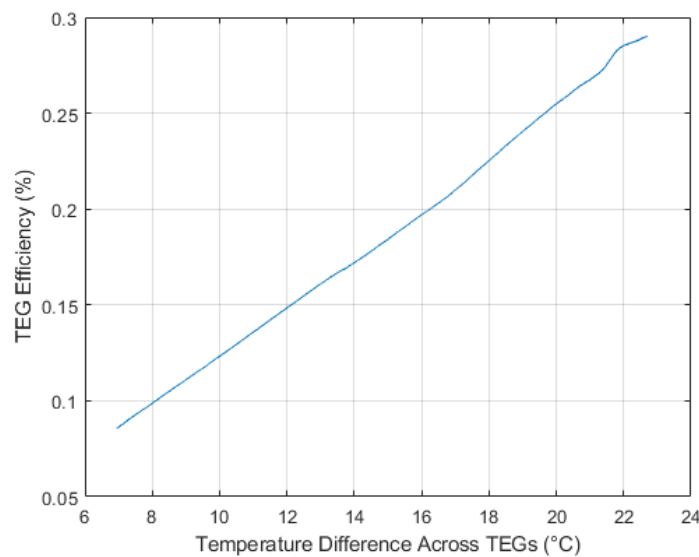


Figure 4.19: TEG efficiency against the TEG temperature difference.

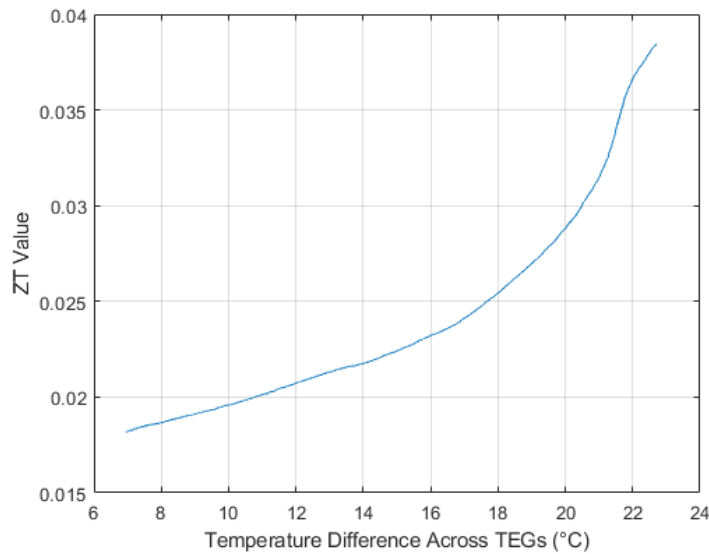


Figure 4.20: TEG array ZT value against the TEG temperature difference.

4.6 Local Coolant Loops and the TEGs

The HS58 test with the local coolant loops and TEGs used the inaccurate sensor arrangement between the water block and steel box as described earlier in section 4.4. The HS72 and HS78 tests used the more accurate sensor arrangement employed in the hybrid test with the local coolant loops. The reason that HS58 was conducted with a different sensor arrangement is that the larger custom sensors had not yet been made and it was deemed important not to delay the project. Unfortunately, it was only upon processing the data that it was realized how large the difference in accuracy was.

Table 4.6: Experimental volumetric energy density values compared to the theoretical with coolant loops and with and without TEGs.

Material	Theoretical Density (kJ/in ³)	Experimental Density with Coolant Loops without TEGs (kJ/in ³)	Percent Difference No TEGs	Experimental Density with Coolant Loops with TEGs (kJ/in ³)	Percent Difference with TEGs
HS58	8.78	6.74	-23.2 %	6.26	-28.7 %
HS72	6.72	5.13	-23.7 %	6.03	-10.3 %
HS78	9.52	7.93	-16.7 %	7.89	-17.1 %

Every material performed worse with the TEGs and the local coolant loops than with just the local coolant loops. This makes sense as the TEGs add thermal resistance which makes the copper exceed its maximum temperature sooner, thus, reducing the time spent absorbing energy. The difference in performance with the HS72 is within the margin of error of our heat flux sensors.

HS58 with TEGs and local coolant loops absorbs considerably more energy than HS58 with TEGs alone. This is because the local coolant loops decrease the thermal resistance between

the heat sink material and the copper block, which is the exact opposite of what the TEGs do. Judging by the volumetric energy density alone, local coolant loops are necessary if one wants to include TEGs.

The local coolant loops not only decrease the thermal resistance between the heat sink material and the copper, they also decrease the temperature gradient that exists within the heat sink material. Without a local coolant loop, heat enters the material from one side, creating a hot and cold side with a large temperature difference. Comparing the curves shown in Figure 4.21, Figure 4.22, and Figure 4.23 with Figure 4.2, Figure 4.3, and Figure 4.4, it is evident how much smaller the temperature difference between the 20% and 80% thermocouples is in the local coolant loop tests than the PCM tests without local coolant loops.

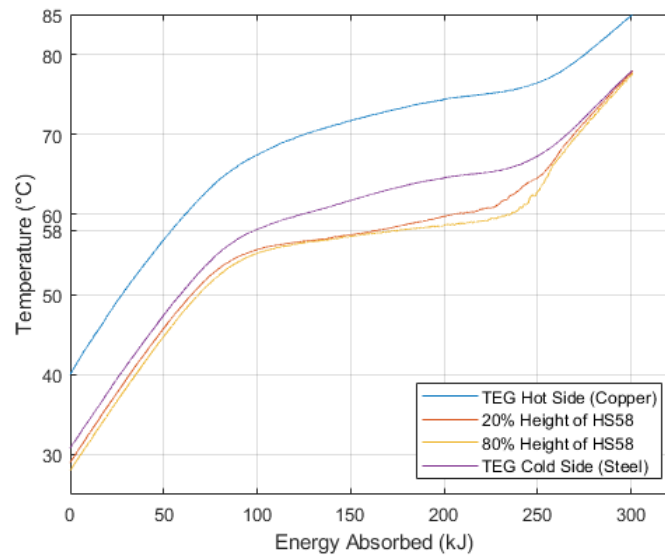


Figure 4.21: Temperature versus energy absorbed by the HS58 with coolant loops and TEGs.

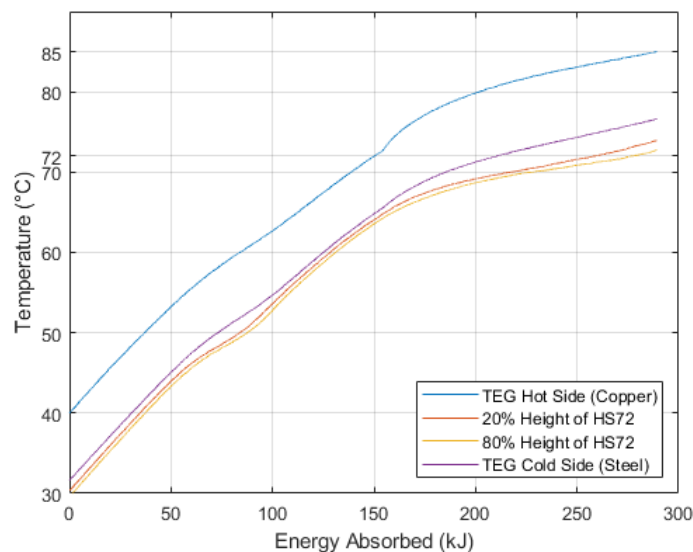


Figure 4.22: Temperature versus energy absorbed by the HS72 with coolant loops and TEGs.

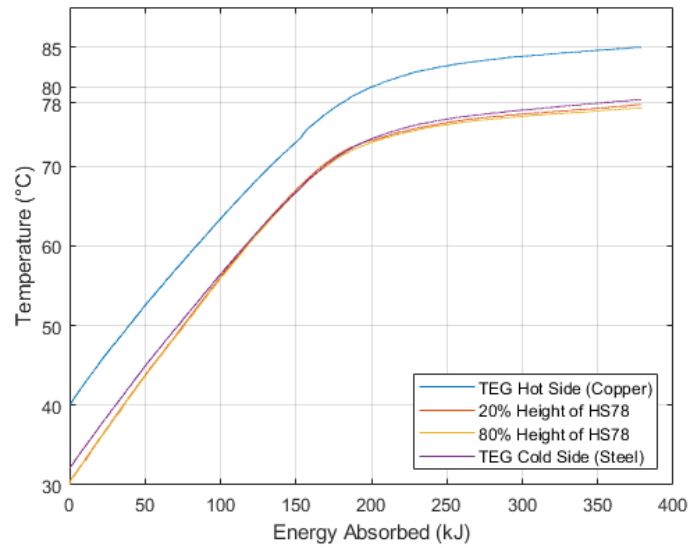


Figure 4.23: Temperature versus energy absorbed by the HS78 with coolant loops and TEGs.

Figure 4.24 shows the power output from the HS58 with the TEG array test when coupled with a local coolant loop. This figure should be contrasted with Figure 4.17. Note how the power output from the TEGs with a local coolant loop is far less than the TEGs without a local coolant loop. The average power output from the TEGs with a local coolant loop is 9.2 mW compared to the 97.6 mW from the TEGs without a local coolant loop. At no point did the TEGs with a local coolant loop come close to generating enough power to power a single piezoelectric pump. This indicates that local coolant loops counteract the effectiveness of the TEGs, at least when the local coolant loops run at 20 mL/min constantly.

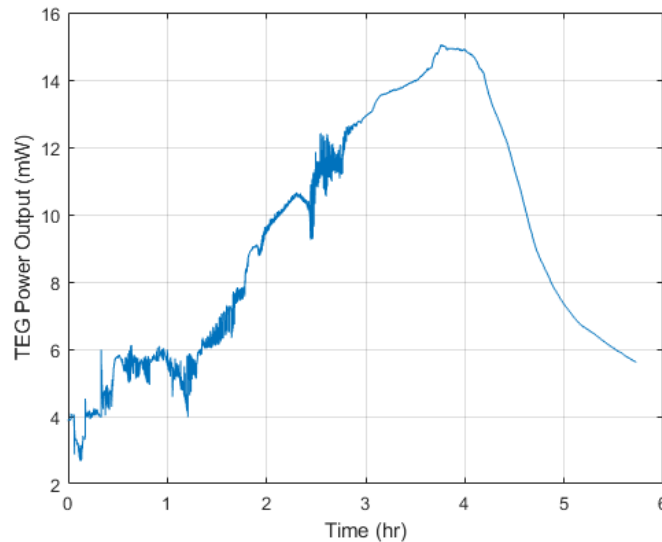


Figure 4.24: TEG power output versus time for the HS58 with coolant loops and TEGs.

It was theorized that the TEGs could power the pumps during times of high temperature difference, which would decrease the temperature difference and then eventually decrease the TEG power so that the pump would stop working. The temperature difference would then increase again and the cycle would repeat. Unfortunately, because the controller on the pumps requires so much energy, it was never possible to directly power any piezoelectric pump with the TEG output.

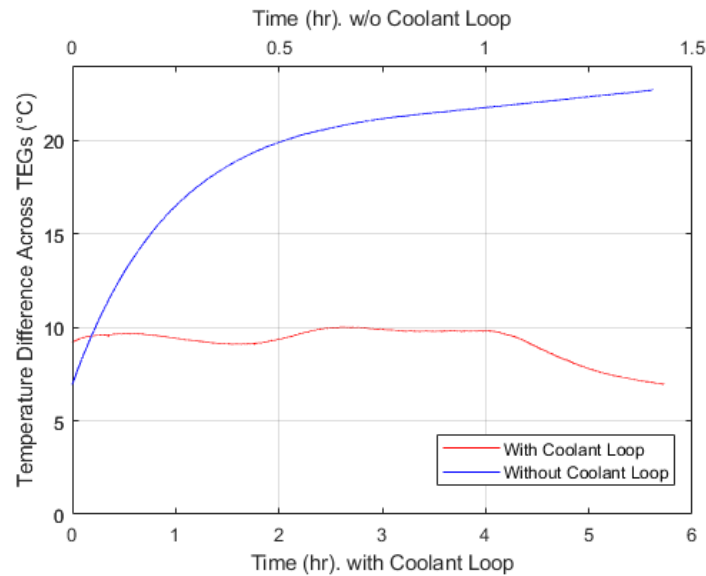


Figure 4.25: Temperature difference across the TEGs versus time for the HS58 with coolant loops and without coolant loops.

The reason there is so much less power generated when local coolant loops are present is due to the temperature difference across the TEGs. Figure 4.25 shows a plot of the temperature difference across the TEGs over time for the HS58 with TEGs and a local coolant loop and HS58 with just TEGs. Note how without the local coolant loop, the temperature difference across the TEGs is much higher than in the test with a local coolant loop. In fact, it is more than double the difference. Because the TEGs with the local coolant loop have a lower temperature difference, they have a lower efficiency. The heat rate through the TEGs is also lower because conduction through a solid is linearly related to the temperature difference. Thus, the smaller temperature difference decreases the power output by decreasing the amount of electricity generated per watt of heat transfer and decreasing the amount of heat transfer. Plots of voltage, efficiency, and ZT value are not provided for the TEGs with the local coolant loop tests because the TEGs behave very erratically at these small heat rates. Note how random the TEG power output is at the start of Figure 4.24.

4.7 Sensor Arrangement

To give a sense of the scale of the impact from the inaccurate sensor arrangements, Table 4.7 and Table 4.8 have been compiled. Both tables show the mean wattage into the steel box from the water block and the copper block, with Table 4.7 summarizing the local coolant loops tests and Table 4.8 summarizing the local coolant loops with TEGs tests. All tests used the inaccurate sensor arrangement except for HS72 and HS78 with the local coolant loops and TEGs. These particular

entries are highlighted. Note how in Table 4.7, the HS58 test sees more wattage from the water block than the HS72 or HS78. This is flipped in Table 4.8.

We can see that the percentage of the total heat that passes through the water block is about constant between both HS58 tests so it is assumed that that should be the case for the HS72 and HS78 test. Next, it is assumed that there is a correction factor X , which can multiply the water block wattage value to align it with the accurate values. This correction factor can be calculated by assuming that, for a given material, the same proportion of the total wattage comes through the water blocks with or without TEGs. To calculate this factor for HS72, the following is done:

$$\frac{2.61X}{2.61X + 24.73} = \frac{9.33}{9.33 + 16.95} = 35.5\%, \quad X = 5.22$$

Doing the same for HS78, the correction factor is found to be

$$\frac{1.83X}{1.83X + 25.57} = \frac{5.78}{5.78 + 14.29} = 28.8\%, \quad X = 5.65$$

The fact that both these X values are similar in magnitude implies that the inaccurate sensor readings are a specific fraction of the accurate readings. Correcting the water block wattage values for HS58, HS72, and HS78 with the local coolant loops results in a 48%, 38%, and 27% increase in the total wattage. The same correction for HS58 with the local coolant loops and TEGs results in a 59% increase in the total wattage. The energy density values in the tables still reflect the inaccurate sensor configuration so these factors here are simply to illustrate the impact of the inaccurate sensor arrangement.

Table 4.7: Impact of heat flux sensor inaccuracies with the local coolant loops and without TEGs.

Material	Mean WB Wattage	Mean Interface Wattage	Mean Total Wattage	WB % of Total
HS58	4.09	29.82	33.91	12.1 %
HS72	2.61	24.73	27.34	9.5 %
HS78	1.83	25.57	27.40	6.7 %

Table 4.8: Impact of heat flux sensor inaccuracies with the local coolant loops and TEGs.

Material	Mean WB Wattage	Mean Interface Wattage	Mean Total Wattage	WB % of Total
HS58	3.12	18	21.12	14.8 %
HS72	9.33	16.95	26.28	35.5 %
HS78	5.78	14.29	20.07	28.8 %

Chapter 5 Conclusions and Recommendations

5.1 Conclusions on Proposed Technologies

Table 5.1 displays the volumetric energy densities of every test compared to the theoretical value. HS58 performed the best among tests that did not use coolant loops or TEGs. HS78 was the best performing PCM among tests with local coolant loops, but the hybrid test is the best heat sink material overall with a local coolant loop. HS78 is also the best heat sink material to have been tested with local coolant loops and TEGs. It is likely that the hybrid test would have outperformed HS78 with local coolant loops and TEGs, but we did not run such a test.

Reed, von Spakovsky, and Raj [5] found that paraffin-based PCMs currently used as heat sink materials have volumetric energy densities of $\sim 2.6 \text{ kJ/in}^3 - 3.2 \text{ kJ/in}^3$. Every heat sink material tested in this report outperforms these paraffin-based materials. It is important to note that the PCMs, HS58, HS72, and HS78, are all reusable while the TTC and hybrid tests are not. The hybrid may perform the best, but it is also the most complicated to set up.

Table 5.1: Experimental volumetric energy density of every test compared with the theoretical volumetric energy density values.

Material Alone	Theoretical Density (kJ/in ³)	Experimental Density (kJ/in ³)	Percent Difference
HS58	8.78	6.99	-20.4 %
HS72	6.72	5.32	-20.8 %
HS78	9.52	4.04	-57.6 %
TTC	3.55	4.17	+17.5 %
Hybrid	13.99	1.18	-91.6 %
Material with Coolant Loops	Theoretical Density (kJ/in ³)	Experimental Density (kJ/in ³)	Percent Difference
HS58	8.78	6.74	-23.2 %
HS72	6.72	5.13	-23.7 %
HS78	9.52	7.93	-16.7 %
Hybrid	13.99	11.47	-18.0 %
Material with TEGs	Theoretical Density (kJ/in ³)	Experimental Density (kJ/in ³)	Percent Difference
HS58	8.78	0.86	-90.2 %
Material with Coolant Loops and TEGs	Theoretical Density (kJ/in ³)	Experimental Density (kJ/in ³)	Percent Difference
HS58	8.78	6.26	-28.7 %
HS72	6.72	6.03	-10.3 %
HS78	9.52	7.89	-17.1 %

TEGs alone create so much thermal resistance that the copper block exceeds its maximum temperature before any appreciable amount of energy can be absorbed, and for that reason, TEGs alone are not a viable technology the way they were used here. Major advances in ZT values would have to take place for TEGs to be able to generate enough power without creating too much thermal resistance. It is possible that TEGs can be viable when paired with a local coolant loop, but as seen in Chapter 4, the coolant loop drastically reduces the power output of the TEGs. If one were to directly power the pumps with the TEGs, then the pumps would only turn on when there is sufficient temperature difference across the TEGs to generate enough power. Once the pumps turn on, the temperature difference quickly decrease, and the power output falls. Once the power output falls by enough, the pumps stop, the temperature difference begins to rise, and the cycle begins again.

Table 5.1 shows us that HS78 and the hybrid heat sink perform substantially better with a local coolant loop than without. HS78 and the hybrid have the highest energy densities of all the materials and so local coolant loops are necessary to achieve the highest energy density possible with our setup.

Table 5.2: Volumetric energy densities with coolant loop volume.

Material with Coolant Loops	Experimental Density without Loop Volume (kJ/in ³)	Effective Density (kJ/in ³)
HS58	6.74	3.00
HS72	5.13	2.28
HS78	7.93	3.52
Hybrid	11.47	7.06

Table 5.2 shows us effective volumetric energy density values that incorporate the volume of the coolant loop (60 in³). The PCMs all had a volume of 48 in³ so adding the 60 in³ of the coolant loop decreases the energy density to less than half the original value. The hybrid energy density value is not impacted as much because the hybrid had 96 in³ of volume to start with, so adding 60 in³ has a smaller proportional effect. Note that the effective energy density of the hybrid with coolant loops is almost the same as the energy density of the HS58 alone, so HS58 becomes more competitive with the hybrid if space is at a premium

5.2 Analysis and Modeling Recommendations

The experimental volumetric energy density of the TTC reaction exceeded the theoretical value by 17.5%, indicating that our model underestimated this energy density. This would make sense because the theoretical calculations did not include the sensible heating of the products and reactants. It is also possible that the amount of energy absorbed by the TTC box was underestimated during the control test or that the sensor arrangement on the full test was over measuring the heat flux due to local hot spots.

HS58 and HS72 alone performed worse than their theoretical values by almost the exact same percentage, which indicates that the control test is probably to blame. This is a reasonable conclusion because it is highly unlikely that the sensor arrangement for the PCM only tests was inaccurate as the entire heat transfer area was covered by a heat flux sensor. HS78 and the hybrid alone performing poorly is to be expected because the phase change temperature is so close to the maximum allowable temperature of the copper heat source.

5.3 Recommended Solution

The steel boxes used in this project are too heavy, absorb too much of the total energy, and create too much thermal resistance between heat source and heat sink material. The control test method used to subtract out the energy absorbed by the steel box alone is an imperfect method. It would be better to have a container that is so light that it stores a negligible amount of energy. A recommendation for a better heat sink box would be to make it out of aluminum, make the walls far thinner (less than 1/8"), and design the box so it can be sealed by itself instead of needing to be sealed in the full test assembly. Having much thinner walls would drastically reduce the thermal resistance between the heat source and the heat sink material. Reducing this resistance may even allow HS78 and hybrid systems to perform to their full potential without the need for a local coolant loop.

Increasing the thermal conductivity inside the PCMs could also reduce the necessity of the coolant loop. A superior fin assembly, a metal foam structure, or a system of heat pipes could all be used to increase the thermal conductivity inside the PCM. Heat pipes would have to be designed to account for the acceleration and vibration of hypersonic flight.

Another recommendation is to put heat flux sensors on every possible surface of the heat sink box. If every surface is covered by a heat flux sensor, then losses can be more accurately measured and accounted for. The control test was used to account for losses because it was assumed that the losses present in the control test are exactly equal to those during a real test, but this may not be completely correct. If all losses can be taken into account, then one could simply use the mass, temperature rise, heat capacity of the box to calculate the energy that entered the heat sink box alone.

The sensor arrangements in these tests are over complicated. Each thermocouple at the same height reads about the same temperature, so one could just use a single thermocouple at 20% and 80% instead of four. This would open room on the sides of the box for heat flux sensors. A multipoint thermocouple would allow measurements to be taken along the length of a single sensor, reducing complexity without reducing the data collected.

An improvement that could be made for the local coolant loops is to use insulated plastic tubes to carry the coolant. Most (>75%) of the energy that entered the coolant loop at the copper block was lost to the environment via the tubes. This did not impact the accuracy of the volumetric energy density values found because these are calculated from the energy that enters the steel box which was measured. This loss does mean that the time data is meaningless because a local coolant loop test experiences a lower heat rate entering the box. This lower heat rate means that the local coolant loop tests take longer, and so we cannot compare the time it takes for the copper to exceed the maximum temperature between tests. This is why virtually every graph uses the energy

absorbed on the x-axis, because half of the heat rate over double the time results in the same amount of energy.

Finally, an important improvement would be to use high temperature peristaltic pumps. The pumps used here had a maximum temperature of 60 °C which caused them to fail during testing. High temperature pumps are very expensive which is why they were not used here. The Dolomite piezoelectric pumps have a maximum temperature of 50 °C and so any system that would seek to incorporate piezoelectric pumps would need to find ones with higher maximum temperatures.

Appendix A Engineering Drawings

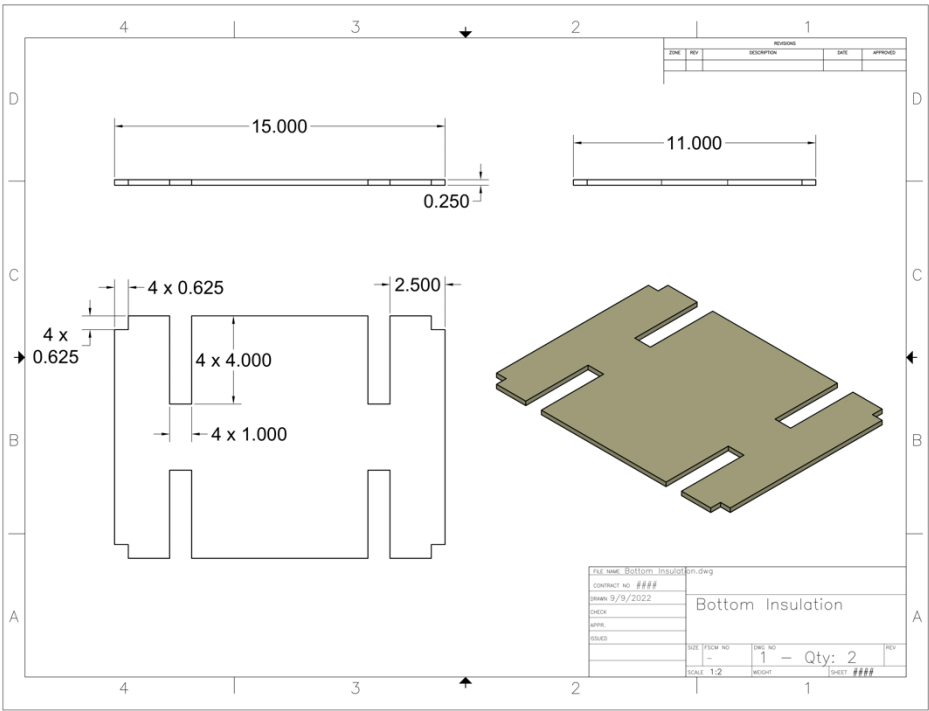


Figure A.1: Bottom insulation.

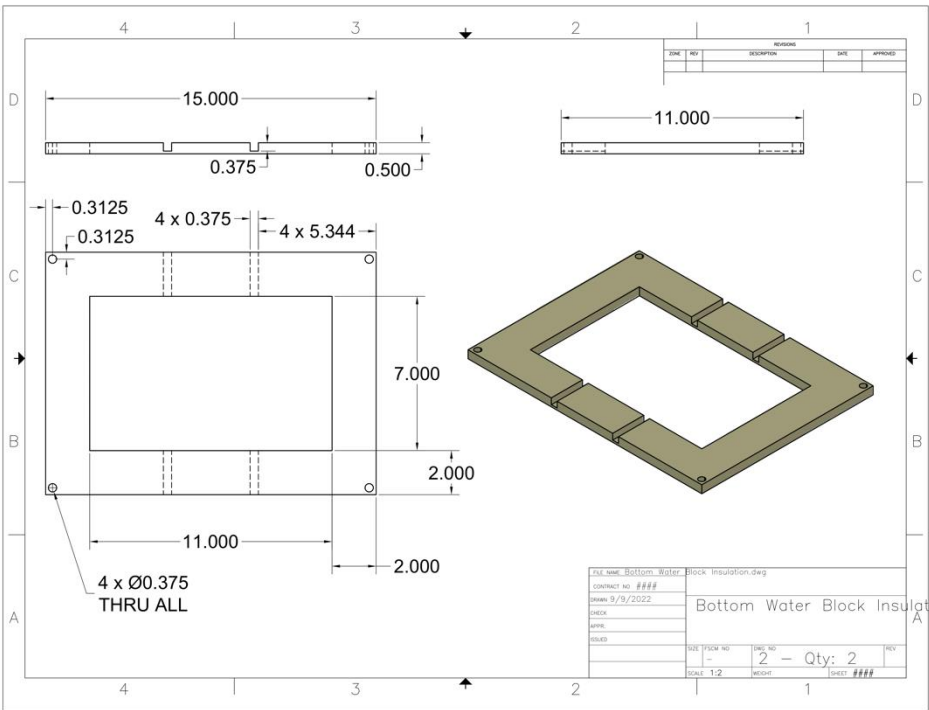


Figure A.2: Bottom water block insulation.

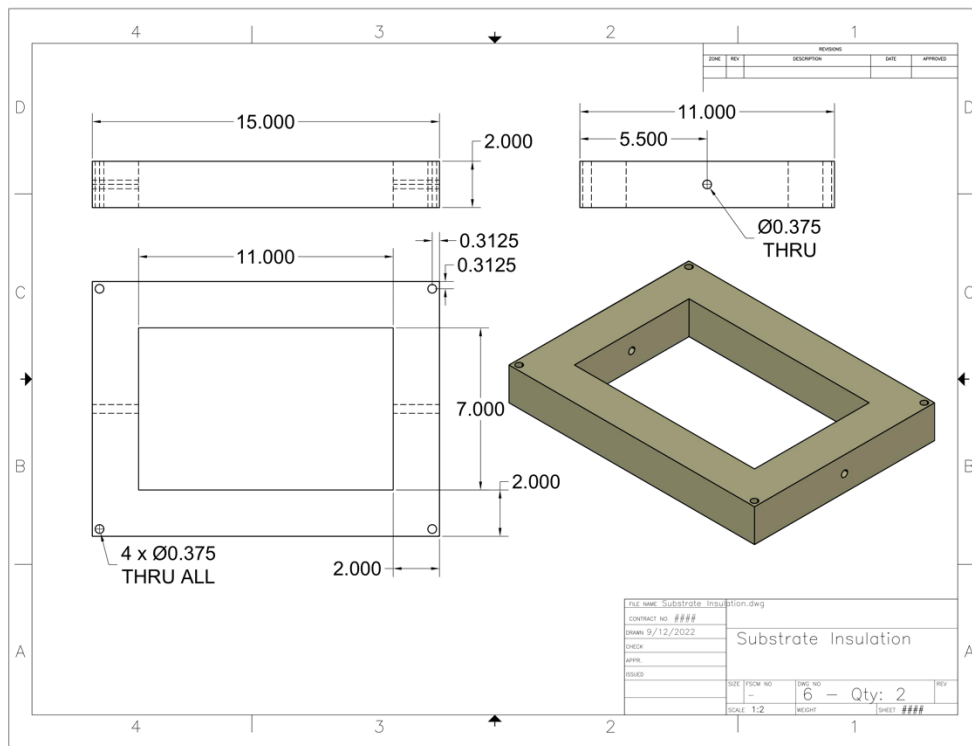


Figure A.3: Copper (substrate) insulation.

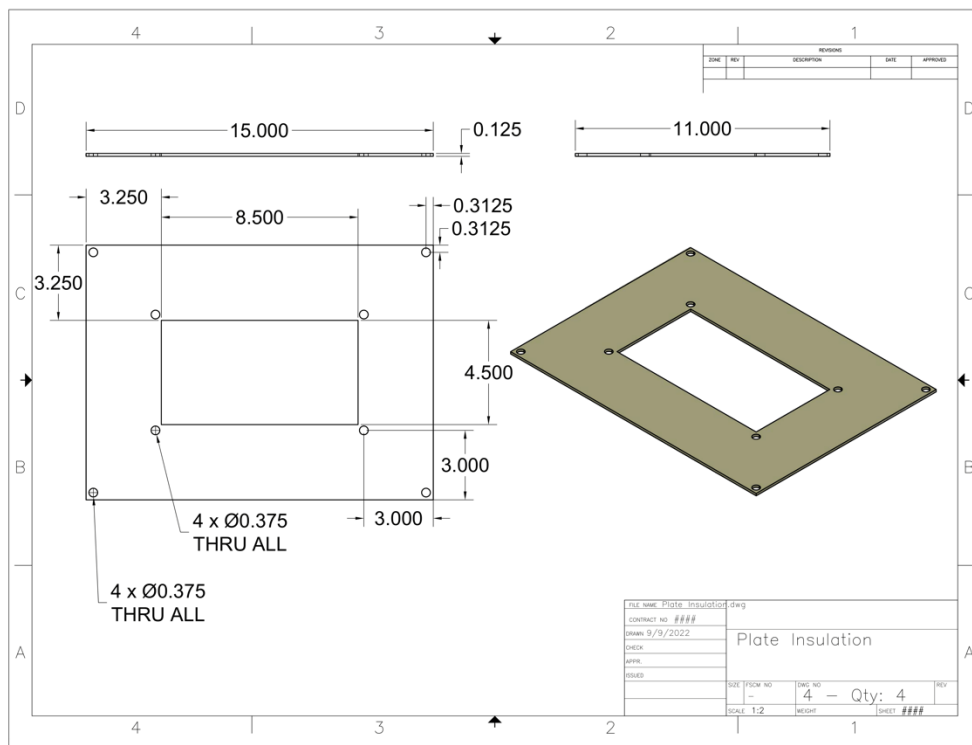


Figure A.4: Thin copper plate insulation.

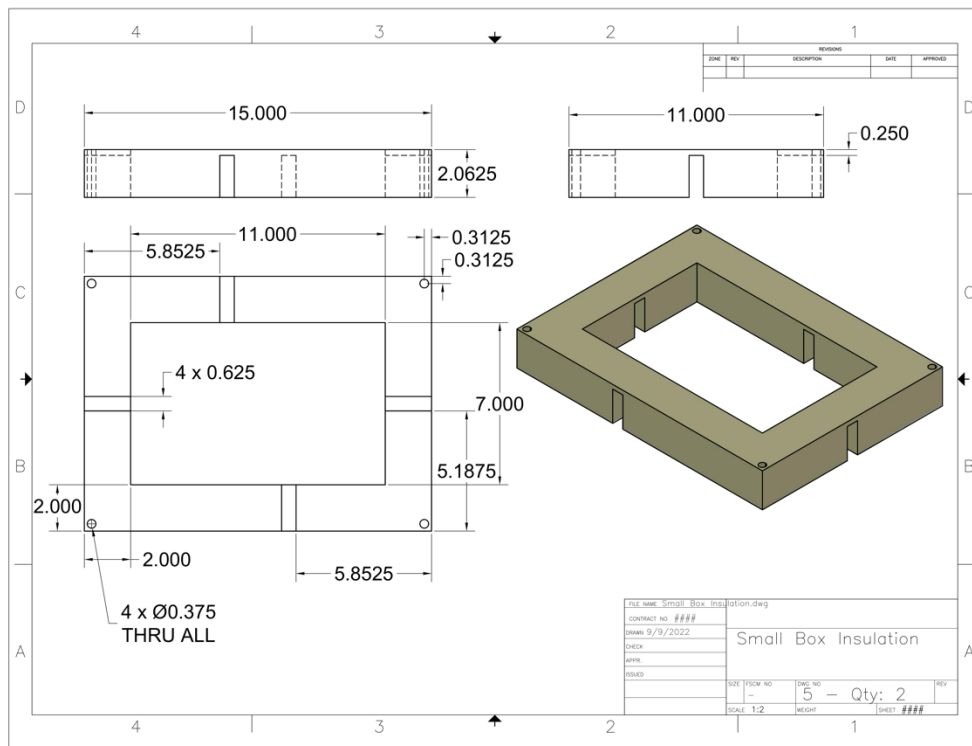


Figure A.5: PCM (small box) insulation.

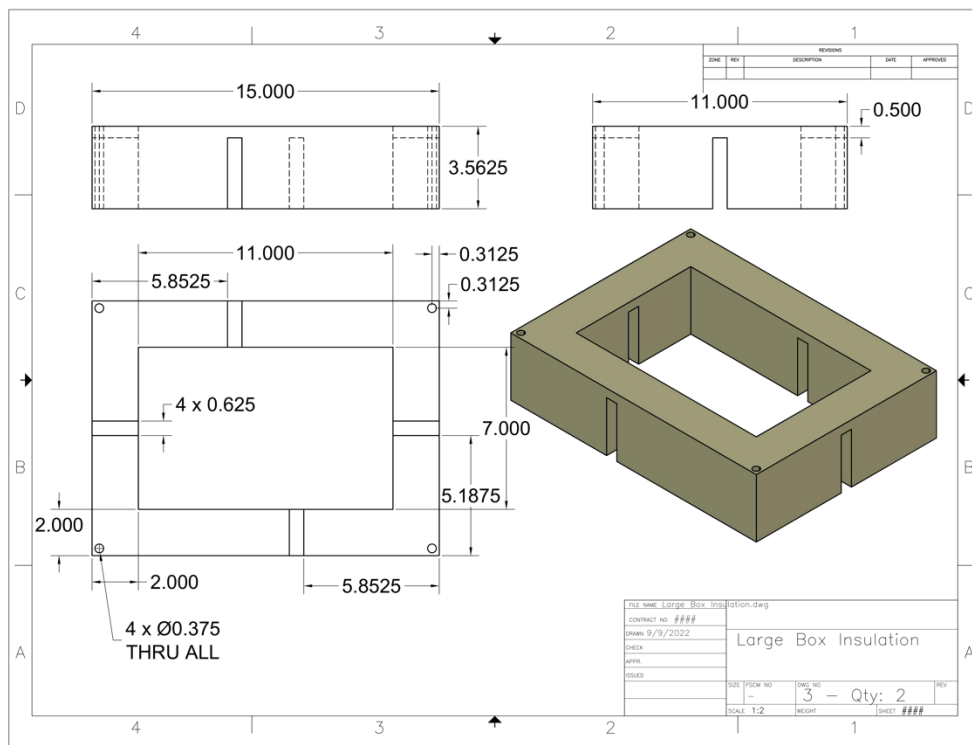


Figure A.6: TTC (large box) insulation.

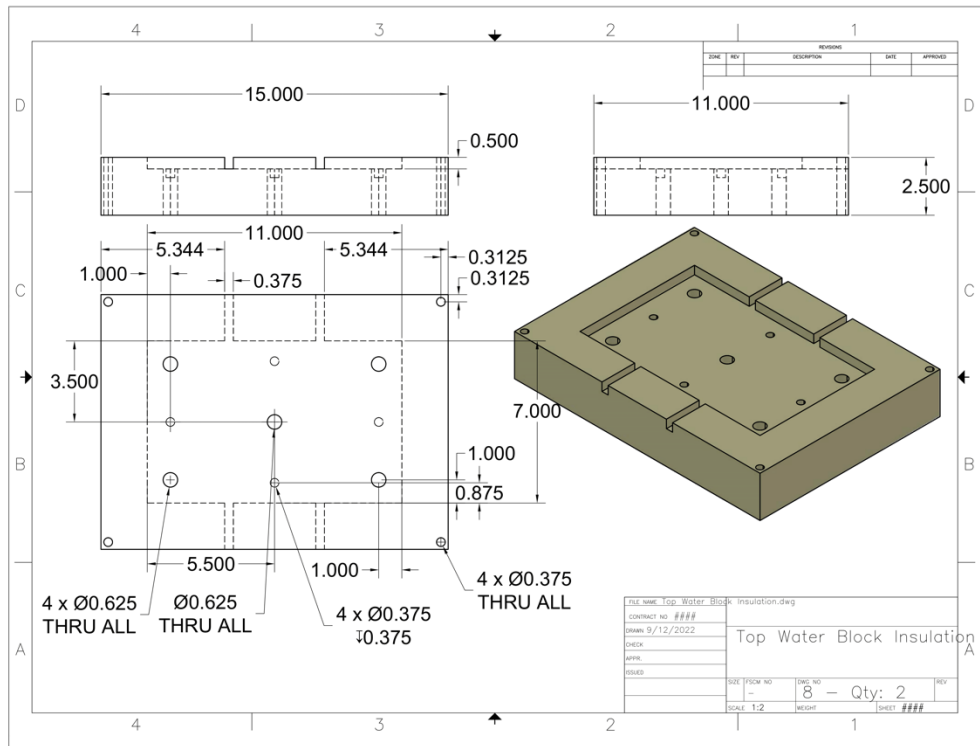


Figure A.7: Top water block insulation.

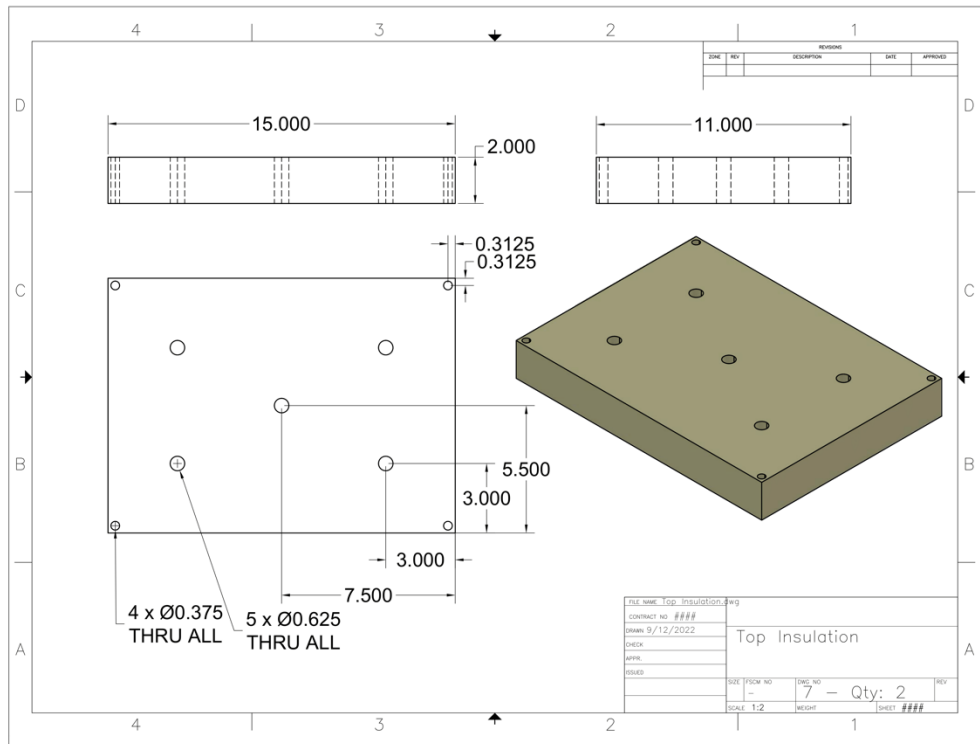


Figure A.8: Top insulation.

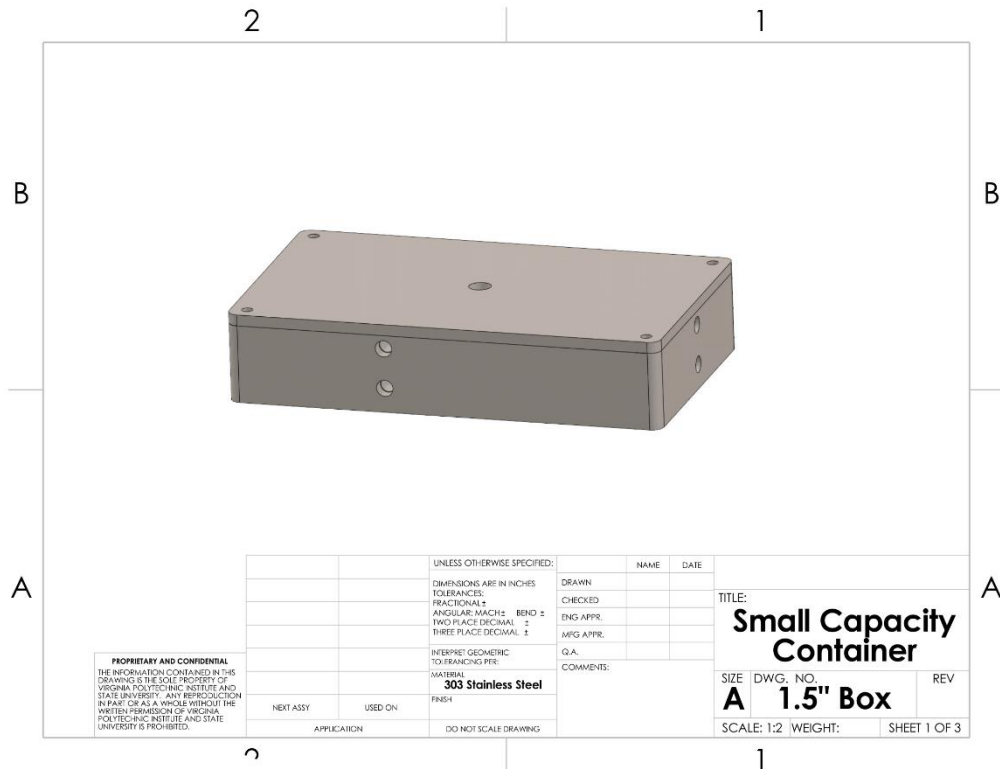


Figure A.9: PCM box assembly.

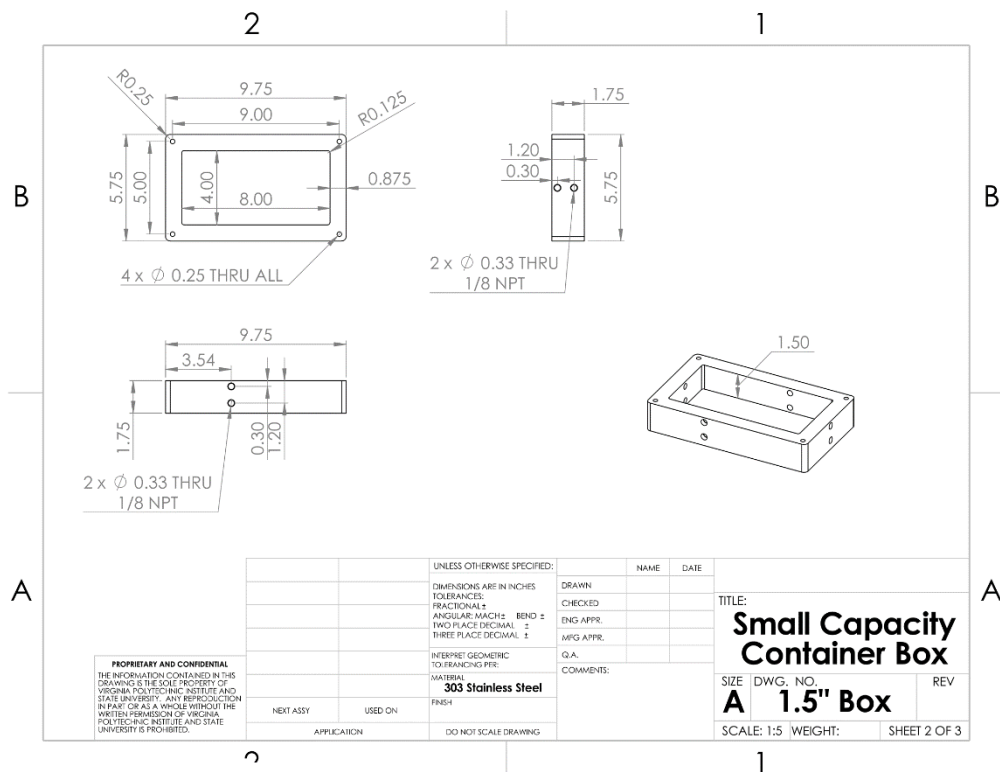


Figure A.10: PCM box base.

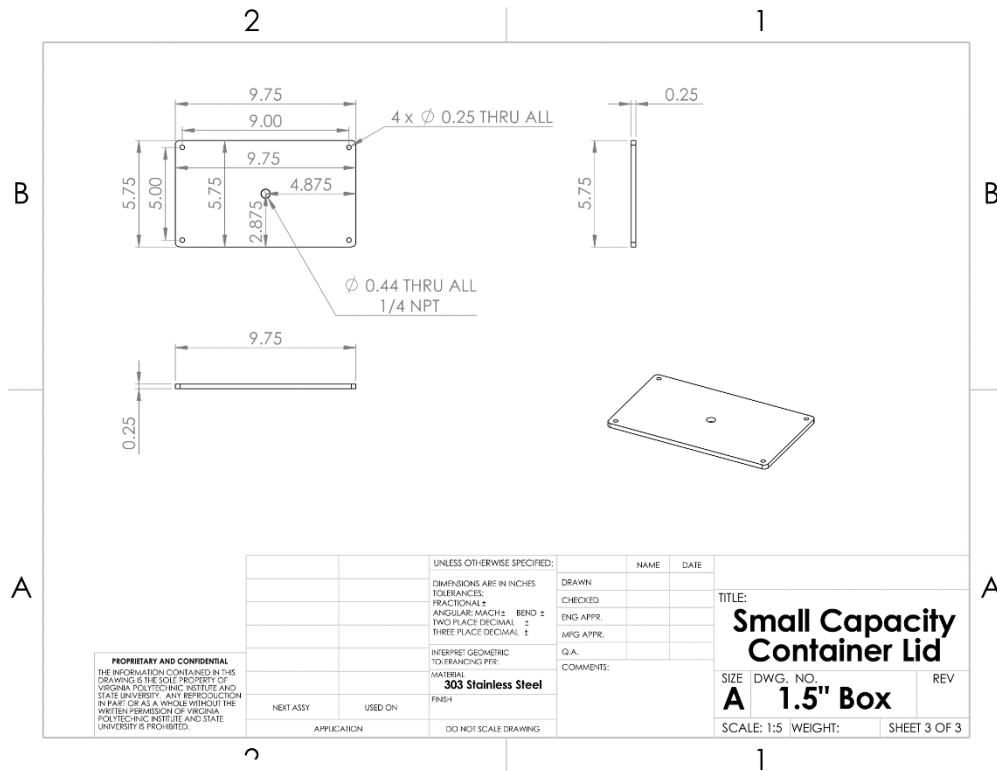


Figure A.11: PCM box lid.

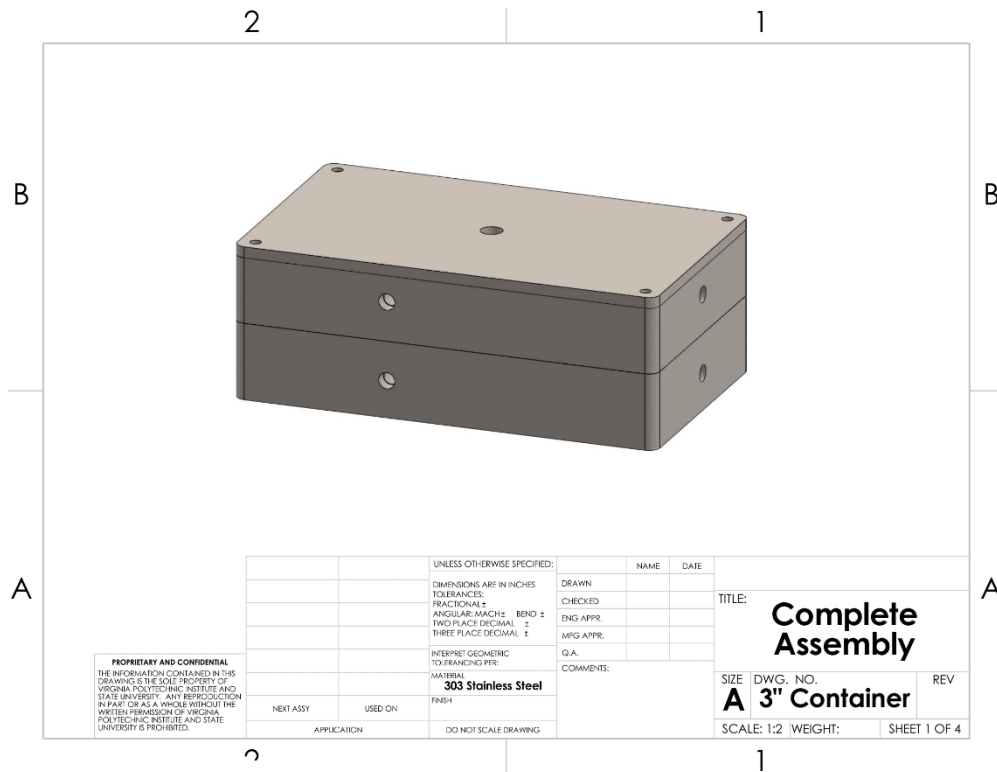


Figure A.12: TTC box assembly.

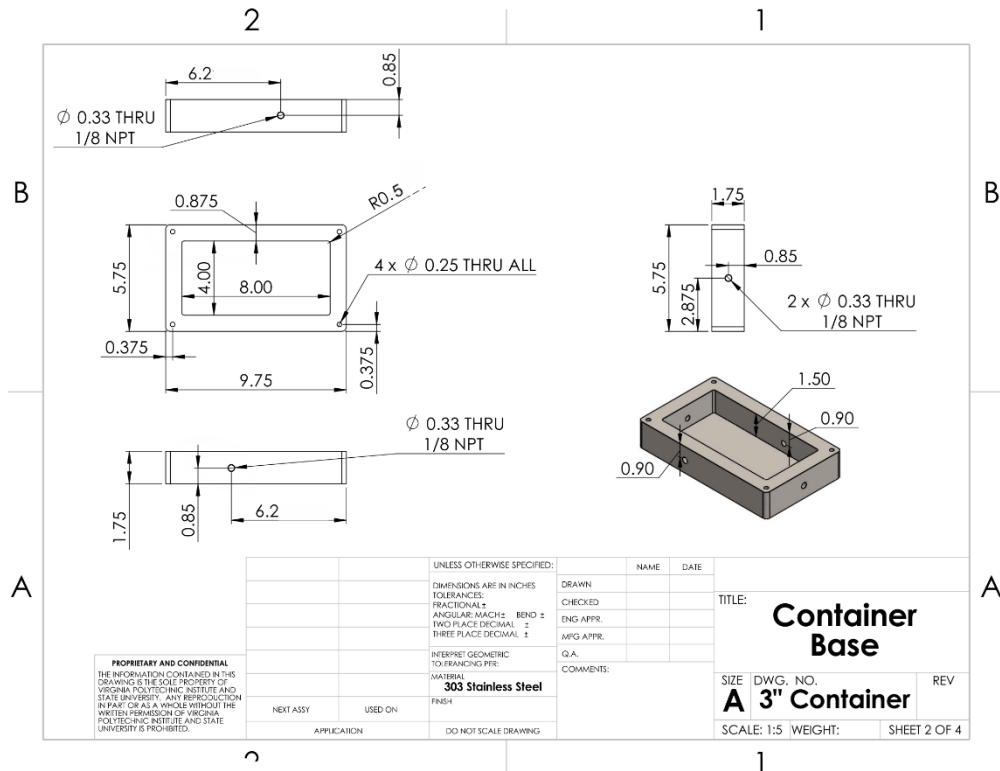


Figure A.13: TTC box base.

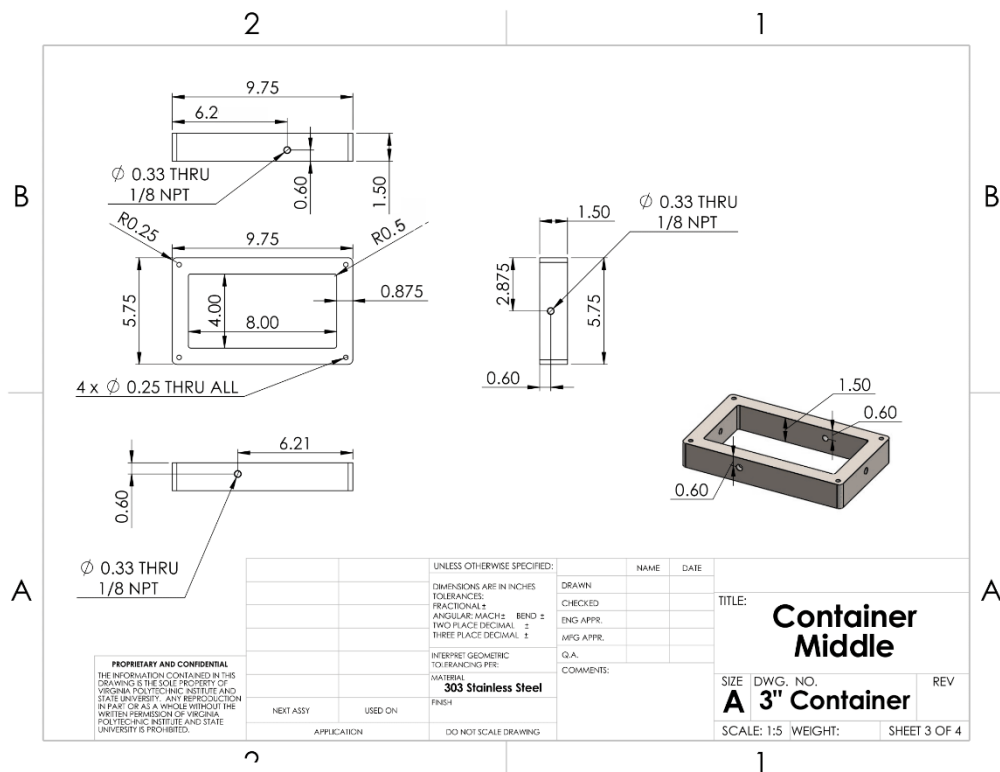


Figure A.14: TTC box middle.

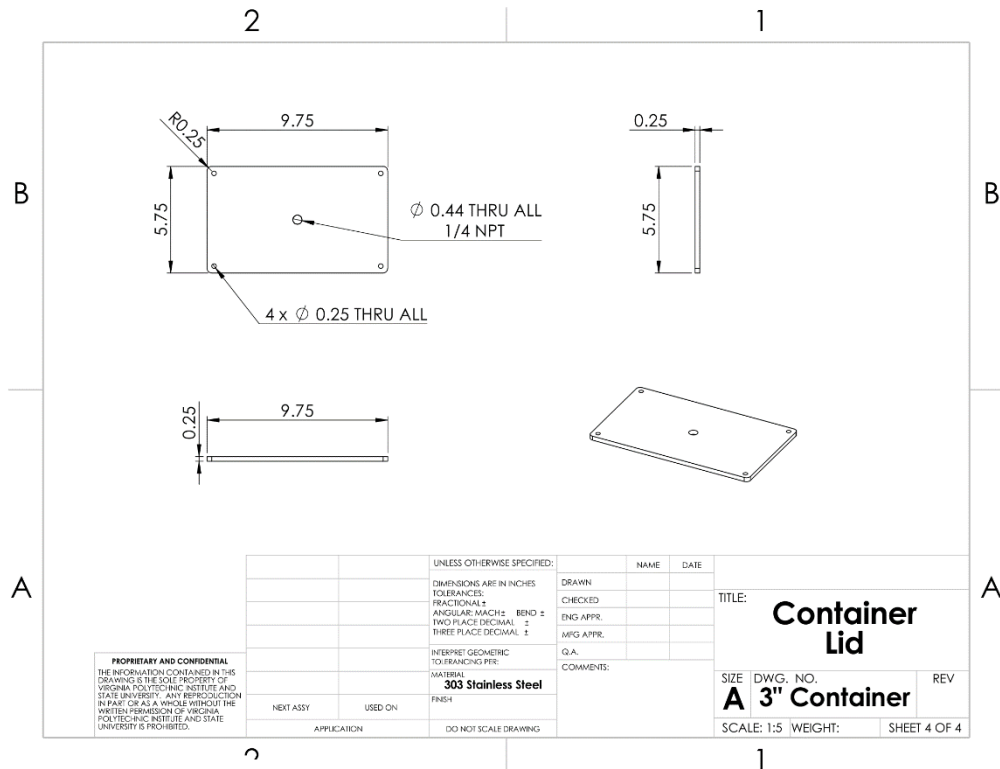


Figure A.15: TTC box lid.

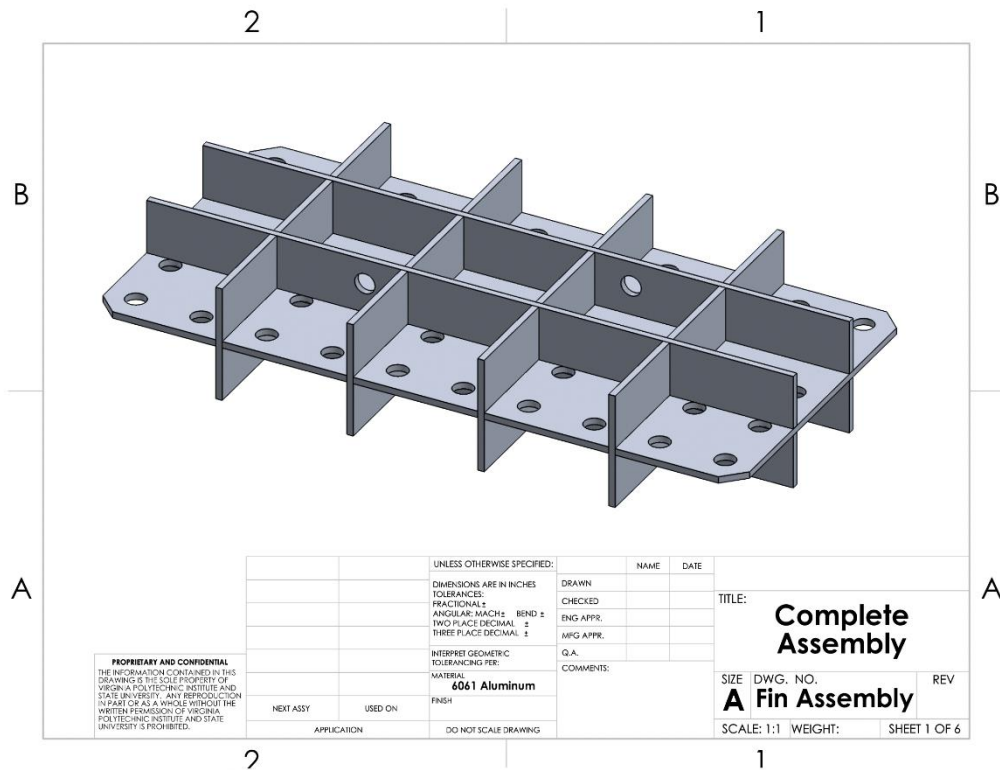


Figure A.16: Aluminum fin assembly.

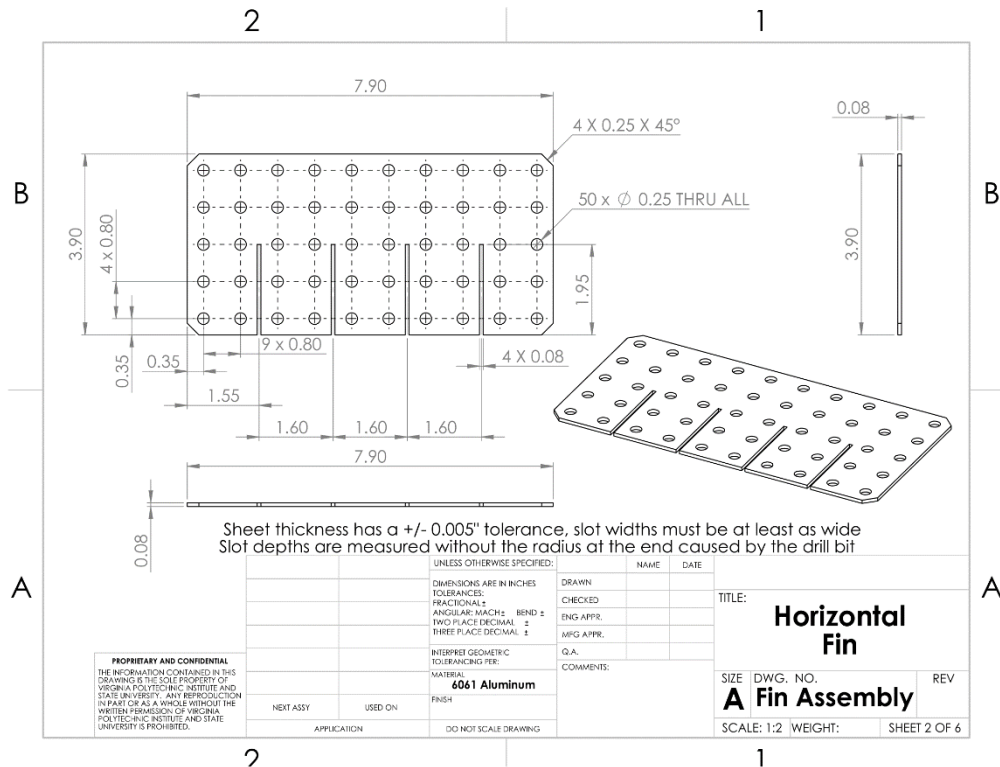


Figure A.17: Horizontal aluminum fin.

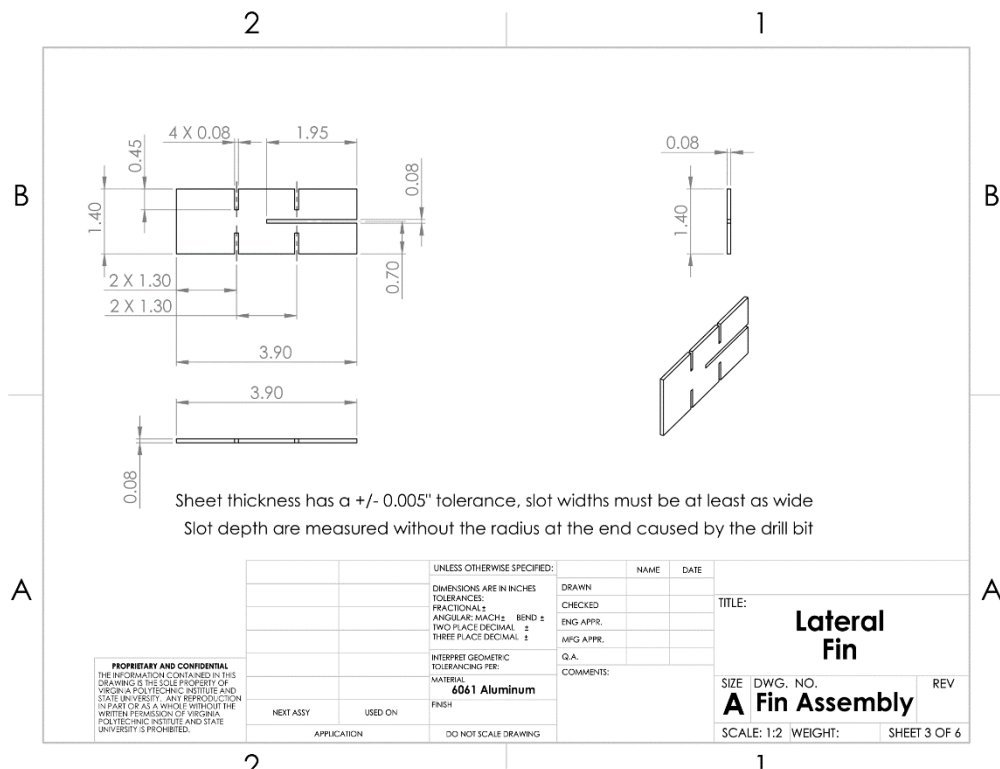


Figure A.18: Lateral aluminum fin.

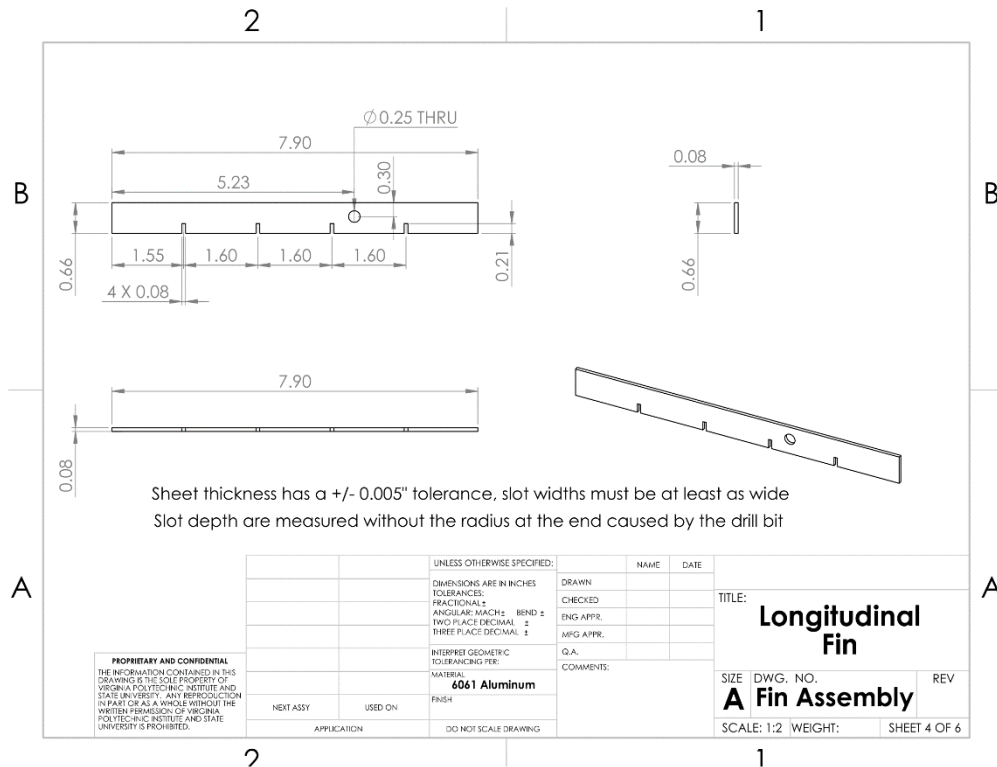


Figure A.19: Longitudinal aluminum fin.

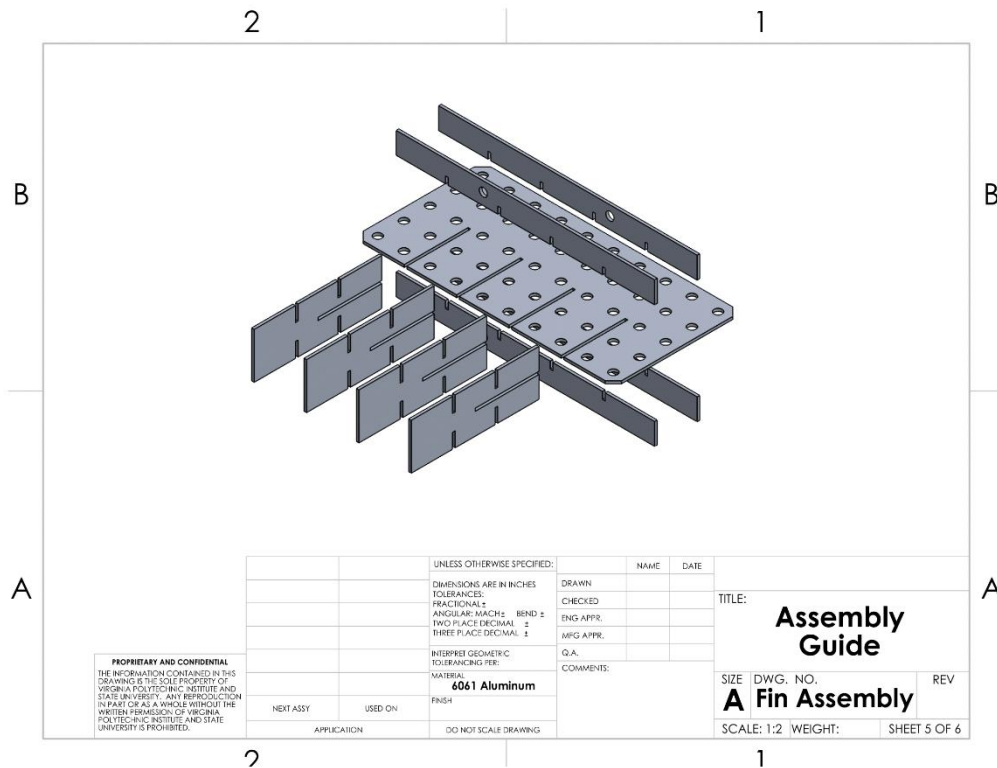


Figure A.20: Aluminum fin assembly guide.

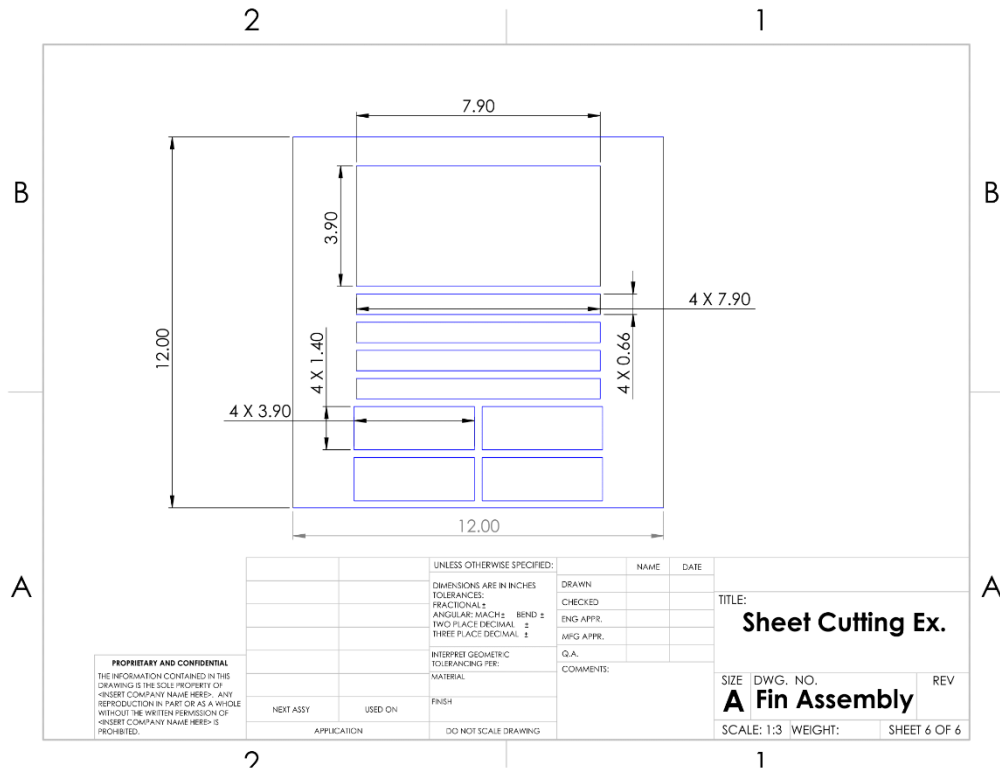


Figure A.21: Aluminum sheet metal cutting guide.

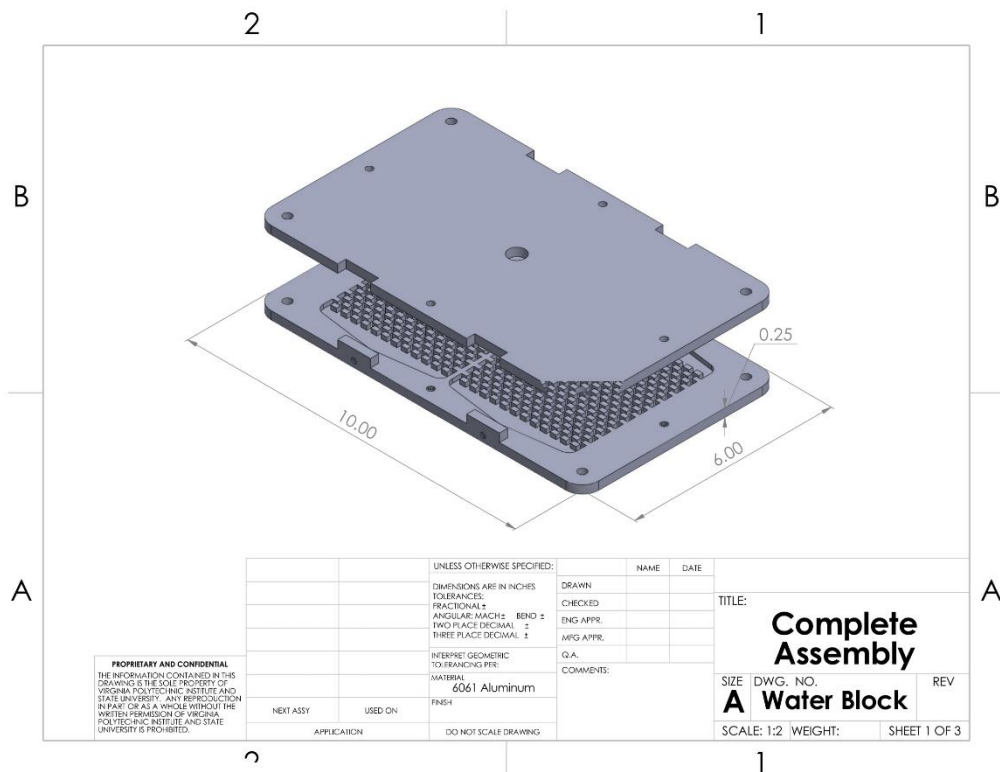


Figure A.22: Water block assembly.

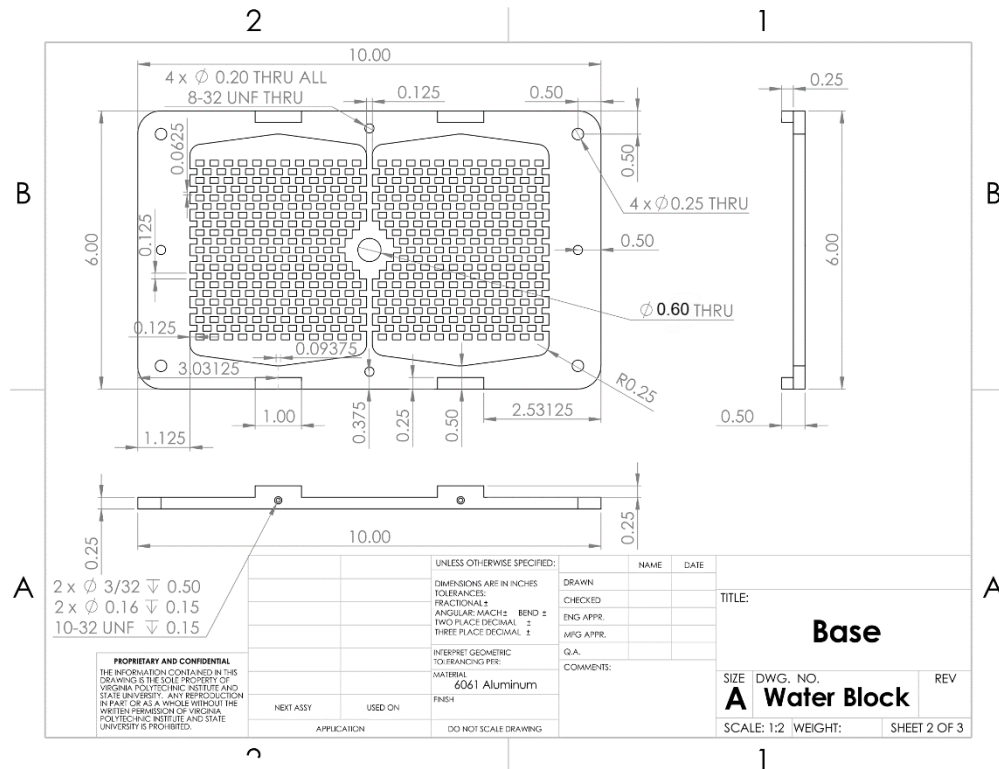


Figure A.23: Water block base.

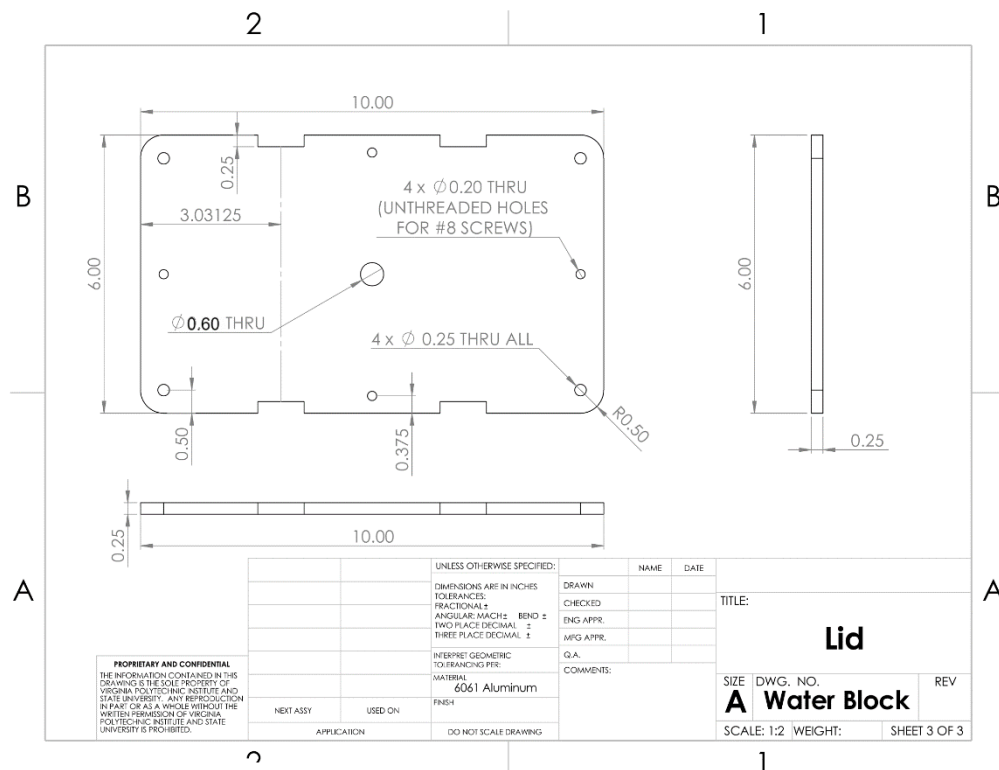


Figure A.24: Water block lid.

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