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Quikchill : thermoelectric water cooler

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QUIKCHILL: THERMOELECTRIC WATER COOLER

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE

IN

MECHANICAL ENGINEERING

Hohyun Lee, Ph.D., Assistant Professor

QUIKCHILL: THERMOELECTRIC WATER COOLER

by

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THESIS

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QUIKCHILL: THERMOELECTRIC WATER COOLER

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Abstract

Motivated by the increasing residential energy utilization projections and the fact that water and ice dispensers consume 20% of total refrigerator energy, a thermoelectric water chiller was designed to provide a more energy efficient alternative. Implementing the chiller under the sink provides a convenient means to source cold, filtered water, thereby eliminating the need for water and nice dispensers as well as filtering pitchers. The cooling chamber design integrates thermoelectric modules (TEMs), which operate on the Peltier effect to cool filtered water down to 14°C. The implementation of TEMs reduced current dispenser energy consumption by 82.4%, from 91 W to 16 W.

Acknowledgements

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Chapter 1 Introduction

1.1 Project Background

Reducing residential energy use is imperative in combating the global energy crisis. The rapid increase in global carbon emissions worldwide contributes to the upward trend of global climate change. The detrimental effect of carbon emissions on the environment encourages change in the lifestyle, especially in terms of energy reduction in homes. The residential sector accounted for 21% of greenhouse gas emissions from the use of fossil fuels to produce electricity [1]. Not only is conserving energy important for the environment, but it also saves money. As seen from Figure 1, residential energy prices in the U.S. are projected to raise dramatically [2]. The star in Figure 1 indicates the current cost of electricity as about $0.14 per Kilowatt hour (KWh).The increase in energy costs motivates people to be more conscious about their home energy consumption.

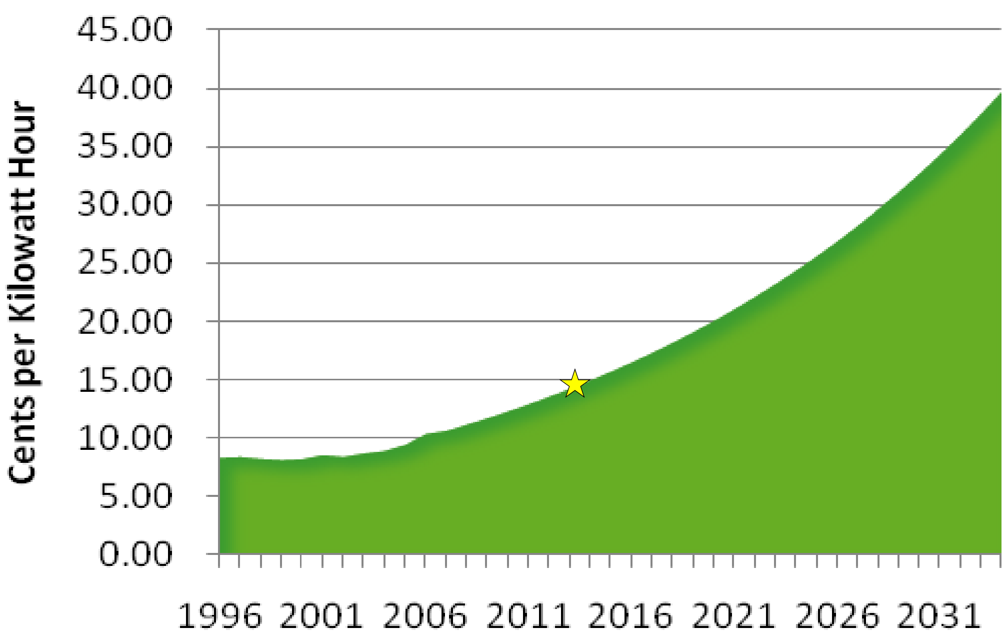


***Figure 1**. Past and Projected U.S. Electricity Costs [2]*

Looking at the energy consumption breakdown of an average California home demonstrated that the refrigerator and freezer consume 20% of the total energy use in the home [3]. Focusing on this number more closely, it was discovered that the water and ice dispenser in the refrigerator consumes 10-15% of the overall energy of the refrigerator [4]. Not only will the water and ice dispenser cost the user $76-114 dollars a year in operating costs, but the accessory adds $75-250 to the initial cost of the refrigerator [4]. Another common water cooling method is to place a filtering pitcher in the refrigerator. This takes up refrigerator space and is inconvenient to fill. Refrigerator space is important to the user because an additional cubic foot to accommodate a Brita or Pur filtering pitcher consumes 20-30 KWh [5]. This additional cubic foot of space costs the user $100 initially in the refrigerator price and about $36 dollars annually in operating costs. Both the water and ice dispenser, and the Brita pitcher, are energy inefficient and unnecessary since water is already available at the sink.

This project aimed to replace the water dispensers in refrigerators by integrating a chiller into a water filtration unit attached to the water line and faucet. The water utilizes low-powered thermoelectric modules to cool the water. By replacing the water and ice dispenser, this unit has the potential to save the user money, as well as reduce the carbon footprint of the consumer. This unit provides a low-energy and affordable solution to a conventional way of drinking cold water. This project answers a need for instant cold water while reducing the burden on our planet.

1.2 Statement of Project Goals

This project integrated a chiller into a water filtration unit to be installed under a typical kitchen sink. The design utilized thermoelectric modules to cool the water in a chamber after it is filtered. The main project objective was to achieve desirable drinking temperatures for the user comparable to the established cooling methods such as the water and ice dispenser. After cooling abilities were met, the unit was designed to be low powered. Creating a low-powered system was important in reducing the amount of energy consumed, which will in turn create a more sustainable future. The system was also designed to be compact in size to fit well underneath a kitchen sink. The project was designed to eventually be compatible with commercially available filters. A filtering element was necessary since water dispenser and Brita pitchers already include this feature. Lastly, the design of the system had to be convenient. Instead of constantly filling up a Brita pitcher or walking over to the fridge, the system needed to provide a convenient way to obtain cold drinking water.

1.3 Literature Review

Research and readings were carried out to consider the critical point relating to how thermoelectric modules (TEMs) and coolers operate and the overall impact that the proposed system would have on the greater community. In *Direct Energy Conversion*, Angrist first observed the phenomena behind thermoelectric generators. From there he went on to analyze the performance of a thermoelectric cooler that transports heat from a low temperature reservoir to a high temperature one by passage of an electric current through a junction of dissimilar materials. The three qualities of interest noted in evaluating thermoelectric cooling performance were: the coefficient of performance, the heat pumping rate, and the maximum temperature difference that the device will produce. All assumptions made in carrying out the analysis of the thermoelectric generator were assumed to hold for the thermoelectric cooler.

Rowe further expounded on these properties and more in the *CRC Handbook of Thermoelectrics*. He explained the thermodynamics, thermoelectric laws and absolute thermoelectric properties that govern TEMs. It is documented that a temperature gradient creates and electrical potential within any isolated conducting material and is known as the Seebeck Effect. Conversely, thermoelectric coolers operate on the Peltier and Thomson Effect when a current flows through a thermoelectric circuit creating a temperature difference within the module. Furthermore, derivation of the optimization of current through a refrigerating couple was explained and it was shown that electrical power is used to overcome the Seebeck Effect as well as the Joule Effect. It was found that the optimum current yields the maximum coefficient of performance.

In *Thermoelectrics: a review of present and potential applications*, Riffat evaluated the large range of applications of thermoelectric devices. He supports this argument by explaining the various advantages of implementing thermoelectric modules into various design. Some of these advantages included the fact that TEMs are solid state devices, reliable energy converters, and are environmentally friendly requiring no CFC gas or refrigerants. Solbrekken applied this to a specific application as seen in *Chip Level Refrigeration of Portable Electronic Equipment Using Thermoelectric Devices.* He explored the possibility of using thermoelectric refrigeration as an integrated solution for heat dissipation accounting for heat sink and interface thermal resistances. He studied parametric ranges of CPU heat flows, heat sink thermal resistances, and thermoelectric material properties which showed that thermoelectric refrigeration had a larger benefit over using just an air cooled heat sink.

A prior art search was conducted; this included patent applications and scientific literature on the thermoelectric modules. Various patents on thermoelectric water coolers and dispensers can be found in Appendix B. References to further scientific literature on thermoelectric generators, thermoelectric phenomena, and energy conversion efficiency can be found in Appendix A. Having completed this search, it was concluded that the team had freedom to operate and does not infringe any existing patent applications.

Chapter 2 System Level Analysis

2.1 Customer Needs

Target customers are key players in the water cooling filtration market. These players include Brita, PUR, GE, and Kenmore. While the team has already reached out to both Brita and PUR, talks and negotiations were stalled until further prototyping or IP protection is completed. The team understands that its unique technology is dependent on early partnerships with customers who have the ability to mass manufacture and ramp scale when the time comes. It will be critical to form these business partnerships and construct contracts early on in the development process in order to ensure future success.

Since a relationship has yet to develop with these companies, conducting a customer needs survey on our own with end users provided substantial data to guide the design process. This product was intended for residential home use. The target customer demographic included a wide range of ages from 18-65, including both males and females. The end user would potentially own or rent a home with a refrigerator. The end user would also be interested in reducing energy consumption, but also value the convenience of on-demand cold water. The customer base would most likely already be interested in clean water and use a different method of filtering and cooling water. The potential customers interviewed for a customer needs assessment varied from typical college students to families.

Two surveys were completed throughout the design process. An initial survey was directed to the overall needs of the consumer regarding water cooling and filtration. The age of the sample interviewed ranged from 20-48 years. The sample size was limited based on time and location constraints, but 13 people answered questions regarding current water filtration devices. A sample questionnaire is shown in Figure 2.

Questionnaire

Name ________________

Age_____________

Gender_____________

Do you own/use a pitcher or faucet water filter?

Do you own a refrigerator that has a filtered water dispenser?

On a scale 1 - 5, 1 being not important and 5 being very important,

What is your opinion of each element in reference to water filters that you have used in the past:

Filtered Water _____

Cold Water _____

Hot Water _____

Energy Consumption _____

Size of Appliance _____

Refrigerator Space _____

Look of the Appliance _____

Water Pressure/Flow Rate _____

Are there any improvements you would make to the water filter you currently use?

***Figure 2**. Sample Customer Needs Questionnaire*

The second survey revolved around testing desirable drinking temperatures for the user. Once the team decided upon focusing on cold water, this survey was necessary to find the optimal temperature range for drinking. The sample size was similar to that of the first survey which included 12 people. The ages of the participants ranged from 21 – 60. The survey lasted 4 days, testing a different temperature range each day. The 4 temperature ranges given to the sample were: 6-7°C, 11-12°C, 15-16°C, and 20-21°C. The water temperatures given to the sample were not in the order listed. Each day the same people would receive a cup of water at a temperature unknown to them. The sample customer could answer if the temperature made them happy (☺), sad (☹), or neutral (😐). Further comments on the temperature were also noted and taken into consideration.

2.1.1 Raw Data

The raw data gathered in the initial questionnaire was summarized to find key trends. Figure 3 displays the average response from the questionnaire and highlights the importance of some features over others. The raw data from the questionnaire can be found in Appendix C. Figure 4 highlights the positive responses related to the temperatures in the second survey.

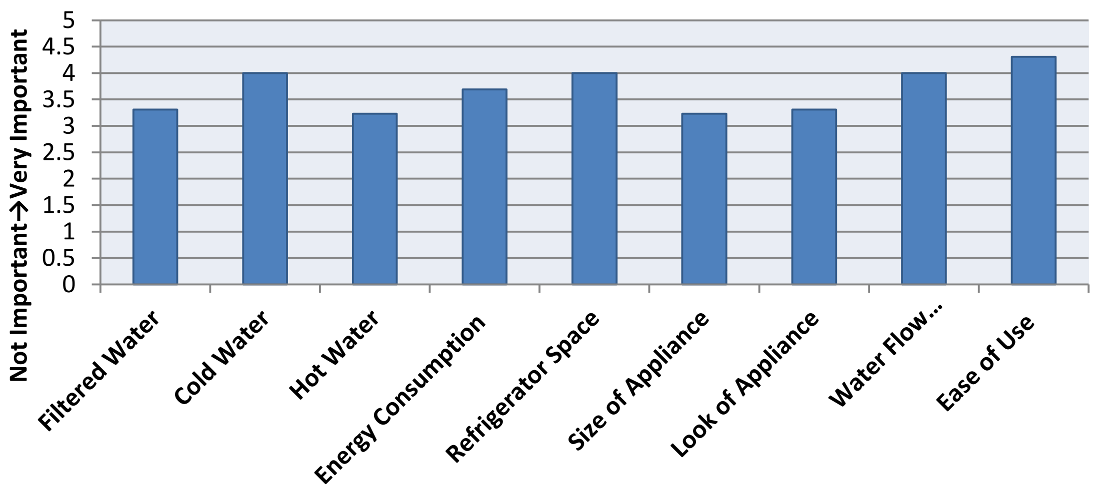


Figure 3. *Average Customer Response in Questionnaire*

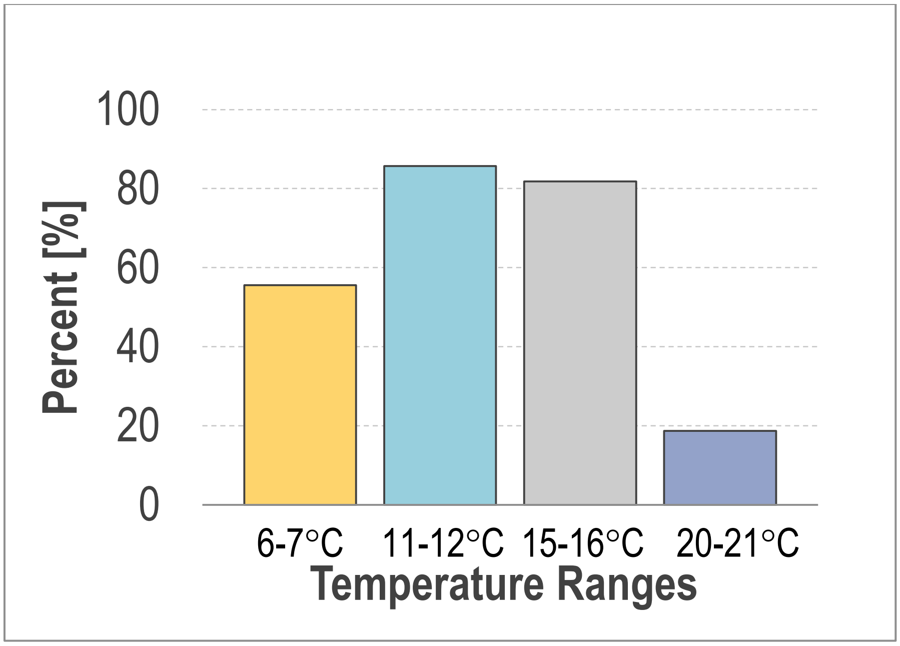


***Figure 4**. Percentage of Satisfied Survey Participants Depending on Water Temperatur*

2.1.2 Data Analysis

The customer needs hierarchy in Table 1 demonstrates the importance of certain design considerations to customers. Customers stated that usability of the product was the most important component. A product that is user-friendly and has a simple interface has been recognized as a vital need to customers. Likewise, cold water temperature, water flow rate, and refrigerator space were deemed more important system characteristics by potential customers. Lastly, in analyzing the data collected, the availability of hot water seemed less important for users.

Table 1: *Customer Needs Hierarchy*

Ease of Use	**Level of Importance 0-3 (Low to high)**
Able to fit onto any faucet	1
Simple user interface	3
Bypass valve accessible	2
Filter Maintenance	3
Temperature Performance	
Provides instant cold water	3
Provides instant hot water	2
Constant temperature	1
Flow Performance	
Provides water quickly	3
Provides water at a steady rate	2
Filters water regardless of time of day	0
Filters water without electricity	0
Aesthetics	
Simplistic design, minimalist style	3
Matches kitchen style	1
Compact size	2
Savings	
Lower cost than refrigerator water dispenser	2
Lower cost than water cooler/filter	1
Eliminates passive energy consumption	3
Electricity bill savings	1
Does not take up space in refrigerator	3

System usability was the highest need observed in consumer interviews. The product must be easy to use, be simple to install, fit under an average kitchen sink and have simple interface. Ideally, the user interface will have a button to power the product. In addition, the product will have a simple release switch to open the device and change the filter. The device will also have an LED indicator to alert the user when filter changes are necessary.

After ease of use, the next most important need was temperature performance. The ability to deliver the lowest cold water temperature has been the focus of the design project. The product must be able to consistently provide cold water at a constant temperature. Unfortunately, current water dispensers on the market are unable to maintain constant temperatures and typically dispense warmer water over periods of continuous use. Since potential customers rated the ability to deliver hot water lower, this was not a main design focus.

The lowest rated consumer need was the aesthetics of the product. The design needs to be kept simple and neutral, to be able to match in any kitchen style. Moreover, since the design was to be placed under a kitchen sink, sizing and overall aesthetics was less of an issue. Aesthetics ranking lowest in the customer needs hierarchy confirmed that the product must be more technically sound and functional than aesthetically appealing.

Though not explicitly expressed in the survey conducted, all customers reported cost as one of the key factors in their choice of appliance. The interviewees widely commented that the product should have a higher return on investment. This was broken into two categories, initial cost and energy cost. The product must be designed to cost less than refrigerator water dispensers or office space water dispensers. Additionally, the product was designed to eliminate constant energy consumption used to maintain a constant water temperature in storage tanks.

The customer data was taken into account during the initial design process. As complications arose in the design, the team decided to narrow the scope of the project to purely cold water based on the customer needs and team preference. The second survey focused on the temperature range of desirable cold water drinking temperatures. Based on the information in Figure 3 and the comments gathered, a temperature range of 11-16°C was found to be the target range for the design. The range of 6-7° was too cold for people and the 20-21°C range was too warm. Since "temperature performance" was found to be crucial to customer needs, achieving this temperature range for the product was a main objective.

2.2 Benchmarking

In order to fully understand key features needed to be applied to the system, three commercially available systems were researched and analyzed. It was observed that while each of these systems possessed valuable features, they also lacked other important functions. Overall, the success of the project was measured on the basis of functionality. The unit must effectively produce cold filtered water while consuming a low amount of power.

As there is no product on the market that substantially cools filtered water in an energy efficient manner, success of system parameters were created based on existing average output temperature, power consumption, and size of potential competitors. These potential competitors fell under the categories of refrigerator dispensers, tanked water cooling, and filtration units. These competitors are categorized in Table 2.

Table2: *Benchmarking Categories*

Refrigerator Dispensers [6]


Filtration Systems [7,8]	
Brita Water Pitchers	PUR Faucet Filters
	

Tanked Water Cooling [9,10,11]		
Oasis Countertop Water Cooler	Avanti Thermoelectric Cooler	Elkay Drinking Fountain
		

Refrigerator water and ice dispensers are a popular, but costly feature in refrigerators. A storage tank that sits in the back of a refrigerator holds 470 mL (16 fluid oz.) of water and cools at the same rate as the rest of the fridge. When all of the water is depleted, the system requires 22 to 24 hours to return back to its initial temperature of ~14°C. Water and ice dispensers increase energy consumption of a fridge by 10 to 15%, and add an extra initial cost of $75 to $250 refrigerator purchases. Just as QuikChill aimed to connect the unit to a water line under the sink, refrigerator dispensers require plumbing installations. Similarly, both QuikChill and some refrigerator dispensers integrate commercially adaptable filtering components. The drawbacks of a water dispenser is that it reduces the freezer and shelf/bin capacity

The Oasis Countertop Water Cooler, Avanti Thermoelectric Cooler, and Elkay Drinking Fountain were tanked water cooling systems the team observed. The Oasis Countertop Cooler is a point-of-use water cooler capable of dispensing both hot and cold water. This cooler dispenses either hot or cold water and illuminates the dispensing area with a blue LED spotlight. Oasis uses a standard push-fit ¼" water line connection creating a streamlined installation process. Both the cold and hot water reservoirs use 300 series stainless steel tanks for quality and sanitation purposes. Water is cooled using internal compressors and refrigerants to ~17°C, and is heated using a 500 Watt heating element. The drawback is that this unit is quite large having a volume of 1.8 ft^3 and consumes a large amount of power at 537 W. Also, since the unit was designed to sit on countertops, it takes up unnecessary space on a kitchen counter.

Like the Oasis Countertop Cooler, Avanti Thermoelectric Coolers also dispenses hot and cold water. Avanti also had two separate ABS acrylic chambers stored the hot and cold water. The main difference is that Avanti uses a thermoelectric module mounted on a fan-cooled spiral heat sink to cool the water down to ~16°C, but still uses heating coils to heat the water. It has selectable operational modes: normal and energy saving. The drawback to the design is that it also rest on a countertop taking up 4.5 ft^3 of space and that it consumes 540 W of power. It is a stand-alone system that can't be connected to a water line, but uses standard 2, 3, or 5 gallon bottles.

Unlike Oasis and Avanti, Elkay Drinking Fountains are only capable of dispensing cold water. This type of water cooler is a self-contained, wall hung, electric water cooler. The water chamber is a combination tube-tank type. The tube is made of copper and the tank is made of stainless steel. It uses universal adapters to connect to a water line and the cooling system is housed in an impact resistant granite vinyl cabinet. The cooling system comprises of a compressor, condenser, and thermostat. The drawback is that this unit uses refrigerants that are harmful to the environment, and requires large compressors increasing the overall size of the system to 4 ft^3. The system consumes 370 W and is not portable as it needs to be mounted unto a wall for use [12].

2.2.1 System Comparison Table

Table 3 displays a summary of average output temperatures, power consumption, size, and retail cost for Tanked Water Cooling (Elkay Drinking Fountain, Avanti Thermoelectric Cooler, and Oasis Countertop Water), Refrigerator Dispensers, and Faucet Filtration Systems. Although the tanked water systems can dispense a larger total output volume at any given time, they consume more power than necessary. Not only do these systems consume power an order of magnitude larger than desired, but they are also not compact, making installation under sinks difficult. The team aimed to design a compact unit that can easily fit under a sink without disrupting the user's current lifestyle. In addition, the system also needed to consume a low amount of power to reduce annual energy costs, and to subsequently decrease the amount of harmful emissions produced. Further comparison on Benchmarking products can be found in Appendix D.

***Table 3**: Benchmarking Results from Water Dispensing Units*

Source	Average Temperature [°C]	Power Consumption [W]	Size [ft^3]	Retail Cost
Tanked Water Cooling				
Elkay Drinking Fountain [12]	12.55	370	4.013	$547.00
Avanti Thermoelectric Cooler	16.04	540	4.480	$89.00
Oasis Countertop Water Cooler	16.76	537	1.810	$379.00
Refrigerator Water Dispensers	13.63	91	0.353	$75 – 250
Filtration Systems				
Brita Water Pitcher (inside a fridge)	20.83	20	0.388	$29.98
PUR Faucet Filters	21.04	N/A	0.069	$25.99

2.3 Target Design Specifications

Certain design parameters were determined based on customer needs survey data, benchmark testing, and product comparison. To properly document system functionality, a

Product Design Specification (PDS) report was made to provide target ranges for design parameters. Tanked water coolers (Elkay Drinking Fountain, Avanti Thermoelectric Cooler, and Oasis Countertop Water Cooler.), refrigerator water dispensers, and filtration systems (Brita Pitcher and PUR faucet filter) were tested to document power consumption and water output temperatures.

Temperature requirements for the system were based off a blind taste testing survey. The survey tested the satisfaction of water drinkers based on given water temperature that was unknown to the surveyed individuals. The survey concluded that customers were most satisfied with a drinking temperature range of 11-16 °C. Size was also a vital component as the team wanted the unit to be as compact as possible so as not disrupt potential users' lifestyles. The unit had to be ≤ 0.3 ft^3 to easily fit under a sink and be comparable to benchmarked competitors. In the benchmarking conducted, it was observed that many of the units consumed substantial amounts of power. Keeping the power consumption as low as possible was crucial in reducing energy costs and carbon emissions. Other design criteria, such as number of thermoelectric modules, cost, and lifetime are also important factors considered and can be found in the PDS in Appendix E. Also, a preliminary Criteria Prioritizing Matrix can be found in Appendix F. This matrix tabulates the key design elements and compares their importance. This was used in the initial design process to narrow our focus on crucial design specifications.

2.4 System Concept and Sketch

The system was designed for use in residential homes to provide a low-powered alternative to costly and high energy consuming refrigerator dispensers and bulky Brita pitchers. The system was designed with size in mind to easily fit under a sink. The main water line would branch off and feed into the filtering system. The filtering system was to be compatible with commercially available filters. The filtered water then enters the QuikChill chamber which utilizes thermoelectric modules to cool the water. Thermoelectric modules (TEMs) operate based on the Peltier Effect wherein a temperature difference is created across the module when a current is applied. Heat is absorbed from the water on the cold side, while simultaneously being rejected on the hot side of the module. TEMs were used in place of compressors and condensers as they are low-maintenance and solid state, making them applicable to small scale cooling. After the water has been cooled, the user can deplete the chamber to get cold filtered water from the kitchen sink. This project approach is illustrated in Figure 5.

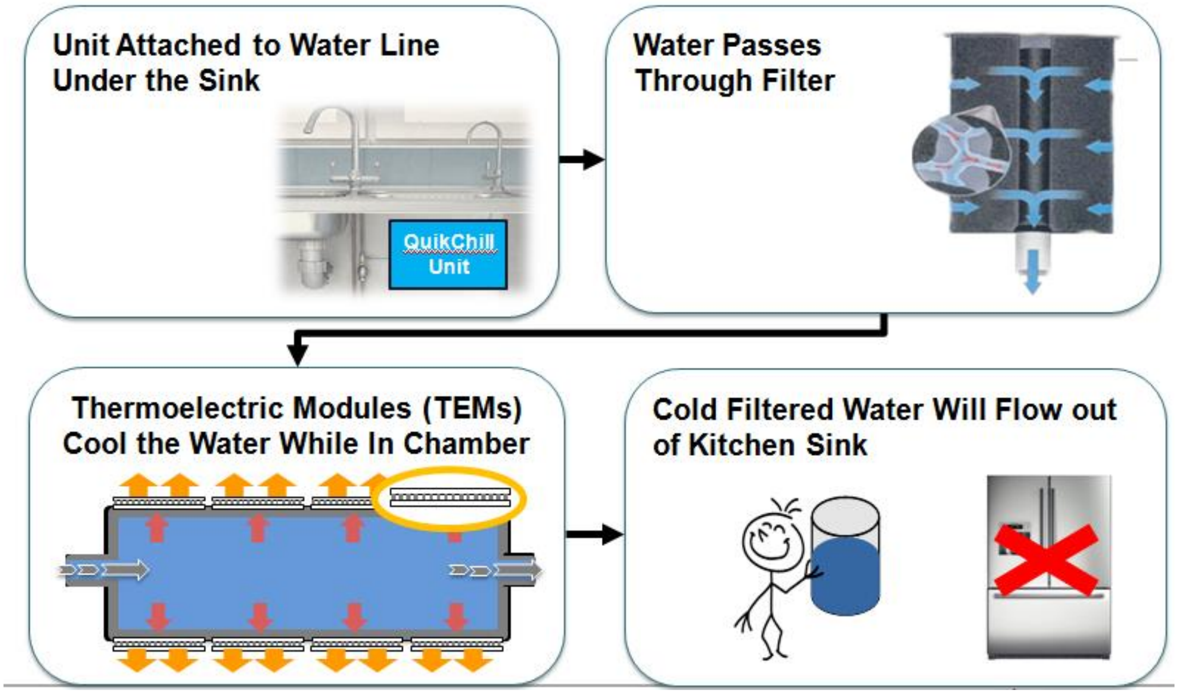


Figure 5*. Project Approach Illustration*

2.5 Functional Analysis

2.5.1 Functional Decomposition

The overall system design was broken down into three primary systems – the cooling system, the heat dissipation system, and the insulation system, each consisting of its own subsystems. The water enters the chamber, and from the cooling system will cool the water using the thermoelectric modules. The heat dissipation system removes the heat from the thermoelectric modules that was absorbed from the water and ejects that heat to the environment. During this process the insulation system prevents heat gain from the environment to the water which will raise the water temperature.

The cooling subsystem involves the water chamber, the thermoelectric modules, and heat sinks that are attached inside chamber. The thermoelectric modules are the cooling mechanism used to reduce the temperature of the water. Operating under the Peltier effect, thermoelectric modules absorb heat from the water which cools it. The chamber itself is included in the cooling system because it is made out of aluminum and has thermoelectric modules attached to it. The aluminum cooling chamber has a high thermal conductivity which facilitates heat transfer from the thermoelectric modules, allowing heat to be absorbed easier into the thermoelectric modules cooling the water more effectively. Heat sinks were also placed inside the water chamber along the inner wall in order to increase the surface area where heat is absorbed even more, and keep the water in the chamber at a more uniform temperature.

The heat dissipation system takes the heat absorbed from the water by the thermoelectric modules and dissipates it to the surrounding environment. This system involves heat sinks, fans, and heat pipes to move and dissipate heat effectively. Heat sinks are used to increase the surface area where heat can be dissipated via convective heat transfer. Fans are used to increase the natural convective heat transfer of air and dissipate heat. Heat pipes were implemented in some design iterations in order to move heat from the thermoelectric module to a separate location either to better insulate the system or to move all the heat from separate modules to a central location where it can all be dissipated.

The insulation system prevents heat gain from the environment into the water chamber. This system involves different types of Styrofoam that can be used to insulate the system. Styrofoam was chosen because of its relatively easy manufacturability and high insulating value.

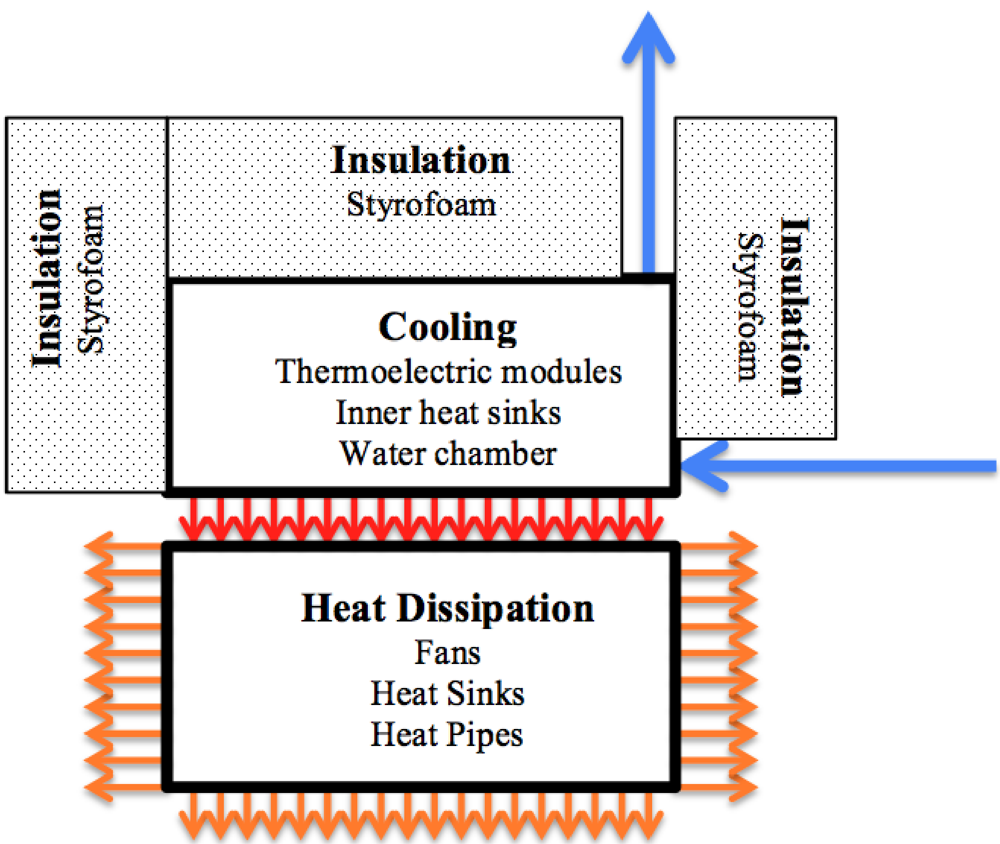


Figure 6. *Functional Analysis Diagram*

The three systems mentioned above are shown as blocks in Figure 6. The insulation surrounds the cooling water chamber as much as possible except where heat dissipation comes into contact with the thermoelectric modules on the water chamber. Heat is rejected from the water to the heat dissipation system as shown by the red. This heat is then dissipated to the surrounding environment shown as the orange arrows. Water flow is shown by the blue arrows. Water enters the system from the water line at the right and then exits the top of the system to a separate nozzle on the kitchen sink countertop. Some of the difficulties with this system were balancing the insulation and heat dissipation that surround the cooling system. Both systems needed to be in contact with the cooling system as much as possible; however, the more we increased the effectiveness of one system, the size of the system increased, leaving less room for the other system.

2.5.2 Inputs and Outputs

The inputs and outputs of this system were the water, heat, and electricity. Current is inputted into the thermoelectric modules in the cooling system as well as the fans in the heat dissipation system. Heat is mainly an output of the system in which the heat absorbed from the water was dissipated into the air. Water is also input from the water line into the inlet, and cold water was outputted from system after cooled.

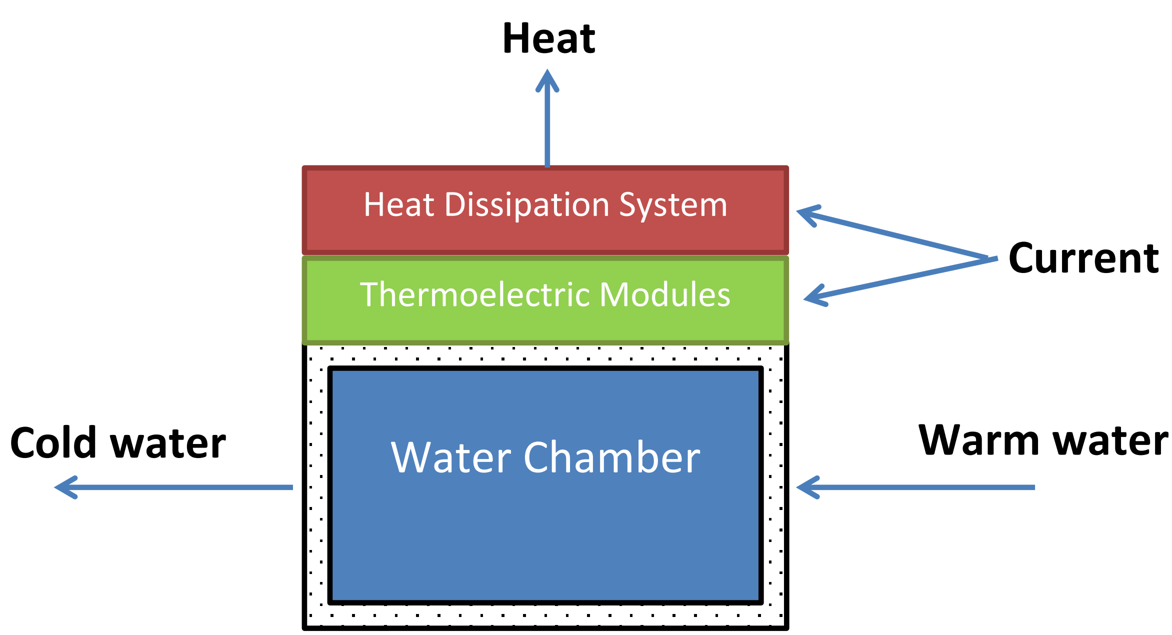


Figure 7. *Heat transfer free body diagram with applied conditions.*

2.6 Key System Level Issues and Constraints

2.6.1 Water Temperature vs. Electric Current

One of the main tradeoffs of the system was the temperature of the water in regards to the amount of current used by the thermoelectric modules. Thermoelectric modules operate under the Peltier effect, in which the cooling power is proportional to the amount of current. This relationship is given by:

$$Q_{Peltier} = SIT_C \qquad \text{Eq. 1}$$

where *S* is the Seebeck coefficient, a material property, *I* is the current, and T_C is the cold side temperature of the thermoelectric module. As seen above, increasing the amount of current will increase the cooling power of the Peltier effect leading to colder water temperatures. However, increasing the amount of current also increases the amount of electricity that the system consumes. In addition, as current is passed through each thermoelectric module Joule heating occurs. Joule heating is shown as:

$$Q_{JH} = I^2R \qquad \text{Eq. 2}$$

where *R* is the electrical resistance of the thermoelectric module. As seen above the amount of Joule heating is proportional to the square of the current. At certain values of current the heat generated by joule heating overcomes the heat removed by the Peltier effect causing the thermoelectric modules to heat the water.

2.6.2 Heat Dissipation vs. Size

As briefly mentioned earlier, thermoelectric modules need proper heat dissipation. As heat is absorbed from the water on the cold side, heat is also simultaneously being ejected on the hot side. Without proper heat dissipation, this heat builds within the thermoelectric module and decreases its cooling performance. With poor heat dissipation, the cooling performance degraded to the point at which the module heated the water instead of cooling it. However, increasing the heat dissipation is difficult since it requires heat sinks and fans. Larger heat sinks and more powerful fans results in faster and greater heat dissipation. Larger heat sinks also made the system much bulkier and heavier, making the system more difficult to implement under the sink. Increasing fan speeds and size also made the system larger, increased the energy consumption of the system, and made the system noisier.

In addition, insulation was necessary to prevent heat gain from the environment to the water. Insulation decreased the time it took to cool the water as well as allowed the water to stay cold for longer, which conserves energy. However, increasing the insulation around the water chamber also increased the size of the system. Furthermore, both heat dissipation and insulation generally needed to be closest to the surface of the box to be effective. Heat dissipation needed to be in contact with the thermoelectric modules to remove heat, and insulation needed to be in contact with the water chamber to reduce heat gain. Because of this, there was a limit to how much of either may be used because of the limited surface area of the water chamber. Increasing either heat dissipation or insulation led to decreasing the other parameter complicating system optimization

2.6.3 Number of Thermoelectric Modules (TEMS) vs. Cost

Based on modeling results, increasing the number of thermoelectric modules increased the performance of the system. However, increasing the number of modules increased both the initial and operating cost of the system. Thermoelectric modules were the most costly component within the system. In addition, as the number of thermoelectric modules increased, so did the energy consumption of the system. This higher energy consumption led to higher operating costs. Based on the modeling, the team decided to use as few modules as possible.

2.6.4 Cooling Power vs. Volume

The volume of the water chamber was a large constraint on the system's design. Increasing the water chamber volume, increased the amount of water that could be cooled and served at once. However, this larger size increased the amount of time it took to cool the water. It was found that an increase in volume of water was not proportional to the cooling time. The increase in cooling time was much greater than the increase in volume. The team contemplated whether being able to serve a large amount of cool water was more important than the time spent waiting for the water to cool. The team referred to its benchmarking results and decided to use a chamber that was as large as one of the competitors. This allowed QuikChill to serve as much water at once and cool that amount of water faster than competitors. This resulted in being able to cool more water over the course of a day than any other competitor.

More tradeoff considerations can be observed in the Quality Functional Diagram (QFD). In Appendix G, the QFD outlines the main customer needs and technical parameters and identifies the relationships between them.

2.7 Team and Project Management

2.7.1 Project Challenges and Solutions

Some of the main project challenges the team faces were time limitations and how the group efficiently budgets and manages time. Many members of the team were involved in extracurricular activities such as clubs, leadership programs, and/or work, which added to the pre-existing time constraints faced. These factors affected how much time each member dedicated to work solely on the project. To address this problem, the team permanently scheduled tri-weekly meetings dedicated to working on the project. In addition, the team assigned tasks and deliverables that each member was held accountable for. These meetings and tasks helped keep the team on track towards a successful completion of the project.

Another challenge the team was confronted with was continuing testing whilst writing design reports and documents. The amount of requirements and documentation requested in terms of the project slightly set back the actual design process. More time was spent on writing documents about tradeoff analysis for class requirements then actually calculating and designing the specific parameters. The team recognized this challenge made efforts to schedule additional time slots during the week for design development in addition to report requirements. Different personality types and work ethic also became difficult aspects of the design process. Busy schedules created a limited amount of time to meet and communicate progress. Also, some members worked better in the morning, while others performed better late at night. This made collaboration tough since members had to adapt to others' work style.

Communication was also difficult in terms of completing projects and reports. Making sure that everyone was on the same page was crucial in getting tasks completed efficiently. The team needed to constantly make sure that everyone was informed. The group handled this by using multiple methods of communicating. The team primarily communicated with one another via email, but also had a Facebook group page. On top of group communication, the Facebook page was created as a means to post general tasks or to share interesting research finds.

In general, project documentation was a key planning exercise used to define the way a project will be managed and implemented. Improper documentation may result in unforeseen consequences in the future. The group had a Dropbox folder which acted as an archive to hold all of the data for the project. All forms of documentation were kept online and in the form of hardcopies. Likewise, all team and advisory meeting minutes were kept in individual design notebooks to allow easy referencing. Experimental results were consistently compiled in tables and graphs for future analysis. The concise and organized documentation of the project's progress will help subsequent senior design teams understand and recreate the project if necessary. It will also assist in the team's application for a provisional patent. Lastly, the group used Google Docs to work together on composing proposals and other technical writing documents for the project. Google Docs allowed the members to simultaneously work on the same document and chat, allowing for instant corrections and feedback.

Finding an ideal testing environment proved to be very difficult. While the team had developed a testing channel, locating a faucet or water source that allowed for a computer set-up nearby was challenging. Since the data acquisition unit and the computer cannot be exposed to liquids, connecting it to the channel was also difficult. The used a tarp or a plastic sheet over the computer unit to prevent water from touching the electronic equipment. Also, no testing equipment can leave the laboratory, which limited the teams' options. Another issue the team faced was not being allowed to use the machine shop equipment to create certain testing channels. Experimental testing was delayed since the team had to seek out a teaching assistant to machine the prototype designs. With all the project challenges faced, the team learned to be flexible with certain processes and account for potential hurdles in the design process.

2.7.2 Budget

The budget constructed by the team focused on material and supply costs. A tabulated budget defining the projected expenses and the team income can be seen in Appendix H. It was developed based on costs encountered during previous research as well as updated as more knowledge on project needs was gained. The budget outlined the grants the team received to use for the supplies necessary. The budget was split into the categories of thermal, piping, electrical, testing, benchmarking, and labor. Tax and shipping were added to the original estimates. The project budget has been updated to reflect most recent estimates and purchases. The main changes and notable differences are outlined below.

Thermoelectric Module Changes

The team realized that purchasing several thermoelectric modules would enhance testing comparison. Throughout this project only brand of module was used, and while the type of module was quite reliable, the team found value in buying other brands and comparing results. Furthermore, buying additional thermoelectric modules allowed the team to carry out multiple different tests on different chambers simultaneously. This quickened the testing process and provided specific comparisons. Thermoelectric modules were also quite expensive when they are not bought in bulk, so the team had to reconsider the earlier estimates.

Insulation and Styrofoam Cutters

Insulation was not a major factor the team considered while creating the initial budget. As testing progressed, the team realized that it was necessary to insulate all exposed areas of the box in order to maintain the desired temperature. The actual Styrofoam used in the final design was not very expensive, but the team explored using spray foam substance to insulate the box. Spray foam performed better but was more difficult to work with and more expensive. Another issue the team was confronted with was how to cut the Styrofoam. The team hadn't factored Styrofoam cutter tools initially in the budget, but they were very necessary to shape the Styrofoam. The Styrofoam cutters performed well but were proven to be very fragile. The team had to buy multiple Styrofoam cutters since they constantly broke.

Thermal Tape

Thermal tape was a purchase which the team had originally under estimated. At first, the team believed that thermal paste could be used to attach the thermoelectric modules and heat sinks to the water chamber, but that was not the case. This was primarily due to gravity and condensation which built up on the box, reducing the hold that the thermal paste had on the chamber. In order to achieve good thermal contact and adhesive quality, thermal tape was the best option. Unfortunately, buying thermal tape in small quantities proved to be quite expensive. This forced the team to increase the budget on thermal tape.

Additional Fittings and Fans

The extra fittings and fans were purchased in order to run multiple testing chambers simultaneously. This allowed for less take-down and assembly time for different chamber iterations as well as a variety of testing chambers. The issue in running multiple tests was that double the amount of fittings, fans, and other accessories were needed. This substantially increased the original budget. A large number of fittings were also bought to better connect with a custom filter; however, the fittings were for Quick Connector fittings. This led to some problems integrating the filter and using the different attachments.

Labor Costs

Originally the team estimated that the final project prototype would be completed in time to have professional casting and a custom circuit board for the design. As testing became prolonged, the labor needed to build the custom prototype was unneeded. While labor costs were not directly needed for the scope of this project, money will have to be allocated to account for these necessary future costs.

Filter Expenses

The team spent more than it had estimated in terms of the filters. In order to make the design universal with any filter, the team bought multiple filters with different attachments to determine the best method of implementing a filter. The team purchased filters from Brita and PUR, as well as other companies to learn how best to adapt the cooler to the filters.

2.7.3 Timeline

The Gantt chart in Appendix I was created to ensure successful and punctual completion of all goals. Included in the fall, winter, and spring timeline were group meetings, advisor meetings, major course assignment deadlines, and subcomponents tasks. To confirm that the team was on track, progress was cross-referenced with the Gantt chart.

The main issues that the team faced were:

- Scheduling issues and time constraints
- Delay of the design process because much of the design revisions and prototyping were dependent on experimental results
- Delay in the process of preliminary patent applications
- Insufficient research on faucet attachments, filters, and materials required

2.7.4 Design Process

For the success of all design projects, a process had to be established. Our process ensured a directional flow towards completion and establishes a basic time and progressing framework. The team broke the process into general segments, starting with research and information gathering, engineering design, design implementation, and testing and re-fabrication. Each segment loosely correlated to the academic school year: summer, fall, winter and spring quarter.

Over the summer of 2012, two members researched and tested the performance of thermoelectric modules (TEMs) under varying conditions. More research on the behavior of thermoelectric modules allowed the team to model and predict refrigeration outcomes. Likewise, varying currents were applied across the TEMs to observe temperature gradients within the module. From these tests, maximum cooling power and current optimization models were derived. Much of the summer was devoted to researching potential applications of solid state refrigeration systems.

The fall of 2012 was the "engineering design" phase in which the team conducted benchmarking tests, gathered relevant information, and used it to create initial design specifications. The first two weeks of the quarter were also devoted to applying for funding and grants. Designs for an instantaneous cooling chamber were laid out and modeled in SolidWorks. After modeling, the first design iteration was machined and tested. The results of the design iteration were then compared to MATLAB models. A Gantt chart was developed to frame the project's timeline. In addition, a comprehensive budget was drafted, which included the cost of all the necessary components.

The team went through more design iterations in the winter. Each iteration was tested and analyzed. All design iterations were drafted in SolidWorks, and cooling power optimization was modeled in MATLAB. After observing the results of each, the team began to conduct Finite Element Analysis simulations in SolidWorks and Comsol. The team also looked into universal fittings and adapters to make the installation of the unit as streamlined as possible. In general, the quarter was reserved for testing, procuring materials, and machining the various components of the design iterations. During the spring of 2013, further testing was completed on the system and microflex heat pipes were added to potentially improve performance. The best design iteration was completed a few weeks before the 43rd Annual Senior Design Conference. The remaining weeks after were spent testing, improving, and slightly modifying the system.

2.7.5 Risks and Mitigations

A risk is any factor that may potentially interfere with successful completion of the design project. By recognizing potential problems, the team attempted to avoid a problem through the proper courses of action. The following issues were determined to be possible risks that needed to be addressed by our project solution are outlined in Table 4.

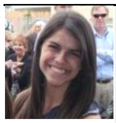
Table 4: *Potential Risks and Mitigation Strategies*

Risks	Consequences	P	S	I	Mitigation Strategy
Logistics and Organization					
Time	Incomplete Project	.8	9	7.2	- Decide on final system design - Create designated time blocks to work solely on project
Conflicting schedules	Group is unable to meet and make decisions	.9	6	5.4	Set meeting dates earlier or in advance
Technical Aspect					
Lack of knowledge on certain technical components	- Time spent learning key features of components - Mistakes in models and calculations - Delays in the project	.8	8	6.4	- Assign specific members an area of expertise to focus on
Inability to reach target system parameters (i.e. - Water temperature - Excess Heat dissipation - Power Consumption - Mass, etc.	- Water will not be as hot/cold as necessary - Improper heat dissipation affects system functionality - More energy consumed equates to a higher cost - Design becomes too bulky	.5	9	4.5	- Thoroughly examine individual components - Increase estimated research time to ensure goals are met - Prioritize parameters according to importance
Poor user interface	- negative consumer experience	.4	7	2.8	Create a simple interface that any consumer could use
Unfamiliar CFD (Computational Fluid Dynamics) and FEA (Finite Element Analysis) modeling protocol	- Time will be spent learning how to properly use CFD and FEA programs to model the system	.9	3	2.7	Familiarize and educate oneself with different modeling softwares
Testing Equipment					
Faulty wiring	- Inconclusive or insufficient results are acquired - Affects how much heating or cooling can occur	.5	10	5	Check system components thoroughly prior to conducting the experiment
Leakages	Affects temperature, flow rate, etc.	.6	9	5.4	Check experimental system components thoroughly

$*Probability, P\ [0-1] \times Severity, S\ [1-10] = Impact, I$

2.7.6 Team Management

Rachel Reid



Rachel is the team leader and focused on delegating task and setting team deadlines. She has been researching the performance of thermoelectric modules for the past year and has been responsible for gathering experimental data from testing the technology. She conducted future experiments to potentially increase the efficiency of thermoelectric refrigeration.

Brandon Ohara

Brandon has worked with the thermoelectric modules this past summer and has been responsible for modeling the temperature gradient of the thermoelectric modules. He continued to produce theoretical models and calculation to optimize thermoelectric efficiency.

Bernadette Tong

Bernie is the team recorder who is responsible for organizing important project documentation. She joined the research team in the summer and has a strong background in tankless water heating that has been invaluable in this project. She organized and compiled data on water flow patterns, and calculated the optimal length of the heat sink fins.

Franz Louie Chua

Louie also joined the team late in the summer and has a strong background in 3D modeling. He continued to modify prototype designs in Solidworks and learned CFD to provide a heat transfer analysis of the channel flow.

Chapter 3 Subsystem Components

3.1 Mechanical Subsystem

3.1.1Overview

QuikChill's goal of being able to cool water required different mechanical subsystems. These subsystems included thermoelectric modules, heat dissipation, water chamber, and insulation. The thermoelectric modules were the main component of the design that cooled the water. Understanding how the modules worked was crucial for each module performing at its max capabilities. Heat dissipation greatly affected the thermoelectric module's performance. The thermoelectric modules required heat dissipation in order to remove the heat that the module absorbs from the water. If the heat dissipation was inadequate, the module could not function as a cooler and, in extreme cases, heated the water instead of cooling it. The water chamber also needed to be carefully selected in order to contain as much water as possible, while still being small enough to allow the water in it to cool in a reasonable amount of time. Insulation also heavily affected the performance of QuikChill. As the water temperature cooled lower and became lower than the environment temperature, heat transfer naturally occurs between the environment and the water. Insulation needed to be carefully chosen and manufactured to reduce heat transfer. Figure 8 demonstrates the relationship between the thermal resistance and heat transfer. Q_H is the heat rejected through the external heat sink between the hot side of the module and the temperature of the air. The symbol, Ψ_H, indicates the thermal resistance of the heat sink. Ψ_C indicates the thermal resistance between the cold side of the module to the water in which Q_C is absorbed. The thermal resistance of the chamber and insulation is represented by $\Psi_{Chamber}$where heat is lost from the chamber to the environment. Further explanation of the phenomena is given in this chapter.

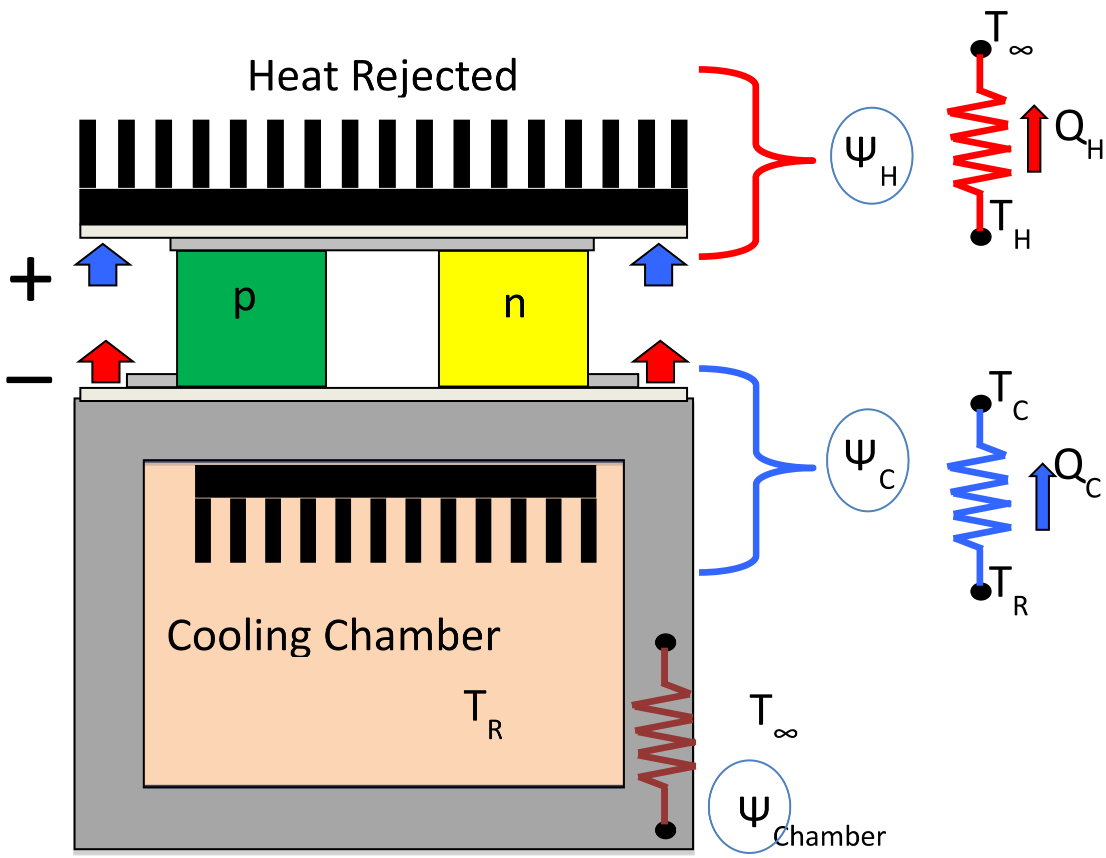


Figure 8. *Illustration of Mechanical Overview*

3.1.2 Heat Sinks

Heat sinks are passive heat exchangers used to increase the surface area for heat transfer. Heat sinks were necessary in the design in order to increase the amount of heat transfer between the heating side of the thermoelectric modules and the environment, and to increase the surface area within the chamber where heat was absorbed from the water for cooling. Figure 8 shows the general locations of the heat sinks inside and outside of the chiller. Heat sinks had to be appropriately sized in order to fit inside or on top of the box while still being effective.

The performance of the fins placed within the chamber was determined based on the enhancement of heat transfer relative to the case that the interior surface of the chamber had no heat sinks. Mathematically, fin effectiveness, ε_{fin} can be expressed as

$$\varepsilon_{fin} = \frac{q_{fin}}{hA_b(T_b - T_\infty)}$$ Eq. 3

where q_{fin} is the conductive heat transfer through the fin, h is the convective heat transfer coefficient across the fins, A_b is the cross-sectional area of the fin base, T_b is the base temperature, and T_∞ is the ambient temperature of the water. Heat transfer through the heat sinks was calculated based on the assumption of an adiabatic tip, and that the only medium was via conduction. This conductive heat transfer can further be expressed as

$$q_{fin} = \left[\sqrt{hPkA_c}\tanh\left(\sqrt{\frac{hP}{kA_c}}L\right)\right](T_b - T_\infty)$$ Eq. 4

where P is the perimeter of the fin, k is the thermal conductivity of the heat sink, A_c is the cross-sectional area of the fin, and L is the length of each fin.

In general, for an adiabatic fin assumption, the ε_{fin} should be ≥ 2 with an upper limit that $\sqrt{\frac{hP}{kA_c}}L$ should be greater than 2.65. If $\varepsilon_{fin} < 2$, this indicated that the addition of fins acts as an insulation, slowing down the heat transfer from the TEM to the water. This may occur when fins are made of low thermally conductive materials. If $\varepsilon_{fin} = 2$, this shows that the addition of fins does not aid or impede heat transfer. The heat transfer through the base to the fin is equal to the heat transferred from the base to the water. In this case, the cost outweighs the addition of the extended surfaces and can be seen as unnecessary. If $\varepsilon_{fin} > 2$, then the addition of the heat sinks are effectively enhancing heat transfer between the water and the TEM.

Fin effectiveness was improved by the choice of material and by choosing heat sinks with a high ratio of the perimeter to the cross-sectional area. For this reason, the use of thin but closely spaced fins was preferred with the provision that the fin gap was not reduced to a value for which the flow between the fins was severely impeded, thereby reducing the convection coefficient. Calculations and modeling were created in MATLAB as shown in Appendix K.4.

While thermoelectric modules have the ability to cool, the heat absorbed on the cold side of the TEM had to be effectively dissipated on the hot side by means of extended surfaces. If this heat was adequately rejected, it would build and decrease the cooling capability of the thermoelectric module. In order to dissipate this heat to the surrounding environment, different approaches were taken. Heat was rejected by attaching fan-cooled heat sinks on the hot side of the modules to increase forced convection heat transfer. Heat can also be dissipated through liquid cooling by flowing water over the hot side of the thermoelectric modules. Flowing water was not a viable option because it meant a separate flow of water over the modules around the chamber. This would overcomplicate the design of the system. In addition, using water to cool the thermoelectric modules meant that a portion of the water from a user would be wasted. The QuikChill design instead implemented heat sinks and fans in order to dissipate as much heat as possible.

Design considerations were made to maximize heat dissipation/absorption while maintaining a compact size, since a larger surface area to volume ratio of the fins allowed for greater heat transfer. Fin design calculations were necessary in this analysis to predict the heat dissipation performance of a given heat sink. A labeled heat sink schematic is seen in Figure 9. Choosing the material, given cost constraints for a heat exchanger was another design consideration. The material had to be cost effective and not too heavy for practical application use. For instance, copper is a more thermally conductive material, but costs three times more than a traditional aluminum heat sink. In general, a heat sink with a highly conductive material was necessary for the design to operate properly. The heat sink also needed a low thermal resistance in order to maximize the heat dissipation from the water to the environment.

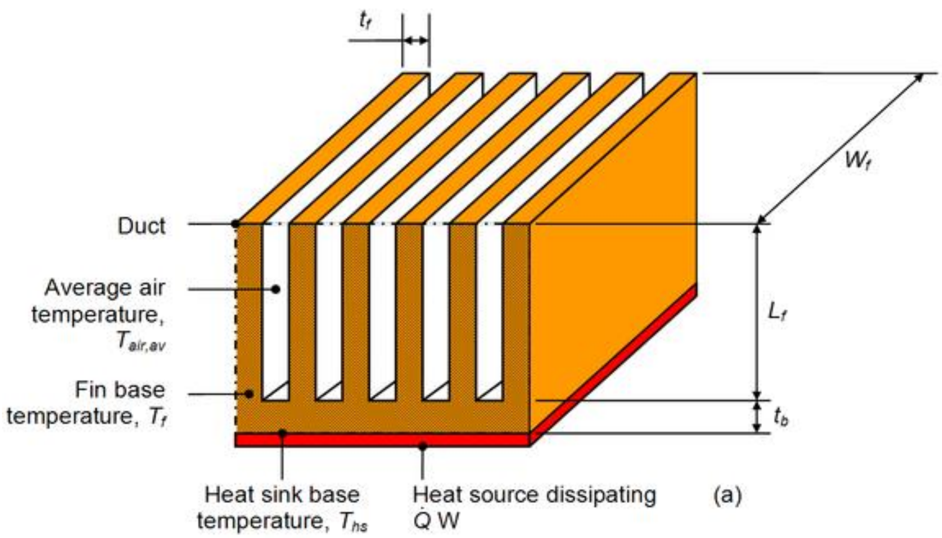


Figure 9. *Heat Sink Diagram*

Fans were also implemented into the system to effectively dissipate the heat. The increase in forced convection increased the amount of heat dissipation. The drawback to integrating fans to the design was added power consumption in the unit. However, the fans did not take up significant amounts of energy, and were necessary to reach desirable drinking temperatures. By increasing the size of heat sinks and the fan velocity, the thermal resistance between the hot side of the TEM and the environment, or ψ_H , was reduced. One possible strategy to cool the water was to increase the number of modules. For each module, however, proper heat dissipation was necessary. Shown in Figure 10 is a comparison of how much the water temperature can be reduced based on the thermal resistance and number of modules. This model assumed that the heat dissipation ψ_H is split evenly among each of the modules. As seen in the Figure 10, colder temperatures can be achieved with lower ψ_H. For each ψ_H value, however, there exists a single point with the minimum temperature indicating the optimum number of modules to use. The red 'x' shows the QuikChill product currently. The best design iteration tested achieved a lowest temperature of 14°C using three modules. The model suggested decreasing the number of modules while keeping ψ_H the same. However, for this iteration, each TEM had its own heat sink and fan. This meant that to keep ψ_H the same for a single module, those three heat sinks would have to be combined to dissipate the heat from that module.

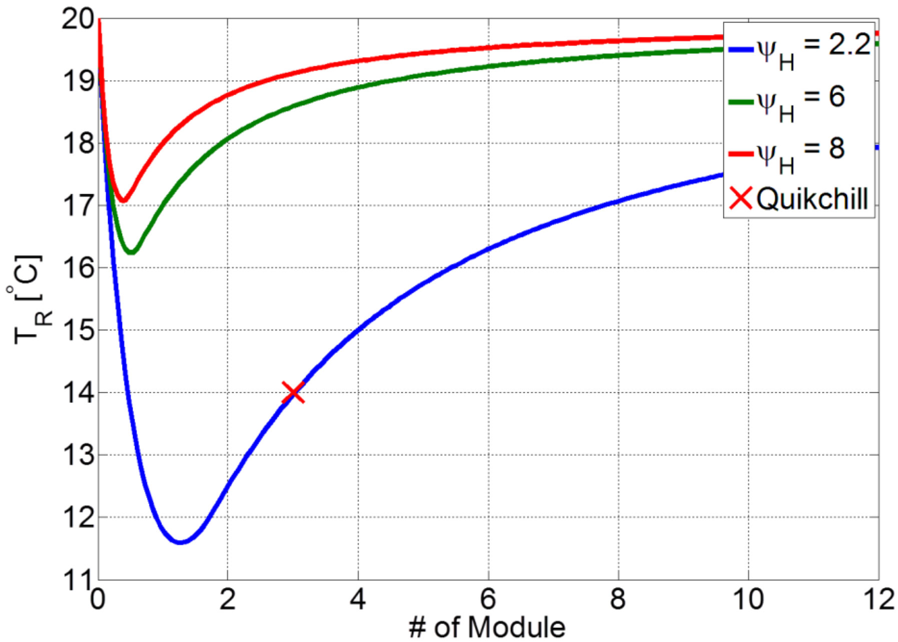


Figure 10. *Coldest temperature achievable based on number of TEMs and* ψ_H

3.1.3 Thermoelectric Modules (TEMs)

To accomplish the goal of cooling water in a low-powered compact manner, thermoelectric modules (TEMs) where implemented to the design. Thermoelectric cooling works based on the Peltier effect. When a current is passed through a junction of two dissimilar materials heat is absorbed at one side and released on the other. Thermoelectric modules consist of many pairs or junctions of two dissimilar materials set up electrically in series and thermally in parallel. When a current is passed through the module, heat is absorbed at one end of the module and released at the other. An illustration of a thermoelectric module can be seen in Figure 11.

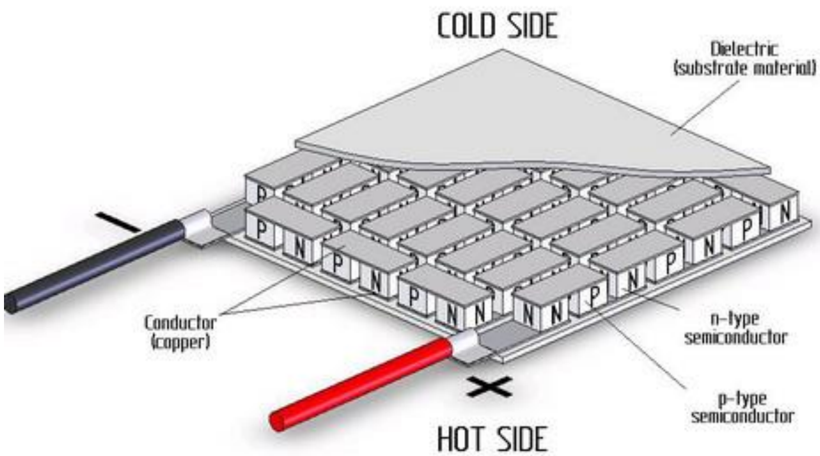


Figure 11. *Thermoelectric Module Schematic*

In selecting a cooling technology, the team chose between thermoelectric refrigeration and traditional refrigeration. Thermoelectric modules were chosen because of the benefits they have at small scale, which aligned with our project goals. Thermoelectric modules are small, which was important for the team because of the limited amount of space under the sink. In addition, thermoelectric modules are solid state devices, meaning the entire phenomenon happens within the material itself. This means that the thermoelectric module is all that is needed to cool, rather than a typical refrigeration cycle which requires a compressor, condenser, and evaporator. Since thermoelectric modules are solid state, they do not have the mechanical moving parts that other systems require. This causes thermoelectric modules to be low maintenance and gives them a longer working life than typical refrigerators. TE Technology, a thermoelectric module producer, estimates that its thermoelectric modules have a working life of 200,000 hours [13], which equates to about 23 years. According to a recent study given by Consumer Reports, the average refrigerator lasts around 13 years [8].

Thermoelectric modules also do not require a refrigerant like a typical refrigeration cycle does. This cuts down on the amount of possible fluorocarbons or hydrofluorocarbons that enter the atmosphere, increasing the greenhouse effect or depleting the ozone layer. Thermoelectric modules also have a fast response time due to not needing moving parts and needing to move the working fluid or refrigerant to begin the cooling process. Lastly thermoelectric modules are scalable. Based on the number and size of the modules, TEMs can be easily scaled to suit application needs.

Once the team decided to use thermoelectric modules, the team then had to select between brands of thermoelectric modules and model numbers. Based on its specifications, cost, and performance, Marlow thermoelectric modules were chosen. The TEMs made by Marlow were specifically manufactured for cooling purposes and use Bismuth Telluride as the thermoelectric material and had the highest Coefficient of Performance among TEMs. Data sheets for the specific Marlow TEMs used and other components can be found in Appendix J.

As mentioned earlier, thermoelectric modules operate as a chiller/heater using the Peltier effect which states that when current is passed through a junction of two dissimilar materials a temperature gradient is generated at either end. Because of the temperature gradient, heat is generated and absorbed at the ends of the TEM. In cooling, the water is passed along the side that absorbs heat, which cools the water by removing heat from it. When operating as a heater, the water is passed along the side that generates heat. The generating side dissipates its heat to the water, heating the water.

By reversing the direction of current through the circuit, the side of the TEM that heats and cools is reversed. Therefore water can be passed along one side of the TEM and be either heated or cooled depending on the current direction. Based on the Peltier effect, cooling power increases with the amount of current passed through the TEM. Here the amount of heat absorbed and emitted by the TEM is given by:

$$Q_C = SIT_c - K(T_H - T_c) - \frac{1}{2}I^2R \quad \text{Eq. 5}$$

$$Q_H = SIT_H - K(T_H - T_c) + \frac{1}{2}I^2R \quad \text{Eq. 6}$$

where Q_C is the heat absorbed from the chamber and Q_H is the heat dissipated by the hot side of the TEM. T_H and T_C are the temperatures of the hot and cold side respectively. S is the overall Seebeck coefficient of the module, I is the current through the TEM, K is the thermal conductance of the module, and R is the electrical resistance of the module. The Peltier effect is seen in Equation 5 and Equation 6 as SIT. In Equation 4 it can be noted that increasing values of current Joule heating (shown as $\frac{1}{2}I^2R$) can overcome the Peltier effect resulting in the cold side of the TEM actually heating up.

Based on the thermal circuit, Q_C and Q_H can be equated to:

$$Q_C = \frac{T_R - T_C}{\psi_C} \quad \text{Eq. 7}$$

$$Q_H = \frac{T_H - T_\infty}{\psi_H} \quad \text{Eq. 8}$$

where T_R is the temperature inside the chamber, ψ_C is the sum of thermal resistances on the TEM cold side to the water in the chamber, and ψ_H is the sum of thermal resistances on the hot side of the TEM to the environment. Combining equations 5 and 7 and equations 6 and 8:

$$\frac{T_R - T_C}{\psi_C} = SIT_c - K(T_H - T_c) - \frac{1}{2}I^2R \quad \text{Eq. 9}$$

$$\frac{T_H - T_\infty}{\psi_H} = SIT_H - K(T_H - T_c) + \frac{1}{2}I^2R \quad \text{Eq. 10}$$

In addition, the heat gain from the environment is given by:

$$mC\frac{dT_R}{dt} = \frac{T_\infty - T_R}{\psi_{chamber}} - \frac{T_R - T_C}{\psi_C} \quad \text{Eq. 11}$$

In the steady state Equation 11 becomes:

$$\frac{T_\infty - T_R}{\psi_{chamber}} = \frac{T_R - T_C}{\psi_C} \quad \text{Eq. 12}$$

Based on equations 9, 10, and 11, by knowing the module properties, the three unknowns (T_R, T_H, and T_C) can be solved for as a function of current. This was the first model which solved for temperatures of the module solely based on current. Previous attempts to model thermoelectric refrigeration required knowledge of the temperature difference across the module or the water chamber temperature to be able to predict the system's performance. The cooling power of TEMs, the desired temperature difference, the number of TEMs were coupled constraints in modeling. The TEMs have a maximum cooling power because Joule heating counteracts the Peltier effect. In order to increase the cooling power, different approaches were taken. Multiple modules were implemented, or the thermal resistances were lowered to increase the amount of heat absorbed/rejected by the TEM. Another analysis will be presented later (5.3.2), and the full MATLAB code can be seen in Appendix K.

3.1.4 Water Chamber

In order to adequately cool the water before release, water was housed in a chamber which was cooled by thermoelectric modules. The water chamber was a necessary subsystem because water could not be instantaneously cooled, which was contrary to our initial instantaneous cooler idea. The water chamber had to be sized appropriately in order to hold enough cold water to satisfy customer needs, but small in order to decrease the thermal mass of the system and reduce the time it takes to cool the water. In order to determine this, the team benchmarked various similar products including the Avanti thermoelectric water cooler, and the water and ice dispenser in a refrigerator. The Avanti and refrigerator dispenser had water capacities of 800mL and 500mL respectively. In order to match the competitors, QuikChill decided to use a chamber with a volume of 800mL.

Two strategies were discussed in selecting the material of the chamber. The first strategy was to use a thermally highly conductive material in order for heat to be absorbed easily through the wall of the chamber by the thermoelectric modules. However, heat gain from the environment also easily affected the water through the aluminum. A second strategy implemented used a highly insulating material in order to decrease the heat gain from the environment as much as possible. However, this also meant that the thermoelectric modules could not easily absorb heat from the water. In order to solve this problem, the team planned to cut a hole in a plastic chamber and insert a heat sink in order to have a small surface area of the chamber where the thermoelectric modules could easily absorb heat. The team, however, decided to go with a highly conductive material, (in the prototype aluminum), and insulate the areas of the chamber not in contact with the thermoelectric modules to minimize heat gain from the environment. Seen in equations 5 and 7, ψ_C is indirectly proportional to the amount of heat absorbed by the TEMs. In addition, $\psi_{chamber}$ as seen in equations 9 and 10, is indirectly proportional to the amount of heat gain from the environment to the system. Having an aluminum chamber decreased ψ_C but will require much more effort to raise $\psi_{chamber}$.

3.1.5 Insulation

Insulation was a necessary component of the system in order to reduce heat gain from the environment. Ideally, the subsystem consists of material with low thermal conductivity and inexpensive to reduce production costs. Low conductivity means that less heat will be transmitted through the material, decreasing the amount of heat coming from the environment into the water. Foam plastic is a material that is abundant and is already used as an insulator. Foam has a low thermal conductivity and is inexpensive. Two types of foam were tested and decided between, Styrofoam and spray foam. Styrofoam has a lower insulating value of 1.8K/W than spray foam with 2 K/W. In addition, Styrofoam was more difficult to work with and required precise cutting in order to fit well onto the chamber. Spray foam was easier to form around the chamber making the system better insulated. Once a mold had been made, spray foam was distributed around the chamber and left to expand. This expansion filled all crevices which made for better contact with the chamber to prevent heat gain. By using equations 7, 8 and 10, and inputting different values of insulation or, $\psi_{chamber}$, the lowest temperature achievable can be seen as a function of insulation in Figure 12. As seen by the red 'x', QuikChill has achieved an insulation thermal resistance of 2 K/W. This led to the minimum temperature achieved of 14°C. If this insulation thermal resistance were to increase, significantly lower temperatures could be reached.

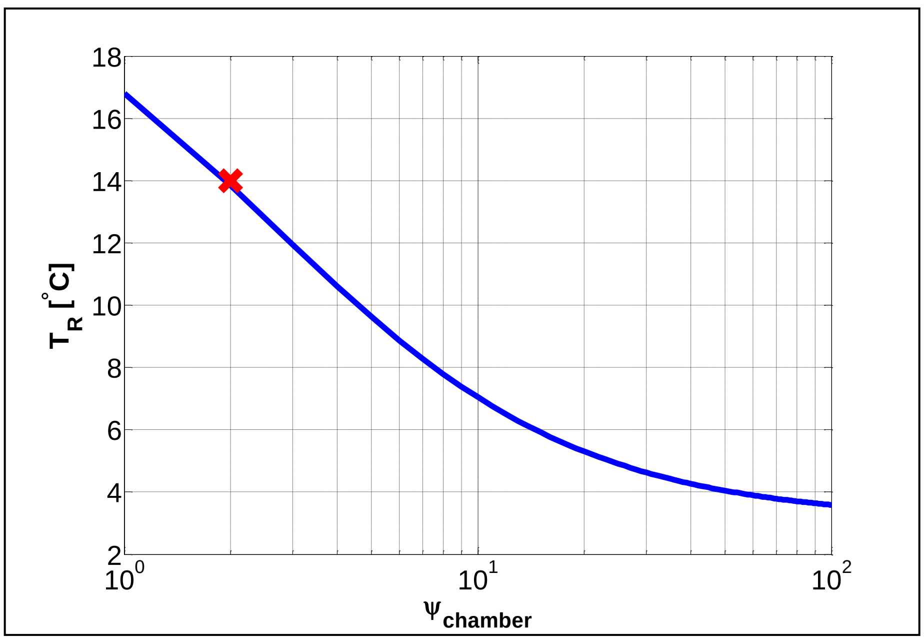


Figure 12. *Lowest Achievable Water Temperature based on* $\psi_{chamber}$

3.2 Electrical Subsystem

3.2.1 Overview

The main electrical components of the system were the control circuit board and an AC/DC converter used to power the thermoelectric modules. This was a necessary component of the design since the modules need a certain amount of direct current to produce cooling. The control board is used to regulate the use of the thermoelectric modules so that they are not cooling all the time. They are only turned on when necessary, which in turn will save energy.

3.2.2 Hardware

The hardware bought for this project was:

- YourDuino Robo1 Arduino board compatible with built-in 3-pin I/O connectors using ATMEGA328.
- Opto-Isolated 2 Channel Relay Board
- Breadboard
- Waterproof Stainless Steel encapsulated Temperature sensor
- DC power adapter

This allowed for control of the modules based on the temperature sensor readings.

3.2.3 Control System Logic

The basic logic of the control circuit can be seen in Figure 13. The system is closed loop in which the waterproof senor reads the temperature, and then a decision is made based on that temperature. If the temperature is above a certain threshold then the relay is initiated to power the thermoelectric modules. If the temperature is below the threshold, the system pauses then reads the temperature again.

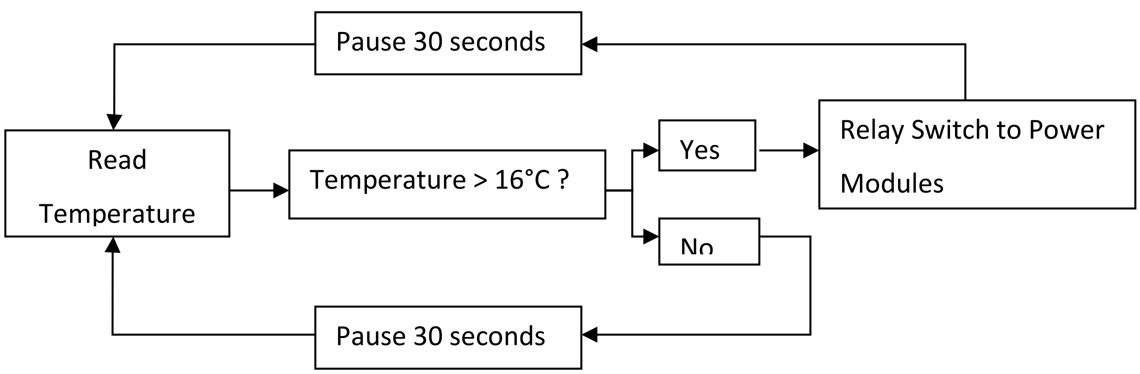


Figure 13. *Control System Diagram*

Chapter 4 System Integration, Experimentation, and Results

4.1 Experimental Protocol

The QuikChill project required many tests to evaluate the different aspects of its performance. Tests were carried out to ensure that the QuikChill product achieved the goals set out in the PDS, which can be found in Appendix E. Tests were run to evaluate the water temperature, the time it took to cool the water, the power consumption of the system, the mass/volume of the system, and the water purifying capabilities of the system, the heat dissipation, and the thermal resistance of the cooling chamber. The experimental protocol for each of the evaluation criterion is tabulated in Table 1 of Appendix M.

Water temperature

Since the main purpose of the system was to achieve water temperatures within the range of 11-16°C, water temperature measurements were one of the key factors measured experimentally. Evaluation of the water temperature indicated the performance of the entire project since many other design criteria affected the water temperature.

The water temperatures were evaluated against the results from the survey that described consumer desire in terms of water temperature. Based on survey data, the target range of water temperature was 11-16°C. The water temperature was measured for every chamber iteration design since it is the main indicator of performance. The tests were performed in the Heat Transfer Lab at various times throughout the quarter. Design iterations were made and the temperature of the water under different conditions was tested shortly thereafter. These design iterations can be seen in Table 2 in Appendix M.

The water temperature of the assembled system was measured using two K-type thermocouples, which were placed inside a water-tight container and connected to a DAQ module. An Agilent Power Supply controlled by a LabView VI was used to input a set current into the modules to effectively cool the chamber. Temperature measurements were made every second. The uncertainty of the measurement can be taken from the uncertainty of the thermocouple, which is 0.4°C. The assumptions made in this test mostly revolved around the position of the thermocouples. The experiment assumed that the position of the thermocouples in the water represents the temperature of the entire chamber. It was also assumed that the thermocouple was not touching the surface of the chamber, but the water. Two thermocouples were used because the temperature throughout the water may not have been uniform, thus an average of both recorded temperatures provided a more accurate representation.

The water temperature tests vary, but lasted two hours on average. The set-up time for the experiments was about two hours, when insulation application is included. It took about 30 minutes to analyze the data from each test since LabView puts the data in Excel form, making graphs easy to create. Temperature tests were run for an acrylic chamber, a large two-liter chamber, and three different design iterations of a smaller, 800 mL box.

The steady state temperature of the water was a function of the current into the modules, the amount of insulation, the heat dissipation for the heat generated by the thermoelectric modules, the amount of water, and the amount of thermal resistance between the cooling side of the thermoelectric modules and the water. A matrix is shown in Appendix F of the parameters altered and tested.

Time to Cool Water

The time taken to cool water was tested in every experiment in which the water temperature was taken. While this metric was gathered for the same tests, and at the same times, as the water temperature test previously mentioned, the time was an important unit to analyze in the experiment. Understanding how long the chamber took to achieve a desired temperature was an important aspect of the design. Achieving the fastest time to target temperature was ideal. The same equipment for the water temperature was used, but more focus can be put on the ending temperature and time. In addition, the temperature of the water after 20 minutes of cooling was recorded and compared against competitors. The team determined that 20 minutes was a relatively short amount of time to wait for cold water.

Tests were repeated for every chamber, and all occurred in the Heat Transfer Lab. Based on the noise of the data, the estimated accuracy for the test was determined to be one minute. It was assumed in these tests that the final temperature is at steady state when recorded. Much like the water temperature test, the set-up time took two hours, the testing time took two hours on average, and the data analysis took about one hour to complete.

Power Consumption

Reduced power consumption was one of the main purposes of the system. The power consumed by the system needed to be lower than the power consumed by the water and ice dispenser accessory of the refrigerator. When the system was running under peak power, consumption was calculated by taking the current and multiplying it by the voltage output of the power supply. Decreasing the amount of power using less current and fewer modules has been an important design consideration.

The power consumption of the system was evaluated during the water temperature and time test. The power supply used in the tests measured the input voltage and current into the modules. The values were displayed in Excel and were manipulated to find power. These values yielded the power consumed by the chamber for the length of the test. The target power range was identified as 0.384 kWhr based on benchmarking results and preliminary tests. This number did not take into account the power needed for future implementation of an Arduino based control system. Because of this, the accuracy of the experiment was estimated to a range of 0.048 kWhr. The man hours needed to conduct the water temperature test were the same for the power consumption evaluation.

Mass/Volume

The mass and volume of the system was important to test because a system that is too heavy could not be easily mounted. Also, the system needed to be small in size since there is limited space under the sink where the system would be installed.

The mass and volume of the system were evaluated against typical Brita water pitchers, the size of refrigerator water dispensers, and tank coolers. Since the prototype will be implemented under a sink, the expected outcome for the mass of the system was predicted to be 3 kg. The tests were performed in the Machine Shop using a special scale to handle the chamber carefully. The test date for this experiment was on April 22nd. Since the mass was not a major design constraint, accuracy is set to within .5 kg of the goal. Three trials were taken to obtain an average mass measurement of the system. This test protocol took about 1 hour to obtain and analyze the data.

Heat Dissipation

The amount of heat dissipated from the hot side of the TEM was crucial for cooling performance. If the TEM did not have a mechanism to dissipate heat, the entire module would heat up which would in turn heat up the chamber. Heat sinks and heat pipes were tested and used as methods of heat dissipation on the hot side of the module. The performance of the heat sink and heat pipe were reflected in the temperature of the water experiment, but there were ways to test the effectiveness of the heat pipes and heat sinks independently of the entire testing chamber.

The heat dissipation was tested for various heat sinks and heat pipes using a hot plate and thermoelectric modules. When thermoelectric modules were placed under a temperature difference, a voltage and current is generated due to the Seebeck effect. By measuring the open circuit voltage and short circuit current of the TEM under a temperature difference, the approximate thermal resistances were found. A thermoelectric module was placed on a heat sink set at a constant temperature. Various heat dissipation methods were used on the opposite side and the open circuit voltages and short circuit currents were measured. With better heat dissipation, a larger temperature gradient was maintained across the thermoelectric module, and more current and voltage are generated. The open circuit voltage and short circuit current were both measured and placed into a MATLAB model which predicts the output voltage and current of a TEM under various thermal resistances. By matching the amount of voltage and current with the model, the heat dissipation thermal resistance was found. The thermal resistances were to characterize how effective the heat sinks or heat pipes were at dissipating the heat.

As mentioned, a hot plate, thermoelectric module and heat sink were needed in the described experiment. Additionally, a DAQ was used to measure the open circuit voltage and short circuit current of the module. This information was gathered and processed using a LabView VI. The results of the tests were also analyzed using a MATLAB code. The experiments took place in late February in the Heat Transfer lab for the heat sinks. The heat pipe tests were completed April 3rd in the Heat Transfer Lab as well. Data points were taken for each test. One of the problems with testing heat dissipation was that there were no outlined goals; we merely observed which module performed better or worse. The thermal resistance results were used in modeling approaches, but the actual open circuit voltage is just used for comparison and cannot be applied to the different conditions of the prototype. The main assumption in this test was that the thermal resistances of the module are the same in the experiment as in the cooler. The accuracy of this test was a little lower than other tests because it was completed by matching a model with the experimental data in order to approximate the thermal resistances. Because of this, the accuracy of this test was 2K/W. The described test protocol took about 30 minutes per heat sink or heat pipe followed with about an hour of data processing.

Thermal Resistance of Chamber (Insulation)

Thermal resistance of the cooling chamber was a vital part of the system. Thermal resistance of the chambers was directly related to the amount of insulation. Insulation and thermal resistance of the chamber was required to keep heat transfer between the water and the environment at a minimum. The thermal resistance of the chamber and the amount of insulation decrease the amount of time it takes to cool the water, as well as the steady state temperature, because the TEMs do not have to overcome the heat coming in from the environment.

In order to accurately evaluate the thermal resistance of the chamber, cold water was placed into the chamber. Then, the temperature over time was measured as the water naturally rose back to ambient temperature. This data was placed into excel, and, assuming a lumped capacitance method, the overall heat transfer coefficient of the system, and thus the insulation, could be quantified. The special equipment used in this experiment was a thermocouple and timer. The measurements were taken using a DAQ and recorded using MATLAB. Only two trials of this test were completed, one for Styrofoam insulation and one for spray insulation. Once the temperature over time was recorded for the water to return to ambient temperature, the overall heat transfer coefficient between the environment and the chamber was found, with the insulation thermal resistance being embedded in the overall heat transfer coefficient. This test interpretation used a lumped capacitance model to calculate the overall heat transfer coefficient. This test required that there was little to no thermal gradient within the water.

The accuracy of these tests was similar to heat dissipation with an accuracy of 2 K/W. These tests were completed after water temperature and time tests in the Heat Transfer Lab. Based on modeling results, the expected outcome of the insulation tests was about 30 minutes to reach ambient. It took about an hour to set-up, run, and analyze the test data.

4.2 Experimental Results

Various system iterations were compared between each other to observe the most efficient system. Temperatures were recorded over time and the temperature difference, ΔT, were compared after twenty minutes, as well as the relative minimum temperature that the system can achieve, which was taken about 1.5 hours into the experiment. A parts list for the iterations can be found in Appendix N. The detailed drawings for machined parts can be found in Appendix O. The complete assembly drawings for the experimental iterations described in this section can be found in Appendix P.

The initial approach to the project was to achieve a system that could instantaneously cool water. The first experiment that was done was with an acrylic chamber. The acrylic chamber was used because the thermal conductivity of the acrylic is low, which would act as an insulation between the water chamber and the environment. Four thermoelectric modules were placed on top of an aluminum sheet that was used as a cover for the acrylic chamber, as shown in Figure 14. The chamber had a volume of about 160 mL.

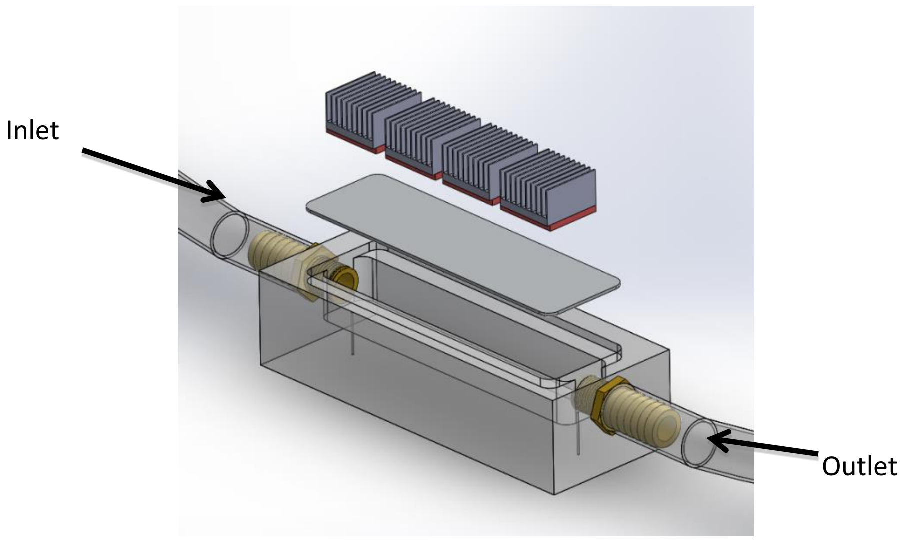


Figure 14. *Acrylic Chamber Design Iteration*

As shown in Figure 14, the inlet and outlet were attached to polycarbonate tubes using copper barb adapters. Results for this experiment showed that a change in temperature, after twenty minutes was about 1.0°C, and the relative minimum temperature achieved was about 20°C, which is high. The small ΔT and high minimum temperature was due to the fact that the system was instantaneous. In other words, the water was continuously flowing at a set mass flow rate, which was set to $0.1m^3/s$. Because the water was continuously flowing, it did not cool to its lowest possible temperature before leaving the chamber, resulting in a small temperature difference after twenty minutes.

The next experimental iteration involved using a water chamber, rather than a continuously flowing water channel. A large aluminum chamber with a volume of 2 Liters was used in order to have better thermal conduction between the cold side of the TEM and the water chamber. Figure 15 shows the experimental set up of the large aluminum chamber experiment.

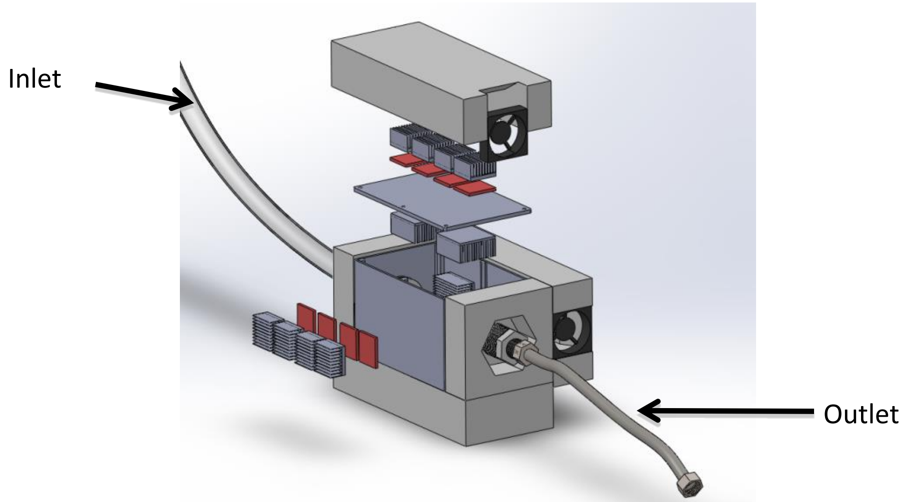


Figure 15. *Large Aluminum Box Design Iteration*

As observed in Figure 15, the large aluminum chamber used twelve thermoelectric modules attached on the left, right and top areas of the box. Heat sinks were attached onto the hot side of the TEM using thermal tape in order to dissipate the heat from the system and produced by the TEM. Fans were also used in order to increase the convection coefficient to dissipate more heat to the environment. Styrofoam insulation was placed around the system to prevent heat gain of the system from the environment. Within the Styrofoam insulation, air channels were carved to concentrate air flow over the heat sinks to facilitate heat dissipation to the environment. Heat sinks were also placed inside the aluminum box in order to increase heat transfer to the water.

The temperature difference achieved in this experiment after twenty minutes was 2.1°C with a relative minimum temperature of 17°C. It is apparent the results from this experimental iteration were better than that of the previous one. However, the minimum temperature achieved is still a degree shy of the desired temperature range of 11°C -16°C. In order to achieve the desired temperature range, the team decided to decrease the overall thermal mass of the system, as the volume of the water was too high. Therefore, the next experimental iteration used a smaller aluminum box with a volume of about 800mL. Figure 16 shows the design of the experiment.

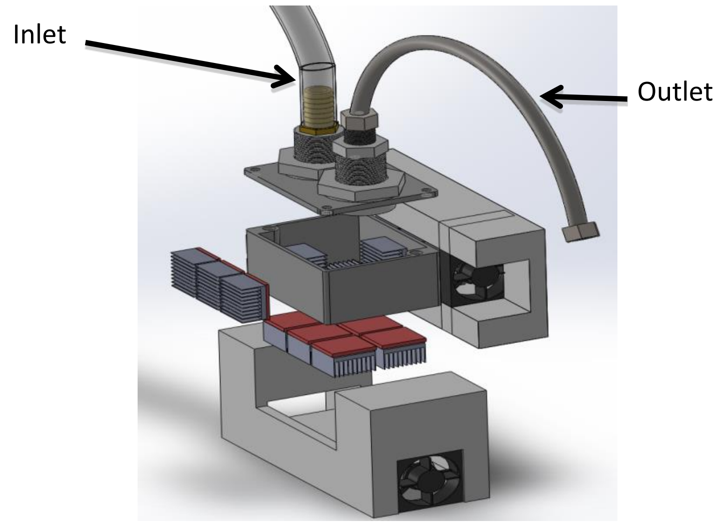


Figure 16. *Small Aluminum Box with Small Heat Sinks Design Iteration*

As observed from Figure 16, the same number of 12 TEMs was used, as well as similar Styrofoam insulation. The inlet and outlet for this experiment were placed on the lid, thus the six TEMs were placed on the bottom of the box. Results for this experimental iteration showed that a temperature difference after twenty minutes was 2.4°C and a relative minimum temperature of 17°C. A greater temperature difference after twenty minutes was acquired compared to the 2.1°C of the previous experiment because the system had a smaller overall thermal mass. A negative aspect to this design was that many TEMs were used, thus the amount of power required to power the system is inefficient. In addition, the coldest temperature achieved had not improved from the previous design iteration and was still outside of the target temperature range. Therefore, the next experimental iteration utilized fewer TEMs and larger heat sinks to dissipate heat from the system, as shown in Figure 17.

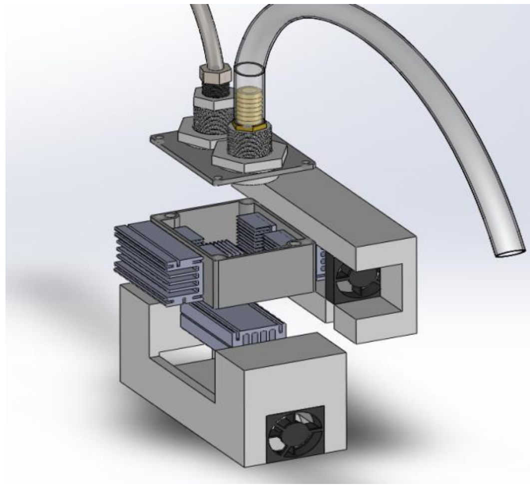


Figure 17. *Small Aluminum Box Design with 3 Modules Design Iteration*

The experimental iteration, as seen in the Figure 17, was based on the theoretical modeling comparing the tradeoff between using more thermoelectric modules or larger heat sinks. Using more thermoelectric modules increased the temperature difference after twenty minutes, but it did not achieve a lower minimum temperature because the heat is not dissipated properly. Therefore, for this experimental iteration, only three thermoelectric modules were used, but larger heat sinks were used to dissipate the heat more efficiently. Results for this iteration showed that a temperature difference of 3.9°C was achieved after twenty minutes and a relative minimum temperature of about 14°C. Not only did this iteration achieve a larger ΔT after twenty minutes and a lower relative minimum temperature. Compared to the previous iteration, it also required less power to run. The improved performance of the system was a result of the large heat sinks used. They were more efficient in dissipating the heat from the system, which, in turn, reduced the overall temperature of the system at a faster rate. A negative aspect, however, in this experiment, was that the overall system was very bulky and heavy due to the large heat sinks. One of the goals of this project was to achieve a compact and portable product, thus the next experimental iteration was designed to be more compact.

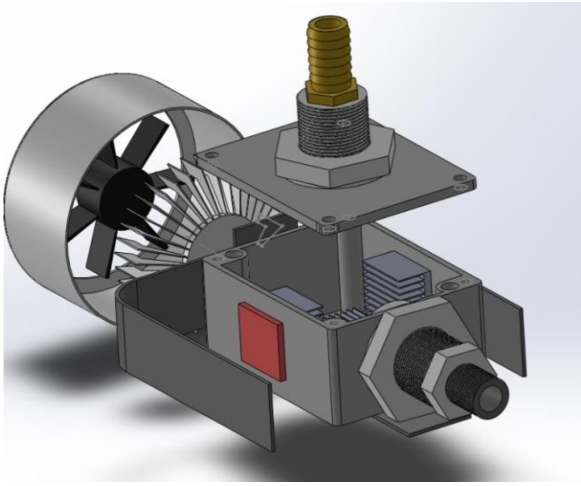


***Figure 18**. Small Aluminum Box with Heat Pipes Design Iteration*

Figure 18 shows the experimental iteration that used heat pipes attached to the hot side of three thermoelectric modules instead of the heat sinks. This not only made the system more compact and portable, but also allowed the heat produced to be redirected to a centralized point. The heat was transferred along the heat pipe using acetone, which is a phase changing material inside the heap pipes. The heat produced by the thermoelectric modules was dissipated in the back area by a large circular heat sink and a circular fan to dissipate the heat. The insulation for this experimental iteration was also improved because using heat pipes allowed more area to be insulated. Therefore, spray insulation was used for this experiment, which has a better thermal resistance than the Styrofoam insulation. Gathered data showed a temperature difference after twenty minutes of 1.7°C and a relative minimum temperature of about 15.5°C. The small temperature difference after twenty minutes was due to the fact that the circular heat sink and fan could not dissipate the heat at a fast enough rate to cool the system. Thus, each of the thermoelectric modules had reduced cooling performance, which resulted in the temperature dropping at a slower rate compared to the previous experimental iteration. The table below shows the results of all the experimental iterations and the specifications of each.

Table 5: *Tabulated Results and Specifications of all Experimental Iterations*

Design Iteration Number	Volume of Chamber (mL)	Number of TEMs	ΔT after 20 minutes [°C]	Minimum Temperature [°C]
Acrylic Chamber	160	4	1.0	20
Large Aluminum Chamber	2000	12	2.1	17
Small Aluminum Chamber w/ 12 Modules	800	12	2.4	17
Small Aluminum Chamber w/ 3 Modules	800	3	3.9	14
Small Aluminum Chamber w/ Heat Pipes	800	3	1.7	15.5

4.3 Modeling

A thermal analysis was completed for the system to predict the performance of QuikChill. Heat transfer was modeled between three bodies, the thermoelectric modules (TEMs), the environment, and the water inside the chamber. Overall, the system parameters were analyzed using MATLAB simulations and a FEA thermal model. The general system modeling was done in a three part process: first, the analysis involved multiple models of heat sinks, and material properties subjected to varied working conditions. The second part consisted of a model that predicted the performance of the TEMs based on the working conditions. Lastly, a finite element analysis (FEA) for thermal analysis was created using SolidWorks to predict temperature and heat distribution within the aluminum chamber.

The assumptions made in modeling were based mostly on the principles surrounding the energy balance equation. The assumptions were that the system has a one-dimensional heat flow, constant properties of all materials, and uniform temperature distribution across an infinitesimally small control volume. The one-dimensional assumption allows for more simplified heat transfer analysis by means of a circuit analogy. Negligible changes were observed over varying temperature for material properties leading to the assumption of constant properties. An infinitesimally small control volume was used to derive the governing heat transfer equations for Q_C and Q_H.

It was also assumed that the only component capable of internal heat generation was the thermoelectric modules, and the system did not undergo thermal expansion over time. The fluid flow within the testing chamber was assumed to be fully incompressible and perfectly laminar, and axial conduction and radiative heat transfer through the pipes was negligible. The effects of all thermal contact resistance and fouling were neglected; losses associated with viscous dissipation and body forces were also ignored. Lastly, it was assumed that the thermal mass of the TEMs is much smaller than the thermal mass of the water.

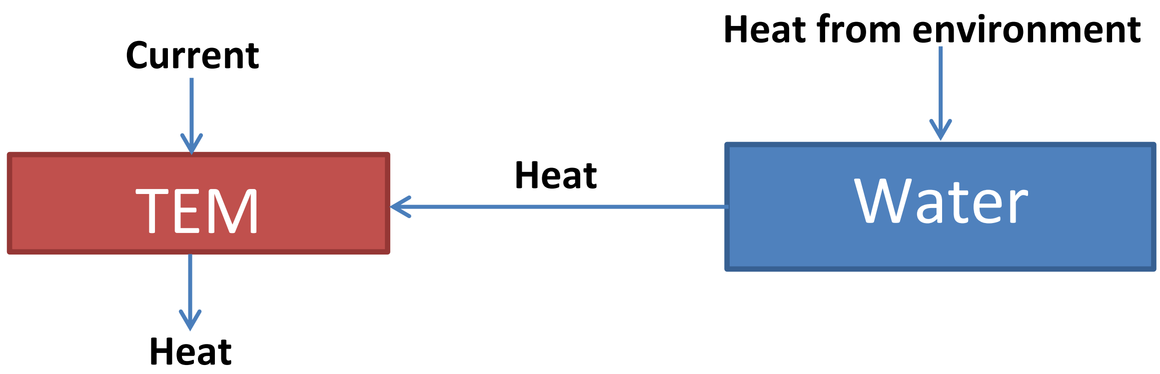


Figure 19. *Heat transfer free body diagram with applied conditions*

The free body diagram observed in Figure 19 demonstrates applied forces to the TEM and the water. While there were a lot of elements that affected the heat transfer, simplifying how the heat travels between these subsystems was helpful in understanding the model. Current was applied to the TEM and the cold side of the TEM absorbs the heat of the water. The heat sink and natural convection mechanisms allowed for that absorbed heat to be dissipated in the air. In addition, while heat was absorbed from the water, the water also gained heat from the environment.

The properties of the fluids used to create the model are tabulated in Table 6. Table 7 demonstrates properties particular to describe thermoelectric modules. The relevant thermal conductivity of the Styrofoam, aluminum chamber, and aluminum heat sink can be observed in Table 8.

Table 6: Fluid Properties used in Model

Air		**Water**	
Temperature (K)	295	Temperature (K)	292
ρ (kg/m³)	1.185	ρ (kg/m³)	998.6
Cp (kJ/kg·K)	1.007	Cp (kJ/kg·K)	4.183
μ (N·s/m²)	1.821E-05	μ (N·s/m²)	0.001
ν (m²/s)	1.545E-05	ν (m²/s)	1.033E-06
k (W/m·K)	0.0259	k (W/m·K)	0.6012
α (m²/s)	2.184E-05	α (m²/s)	1.439E-04
Pr	0.7083	Pr	7.184

Table 7: Thermoelectric properties used in model

Thermoelectric Module	
α, Seebeck Coefficient, (V/K)	1.830E-04
ρ, Resistivity (Ω·m)	6.800E-06
k, Thermal Conductivity (W/m·K)	1.82
Rc, Leg Electrical Contact Resistance	3.405E-10
Module Area (m²)	9.000E-04
Module Leg Length (m)	1.600E-03

Table 8: Thermal Conductivities of Certain Materials Used in Model

T = 298 K	**Styrofoam**	**Aluminum Alloy Chamber (AA 383)**	**Aluminum Heat Sink (AL 6061)**
k (W/m·K)	0.408	96.23	167

Appendix Q shows the hand calculations for thermal resistances, steady state thermoelectric performance, one iteration for transient TEM performance, forced external convection, free internal convection, and fin effectiveness.

4.3.1 Finite Element Analysis

A finite element analysis (FEA) was done on the experimental iterations that yielded the best results, which was the Small Testing Assembly 2, or TSA2. Figure 20 below shows the thermal analysis of the experiment without the water in the chamber and the heat dissipation system. Additionally, the hot side of the TEM was removed in this analysis in order to distinguish the difference in temperatures of the box. Including the hot side of the modules would have made the range of temperatures in the analysis much larger, making it difficult to examine the smaller temperature differences within the chamber.

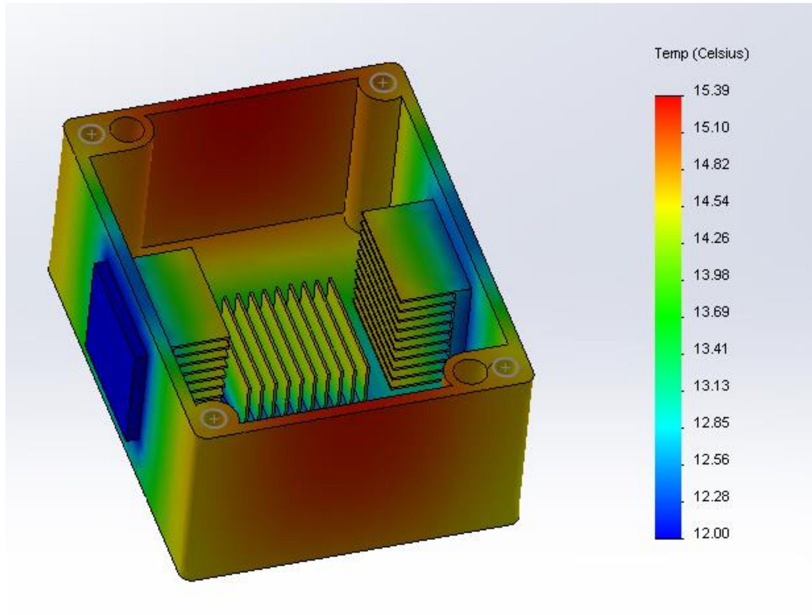


Figure 20. *Thermal Analysis of the Small Testing Assembly 2 (without external heat sinks)*

As observed in Figure 20, there existed a temperature distribution internally within the box. For this analysis, the box was assumed to be insulated in order to prevent heat gain from the environment. Another thermal analysis was completed for the TSA2 experimental iteration with the water present, as shown in Figure 21.

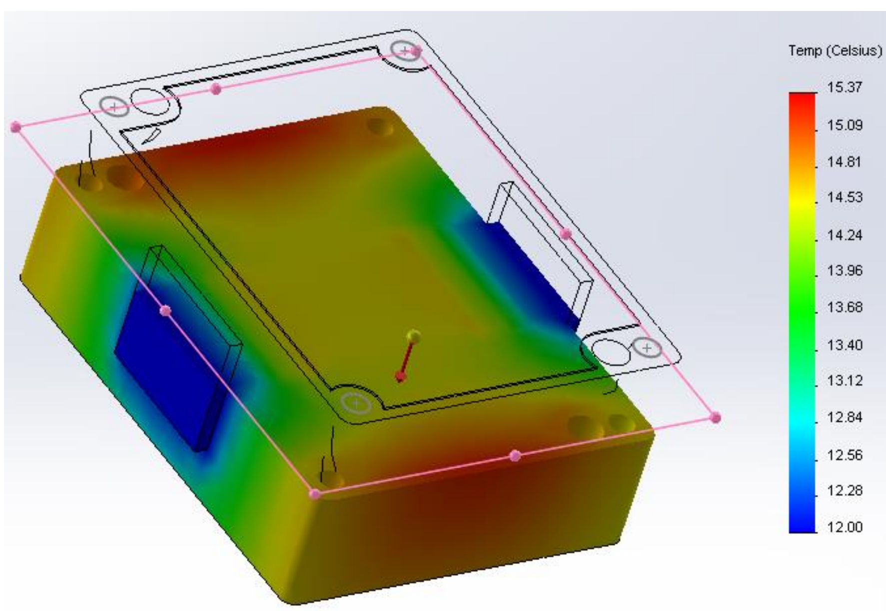


Figure 21. *Thermal analysis of the water*

As observed in Figure 21, the water achieved a temperature distribution ranging from 13 – 15°C, which was well within the desired temperature range. Another important observation was that the temperature distribution across the water was not uniform. This was verified by the temperature readings experienced by the two thermocouples used in each experiment testing. Another aspect taken into account was that the water may experience internal flow from varying temperatures as well, which would further cause a distribution in temperature across the water.

This modeling was consistent with testing. Many times the two thermocouples did not measure the same temperature. While this could be a calibration error, it was most likely because different locations in the water chamber are experiencing different temperatures. While the modeling was a rough estimate the, majority of the water shown in Figure 14 was 14°C, which is consistent with experiments.

4.3.2 MATLAB Modeling

In order to predict the performance of the design iterations, a MATLAB code was written. This MATLAB code can be seen in Appendix K. A thermal analysis was conducted by studying heat transfer between three bodies; the water in the cooling chamber, the environment, and the thermoelectric modules. Heat was absorbed from the water into thermoelectric modules cold-side. At the same time heat is also rejected on the hot-side of the module to the environment. In addition, heat is transferred from the environment into the water. As mentioned earlier, in order to determine the amount of heat absorbed and rejected by the thermoelectric modules, an energy balance was conducted by matching heat transfer from the thermoelectric modules with temperature differences between the module and the environment or the water. The amount of heat transfer from a thermoelectric module is well documented by both Angrist [15] and Rowe [16].

Assumptions placed into these MATLAB models were that the material properties of the thermoelectric modules (thermal conductivity, electrical resistance, Seebeck Coefficient) were kept constant, as well as the thermal resistances. In addition, it was assumed for the transient model that the water was lumped capacitance, or a uniform temperature, and that the thermal mass of the thermoelectric materials in the module were much smaller than the thermal mass of the water. In the modeling completed, the working conditions were necessary to perform the analysis. The working conditions include the material properties of the thermoelectric modules and the thermal resistances between the TEMs, the water, and the environment ($\psi_C, \psi_H, \& \, \psi_{Chamber}$).

As mentioned previously, a steady state and transient analysis were carried out to predict the cooling power and temperature distribution. The steady state model was developed to find the steady state temperature of the water in the chamber for the given working conditions. Using the various working conditions, the cooling power and temperature of the fluid was modeled as a function of the current running through the TEMs. The amount of current where the maximum cooling power and lowest refrigerator temperature occurred was the optimum current for the given working conditions. The main goal of the steady state analysis was to determine the optimum current to run the modules under, and the expected lowest temperature of the water.

The transient model was used to model how the water in the chamber changed over time as it approached steady state. The temperature of the water was solved using an initial temperature of the water out of the tap, and successive iterative temperatures over time were calculated. The change in the temperature of the thermal mass of the water was matched with the cooling power of the thermoelectric modules and the heat loss to the environment. The model used the optimum current from the steady state to find the cooling power at each discrete time. Some assumptions made were that the change in the temperature of the water was linear across a small amount of time. In addition, the assumption was made that the temperature of the hot and cold side of the TEMs changed much more quickly than the water across a small amount of time. This assumption is validated by comparing the thermal mass of the TEM material with that of the water.

4.3.3 Predicted Output Expectation

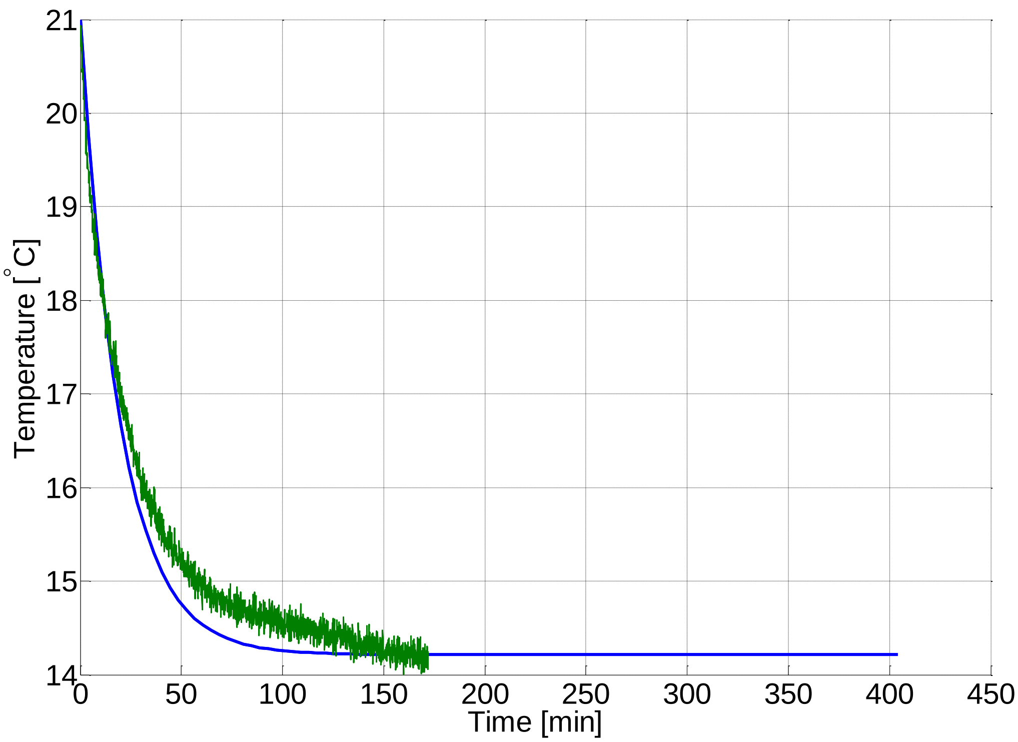


Figure 22. *Theoretical and Experimental Water Temperature versus Time*

Figure 22 shows the comparison between the experimental and theoretical performance of the system. The theoretical model reaches steady state much faster than the experiment. This difference between the theoretical and experimental results might be attributed to uncertainties within the modeling parameters. For example, the thermal resistances between the thermoelectric modules and the water and the environment were measured based off of other experiments. However, these measurements have uncertainties, which meant that the resistances may not be exact. In addition, it was assumed for this model that all three modules were under the same conditions. This assumption may not be true, depending on the manufactured, so that their properties and the amount of heat dissipation on each module may have varied if one fan or heat sink was slightly different. This would change the optimum current for that specific module, and it would perform differently from the other modules which may have degraded the performance of the system overall. Additionally, the properties of the system may change as time lapses and temperatures change. Properties of the materials were assumed to be constant but may change with temperature. Water movement also was not taken into account, but water may have been moving due to vibrations of the fan on the system and induced water movement as the temperature of the water decreased. Water movement, for example, would increase the heat transfer coefficient between the water and the cold side of the thermoelectric modules, reducing the thermal resistance. This would increase the amount of heat absorbed and decrease the temperature of the water. However, this would also decrease the thermal resistance between the environment and the water which would increase heat gain from the environment raising the water temperature higher. Water movement would have been too complicated to model without a more detailed analysis tool like computational fluid dynamics (CFD).

There have been inaccuracies in certain modeling strategies used simulate the temperature of the water as it is cooled. The difficulty of the modeling strategy as a whole stems from the lengthy hierarchy in calculations seen in Appendix Q. The steady state and thermal analysis require working conditions of the module and thermal resistances to run. However, these working conditions themselves are found through calculations and tests based on assumptions. To illustrate, the Seebeck coefficient of the module was found by performing a power generation test. In this test, a module was placed under different temperature gradients and the open circuit voltage of the module is recorded. A linear relationship was found between the temperature gradients and the voltage generated, and the slope of that line was taken as the Seebeck coefficient. If the measurements of some points were off, then the slope of that line would change, altering the value of the Seebeck coefficient. This altered Seebeck coefficient would be inputted into the thermal analysis and change the amount of cooling and temperature predicted of the water. In other words, one assumption or improper measurement made in one step in the process then yields a result that was used to model a certain condition that was applied to another model, and so on. The problem with this strategy lies in the fact that it was difficult to trace errors, since certain assumptions and parameters were made at different times in the process. The team encountered this problem when tracing back conditions in certain points in the model. To combat this problem, we attempted to streamline the MATLAB code as well as set-up a master sheet that lists all the input/output parameters in the model. This allowed for easy adjusting and tracing errors in the model.

Chapter 5 Cost Analysis

5.1 Potential Market

The target market for the thermoelectric chiller is the residential sector, specifically those who valued cold drinking water. The team conducted a customer needs survey and found that over half of the thirteen survey takers had water and ice dispensers in their homes. Additionally, 39% of the survey takers had a Brita pitcher which they kept in the refrigerator. It was assumed that these results can be extrapolated to all of the residents of the US. According to the 2011 US census, there are 132 million households in the United States [17]. Assuming there is an average of one refrigerator per household, and based off the survey where half of these households have water and ice dispensers, there are an estimated total of 66 million refrigerators with water and ice dispensers in the United States. This project has the potential to penetrate the market and change 66 million water and ice dispensers to the QuikChill product.

5.2 Cost of Production

The cost of the parts for the small aluminum chamber with 3 modules, which was the iteration that produced the minimum temperature, as well as the largest temperature difference, can be seen in Table 9.

Table 9: *Cost or Prototype Parts*

Part	Quantity	Cost
Thermoelectric Modules (TEM)	3	$25 x 3
Aluminum Chamber	1	$15
Heat Sinks	3	$6 x 3
Fans	3	$4 x 3
Styrofoam	1	$2
Fittings and Piping	~4	$ 20
Raw Total		$142

The cost of production of the unit will decrease dramatically when considering mass production. If 10,000 units were made at a time, the cost of certain raw materials would decrease. Buying items like thermoelectric modules in bulk will bring the price of the modules to about $5 each. The cost of aluminum will also drop, when aluminum boxes are ordered in bulk through a partnership with a manufacturer. Buying fans and heat sinks straight from a distributor will also decrease the cost. Mass production would drive costs down by around 80% of the total prototype cost, making the cost per unit about $28.40 dollars. Labor and capital equipment costs need to be factored in as well. Machinery used could total about $3000. Also, with the rate of labor at $10 per hour and it can be estimated that 1000 man-hours were needed for 10000 units. This will add $1.30 to the cost of production for the product. Based on this estimate, the total production cost for the unit was $29.70.

5.3 Potential Savings

Based on the production costs and a 50% markup, the price of the unit will be about $60. If we sold all 10,000 units, a profit of $30 per unit would be made totaling a gross profit of $297,000. The initial price of the unit can be compared with the initial price of the water and ice dispenser accessory as well as the Brita pitcher.   As previously mentioned, the water and ice dispenser accessory adds $75-250 to the initial cost of the refrigerator. While the Brita pitcher only costs $20, the space necessary to accommodate the Brita pitcher might cost the user $100 initially for an additional cubic foot of refrigerator space. This would total $120 dollars in initial cost to use the Brita pitcher. With the price of $60, the QuikChill product is a cheaper alternative to both the water and ice dispenser as well as the Brita pitcher.

Consumers will also save money in terms of operating costs if they switched to the QuikChill product. Since the best design iteration only consumes 16W of power, the cost to power the device will be less. The water and ice dispenser requires 90 W to be powered, while the extra cubic foot of refrigerator space used to accommodate the Brita requires 20 W to cool. The yearly cost savings when the user switched to QuikChill is demonstrated below using the cost of electricity in the Bay Area as $0.21 per KWh.

Water and ice Dispenser → QuikChill

$$\frac{(90.6\,W - 16\,W)}{1000} * \frac{24\,hr}{day} * \frac{365\,day}{year} * \frac{\$0.21}{KWhr} = \$\mathbf{136}$$

Brita Picther → QuikChill

$$\frac{(20\,W - 16\,W)}{1000} * \frac{24\,hr}{day} * \frac{365\,day}{year} * \frac{\$0.21}{KWhr} = \$\mathbf{7.36}$$

Chapter 6 Patent Search

6.1 Overview

A preliminary patent investigation provided insight to prior art in the field of thermoelectric water chillers. It was found that while some patents included thermoelectric cooling for on-demand water dispensing, the thermoelectric module configuration consisted of a single module connected to a probe used to create ice. The proposed thermoelectric water chiller contained 5 unique features—mainly the application of multiple modules, fans and external heat sinks, Styrofoam channels for ease of forced convection over external heat sinks, a cooling chamber made of aluminum, low power consumption, and interior heat sinks.

6.2 Technical Description

The invention used thermoelectric modules to cool water in an aluminum chamber. The invention had 5 key features - the application of multiple modules (8), fans (4) and external heat sinks (3), Styrofoam channels (5,6,7) for ease of forced convection over external heat sinks, a cooling chamber (1) made of aluminum, low power consumption, and interior heat sinks (2) as highlighted in Figure 23.

The application of three thermoelectric modules in series was a unique feature to the design. When a current is applied, the cold side of the module cooled the water chamber, while the hot side of the module was attached to a heat sink which dissipated heat being absorbed from the water. Conductive thermal tape was used to attach internal and external heat sinks to facilitate heat transfer from the water, through the module, and into the air. The thermoelectric modules required adequate heat dissipation in order to remove the excess heat that the cold side of the module absorbed from the water. Attached to each module was an external fan-cooled heat sink that aided in the heat dissipation of the hot side of the modules. As heat dissipation greatly affected thermoelectric performance, proper design and optimization increased the cooling power of the system.

Insulation also strongly affected the performance of the system. As the temperature of the water dropped below ambient temperatures, heat transfer naturally occurred between the chamber and the environment. The unique feature of a three channel design allowed for heat gain to be kept at a minimum and also created room for each module to have a set of fan-cooled heat sinks. Furthermore, the addition of these custom-cut Styrofoam channels allowed for an increase in forced convection over the external heat sinks. This method of heat dissipation was a creative approach to also prevent Joule heating from occurring within the modules.

The use of an 800 mL aluminum chamber resulted in better thermal contact and heat transfer from the modules to the water. The aluminum chamber had a detachable lid with a silicon gasket to ensure that the system did not leak. Aluminum was chosen due to its high thermal conductivity, which resulted in a lower thermal resistance. Low thermal resistance allowed for better heat transfer between the module, the aluminum chamber, and the water. Interior heat sinks were also employed within the chamber to further facilitate cooling. The extended surfaces within the chamber helped to draw the heat away from the water at a faster rate. With all key features combined, the design was able to achieve 6°C of cooling in an hour. This is superior to the refrigerator water and ice dispenser that are only capable of cooling 2°C in an hour. Moreover, since the system only required 3 modules and 3 fans, the thermoelectric water chiller only used 16 Watts of energy, while refrigerator water and ice dispensers consume 91 Watts.

6.3 System Modification and Variation

Possible variations to the unit include changes in the size, insulation, material of the chamber, chamber lining, and the addition of a filtering element. The unit used sheeted Styrofoam insulation making the overall system larger to install. While the current design that incorporates heat sinks, multiple fans and sheeted insulation was effective, the invention could be modified to decrease the overall size of the system while still maintaining the same cooling power. The use of spray foam insulation could more effectively insulate the system and simultaneously decrease the size. More design work will be completed to implement heat pipes or other heat transfer mechanisms that dissipate the same amount of heat in a smaller area. Since each module required a heat sink and fan, reducing the number of modules would also decrease the total size of the invention.

The invention uses an aluminum chamber that has a high thermal conductivity, which increases cooling losses and makes insulating the system a challenge. A possible variation could be the use of a plastic chamber with the addition of internal heat sinks to cool the water. Another modification to the design could have been better system integration of the filtering element for easy replacement. Other modifications would be addressed to make the chamber safer for drinking water. This could have been done by adding an internal oxide layer to prevent the water from reacting with the chamber walls or varying the chamber material altogether. Lastly, another variation could have been the addition of photovoltaic panels to power the system in rural communities to cool and preserve milk. This thermoelectric chamber could also be used as a refrigerator to also keep vaccines cool in off-grid communities.

6.4 Competing Technologies

There were many existing technologies that mainly cool water, such as refrigerator water dispensers and coolers. The Brita pitcher stored in a refrigerator could also be viewed as a competing technology. As mentioned earlier in the technical description, the designed thermoelectric water cooler used less energy than traditional refrigerator water dispensers and is a much more convenient option. The prototype was also much more compact than Brita pitchers which would eliminate the potential for wasted space in a refrigerator.

The invention discussed was more similar to coolers that utilize thermoelectric modules to cool water. The thermoelectric chiller developed was compared to an Avanti© table-top water cooler that uses thermoelectric modules to cool the water and a heating element to heat water. Another brand, Regalta©, had a similar product that uses a water tank for table-top water dispensing. Benchmarking was conducted on the Avanti system during the design process. Avanti used an 800 mL double-walled plastic cooling tank that has a heat sink insert. The cold side of Avanti's thermoelectric module was mounted unto the heat sink insert, while the hot side of the thermoelectric module was attached to a fan-cooled spiral heat sink. The concept of a fan-cooled heat sink was similar to that of the proposed invention, but different from the exact design and application. The proposed design used a channel to force convection over the outer fan-cooled heat sinks, and was also design to be installed underneath a sink instead resting on a countertop. Furthermore, the prototype used less energy (16W) than the Avanti water cooler (560W). It should be noted that the Avanti thermoelectric cooler also heats water.

It was observed in the patent searches conducted that only a few describe water cooling using thermoelectric modules. Patent US6003318 A, which also has 7 other variations, described water cooling through the use of a probe connected to the cold side of the module. This probe created ice when chilled and then released the ice into the liquid. The proposed invention did not incorporate ice into the design application. Patent US 5572872 A described a liquid cooling, storing, and dispensing device that used thermoelectric modules. This cooler was designed for packaged liquids, which they described as milk or coffee creamers. While similar in technical design, the intended application of the system was not used for water cooling nor will the system be connected to a water line under the sink.

6.5 Commercialization Potential

This invention is still in the design process stage. Substantial cooling while consuming low amounts of energy was completed; however, the units could have been improved in certain areas in preparation for commercialization. The inner surface of the chamber needed to be lined to meet health and safety requirements for drinking water. Heat dissipation mechanisms such as fan-cooled heat sinks and insulation could have been improved to reduce the overall size of the unit. Once size requirements were fully met, universal fittings and attachments to the filter and the main water line needed to be developed. The protective housing also needed to be designed for a product to be completed and marketable. Finally, when all criteria were met, the team would have looked to make partnerships and licensing agreements with filtering companies to integrate the cooling chamber design with established filtration methods.

6.6 Key Dates

Invented

12 September 2012, Santa Clara University

Brought to Practice

22 March 2013, Santa Clara University

Publicized

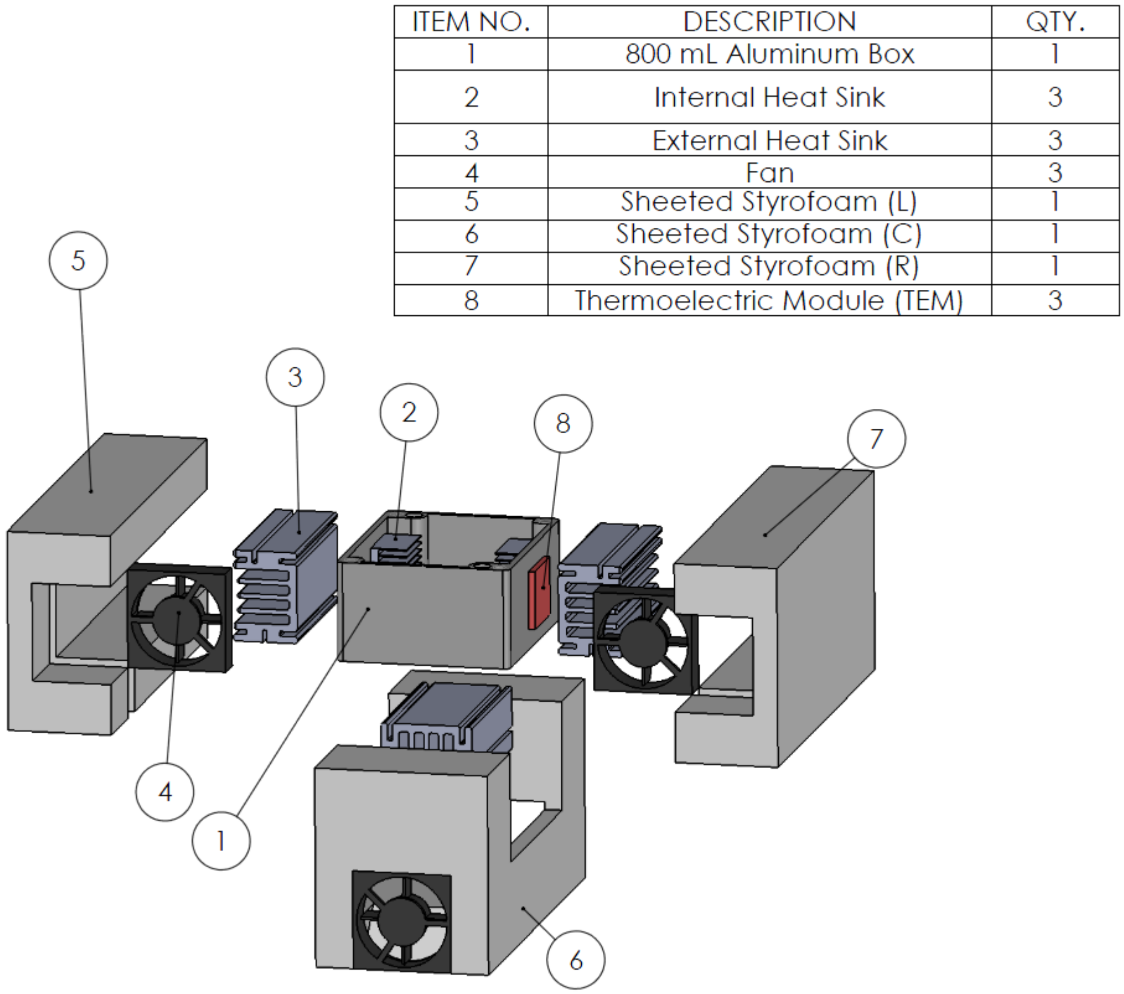
23 February 2013, Santa Clara University, Family Weekend (Initial)

14 April 2013, Santa Clara University, Preview Day

9 May 2013, Santa Clara University, 43rd Annual Senior Design Conference

12 June 2013, Santa Clara University, Thesis Submissions to Santa Clara University Library

6.7 Sketch



ITEM NO.	DESCRIPTION	QTY.
1	800 mL Aluminum Box	1
2	Internal Heat Sink	3
3	External Heat Sink	3
4	Fan	3
5	Sheeted Styrofoam (L)	1
6	Sheeted Styrofoam (C)	1
7	Sheeted Styrofoam (R)	1
8	Thermoelectric Module (TEM)	3

Figure 33. *Overall System Sketch*

6.8 Summary of Patent Classifications

Cooler and Cooling (See Congelation; Quenchers; Refrigeration)

- Cooling and heating apparatus – 165/ 58+
  - Design – D23
- Water
  - Cooler, machine design – D07/ 304
- Thermal
  - Refrigeration, heat transmission – 62/ 383
- Thermocouple

- Refrigerator – 62/ 3.2+

6.9 Review of Prior Art Search

Patent Name: ***Water Chiller***

Patent Application Number: US 7143600

Class: **62/389**; 62/3.2; 62/3.64

The water chiller described in the patent is a reservoir with an inlet and outlet in which water is chilled using a thermoelectric chilling probe. The probe extends from the bottom surface of the reservoir into the water. This patent focused on the flow control device using a baffle as well as a vent to release air bubbles when the tank is filled. The baffle prevents mixing of the water being dispensed and the inlet to extend the amount and temperature of the cold water. The patent also outlined that ideally the reservoir would be 100 ounce or about 2600 mL and attempt to cool the water to 10°C.

The water chiller described uses thermoelectric modules to cool water in a tank which is similar to the purpose of QuikChill. While heat transfer optimization of the thermoelectric modules was a main design consideration of our invention, the patent does not go into great detail regarding the heat transfer between the thermoelectric probe and the water. QuikChill does not use a probe, which many other chillers researched use. The water chiller patent does not describe any heat sinks or fans used to dissipate the heat, but instead introduced a method to combat temperature mixing between the inlet and outlet. This consideration is something our invention should explore so we do not lose cooling performance when dispensing the water. The application of the water chiller was also confusing in the patent since it did not describe where it will be used. After reading this patent, our invention may have the same purpose, but the technical descriptions have very different focuses to them.

Patent Name: Thermoelectric Water Chillers

Patent Number: US 5501077 A

Class: **62/3.64**; 62/390; 62/397

This patent presented a thermoelectric water chiller used to chill a 5-gallon water tank under the sink. The tank was connected to the system where a thermoelectric module cools the water using what is described as a heat sink, but appears to be more of a probe in the illustrations. The probe reached cold temperatures which produced ice and cool the chamber. The patent also described the heat sink assembly as well as a thermal barrier to act as insulation.

The thermoelectric chiller had a warm and a cold chamber, and a mixing valve was used for the user to obtain desired water temperature. An interesting aspect of the design was that the fan speed was regulated based on temperature, meaning the cooling power was controlled by the temperature of the chamber. The patent included a very detailed explanation of the assembly and ease of disassembly to maintain the unit. This patent included many corresponding patents and applications connected to it by the Oasis Corporation.

This thermoelectric water chiller was similar to the one QuikChill designed in terms of an under-the-sink application and heat sink configuration. There were some differences in the invention that standout. The water source for this unit was a tank that needs replacing, while the prototype will be connected to a water line. The proposed invention also does not need a probe to create ice nor does it need two chambers to mix water temperatures. The invention designed only uses a cold chamber with the temperature range matching that of the chamber. While Oasis' invention used one module, QuikChill used three in a rectangular insulated container. These two inventions have the same names, but the design and application of each are quite different.

Patent Name: Water Chiller

Patent Number: US 6508070

Patent Classification: 62/201; 62/389

This water chiller was designed to be mounted underneath a sink and connected to a water line or 5 gallon tank. The patent described the unit as one that also used a thermoelectric probe to cool the water. The patent went into great detail about how the density of the water increases when water is cold. The cold water will go to the bottom of the tank, while the warmer water will rise to the ice probe on the top of the chamber and cool down. This cycle was claimed to keep the temperature at optimal condition below 4°C. Another feature of the chiller was the fan configuration of the hot side of the heat sink. The patent described the placement of the fan in which the heat sink is subject to the coldest inlet temperature possible maximizing cooling power. The system was also designed to be integrated with a filter.

This water chiller dived into great detail about the heat dissipation, which was comparable to our product. However, our product used three channels to force convection over the heat sinks and the target water temperature range was much higher at 11-16°C. Much like the other patents, ice formed on the probe of the thermoelectric cooler, while our design used heat sinks to distribute cooling into the water. Our design also did not go into detail about the density of the water and mixing. It did include a filter which was a similar feature. This invention had the same application as our thermoelectric chiller, but the cooling probe and the heat sink configuration differed from the design of QuikChill.

Patent Name: Beverage Cooling Device

Patent Number: WO 2012120766 A1

Patent Classification: F25D11/00; B67D1/08

This patent was filed internationally and originated in Japan. The patent described a complete beverage cooling device. The main liquid discussed in the patent was beer. The design had a two-stage cooling system. The beverage first goes through what is called an “ice-cooling” mechanism that uses a coolant or refrigerant to cool the liquid. The liquid then goes through a second stage which was a thermoelectric cooler tank using two modules. The patent also included the dispensing faucet design. This system was ideally attached to a keg or barrel. The patent maintained that this two-stage cooling design allowed for the liquid to reach sub-zero temperatures. In terms of the thermoelectric set-up, a cooling pipe laid on one side of the modules while coolant ran past the other as a heat sink.

The application and design of this chiller was very different from QuikChill. This invention seemed to focus on cooling and dispensing beer. This two-stage system also did not seem energy efficient since it is using both a refrigerant and thermoelectric modules. Our chiller was designed to save the consumer energy, while this invention focused on reaching very low temperatures. It would be interesting to see a working unit, since the patent was difficult to follow given that it was a Japanese translation. The system made hefty claims in terms of performance, so results and corresponding power consumption would be interesting in understanding the potential of this invention. While it was a thermoelectric chiller, this system was also very different from the proposed invention.

Chapter 7 Potential Societal Application

7.1 Motivation and Reach

Since the QuikChill unit only required 16 W to power there is potential for the project to be used in developing nations. Through discussions with CSTS patrons, we found that the system could probably be used to cool and preserve milk in communities where refrigeration is not readily available. Milk plays an important role in providing nutrients to people in developing nations, especially babies. India has become the largest producer of milk in the world [18]. While the country is producing milk, some of the poorest residents still can benefit from cooling milk. The Food and Agricultural Organization of the United Nations maintained that the average diet of the poorer sections in India is deficient in several nutrients which most can be made up by supplementing the diet with milk [19]. The problem with milk is it is perishable and a perfect place for bacteria to breed. In rural areas like India, milk goes bad within a day due to inadequate cooling. Improving low powered refrigeration methods will benefit communities in India who rely on milk as part of their diet.

Another potential in developing communities for QuikChill is using the unit as a micro business. Discussions with individual who have traveled and study in places like India mentioned that people are less likely to buy filtered water, because they can't physically tell the difference and therefore do not find it a motivating reason to pay more. Dr. Keith Warner suggested that people are willing to pay more for water that is cold and filtered, since the cold is a noticeable physical difference. QuikChill could be a way to provide cold, filtered water to populations in India.

7.2 Approach

Based on the motivation, QuikChill could have potential application in India and other developing countries in two ways: through milk refrigeration and filtered, cold water dispenser. Both systems would require power to make the system usable. Since the unit only requires 16W a photovoltaic panel attachment of about 0.1 m^2 could be used to power the system.

Milk Refrigeration

The thermoelectric water chiller could be retrofitted to cool milk in developing nations. The inlets would be changed to easily funnel in the milk from the cow into the system and the outlets would be designed more like a water cooler dispenser. The milk will sit in the cooling chamber to extend the preservation of the milk for drinking purposes. The thermoelectric modules would need to reach lower temperatures to further cool the milk in warmer climates.   There will be no need for a filter in this design. The thermoelectric chiller would be a means for rural communities to keep milk cool in a standalone system.

Cold Filtered Water Dispenser Micro Business

The QuikChill product could also be used as a small sustainable business to deliver cold, filtered water to the community. The approach to this idea is to lease the product to individual who will sell the cold, filtered water to passerbys. This will enhance the quality of life to not only the consumers, but also provide a sustainable source of income to the individual selling the water. The system would need to be retrofitted to easily attach to any source of water as well as made to be more durable and portable so he or she can bring the unit to any location.

7.3 Design Constraints

Implementing this technology in developing countries adds more design constraints on the implementation the product. First, since the potential power source would be from a photovoltaic panel, the power consumption of the unit needs to remain low or be even lower to compensate of cloudy days and intermittent sun. Also, if we were to use the system for milk, the chamber would need to be designed for stricter sanitary means. The chamber would need to be made of stainless steel rather than aluminum. Milk also requires lower temperatures to keep from spoiling, so the target temperature of the liquid to keep fresh needs to be around 2 °C based on the Western Dairy Association. The system would also need to be designed for harsher conditions meaning it would need to be more durable. This might mean an extra layer of protection and a more durable plastic shell mold. Another notable design constraint, when implementing the technology is using off the shelf parts in case the system needs maintenance. This is the main problem with thermoelectric modules since they are not readily available.

Chapter 8 Engineering Standards and Realistic Constraints

8.1 Sustainability/Environmental

Although the United States hosts only 4.46% of the world's population, it causes over 50% of the harmful emissions released into the environment [20]. The rapid increase in global carbon emissions contribute to the upward trend of global climate change encouraging the emergence of more energy efficient technologies. Furthermore, the residential sector accounted for 21% of greenhouse gas emissions from the use of fossil fuels to produce electricity [1]. As shown in Figure 24, the fridge and freezer comprise of 20% of the total energy use in the typical California home. Focusing on refrigerator consumption alone, it was observed that water and ice dispensers consume 10-15% of the total energy used by refrigerators [4]. This is a substantial amount of energy for dispensing water that is already available at the sink.

In order to reduce this QuikChill aimed to impact the residential sector and the clean energy sector. Integrating QuikChill units into homes across the US to replace costly refrigerator water and ice dispensers will reduce the amount of energy currently needed to cool water. By reducing residential energy consumption, the system will have a positive impact on the environment. The use of thermoelectric modules also contributes to the clean energy cause because they do not require refrigerants that are ozone depleting and climate change inducing compounds. The impact of QuikChill rests on the assumptions that the data and sample sizes in California reflect that of the entire US population and that everyone would want to make this lifestyle change. Also, it was assumed that the refrigerator was continuously running for the entire year and that the internal capacity of all refrigerators across the US were 16 ft^3.

Brita pitchers are an alternative to filtered water but placing these pitchers in the fridge to cool water takes up space. Not only is the loss of space inconvenient, but is also quite costly. Every additional cubic foot of refrigerator space adds 20-30 kWh to the current refrigerator energy consumption [21]. Since extra space is needed to accommodate for Brita pitchers, larger refrigerators will be needed leading to an increase in total energy consumption.

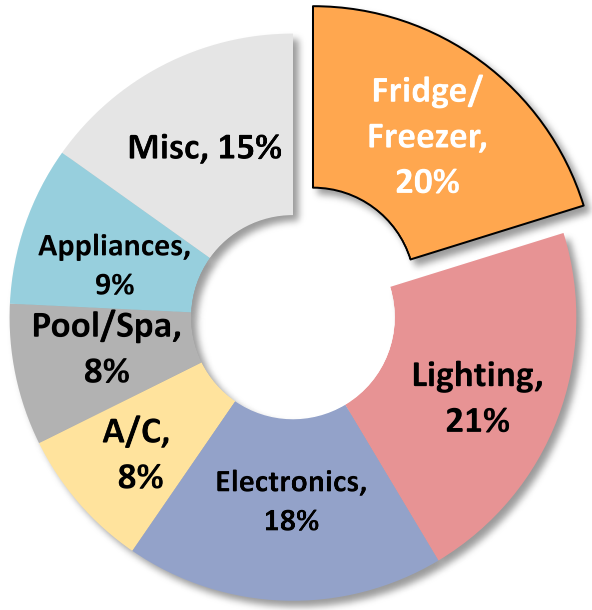


Figure 24. *Energy Consumption in an Average Californian Home, 2009 [3]*

QuikChill will not only eliminate the need of a refrigerator water dispenser, but also reduce the carbon footprint of consumers. The US Department of Energy (DOE) estimates that the average frost-free refrigerator consumes 725 Whrs while running [22] and 1.12 pounds of carbon dioxide are emitted for every kilowatt hour of energy consumed [23]. Assuming that there is an average of one refrigerator per household, the US emits 33.9 billion pounds of carbon dioxide every year. By providing a low-energy alternative to in-door water dispensers, 3.4 billion pounds of carbon dioxide emissions can be reduced per year. As of July 2012, the average retail price of electricity was 12.04 cents per kWh [2]. Rather than using costly refrigerator dispensers, implementation of the prototype will save the US $360 million annually in energy production. This unit provides a low-energy and affordable solution to a conventional way of drinking cold water answering the need for instant cold water with less of a burden on our planet.

The team conducted a customer needs survey and found that over half of the thirteen survey takers had water and ice dispensers in their homes. Additionally, 39% of the survey takers had a Brita pitcher which they kept in the refrigerator. It was assumed that these results can be extrapolated to the all the residents of the US. According to the 2011 US census, there are 132 million households in the United States [24]. Assuming there is an average of one refrigerator per household, and based off the survey where half of these households have water and ice dispensers, there are an estimated total of 66 million refrigerators with water and ice dispensers in the United States. An average of the 10 to 15% that a refrigerator dispenser alone consumed (12.5%) was used to calculated the amount of energy that these dispensers consume, adding up to 90.6 Watts [5]. This further totals to 793 kWh/yr., costing the 66 million consumers $95 yearly to upkeep. Moreover, after conducting tests to evaluate the performance of the water and ice dispenser in the refrigerator, it was concluded that the refrigerator has a storage tank of 16 fl. oz. or 0.47 liters. After this tank is depleted, it takes a full day or 24 hours for the temperature of the water to return back to its initial temperature. This means that you are limited to 0.47 L of cold water a day.

QuikChill had a peak energy consumption of 16W or 0.384 kWh a day. In the future, the team plans to implement a controller mechanism which will increase the peak energy consumption to 18 W or 0.432 kWh a day. The supplementary feature operates on a closed loop system that detects the temperature of the water. If the temperature of the water is below or within the target temperature range, the controller will send a signal to switch the modules off, and put the system in an energy saving mode. The increase in power consumption caused by the Arduino controller will be offset by amount of time that the system needs to cool the water. It was estimated that the system will then run at a maximum of 16 hours per day resulting in a lower overall consumption of 0.288 kWh a day. In addition, the controller will turn the system off at night when cold water isn't as necessary. This leads to an energy consumption of 105 kWh/yr or $12.66 annually to run. Based on experimental iterations conducted on the product, QuikChill took an hour and a half to achieve the lowest temperature. Based on the amount of cooling time (1.5 hours) and volume that the system can hold (800 mL), QuikChill was able to produce 8.53 L of cooled water daily. If every water and ice dispenser in the US was converted to QuikChill's unit, there would be 45.5 billion kWh saved annually equating to a savings of $5.46 billion annually and 50.85 billion pounds of carbon dioxide emissions.

The necessary size of the refrigerators would also be reduced if the dispensers and Brita pitchers are replaced by QuikChill. The reduction in size is directly proportional to the decline of refrigerants used. In general, refrigerants are phase change materials used to enhance the efficiency of refrigeration cycles. Unfortunately, traditional refrigerants like fluorocarbons and chlorofluorocarbons have no natural sources and only come from human-related activities. One of the ways of measuring the effects of unsustainable refrigerants is using the global warming potential. Global warming potential or GWP is the measurement of how much mass of a chemical substance contributes to global warming over a time period relative to the same mass of carbon dioxide. Many fluorinated gases have very high global warming potentials (GWPs) relative to other greenhouse gases, so small atmospheric concentrations can have large effects on global temperatures. According to the EPA, many of the hydro fluorocarbons used in refrigerant blends have a global warming potential (GWP) ranging from 500 to 10,000 [25]. By reducing the size of the refrigerator by a cubic foot, the amount of energy and refrigerants could be reduced.

In summary, QuikChill could potentially have a positive impact on the environment. Through the use of low-powered thermoelectric modules, the system used less energy than its counterpart, a refrigerator water and ice dispenser. This savings in energy will translate to a reduction of harmful carbon emissions. These harmful emissions are damaging the ozone and the environment in which we live. This situation necessitates technologies that focus on reducing the amount of energy and in turn, reducing the amount of pollutants in the atmosphere. QuikChill was designed with this pressing issue in mind and focus was placed on using the least amount of power from the modules while still maintaining maximum cooling. Based on results, QuikChill has the potential impact to save about 50.85 billion pound of carbon dioxide emissions if chosen as a water cooling alternative.

8.2 Health and Safety

A primary concern for the health and safety of the user is the internal electrical wiring of the system was important in the design process. The overall system implemented TEMs in the system which requires electricity to function; however, because the circuitry was near the water there was a danger of electrocution. Important steps were taken such as securing the wires with electric tape, or perhaps ensuring that the materials used to make the water channels are secure. Securing the water channels was paramount as it prevented water leakages which may make the user vulnerable to electrocution. Another potential risk to users was the materials used in the chamber and the potential to contaminate the drinking water. The idea of implementing a protective layer into the chamber was analyzed to ensure harmful materials do not seep into the water.

8.3 Manufacturability

The manufacturability of a product was an important aspect that can determine many of the final aspects of the product including: how much the unit will cost, where the item must be manufactured, and how much it will cost to ship the product. Therefore the manufacturability of the product should be such that it is easy, inexpensive, and rapid to manufacture so that it can be made anywhere.

In order to make the product QuikChill made use of as many "off the shelf" or standardized parts as possible. Utilizing "off the shelf parts" was important because they do not require customization which required special attention and raised the price while potentially limiting the locations for manufacture. In addition, many of the designs of the subsystems were simplified to include minimal parts, in most cases the parts for each subsystem were no more than two parts many with simple milling operations. Some of these operations may be changed to stampings to further reduce machining steps. The channel may be casted or stamped. The subsystem required the most effort in manufacturing will be the heat sinks and the bypass valve. Both the heat sink and bypass valve will most likely be purchased from a standard heat sink manufactured by an outside company. The housing will be split in half and will use simple snap in male-female connections seen in many plastic assemblies; in addition it will have holes or slots where the subsystems contained fit to make assembling easier and faster. The housing will be made of plastic which will be stamped or molded in order to achieve the proper shaping.

8.4 Economic

Considering the costs of the product was crucial to our design. The main goal of the product was to reduce the amount of energy the unit consumes in order to impact the customer in terms of energy bills. While saving money in terms of operating costs was important for the user, designing the system for a low initial cost is important as well. The thermoelectric water chiller is an alternative to the costly water and ice dispenser accessory as well as inconvenient Brita pitchers. The economic advantage of the product was considered in the design to compete with both the initial cost of the two competitors as wells as, the overall operating costs of the product related to energy consumption.

The scope of the impact was assumed to be people in the residential sector that currently cool their water in the refrigerator or anyone with the desire for cold filtered water. Since 100% of homes have a refrigerator, we assumed the impact to extend to all households [26]. We also assumed that the consumer will value the cost saving of our product over the established methods of cooling. While many people do not like breaking a routine, it was assumed that a large population will want a more economically sustainable option to cool water.

Certain design considerations were made to reduce the initial cost of the product, while maintaining a low operating cost. In terms of raw materials, the most expensive element in the design was the thermoelectric modules. In many of the initial design iteration, 12 modules with small heat sinks were used to reach maximum cooling. While the modules were effective, the unit was quite expensive. After research we learned that larger heat sinks increased the overall cooling power of the module. Based on this discovery, we were able to create a prototype using 3 modules attached to larger heat sinks that achieved the same amount of cooling as the previous iteration with 12 modules. The larger heat sinks were not as expensive as increasing the number of modules, but the heat sinks does add more weight to the overall design. This decreased the cost of the design $225. In the end, the design with 3 modules was chosen since not only was the material cost lower, but less power was required to power the modules, resulting in a lower operating cost.

The major economic benefit of our design was witnessed in operating costs. The QuikChill design only consumed 16 Watts. The amount of energy the refrigerator water and ice dispenser used was found based on the data that this accessory consumer 10-15% of your total refrigerator energy consumption. Using 725 W for the entire refrigerator, the average consumption of the dispenser was found to be 90.6 W. Using this number the following equation could be used to find the savings in changing from a water and ice dispenser to QuikChill,

$$\frac{(90.6\,W - 16\,W)}{1000} * \frac{24\,hrs}{day} * \frac{365\,days}{year} * \frac{\$0.21}{KWhr} = \$137.2\ saved\ per\ year$$

This saving will have a huge impact on the customer and basically pay off the initial cost of the product in one year of energy bill savings.

8.5 Usability

With the rapid adoption of smart phones and tablet computers, this “always on” world with its huge amounts of content available on the internet has significant implications for the present generation’s attention span. The present generation thrives on being able to quickly access and learn new technologies, which is why design usability greatly impacts the overall creative design process. Instant access to a wealth of information from numerous sources decreases the attention span and desire for in-depth analysis.

The necessity for instant gratification and quick fixes requires that the overall system have a user interface that is relatively easy to understand. The user should easily learn how to operate or use the product with minimal help from an instruction manual. The instantaneous water heater/cooler should effectively and efficiently serve its purpose of producing on-demand hot/cold filtered water. Over its entire lifespan, the product should not fail too often. If it does encounter failures, the system problems should generally be minor non-technical problems that the user can fix at home.

Since the team plans to commercialize the final project design, an instruction manual will be created to help the user understand all safety rules and operating instructions. The instruction will be written in a manner that is easy to learn, remember and follow. It will consist of the following:

- Warnings and Disclaimers
- Parts and features (with a detailed system drawing)
- Important safety instructions
- Installation guidelines
- Operating instructions
- Electrical connections and components
- Wiring diagram
- Water filter replacement
- Control and display panel
- System modes (regular vs. energy saving)
- Care and maintenance
- Troubleshooting guide
- Service for your water dispenser
- Warranty and Product Registration
- Instructions in a foreign language

9.1 Summary

In conclusion the project QuikChill achieved many of its goals. The project began by investigating a potential source of wasted energy in residential homes in order to reduce the overall energy consumption of the residential sector in the US. QuikChill targeted wasteful energy spent on cooling water through using a water and ice dispenser in refrigerators or by playing a Brita filter inside of the refrigerator. The team benchmarked the potential competitors on the market as well as surveyed potential consumers wants and needs. Using the research gathered, the team was able to create target design specifications for their solution. Once the goals were set the team came up with an approach to gain cold water from the water line connected to the kitchen faucet. QuikChill aimed to use thermoelectric modules to cool water faster and using less energy than water and ice dispensers and Brita filters. The team carried out modeling in order to determine how the system would perform once built. After modeling, the team built a prototype and tested its performance. Further modeling was carried out to determine how to achieve temperature range found to be preferable by the survey takers. The team went through the modeling-prototype-experiment cycle multiple times before achieving the desired temperature. QuikChill reached a coldest temperature of 14°C, and had cooled 4°C in 20 minutes through a design iteration using 3 TEMs and an 800mL chamber. QuikChill achieved the most cooling after 20 minutes when compared it its competitors. After 20 minutes, the closest competitor has only cooled 1.8°C. The other main goal of Quickhill was to use less energy than its competitors. QuikChill measured a peak energy consumption of 16W. This was less than any of the other competitors. The refrigerator water and ice dispenser was estimated to have a peak energy consumption of 90.6W, and placing a Brita in the fridge had a peak energy consumption of 20W. Over the course of a year, the product has the potential to save 653.5 kWhr when he or she changes to QuikChill from their current water and ice dispenser. Furthermore the system was within the size constraint making it more compact than all other competitors. QuikChill is a thermoelectric water chiller that was successfully designed to save the user energy as well as money.

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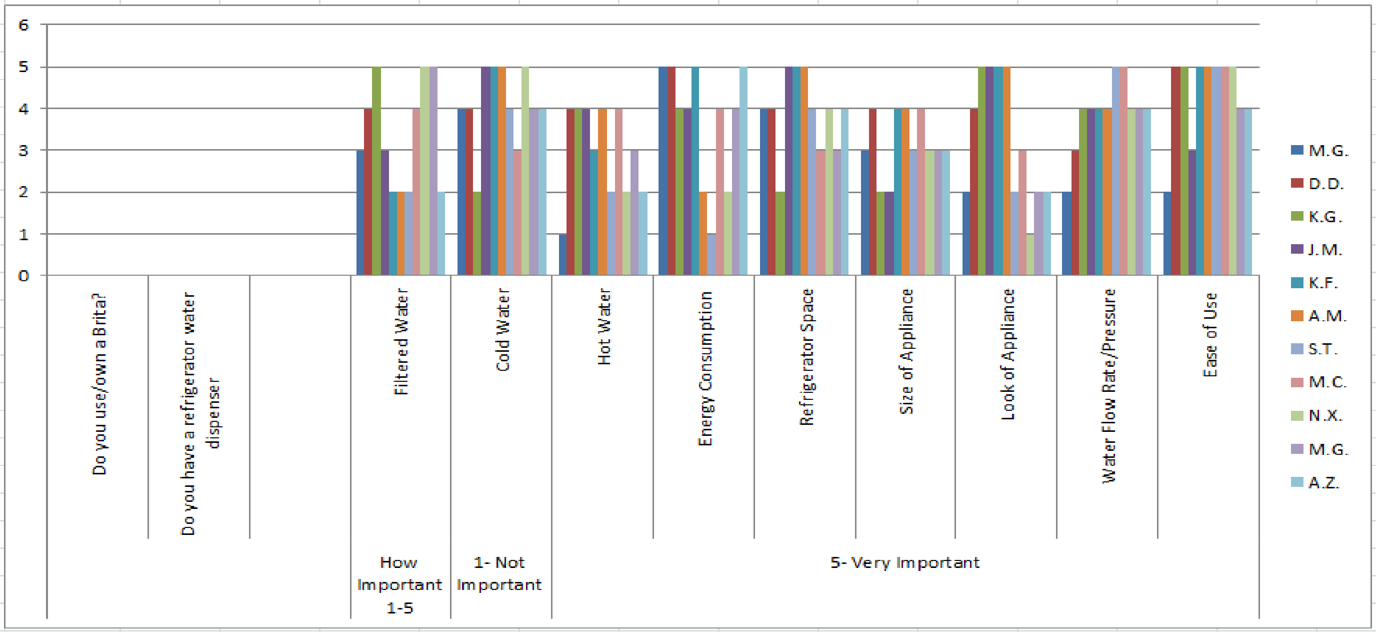
Appendix C: Customer Raw

	M.G.	D.D.	K.G.	J.M.	K.F.	A.M.	S.T.	M.C.	N.X.	M.G.	A.Z.	T.R.	J.R.		
Do you use/own a Brita?	Yes	No	Yes	No	No	No	Yes	Yes	No	Yes	No	No	No		
Do you have a refrigerator water dispenser	No	No	No	Yes	Yes	No	Yes	No	Yes	Yes	No	Yes	Yes		
															Average
Filtered Water	3	4	5	3	2	2	2	4	5	5	2	3	3		3.307692
Cold Water	4	4	2	5	5	5	4	3	5	4	4	4	3		4
Hot Water	1	4	4	4	3	4	2	4	2	3	2	5	4		3.230769
Energy Consumption	5	5	4	4	5	2	1	4	2	4	5	3	4		3.692308
Refrigerator Space	4	4	2	5	5	5	4	3	4	3	4	5	4		4
Size of Appliance	3	4	2	2	4	4	3	4	3	3	3	3	4		3.230769
Look of Appliance	2	4	5	5	5	5	2	3	1	2	2	3	4		3.307692
Water Flow Rate/Pressure	2	3	4	4	4	4	5	5	4	4	4	4	5		4
Ease of Use	2	5	5	3	5	5	5	5	5	4	4	4	4		4.307692

*Importance (1 -5: low to high)



Appendix D: Benchmarking

Information	Products					
	Brita: Basic Faucet Filter System	Brita: Complete Faucet Filter System	PUR: Basic Faucet Filter	PUR: Advanced Faucet Filter	Avanti Thermoelectric Water Dispenser	Side by Side Refrigerator
Manufacturer	Brita	Brita	PUR	PUR	Avanti	Whirlpool
Price	$18.99	$29.99	$25.99	$34.99 - $44.99	$50	$1,399
Sales	$1,304 Million (The Clorox Company)		$690 Million (The Helen of Troy Company)		N/A	$18,666 Million
Customer Ratings	1.8/5	2.6/5	2.3/5	2.7/5	3/5	3/5
Features	• The filter attachment is a simple mechanism that can be easily removed and reattached. • The filter costs about $18.99 and should be replaced every 100 gallons of filtered water or every four months. The filters also have a valve that allows the water to be filtered or unfiltered.		• The filter has a lifespan of 3 months with an electronic indicator with green being fine to yellow and red being replacement is necessary. A filter costs about $19.99 • One click attachment to the faucet, which makes it easy to install and uninstall.		• Capable of holding 3 to 5 Gallon bottles • Countertop model • Light weight and energy efficient	• Energy Star qualified • Water and ice dispenser • 25.1 cubic feet • Water filter costs about $39.99, which needs to be replaced every 6 months
Restrictions/ Limitations	The filter can only handle cold water and warm water with a maximum temperature of 100^0F/38^0C as it may damage the filter.				• Need to wait one hour for water to reach optimal temperature if 2 or more 8oz of water is consumed • Requires electricity, 115 Volts	• Requires electricity • Heavy and needs professional installation •
Additional Features	Standard filter indicator that monitors the lifespan of the filter, which includes green and red. The filter only has a 2 weeks lifespan left, or 20 gallons of water left to effectively filter when the indicator is red	Electronic filter indicator, and flow rate options such as spray or stream.	• PUR Faucet Mounts	• PUR Horizontal Mounts • PUR Vertical Mounts • PUR Flavor Options	• Cold water control. Indicator is yellow means that the process is starting. The indicator is green once the desired temperature is reached.	• Do not install near an oven, radiator or other heat source, nor areas below 13^0C/55^0F
Specifications	8.8” x 2.5” x 6” 15.2 ounces	6.7 x 2.5 x 9.8 in. 12 ounces	10" x 8" x 8" 15.2 ounces	8” X 7” X 3” 16 ounces	10.75" x 15.25" x 12" 7 pounds	35.5” X 69.75” X 33.75” 301 pounds
Pictures						

Appendix E: PDS

PROJECT DESIGN SPECIFICATION

Design Project: Water Purifier with Thermoelectric Chiller

Team: QuikChill Date: 5/23/12 Revision: 6

Datum description: Previous Brita and Pur Filters, Website, Candidates Interview, Current Refrigerators Specifications, Energy Star Reports, Based on Experimental Results

ELEMENTS/		PARAMETERS	
REQUIREMENTS	UNITS	DATUM	TARGET - RANGE
Temperature of Water	°C	12°C	11-16°C
Temperature of Water Source	°C	21°C	20-25°C
Heat Dissipation	K/W	5 K/W	5 K/W
Pressure	kPa	300 kPa	210 - 550 kPa
Number of TEMs	#	N/A	1-3
Type of Water Purifier	µm	5 µm	<1µm
Thermal Resistance of Chamber	K/W	6 K/W	>5 K/W
Thermal Conductivity of Heat Sinks	W/m·K	174 W/m·K	100 – 300 W/m·K
Purifier Operation Temperature	°C	40°C	<37°C
Mass	kg	2.5 kg	3 kg
Volume	Ft^3	0.353 Ft^3	<.4 Ft^3

Aesthetics	N/A	White/Chrome	Soft Edges, Finish that matches kitchen
Material (for Sanitation)	N/A	Aluminum	300 Series Stainless Steel
Packaging	kg	.1 kg	< .1 kg
Price	$	>$25.00 Brita Under the sink filters >$200 $100 saved refrigerator space	~ $40
Production Cost	$	~$8.00	~$28
Power Consumed	W·hr	20-30 W·hr	<15-25 W·hr
Lifetime of Product	yrs	3 yrs	~3yrs
Usability	# of buttons	2 Buttons	1 Buttons
Time to Change Temperature of Water	hr	24 hrs	2 hr to achieve temperature
Insulation Thickness	m	N/A	0.0254 – 0.0762 m
Daily water consumption	L	2.7 L/day	0.7 – 3.8 L/day

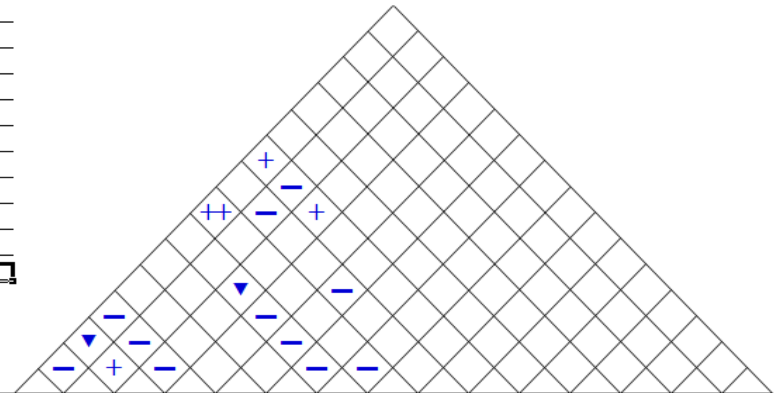
Appendix F: Criteria Prioritizing Matrix

	Criterion	1	2	3	4	5	6	7	8	9	10	11	12	SUM	FACTOR
1	Temperature of Water		0.5	0.5	1	1	0.5	1	1	0.5	1	1	1	9	7
2	Water Flow Rate	0.5		0.5	0.5	1	1	1	1	0.5	1	0.5	1	8.5	6
3	Heat Dissipation	0.5	0.5		0.5	1	0.5	0	1	0.5	0.5	1	1	7	5
4	Pressure	0	0.5	0.5		0.5	1	1	1	0.5	1	1	1	8	6
5	Mass	0	0	0	0.5		0	0	0	0.5	0	0.5	0.5	2	1
6	Length of TEMs	0.5	0	0.5	0	1		0	0	0	1	0.5	1	4.5	3
7	# of TEMs	0	0	1	0	1	1		0	1	1	0.5	1	6.5	4
8	Cost	0	0	0	0	1	1	1		0	1	0.5	0	4.5	3
9	Energy Consumption	0.5	0.5	0.5	0.5	0.5	1	0	1		1	0.5	0.5	6.5	4
10	Time to reach SS	0	0	0.5	0	1	0	0	0	0		0	0	1.5	1
11	Usability	0	0.5	0	0	0.5	0.5	0.5	0.5	0.5	1		1	5	4
12	Size of water chamber	0	0	0	0	0.5	0	0	1	0.5	1	0		3	2

Appendix G: Quality Function Development (QFD)

Title: QuikChill Product
Author: Rachel Reid
Date: 11/12/2012
Notes:

Legend		
⊖	Strong Relationship	9
○	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	



				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▲	▲	▲	▲	▲	x	▲							
Row #	**Max Relationship Value in Row**	**Relative Weight**	**Weight / Importance**	**Quality Characteristics** (a.k.a. "Functional Requirements" or "Hows") / **Demanded Quality** (a.k.a. "Customer Requirements" or "Whats")	Heat Dissipation	Length of Channel	Number of TEMS	Filter Operating Temperture	Housing strength	Ability to Connect to All Faucets	Cost	Thermal Conducivity of Material	Water Pressure	Time to Reach Steady State					
1	9	18.2	6.0	Fast Flow Rate		○							⊖	▲					
2	9	21.2	7.0	Water Temperture	⊖	⊖	⊖	⊖				○		▲					
3	9	6.1	2.0	Compact Size		⊖	⊖				▲		▲						
4	9	6.1	2.0	Energy Consumption	▲		⊖							▲					
5	9	9.1	3.0	Price			⊖		▲		⊖	▲							
6	3	15.2	5.0	Kitchen Aesthetics		○			▲	▲									
7		12.1	4.0	Usabilitly															
8	1	12.1	4.0	Low Maintenance					▲	▲									
9																			
10																			
				Target or Limit Value	N/A	<.1m	5-Apr	<37 C	strong	yes	~ $50	N/A	30-80 psi						
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)															
				Max Relationship Value in Column	9	9	9	9	1	1	9	3	9	1					
				Weight / Importance	197.0	345.5	381.8	190.9	36.4	27.3	87.9	72.7	169.7	45.5					
				Relative Weight	12.7	22.2	24.6	12.3	2.3	1.8	5.7	4.7	10.9	2.9					

Competitive Analysis
(0=Worst, 5=Best)

Row #	Our Company	Competitor 1	Competitor 2	Competitor 3	Competitor 4	Competitor 5
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

Our Company
Competitor 1
Competitor 2
Competitor 3
Competitor 4
Competitor 5

0 1 2 3 4 5

Powered by QFD Online (http://www.QFDOnline.com)

Appendix H: Budget

Budget Update

TEAM	QuikChill
Date	June-2-2013

INCOME

Category	Source	Sought	Committed	Pending	
Grant	Clare Luce Boothe		$515.93		
	Dean's Fund	$3,402.00	$1,702.00		
	CSTS Roelandts	$3,402.00	$2,500.00		
	TOTAL	**$6,804.00**	$4,717.93	0	$4,717.93

EXPENSES

Category	Description	Estimated	Spent	Pending
Thermal	TE Modules	$1,000.00	$671.68	
	Heat Sinks	$300.00	$197.33	
	Thermocouples	$200.00		
	Waterproof Adhesive	$8.00	$10.00	
	Thermal Paste	$7.00	$16.00	
	Fan	$40.00	$40.00	
	Silicone Sealant	$6.00	$6.00	
	Thermal Tape	$120.00	$180.00	
	Thermowell	$390.00	$390.00	
Piping	Stainless Steel Plate	$20.00		
	Plastic Piping	$20.00		
	Gaskets	$6.00		
	Rotameter	$2.00		
	Aluminum Cooling Chamber	$35.00	$83.69	
	Plastic Body Mold	$30.00		
	Insulation Styrofoam	$40.00	$36.00	
	Threaded Water Line Attachment	$14.00		
	Screws	$7.00		
	Bulkhead Fitting	$30.00		
	Plastic Tubing	$15.00		
	Brass Push Fit Female	$5.00		
	Reducer Coupling	$5.00		
	T Valve	$8.00		
	Pressure Reducing Valve	$30.00		
	Filter connectors	$30.00		
	Miscellaneous Connections	$40.00		

Electrical	Wiring	$20.00	$10.00	
	Switch	$10.00		

	Control Board	$60.00	$30.00	
	Plug Attachment	$20.00	$9.00	
	Temperature Sensor	$10.00	$10.00	
Testing				
	Hose Barb Adapter	$5.00	$3.11	
	Brass Pipe Bushing	$2.00	$4.51	
	Stainless Steel Clamp	$4.00	$1.90	
	Faucet Adaptor	$5.00	$2.67	
	Acrylic Block	$55.00	$54.90	
	Brass Hose Barb Adaptor	$12.00	$7.34	
	Dishwasher Snap Nipple	$2.00	$1.68	
	Clear Vinyl Tube 3/4"	$12.00	$5.65	
	Clear Vinyl Tube 1/8"	$10.00	$10.00	
	Flowmeter .2-2.5 gph	$59.00	$58.60	
	Flowmeter .2.5+ gph	$50.00		
	Globe Valve	$5.32	$5.32	
	Aluminum Cast Box	$80.00	$19.00	
	Bulkhead Fittings	$22.94	$71.92	
	Flexible Riser	$2.87	$2.87	
	Flow Sensor	$70.00		
	1/2" Nipples	$6.00	$7.00	
	Metal Braid Piping	$30.00	$25.00	
	T-valve	$4.00	$4.00	
	Ball Valve	$7.00	$6.00	
	Reducer coupling	$4.00	$3.00	
	WaterWeld	$6.00	$6.00	
	CPU Coolers	$50.00	$50.00	
Benchmarking	Brita Filter	$30.00	$25.00	
	Pur Filter	$30.00	$25.00	
	Avanti Cooler	$120.00	$89.00	
	Filters	$50.00	$110.00	
	Used Refrigerator	$150.00		
	Under Counter Filter	$37.00	$37.00	
Labor	Pipe Manufacturing	$50.00		
	Custom Circuit Board	$100.00		
	Custom Cast	$200.00		

Miscellaneous	Poster Board	$5.00	$5.00	
	Styrofoam Cutter	$48.00	$48.00	
	Wire Grabbers	$10.00	$10.00	
	Shipping for Repair	$18.34	$18.34	

TOTAL	**$3,880.47**	$2,407.51	0	$2407.51
Net Reserve (Deficit)		$2,310.42	0	$2310.42

Appendix I: Gantt Chart

Fall Gantt Chart: QuikChill	Fall										
Week	1	2	3	4	5	6	7	8	9	10	F
NCIIA Grant Proposal Narrative											
NCIIA Letters of Support											
Calculations for Qc											
Measure Flow Rate of Faucet and Drinking Fountain											
Determine Optimal Channel Size/ Water Pathways											
Research Refrigeration and Thermoeletric Cooling Process											
Research Ideal Heating and Cooling Temperatures											
Apply for CSTS and SoE Grant (10/18 & 10/21)											
Measure Flow Rate of Oasis Dispenser and Avanti Cooler											
Order Parts for Prototype Testing and Design											
Determine materials required											
Research thermal conductivity, resistivity, etc.											
Prototype sizing: Length, Width and Volume calculations											
Review Project Planning											
Apply for CSTS grant and School of Engineering Grant (10/18 & 10/21)											
Research temperature control switches to regulate ΔT											
Research implementation of Flow Sensor											
Information Gathering & Customer Needs Paper											
Work on the Petroski paper											
Research and Order Optimal TEM's											
Patent Application											
Ten + Ideas paper											
CDR Draft											
Revised Prototype Design											
Work on Conceptual Design Report											
Final CDR write-up											

Winter Gantt Chart (Updated): QuikChill	Winter									
	1	2	3	4	5	6	7	8	9	10
Update Blog On Progress										
Meetings with Dr. Lee (Mondays @ 1) and Dr. Hight (Tuesdays @ 2)										
Decide on Weekly Meeting Schedule										
NCIIA Conference Call (Jan. 8 @ 9:30)										
Pass Machine Shop Safety Exam										
Purchase Testing Chamber										
Update Gantt Chart										
Reevaluate Prototype and Testing Chamber Design										
Calculate Heat Transfer Coefficient for Natural Convection										
Calculate Fin Effectiveness and Plot Temperature Distribution										
Evaluate Working Conditions (Temperature, etc.)										
Revised Budget Analysis										
Delegate Specific Research Sections										
CFD/FEA										
DUE: Revised Schedule for Winter and Spring, Parts List										
Draft Design for Testing Chamber in Solidworks (SW) (Thursday)										
Individual Research										
Prototype Design and Build										
Test Protocol Development										
Flow Channel Design										
Build Testing Chamber (Tuesday)										
Assemble Testing Chamber (Wednesday)										
Run Experimental Iterations for Testing Chamber										
Sign up for Senior Design Conference (DEADLINE: Feb. 1)										
DUE: Ethics/Professionalism, Budget Update										
Draft Aluminum Chamber Drawings in SW (Tuesday)										
Assemble Aluminum Chamber (Friday-Monday)										
DUE: Detailed Drawings										
Informal Oral Presentation										
Test and Modification										
Draft Thermal Component in SW (Tuesday)										
Assemble Thermal Component (Friday)										
Draft External Piping in SW (Tuesday)										
Machining External Piping (Wednesday-Friday)										
Assemble External Piping										
Draft Electrical Schematic in SW (Friday)										
DUE: Analysis Report										
Wiring and Connections										
DUE: Zen Paper (Prisig)										
Finalize Design										
DUE: Formal Written and Oral Progress Report										
DUE: Assembly Drawings, Specific Hardware Goals										

Spring Gantt Chart: QuikChill		Spring										
		1	2	3	4	5	6	7	8	9	10	Finals
Update Blog On Progress												
Research Arduino Microcontroller												
Draft Electrical Schematic and Build Electrical Component												
Update MATLAB code for Heat Transfer Coefficient/ Fin Effectiveness												
Update MATLAB code for Current and Thermal Resistance												
DUE: Thesis table of contents and Draft introduction												
DUE: Resume + review of community service at SCU												
DUE: Experimental protocol and updated PDS (Tentative)												
Build Final Design												
Draft Body Shell/ Aesthetical Component												
Test Protocol Development												
Test and Modification												
Preparation for Senior Design Conference												
Integrate Microcontroller												
Integrate Filter Component												
Senior Design Conference (May 9)												
DUE: Societal/environmental impact presentation												
DUE : Final thesis draft												
Final Report												
Prepare for Final Presentation												
Product Integration into Manufacturing and Distribution												
DUE: Patent Search or Business Plan												
DUE: Experimental Results (Tentative)												
DUE: Open House/ Hardware												
Initial Market Analysis												
File for Patent Application												
DUE: Final Thesis (2 bound hard copies, 1 complete soft copy on CD)												

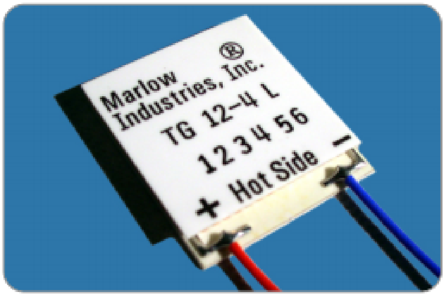
Legend

BT	RR
BO	Team
FC	MECH 196

Appendix J: Data Sheets

marlow industries, inc.
Subsidiary of II-VI INCORPORATED

TECHNICAL DATA SHEET
Preliminary

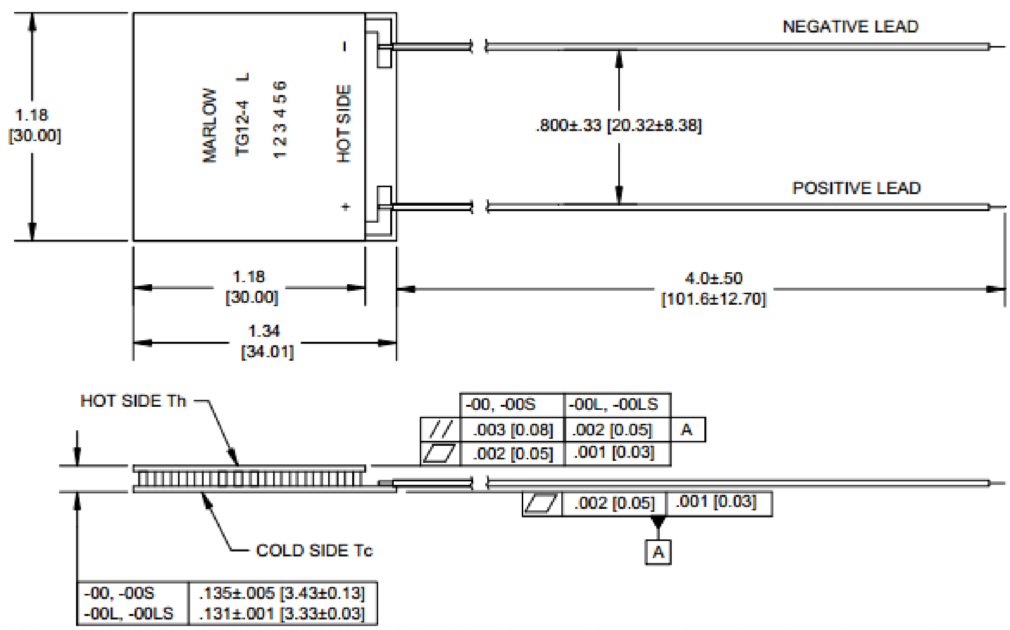


TG12-4
Thermoelectric Generator

TYPICAL PERFORMANCE VALUES

Tc (°C)	27 ± 2
ACR (Ω)	2.76 - 3.41
Device ZT_c	0.71

MECHANICAL CHARACTERISTICS



ORDERING OPTIONS

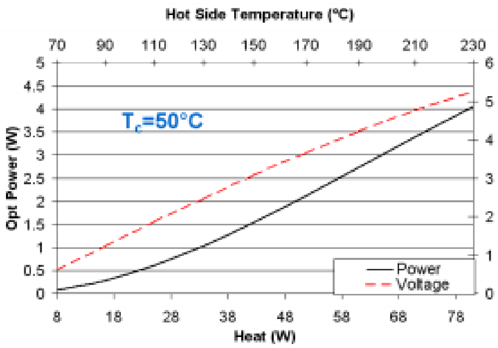
Model Number	Description
TG12-4-00	Cooler, No Lapping, No Seal
TG12-4-00L	Cooler, Lapped Model, No Seal
TG12-4-00S	Cooler, Sealed Model, No Lapping
TG12-4-00LS	Cooler, Lapped and Sealed Model
TG12-4-00LSG	Cooler, Lapped, Sealed, and Graphite Interface Pads

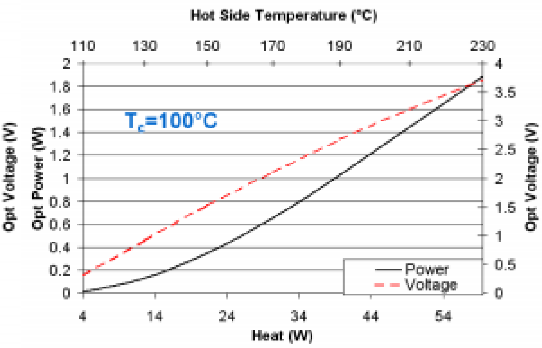
AVAILABLE MODIFICATIONS

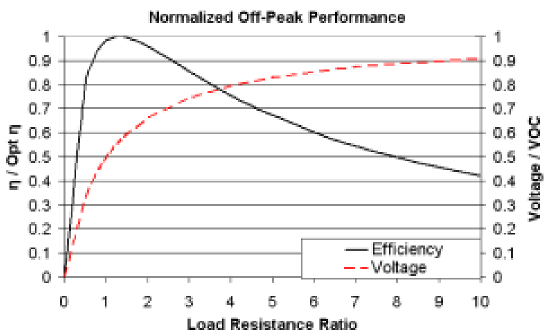
Non-standard cooler wiring; red lead wire is positive and blue lead wire is negative.
For more modification information, consult one of our Applications Engineers.

DOC # 102-0342 REV K - PAGE 1 OF 2

TYPICAL PERFORMANCE CURVES







Hot Side Temperature (°C)	230	170	110
Cold Side Temperature (°C)	50	50	50
Optimum Efficiency, η (%)	4.97	4.08	2.39
Optimum Power (W)	4.05	2.12	0.61
Optimum Voltage (V)	5.26	3.66	1.86
Load Resistance for Opt η (Ω)	6.83	6.32	5.72
Open Circuit Voltage, VOC (V)	9.45	6.50	3.28
Closed Circuit Current (A)	1.71	1.32	0.75
Thermal Resistance (°C/W)	2.21	2.31	2.37

Performance information is given in a nitrogen environment and cold side temperatures of 50°C and 100°C. TG device temperature does not include thermal resistance of heat sinks. For performance information in vacuum, other cold side temperatures, or specific heat sinks, consult one of our applications engineers.

Installation
Recommended mounting methods: TG's are typically mounted under compression not to exceed 200 psi with thermal grease or flexible graphite. For additional information, please contact an applications engineer.

Operation Cautions
For maximum reliability, continuous operation below 200°C (cold side and hot side) and intermittent operation up to 250°C on the hot side of the TG is recommended.

CONTACT US:

For customer support or general questions please contact a local office below or consult our website for distributor information.

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Appendix K: MATLAB Codes

K.1 Forced External Convection (Air)

```
function [h_1 h_2 Re_L Re_D Nu_L1 Nu_L2] = forcedconv(rho,v,mu,L,D_h,Pr,k)
Re_L = (rho*v*L)/mu;
Re_D = (rho*v*D_h)/mu;
f = ((0.790*(log(Re_D)))- 1.64)^(-2); %friction factor
Nu_L1 = 0.664*(Re_L^0.5)*Pr^(1/3); %forced external convection for flat plate
Nu_L2 = ((f/8)*(Re_D - 1000)*Pr)/(1+ 12.7*((f/8)^.5)*(Pr^(2/3)-1)); %forced
internal convection for enclosed surface

h_1 = (Nu_L1*k)/L;
h_2 = (Nu_L2*k)/D_h;
```

K.2 Forced Internal Convection (Air)

```
function [h Nu_L Ra_L] = naturalconv(vu,A,g,B,Ts,Tamb,L,Pr,k)
Ra_L = g*B*(Ts-Tamb)*L^3/(vu*A);
Nu_L = 0.68 + (.670*Ra_L^(1/4))/((1+(.492/Pr)^(9/16))^(4/9)); %More accurate
for laminar flow

%%Nu_L = (0.825 + ((.387*Ra_L^(1/6))/((1 +(0.492/Pr)^(9/16))^(8/27))))^2;
%Applicable to entire range of Ra_L
%%Nu_L = 0.1*(Ra_L^(1/3)); %General for turbulent flow
%%Nu_L = 0.59*(Ra_L^(1/4)); %General for laminar flow

h = (Nu_L*k)/L;
```

K.3 Testing Chamber Calculations for Convective Heat Transfer Coefficients

```
format compact
format short
clear; close all

%% Water Properties
% taken at 298.15K and
rho_c = 996.43;               %[kg/m^3]
Cp_c = 4177.83;               %[J/kg*K)]
mu_c = 793.92*10^-6;          %[N*s/m^2]
k_c = .61711;                 %[W/(m*K)]
Pr_c = 5.366;                 %Prandtl Number
vu_c = mu_c/rho_c;            %Kinematic Viscosity [m^2/s]
beta_c = 304.64*10^-6;        %Expansion Coefficient [1/K]
alpha_c = k_c/(rho_c*Cp_c); %Thermal Diffusivity [m^2/s]

%% Air Properties
% taken at 295.15K and
rho_a = 1.1840301;            %[kg/m^3]
```

```
Cp_a = 1006.903;            %[J/kg*K)]
mu_a = 182.175*10^-7;       %[N*s/m^2]
k_a = 0.025912;             %[W/(m*K)]
Pr_a = 0.708261;            %Prandtl Number
vu_a = mu_a/rho_a;          %Kinematic Viscosity [m^2/s]
alpha_a = k_a/(rho_a*Cp_a); %Thermal Diffusivity [m^2/s]

%% Cooling Requirements
DelT = 12;          %[K]
mdot = 2/1000;      %[kg/s]
W = 0.1212;         % Width of the large Al box
L = 0.1722;         % Length of the large Al box
H = 0.1069;         % Height of the large Al box
Ts = 298.15;        %[K]
Tamb = 286.15;      %[K]
g = 9.81;           %[m/s^2]

wb_s = 1.26*0.0254; % Fin base width of Small heat sink [m]
lb_s = 1.26*0.0254; % Fin base length of Small heat sink [m]
hf_s = 0.74*0.0254; % Fin height off base of Small heat sink [m]
tf_s = 0.028*0.0254;% Fin thickness of Small heat sink [m]

W_top = 2.3845*0.0254; % Top Styrofoam Channel width [m]
H_top = 1.5275*0.0254; % Top Styrofoam Channel height [m]
L_top = 6.8405*0.0254; % Top Styrofoam Channel length [m]

W_sd = 1.464*0.0254; % Side Styrofoam Channel width [m]
H_sd = 1.623*0.0254; % Side Styrofoam Channel height [m]
L_sd = 8.924*0.0254; % Side Styrofoam Channel height [m]

v_fan = 1.92;       %[m/s]

% Qtot = mdot*Cp*delT;

%% Hydraulic Diameter of the Al Box
A_c = L*W;
P = 2*(L+W);
D_h = (4*A_c)/P;

%% Hydraulic Diameter of the Styrofoam Insulation
A_sty = W_top*H_top;
P_s = 2*(W_top+H_top); %Styrofoam Perimeter [m]
D_sty = (4*A_sty)/P_s;

A_sd = W_sd*H_sd;
P_sd = 2*(W_sd+H_sd); %Styrofoam Perimeter [m]
D_sd = (4*A_sd)/P_sd;
```

```
%% Natural Free Convection
[h Nu_L Ra_L] = naturalconv(vu_c,alpha_c,g,beta_c,Ts,Tamb,L,Pr_c,k_c)

%[h Nu_S Ra_S] =
naturalconv_parallelplate(vu_c,alpha_c,g,beta_c,Ts,Tamb,S,L,k_c)

%% Forced Convection of the Fans
[h_1 h_2 Re_L Re_D Nu_L1 Nu_L2] =
forcedconv(rho_a,v_fan,mu_a,L_top,D_sty,Pr_a,k_a)

[h_3 h_4 Re_L Re_D Nu_L3 Nu_L4] =
forcedconv(rho_a,v_fan,mu_a,L_sd,D_sd,Pr_a,k_a)
```

K.4 Fin Calculations for the Heat Sink

```
clear; close all
format compact
format short

%Heat Sink Fin Calculations

%% Water Properties
% taken at 298.15K and
rho_c = 996.43;             %[kg/m^2]
Cp_c = 4177.83;             %[J/kg*K)]
mu_c = 793.92*10^-6;        %[N*s/m^2]
k_c = .61711;               %[W/(m*K)]
Pr_c = 5.366;               %Prandtl Number
vu_c = mu_c/rho_c;          %Kinematic Viscosity [m^2/s]
beta_c = 304.64*10^-6;      %Expansion Coefficient [1/K]
alpha_c = k_c/(rho_c*Cp_c); %Thermal Diffusivity [m^2/s]

%% Cooling Requirements
DelT = 12;              %[K]
mdot = 2/1000;          %[kg/s]
S = 3.015625*0.0254;    %Width of the Aluminum Testing Chamber [m]
L = 4*0.0254;           %Length of the Aluminum Testing Chamber [m]
H = 1.953125*0.0254;    %Height of the Aluminum Testing Chamber [m]
Ts = 298.15;            %[K]
Tamb = 286.15;          %[K]
g = 9.81;               %[m/s^2]
Q_c = 11.75;           %Total Cooling Power of the TEMs [W]

%% Fin Properties and Geometry
t = 0.028*0.0254; %thickness of the fin [m]
ws = 1.26*0.0254; %base width of the fin (small heat sink) [m]
```

```
ls = 1.26*0.0254; %base length of the fin (small heat sink) [m]

wb = 1.772*0.0254; %base width of the fin (larger heat sink) [m]
lb = 1.772*0.0254; %base length of the fin (large heat sink) [m]

% h_ext = ; %external convective heat transfer coefficient [W/m^2K]
[h_conv] = naturalconv(vu_c,alpha_c,g,beta_c,Ts,Tamb,L,Pr_c,k_c) %internal
convective heat transfer coefficient [W/m^2K]
k_f = 167; %Al 6061, conductive heat transfer coefficient of the fin [W/m*K]
T_b = 285.23; %base fin temperature [K]
T_inf = 23 +273.15; %ambient temperature [K]

Theta_b = T_inf - T_b;
%% Misc. Calcs
Ps = 2*ws + 2*t; %Perimeter (small heat sink) [m]
Pb = 2*wb +2*t; %Perimeter (large heat sink) [m]
A_s = ws*ls;
A_b = wb*lb;
% Ns = 10;
Nb = 16;

% m = ((h_conv*Ps)/(k_f*A_s))^0.5       % m for small heat sinks
% M = sqrt(h_conv*Ps*k_f*A_s)*(Theta_b) % M for small heat sinks

m = ((h_conv*Pb)/(k_f*A_b))^0.5         % m for large heat sinks
M = sqrt(h_conv*Pb*k_f*A_b)*(Theta_b)   % M for large heat sinks

Qtot = mdot*Cp_c*DelT;
%Assume Qc = q_f

% q_f = Q_c/Nb;

%% Assumption 1: Adiabatic Tip **q_f = M tanh(mL)
% L = ((atanh(q_f/M))/m) *100
q_f = M*tanh(m*0.0188)

%% E, Fin Effectiveness
Qb = h_conv*A_b*(Theta_b)
E = q_f/Qb

%% Minimum Length at E = 2
% L = ((atanh((2*Qb)/M))/m) *100

%% Thermal Resistance
Rb = 1/(h_conv*A_b);
Rf = 2*1/(h_conv*A_b)
```

K.5 Finding Optimum Current for Multiple Module Refrigeration

```
close all
clear all
clc
format compact

%% Module Properties
alpha = 1.83e-4; %Seebeck per leg [V/K]
rho = 6.800E-06;
k = 1.82;
Z = alpha^2/(rho*k);
Rc = 3.4053E-10;              %[Ohm*  m^2]   Contact Resistance per area


Amod = .03^2;           %[m^2]       Area of thermomodule plate
FF = 0.245533333;              %[]          Fill Factor
L = 0.0016;               %[m]         Leg Length
% Atem =;           %[m^2]       Area of individual thermocouple
N = 127;  %[]          Pairs of legs

Atem = FF*Amod/(2*N);
%N = FF*Amod/(2*Atem);

Ta = 293; %ambient temperature

n = 100;
I = linspace(0,1,n);
n_mod = 3

psi_C = 1;           %[K/W]      = yh
psi_H = 6;
psi_chamber = 2;          %Experiment

K=FF*Amod*k/L;
R=4*N^2*(rho*L+2*Rc)/Amod/FF;
S=2*N*alpha;

for j=1:n
    i=I(j);

    c1 = -n_mod*K;
    c2 = n_mod*S*i+n_mod*K+n_mod/psi_C;
    c3=-n_mod/psi_C;
    c4 = n_mod*i^2*R/2;

    e1=0;
    e2=-n_mod/psi_C;
    e3=n_mod/psi_C+1/psi_chamber;
    e4=Ta/psi_chamber;

    d1 = n_mod*S*i-n_mod*K-n_mod/psi_H;
    d2 = n_mod*K;
    d3=0;
```

```
    d4 = -Ta*n_mod/psi_H-n_mod*i^2*R/2;

    A = [ c1 c2 c3; e1 e2 e3; d1 d2 d3];
    b = [c4;e4;d4];
    T = A\b;

    Th(j)=T(1);
    Tc(j)=T(2);
    TR(j)=T(3);
end

Qc = n_mod*(S*I.*Tc - I.^2*R/2 - K*(Th-Tc));
% V= S*Th;
W = n_mod*(S*I.*(Th-Tc) + I.^2*R);
Qh=Qc+W;
CoP = Qc./W;
[Qcmax xmax] = max(Qc)
Iopt = I(xmax)
Wmax = W(xmax)
CoP_Qc = CoP(xmax)
TRmin = min(TR)
deltatT = Ta-min(TR)

figure
plot(I,TR,'LineWidth',3)
grid on
xlabel('I [A]','fontsize',16','fontweight','b')
ylabel('T_R [K]','fontsize',16','fontweight','b')
set(gca,'FontSize',16);
```

K.6 Transient Cooling Refrigeration

```
close all
clear all
clc
format compact

%% water properties
% mdot=0.002; %[kg/s] water flow rate
% Cp=4200; % [J/kgK] water specific heat
% deltaT=1; % temperature decrease per module
%% water
volL = 0.8;       %Volume [L]
volm = volL/1000;   %Volume [m^3]
rho_w = 998;        %Density [kg/m^3]
mass = volm*rho_w
Cp = 4205;          %Specific Heat [J/kgK]

%% Module Properties
alpha = 1.83e-4; %Seebeck per leg [V/K]
rho = 6.800E-06;
k = 1.82;
Z = alpha^2/(rho*k);
Rc = 3.4053E-10;              %[Ohm*  m^2]   Contact Resistance per area
```

```
Amod = .03^2;           %[m^2]       Area of thermomodule plate
FF = 0.245533333;               %[]          Fill Factor
L = 0.0016;                 %[m]         Leg Length
% Atem =;           %[m^2]       Area of individual thermocouple
N = 127;  %[]           Pairs of legs

Atem = FF*Amod/(2*N);
%N = FF*Amod/(2*Atem);

Ta = 20+273; %ambient temperature
% Qc=mdot*Cp*deltaT;

n = 100;
I = linspace(0,1,n);
n_mod = 3

psi_C = .0000000001;           %[K/W]      = yh
psi_H = 6.45;
psi_chamber = 2;           %Experiment

K=FF*Amod*k/L;
R=4*N^2*(rho*L+2*Rc)/Amod/FF;
S=2*N*alpha;

for j=1:n
    i=I(j);

    c1 = -n_mod*K;
    c2 = n_mod*S*i+n_mod*K+n_mod/psi_C;
    c3=-n_mod/psi_C;
    c4 = n_mod*i^2*R/2;

    e1=0;
    e2=-n_mod/psi_C;
    e3=n_mod/psi_C+1/psi_chamber;
    e4=Ta/psi_chamber;

    d1 = n_mod*S*i-n_mod*K-n_mod/psi_H;
    d2 = n_mod*K;
    d3=0;
    d4 = -Ta*n_mod/psi_H-n_mod*i^2*R/2;

    A = [ c1 c2 c3; e1 e2 e3; d1 d2 d3];
    b = [c4;e4;d4];
    T = A\b;

    Th(j)=T(1);
    Tc(j)=T(2);
    TR(j)=T(3);
end

Qcss = n_mod*(S*I.*Tc - I.^2*R/2 - K*(Th-Tc));
```

```
% V= S*Th;
W = S*I.*(Th-Tc) + I.^2*R;
Qh=Qcss+W;
CoP = Qcss./W;
[Qcmax xmax] = max(Qcss)
Iopt = I(xmax)
SS_Tr = min(TR);

u = 100;
Trr = rand(1,u);
tend = 24000;
tt = linspace(0,tend,u);
deltat = tend/(u-1);
Trr(1) = Ta;
for z = 1:u
    Tr = Trr(z);

    a1 = psi_H*K - psi_H*S*Iopt + 1;
    a2 = -psi_H*K;
    a3 = Ta + psi_H*Iopt^2*R/2;

    b1 = -psi_C*K;
    b2 = psi_C*S*Iopt + psi_C*K + 1;
    b3 = Tr +psi_C*Iopt^2*R/2;

    A = [ a1 a2; b1 b2 ];
    B = [ a3; b3];
    T = A\B;
    DDet(z) = det(A);
    Thh(z) = T(1);
    Tcc(z) = T(2);

    TH = Thh(z);
    TC = Tcc(z);

    Qc(z) = n_mod*(S*Iopt*TC - K*(TH-TC) - Iopt^2*R/2);
    Trr(z+1) = -deltat*Qc(z)/mass/Cp + deltat*(Ta-Tr)/psi_chamber/mass/Cp +
Tr;
    tt(z+1) = tt(z)+deltat;
end

tt_Qc = tt;
tt_Qc(u+1) = [];
for y = 1:u
    if Trr(y)<273
        r_time = tt(y)
        break
    else
    end
end


min_Trr = min(Trr)
figure(1);
hold on
```

```
plot(tt/60,Trr-273,'LineWidth',3)
grid on
xlabel('Time [min]','fontsize',16)
ylabel('Temperature [K]','fontsize',16)
hold off

figure
plot(tt_Qc/60,Qc,'LineWidth',3)
grid on
xlabel('Time [min]','fontsize',16)
ylabel('Q_c [W]','fontsize',16)

figure
plotyy(tt/60,Trr-273,tt_Qc/60,Qc)
[AX,H1,H2] = plotyy(tt/60,Trr-273,tt_Qc/60,Qc,'plot');
set(get(AX(1),'Ylabel'),'String','T_R [K]','fontsize',16,'fontweight','b')
set(get(AX(2),'Ylabel'),'String','Q_c [W]','fontsize',16,'fontweight','b')
set(H1,'LineWidth',2);
set(H2,'LineWidth',2,'LineStyle','--');
set(AX,'FontSize',14);
xlabel('Time [min]','fontsize',16','fontweight','b')
grid on
hold on
```

K.7 Hot Side Thermal Resistance vs. Number of TEMs Refrigeration

```
close all
clear all
clc
format compact

%% water properties
% mdot=0.002; %[kg/s] water flow rate
% Cp=4200; % [J/kgK] water specific heat
% deltaT=1; % temperature decrease per module

%% Module Properties
alpha = 1.83e-4; %Seebeck per leg [V/K]
rho = 6.800E-06;
k = 1.82;
Z = alpha^2/(rho*k);
Rc = 3.4053E-10;              %[Ohm*  m^2]   Contact Resistance per area


Amod = .03^2;           %[m^2]       Area of thermomodule plate
FF = 0.245533333;               %[]          Fill Factor
L = 0.0016;                  %[m]         Leg Length
% Atem =;              %[m^2]       Area of individual thermocouple
N = 127;  %[]           Pairs of legs

Atem = FF*Amod/(2*N);
%N = FF*Amod/(2*Atem);
```

```
Ta = 293; %ambient temperature
% Qc=mdot*Cp*deltaT;

n = 100;
I = linspace(0,1,n);
p = 200;
p2 = 3;
n_modmod = linspace(.0001,12,p);
% psi_ambamb = linspace(1,12,p2);
psi_Hh = [2.15 6 8];
K=FF*Amod*k/L;
R=4*N^2*(rho*L+2*Rc)/Amod/FF;
S=2*N*alpha;

for u = 1:p
    n_mod = n_modmod(u);
    psi_C = .5;           %[K/W]      = yh

    psi_chamber= 2;      %Aluminum box
    % psi_chamber =.8072;     %Small acrylic boxes

for z = 1:p2
    psi_H = psi_Hh(z)*n_mod;


for j=1:n
    i=I(j);

    c1 = -n_mod*K;
    c2 = n_mod*S*i+n_mod*K+n_mod/psi_C;
    c3=-n_mod/psi_C;
    c4 = n_mod*i^2*R/2;

    e1=0;
    e2=-n_mod/psi_C;
    e3=n_mod/psi_C+1/psi_chamber;
    e4=Ta/psi_chamber;

    d1 = n_mod*S*i-n_mod*K-n_mod/psi_H;
    d2 = n_mod*K;
    d3=0;
    d4 = -Ta*n_mod/psi_H-n_mod*i^2*R/2;

    A = [ c1 c2 c3; e1 e2 e3; d1 d2 d3];
    b = [c4;e4;d4];
    T = A\b;

    Th(j)=T(1);
    Tc(j)=T(2);
    TR(j)=T(3);
end

Qc = n_mod*(S*I.*Tc - I.^2*R/2 - K*(Th-Tc));
% V= S*Th;
```

```
% W = n_mod*(S*I.*(Th-Tc) + I.^2*R);
% Qh=Qc+W;
% CoP = Qc./W;
[Trmin(z) xmin] = min(TR);
[Qcmax(z) xmax] = max(Qc);
Iopt = I(xmax);
IoptTr = I(xmin);
% Wmax = W(xmax);
% CoP_Qc = CoP(xmax);
% min(TR);
% deltatT = Ta-min(TR);
end

maxQc(u,:) = Qcmax;
minTr(u,:) = Trmin;

end
MIN_TR = min(min(minTr));
%% Sensitivity
Tr101 = minTr;

figure
mesh(psi_Hh,n_modmod,maxQc*1000)
ylabel('\psi_H [K/W]','fontsize',16)
xlabel('N_m_o_d','fontsize',16)
zlabel('Max Qc [mW]','fontsize',16)
% set(gca,'YTickLabel',num2str(get(gca,'YTick')','%3.3f'));
% set(gca,'XTickLabel',num2str(get(gca,'XTick')','%2.1f'));
% set(gca,'ZTickLabel',num2str(get(gca,'ZTick')','%3.0f'));
% set(gca,'FontSize',14);                                     %Adjustment
With Set() to Size 14 Throws Off Y-Axis Numbers
hold on
% title('\psi_H = 6.11, \psi_C = .6636, \psi_Chamber = 5.8326, T_\infty = 293
FFopt = 1, LLopt = .0273 Max Qc = 1.1457W')

figure
mesh(psi_Hh,n_modmod,minTr)
ylabel('\psi_H [K/W]','fontsize',16)
xlabel('N_m_o_d','fontsize',16)
zlabel('Max Qc [mW]','fontsize',16)

T10 = 11*ones(1,p);
T13 = 16*ones(1,p);

figure
plot(n_modmod,minTr(:,1)-273,n_modmod,minTr(:,2)-273,n_modmod,minTr(:,3)-
273,'LineWidth',6)
grid on
xlabel('# of Module','fontsize',36)
ylabel('T_R [^\circC]','fontsize',36)
set(gca,'FontSize',36);                               %Adjustment With
Set() to Size 14 Throws Off Y-Axis Numbers
hold on
plot(3,14,'rx','LineWidth',36)
legend('\psi_H = 2.2','\psi_H = 6','\psi_H = 8','Quikchill')
```

K.8 Chamber Thermal Resistance Refrigeration

```
close all
clear all
clc
format compact

%% water properties
% mdot=0.002; %[kg/s] water flow rate
% Cp=4200; % [J/kgK] water specific heat
% deltaT=1; % temperature decrease per module

%% Module Properties
alpha = 1.83e-4; %Seebeck per leg [V/K]
rho = 6.800E-06;
k = 1.82;
Z = alpha^2/(rho*k);
Rc = 3.4053E-10;              %[Ohm*  m^2]   Contact Resistance per area


Amod = .03^2;          %[m^2]       Area of thermomodule plate
FF = 0.245533333;              %[]          Fill Factor
L = 0.0016;                 %[m]         Leg Length
% Atem =;           %[m^2]       Area of individual thermocouple
N = 127;  %[]          Pairs of legs

Atem = FF*Amod/(2*N);
%N = FF*Amod/(2*Atem);

Ta = 22+273; %ambient temperature

n = 500;
I = linspace(.5,.7,n);
n_mod = 3;

psi_C = .4;            %[K/W]      = yh
psi_H = 5;

u = 100;
psi_cc = linspace(1,100,u);
for z = 1:u;
    psi_chamber=psi_cc(z);

K=FF*Amod*k/L;
R=4*N^2*(rho*L+2*Rc)/Amod/FF;
S=2*N*alpha;

for j=1:n
    i=I(j);

    c1 = -n_mod*K;
    c2 = n_mod*S*i+n_mod*K+n_mod/psi_C;
    c3=-n_mod/psi_C;
    c4 = n_mod*i^2*R/2;
```

```
    e1=0;
    e2=-n_mod/psi_C;
    e3=n_mod/psi_C+1/psi_chamber;
    e4=Ta/psi_chamber;

    d1 = n_mod*S*i-n_mod*K-n_mod/psi_H;
    d2 = n_mod*K;
    d3=0;
    d4 = -Ta*n_mod/psi_H-n_mod*i^2*R/2;

    A = [ c1 c2 c3; e1 e2 e3; d1 d2 d3];
    b = [c4;e4;d4];
    T = A\b;

    Th(j)=T(1);
    Tc(j)=T(2);
    TR(j)=T(3);
end

Qc = n_mod*(S*I.*Tc - I.^2*R/2 - K*(Th-Tc));
% V= S*Th;
% Qh = S*I*Th+I.^2*R/2 - K*(Th-Tc);

[Qcmax(z) xmax] = max(Qc);
Iopt(z) = I(xmax);
W(z) = S*Iopt(z)*(Th(xmax)-Tc(xmax)) + Iopt(z).^2*R;
CoP(z) = Qcmax(z)/W(z);
Tr_min(z) = min(TR);
CoP_ID(z)=1/(Th(xmax)/Tc(xmax)-1);
CoP_ratio(z)=CoP(z)/CoP_ID(z);

end

figure
plotyy(psi_cc,Tr_min,psi_cc,Qcmax)
[AX,H1,H2] = plotyy(psi_cc,Tr_min,psi_cc,Qcmax,'plot');
set(get(AX(1),'Ylabel'),'String','T_R [K]','fontsize',36,'fontweight','b')
set(get(AX(2),'Ylabel'),'String','Q_c [W]','fontsize',36,'fontweight','b')
set(H1,'LineWidth',4);
% set(H2,'LineWidth',4,'LineStyle','--');
set(H2,'LineWidth',4);
set(AX,{'ycolor'},{'b';'r'},'FontSize',36);
xlabel('\psi_c_h_a_m_b_e_r [K/W]','fontsize',36','fontweight','b')
grid on
hold on

figure
plot(psi_cc,(Tr_min-273),'LineWidth',8)
grid on
xlabel('\psi_c_h_a_m_b_e_r','fontsize',36','fontweight','b')
ylabel('T_R [^\circC]','fontsize',36','fontweight','b')
set(gca,'FontSize',36);
hold on
plot(2,14,'rx','LineWidth',36)
```

Appendix L: MATLAB Nomenclature

alpha	Single leg Seebeck Coefficient
rho	Single leg electrical resistance
k	Single leg thermal conductance
Z	Figure of Merit
Rc	Contact Resistance
Amod	Area of module
FF	Fill factor
L	Leg length
N	Number of pairs of TE legs
Atem	Area of single TE leg
Ta	Ambient temperature
I	Current
n_mod	Number of modules
psi_H	Hot side thermal resistance
psi_C	Cold side thermal resistance
psi_chamber	Chamber thermal resistance
K	Module thermal conductance
R	Module electrical resistance
S	Module Seebeck coefficient
Th	Hot side TEM temperature
Tc	Cold side TEM temperature
TR	Water temperature
volL	Volume of water liters
volm	Volume of water m^3
rho_w	Density of water
mass	Mass of water
Cp	Thermal capacity of water

Appendix M: Experimental Protocol Tables

Evaluation	Location/Time	Equipment	Accuracy	Trials	Expected Outcome	Formulae or assumptions	Man-Hours
Water Temperature	Heat Transfer Lab	DAQ, Power Supply, Thermocouples	.4 °C	12	12-13°C	Water is the same temperature throughout chamber, thermocouples measure water temperature not wall temperature.	4.5
Heat Dissipation	Heat Transfer Lab	DAQ, thermocouple, heater, heat sink, heat pipe, thermal paste	2 K/W	2	5K/W	Power generation heat dissipation also works for refrigeration	1.5
Mass/Volume	Machine Shop	Large scale/ Ruler	.5 kg	3	3 kg/1.2E-3 m^3	Scale is accurate	1
Time to Cool	Heat Transfer Lab	DAQ, Power Supply, Thermocouples	1 min	12	120 min	Water is the same temperature throughout chamber, thermocouples measure water temperature not wall temperature.	5
Thermal Resistance of Chamber	Heat Transfer Lab	DAQ, Thermocouples	2 K/W	3	6 K/W	Lumped capacitance model for water	1.5
Purifier	Heat Transfer Lab	Water Test Kit for Nitrates,	5%	6	1μm	Testing kit is accurate	2
Power Consumption	Heat Transfer Lab	DAQ, power supply	2 W	12	16 W	LabView/Power supplies are accurate	4.5

Appendix N: Parts List

Project	QuickChill													
Subsystem	Component Description	Part #	# of items	B/M/O[1]	Vendor	Cost / part	Responsible person	Man-hours[2]	Des	Proc	Build (ea)	Assm	Order or start date	Receive or finish date
Benchmarking Parts														
	Brita Water Filter	B001	1	B	Target	$21	Rachel	0.6	0.2	0.2	0.2		28-Sep	28-Sep
	Pur Water Filter	B002	1	B	Target	$27	Rachel	0.6	0.2	0.2	0.2		28-Sep	28-Sep
	Avanti Filter	B003	1	B	Amazon	$69	Rachel	1.4	0.2	0.2	1		10-Oct	12-Oct
	Avanti 3 Gallon Tank	B004	1	B	Amazon	$75	Rachel	0.2		0.2			10-Oct	12-Oct
	Sub System Totals					**$192**		**2.8**						
Testing Accessories														
	Flowmeter .2-2.5 gph	A001	1	B	McMaster Carr	$59	Rachel	1.7	1	0.5	0.2		5-Nov	7-Nov
	Flowmeter 2.5 gph+ (projected)	A002	1	B	McMaster Carr	$50	Rachel	1.5	1	0.5	0.2		N/A	N/A
	K-type Thermocouples	A003	5	D	HTL	$15	Louie	0.2	0.1	0.1			27-Jan	14-Feb
	Sub System Totals					**$134**		**3.6**						
Acrylic Testing Channel														
	Acrylic Block	T001	1	B/M	Tap Plastics	$55	Rachel, Bernie	6	2	3	2		19-Oct	19-Oct
	Aluminum Plate	T002	1	D	Machine Shop	*$3*	Bernie, Brandon	0.6	0.3	0.1	0.2		20-Nov	20-Nov
	Heat sink #4	T003	1	D	HTL	*$2*	Rachel	0.2	0.1	0.1			20-Nov	20-Nov
	Thermal Paste	T004	1	D	HTL	*$7*	Rachel	0.2	0.1	0.1			20-Nov	20-Nov

	Silicone Rubber Sealant	T005	1	B	Lowes	$5	Rachel	0.2	0.1	0.1			18-Nov	18-Nov
	JB Water Weld	T006	1	B	Lowe's	$6	Rachel	0.3	0.1	0.2			18-Nov	18-Nov
	Hose Barb Adapter 5/8" x 1/2" MIP	T003	1	B	Lowe's	$5	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Brass Pipe Bushing 1/2" MIP x 1/8 " MIP	T004	1	B	Lowe's	$2	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Stainless Steel Clamp #8	T005	1	B	Lowe's	$4	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Faucet Adaptor	T006	1	B	Lowe's	$5	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Brass Hose Barb MIP 007Adaptor	T007	2	B	Lowe's	$6	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Dishwasher Snap Nipple	T008	1	B	Lowe's	$2	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Clear Polycarbonate Tubing 1/8"	T009	1	B	Lowe's	$10	Rachel	0.2	0.1	0.1			5-Nov	5-Nov
	Clear PolyCarbonate 3/4"x5/8"x10ft.	T010	1	B	Lowe's	$12	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Marlow Thermoelectric Modules	T011	4	B	Marlow	$27	Rachel	2	1.5	0.5			19-Oct	22-Oct
	Acrylic Block (Channel Assembly)	**TA1**	**1**	**M**			Rachel, Bernie, Brandon	10	3	1	2	4	19-Nov	20-Nov
	Sub System Totals					**$151**		**22.1**						
Small Testing Tank 1														
	Aluminum Cast 800mL Small Box	TS001	1	M	Amazon	$19	Bernie, Rachel	2	1	2			11-Jan	13-Jan
	Milled Bulkhead Fittings	TS002	2	M	HomeDepot	$11	Brandon	4	1	1	2		13-Jan	11-Feb
	Stainless Steel Pipes 1/2" NPT Female	TS003	2	B	Conleff	$15	Brandon	1	0.5	0.5			24-Jan	24-Jan

	1/2" NPT Nipples	TS004	3	B	Conleff	$2	Brandon	1	0.5				24-Jan	24-Jan
	Internal Heat Sinks ATS 1194	TS005	6	B	DigiKey	$14	Rachel	5	2	1	1		8-Feb	13-Feb
	Ball Valve	TS006	1	B	Conleff	$5	Brandon	1	0.5	0.5			24-Jan	24-Jan
	Styrofoam Right	TS007	1	M	HomeDepot	$12	Bernie	5	1	2	2		8-Feb	9-Feb
	Styrofoam Left	TS008	1	M	HomeDepot	$12	Bernie	5	1	2	2		8-Feb	9-Feb
	Styrofoam Bottom	TS009	1	M	HomeDepot	$13	Bernie	5	1	2	2		8-Feb	9-Feb
	Fans	TS010	3	B	Frys	$6	Bernie	1	0.5	0.5			11-Feb	11-Feb
	Modified Lid with Holes	TS011	1	M	Amazon	$19	Bernie	5	1	1	3		11-Feb	11-Feb
	Male to Female Adaptor	TS012	1	B	HomeDepot	$1	Bernie	1	0.5	0.5			11-Feb	11-Feb
	Heat Sink X	TS013	12	B	DigiKey	$6	Rachel, Bernie	1	0.5	0.5			11-Feb	14-Feb
	Thermal Paste	T004	1	D	HTL	*$7*	Rachel	0.2	0.1	0.1			20-Nov	20-Nov
	Silicone Rubber Sealant	T005	1	B	Lowes	$5	Rachel	0.2	0.1	0.1			18-Nov	18-Nov
	JB Water Weld	T006	1	B	Lowe's	$6	Rachel	0.3	0.1	0.2			18-Nov	18-Nov
	Hose Barb Adapter 5/8" x 1/2" MIP	T003	1	B	Lowe's	$5	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Brass Pipe Bushing 1/2" MIP x 1/8 " MIP	T004	1	B	Lowe's	$2	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Stainless Steel Clamp #8	T005	1	B	Lowe's	$4	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Faucet Adaptor	T006	1	B	Lowe's	$5	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Brass Hose Barb MIP 007Adaptor	T007	2	B	Lowe's	$6	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Dishwasher Snap Nipple	T008	1	B	Lowe's	$2	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Clear Polycarbonate Tubing 1/8"	T009	1	B	Lowe's	$10	Rachel	0.2	0.1	0.1			5-Nov	5-Nov

	Clear PolyCarbonate 3/4"x5/8"x10ft.	T010	1	B	Lowe's	$12	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Marlow Thermoelectric Modules	T011	12	B	Marlow	$27	Rachel	2	1.5	0.5			19-Oct	22-Oct
	Small Testing Tank Assembly	TSA1	1	M			Rachel, Bernie	8	1	2	2	3	14-Feb	15-Feb
	Sub System Totals					**$226**		**20.3**						
Small Testing Tank 2														
	Heat Sink Z	TS014	3	B	HTL	$9	Bernie	1	0.5	0.5			20-Mar	20-Mar
	Aluminum Cast 800mL Small Box	TS001	1	M	Amazon	$19	Bernie, Rachel	2	1	2			11-Jan	13-Jan
	Milled Bulkhead Fittings	TS002	2	M	HomeDepot	$11	Brandon	4	1	1	2		13-Jan	11-Feb
	Stainless Steel Pipes 1/2" NPT Female	TS003	2	B	Conleff	$15	Brandon	1	0.5	0.5			24-Jan	24-Jan
	1/2" NPT Nipples	TS004	3	B	Conleff	$2	Brandon	1	0.5				24-Jan	24-Jan
	Internal Heat Sinks ATS 1194	TS005	3	B	DigiKey	$14	Rachel	5	2	1	1		8-Feb	13-Feb
	Ball Valve	TS006	1	B	Conleff	$5	Brandon	1	0.5	0.5			24-Jan	24-Jan
	Styrofoam Right	TS007	1	M	HomeDepot	$12	Bernie	5	1	2	2		8-Feb	9-Feb
	Styrofoam Left	TS008	1	M	HomeDepot	$12	Bernie	5	1	2	2		8-Feb	9-Feb
	Styrofoam Bottom	TS009	1	M	HomeDepot	$13	Bernie	5	1	2	2		8-Feb	9-Feb
	Fans	TS010	3	B	Frys	$6	Bernie	1	0.5	0.5			11-Feb	11-Feb
	Modified Lid with Holes	TS011	1	M	Amazon	$19	Bernie	5	1	1	3		11-Feb	11-Feb
	Male to Female Adaptor	TS012	1	B	HomeDepot	$1	Bernie	1	0.5	0.5			11-Feb	11-Feb

	Heat Sink X	TS013	12	B	DigiKey	$6	Rachel, Bernie	1	0.5	0.5			11-Feb	14-Feb
	Thermal Paste	T004	1	D	HTL	$7	Rachel	0.2	0.1	0.1			20-Nov	20-Nov
	Silicone Rubber Sealant	T005	1	B	Lowes	$5	Rachel	0.2	0.1	0.1			18-Nov	18-Nov
	JB Water Weld	T006	1	B	Lowe's	$6	Rachel	0.3	0.1	0.2			18-Nov	18-Nov
	Hose Barb Adapter 5/8" x 1/2" MIP	T003	1	B	Lowe's	$5	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Brass Pipe Bushing 1/2" MIP x 1/8 " MIP	T004	1	B	Lowe's	$2	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Stainless Steel Clamp #8	T005	1	B	Lowe's	$4	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Faucet Adaptor	T006	1	B	Lowe's	$5	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Brass Hose Barb MIP 007Adaptor	T007	2	B	Lowe's	$6	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Dishwasher Snap Nipple	T008	1	B	Lowe's	$2	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Clear Polycarbonate Tubing 1/8"	T009	1	B	Lowe's	$10	Rachel	0.2	0.1	0.1			5-Nov	5-Nov
	Clear PolyCarbonate 3/4"x5/8"x10ft.	T010	1	B	Lowe's	$12	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Marlow Thermoelectric Modules	T011	3	B	Marlow	$27	Rachel	2	1.5	0.5			19-Oct	22-Oct
	Small Testing Tank Assembly 2	TSA2	1	M			Rachel, Bernie	8	1	2	2	3	22-Mar	22-Mar
	Sub System Totals					**$226**		**25.3**						
Small Testing Tank 3														
	Spiral Heat Sink	TS015	1	O	Avanti	n/a	Rachel	1	0.5	0.5			10-Oct	10-Oct
	Circular Fan	TS016	1	O	Avanti	n/a	Rachel	1	0.5	0.5			10-Oct	10-Oct
	Milled Lid with	TS017	1	M	Amazon	$19	Brandon	4	1	2	1		12-Apr	12-Apr

	one hole													
	Milled Aluminum Cast with one hole 800mL	TS018	1	M	Amazon	$19	Brandon	4	1	2	1		12-Apr	12-Apr
	Bent Heat Pipe	TS019	3	M	MTRAN	n/a	Rachel	2	1	0.5	0.5		12-Apr	12-Apr
	Spray foam Insulation	TS020	**1**	B	HomeDepot	$7	Brandon	2	0.5	1	0.5		12-Apr	12-Apr
	Internal Heat Sinks ATS 1194	TS005	3	B	DigiKey	$14	Rachel	5	2	1	1		8-Feb	13-Feb
	Ball Valve	TS006	1	B	Conleff	$5	Brandon	1	0.5	0.5			24-Jan	24-Jan
	Styrofoam Right	TS007	1	M	HomeDepot	$12	Bernie	5	1	2	2		8-Feb	9-Feb
	Styrofoam Left	TS008	1	M	HomeDepot	$12	Bernie	5	1	2	2		8-Feb	9-Feb
	Styrofoam Bottom	TS009	1	M	HomeDepot	$13	Bernie	5	1	2	2		8-Feb	9-Feb
	Fans	TS010	3	B	Frys	$6	Bernie	1	0.5	0.5			11-Feb	11-Feb
	Modified Lid with Holes	TS011	1	M	Amazon	$19	Bernie	5	1	1	3		11-Feb	11-Feb
	Male to Female Adaptor	TS012	1	B	HomeDepot	$1	Bernie	1	0.5	0.5			11-Feb	11-Feb
	Thermal Paste	T004	1	D	HTL	*$7*	Rachel	0.2	0.1	0.1			20-Nov	20-Nov
	Silicone Rubber Sealant	T005	1	B	Lowes	$5	Rachel	0.2	0.1	0.1			18-Nov	18-Nov
	JB Water Weld	T006	1	B	Lowe's	$6	Rachel	0.3	0.1	0.2			18-Nov	18-Nov
	Hose Barb Adapter 5/8" x 1/2" MIP	T003	1	B	Lowe's	$5	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Brass Pipe Bushing 1/2" MIP x 1/8 " MIP	T004	1	B	Lowe's	$2	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Stainless Steel Clamp #8	T005	1	B	Lowe's	$4	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Faucet Adaptor	T006	1	B	Lowe's	$5	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Brass Hose Barb MIP 007Adaptor	T007	2	B	Lowe's	$6	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Dishwasher Snap Nipple	T008	1	B	Lowe's	$2	Louie	0.2	0.1	0.1			22-Oct	22-Oct

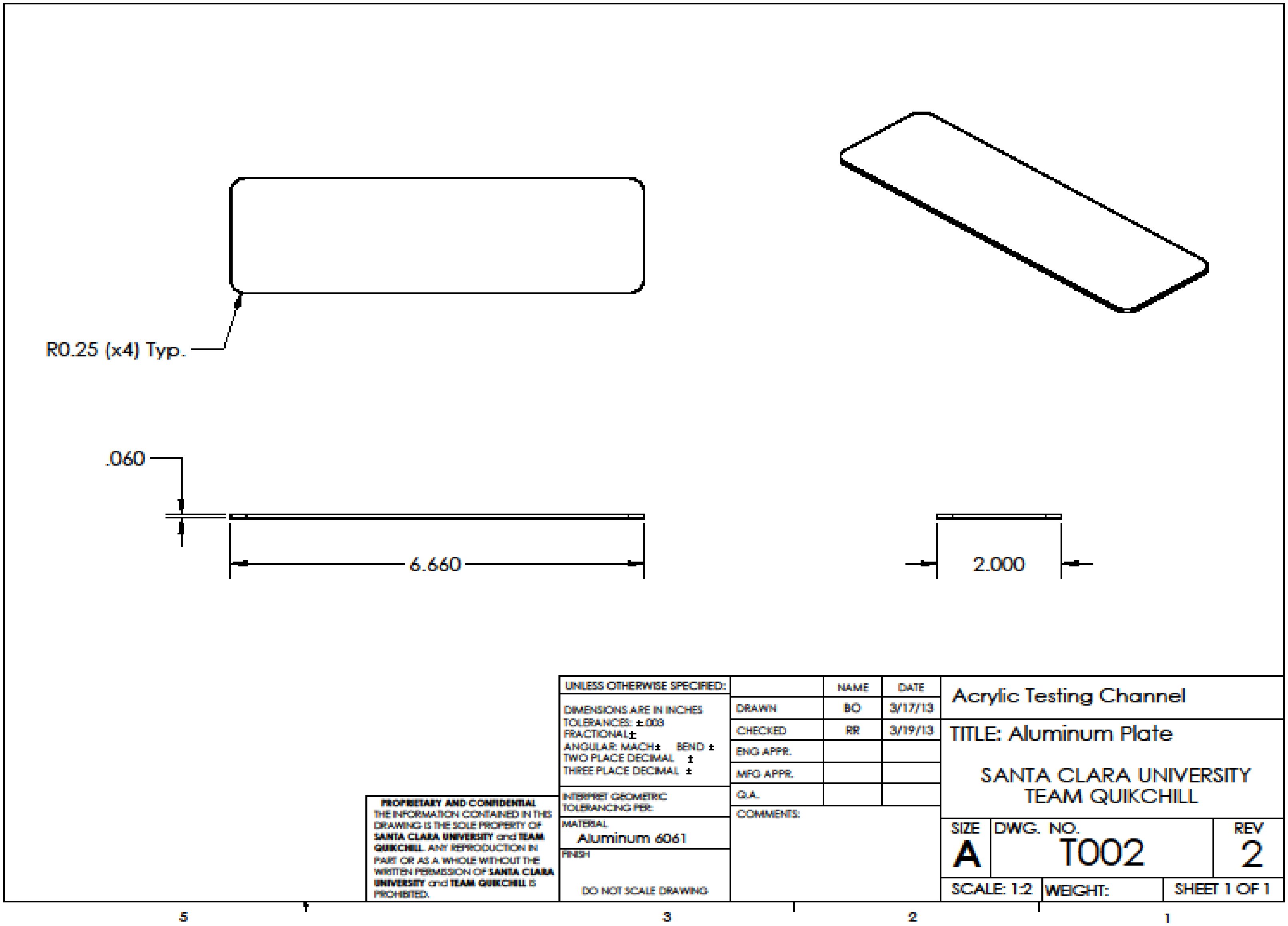
	Clear Polycarbonate Tubing 1/8"	T009	1	B	Lowe's	$10	Rachel	0.2	0.1	0.1			5-Nov	5-Nov
	Clear Polycarbonate 3/4"x5/8"x10ft.	T010	1	B	Lowe's	$12	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Marlow Thermoelectric Modules	T011	3	B	Marlow	$27	Rachel	2	1.5	0.5			19-Oct	22-Oct
	Internal Heat Sinks ATS 1194	TS005	3	B	DigiKey	$14	Rachel	5	2	1	1		8-Feb	13-Feb
	Small Testing Tank Assembly 3	TSA3	1	M			Brandon	10	1	2	2	5	15-Apr	16-Apr
	Sub System Totals					**$232**		**32.3**						
Large Testing Tank														
	Aluminum Cast 2L box	TL001	1	M	Amazon	$22	Bernie	6	2	2	2		30-Jan	3-Feb
	External Heat Sinks ATS 91240	TL002	12	B	DigiKey	$8	Rachel	5	2	1	1		8-Feb	13-Feb
	Bulkhead Fittings	TL003	2	B	Home Depot	$11	Bernie	1	0.5	0.5			11-Feb	11-Feb
	Styrofoam Left, Right & Top	TL004	1	M	Home Depot	$12	Bernie	5	1	2	2		8-Feb	9-Feb
	Styrofoam Bottom	TL005	1	M	Home Depot	$13	Bernie	5	1	2	2		8-Feb	9-Feb
	Styrofoam Front&Back	TL006	2	M	Home Depot	$14	Bernie	5	1	2	2		8-Feb	9-Feb
	Thermal Paste	T004	1	D	HTL	*$7*	Rachel	0.2	0.1	0.1			20-Nov	20-Nov
	Silicone Rubber Sealant	T005	1	B	Lowes	$5	Rachel	0.2	0.1	0.1			18-Nov	18-Nov
	JB Water Weld	T006	1	B	Lowe's	$6	Rachel	0.3	0.1	0.2			18-Nov	18-Nov
	Hose Barb Adapter 5/8" x 1/2" MIP	T003	1	B	Lowe's	$5	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Brass Pipe	T004	1	B	Lowe's	$2	Louie	0.2	0.1	0.1			22-Oct	22-Oct

	Bushing 1/2" MIP x 1/8 " MIP													
	Stainless Steel Clamp #8	T005	1	B	Lowe's	$4	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Faucet Adaptor	T006	1	B	Lowe's	$5	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Brass Hose Barb MIP 007Adaptor	T007	2	B	Lowe's	$6	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Dishwasher Snap Nipple	T008	1	B	Lowe's	$2	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Clear Polycarbonate Tubing 1/8"	T009	1	B	Lowe's	$10	Rachel	0.2	0.1	0.1			5-Nov	5-Nov
	Clear Polycarbonate 3/4"x5/8"x10ft.	T010	1	B	Lowe's	$12	Louie	0.2	0.1	0.1			22-Oct	22-Oct
	Marlow Thermoelectric Modules	T011	12	B	Marlow	$27	Rachel	2	1.5	0.5			19-Oct	22-Oct
	Testing Tank Assembly	**TLA1**	**1**	**M**			Team	9	3	1	1	4	15-Jan	16-Jan
	Sub System Totals					**$171**		**226.2**		.				
Project Totals						**$1,332**		**332.6**	**71.1**	**76**	**88.8**	**19**		

[1] B = bought, M = made by you, O = made by others, D = Donated

[2] Total team hours in design, procurement, manufacture, and assembly

Appendix O: Detailed Drawings


R0.25 (x4) Typ.
.060
6.660
2.000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±.003
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum 6061
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
BO
3/17/13
CHECKED
RR
3/19/13
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PROPRIETARY AND CONFIDENTIAL
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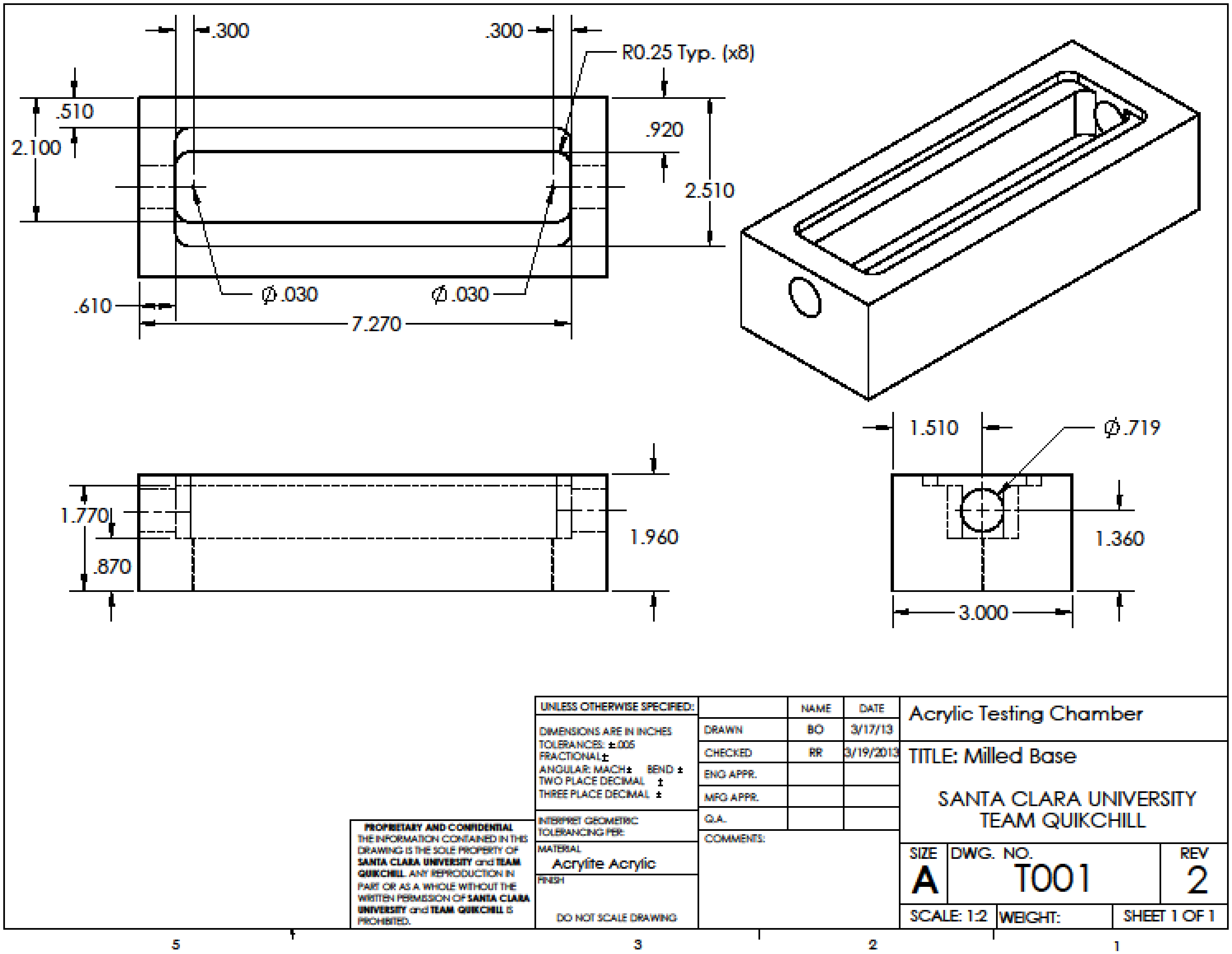
Acrylic Testing Channel
TITLE: Aluminum Plate
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL
SIZE
A
DWG. NO.
T002
REV
2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



.300
.300
R0.25 Typ. (x8)
.510
2.100
.920
2.510
Ø.030
Ø.030
.610
7.270
1.510
Ø.719
1.770
.870
1.960
1.360
3.000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±.005
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Acrylite Acrylic
FINISH
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
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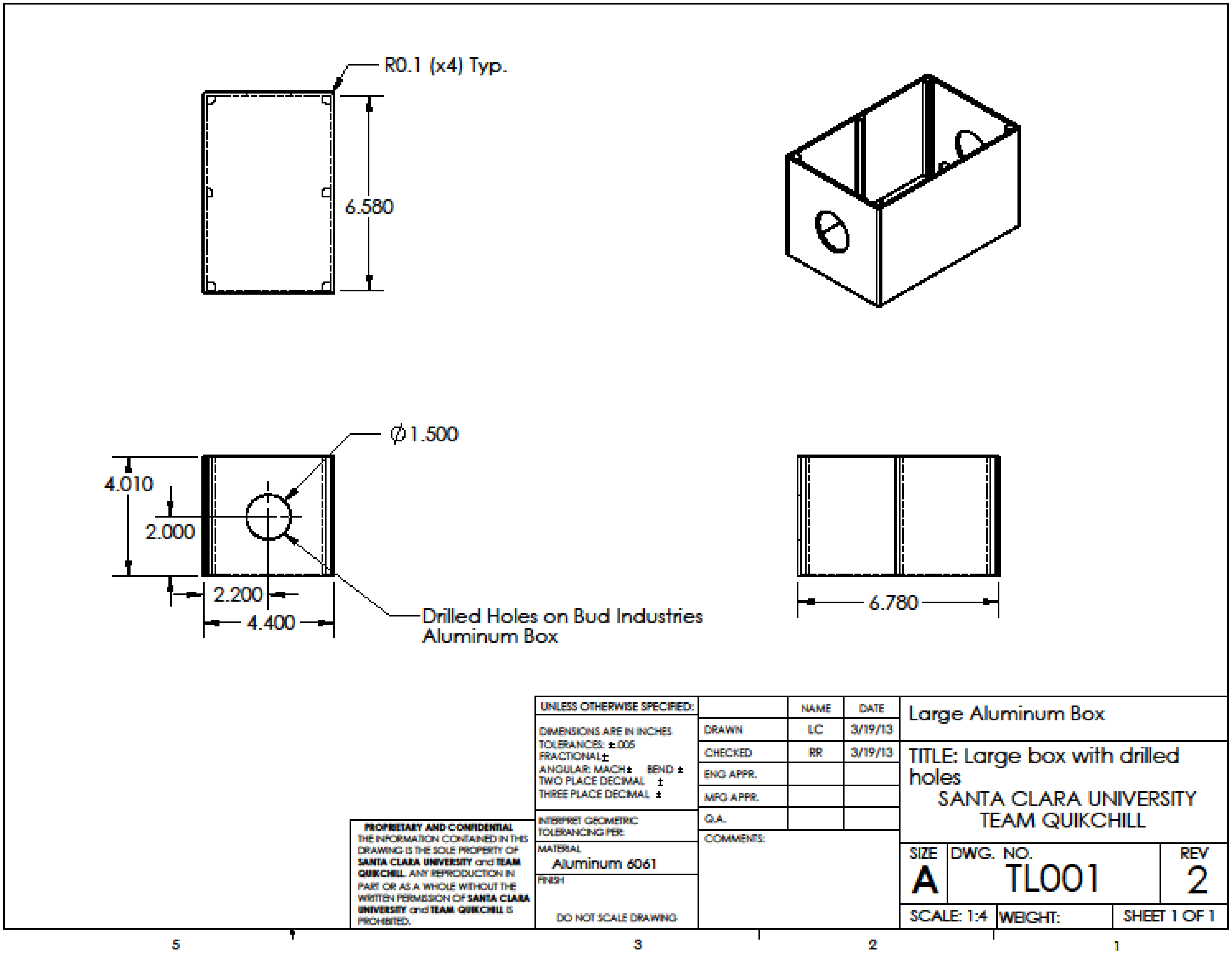
NAME DATE
DRAWN BO 3/17/13
CHECKED RR 3/19/2013
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Acrylic Testing Chamber
TITLE: Milled Base
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL
SIZE A
DWG. NO. T001
REV 2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
3
2
1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Large Aluminum Box
DIMENSIONS ARE IN INCHES TOLERANCES: ±.005 FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LC	3/19/13	TITLE: Large box with drilled holes SANTA CLARA UNIVERSITY TEAM QUIKCHILL
	CHECKED	RR	3/19/13	
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL Aluminum 6061	COMMENTS:			SIZE A | DWG. NO. TL001 | REV 2
FINISH DO NOT SCALE DRAWING				SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL
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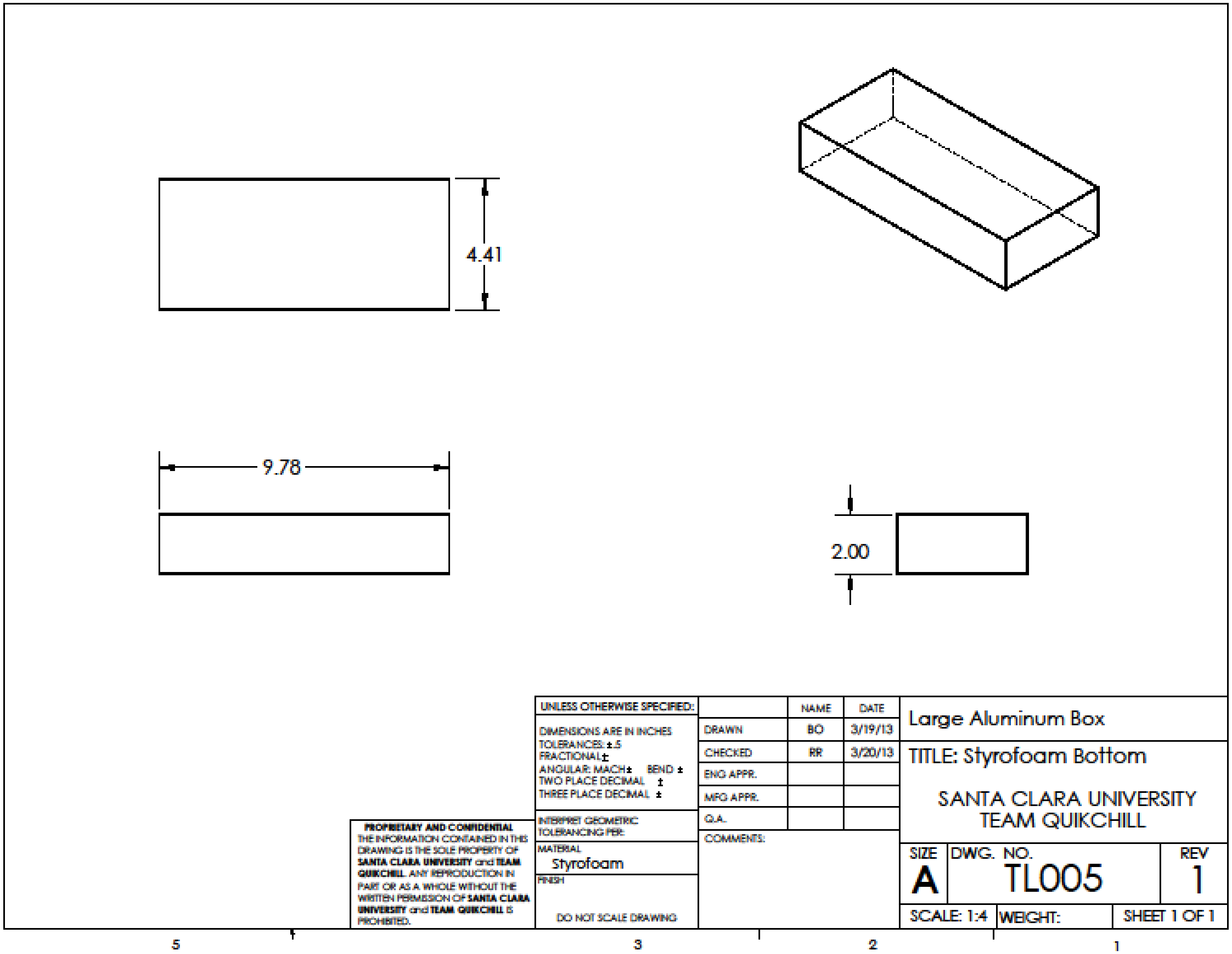
4.41
9.78
2.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±.5
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Styrofoam
FINISH
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
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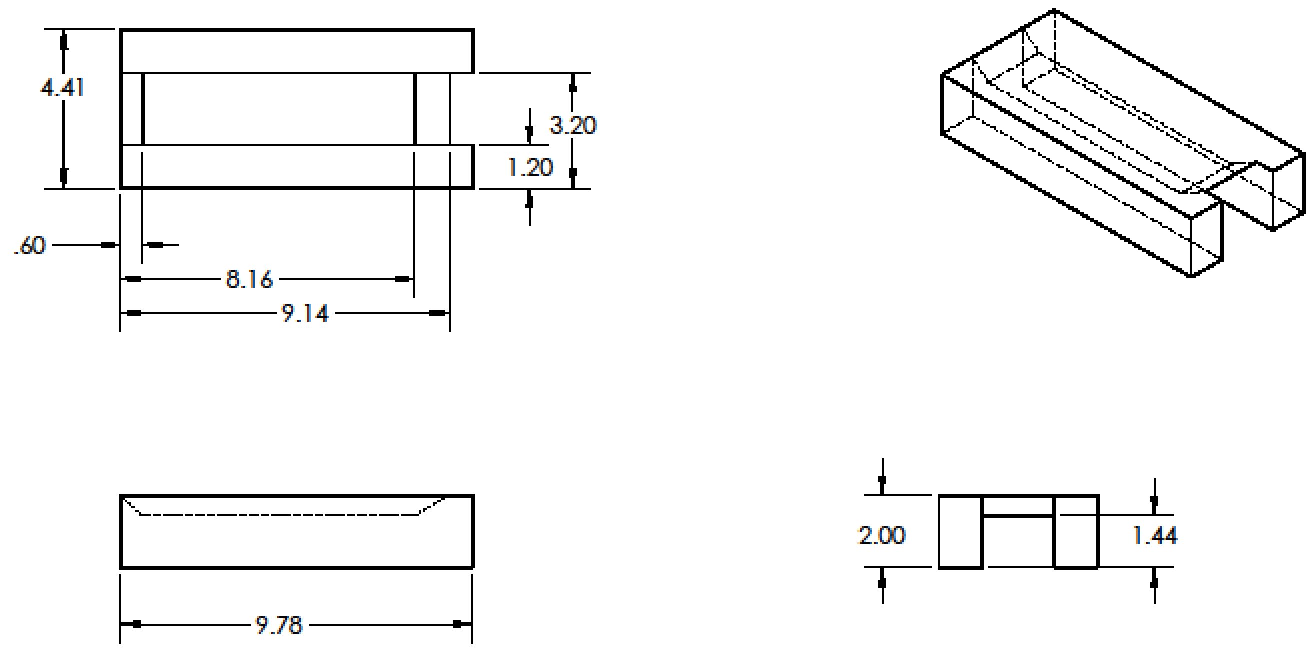
NAME
DATE
DRAWN
BO
3/19/13
CHECKED
RR
3/20/13
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Large Aluminum Box
TITLE: Styrofoam Bottom
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL
SIZE
A
DWG. NO.
TL005
REV
1
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
5
3
2
1



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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±.5
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Styrofoam
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	BO	3/19/13
CHECKED	RR	3/20/13
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

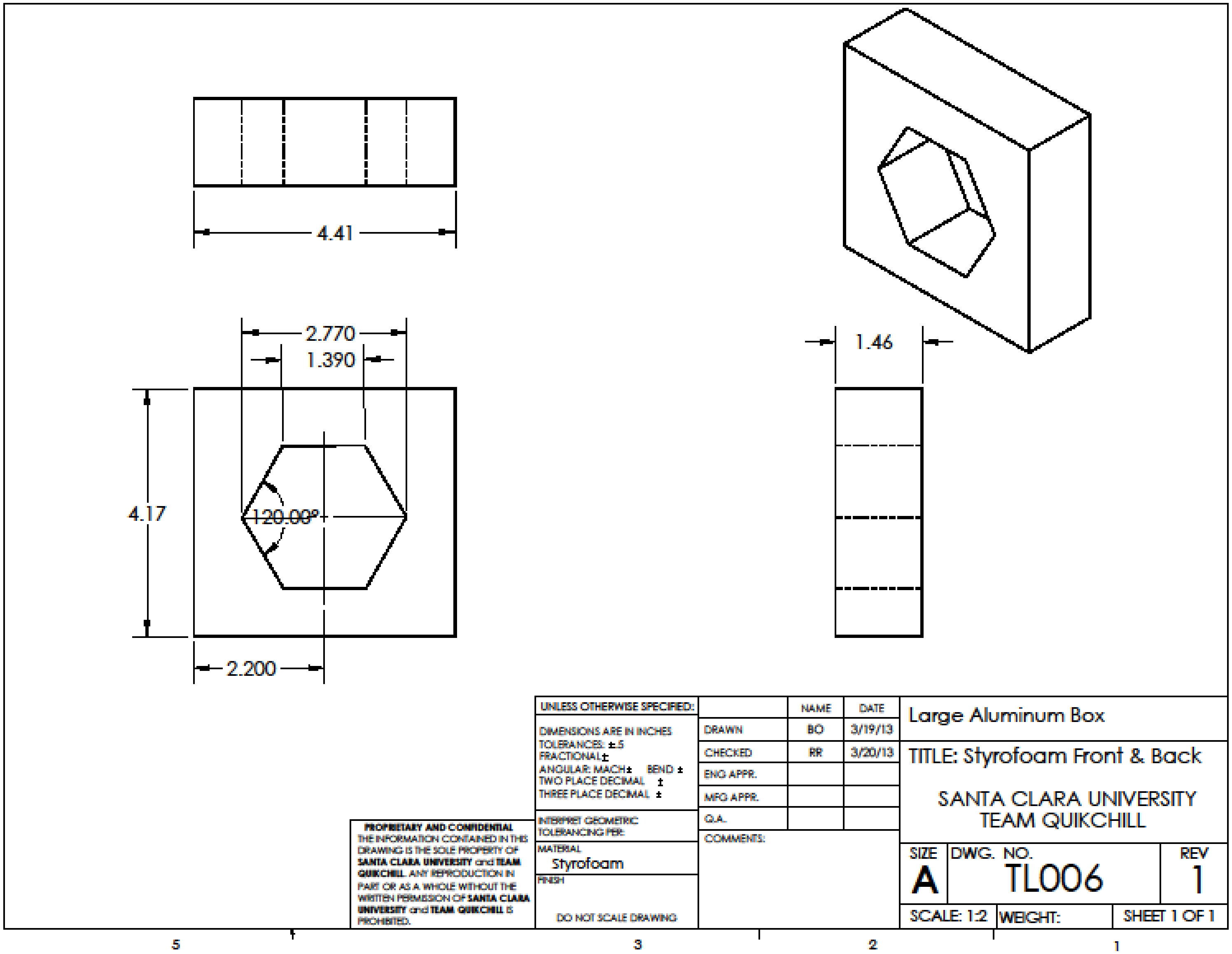
Large Aluminum Box

TITLE: Styrofoam Left, Right & Top
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE	DWG. NO.	REV
A	TL004	1

SCALE: 1:4 WEIGHT: SHEET 1 OF 1

5 3 2 1


4.41
2.770
1.390
4.17
120.00°
2.200
1.46
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±.5
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Styrofoam
FINISH
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
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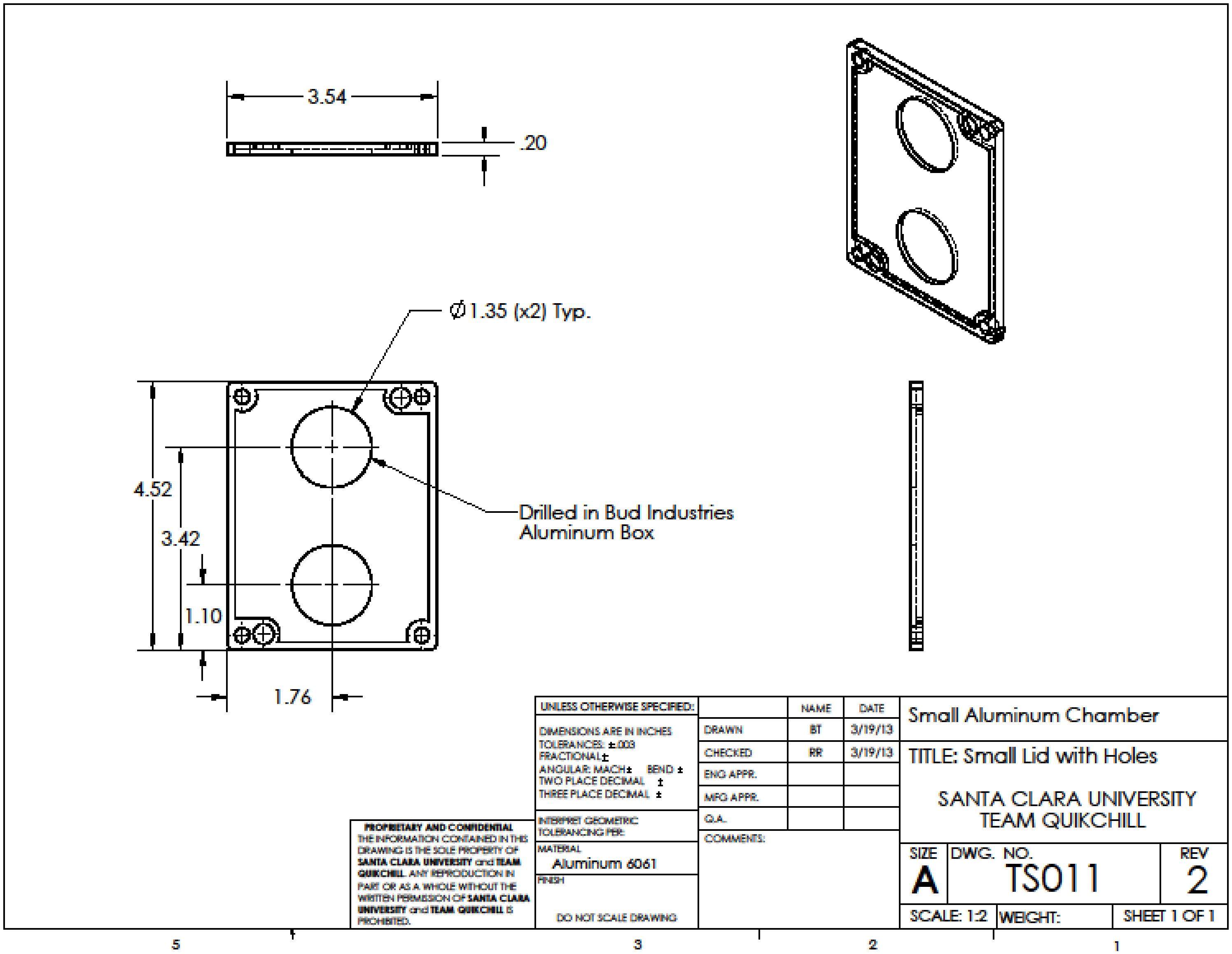
NAME
DATE
DRAWN
BO
3/19/13
CHECKED
RR
3/20/13
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Large Aluminum Box
TITLE: Styrofoam Front & Back
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL
SIZE
A
DWG. NO.
TL006
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
3
2
1



3.54
.20
Ø1.35 (x2) Typ.
4.52
3.42
1.10
1.76
Drilled in Bud Industries Aluminum Box
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±.003
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum 6061
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
BT
3/19/13
CHECKED
RR
3/19/13
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Small Aluminum Chamber
TITLE: Small Lid with Holes
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL
SIZE
A
DWG. NO.
TS011
REV
2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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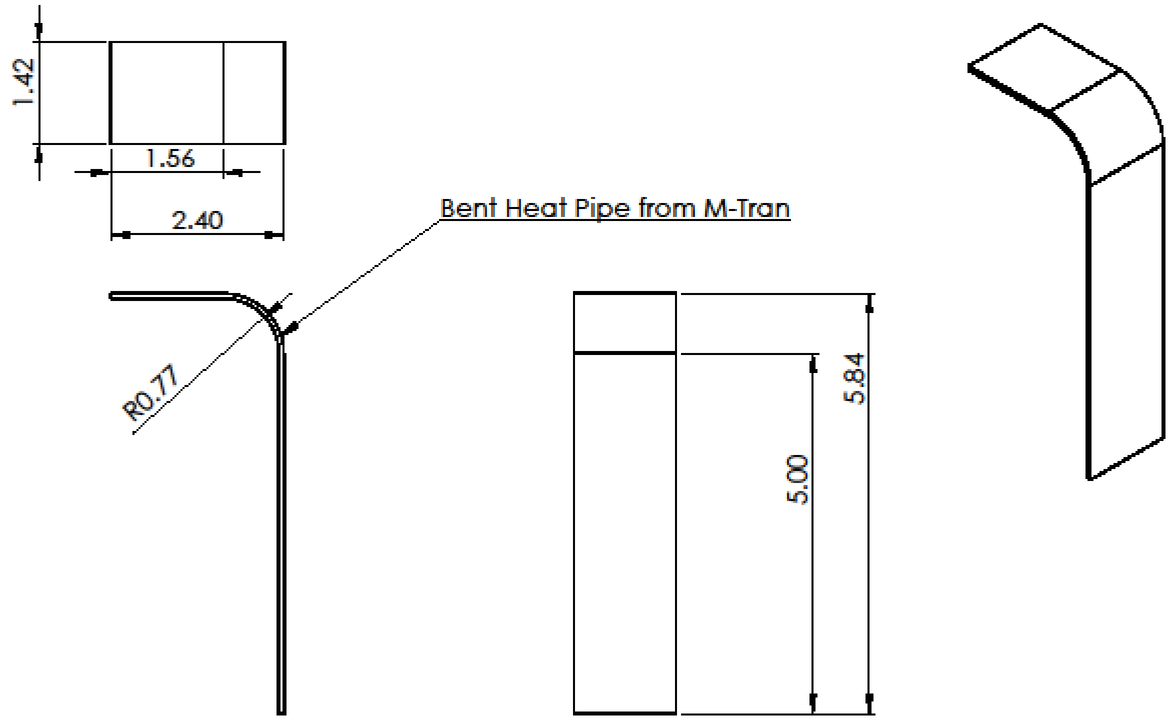
5
3
2
1



PROPRIETARY AND CONFIDENTIAL
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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Aluminum Alloy w/ Acetone

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LC	4/29/13
CHECKED	RR	3/22/13
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

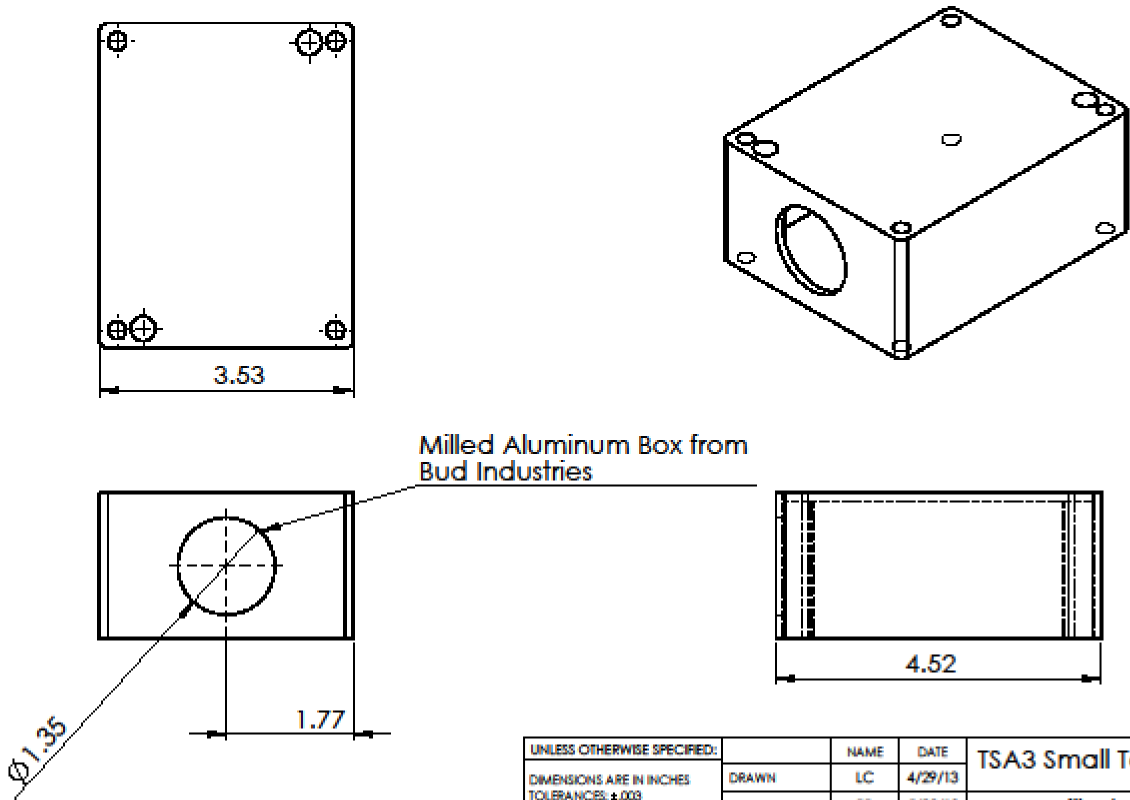
TSA3 Small Testing Assembly 3
TITLE: Bent Heat Pipe

SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE A | DWG. NO. TS019 | REV 1

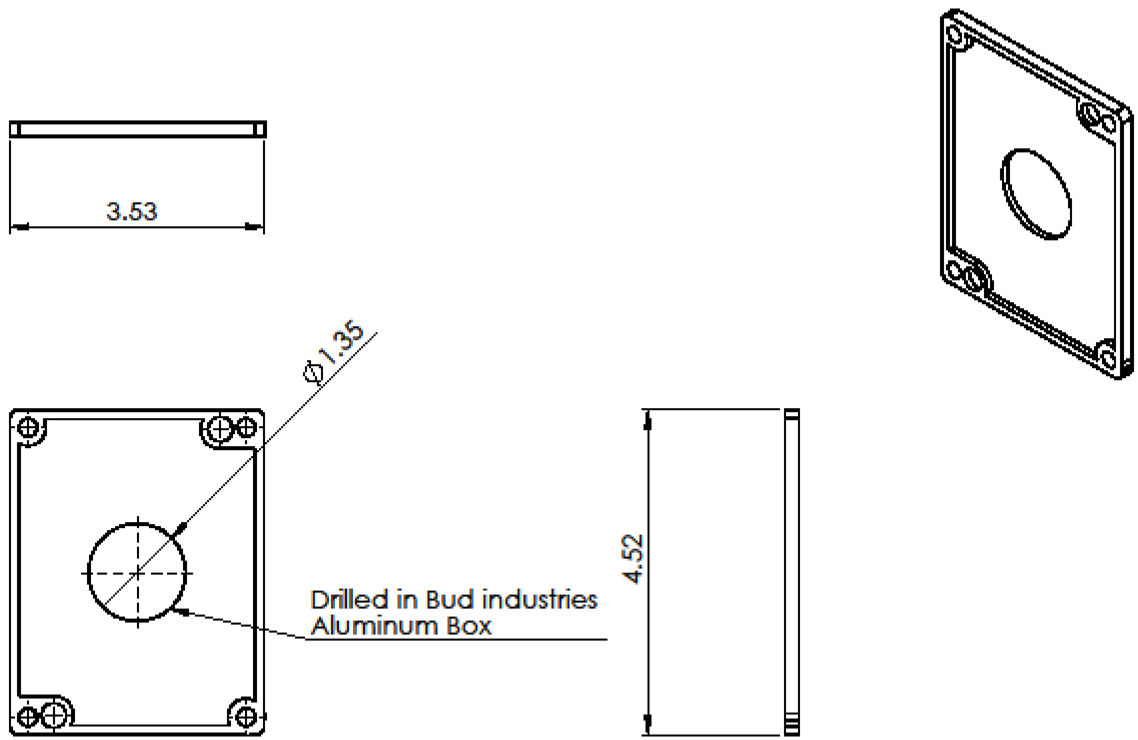
SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TSA3 Small Testing Assembly 3
DIMENSIONS ARE IN INCHES TOLERANCES: ±.003 FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LC	4/29/13	TITLE: Milled Aluminum Box with One Hole SANTA CLARA UNIVERSITY TEAM QUIKCHILL
	CHECKED	RR	5/22/13	
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL Aluminum 6061	COMMENTS:			SIZE A | DWG. NO. TS018 | REV 1
FINISH DO NOT SCALE DRAWING				SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

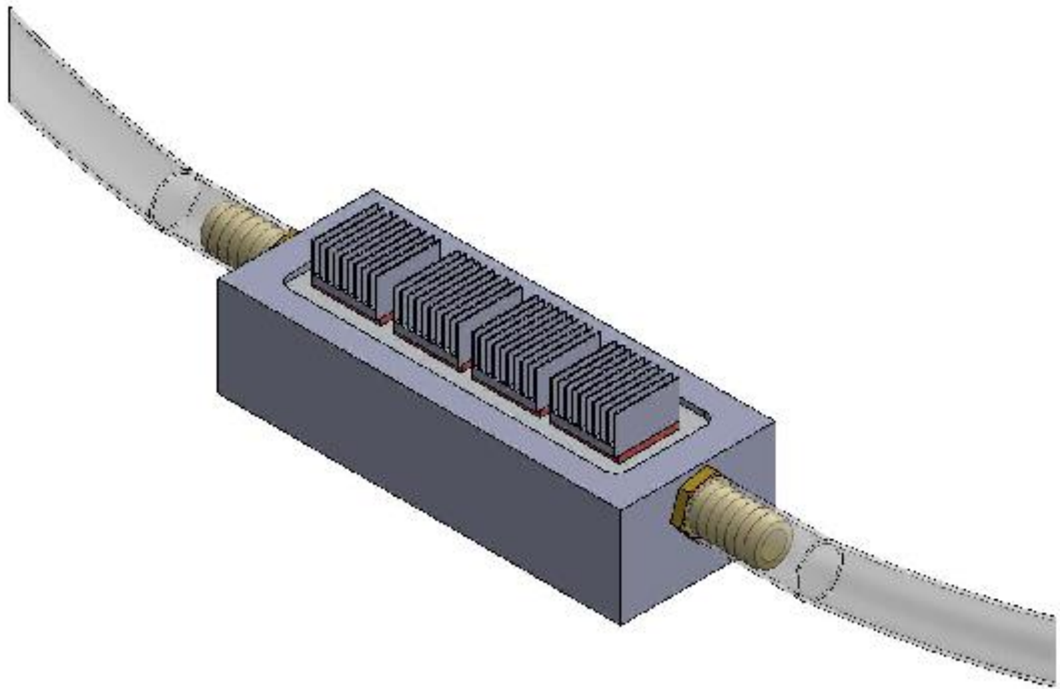
5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TSA3 Small Testing Assembly 3
DIMENSIONS ARE IN INCHES TOLERANCES: ±.003 FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LC	4/29/13	TITLE: Milled Lid with One Hole
	CHECKED	RR	5/22/13	
	ENG APPR.			SANTA CLARA UNIVERSITY TEAM QUIKCHILL
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL Aluminum 6061	COMMENTS:			SIZE A DWG. NO. TS017 REV 1
FINISH DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT: SHEET 1 OF 1

5 4 3 2 1

Appendix P: Assembly Drawing



PROPRIETARY AND CONFIDENTIAL
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UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LC	4/29/13
	CHECKED	RR	5/22/13
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

Acrylic Testing Assembly

TITLE: Acrylic Chamber Assembly

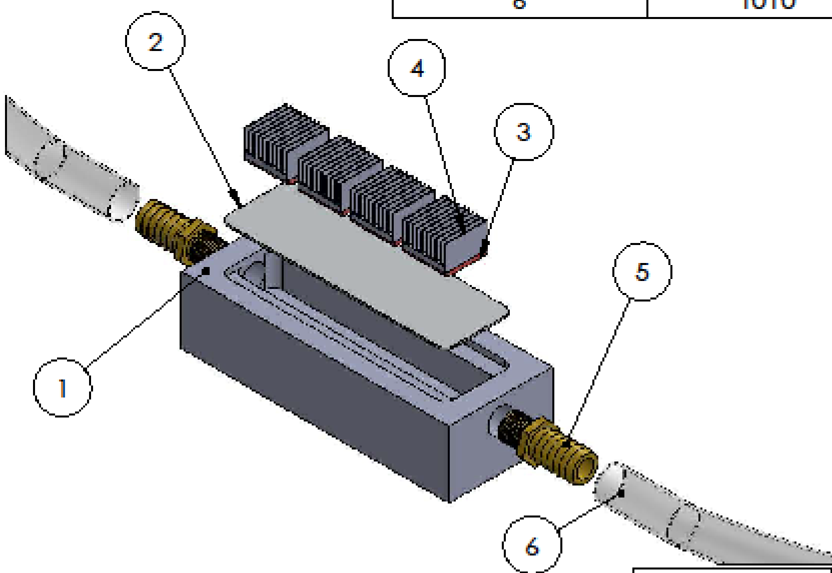
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE	DWG. NO.	REV
A	TA1	1

SCALE: 1:2 WEIGHT: SHEET 1 OF 2

5 3 2 1

Item No.	Part Number	Description	QTY.
1	T001	Acrylic Milled Block	1
2	T002	Aluminum Plate	1
3	T011	TEM	4
4	T003	Heat Sink #4	4
5	T007	Hose Bab Adaptor	2
6	T010	Polycarbonate Tube	2



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LC	4/29/13
CHECKED	RR	5/22/13
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

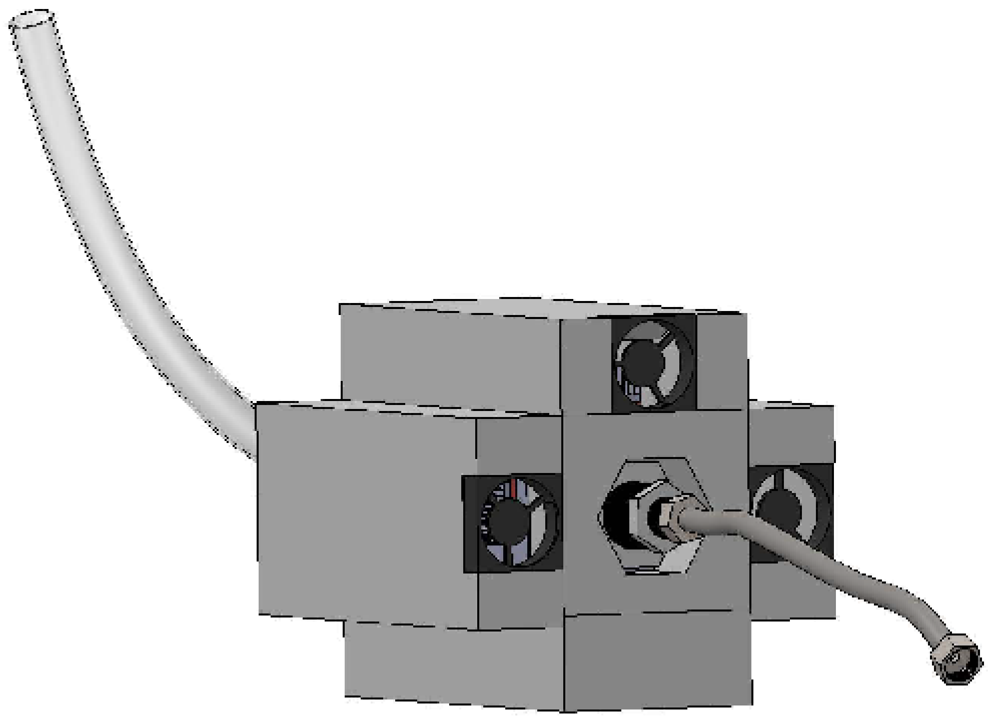
Acrylic Testing Chamber

TITLE: Acrylic testing Chamber Exploded View
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE A | DWG. NO. TA1 | REV 1

SCALE: 1:2 | WEIGHT: | SHEET 2 OF 2

5 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Large Testing Assembly
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LC	4/29/13	TITLE: Large Testing Assembly
	CHECKED	RR	5/22/13	
	ENG APPR.			SANTA CLARA UNIVERSITY TEAM QUIKCHILL
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE A — DWG. NO. TLA1 — REV 1
FINISH	TLA1			
DO NOT SCALE DRAWING				SCALE: 1:3 — WEIGHT: — SHEET 1 OF 3

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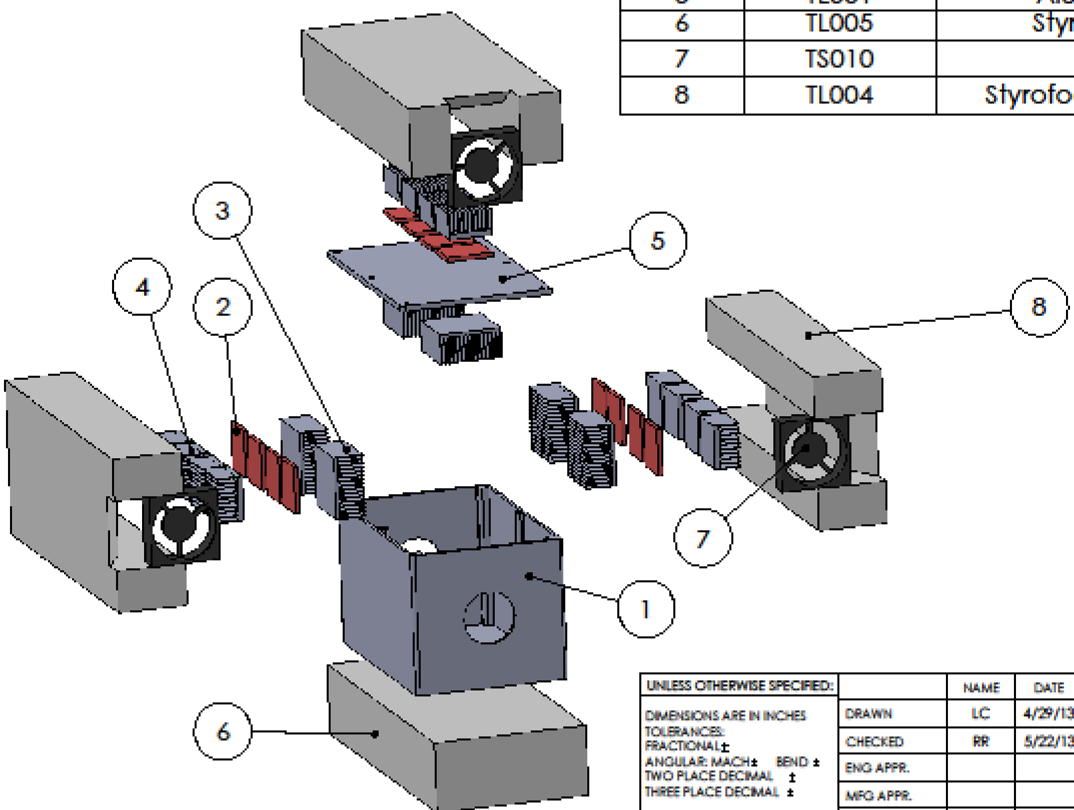
5 3 2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	TL001	Lage 2L Aluminum Box	1
2	T011	TEM	12
3	TS014	Internal Heat Sink	6
4	TS013	External Heat Sink X	12
5	TL001	Aluminum Box Lid	1
6	TL005	Styrofoam Bottom	1
7	TS010	Fans	3
8	TL004	Styrofoam Left, Right, Top	3



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Large Testing Assembly
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LC	4/29/13	TITLE: Large Testing Assembly Front Exploded View SANTA CLARA UNIVERSITY TEAM QUIKCHILL
	CHECKED	RR	5/22/13	
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE A
FINISH	TLA1			DWG. NO. TLA1
DO NOT SCALE DRAWING				REV 1
				SCALE: 1:4 / WEIGHT: / SHEET 2 OF 3

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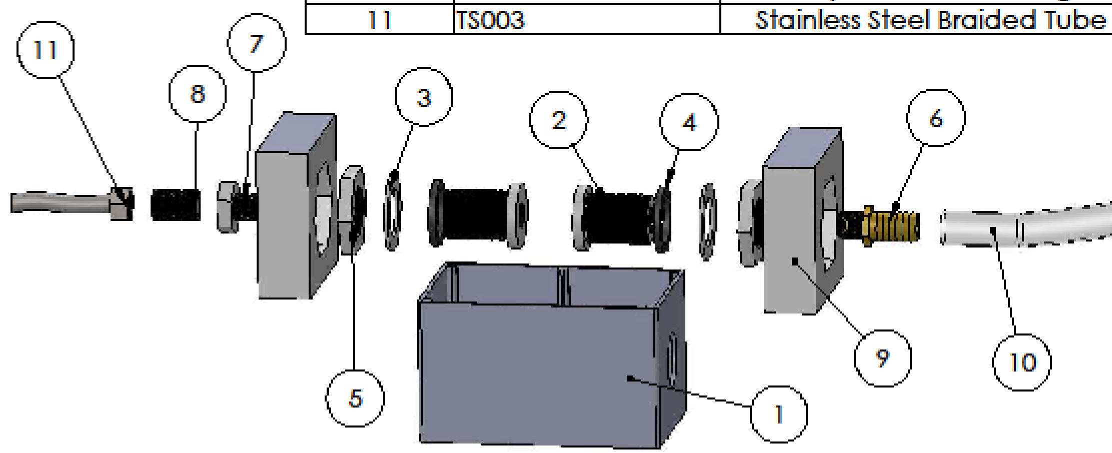
5 4 3 2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	TL001	Lage 2L Aluminum Box	1
2	TS002	Base of Bulk Head	2
3	TS002	Washer for Bulk Head	2
4	TS002	Rubber Part of Bulk Head	2
5	TS002	Cap for Bulk Head	2
6	T007	Hosebarb Adapter	1
7	TS012	Male to Female Adapter	1
8	TS004	Nipple	1
9	TL006	Front & Back Styrofoam	2
10	T010	Polycarbonate Tubing	1
11	TS003	Stainless Steel Braided Tube	1



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TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LC	4/29/13
CHECKED	RR	5/22/13
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
TLA1

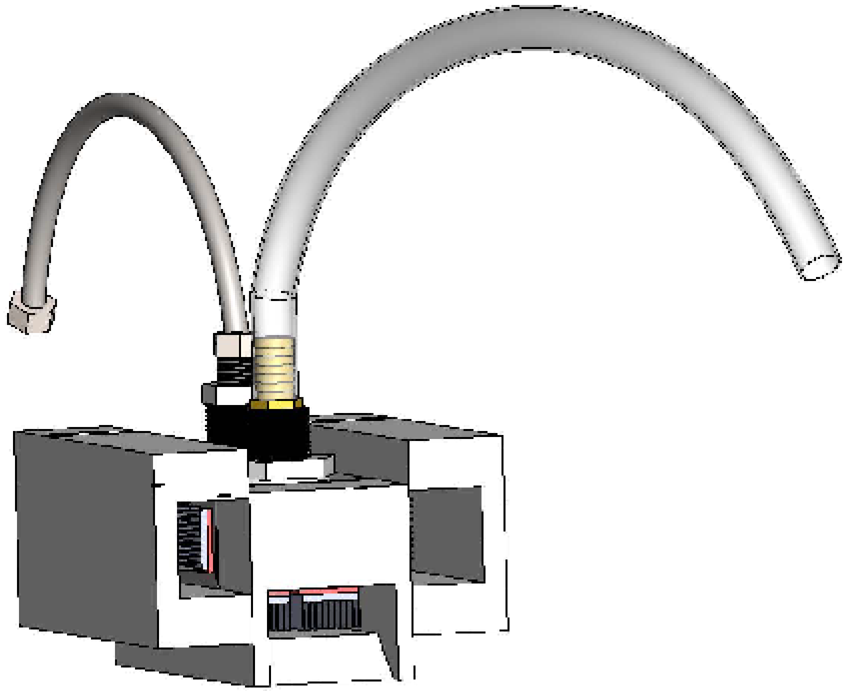
Large Testing Assembly

TITLE: Large Testing Assembly
Side Exploded View
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE A | DWG. NO. TLA1 | REV 1

SCALE: 1:4 | WEIGHT: | SHEET 3 OF 3

5 4 3 2 1



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FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LC	4/29/13
CHECKED	RR	5/22/13
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
TSA1

Small Testing Chamber 1

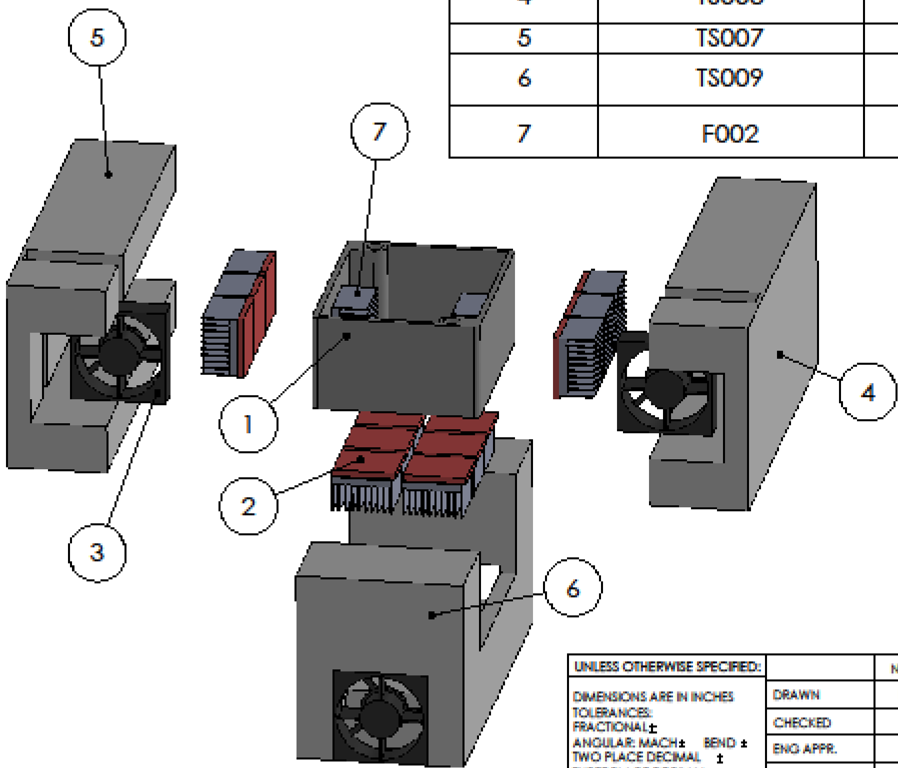
TITLE: Small Testing Chamber 1
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE A
DWG. NO. TSA1
REV 1

SCALE: 1:3 WEIGHT: SHEET 1 OF 3

5 3 2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	TS001	800mL Aluminum Box	1
2	T011 & TS005	TEM & Small heat sink attached to the Box	12
3	TS010	Fan	3
4	TS008	Styrofoam Left	1
5	TS007	Styrofoam Right	1
6	TS009	Styrofoam Bottom	1
7	F002	Internal Heat Sink	3



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LC	4/29/13
	CHECKED	RR	5/22/13
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

Small Testing Assembly

TITLE: Small Testing Assembly Body Exploded View
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE	DWG. NO.	REV
A	TSA1	1

SCALE: 1:3 | WEIGHT: | SHEET 2 OF 3

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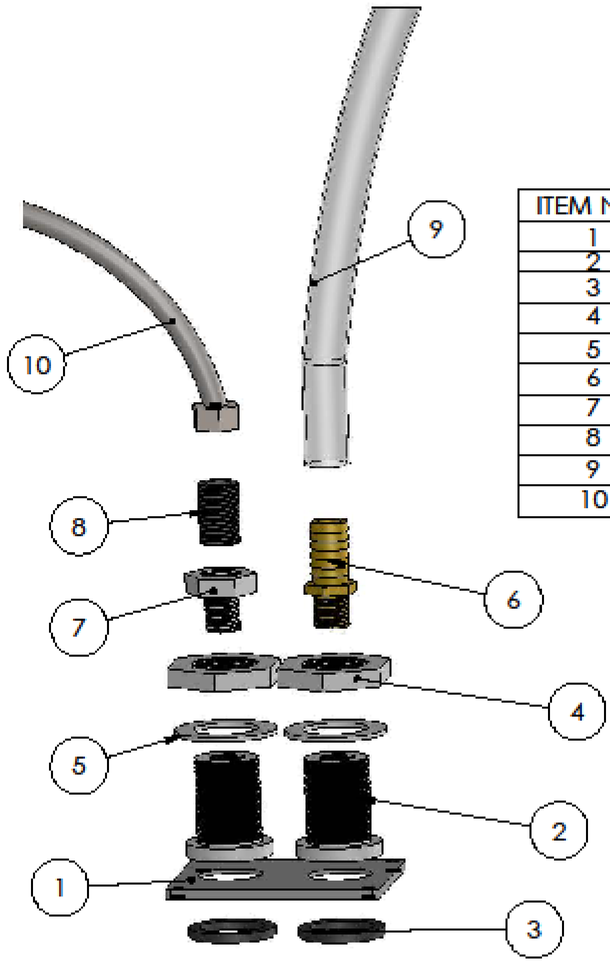
5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	TS011	Aluminum Box Lid with Holes	1
2	TS002	Base of Bulk Head	2
3	TS002	Rubber Part of Bulk Head	2
4	TS002	Cap for Bulk Head	2
5	TS002	Washer for Bulk Head	2
6	T007	Hosebarb Adapter	1
7	TS012	Male to Female Adapter	1
8	TS004	Nipple	1
9	T010	Polycarbonate Tubing	1
10	TS003	Braided SS Pipe	1

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LC	4/29/13
	CHECKED	RR	5/22/13
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

Small Testing Chamber 1

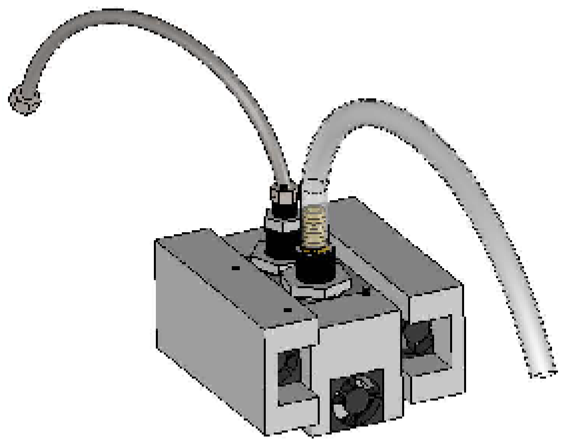
TITLE: Small Testing Chamber 1 Lid Exploded View

SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE	DWG. NO.	REV
A	TSA1	1

SCALE: 1:3 | WEIGHT: | SHEET 3 OF 3

5 4 3 2 1



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FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LC	4/29/13
CHECKED	RR	5/22/13
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Small Testing Chamber 2

TITLE: Small Testing Chamber 2

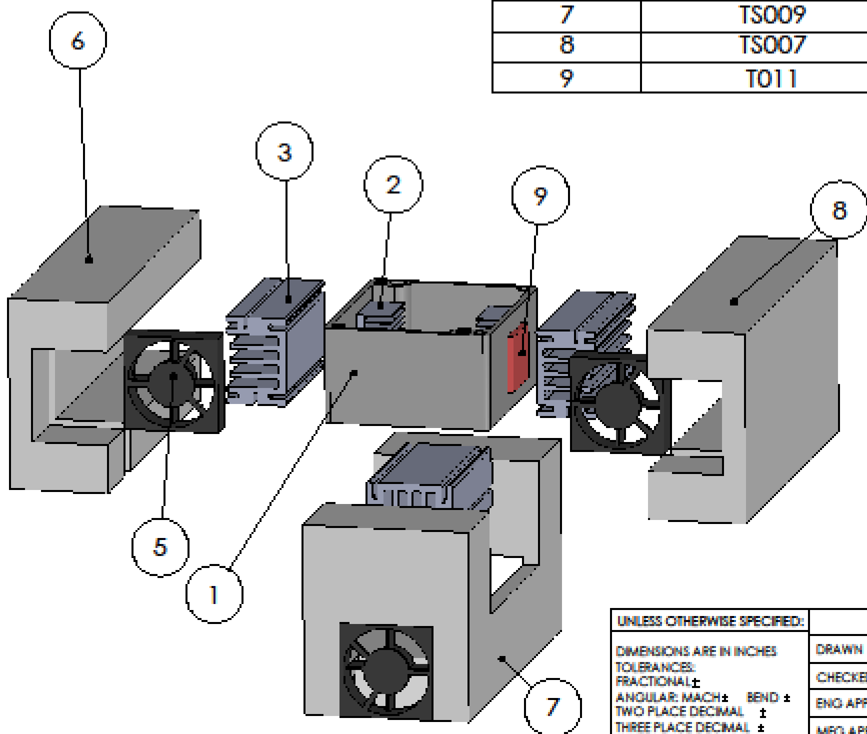
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE	DWG. NO.	REV
A	TSA2	1

SCALE: 1:5 WEIGHT: SHEET 1 OF 3

5 4 3 2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	TS001	800mL Aluminum Box	1
2	TS013	Internal Heat Sink Z	3
3	TS014	Heat Sink Z	3
5	TS010	Fan	3
6	TS008	Styrofoam Left	1
7	TS009	Styrofoam Bottom	1
8	TS007	Styrofoam Right	1
9	T011	TEM	3



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LC	4/29/13
	CHECKED	RR	5/22/13
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

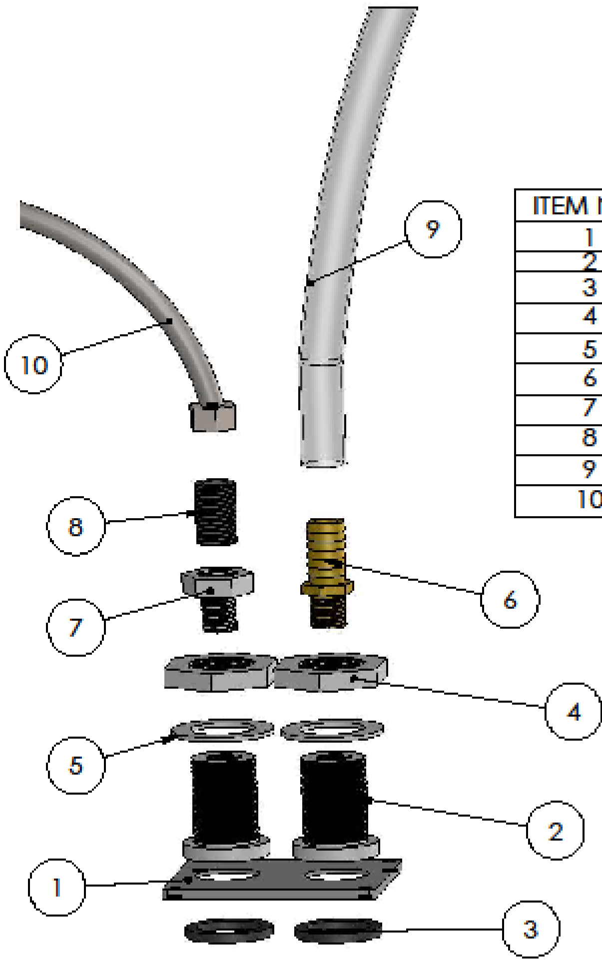
Small Testing Assembly 2

TITLE: Small Testing Assembly 2
Front Exploded View
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE A | DWG. NO. TSA2 | REV 1

SCALE: 1:3 | WEIGHT: | SHEET 2 OF 3

5 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	TS011	Aluminum Box Lid with Holes	1
2	TS002	Base of Bulk Head	2
3	TS002	Rubber Part of Bulk Head	2
4	TS002	Cap for Bulk Head	2
5	TS002	Washer for Bulk Head	2
6	T007	Hosebarb Adapter	1
7	TS012	Male to Female Adapter	1
8	TS004	Nipple	1
9	T010	Polycarbonate Tubing	1
10	TS003	Braided SS Pipe	1

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FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LC	4/29/13
CHECKED	RR	5/22/13
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
TSA1&TSA2

Small Testing Assembly 2

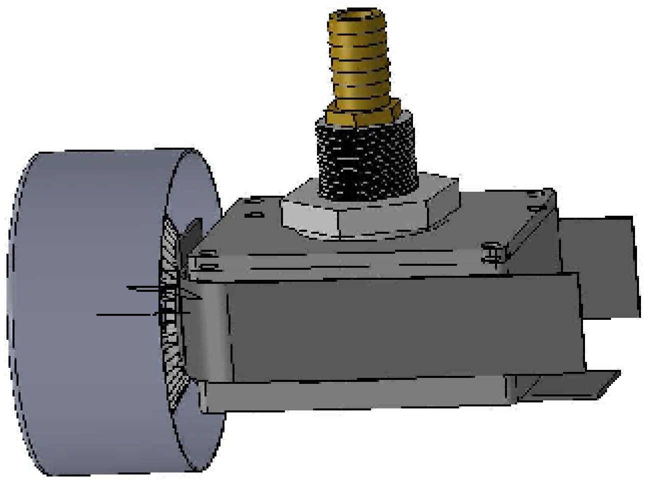
TITLE: Small Testing Assembly Lid Exploded View

SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE A | DWG. NO. TSA2 | REV 1

SCALE: 1:3 | WEIGHT: | SHEET 3 OF 3

5 3 2 1



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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LC	4/29/13
CHECKED	RR	5/22/13
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Small Testing Chamber 3

TITLE: Small Testing Chamber 3

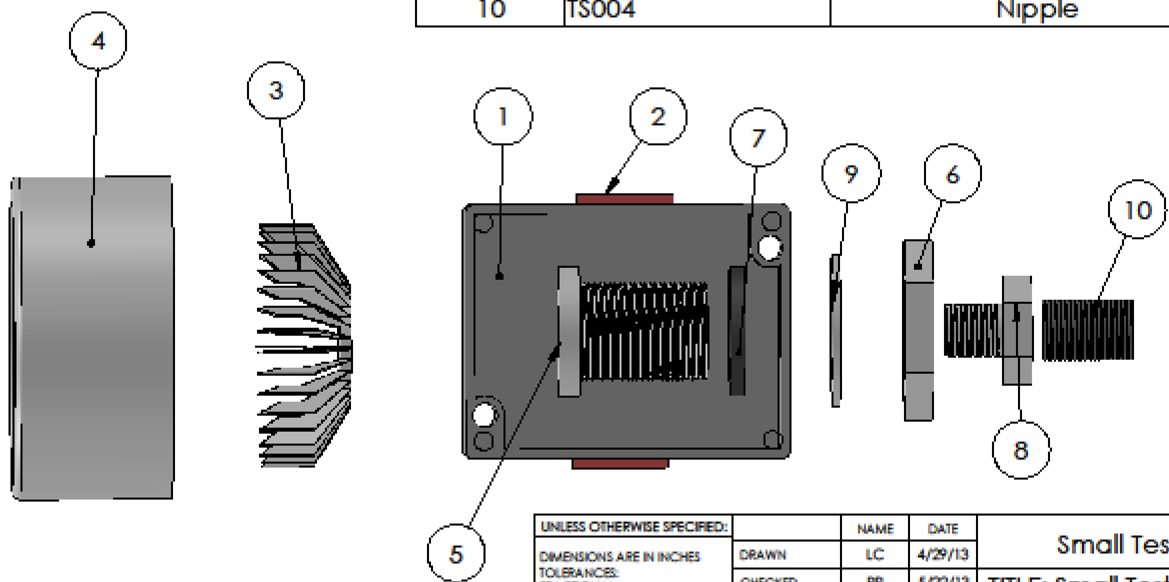
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE	DWG. NO.	REV
A	TSA3	1

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 3

5 3 2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	TS018	800mL Aluminum Box with one hole	1
2	T011	TEM	3
3	TS015	Spiral External Heat Sink	1
4	TS016	Cicular Fan	1
5	TS002	Base of Bulk Head	1
6	TS002	Cap for Bulk Head	1
7	TS002	Rubber Part of Bulk Head	1
8	TS012	Male to Female Adapter	1
9	TS002	Washer for Bulk Head	1
10	TS004	Nipple	1



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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LC	4/29/13
CHECKED	RR	5/22/13
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
TSA3
Spray Foam Insulation Used

Small Testing Chamber 3

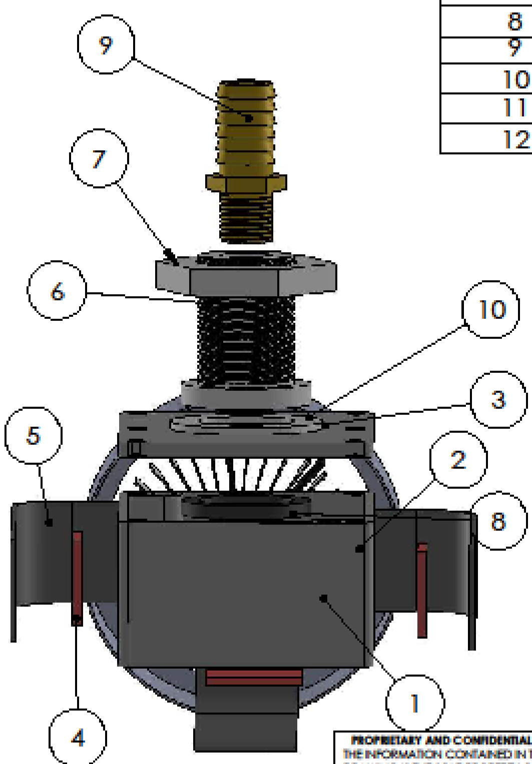
TITLE: Small Testing Chamber 3
Top Exploded View
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE A | DWG. NO. TSA3 | REV 1

SCALE: 1:2 | WEIGHT: | SHEET 2 OF 3

5 4 3 2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	TS018	800mL Aluminum Box with hole	1
2	TS005	Internal Heat Sink	3
3	TS017	Aluminum Box Lid with One Hole	1
4	T011	TEM	3
5	TS019	Bent Heat Pipe	3
6	TS002	Base of Bulk Head	1
7	TS002	Cap for Bulk Head	1
8	TS002	Rubber Part of Bulk Head	2
9	T007	Hosebarb Adapter	1
10	TS002	Washer for Bulk Head	1
11	TS014	Spiral External Heat Sink	1
12	TS015	Cicular Fan	1



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ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LC	4/29/13
CHECKED	RR	5/22/13
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
TSA3
Spray Foam Insulation Used

Small Testing Assembly 3

TITLE: Small Testing Assembly 3
Side Exploded View
SANTA CLARA UNIVERSITY
TEAM QUIKCHILL

SIZE A | DWG. NO. TSA3 | REV 1

SCALE: 1:2 | WEIGHT: | SHEET 3 OF 3

5 4 3 2 1

Appendix Q: Hand Calculations

FORCED EXTERNAL CONVECTION (AIR)

Calculating for h

* Assume air flow over parallel flat plates (fan)

@ $V_{air} = 1.92\ m/s \approx 2$

$L_c = 0.1758\ m$ (Length of channel)

$$Re_L = \frac{\rho V L_c}{\mu}$$

$$= \frac{1.184(2)(0.18)}{180.15 \times 10^{-7}}$$

$= 22585.08 \Rightarrow$ Here is turbulent flow

$$Nu_L = 0.664\ Re_L^{1/2}\ Pr^{1/3}$$

$$= 0.664\ (22585)^{1/2}(0.71)^{1/3}$$

$= 89.02$

General eq.

$$Nu_L = \frac{h L_c}{k_f}$$

$$h = \frac{Nu_L k_f}{L_c}$$

$$= \frac{89.02(0.0259)}{0.1758}$$

$= 13.27\ W/m^2K$

Air PROPERTIES: (all taken @ 298.15 K)

$\rho_{air} = 1.184\ kg/m^3$

$\mu = 180.15 \times 10^{-7}\ N \cdot s/m^2$

$Pr = 0.708$

$k = 0.0259\ W/mK$

37

FORCED INTERNAL CONVECTION (AIR)

Calculating for h

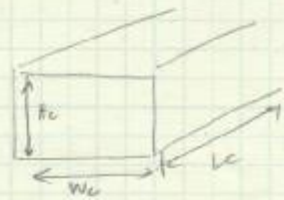
* Assume air flow thru a channel (for fan used in cooling)

@ $V_{air} = 1.92\ m/s$

$L_c = 0.1937\ m$ $W_c = 0.0606\ m$ $H_c = 0.0588\ m$

D_h, hydraulic diameter

$$D_h = \frac{4A_c}{P}$$



$$A_c = W_c(H_c)$$
$$= 0.00135\ m^2$$

$$P = 2W_c + 2H_c$$
$$= 0.1987\ m$$

$$D_h = 0.01182\ m$$

$$Re_D = \frac{\rho V D_h}{\mu}$$
$$= \frac{1.124(1.92)(0.01182)}{182.18 \times 10^{-7}}$$
$$= 1494.97 \quad \therefore \text{laminar}$$

$$f = 64/Re_D$$
$$= 0.04279$$

if turbulent

$$f = (0.79 \ln(Re_D) - 1.64)^{-2}$$
$$= 0.04144$$

not too different

$$Nu_D = \frac{f/8\,(Re_D - 1000)\,Pr}{1 + 12.7\,(f/8)^{1/2}\,(Pr^{2/3} - 1)}$$
$$= 3.595$$

$$h = \frac{Nu_D\, k_f}{D_h}$$
$$= \frac{3.595\,(0.02597)}{0.01182}$$
$$= 7.926\ W/m^2K$$

38

FREE CONVECTION IN Al BOX (WATER)

* flow across fins

$$Ra_L = \frac{g\beta (T_s - T_\infty) L^3}{\nu \alpha}$$

$$\alpha = \frac{k}{\rho c_p} = \frac{0.617}{998 (4172)}$$

$$= 1.432 \times 10^{-7} \ m^2/s$$

$$\nu = \mu/\rho$$

$$= 795.92 \times 10^{-6} / 998$$

$$= 7.955 \times 10^{-7} \ m^2/s$$

$$= \frac{9.81 (304.64 \times 10^{-6}) (12) (0.1722)^3}{7.955 \times 10^{-7} (1.432 \times 10^{-7})}$$

$$= 1.635 \times 10^{11}$$

$$Nu_L = \left\{ 0.825 + \frac{0.387 \, Ra_L^{1/6}}{\left[1 + (0.492/Pr)^{9/16} \right]^{8/27}} \right\}^2$$

$$= 110.39$$

$$Nu_L = \frac{hL}{k_f}$$

$$h = \frac{Nu_L \, k_f}{L}$$

$$= \frac{110.39 (0.617)}{0.1722}$$

$$= 395.53 \ W/m^2K$$

Water properties

$\rho = 998 \ kg/m^3$

$\mu = 795.92 \times 10^{-6} \ N \cdot s/m^2$

$k = 0.617 \ W/mK$

$Pr = 5.36$

$\beta = 304.64 \times 10^{-6} \ 1/K$

$c_p = 4172 \ J/kg\,K$

$\Delta T = 12$

$T_s - T_\infty$

$l = 0.1722 \ m$

(length of Al box)

59

FIN CALCULATIONS

$$\varepsilon = \frac{q_f}{h A_{c,b} \theta_b} < 2$$

where

$\theta_b = T_b - T_\infty = 10$

h = natural convection in box

$A_{c,b}$ = area of the base

$$q_f > 2(h A_{c,b})(10)$$
$$> 2(395.53)(0.00258)(10)$$
$$> 20.414 \text{ W}$$

$A_{cs} = L \times W$ of heat sink

$= 8(2)(0.0254)^2$

$= 0.00258 \text{ m}^2$

$A_c = W \cdot t$ (t = thickness)

$= 1.26(0.023)(0.0254^2)$

$= 2.396 \times 10^{-5} \text{ m}^2$

$P = 2(w + t)$

$= 2(1.26 + 0.058)(0.0254)$

$= 1.0634 \text{ m}$

q_f

assume: adiabatic tip

$q_f = M \tanh(mL)$

$$m = \sqrt{\frac{hP}{kA_c}} = \sqrt{\frac{395(0.0634)}{(0.617)(2.396\times10^{-5})}} = 4146$$

$$M = \sqrt{hPkA_c}\,\theta_b = \sqrt{(395)(0.0634)(0.617)(2.396\times10^{-5})}(10) = 0.1985$$

If $q_f = \theta_c$ $\qquad N = 16$ fins

$= 0.858 \text{ W}$

$$L = \frac{1}{m}\,\text{atanh}\left(\frac{q_f}{M}\right) = \frac{1}{4146}\,\text{atanh}\left(\frac{0.858}{0.1985}\right)$$

$\approx 3 \text{ m}$?

10

Values used

$$FF = \frac{2N A_{TEM}}{A_{mod}} = \frac{2(127)(8.7\times10^{-7})}{9\times10^{-4}} = 0.246$$

$$S = 2N(\alpha_p - \alpha_n) = 2N(\alpha_{p-n})$$

$$S = 2(127)(1.83\times10^{-4})$$

$$S = 0.0465$$

$$R = \frac{(2N)^2(\rho L + 2\rho_c)}{FF A_{mod}} = \frac{[2(127)]^2(6.8\times10^{-6})(.001)}{0.246(9\times10^{-4})} + \frac{[2(127)]^2\, 2(3.9053\times10^{-10})}{0.246(9\times10^{-4})}$$

$$R = 3.375$$

$$K = \frac{FF A_{mod} k}{L} = \frac{0.246(9\times10^{-4})(1.82)}{0.0016} = 0.2514$$

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Steady State

$$FF = \frac{2 N A_{TEM}}{A_{mod}}$$

$$S = 2N(\alpha_p - \alpha_n) \qquad N = \text{\# of pairs per module}$$

$$R = 2N \frac{\rho L}{A_{TEM}} + R_{contact} = (2N)^2 \frac{\rho L}{FF A_{mod}} + \frac{(2N)^2\, 2\, R''_c}{FF A_{mod}}$$

$$K = 2N \frac{k A_{TEM}}{L} = \frac{FF A_{mod}\, k}{L}$$

$$Q_c = S I T_c - \frac{1}{2} I^2 R - K(T_H - T_c)$$

$$\frac{T_R - T_c}{\Psi_c} = Q_c$$

$$\frac{T_R - T_c}{\Psi_c} = S I T_c - \frac{1}{2} I^2 R - K(T_H - T_c)$$

$$T_R - T_c = \Psi_c S I T_c - \frac{1}{2} \Psi_c I^2 R - \Psi_c K(T_H - T_c)$$

$$T_R = T_c + \Psi_c S I T_c - \frac{1}{2} \Psi_c I^2 R - \Psi_c K(T_H - T_c)$$

$$T_R = [-\Psi_c K] T_H + [\Psi_c S I + \Psi_c K + 1] T_c - \frac{1}{2} \Psi_c I^2 R$$

$$T_R + \frac{1}{2} \Psi_c I^2 R = [-\Psi_c K] T_H + [\Psi_c S I + \Psi_c K + 1] T_c$$

$$\frac{1}{2} \Psi_c I^2 R = [-\Psi_c K] T_H + [\Psi_c S I + \Psi_c K + 1] T_c + [-1] T_R \qquad \text{Eqn 1}$$

$$Q_H = S I T_H - K(T_H - T_c) + \frac{1}{2} I^2 R$$

$$\frac{T_H - T_\infty}{\Psi_H} = Q_H$$

$$\frac{T_H - T_\infty}{\Psi_H} = S I T_H - K(T_H - T_c) + \frac{1}{2} I^2 R$$

$$T_H - T_\infty = \Psi_H S I T_H - \Psi_H K(T_H - T_c) + \frac{1}{2} \Psi_H I^2 R$$

$$T_H - \Psi_H S I T_H + \Psi_H K(T_H - T_c) = T_\infty + \frac{1}{2} \Psi_H I^2 R$$

$$[1 + \Psi_H K - \Psi_H S I] T_H + [-\Psi_H K] T_c = T_\infty + \frac{1}{2} \Psi_H I^2 R \qquad \text{Eqn 2}$$

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$$\frac{T_\infty - T_R}{\psi_{chamber}} = \frac{T_R - T_c}{\psi_c}$$

$$\left[\frac{1}{\psi_{chamber}}\right] T_\infty = \frac{T_R}{\psi_{chamber}} + \frac{T_R}{\psi_c} - \frac{T_c}{\psi_c}$$

$$\frac{T_\infty}{\psi_{chamber}} = \left[\frac{1}{\psi_{chamber}} + \frac{1}{\psi_c}\right] T_R + \left[\frac{-1}{\psi_c}\right] T_c \qquad \text{Eqn 3}$$

$$\begin{bmatrix} -\psi_c K & \psi_c S I + \psi_c K + 1 & -1 \\ 1 + \psi_H K - \psi_H S I & -\psi_H K & 0 \\ 0 & -\frac{1}{\psi_c} & \frac{1}{\psi_{chamber}} + \frac{1}{\psi_c} \end{bmatrix} \begin{bmatrix} T_H \\ T_c \\ T_R \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\psi_c I^2 R \\ T_\infty + \frac{1}{2}\psi_H I^2 R \\ \frac{T_\infty}{\psi_{chamber}} \end{bmatrix}$$

Values

$$\begin{bmatrix} -0.6636(0.2514) & 0.6636(0.0455)(0.65)+0.6636(.2514)+1 & -1 \\ 1+6.11(0.2514)-6.11(.0465)(.65) & -6.11(.2514) & 0 \\ 0 & -\frac{1}{0.6636} & \frac{1}{5.8326}+\frac{1}{0.6636} \end{bmatrix} \begin{bmatrix} T_H \\ T_C \\ T_R \end{bmatrix} = \begin{bmatrix} \frac{1}{2}(0.6636)(466)^2 3.3\ldots \\ 293+\frac{1}{2}(6.11)(0.3665)^2(3.3\ldots) \\ \frac{293}{5.8326} \end{bmatrix}$$

$$\begin{bmatrix} -0.16683 & 1.1869 & -1 \\ 2.3514 & -1.536 & 0 \\ 0 & -1.5069 & 1.6784 \end{bmatrix} \begin{bmatrix} T_H \\ T_C \\ T_R \end{bmatrix} = \begin{bmatrix} 0.47313 \\ 297.356 \\ 50.2341 \end{bmatrix}$$

$$\begin{bmatrix} T_H \\ T_C \\ T_R \end{bmatrix} = \begin{bmatrix} 313.25 \\ 285.95 \\ 286.66 \end{bmatrix}$$

Transient Process

$$Q_c = SIT_c - \frac{1}{2}I^2R - K(T_H - T_c)$$

$$\frac{T_R - T_c}{\Psi_c} = Q_c$$

$$\frac{T_R - T_c}{\Psi_c} = SIT_c - \frac{1}{2}I^2R - K(T_H - T_c)$$

$$T_R = T_c + \Psi_c SIT_c - \frac{1}{2}\Psi_c I^2R - \Psi_c K(T_H - T_c)$$

$$[1]T_R = [-\Psi_c K]T_H + [\Psi_c SI + \Psi_c K + 1]T_c - \frac{1}{2}\Psi_c I^2R$$

$$T_R + \frac{1}{2}\Psi_c I^2R = [-\Psi_c K]T_H + [\Psi_c SI + \Psi_c K + 1]T_c$$

$$Q_H = SIT_H - K(T_H - T_c) + \frac{1}{2}I^2R$$

$$\frac{T_H - T_\infty}{\Psi_H} = Q_H$$

$$\frac{T_H - T_\infty}{\Psi_H} = SIT_H - K(T_H - T_c) + \frac{1}{2}I^2R$$

$$T_\infty + \frac{1}{2}\Psi_H I^2R = [1 + \Psi_H K - \Psi_H SI]T_H + [-\Psi_H K]T_c$$

$$\begin{bmatrix} 1 + \Psi_H K - \Psi_H SI & -\Psi_H K \\ -\Psi_c K & \Psi_c SI + \Psi_c K + 1 \end{bmatrix} \begin{bmatrix} T_H \\ T_c \end{bmatrix} = \begin{bmatrix} T_\infty + \frac{1}{2}\Psi_H I^2R \\ T_R + \frac{1}{2}\Psi_c I^2R \end{bmatrix}$$

$$mC_p \frac{dT_R}{dt} = -Q_c + Q_{w\text{-}s}$$ Transient steps

$$mC_p \frac{dT_R}{dt} = -Q_c + \frac{T_\infty - T_R}{\Psi_{chamber}}$$

$$mC_p \frac{T_{R_2} - T_{R_1}}{\Delta t} = -Q_c + \frac{T_\infty - T_{R_1}}{\Psi_{chamber}}$$

$$T_{R_2} - T_{R_1} = \frac{\Delta t}{mC_p}\left(\frac{T_\infty - T_{R_1}}{\Psi_{chamber}}\right) - \frac{\Delta t\, Q_c}{mC_p}$$

$$T_{R_2} = T_{R_1} + \frac{\Delta t}{mC_p}\left(\frac{T_\infty - T_{R_1}}{\Psi_{chamber}}\right) - \frac{\Delta t\, Q_c}{mC_p}$$

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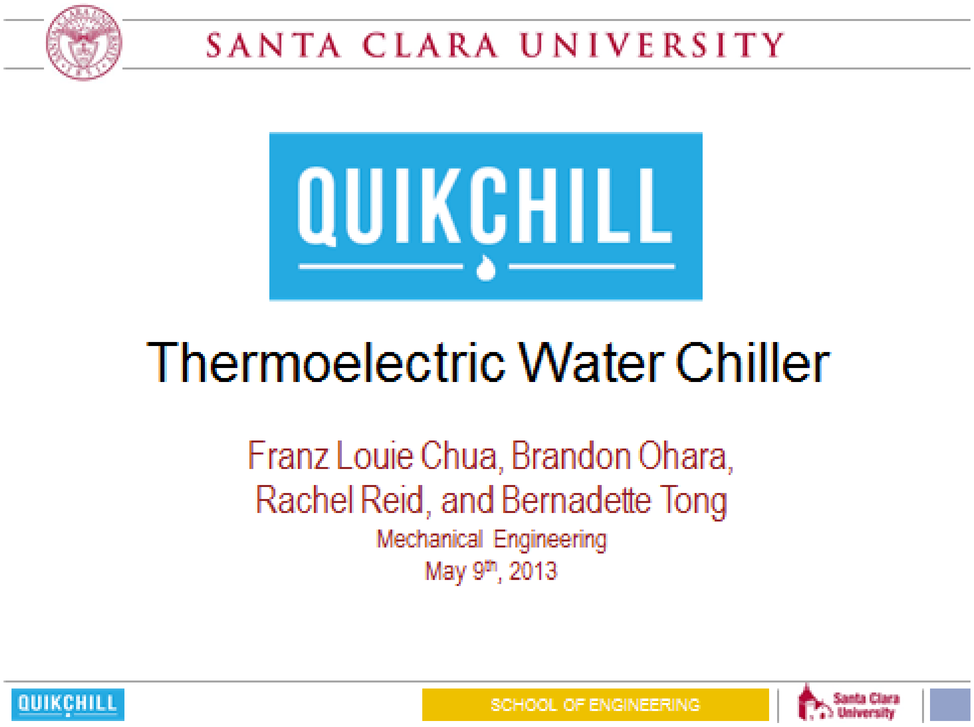
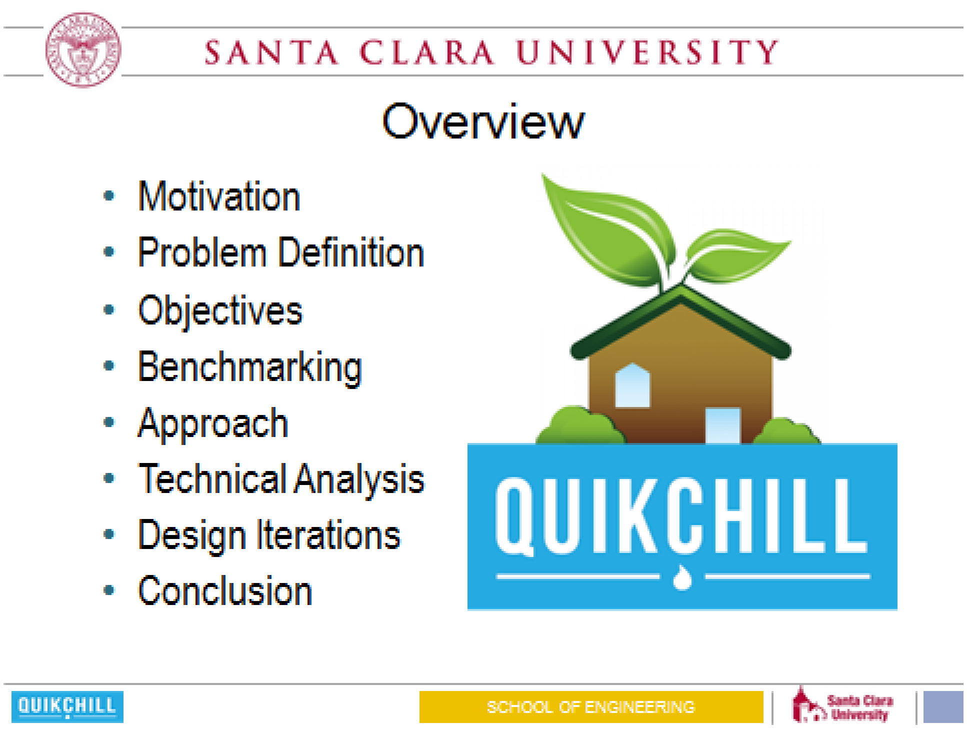
Appendix R: PowerPoint Slides

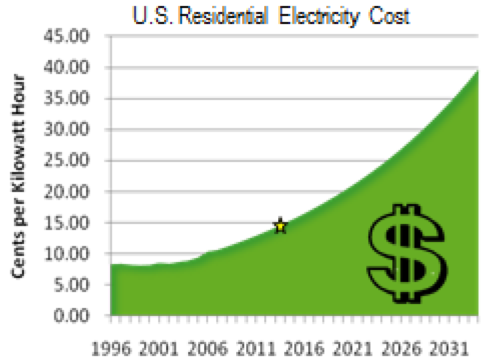




Motivation:
Save the Environment & Save Money

Why reduce energy use in homes?

- Reduce amount of harmful carbon emissions
- Conserve limited supply of resources

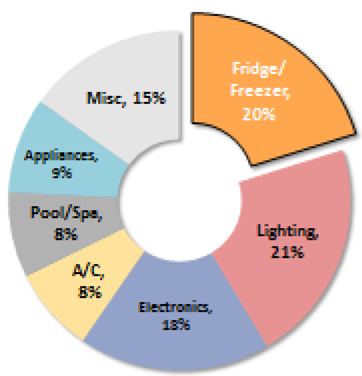


San Francisco Bay Area - $0.21/KWh

http://www.bls.gov/ro9/cpisanf_energy.pdf

Focus: Refrigerators and Water Cooling

Appliance Saturation – Energy Use in the Average California Home



- **Cold Water**
  - Easily available through kitchen faucet
  - Takes up refrigerator space
  - Water/Ice Dispenser

http://sdec.wpengine.com/your-homes-energy-usage-and-how-you-can-save-more/

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Problem Definition

Space

Additional 1 ft^3
≈ \$100 initial cost[1]
≈ \$ 36 yearly cost (operating)

Water / Ice Dispenser

≈ \$75-250 initial[2]
≈ \$76-114 yearly (operating)

[1] https://www.energyguide.com/library/EnergyLibraryTopic.asp?bid=pse&prd=10&TID=12187&SubjectID=7547
[2] http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=RF

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Project Objectives

- Desirable Drinking Temperature
- Low-powered
- Compact Size
- Low Cost
- Filtering Element
- Convenience

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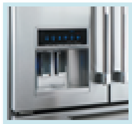
Benchmarking/ Competitors



	Refrigerator Dispenser	Avanti: Thermoelectric Cooler	Brita Pitcher (In Refrigerator)
Time to reach temperature	24 hours	1.5 hours	2.0 hours
ΔT after 20 min	1.0°C	1.5 °C	1.2 °C
Price	$75 - 250	$50	$20
Power Consumption	91 W	560 W	20 W
Size/Volume	0.353 ft³	4.480 ft³	0.388 ft³

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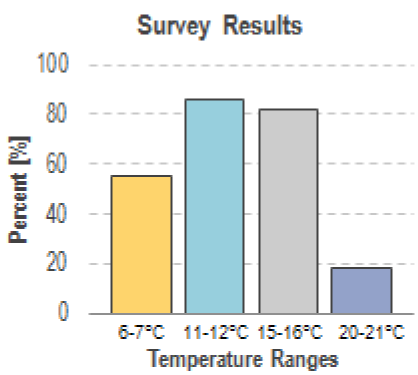
Target Design Specifications

- Water Temperature
  - 11 -16 ° C
- Size (Volume)
  - < 0.3 ft^3
- Power Consumption
  - < 20 W



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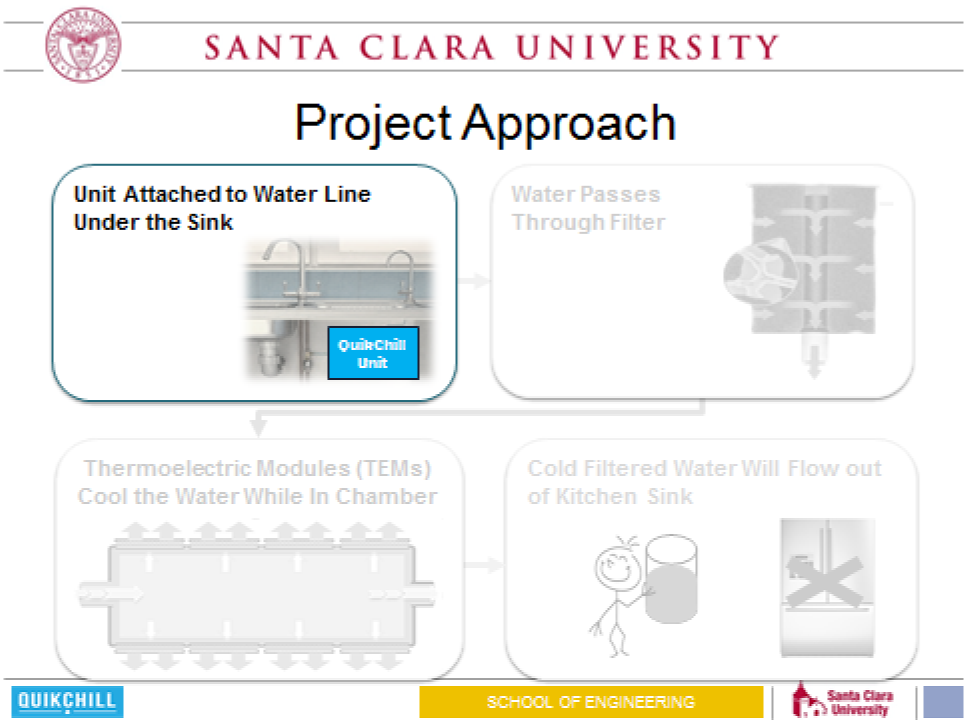
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Project Approach
Unit Attached to Water Line Under the Sink
QuikChill Unit
Water Passes Through Filter
Thermoelectric Modules (TEMs) Cool the Water While In Chamber
Cold Filtered Water Will Flow out of Kitchen Sink
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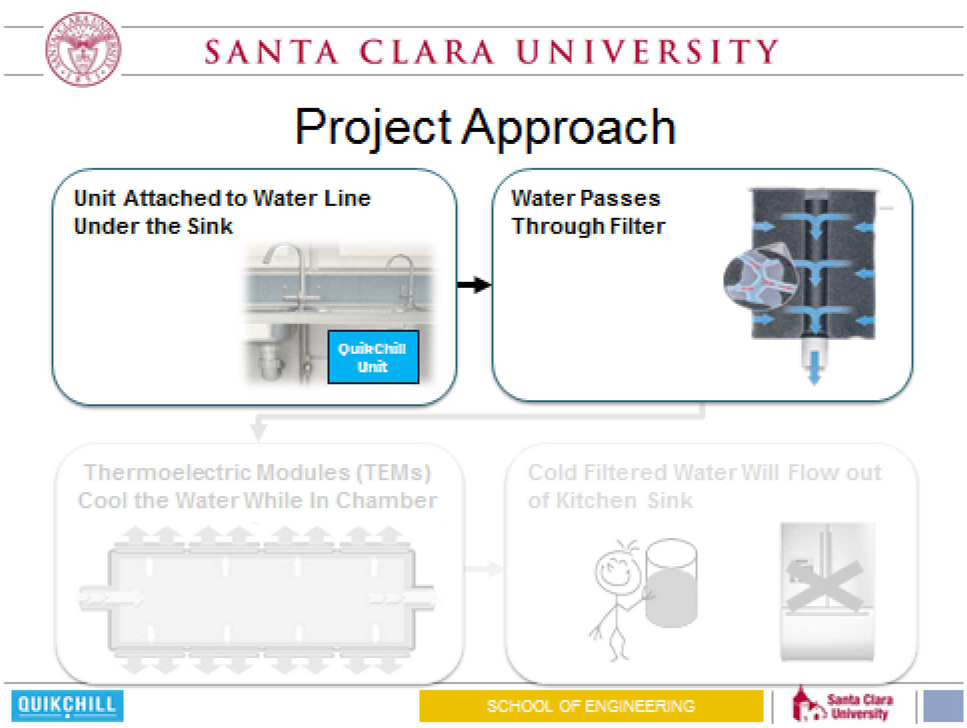
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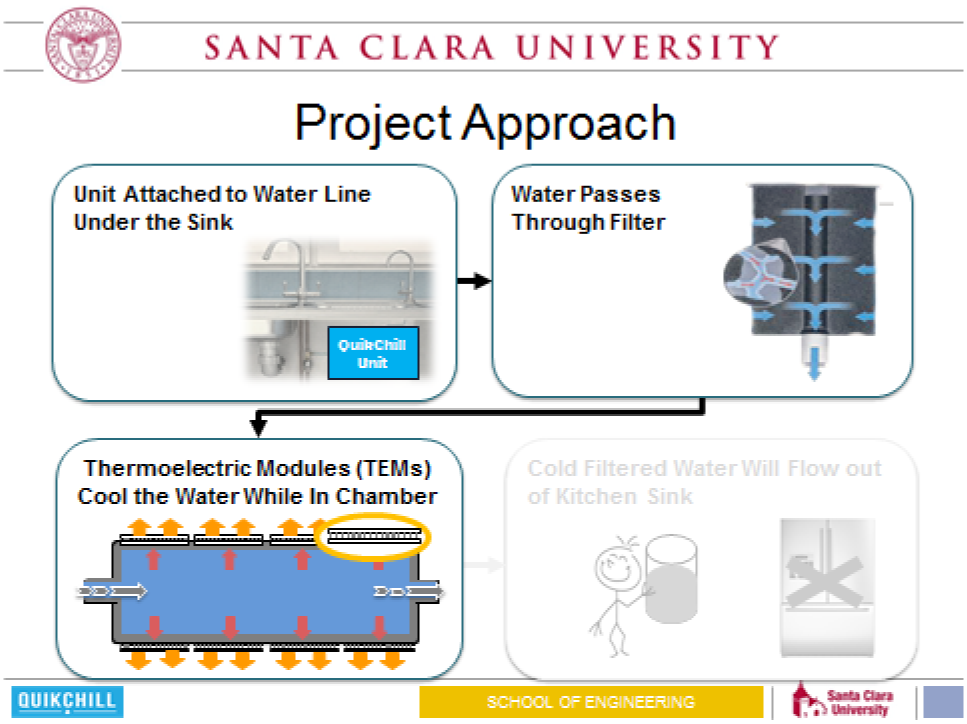
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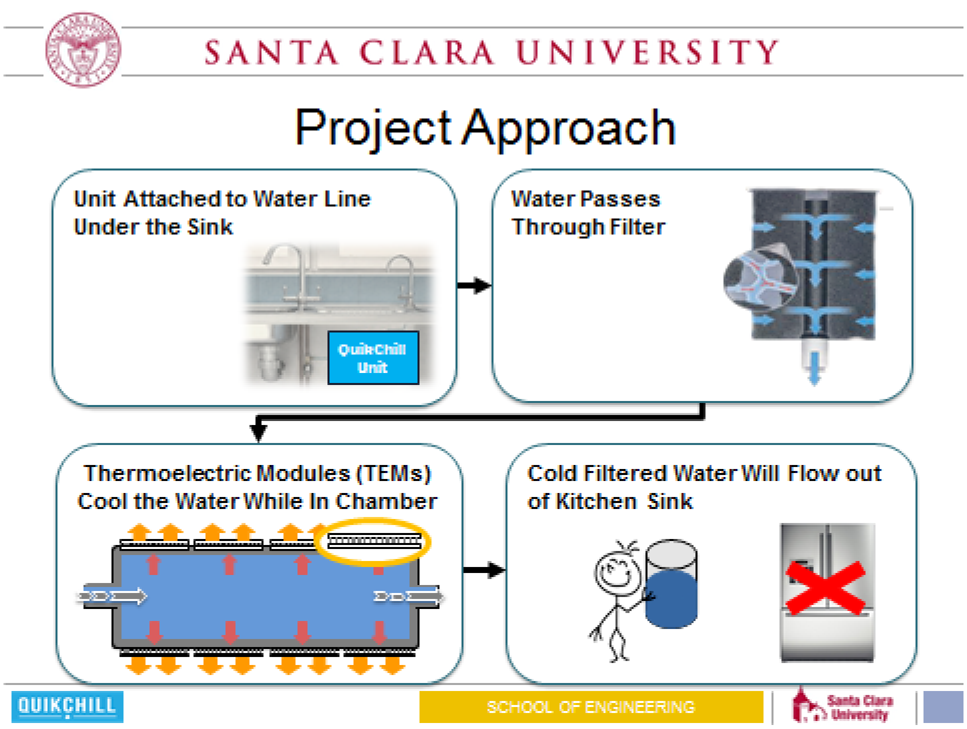
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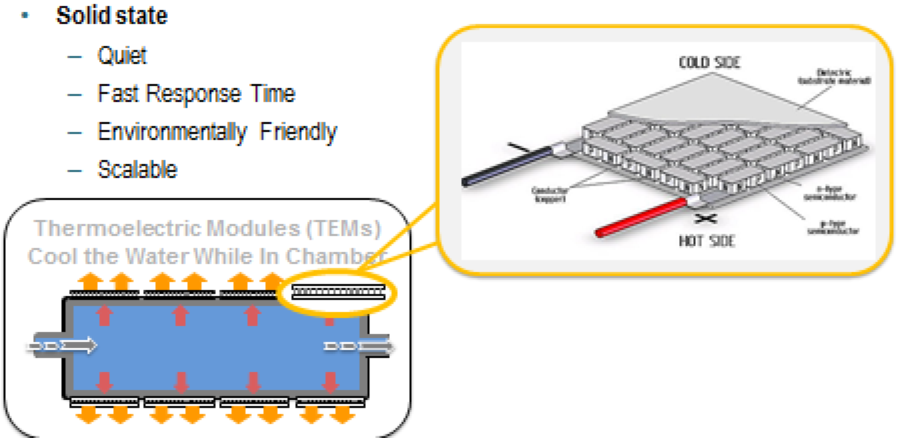
Thermoelectric Modules

- Peltier Cooling
  - Proportional to Current
- Solid state
  - Quiet
  - Fast Response Time
  - Environmentally Friendly
  - Scalable



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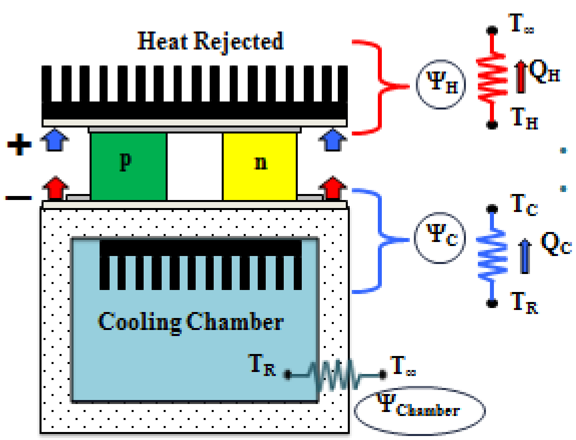
Design Analysis



- Increase $\psi_{Chamber}$
- Decrease ψ_C and ψ_H

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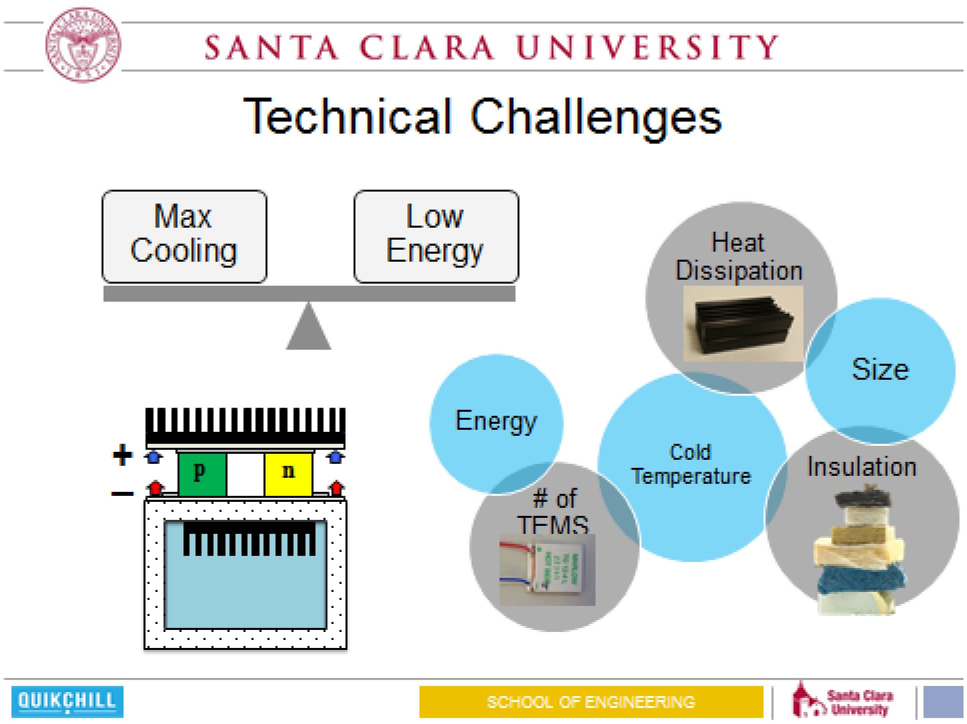
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Technical Challenges
Max Cooling
Low Energy
+
−
p
n
Heat Dissipation
Size
Energy
Cold Temperature
Insulation
# of TEMS
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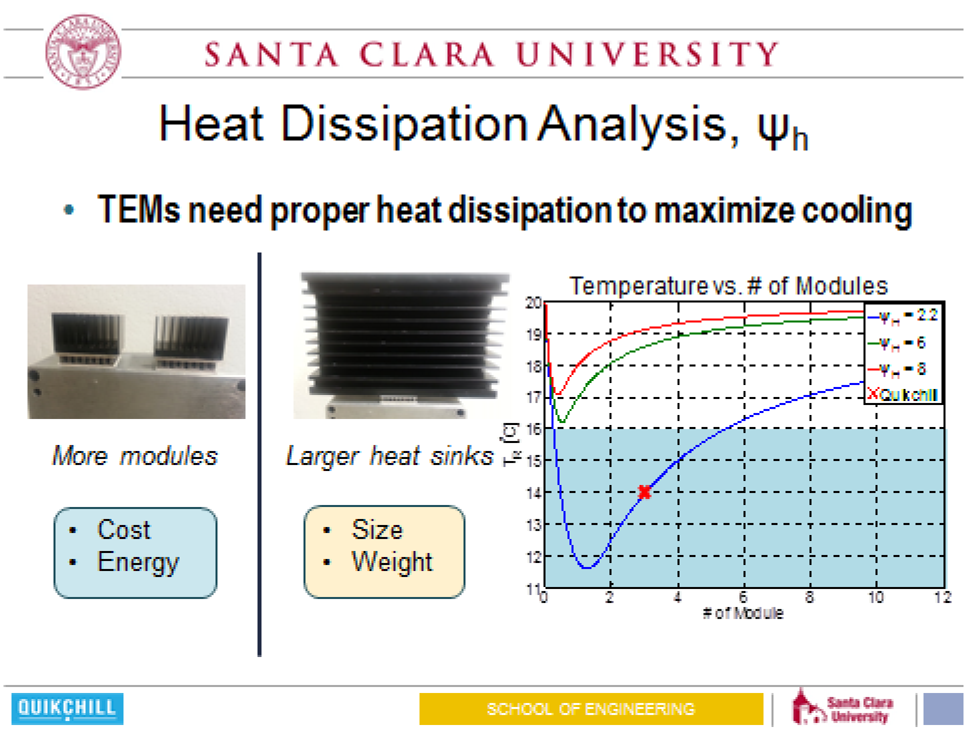
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Heat Dissipation Analysis, ψh
• TEMs need proper heat dissipation to maximize cooling
More modules
• Cost
• Energy
Larger heat sinks
• Size
• Weight
Temperature vs. # of Modules
ψh = 2.2
ψh = 6
ψh = 8
Quikchill
Tk [C]
# of Module
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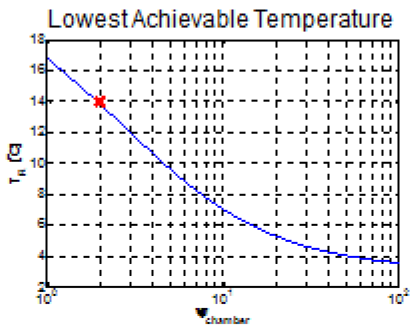
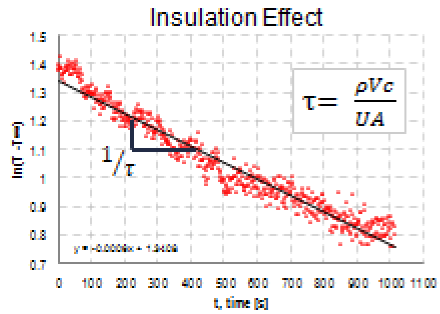
Insulation Analysis, ψ_c

- Less heat gain from environment
  - Lower steady state (final) temperature
  - Faster time to cool
- Styrofoam Vs. Spray Insulation

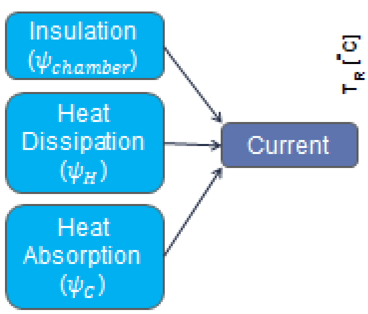


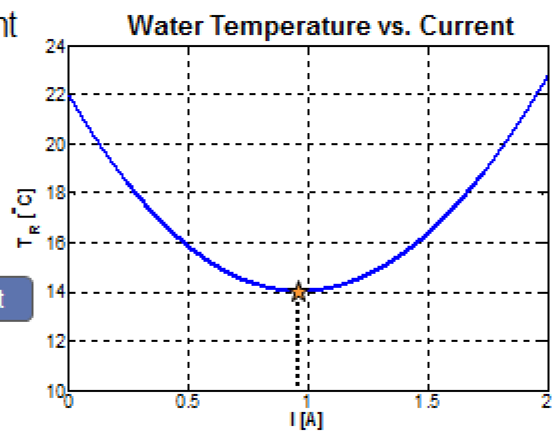


Insulation Thermal Resistance [K/W]	
Avanti Water Cooler	10
Styrofoam	1.8
Spray Insulation	2

Optimal Current Modeling

- Water varies with current
  - Peltier Effect
  - Joule Heating





I_{opt} = .96 [A]

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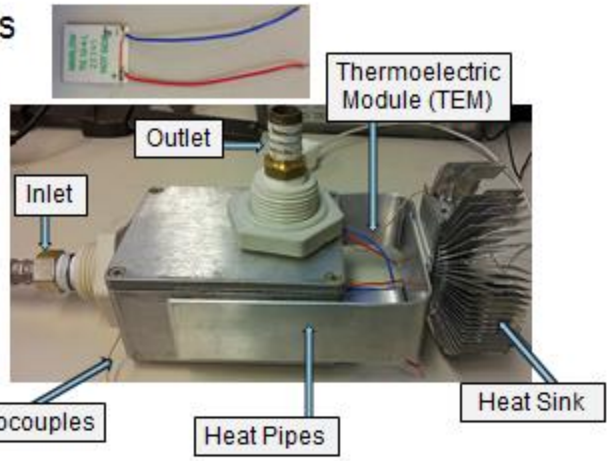
Experimental Setup

- Measurements
  - Temperature
    - Water
    - Ambient
  - Voltage
  - Current



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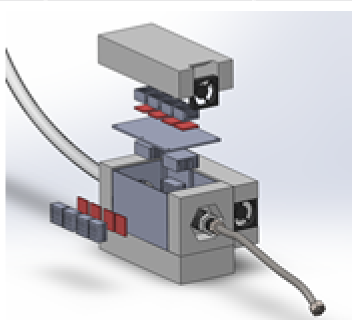
Experimental Results

Design Iteration	Volume of Chamber [mL]	# of TEMS	ΔT after 20 mins. [°C]	Minimum Temperature [°C]
1	2000	12	2.1	17
2	800	12	2.4	17
3	800	3	3.9	14
4	800	3	1.7	15.5

PROS
- Larger Volume



CONS
- More TEMs
- Minimal Cooling

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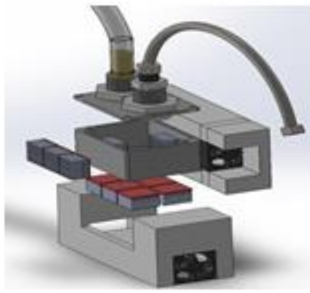
Experimental Results

Design Iteration	Volume of Chamber [mL]	# of TEMS	ΔT after 20 mins. [°C]	Minimum Temperature [°C]
1	2000	12	2.1	17
2	800	12	2.4	17
3	800	3	3.9	14
4	800	3	1.7	15.5

PROS
- Smaller Thermal Mass



CONS
- More TEMs

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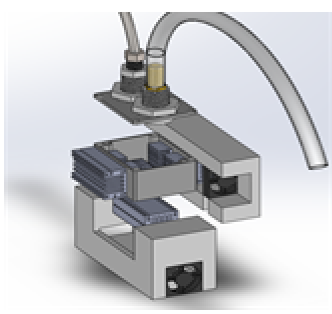
Experimental Results

Design Iteration	Volume of Chamber [mL]	# of TEMS	ΔT after 20 mins. [°C]	Minimum Temperature [°C]
1	2000	12	2.1	17
2	800	12	2.4	17
3	800	3	3.9	14
4	800	3	1.7	15.5

PROS
- Best Iteration
- Less TEMs
- Less Power



CONS
- Bulky and Heavy
- Large Heat Sinks

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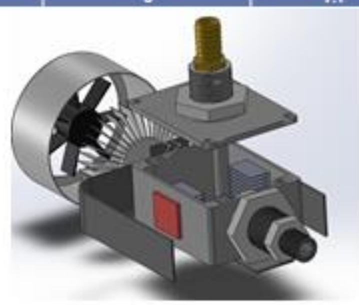
Experimental Results

Design Iteration	Volume of Chamber [mL]	# of TEMS	ΔT after 20 mins. [°C]	Minimum Temperature [°C]
1	2000	12	2.1	17
2	800	12	2.4	17
3	800	3	3.9	14
4	800	3	1.7	15.5

PROS
- Compact Size
- Spray Insulation



CONS
- Limited Heat Dissipation

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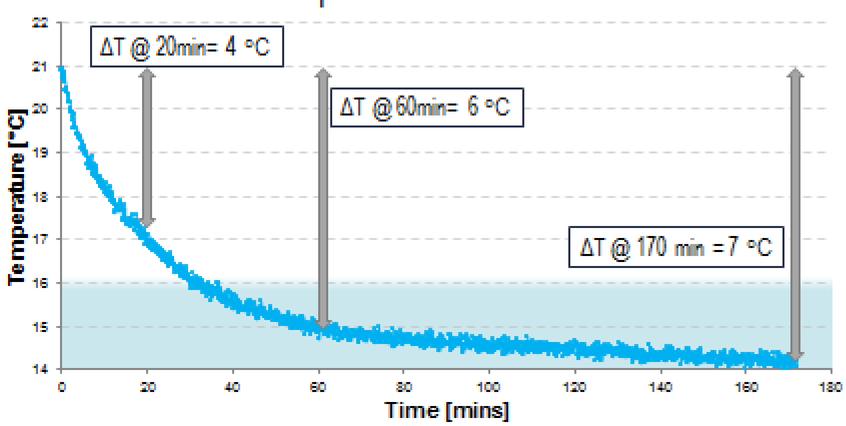
Test Results

Current = 0.96 Amps



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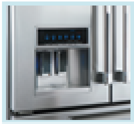
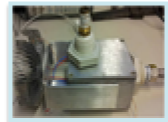
Benchmarking / Competitors



	Refrigerator Dispenser	Avanti: Thermoelectric Cooler	Brita Pitcher (In Refrigerator)	QuikChill
Time to reach temperature	24 hours	1.5 hours	2.0 hours	3 hours
ΔT after 20 min	1.0°C	1.5 °C	1.2 °C	3.9°C
Price	$75 - 250	$50	$20	$35
Power Consumption	91W	560 W	20 W	16 W
Size/Volume	0.353 ft^3	4.480 ft^3	0.388 ft^3	0.25 ft^3

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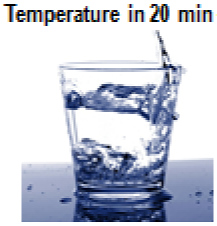
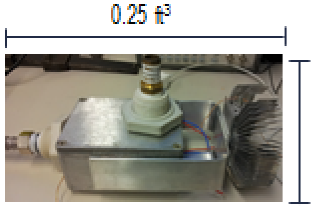
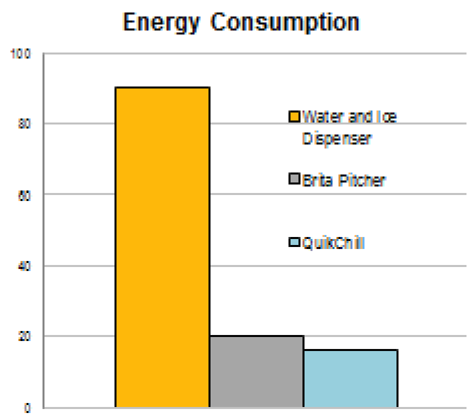
Conclusion

Minimum Temperature – 14 °C
Temperature in 20 min – 4 °C



Space Requirements –
0.25 ft^3





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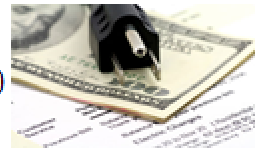
Cost Analysis

- Initial Cost
  - Water Dispenser - $ 75- $250
  - Brita Pitcher (In Fridge) - $100 + $20
  - QuikChill - **$35**



- Switching to QuikChill → Operating Cost Savings
  - Water Dispenser

$$\frac{(90.6\ -16)\ W^{1}}{1000} * \frac{24\ hr}{day} * \frac{365\ days}{year} * \frac{\$0.21}{KWhr} = \$\mathbf{136}$$

  - Brita Pitcher

$$\frac{(20-16)\ W^{2}}{1000} * \frac{24\ hr}{day} * \frac{365\ days}{year} * \frac{\$0.21}{KWhr} = \$\mathbf{7.36}$$

[1] http://energy.gov/energysaver/articles/estimating-appliance-and-home-electronic-energy-use
[2] https://www.energyguide.com/library/EnergyLibraryTopic.asp?bid=pse&prd=10&TID=12187&SubjectID=7547

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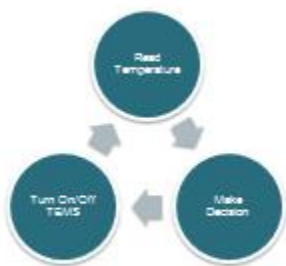
Future Work

- Design Installation Accessories
  - Mounting
  - Connections



- Reduce Power
  - Arduino Control Sensor
  - Implement an "Energy Saving Mode"
- Viable Option for Developing Countries
  - Photovoltaic Integration
  - Portable

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Questions?

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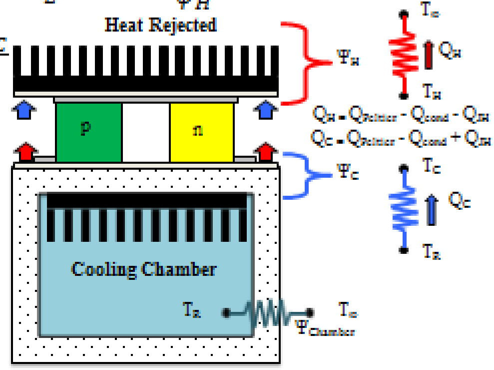
General Analysis

- $Q_C = SIT_C - K(T_H - T_C) - \frac{1}{2}I^2R = \frac{T_R - T_C}{\psi_C}$
- $Q_H = SIT_H - K(T_H - T_C) + \frac{1}{2}I^2R = \frac{T_H - T_\infty}{\psi_H}$
- $mc\frac{dT}{dt} = \frac{T_\infty - T_R}{\psi_{Chamber}} - \frac{T_R - T_C}{\psi_C}$



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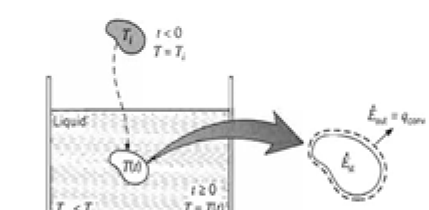
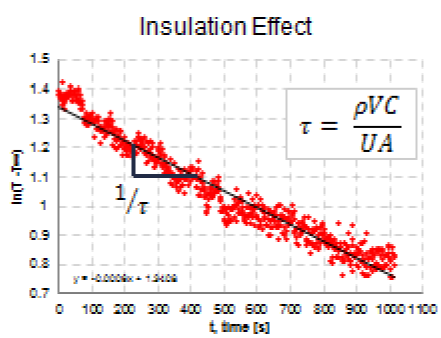
Appendix B: Lumped Capacitance Method

- $-UA_s(T - T_\infty) = \rho Vc\frac{dT}{dt}$
- $t = \frac{\rho Vc}{UA_s}\ln\frac{T_i - T_\infty}{T - T_\infty}$

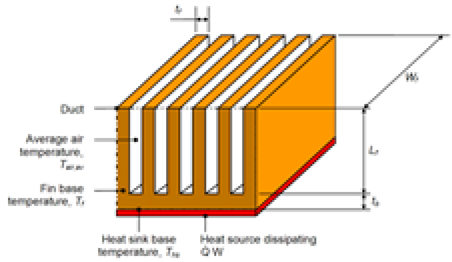


Fundamentals of Heatand Mass Transfer, 7th ed. Incropera, DeWitt, Bergman, Lavine.



Appendix C: Fin Effectiveness

- $q_{fin} = \sqrt{hPkA_c}\tanh\left(\frac{hP}{kA_c}\right)$
  - Assumption: Adiabatic Tip Condition (mL >2.65)
- $q_b = hA_s(T_b - T_\infty)$
- $\varepsilon_{fin} = {}^{q_{fin}}/_{q_b}$



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Appendix D: Coefficient of Performance (COP)

- $COP_{cooling} = \frac{|Q_C|}{W}$
  - Qc: heat removed from the cold side reservoir
  - W: work consumed
- Refrigeration – 3.5
- Air Conditioner – 2.8
- TEM – 0.46

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