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Smart Control for Home Water Heater Saving

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ENTITLED

Smart Control for Home Water Heater Saving

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

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Smart Control for Home Water Heater Saving

By
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SENIOR DESIGN PROJECT REPORT

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Abstract

Existing gas or electric water heaters can become inefficient through the overheating of water and through parasitic heat loss. These inefficiencies are able to be solved by monitoring when a home uses hot water. AquAdapt is a smart sensor which is capable of attaching to any existing residential gas or electric water heater. By constantly monitoring the temperature change of a home water heater, the first law of thermodynamics can be used to relate temperature change to the amount of hot water leaving the water heater. Utilizing this information, a schedule can be generated to optimize the heating of home hot water. Regulating the on-off state of a water heater based on the household's learned usage pattern, allows AquAdapt to reduce residential water heating energy consumption by up to 33%. With a final product cost of $60, the return on investment of AquAdapt is estimated to be 8 months.

Acknowledgments

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1 Introduction

1.1 Background and Motivation

Currently, electric water heaters account for 18% of the average household's total energy use [1]. A study done by the US Department of Energy in 2009 found that 46.3% of US homes use electric water heaters. The same study also found that 60% of those households have their hot water temperatures set to 120 degrees Fahrenheit with the rest ranging between 120 and 140 degrees. This temperature set-point, along with heater efficiency, shower hot water percentage, household size, shower flow rate, and faucet flow rate, have the biggest impact on total energy used within a household [2].

A pilot study was performed by Lawrence Berkeley National Laboratory in order to find the average amount of water wasted in a household each day. This study found that, in respect to total daily hot water usage, sinks use 5.2 gallons, dishwashers use 2.2 gallons, showers use 27.8 gallons, and clothes washers use 2 gallons. This totals to 37.2 gallons of total water used in a given day in a single household [3]. Electric water heaters can be extremely efficient depending on how often they are in use. If a water heater is in high use, its efficiency is very close to 100%. However, when it is in low use, its efficiency can drop to as low as 30% due to parasitic heat loss[4]. Additionally, the typical household does not need hot water at its highest temperature (or set-point) over the course of the entire day. When hot water is used, it is usually mixed with cold water to achieve the desired temperature, resulting in entropy generation and wasted energy. In total, the average amount of hot water wasted in a household each day has been calculated to be 10.9 gallons [5]. Assuming 10.9 of the 37.2 gallons of hot water in a home are not being utilized, 29% of hot water is being wasted per day, summing up to an estimated 4,000 gallons a year. With this much water and energy being wasted in a single household, AquAdapt is designed to be a sustainable solution.

1.2 Literature Review

A study performed by Adel Abdallah provides research into typical household hot water usage amounts in America. This study concludes that the water heater temperature set-point, followed by intake temperature of cold water, heater efficiency, shower hot water percentage usage, household size, shower flow rate, and faucet flow rate, have the highest effect on household energy use in regards to water heating. This article also gives insight into what major appliances in a house contribute to the most energy consumption in regards to residential home water heaters. By knowing these appliances, we can ensure that our sensor accurately measures the water flow rate used for these appliances so proper estimation and characterization of hot water usage can be implemented.[2]

According to James Lutz, in a 2005 article, there are many technical hurdles associated with energy-efficient technologies that are aimed to save energy consumed by hot water heaters. By understanding issues that have arisen in past experiences, our team can insure that our product does not fall into these same pitfalls. A feasibility study is also performed in this paper. The study analyzes multiple data sets from residential homes and gives an average value associated with the volume of hot water wasted in showers. Using this as a datum, our team can ensure that our project saves a fraction of this hot water waste, in turn saving more energy. [3]

In an article written by William Healy titled "Input-Output Approach To Predicting The Energy Efficiency Of Residential Water Heaters," an analysis of various hot water heater models used in residential homes is performed. The efficiency of multiple water heaters are calculated and recorded in this paper. By comparing how our sensor can increase the efficiency of a standard water heater, we can have concrete evidence into how much money our sensor can save over time. This article also calculates the efficiency of gas water heaters, which can be used in respect to the gas water heater control system of our project.[4]

Another study performed by James Lutz provides research into the field of wireless sensors and how they can be used with residential water heaters. The conclusion of this study states that using wireless sensors to measure temperature and energy usage of hot water heaters is feasible. Several case studies are summarized and their results are given throughout the report. By reading each case study, our team can use this information to further improve our wireless sensor. This information can also be used in our informational report section of our design thesis, to prove that this product is feasible and has a place in the future market. [5]

The Resource Handbook of Electronics, by Whitaker, is a key textbook that provides insight into designing an optimum PCB. A detailed list of electronic components can be found in this textbook and it can be used to ensure that the proper materials are used on our PCB. It is difficult to find academic research into which components will suit an application best, because manufacturers of these parts dominate the web, leading to biased opinions. This academic source gives an unbiased opinion as to what component should be used in each application. Also, this textbook discusses the use of high voltage traces in PCBs which will allow our team to create a PCB that meets safety requirements. [6]

1.3 Project Objectives

The purpose of this project is to aid homeowners with existing gas or electric water heaters in saving energy. By implementing an inexpensive smart sensor on residential water heaters, energy consumption per household will decrease.

Any person with an electric or gas water heater can directly benefit from our sensor. Our goal is to design a low cost product that has a rapid return on investment (ROI). According to Index Mundi, developed countries have a portion of their population living under the poverty line, such as Italy, 29.9%, Egypt, 22%, and the United States, 15.1% [7]. Those that live below this poverty line will benefit greatly from this project because of its quick

ROI.

A typical homeowner spends approximately $2/3$ of the day either at a job, or asleep. During this time there is no need for hot water to be generated. The sensor insures hot water is not being generated during these times, this allows our sensor to save approximately $1/3$ of overall energy usage by a hot water heater. Having a water heater consume $1/3$ less energy than it typically consumes adds to 1200 kWh a year of energy savings. This amount of energy savings leads to an ROI period of 8 months for our sensor. After this 8 month period, the money acquired from energy savings will be directly returned to the customer.

2 | Systems Level

2.1 Overview

The AquAdapt smart sensor consists of three subsystems, the data collection, communication, and control unit (DCCU) attached to the water heater, the off-site server (OSS) doing the data analysis, and the housing that holds the sensor and electrical components together. The controller, powered through an electrical outlet, will collect the water heater temperature data, and send that data to the OSS for data analysis. These servers will perform machine learning algorithms to create a usage pattern for the water heater. This usage pattern will translate into a set of appropriate times sent to the controller to turn the water heater on and off by interacting with the existing water heater control system.

2.2 Customer Needs

In order to correctly design the product, we looked into who would use the product, and what they would want out of a product such as this. The customer is likely to be a middle to lower income homeowner who is looking to save energy costs from the water heater to improve the overall efficiency of the home.

Some overall goals of the product are to be:

1. Non-Invasive
2. Long Lasting
3. Inexpensive

We do not want the product to be an inconvenience that homeowners have to deal with. If there is extraneous effort to keep the system running, it will be less attractive to purchase the product. We want a one-and-done mindset, where the user can experience all the benefits with practically no effort. All the customer will see is a decrease in his or her utility bill. A long lasting product should be able to match the lifespan of the home water heater. Thus, essentially transforming the average water heater into a high tech, energy saving water heater until a new heater needs to be purchased. Furthermore, an inexpensive sensor will create more affordability to those who may not be able to purchase a new, high-end water heater. This customer will also be able to experience a quick ROI.

To gain an understanding of what our system will need to accomplish, a questionnaire was created and submitted to an audience of friends and family from the West coast to the East cost. This survey aimed to receive input from typical Americans as to what his or her typical hot water usage patterns their household may have. Looking at 71 responses from people in various places in the US, we determined that the group of people who would benefit most from our product are the 85% of those who either knew about or had access to their gas or electric water heater. Results shown in Appendix A.1 consists of the top 27 responses from persons who have the shortest shower times and a minimal number of persons living in his or her home (2-10). The households with the lowest total shower time will need AquAdapt the most because they use the least amount of hot water while still constantly running their hot water heater.

The most important question analyzed from the data is, if someone is given the opportunity to purchase this sensor for their home, would they purchase it? This yes or no answer gives our team insight into whether our sensor will have a chance to be successful in the general market. From there, the amount of time those living in the house spent in the shower daily is then analyzed. Since showers consume the highest amount of hot water per household, it is then evident that those who spend the least amount of time in the shower are consuming little hot water, and this in turn, leads to their hot water heater being underutilized, wasting energy in the process.

According to these customer needs, it is important that our team holds final sensor cost to $60. Our sensor must also be compatible with both gas and electric water heaters, allowing for accurate calculations of the amount of water leaving the tank to properly control water.

2.3 System Sketch with Scenario

The only required user interaction for the product is the installation. Following the given instructions, he or she will need to break the electrical connection with the water heater, and run the power into the controller first. The input power will be placed in the circular hole shown in the 3-D model in Figure 2.1. Afterwards the sensor needs to connect to the internet. Once the controller has power, the customer will simply place the temperature sensor in the instructed location on the water heater. The temperature sensors will retract from the openings on top of the housing shown in Figure 2.1. Once the system is running and connected to the internet, there are no further requirements, and the system will begin the process of saving energy.

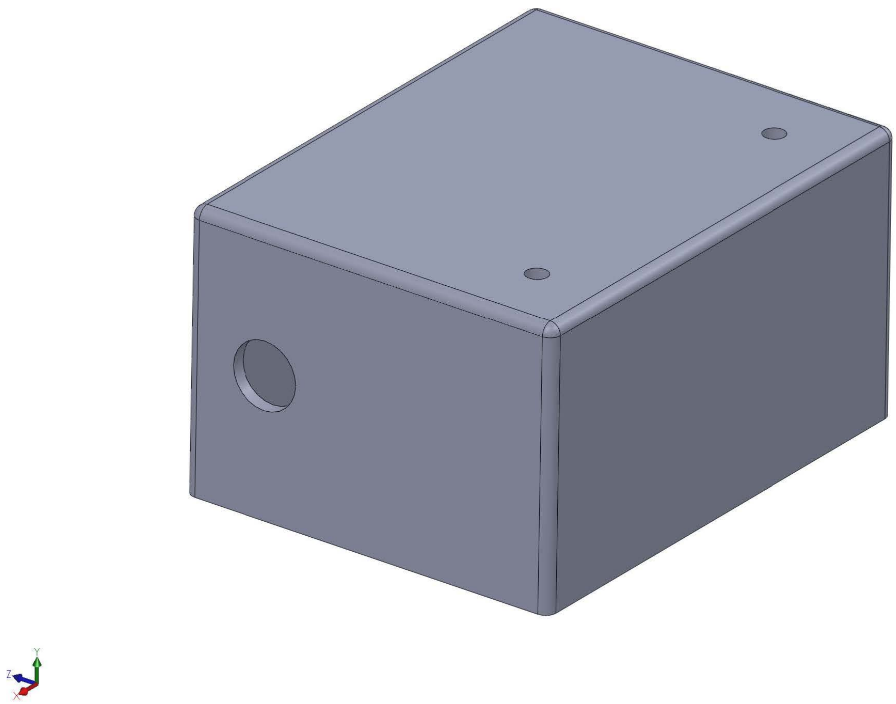


Figure 2.1: 3-D model of housing for PCB and thermocouples.

2.4 Functional Analysis

2.4.1 Functional Decomposition

The main functions associated with the smart sensor are:

1. Measure temperature of hot and cold water pipes
2. Send temperature data to the cloud
3. Determine mass flow rate pattern from pipe temperatures
4. Control power/gas to water heater
5. Protect electronic components with an enclosed housing for all parts
6. Secure all electronic components to insure no damage can be done to the sensor

A sub-function of this system is the housing for the printed circuit board (PCB), microprocessor and temperature sensors. This housing needs to be constructed of high grade material that can withstand the ambient heat associate with having the PCB close to a water heater. Also the housing must be durable enough to insure that the electronic components do not break or become damaged if the sensor happens to fall from a 6' height. An aesthetic appeal must also be applied to the housing due to the fact that this smart sensor may one day be applied to the market.

Another sub-function is the PCB and electronic components. The PCB must be compact to allow for the entire sensor to rest on top of nearly any hot water heater. Also the PCB must be able to safely transmit 240 Volts at 16 amps of current. This board can not have any damage from this high current and voltage, because the board must have a long operating life. The electronic components on the PCB must all be generic. This will allow for the PCB to have higher manufacturability and lower overall cost. There should be little to no custom parts used on the PCB.

The final sub-function associated with the sensor is the algorithm that converts the change in tank temperature to mass flow rate of hot water leaving the tank. This algorithm must be able to accurately find the mass flow rate vs. time from the water heater throughout the day. The algorithm is written in MATLAB, and will be implemented when the sensor sends the temperature data to the cloud.

2.4.2 Specific Inputs and Outputs

For the device which physically attaches to a user's home water heater, there must be power input for the PCB and the components to function. This input will come in the form of a typical home wall outlet of 120 VAC. A vital input which the software will use to create a heating schedule is the temperature of both the hot outlet pipe and cold inlet pipe as well as the ambient air temperature. The use of these temperature readings are further explained in Chapter 4. Finally, capability for receiving the water heating schedule is required as an input.

Outputs of the physical system are the raw temperature data to the cloud for our software to analyze, lights used to monitor the state of the water heating, as well as the actual energy output to the water heater. This output may be different depending if the heater is gas or electric. What the software will output is data such as the mass flow rate, amount of water drawn, time of water draw, and duration of water draw.

Thinking about the use of the sensor, there are certain restrictions. The area which our sensor can take up is restricted by the space surrounding water heater and components. Access to the system is also restricted because water heaters are usually in either a basement or a closet, away from usual home activity. We also wanted to restrict the total cost of the system in order for it to be accessible to most home incomes (under $100). Lastly, the method of temperature collection is restricted by a limited number of access points a water heater has. A summary of the inputs, outputs, and constraints are found in Table 2.1.

Table 2.1: Summary of inputs, outputs, and constraints of the AquAdapt smart controller.

Inputs	Outputs	Constraints
Power from outlet	Power to water heater	Temperature
Hot and Cold pipe temperature	Temperature data to the cloud	Size
Ambient air temperature	Mass flow rate approximation	Access
Usage pattern from control algorithm	LED lights to inform user the sensor is working properly	Cost

2.5 Benchmarking Results

Before the design process, it is important to know and evaluate what similar products are on the market. Through this market study, the successes and failures of various products are taken into account in the new product design. With this acquired information, our team will be able to further understand which aspects of existing products customers are most pleased with. This will allow for our team to design our sensor in a manner that incorporates these positive aspects.

The first product we came across was a water heater controller called Aquanta designed by Sunnovations. The Aquanta controller essentially functions the same way as our controller. It measures energy usage by attaching to a water heater's temperature and pressure relief valves and recognizes patterns in your water heating. Aquanta can also notify you if there are any leaks within the tank and connects to a phone app via WiFi. Though Aquanta has yet to reach the market, it is estimated that it would sell for around $150 [8]. Aquanta can improve by finding another way to measure the water temperature. Currently, they require tampering with the pressure release valve in order to place a temperature sensor inside the tank, which in turn voids the warranty of the water heater. They also must work on reducing the price if they wish to see the market.

The Iris Energy Smart Electric Water Heater Controller also attaches to the top of a water heater and allows you to create customized schedules for your water heating. It connects to a home's WiFi and allows you to set your water temperature from an app. It also notifies you when you are low on hot water. This product sells for about $70 [9]. The Iris Smart Controller can improve by being compatible with all water heaters and by reducing the price.

Another product we found was the Energy Smart® Electric Water Heater by Whirlpool. This is a water heater in which the controller is already installed. When in Energy Smart mode, the water heater reacts to a homeowner's water usage patterns and reduces heat loss. The cost of this water heater is about $450 with an annual operating cost of about $570, falling close to typical low-efficiency water heaters on the market. Standard water heaters can range from $350 to $700. Whirlpool can improve their product by developing an app that can connect to the water heater to be controlled remotely. They also would need to increase its reliability by fixing the bug that causes the water heater to malfunction after a couple years of use.

2.6 System Options and Trade-offs

2.6.1 Temperature Sensors and attachment

To achieve the goal of energy reduction, our team set intermediate goals to act as milestones through the project. First, we had to conduct research and develop an effective method to securely attach temperature sensors to the water heater for both accurate measurements as well as long-term reliability. Currently, some brand-specific devices, such as Iris for Energy

Smart Electric Water Heaters, have built-in thermocouples located inside the water heater tank which read the internal water temperature accurately and reliably. However, since these devices are brand specific, the entire water heater system would have to be purchased. Our team found that by securing temperature sensors directly on the cold inlet and hot outlet pipes of the water heater, a similar accuracy and reliability can be achieved. By striving to maximize the lifetime reliability of the temperature sensors, required maintenance will be decreased and user satisfaction will be increased.

2.6.2 PCB Components and Manufacturing

Another milestone which we will address is the wireless communication of data from the controller to a computer. From a previous senior design project, Smart Water Heater Controller, a system was created where the microprocessor was hardwired to a Xbee wireless module which communicated with various sensors. Our control system will be an all-in-one sensor and microprocessor, eliminating unnecessary data transfer. This system will be contained on a PCB (printed circuit board), allowing for compact and reliable electrical connections between microprocessor and the temperature sensors. Our system, in the form of a PCB, will collect data from sensors, process the data, and transmit the data wirelessly through a Wi-Fi enabled microprocessor for further analysis in real time. Because this compact design will reduce the amount of hardware needed, the overall cost of the product will remain low.

2.6.3 Data Analysis Software

One of the more innovative goals our team sought to complete was to develop the relation between the rate of change of collected temperature data to the mass flow rate of hot water leaving the water tank. Typically, to know the amount of water leaving the water heater, a mass flow rate sensor is installed, which can be time and labor intensive, as the water in the tank needs to be drained. Instead, we replaced the mass flow rate sensor with temperature sensors measuring the change in temperature of the inlet and outlet pipes, resulting in reduction of both the manufacturing and installation costs. With this temperature data we will know when and how much hot water is being used.

2.6.4 Gas Water Heater Controller

In addition, we strive to develop a control system specific to gas water heaters. While the controlling of electric water heaters consists of simply connecting or breaking the electrical supply to the tank, controlling gas water heaters induces more danger due to dealing with the flow of natural gas. Therefore, instead of developing a completely new gas flow mechanism, AquAdapt manipulates the gas water heater's existing control mechanism. In other words, we will not directly control the gas flow, but rather control the existing system that controls the gas flow. Doing this will create a much safer and effective method to control the gas flow of a water heater.

2.6.5 System Housing

Our final goal was to construct a safe and secure housing for our system which can be easily implemented to the customer's water heater. We are aware of potential dangers including earthquakes and flooding that a household may experience, and planned to design for those criteria to further increase the reliability of our product. We wanted this housing to reflect the security of the customer's investment. A decision matrix that is used to pick the material for the housing is seen in Appendix D and E.

2.7 Layout of System Level Design

Figure 2.2 represents the general design of the system for an electric water heater. The arrows represent the inputs and outputs of the PCB data. After temperature inputs are collected and sent out by the microprocessor, a server analyzes the data and outputs a usage pattern, which the microprocessor receives and controls the power to the water tank. Also represented are the possible sources of heat that may be generated.

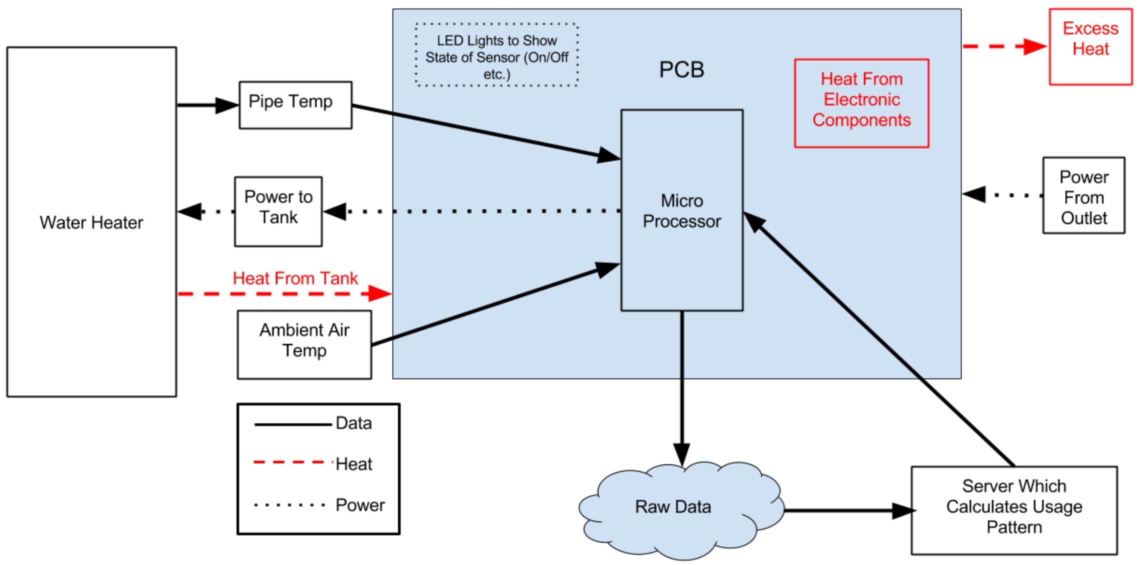


Figure 2.2: System layout of sensor, showing the inputs and outputs of the AquAdapt PCB

2.8 Team and Project Management

2.8.1 Project Challenges and Constraints

This projects contained several challenges and constraints which our team was determined to overcome. The greatest challenge was to achieve functionality across the majority of residential gas and electric water heaters. To complete this challenge, extensive research was conducted in order to account for the various makes and models of water heaters. We created software which is capable of adapting to various water heaters. Similarly, the attachment method is capable of fitting to all water heaters.

A second key constraint we overcame, is that of cost. Because the basis of this project was to allow those of all incomes to achieve energy savings, the designs were heavily influenced by pricing. To deal with this issue, we had to reduce maintenance and installation costs. However, this caused further challenges. One of those challenges was to anticipate the mass flow rate of the water leaving the tank based on the temperature change of the inlet and outlet pipes. Though this problem could have beeen solved through installing a flow rate sensor, manufacturing and installation cost would both increase. Therefore, using temperature sensors, we were able to analyze the rate of change of temperature and translate that into a flow rate.

Overall, we wanted to make the customer exert as little effort as possible. Therefore, we made our system last as long as the life of their existing water heater as well as be as non-invasive as possible. This is achieved through the combination of hardware and software working in unison.

2.8.2 Budget

For this project we received $1800 from the Roelandts grant and $1500 from the School of Engineering. This total of $3300 was used to purchase various test parts such as a gas water heater controller, various versions of the PCB, and various types of housing. A detailed budget can be found in Appendix C.1.

2.8.3 Timeline

On September 28th, our team began to collect data from a standard 50 gallon electric water heater. With this data we were aiming to determine the mass flow rate of water leaving the tank to give us an understanding of how much water would be used on a daily basis and at what times of the day. Starting October 12th our team began to research other competitors, what they have done with their products, and why they have been unsuccessful.

By October 19th our team researched safety requirements for water heaters as well as different temperature sensors we could implement to take accurate temperature values for the inlet and outlet pipes of the water heater. Also, the most efficient and cost effective electrical components for the PCB were identified during the week of October 19th. Starting October 26th our team began to analyze the temperature data collected from the standard 50 gallon tank. Specifically, the existing MATLAB code generated to relate the surface temperature of a 10 gallon electric water heater is being manipulated to accurately give a value for the mass flow rate of hot water leaving the tank in relation to the 50 gallon tank temperature. Lastly, for this same week we started to create our first prototype for the housing of the PCB using a laser cutter. On November 16th our team purchased all of the necessary components needed for the remainder of the project. This completed the initial phase of the project. A detailed Gantt chart can be seen in Appendix F.

In the second phase, beginning January 4th and ending March 11th, we created detailed drawings of our system and finalized our PCB design. On January 18th the first iteration of the gas and electric PCB was manufactured. Data collection began to be taken on both a residential gas and electric water heater during the week of January 18th as well. During the week of February 22nd, FEA was used to calculate the thermal capacity of a standard 50 gallon water heater. Lastly, we needed a way to easily attach our temperature sensors to the inlet and outlet pipes of a water heater. Therefore, we designed clamps to allow for easy installation. These clamps were then 3D printed and implemented into our design. The final phase began March 29th and ended in June. During this phase we were able to successfully determine the mass flow rate of water leaving a 50 gallon water heater. This time consisted of fabrication, assembly, and testing. We also used this time to make minor adjustments to fine tune our product. In May, we created a final product for use in a presentation. Slides for this presentation are found in Appendix K.

2.8.4 Design Process

When designing the housing of our device, we considered several objectives. The design needed to be sleek and compact in order to fit into tight places and shaped to be aesthetically pleasing. The design would also hide any internal components from the consumer. At the same time we needed the material to be cheap, durable, and easy to manufacture. We chose to make the housing out of acrylic as it met all of those criteria. We used modeled the housing using AcrylDraw and the SCU Maker Lab to laser cut and create the housing.

Table 2.2: Design Considerations for subsystems.

Subsystem	**Function**	**Design Consideration**
Printed Circuit Board (PCB)	Receives temperature data and regulates the operation of the water heater	PCB will be hidden within the housing unseen to users
Temperature Sensors	Measures the temperature of the water heater and relays that information to the PCB board	Temperature sensors will be attached to wiring to achieve the needed length
Power Inlet	Plugs into any standard outlet to provide power to the product.	Power cord should be long enough the reach a power outlet to avoid use of an extension cord

Table 2.3: List of how certain features relate to the aesthetics.

Feature	Aesthetics
Housing	• Hides internal electrical components • Forms nice clean package
Small size	• Allows easy transport of device • Allows user to place the device in a convenient location
Shape	• Shows that the design is symmetrical • Incorporates fillets to eliminate sharp corners

2.8.5 Risks and Mitigations

Working with electric water heaters subjects us to high voltages of up to 240V and amperage of up to 15 amps plus, where water is likely to be present. This is enough to be lethal. In order to minimize the risk we are taking working with electric water heaters, we ensured that the water heater was completely unplugged before incorporating our device. We also consulted with Electrical Engineering professors to get recommendations on how we should design our PCB to handle the required voltage and current.

Another potential risk we faced was exposure to gases. The second phase of our project focuses on regulating gas water heaters. To mitigate this risk, we ensured that all gas valves were closed when working with the heater, the area is well ventilated, and that there was nothing that could cause a potential spark in the area. By taking all the necessary precautions, we ensured that we would not be facing any danger while working on our project.

2.8.6 Team Management

There were six different team roles that are split up between our three different team members. The role of Devil's Advocate and the Weekly Activity Report were the responsibility of Joe Singer. The role of the Recorder and Timekeeper were the responsibility of Michael Simmons. The role of the Team Leader and Facilitator were the responsibility of Scott Jansen.

Table 2.4: List of roles and their responsibilities.

Role Position	Responsibility
Leader	Coordinate team to insure all deadlines and responsibilities are meet
Devil's Advocate	Challenge members thought process with outside point of view
Weekly Activity Report	Compose a weekly activities report highlighting key issues and advancements in the project.
Facilitator	Insures that each member is completing their weekly and project goals
Recorder	Takes detailed notes of each meeting
Timekeeper	Records timestamp of each new topic discussed

If issues arose within the group, it was predetermined that face to face meetings would be scheduled with the two parties to insure an agreement was made. Most of the conversations between group members were face to face instead of through email or text.

Responses to issues were approached in a respectful and timely manner. In order to insure issues did not propagate, responses were performed within two days.

3 Subsystem 1: Data Collection, Communication, and Control Unit

3.1 Subsystem Overview

3.1.1 Subsystem Role and Requirements

The data collection, communication, and control unit (DCCU) is the main hardware of AquAdapt, all combined onto one printed circuit board (PCB). This PCB is designed to collect the temperature data, send the data out wirelessly to be analyzed, and receive a heating schedule which is used to control the water heater. Therefore the DCCU incorporates temperature sensors, wireless microprocessor, and a method to control a gas or electric water heater. An important aspect that was kept in mind through the design process of the DCCU is the price of the components. To assure our product will be affordable to many, we set a requirement for the total cost of the DCCU to be under $40 after incorporation of mass production.

3.1.2 Detailed Design Description

Water heaters are typically kept in locations which are not often visited, such as a basement or a specific water heater closet. To collect data, send data, and control the water heater, our project's DCCU utilizes a WiFi enabled microprocessor that can connect to a home's wireless network. The processor takes input from two temperature sensors attached respectively to a hot water heater's hot outlet and cold inlet pipes to monitor pipe temperature change, explained more in Chapter 5. After sending the data through a home's wireless network, an off-site server analyzes the data (further described in Chapter 4) and returns a schedule which the DCCU uses to control the gas or electric water heater. Figure 3.1 represents these inputs and outputs involved in the DCCU. All of these aspects described are compiled together in the form of a PCB allowing for compact and reliable usage. Additionally, in order to achieve our goal of having an affordable product, all individual parts in the DCCU are generic and not customized. The DCCU has a slightly different design depending on the type of water heater (gas or electric). The electric and gas PCB designs are respectively shown in Appendices F.1 and F.2.

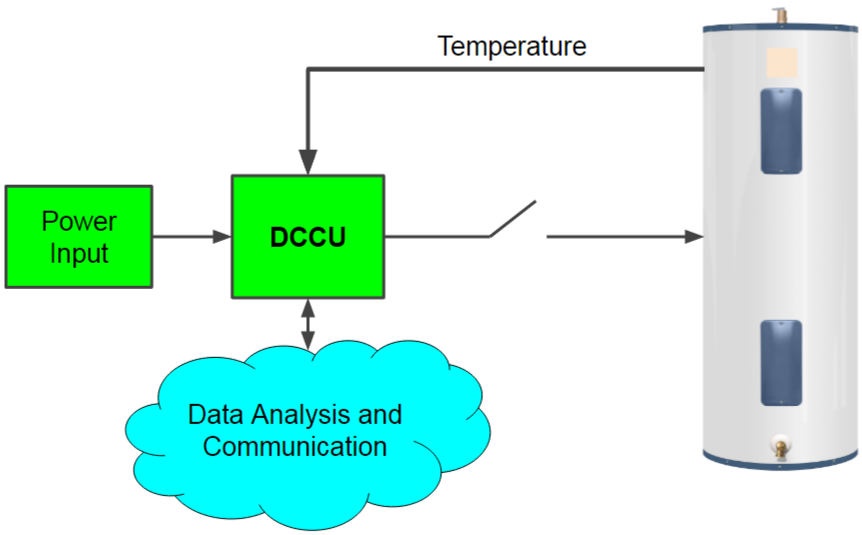


Figure 3.1: Diagram of the DCCU representing inputs (power, temperature, analysis results) and outputs (temperature data, heater control). Water heater represented on right.

3.2 Subsystem Components

3.2.1 Temperature Collection

3.2.1.1 Introduction and Requirements

The temperature collected from a water heater is the starting point for the AquAdapt system. Because it is such a vital concept, we decided to look into the best methods to collect this temperature data. Certain requirements that we wanted to keep in mind are:

1. Low-cost

2. Accuracy in temperature readings up to ±2°C.
3. Reliability of long lifespan to survive as long as the water heater.
4. Compatibility with microprocessors.

After taking all of these into account, the TMP36 temperature sensor from Analog Devices was chosen because it can be read easily with a microprocessor in addition to its low-cost, reliability, and ±2°C accuracy.

3.2.1.2 Trade-offs and Design Choice

Temperature sensors come in forms of thermocouples, bimetallic strips, and diode-based sensors. Thermocouples tend to have a range of accuracy from ±0.5°C to ±2.2°C, adequate for measuring temperature changes, and work based on temperature differences through given materials, creating a low voltage differential. However, amplifying the small voltage from a thermocouple requires additional hardware to be read by a microprocessor, making it not suitable for the low-cost goal.

Bimetallic strips could be utilized to flip switches in a circuit through the expansion of metal when exposed to heat. Though these strips can be accurate, they are not easy to implement in a way readable by a microprocessor because much calibration would be needed.

Diode-based temperature sensors are both cheap and designed for use with microprocessors. Broken down, these sensors are a single diode with a known response based on temperature change. A TMP36 temperature sensor is a diode-based sensor whose output is based at 750 mV at 25°C. It has a known linear response at 10 mV/°C, making it easily readable by a microprocessor with a 0 to 3.3 V input.

3.2.2 Data Communication

3.2.2.1 Introduction and Requirements

The communication of the DCCU allows for the temperature data to be sent to and analyzed at an off-site server, reducing the memory needed by more than 150 MB (more than what most microprocessors can handle). So, incorporating a good microprocessor within the DCCU serves as an important tool. When researching various microprocessors for collection and communication purposes, it was essential that these requirements were kept in mind:

1. Easily implemented wireless capabilities
2. Low-cost
3. Extensive documentation
4. Flexible analog and digital inputs/outputs

The choice of microprocessor was the Photon made by Particle because of its efficient, easy to learn, built-in wireless capabilities. Additionally, the Particle company advertises themselves as a platform to develop internet of things (IOT) products. The Photon is able to incorporate all the necessary components needed for the DCCU to operate effectively.

3.2.2.2 Trade-offs and Design Choice

There are a few good options when choosing microprocessors. An Arduino was considered for its popularity and versatility, but additional hardware would be required to create a wireless connection. A Photon by the company Particle makes a similar, but smaller product which has wireless capability. What is beneficial about this device is the thorough documentation allowing for various possibilities for implementation. Additionally, there is an option to only purchase the wireless module/processor, such that the price will be cut nearly in half, from $19 to $10, making it suitable for low-cost mass production.

3.2.3 Water Heater Control

3.2.3.1 Introduction and Requirements

The requirements for controlling the water heater differ depending on whether it is a gas or electric water heater. If it is electric, the DCCU can externally control the power input to the water heater, but the switch needs to be able to handle about 15 - 20 Amps of current. For gas water heaters, a voltage ranging from 0 - 750 mV is generated from thermopiles, or thermocouples, and is used to power and control the heater. One of our requirements for this is to allow for the DCCU to intercept and manipulate this voltage signal to control the on/off state of the water heater.

3.2.3.2 Trade-offs and Design Choice

For an electric water heater, the simple option was to externally control the power going into the water heater from the grid. It was quickly discovered that this method would be much easier than trying to manipulate the existing control system on-board the existing water heater. Manipulating the existing system would also require professional knowledge of the workings of various types of water heater brands and controllers. By externally controlling the input power, installation is simple and a more universal method is achieved.

For a gas water heater, more issues arise. Foremost, working with natural gas lines is much riskier due to potential leaks. The liability of our product would be much higher. So, we looked to controlling a gas water heater more specifically. Internally, a standard gas controller receives power from the voltage generated from thermopiles attached to both the pilot light and the hot water heater. The path we decided to go down is to simulate the voltage produced from the thermopiles, and power/manipulate the controller that way. Though different brands may have different voltages, there can be different settings or a calibration time to accurately control.

3.3 Verification of System

Upon receiving our designed PCB from a company called Dirty PCB, we soldered all the necessary parts on, and tested the internet connection, temperature readings, and control systems. After we verified each component worked correctly, we utilized the internet connection and temperature readings at several different water heater locations of friends and family. So, for 3 months, the DCCU was actively collecting data, with no hardware failures. However, testing was never fully implemented on a 50 gallon water heater, as we did not want to risk potential hazard or failure of a family or friends water heater.

4 | Subsystem 2: Data Analysis

4.1 Subsystem Overview

It was initially determined that the inner surface tank temperature of a home water heater can be used to find the mass flow rate of hot water leaving the tank for any given time. This assumption was not proved to be false, however the fact that not all residential water heaters have access to the inner tank surface creates the issue of allowing AquAdapt to be universial if the inner tank surface temperature was used to find the mass flow rate. Also the fact that 40-60 gallon water heaters have a large thermal mass, means their internal temperature does not change rapidly with time. These two facts made it difficult to calculate the mass flow rate of hot water leaving the tank using just the inner surface tank temperature. This lead to the AquAdapt team using the hot outlet and cold inlet pipe temperatures to find the mass flow rate of hot water leaving the tank.

4.1.1 Preliminary Design

In order to test the hypothesis that the conservation of energy equation could be used to find the mass flow rate of hot water leaving the tank, a 10 gallon water heater was utilized and connected to a traditional kitchen sink. This 10 gallon water heater had a temperature sensor attached to the inner tank's surface. Using the changing temperature of the water heater, the mass flow rate can be calculated using curve fitting techniques. The experimental set up for the 10 gallon tank can be seen in Figure 4.1 below.

Figure 4.1: 10 Gallon Water Heater Experimental Set Up

To first relate the temperature of the tank with the mass flow rate of hot water leaving the tank, the first law of thermodynamic must be implemented. The following equation is implemented to relate the tank temperature to the flow rate of hot water leaving the tank:

$$mC_p\frac{dT_{tank}}{dt} = \dot{W} - \frac{(T_{tank} - T_{\infty})}{\psi} - \dot{m}C(T_{hot} - T_{cold}) \tag{4.1}$$

Before the equation can be used, the constant values must first be calculated using a cold start equation. The first cold start equation used is:

$$mC_p\psi = \tau = -\frac{\Delta t}{ln(\frac{T_{tank}(t)-T_{\infty}}{T_{tank}(t=0)-T_{\infty}})} \tag{4.2}$$

This equation is derived from equation 1, however the tank is assumed to be turned off and there is no mass flow rate being drawn from the tank. In order to calculate tau, linear curve fitting must be implanted. Knowing both the ambient air temperature and the temperature of the tank along with time at which the data was recorded, these values can be plotted against each other. Solving equation 2 in terms of the tank temperature the following equation is reached:

$$T_{tank}(t) = (T_{tank}(t=0) - T_{\infty})e^{\frac{-\Delta t}{\tau}} + T_{\infty} \tag{4.3}$$

Using multiple days of data, and averaging the values of tau calculated for each day the following value for the thermal time constant is found to be equal to 119000. Once the thermal time constant τ is calculated it is used to solve the second cold start calculation:

$$e^{-\frac{t}{\tau}} = \frac{T_{tank}(t) - T_{\infty} - \frac{\dot{W}mC_p}{\tau}}{T_{tank}(t=o) - T_{\infty} - \frac{-\dot{W}mC_p}{\tau}} \tag{4.4}$$

This cold start equation is valid under the assumption that the heating element is on heating the water in the tank but no water is being drawn from the tank. This can also be characterized as when the water in the tank is near ambient temperature and is then heated to the required temperature level according to the thermostat. Equation 4 is used to calculate the constant value of mC_p. Over multiple data sets it was found that the value for mC_p of the 10 gallon electric hot water heater is approximately $\frac{J}{K}$. Knowing the average value for mC_p and τ, the value for the thermal resistance ψ can be calculated using the relationship in equation 4.2. The value for ψ of the 10 gallon tank was found to be $3.3\frac{m^2K}{W}$.

Once the value of the constants mC_p, τ, and ψ are known, the mass flow rate of hot water leaving the tank can be calculated. THe following equation was used to find the mass flow rate:

$$T_{tank} = x(1) + x(2)e^{-xdata(x(3))} \tag{4.5}$$

Where the constants $x(1), x(2), x(3)$ are as follows:

$$x(1) = T_\infty \frac{1}{1+\psi\dot{m}c} - (5 - T_c)\frac{\dot{m}c}{\frac{1}{\psi}+\dot{m}c} + \frac{\dot{W}}{\frac{1}{\psi}+\dot{m}c} \tag{4.6}$$

$$x(2) = T_o - T_\infty \frac{1}{1+\psi\dot{m}c} + (5 - T_c)\frac{\dot{m}c}{\frac{1}{\psi}+\dot{m}c} - \frac{\dot{W}}{\frac{1}{\psi}+\dot{m}c} \tag{4.7}$$

$$x(3) = \frac{1}{\psi mC_p} + \frac{\dot{m}c}{mC_p} \tag{4.8}$$

Using the MATLAB function lsqcurvefit, a curve representing temperature vs. time can be derived and calculated using equation 4.5. Lsqcurvefit generates a curve that best fits a certain data set. In this case the data set lsqcurvefit is trying to match is the temperature vs. time data set. By inputting equation 4.5 into the lsqcurvefit function, MATLAB attempts to best fit the temperature vs. time data set using a curve which has the same characteristics as equation 4.5. The better the fit, the better the approximation for the mass flow rate of hot water leaving the tank. In order to insure that the best fit for each data set is obtained, the temperature vs. time data is subjected to multiple iterations of lsqcurvefit over varying time ranges. An example of a good fit can be seen in figure 4.2 below:

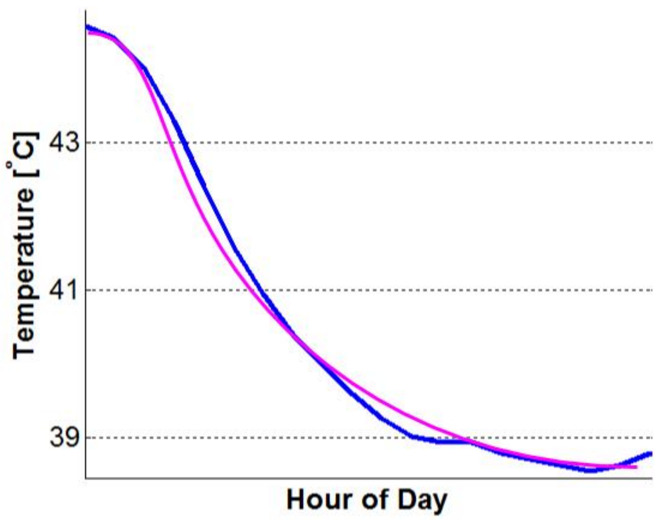


Figure 4.2: lsqcurvefit on Hot Water Draw. Blue is the collected data, smooth purple is the calculated data with lsqcurvefit.

where the blue line is the temperature of the inner tank surface, and the pink line is the generated curve output from the MATLAB function lsqcurvefit. Lsqcurvefit outputs the value for the constants $x(1), x(2), x(3)$ once an accurate curve fitting representation is achieved. Using the value of the constant $x(1)$, the massflow rate $\dot{m}$ can be calculated. In the case of figure 4.2 the mass flow rate was calculated to be $9\frac{L}{min}$.

However, in order for the AquAdapt sensor to be universal, the inner tank surface temperature could not be used to find the mass flow rate. This is because not all 40-60 gallon water heaters have access to the inner tank surface. Also 40-60 gallon water heaters have a much higher thermal mass compared to a 10 gallon water heater, which makes the internal water heater temperature change at a much slower rate. With both of these setbacks, it was determined that the hot outlet and cold inlet pipes must be used to acquire temperature data which will then be used to find the mass flow rate of hot water leaving the tank.

4.1.2 Role and Requirements

Once the temperature data from the hot outlet and cold inlet is measured, the first law of thermodynamics is applied to find the mass flow rate of hot water leaving the tank vs. time. The first law of thermodynamics can be seen in the equation below:

$$\dot{U} = \dot{W} - \dot{Q} + (\dot{m}h)_{in} - (\dot{m}h)_{ex} \tag{4.9}$$

This equation is expanded in order to find the internal heat transfer coefficient of the fluid flowing through the hot outlet and cold inlet pipes. The equation, further expanded, can be seen below:

$$\frac{dT_h}{dt} - \frac{dT_c}{dt} = \tau_{o,h}(((\frac{UP_{o,h}}{h_{i,h}P_{i,h}})T_{w,h} - T_\infty) - T_h(1 + (\frac{UP_{o,h}}{h_{i,h}P_{i,h}}))) - \tau_{o,c}(((\frac{UP_{o,c}}{h_{i,c}P_{i,c}})T_{w,c} - T_\infty) - T_c(1 + (\frac{UP_{o,c}}{h_{i,c}P_{i,c}}))) \tag{4.10}$$

where $\frac{dT_h}{dt}$ is the changing surface temperature of the hot outlet pipe, and $\frac{dT_c}{dt}$ is the changing temperature of the cold inlet pipe. The thermal time constant τ is defined as:

$$\tau = \frac{hP}{(\rho A_c Cp)_{pipe}} \tag{4.11}$$

where h is the internal heat transfer coefficient of the fluid which is flowing through the hot outlet and cold inlet pipe, P is the inner perimeter of the hot and cold pipe, ρ is the density of the pipe, A_c is the cross sectional area of the pipe, and C_p is the heat capacity of the pipe.

Returning to equation (4.2), U is the overall heat transfer coefficient, T_w is the water temperature of the hot or cold fluid which is flowing through the pipe, T_∞ is the ambient air temperature surrounding the water heater.

The internal heat transfer coefficient h can not be solved analytically in equation (4.2). Therefore multi-variable linear regression must be utilized in MATLAB to find the internal heat transfer coefficient. Once h has been calculated, the Nuzzelt Number, Nu can be calculated through the following equation derived in Fundamentals of Heat and Mass Transfer [11]:

$$h = \frac{k}{D} Nu \tag{4.12}$$

where k is the thermal conductivity of water, and D is the diameter of the quantity of hot water leaving the tank. Once the Nu has been calculated, the Reynold's number is then calculated using the following equation [11]:

$$Nu = 0.023 Re^{\frac{4}{5}} Pr^{n} \tag{4.13}$$

where Re is the Reynold's number, and Pr is the Prandlt number associated with the flowing water. Once Re is known, the mass flow rate of the water flowing through the pipe can then be calculated using the following equation [11]:

$$Re = \frac{\dot{m}}{4D\mu} \tag{4.14}$$

where $\dot{m}$ is the mass flow rate of water flowing through the pipe, and μ is the viscosity of the water flowing through the pipe.

Once the mass flow rate is calculated, the duration over which the hot water draw took place is calculated and recorded along with the time of day the water draw occurred. After multiple days, the average mass flow rate of hot water leaving the tank vs. time for 15 minute intervals throughout a 24 hour period is calculated. With this information, it can be inferred when the user will most likely use hot water. The program will then relay this information to the sensor, which will turn off and on the water heater as needed according to the calculated usage pattern.

The overall requirements for the program that will analyze the temperature data are as follows:

1. Accurately calculate mass flow rate of hot water leaving the tank from temperature data received from sensor
2. Derive the mass flow rate of hot water leaving the tank vs. time for 15 minute intervals over a 24 hr. daily and weekly period
3. Return hot water usage pattern to sensor

4.1.3 Options and Trade-offs

The multivariable linear regression program which is used to calculate the mass flow rate of hot water leaving the tank can be written in a variety of languages. MATLAB is the most user friendly program to use when reading information from Excel files. Also the REGRESS function in MATLAB calculates an accurate approximation to the mass flow rate of hot water leaving the tank. Due to this fact, MATLAB is being used to calculate the pattern of mass flow rate vs. time for this project. However, MATLAB is not as compatible with large scale data analysis. Because of this, Python may have to be implemented when the sensor becomes mass produced. Python is also compatible with the Photon core's servers.

The time interval in which the mass flow rate is average is also an area that can be altered throughout the design process if need be. Right now a 15 minute interval is selected due to the fact it will deliver a precise estimate of the mass flow rate pattern throughout the day. A 30 minute interval can be used as well, which would require less data to be relayed to the sensor, but the 30 minute interval will contain a mass flow rate pattern that is not as accurate as a 15 minute interval.

4.2 Detailed Design Description

The following assumptions were used when calculating the mass flow rate of hot water leaving the hot water heater:

1. Constant Volume
2. 1 Dimensional
3. Density of pipe is that of stainless steel: $\rho = 8050 \frac{kg}{m^3}$
4. Cross sectional area of the hot outlet and cold inlet pipe: $A_c = 2.03e^{-3}m^2$
5. Heat capacity of the hot outlet and cold inlet pipe: $C_p = 0.4 \frac{J}{kgK}$
6. The temperature of the hot water as it leaves the tank: $T_{w,h} = 41°C$

7. The temperature of the cold water as it enters the tank: $T_{w,c} = 25°C$
8. The calculated thermal time constant of the water heater: $\tau = 13.0\frac{1}{s}$

4.3 Analysis and Results

The following graph shows a temperature profile from a residential home hot water heater over a 24 hour period:

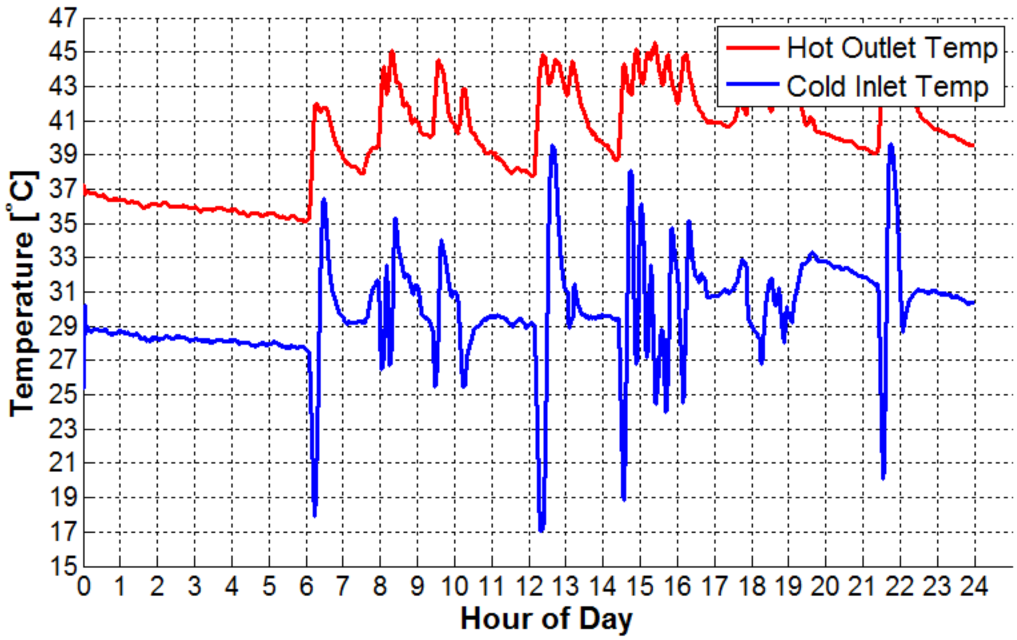


Figure 4.3: Temperature profile of hot outlet and cold inlet pipe over 24 hour period

It can be seen that there are multiple temperature spikes throughout the course of the day. When the cold inlet pipe temperature decreases and the hot outlet pipe temperature increases it denotes that a hot water draw is taking place. This is because when hot water is being drawn from a hot water appliance, hot water is leaving the tank flowing through the hot outlet pipe in turn heating the hot outlet pipe temperature. At the same, time cold water is flowing into the tank in order to replace the leaving hot water, in turn decreasing the temperature of the cold inlet pipe. Using equation 4.3 the thermal time constant can be calculated by curvefitting the temperature profile from 12AM to 5 AM. It was found that the thermal time constant of the tank was $\tau = 13.0\frac{1}{s}$. This thermal time constant value was used in further calculations to find the mass flow rate of hot water leaving the tank. Closer inspection of the first water draw, which occurred at approximately 6:15 AM, can be seen in the figure below:

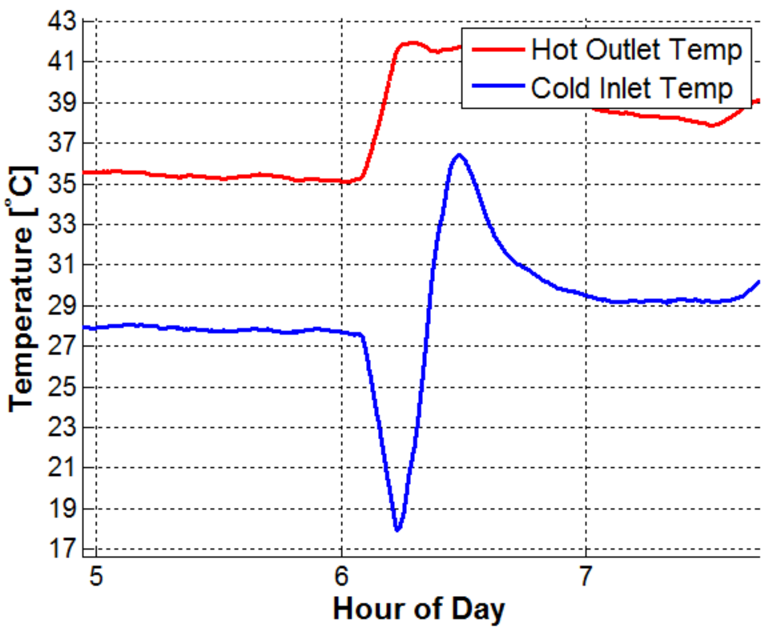


Figure 4.4: Temperature profile of hot water water draw

Using equation (4.2), the internal heat transfer coefficient can be calculated for this water draw. Once the internal heat transfer coefficient is known, the mass flow rate can be calculated using equation (4.6), it was found that the mass flow rate of hot water leaving the tank for this draw was $2\frac{L}{min}$. Through testing data taken from the 10 gallon water heater, it was found that the typical hot water draw is between $0 - 16\frac{L}{min}$. This verifies that the calculated hot water draw falls between the typical range of water draw from a water heater. Further testing and continued fine tuning of data acquisition will lead to more accurate hot water flow rate approximations.

5 | Subsystem 3: Housing and Clamps

5.1 Subsystem Overview

5.1.1 Role and Requirements

The housing holds all of the internal components in place and creates a nice solid package. All housing models were designed using SolidWorks. Prototypes of the housing were 3D printed in various shapes and sizes to get the best fit for our PCB. The housing must be:

1. Low cost
2. Aesthetically pleasing
3. Compact to fit in tight places
4. Attachable to any water heater
5. Durable to withstand potential impact with the floor
6. Easy to manufacture

These requirements will ensure that the housing is safe and reliable to the user while still maintaining a pleasant look. This is important because it must catch the eye of potential buyers.

Our product uses temperature sensors attached to the inlet and outlet pipes of a water heater to calculate the mass flow rate. However, we needed an easy way to attach the sensors to the pipes. Therefore we modeled clamps that would fit around the pipes of the water heater. These clamps are color coded, so the user knows where to place them. Red is for the hot pipe and blue is for the cold pipe.

5.1.2 Options and Trade-offs

There are two viable options for manufacturing the clamps: 3D printing or Injection Molding. The best option depends on the scale that they are manufactured. 3D printing would be more cost effective if manufacturing on a low scale (5000 parts). 20 3D printers can be purchased for the cost of one industrial sized injection molder. These 3D printers would also require a small amount of labor. If manufacturing on a high scale (10,000 parts) injection molding would be the more cost effective method [11]. Another option would be to outsource the manufacturing of these clamps however, this would not be a very economic option as it adds international shipping cost. Also by manufacturing in house, we can make needed changes to our clamps quickly and effectively. For the scale of this project 3D printing is the best option for manufacturing the clamps. However, if the product continues to develop, it may be best to use injection molding.

The options for the housing were to laser cut or to 3D print. While 3D printing the housing would create a strong, visually pleasing design, it would require up to 6 hours to print each individual design. This was time that we did not have to go through multiple iterations. Therefore, we choose to laser cut an acrylic housing because this could be done in a matter of minutes. The design may not be as strong, but it allowed for time to change the specification of the design if needed. In the future, when we have more time and resources, 3D printing or injection molding may become the more viable options.

5.2 Detailed Design Description

The housing was modeled using AcryDraw software using the following specifications:

1. Size: 4.5x3.5x2.5 inches
2. Electric hole placement
3. Gas hole placement

The clamps were modeled using SolidWorks with the following specifications

1. $\frac{3}{4}$ inch diameter to fit around pipes
2. $\frac{2}{5}$ inch tall
3. #11 size screw holes

5.3 Analysis and Results

To evaluate the strength of the housing it was subjected to a drop test. This test aimed to discover if the housing which is made out of acrylic could withstand a drop from 1.52 m. The typical hot water heater has a height of 1.52 m, and the AquAdapt sensor will be secured to the top of a hot water heater. In case of a sudden external force such as an Earthquake is applied to the AquAdapt sensor, it could cause the sensor to fall from its location on the top of the water heater. Therefore we had to determined that the housing for the sensor could withstand this force. The acrylic that was used for the housing has a compressive modulus of elasticity of $2.96x10^9 Pa$. The cross sectional area which is effected by the impact force is $1.82x10^{-3}m^2$.

To simulate a drop 3Gs of force was applied to the top of the housing. This was performed using Abacus and the results are shown below in Figure 5.1.

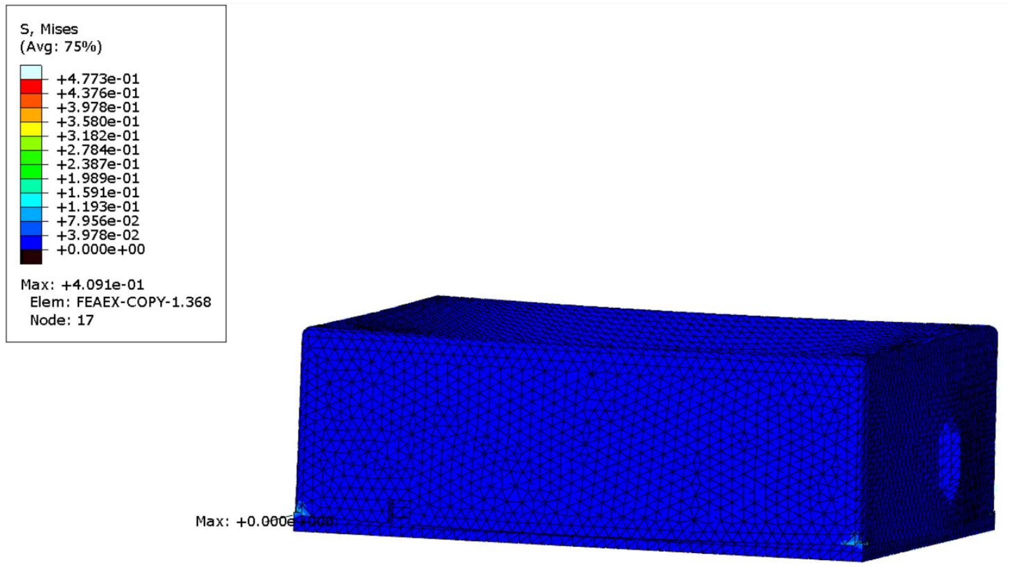


Figure 5.1: Deformation due to 3G force being applied to housings upper surface

From these results we could see that acrylic may not be the best material for the housing. We will have to use a stronger, less brittle material that will not break from a 1.52 m fall. However, using another material could potentially make it more difficult to manufacture the housing. We will take this into consideration for our final product.

6 Computational Analysis: Inlet and Outlet Pipes

6.1 Overview

This section is going to be analyzing the chosen location of the temperature sensors. Determined through testing and various data collection, the locations containing the most useful temperature profile changes of the water are the inlet and outlet pipes of a water heater. However, the true temperature of the water is likely to be different than the measured temperature of the sensors. Therefore our analysis will be considering two cases; one for calculating temperature through the cold water inlet pipe, and one for calculating temperature through the hot water outlet pipe.

6.2 Description of System

For this system, the cold water pipe will be heated through parasitic heat loss from the hot water in the tank during a state where no hot water is being drawn. However, when water is being drawn, the cold water pipe will experience a significant decrease in temperature due to water inlet temperature of about 5°C. The hot water outlet temperature will cool down due to parasitic heat loss to the ambient air during a "no water draw" state, and will heat up slightly as hot water from the tank is being drawn by the user.

The assumption would be that both the cold inlet pipe and hot outlet pipe will have a similar steady state value (when no water has been drawn for a long time). One assumption is that the hot water exiting the tank is constant. With the analysis done in ANSYS, we will verify this assumption. In the analysis, the tank will be insulated, and the water in the tank is at a starting temperature of 49°C. The cold water coming in at 5°C will be traveling at 2 m/s.

After one minute water draw, the temperature profile of the tank will be analyzed to verify the actual temperature that would be exiting through the hot water pipe. Afterwards, heat transfer analysis will be conducted to take into account the heat loss through the assumed brass pipe.

6.3 Diagram

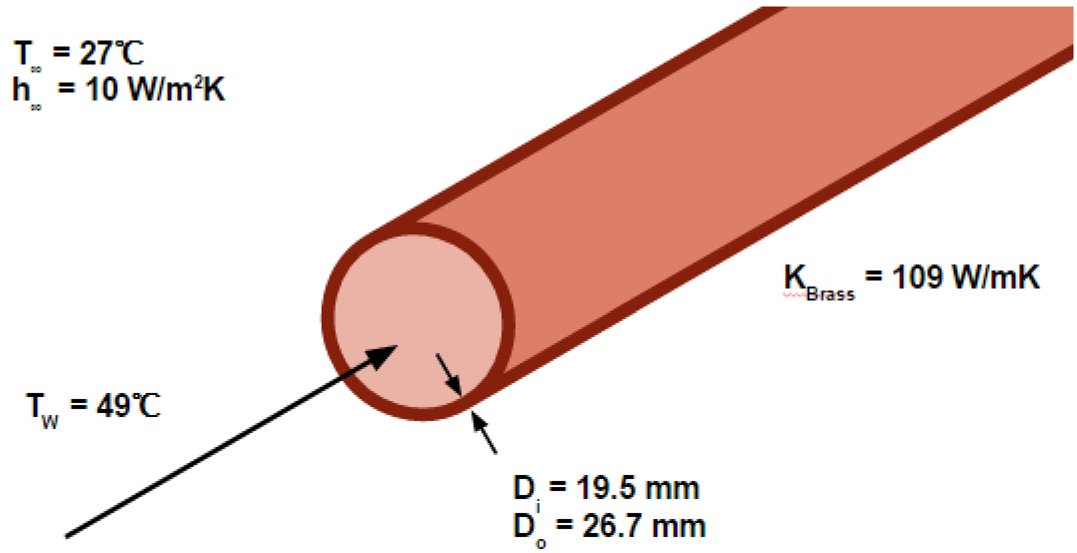


Figure 6.1: Sketch of Physical conditions of a hot outlet pipe, where T_W is the temperature of the hot water, D_i and D_o are the inner and outer diameters of the pipe, respectively, K is the thermal conductivity, and h is the convective heat transfer coefficient.

6.4 Materials and Properties

The pipe which was analyzed had material properties of brass. This includes an outer radius of 26.67 mm, inside radius of 19.05 mm, and a thermal conductivity of $K_{brass} = 109\frac{W}{mK}$. Outside of the pipe is ambient air at a temperature of $T_{ambient} = 300K$, along with a convective heat transfer coefficient of $h_{air} = 10\frac{W}{m^2K}$.

6.5 Simplifying Elements and External Conditions

In order to simplify the model, it was assumed that the interior of the cylindrical pipes were perfectly smooth with no corrosion. The tank was initially filled with 49°C water, and cold water at 5°C is continuously flowing in at 2 m/s. Water also leaves the hot outlet pipe at the same speed. Heat generation is ignored and the results are taken after 1 minute of water draw.

6.6 Output Expectations

The temperature readings for the inlet and outlet pipes are not expected to be the exact same temperature of the water flowing through them due to conductive and convective heat transfer principles. While much of the heat will be conducted through walls of the pipes, there will also be convective heat transfer from the ambient air. The next section will show the calculations made to identify the actual temperature of the outer surface of each pipe.

6.7 Hand Calculations

To find the temperature values that our sensors should read, the temperature of the outer surface of the inlet and outlet pipes of the water heater, needed to be found. Using heat transfer principles, these values, were calculated. These calculations were made under the assumptions of one-dimensional heat transfer, steady state behavior, constant properties, no radiation, and no work done by the system. It was also assumed that the temperature of the hot water leaving the water heater was 49°C and the temperature of the cold water coming in was 5°C. The pipes had an outer radius of 26.67 mm and an inner radius of 19.05 mm.

The equations used are shown below:

$$q = \frac{(T_1 - T_2)(2\pi kL)}{ln(r_2/r_1)} \tag{6.1}$$

$$q = \frac{T_1 - T_\infty}{\Psi} \tag{6.2}$$

$$\Psi = \frac{ln(r_2/r_1)}{2\pi kL} + \frac{1}{h(2\pi rL)} \tag{6.3}$$

Where q is the conductive heat transfer through the pipe, T_1 is the internal pipe temperature, T_2 is the pipe surface temperature, T_∞ is the ambient air temperature, k is thermal conductivity, r_1 and r_2 are the inner and outer radii, Ψ is thermal resistance, and h is the convective heat transfer coefficient. By combining these equations, the value of T_2 can be found. These calculations show that there is about a 2°C temperature change through the hot water pipe and a 1 degree change through the cold water pipe. Therefore, when water is drawn, our temperature sensors should give us readings of about 47°C for the hot water outlet pipe and 6°C for the cold water inlet pipe.

6.8 Modeling Problems Encountered

During the modeling process in ANSYS, there were several problems that were encountered. The biggest issue we faced that resulted in most of the problems was the fact that we did not know how to work the program. FEA analysis is very complex, so learning every detail is difficult. Therefore, we made many assumptions and modeling choices that were very simplified. Stemming from the lack of knowledge of the program, we were not able to make an internal pipe within the geometry. Typically the cold water pipe enters the tank through the top similar to the hot water outlet, but does not expel cold water until an internal pipe nears the bottom. Therefore, in our analysis, the cold water inlet is simply expelling water from the bottom, making the flow of water flow in the wrong direction.

Another issue in the model was the use in incorrect values for temperature. Much after the analysis was complete, we noticed that the initial tank temperature was input incorrectly, resulting in a tank temperature of about 60°C hotter than expected. Time was not sufficient enough to recreate the model.

6.9 Modeling Results

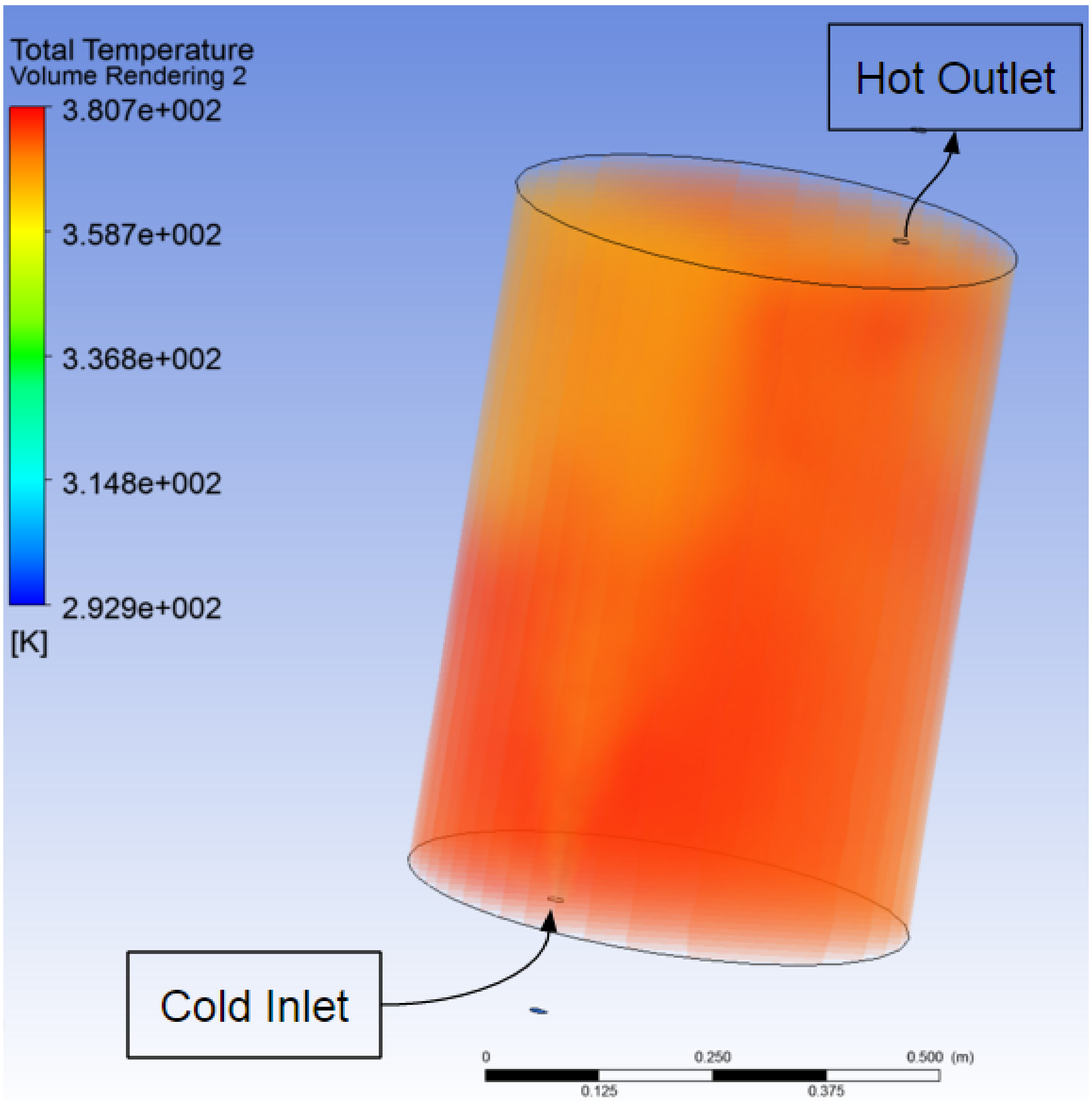


Figure 6.2: ANSYS model of water tank temperature distribution of water after 1 minute.

Figure 6.2 is a transparent view of a model of a hot water tank after 1 minute of water draw. For simplicity, we placed the cold water inlet at the bottom and the hot water outlet at the top. The streamline of cold water can be seen as it mixes at the top of the tank.

6.10 Interpretation of Results

These results seem to be fairly accurate. With this knowledge it can be seen that the values read by our temperature sensors should be close to the actual temperature of the water going into and leaving the tank. However, because in reality the cold water inlet would be facing down and not up, the results would likely by reversed, where the mixture of cold and hot water would actually be on the bottom. With this knowledge, the hot water outlet can actually be assumed the temperature seen at the bottom of the tank in Figure 6.2, which is around 380 K. Addtionally, the value itsself of 380K is much too high, as mentioned in section 1.8. What this can mean is that there will be more of a distribution of cold water throughout the tank. However, the results showed that only one end of the tank was affected by the mixing. The assumption of the results is that this trend will stay true in a more accurate model.

6.11 Conclusion

In conclusion, we determined through ANSYS modeling what the approximate water temperatures would be within the pipes after water draw, then we determined the actual temperature which our sensors would be reading through heat transfer calculations. Given the scope of our project as in addition to the problems encountered, this model still proved the reliability of our temperature data by showing us that we are receiving relatively accurate readings from our sensors. In otherwords, the hot water exiting the tank will likely remain the temperature of the initial water temperature.

7 | System Integration, Test, and Results

7.1 Testing Procedure

In order to test the hypothesis of using the first law of thermodynamics to find the mass flow rate of hot water leaving the tank, two separate tests had to take place. The first test which took place utilized a 10 gallon water heater tank that had temperature sensors attached to the inner tank surface. The second test which took place incorporated a 50 gallon water heater which had temperature sensors attached to the cold inlet and hot outlet pipes. By taking the temperature values from both the 10 gallon and 50 gallon water heater the mass flow rate can be estimated through multiple iterations hot water draw and tests.

7.2 Small Scale: 10 Gallon Water Heater

7.2.1 Test Environment

A small 10 gallon electric water heater was placed inside a hutch which was located in the engineering quad at Santa Clara University. This small hutch consisted of a 25 Sq. Ft room which had one window. This hutch acted as a water heater closet in which a typical water heater would be placed in a standard home. A hot outlet hose was connected from the 10 gallon tank to a standard kitchen sink which was placed outside the hutch. This standard kitchen sink acted as a source in which hot water could be drawn from the tank. Once hot water was drawn from the tank, the internal tank temperature would drop because of cold water entering the tank replacing the hot water leaving. Using the method described in Section 4, the hot water mass flow rate can then be approximated. Once the hot water usage pattern is known, the temperature set point of the hot water heater can then be controlled in order to provide hot water when the user is in need of hot water.

For a two week period the AquAdapt team drew hot from the kitchen sink which was hooked up to the 10 gallon water heater at the same point each day. For the first week the 10 gallon water heater was operating on its own traditional control system. This means the water heater turned on and off when it deemed necessary. After the first week of water draw, a hot water usage pattern was determined using the estimated hot water usage over time. Using the calculated hot water usage pattern, the AquAdapt sensor was then implemented and used to control the on off state of the 10 gallon water heater for the second week.

7.2.2 Test Results

The energy consumed by the 10 gallon water heater during the first week of operation can be seen on the left of the figure below, while on the graph on the right shows the energy consumption from the 10 gallon water heater with the AquAdapt sensor controlling the on and off state of the water heater.

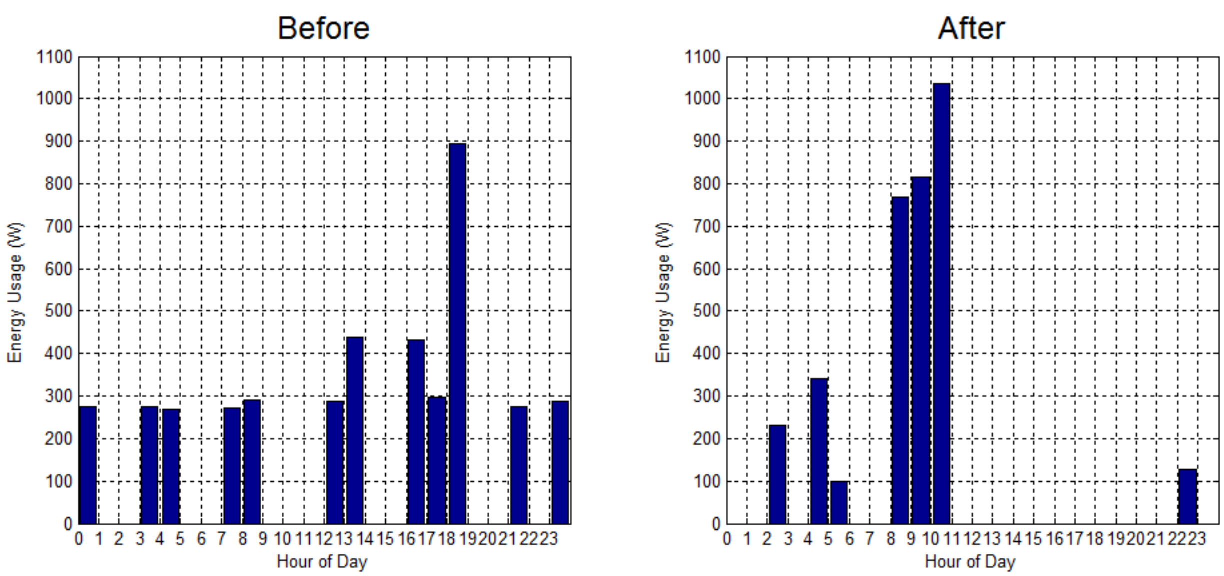


Figure 7.1: Energy Consumption by 10 Gallon Water Heater

It can be seen that the energy consumed by the water heater with the AquAdapt sensor installed leads to a reduction in energy being consumed. 33% less energy was consumed by the 10 gallon water heater with the AquAdapt sensor installed.

7.3 Large Scale: 50 Gallon Water Heater

7.3.1 Test Environment

In order to gather temperature data from a 50 gallon water heater, two different home water heaters were used. One home water heater was an electric 50 gallon water heater which belonged to Joe Singer's parents. The other water heater was a gas 50 gallon water heater which belonged to Michael Simmons. The AquAdapt sensor had its temperature sensors placed on the hot outlet and cold inlet pipes for both water heaters. The sensor was then connected to the internet and relayed temperature data from the water heater to the cloud. Using the temperature values measured, the mass flow rate of hot water can be approximated using techniques outlined in Section 4.

7.3.2 Test Results

Due to safety factors, and the fact that there were no volunteers willing to allow the AquAdapt sensor to fully take control of their home water heater, the possible energy savings by utilizing the AquAdapt sensor were not calculated. The next step in the design process would be allowing an AquAdapt sensor to take full control of a home water heater, thus further measuring the possible energy savings.

8 | Costing Analysis

8.1 Prototype Cost

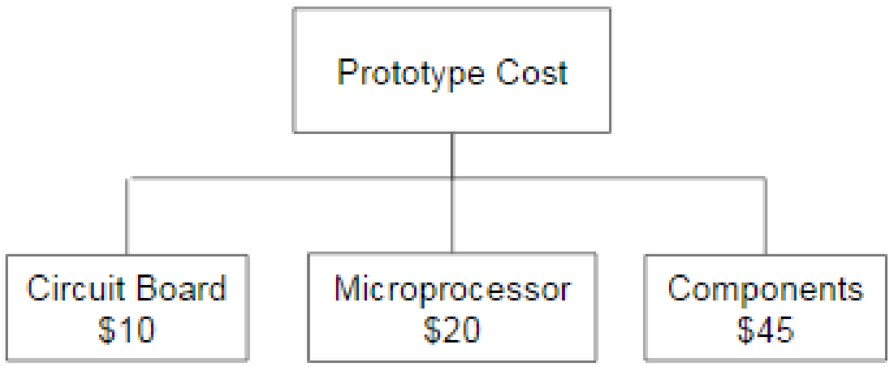


Figure 8.1: Prototype Cost Breakdown

In Figure 8.1 above, the prototype cost breakdown can be observed. The average cost to print a single 2 layered PCB is $10 for a single print. Our team will mostly be printing PCBs one at a time, in order to insure each PCB iteration can handle the desired requirements safely and effectively. The Photon microprocessor retails for $20 through the Particle website. As for the components that will go on the PCB, the estimated $45 stems from various components that will convert AC power to DC power to control the overall state of the water heater. This may involve components such as transformers, relays, transistors, resistors, etc. A further cost breakdown can be observed in Appendix J.1

8.2 Final Cost

Through bulk purchasing and the act of setting up direct purchasing from vendors, the total material cost per AquAdapt sensor totals $40. With mass production, the cost to manufacture one sensor will be minimal in relation to the material cost for each unit. This means that the final product cost for one AquAdapt sensor at retail will be $60. This allows for a %50 markup to be applied to the sensor, allowing for a profit to be made on each sensor sale of $20.

The only other universal smart hot water heater sensor, which hasn't even reached the market yet, is set to retail at $150. The next closest competitor to AquAdapt is the Iris sensor which works exclusively with Energy Smart water heaters. The Iris sensor has a retail price of $70. This means that AquAdapt will have a retail price which is competitive to existing products in the market.

9 | Cost Analysis

9.1 Potential Markets

Due to there not being an established product which achieves the same goal as AquAdapt, it is difficult to find reports on earnings generated from these products. Therefore the Smart Thermostat industry will be analyzed due to the technology between AquAdapt and Smart Thermostats being relatively similar.

The current Smart Thermostat market is valued at $897 million dollars. This market is still increasing and a recent study it found that the market increased 123% in 2015 [13]. The study then goes on to state that the predicted Smart Thermostat market will be valued at $4.7 billion dollars in the year 2021. This market can relate directly to the IoT market and shows the growing opportunity for a product such as AquAdapt.

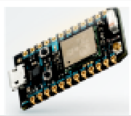
The current consumer of IoT items is upper-middle class with knowledge of advancing technology. This is because the IoT market is emerging and expensive at this time. The products on the market which are associated with the IoT are still within their first few product cycles and carry prices ranging from $150 and higher.

Before AquAdapt could be introduced to the masses it would have to be released online first. This would insure that there is demand for the product. Once that demand is set the product will then have the ability to be distributed through mass production to large retail stores such as Target and Walmart. By letting the AquAdapt sensor be sold exclusively through a website it increases the demand for the product because it seems unique. But in order to generate a larger profit off of AquAdapt it will have to be sold nationwide once the demand has been established.

9.2 Competition

The table 9.1 shown below shows a summary of the comparison between AquAdapt and the present competition on the market.

Table 9.1: Product comparison between AquAdapt, Aquanta, and Iris

	Product	Cost	Universal (Y/N)	Still Under Warranty (Y/N)
	AquAdapt	$60	Y	Y
	Aquanta	~$150	Y	N
	Iris	$70	N	Y

9.3 Sales and Marketing Strategy

Advertising:

Advertising for the AquAdapt sensor will take place through internet advertisements and magazine publications. The best case scenario would have AquAdapt be featured in a large magazine such as Time which tends to highlight recent achievements in technology. This will allow for free advertising on a large scale due to Time having such a large reader base.

Salespeople:

AquAdapt will not need to hire salespeople to make calls to customers in order to try and sell the product. The sales team associated with AquAdapt will work on creating an distribution and advertising strategy which will increase sales of the sensor on a nationwide scale.

Distribution:

Online sales will have to be shipped either through the US Postal service or a similar shipping network. Once the AquAdapt sensor is being sold in large retail stores, a distribution channel will have to be created. This means that freight and possibly overseas shipping will have to take place.

9.4 Manufacturing Plans

Due to the AquAdapt sensor being designed to be created on a mass production scale, it will have the availability to be produced in a number of existing manufacturing facilities. Even though it would be cheaper to manufacture AquAdapt overseas, we as a company choose to manufacture AquAdapt in America. Due to AquAdapt being a small compact product with generic electronic components, it will take a matter of hours to construct one sensor from start to finish on a large scale.

AquAdapt aims to manufacture 100,000 units in the first year. In order to have funding to acquire this goal, AquAdapt must secure $6 million dollars in funding. With $6 million in funding all of the electronic components and housing materials can be purchased, along with hiring the required technicians and manufacturing space.

In order to expand AquAdapt, more funding would be required to purchase its own dedicated manufacturing facility. Once a dedicated manufacturing facility is established, AquAdapt will have the availability to increase production up to 1 million units a quarter or as the market demand is set at.

9.5 Service and Warranties

Due to AquAdapt having no moving parts, it allows for AquAdapt to have a long active life span. The goal is to allow for AquAdapt to be functioning for 8 years inside a home. The reason for a 8 year life cycle is because this time frame matches a standard water heaters warranty period. Meaning when the water heater should be replaced so should the sensor. If the sensor does happen to break when it is under operation or during installation it would be more economic to have the user ship the broken sensor back to our manufacturer rather than having a technician being dispatched to the user's home. Then the customer will receive a new sensor based on the act that caused the sensor to break.

Any technical support for AquAdapt can be handled either online or over the phone. If a user needs assistance to physically install the sensor in their home, then AquAdapt can pursue a 3rd party installation company which can be utilized at a premium to the user.

9.6 Financial Plan

In order to have enough funding to generate 100,000 units, along with paying for employees, office space, distribution, and equipment, AquAdapt will need 6 million dollars in funding. This money would ideally come from Angel Investors who are willing to invest in AquAdapt for a portion of the AquAdapt company. It would take 3 years for AquAdapt to fully return the initial $6 million investment, if AquAdapt continues to produce and sell 100,000 units a year.

This means that an investor will have a return on investment (ROI) of only 3 years. If AquAdapt continues to produce just 100,000 units per year it will be valued at 6 million dollars by the fourth year of creation. By increasing sales and production AquAdapt could be valued at a much higher value.

AquAdapt's contingency plan entails investing 30% of profits back into safe Bonds. This will insure that if a disaster is to strike AquAdapt, there will be ample amount of money invested which could help keep AquAdapt in production.

10 Engineering Standards and Realistic Constraints

10.1 Health and Safety

Safety was the most important issue in regards to our project. Large water heaters operate at high voltage and current levels, leading to the potential for shock to occur. The manufactured PCB needed to be able to transmit 240 volts at a current of 15 amps. To ensure that the manufactured PCB can handle this voltage, the initial design was presented to an ELEN professor which has experience in the field of PCB design. Also when testing, we ensured that the PCB was in a controlled safe environment before running the test voltage across the board. Multiple iterations of the PCB will be designed and tested before they are used on a working 50 gallon water heater.

10.2 Environmental

This product should not cause any detrimental effects to the environment while it is in use. However, it should follow standard disposal procedures for electrical devices. It should not simply be thrown into the trash. It should be recycled properly at any local electronic store that accepts old hardware. There are also public programs that will retrieve your device per request. Failure to do so could result in potential health and environmental risks as improperly disposed electronic goods are burned and release toxic chemicals.

10.3 Economics

This product needed to be aesthetically pleasing. If it is to make it in the market, it must look good on the selves of stores to catch the eye of consumers. Even though users will rarely see the product in their homes, consumers will not buy something that they do not like to look at. To compensate for this the product should be small and symmetrical. It should also eliminate excess wiring wherever possible. The thermocouple wires should be a decent length because the location of the product will depend on the water heater and where the user would prefer to place it. Therefore, to keep the outside wiring to a minimum, a retractable system will be implemented.

10.4 Manufacturability

Another engineering concern was the size and manufacturability of the PCB. The PCB must be as small as possible to fit the housing, allowing it to fit into tight places. Many water heaters are in cramped locations of a household. Therefore, in some cases, there will not be much space to place this product. If the size of the PCB is kept down, this should not be an issue to be concerned about. Also with the final design of the PCB complete, they are not difficult to manufacture.

10.5 Social Benefits

This project has the potential to save homeowners across the United States $144 per year. The goal is to have the final product price of $60 to make it affordable to all. With the initial investment of $60, a consumer will see a quick ROI of about 8 months and continue to save money from that point on. This will especially benefit those below the poverty line where every dollar counts.

11 | Summary

The Aquadapt control system is a low cost, non-invasive device which reduces the amount of energy consumed by a typical household's gas or electric water heater by up to 33%. Three subsystems will be implemented. First, temperature data will be collected and wirelessly sent to an off-site server for analysis. This server will parse through the data to create a usage pattern reflecting the amount of hot water that is required at a given hour of the day. This knowledge of required hot water needed will translate into times to turn on and off the water heater. Lastly, we made sure that the system was safely secured in a housing along with clamps that make installation simple for a typical homeowner.

The AquAdapt sensor has had the ability to demonstrate that current water heaters have the opportunity for energy savings. Further more the sensor has proven that the on off state of the water heater can be controlled for both gas and electric water heaters with an external controller. Finally AquAdapt has successfully demonstrated that a flow rate sensor is not necessary in order to calculate the mass flow rate of hot water leaving the tank. Further work includes creating a phone application which will allow the user to fully control their water heater remotely. Also creating a recognition code which will allow the sensor to recognize when different hot water appliances are being used.

Bibliography

[1] "Water Heating." Energy.gov. N.p., n.d. Web. 05 Dec. 2015. <http://energy.gov/energysaver/water-heating>.

[2] Abdallah, Adel M. "Heterogeneous Residential Water and Energy Linkages and Implications for Conservation and Management." Journal of Water Resources Planning & Management 140.3 (2014): 288-297. Academic Search Complete. Web. 4 Nov. 2015.

[3] Lutz, James. (2005). Estimating Energy and Water Losses in Residential Hot Water Distribution Systems. Lawrence Berkeley National Laboratory. Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory.

[4] Healy, William M., Tania Ullah, and John Roller. "Input-Output Approach To Predicting The Energy Efficiency Of Residential Water Heaters–Testing Of Gas Tankless And Electric Storage Water Heaters." ASHRAE Transactions 117.2 (2011): 521-532. Academic Search Complete. Web. 4 Nov. 2015.

[5] Lutz, James D., Peter Biermayer, and Derek A. King. "Pilot Phase Of A Field Study To Determine Waste Of Water And Energy In Residential Hot-Water Distribution Systems." ASHRAE Transactions 117.1 (2011): 755-768. Academic Search Complete. Web. 4 Nov. 2015.

[6] Whitaker, Jerry C. The Resource Handbook of Electronics. Boca Raton, FL: CRC, 2001. Print.

[7] "Country Comparison Population below Poverty Line." Population below Poverty Line.

N.p., n.d. Web. 16 Nov. 2015.

[8] Brown, Michael. "The Aquanta Smart Water-heater Controller." TechHive. N.p., n.d. Web. 05 Dec. 2015.< http://www.techhive.com/article/2849816/the-aquanta-smart-water-heater-controller-promises-to-slash-your-energy-bill.html>.

[9] "EnergySmart Energy Smart Electric Water Heater Controller Works with Iris." Lowes.com. N.p., n.d. Web. 05 Dec. 2015. <http://www.lowes.com/pd_612026-135-6911211_0__?productId=50292493>.

[10] "Energy Smart® Electric Water Heaters." Energy Smart® Electric Water Heater. N.p., n.d. Web. 05 Dec. 2015. <http://www.whirlpoolwaterheaters.com/learn-more/electric-water-heaters/6th-sense%E2%84%A2/energy-smart%C2%AE-electric-water-heaters>.

[11] Incropera, Frank P., and Frank P. Incropera. Fundamentals of Heat and Mass Transfer. Hoboken, NJ: John Wiley, 2007. Print.

[12] "Is 3D Printing a Viable and Affordable Alternative to Injection Molding Production?" 3ders.org. N.p., n.d. Web. 06 Dec. 2015. <http://www.3ders.org/articles/20141106-is-3d-printing-technology-a-viable-and-affordable-alternative-to-injection-molding-production.html>.

[13]"Global Smart Thermostat Market Grew 123% in 2015, Smart Home Becoming Mainstream." IoT Analytics Market Insights for the Internet Of Things. N.p., 08 Mar. 2016. Web. 31 May 2016.

Appendices

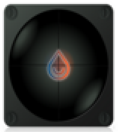
A Customer Needs Survey Results

Table A.1: Results of customer needs survey.

Number of People in Household	Average Shower Time (minutes)	Total Shower Time (minutes)
1	10	10
2	5	10
2	5	10
2	5	10
2	6	12
2	6	12
2	7	14
2	8	16
2	10	20
2	10	20
2	10	20
2	10	20
3	8	24
2	13.5	27
4	7	28
2	14	28
6	5	30
4	8	32
4	10	40
2	20	40
4	10	40
3	15	45
4	12	48
4	12	48
10	5	50
5	12	60
8	10	80

B Product Comparison

Table B.1: List of various products and their pros and cons.

Product	Pros	Cons
Energy Smart® Electric Water Heaters Whirlpool  http://www.whirlpoolwaterheaters.com/learn-more/electric-water-heaters/6th-sense%E2%84%A2/energy-smart%C2%AE-electric-water-heaters/	• Environmentally friendly Non-CFC insulation (chlorofluorocarbons, does not affect ozone layer) • Adjusts to usage • Vacation mode	• People have complained of it not lasting long (2-3 years) • Not recognizing water in tank
Iris Energy Smart Electric Water Heater Controller  http://www.lowes.com/pd_612026-135-6911211_0__?productId=50292493	• Attaches to top of water heater • Control water heater from phone • Updates on when you are low on hot water • Custom Schedules • Wi-Fi	• Works exclusively with Energy Smart electric water heaters. • $70
Aquanta  http://www.techhive.com/article/2849816/the-aquanta-smart-water-heater-controller-promises-to-slash-your-energy-bill.html	• Wi-fi • Predicts usage patterns • Control from a phone app	• Never made it into the market • Connects to valves thus voiding water heater warranty • $150

C Budget

Table C.1

Budget		
Temperature Sensors and Adhesives		
Thermocouple	Various types desired for testing.	250
Adhesives	Various types desired for testing.	250
TOTAL		**500**
PCB Components and Manufacturing		
Electrical Components	Many components required to build effective circuit.	600
Manufacturing	Printing of complex PCB designs.	500
TOTAL		**1100**
Gas Water Heater Controller		
Gas Controllers	Existing controllers required for manipulation.	800
Additional Components	Any extra components used for system.	200
TOTAL		**1000**
System Housing		
Materials	Various materials desired for construction.	500
Manufacturing	The actual construction of housing.	500
TOTAL		**1000**
GRAND TOTAL:		**3600**

D | Decision Matrices

Table D.1: Decision Matrix for Housing

Date: Today

	Criterion	1	2	3	4	5	6	7	8	9	10	11	12	SUM	FACTOR
1	Weight		0	0	0	0								0	0.5
2	Size	1		1	0	0								2	2
3	Shape	1	0		0	0								1	1
4	Safety	1	1	1		1								4	5
5	Security	1	1	1	0									3	4
6		1	1	1	1	1								5	
7		1	1	1	1	1	1							6	
8		1	1	1	1	1	1	1						7	
9		1	1	1	1	1	1	1	1					8	
10		1	1	1	1	1	1	1	1	1				9	
11		1	1	1	1	1	1	1	1	1	1			10	
12		1	1	1	1	1	1	1	1	1	1	1		11	

Table D.2: Decision Matrix for Housing

Design Project = AquAdapt **System=**

	TARGET or	DESIGN IDEAS																			
CRITERIA	FACTOR	1 = Baseline		Sheet Metal		Vaccum Seal Mold		four		five		six		seven		eight		nine		ten	
Time – Design	2	2		2		4															
Time – Build	4	4		5		2															
Time – Test	1	1		2		1															
Time Score	10		10		14.17		11.67		0.00		0.00		0.00		0.00		0.00		0.00		0.00
Cost – Prototype	2	$ 2.00		$ 5.00		$ 6.00															
Cost – Production	0.5	$ 0.50		$ 1.50		$ 0.10															
Cost Score	10		10		27.50		16.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00
Weight	0.5	3	1.5	2	1	2	1	1			0		0		0		0		0		0
Size	2	3	6	2.5	5	3	6	1			0		0		0		0		0		0
Shape	1	3	3	2.5	2.5	2	2	1			0		0		0		0		0		0
Safety	5	3	15	2	10	2	10	1			0		0		0		0		0		0
Security	4	3	12	3.5	14	2	8	1			0		0		0		0		0		0
0	0	3	0		0		0	1			0		0		0		0		0		0
0	0	3	0		0		0	1			0		0		0		0		0		0
0	0	3	0		0		0	1			0		0		0		0		0		0
0	0	3	0		0		0	1			0		0		0		0		0		0
0	0	3	0		0		0	1			0		0		0		0		0		0
0	0	3	0		0		0	1			0		0		0		0		0		0
0	0	3	0		0		0	1			0		0		0		0		0		0
	TOTAL		37.5		10.8		19.3		20.0		20.0		20.0		20.0		20.0		20.0		20.0
	RANK																				
	% MAX		100.0%		28.9%		51.6%		53.3%		53.3%		53.3%		53.3%		53.3%		53.3%		53.3%
	MAX	37.5																			

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE = Acrylic

Design Idea Descriptions

2 Sheet Metal
3 Vaccum Seal Mold

E | Gantt Charts

Table E.1: Gantt Chart for 1st Phase of Design Process

ACTIVITY	PLAN START (Week)	PLAN DURATION (# Weeks)	ACTUAL START (Week)	ACTUAL DURATION (# Weeks)	LEAD PERSON	PERCENT COMPLETE	PERIODS 1 Period = 1 Week 1 2 3 4 5 6 7 8 9 10
Fall							
Apply For Funding	3	2	3	2	ALL	100%	
Assign Specific Overall Goals	3	1	3	1	ALL	100%	
Begin Collecting Data on 50 Gallon WH	3	7	3	7	Scott	100%	
Move Hutches in Quad	3	1	3	1	ALL	100%	
Check Local Appliance Stores	3	1	3	1	ALL	100%	
Research on Competitors	4	2	4	2	Michael	100%	
Research on what has already been done	4	2	4	2	Michael	100%	
Check Neighboors Water Heater	3	2	3	2	ALL	100%	
Housing sketch made	5	2	5	2	Michael	100%	
Research Water Heater Safety Requrements	5	2	5	2	Scott	100%	
Research Different Thermocouples	5	2	5	2	Scott	100%	
Research Parts for PCB	5	2	5	2	Joe	100%	
Create System of Retractable Thermocouples	5	2	5	2	Michael	100%	
Create Way to Attach Thermocouple to Tank	6	2	6	2	Joe	100%	
MATLAB Code, Implement/Debug for 50 Gallon Tank	6	2	6	2	Scott	100%	
PCB Trace (Replace Traces with Larger Ones)	7	3	7	3	Joe	100%	
First Prototype for Housing (Inital 3D print or Vacuum Mold)	7	2	7	2	J, M	100%	
Purchase Thermocouples	9	1	9	1	Scott	100%	
Purchase PCB components	9	1	9	1	Joe	100%	
Purchase Thermocouple Attachments (Clamps, Magnets or Stick)	9	1	9	1	Scott	100%	

Table E.2: Gantt Chart for 2nd Phase of Design Process

ACTIVITY	PLAN START (Week)	PLAN DURATION (# Weeks)	ACTUAL START (Week)	ACTUAL DURATION (# Weeks)	LEAD PERSON	PERCENT COMPLETE	PERIODS 1	2	3	4	5	6	7	8	9	10
Winter																
Manual Code Running	1	2	1	2	Scott	100%										
Print and Test PCB (High voltage)	1	1	1	1	Joe	100%										
Finalize Housing Design and Material	1	3	1	3	Mike	100%										
Look into surface mount printing	3	1	3	1	Joe	100%										
Automated Code	3	6	3	6	Scott	100%										
Gas Water Heater Research	3	2	1	2	Mike	100%										
Design PCB for gas Heater	6	10	6	10	ALL	100%										
5 Complete PCBS Complete	1	10	1	10	ALL	100%										
Revised Schedule, Hardware goals, Part List	2	1	2	1	ALL	100%										
Ethics/Professionalism, Safety Assignment, Protocols	4	1	4	1	ALL	100%										
Budget update	4	1	4	1	ALL	100%										
Detail Drawings	5	1	5	1	ALL	100%										
Analysis Report	8	1	8	1	ALL	100%										
Assembly Drawings, Hardware	10	1	10	1	ALL	100%										

1 Period = 1 Week

Table E.3: Gantt Chart for 3rd Phase of Design Process

ACTIVITY	PLAN START (Week)	PLAN DURATION (# Weeks)	ACTUAL START (Week)	ACTUAL DURATION (# Weeks)	LEAD PERSON	PERCENT COMPLETE	PERIODS 1	2	3	4	5	6	7	8	9	10
Spring																
Analyze Data from Given Out PCBs	1	1	1	1	ALL	100%	■									
Review feedback from 5 PCB users	1	2	1	2	ALL	100%	■									
Thesis Table of Contents/Intro/Drawings/Timeline	2	1	2	1	ALL	100%		■								
Complete Final Housing/Attachment Design	2	1	2	1	S/M	100%		■								
Experimental Protocol, PDS Update	3	1	3	1	ALL	100%			■							
Full Draft of Presentation	3	2	3	2	ALL	100%			■							
Mass Flow Rate Code Completion	4	2	4	2	ALL	100%				■						
Societal/Enviornmental Impact Presentation	5	1	5	1	ALL	100%					■					
Machine Learning Implementation	5	3	5	3	Joe	100%				■	■	■				
Market Analysis for Cost of Sensor	5	1	5	1	ALL	100%					■					
Senior Design Presentation	6	1	6	1	ALL	100%						■				
Full Draft of Thesis	7	1	7	1	ALL	100%							■			
Patent Search/Buisness Plan	8	1	8	1	ALL	100%								■		
Final Written Report	10	1	10	1	ALL	100%										■

1 Period = 1 Week

F | PCB Drawings

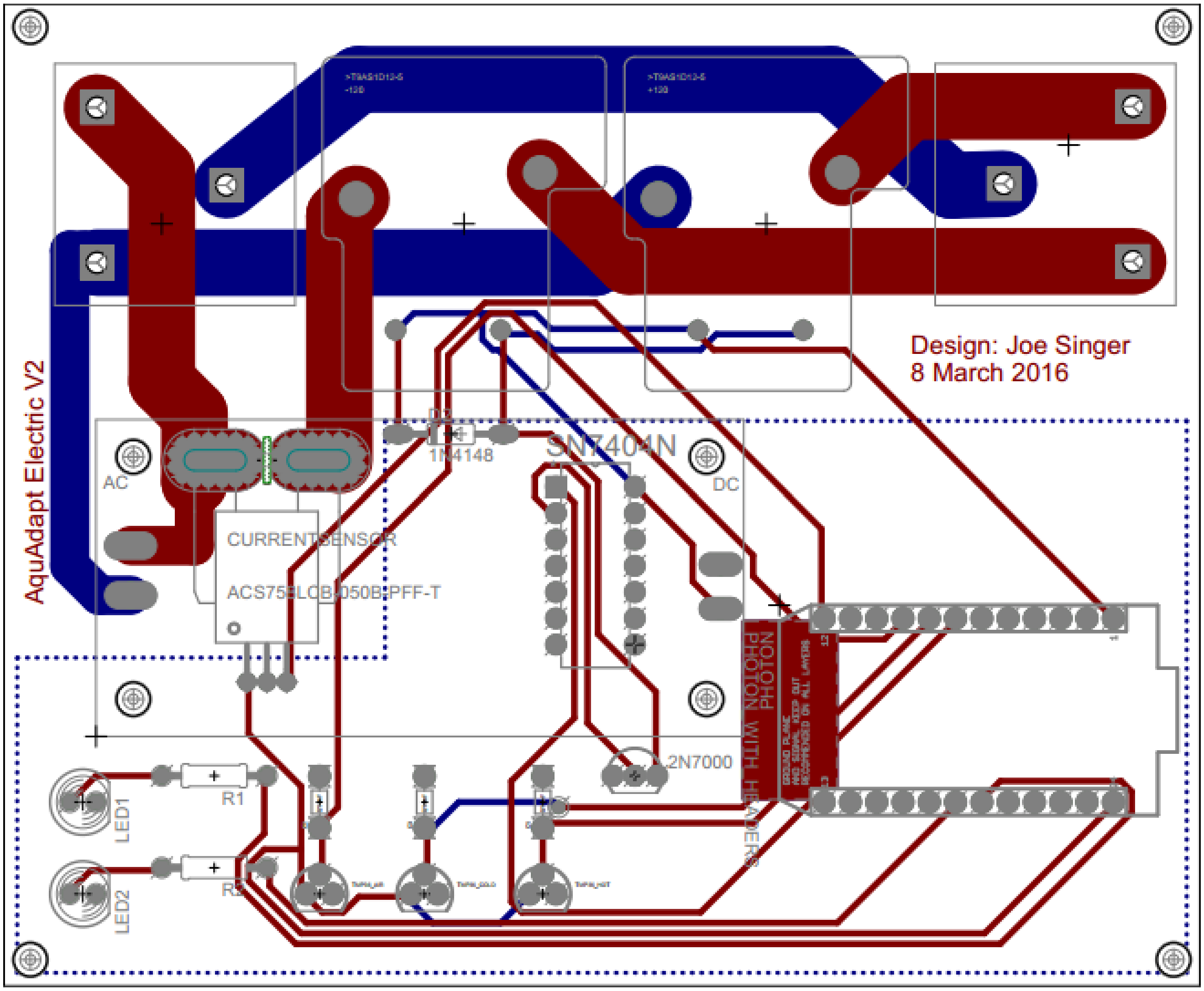


Figure F.1: Electric water heater PCB

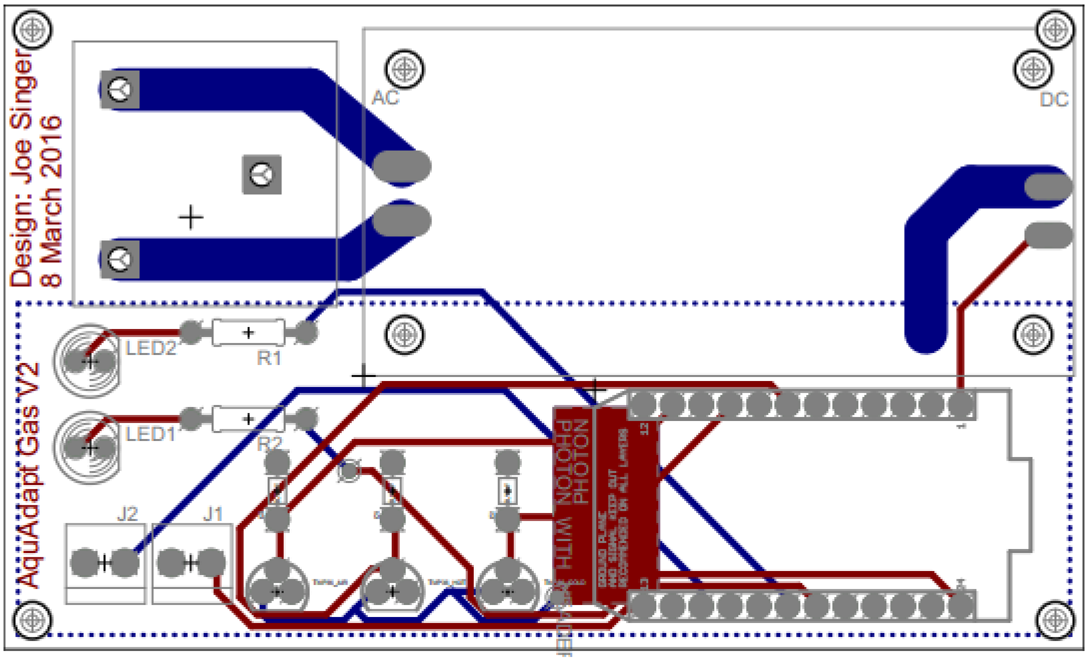


Figure F.2: Gas water heater PCB

G PDS

Table G.1: PDS

ELEMENTS/ REQUIREMENTS		PARAMETERS	
	UNITS	DATUM	TARGET-RANGE
PERFORMANCE			
PCB Power Usage	W	-	3
Energy Savings	%	30	35
Annual Energy Savings	kWh	1095	1200
Temperature Accuracy	%	-	95
Equation Accuracy	%	-	80
Operating Cost	$/Year	2.10	4.50
Durability (From Drop Test)	ft	-	6
Operating Temperature	C	-	0-49
PCB Layers	#	-	3
Product Cost	$	250	40
Market Price	$	-	60
Size	ft^3	4.41	0.125
Life Span	years	13	15
Shelf Life	years	-	30
Housing Material	-	Acrylic	ABS
Weight	kg	1.5	1
Installation Time	Hours	0.5	0.25

H | Housing Sketch and Drawings

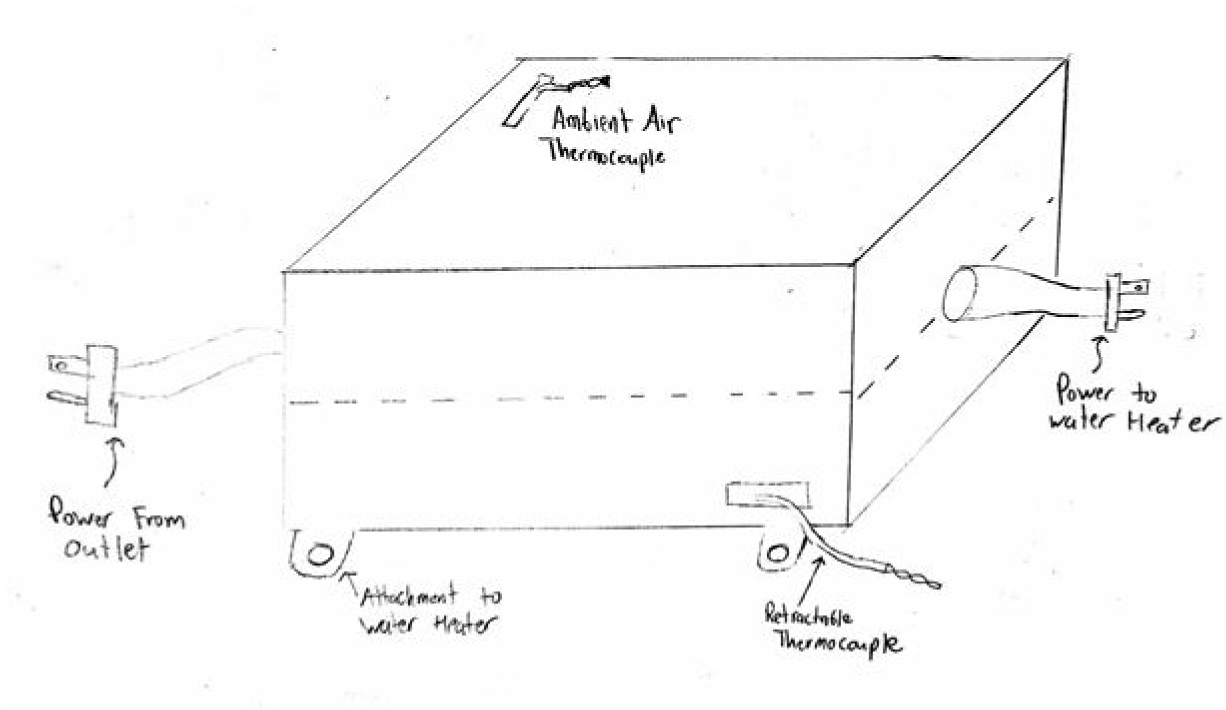


Figure H.1: Initial Housing Sketch Drawn By: Scott Jansen

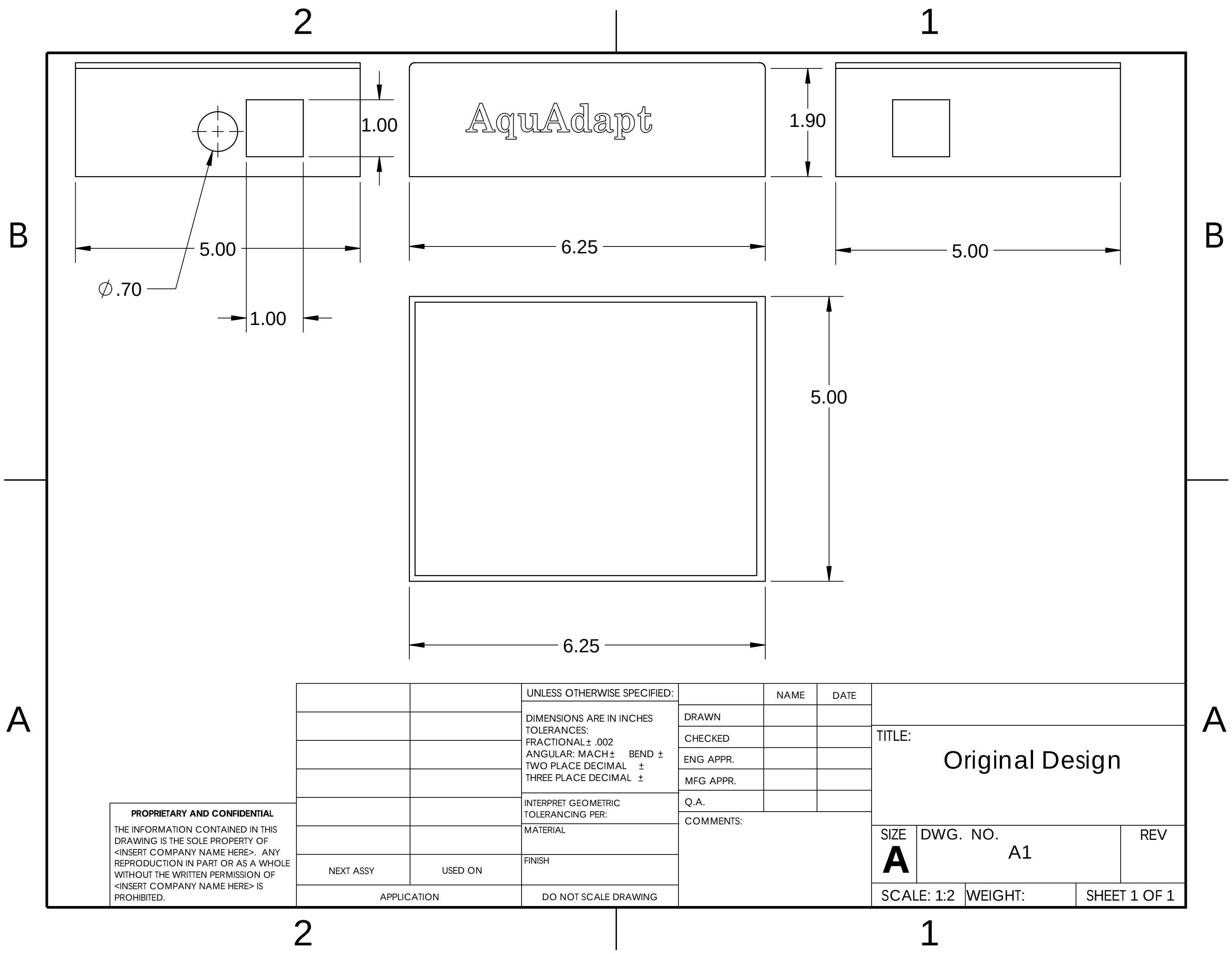


Figure H.2: Original 3D Modeled Housing By: Michael Simmons

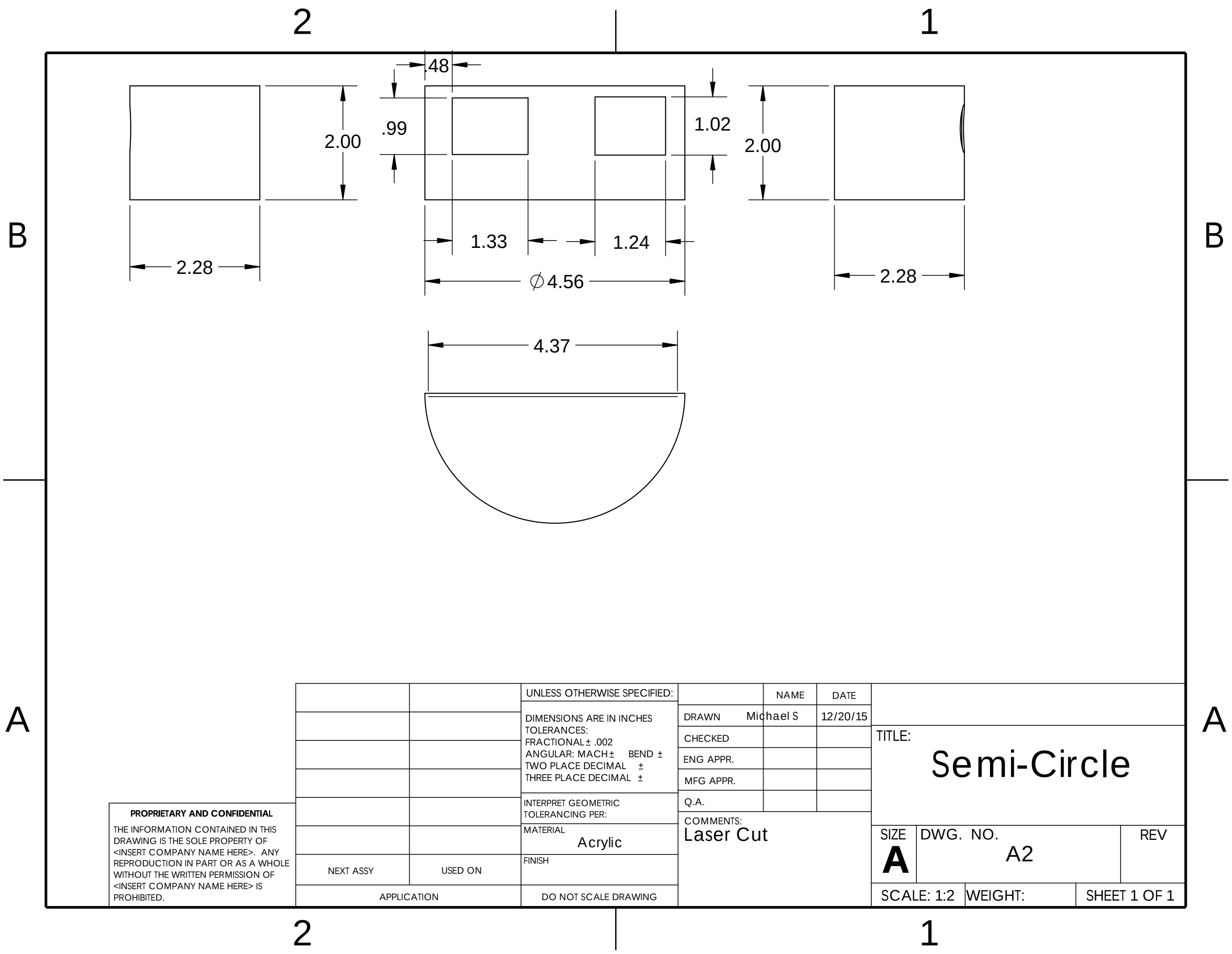


Figure H.3: Semi-circle Housing Design By: Michael Simmons

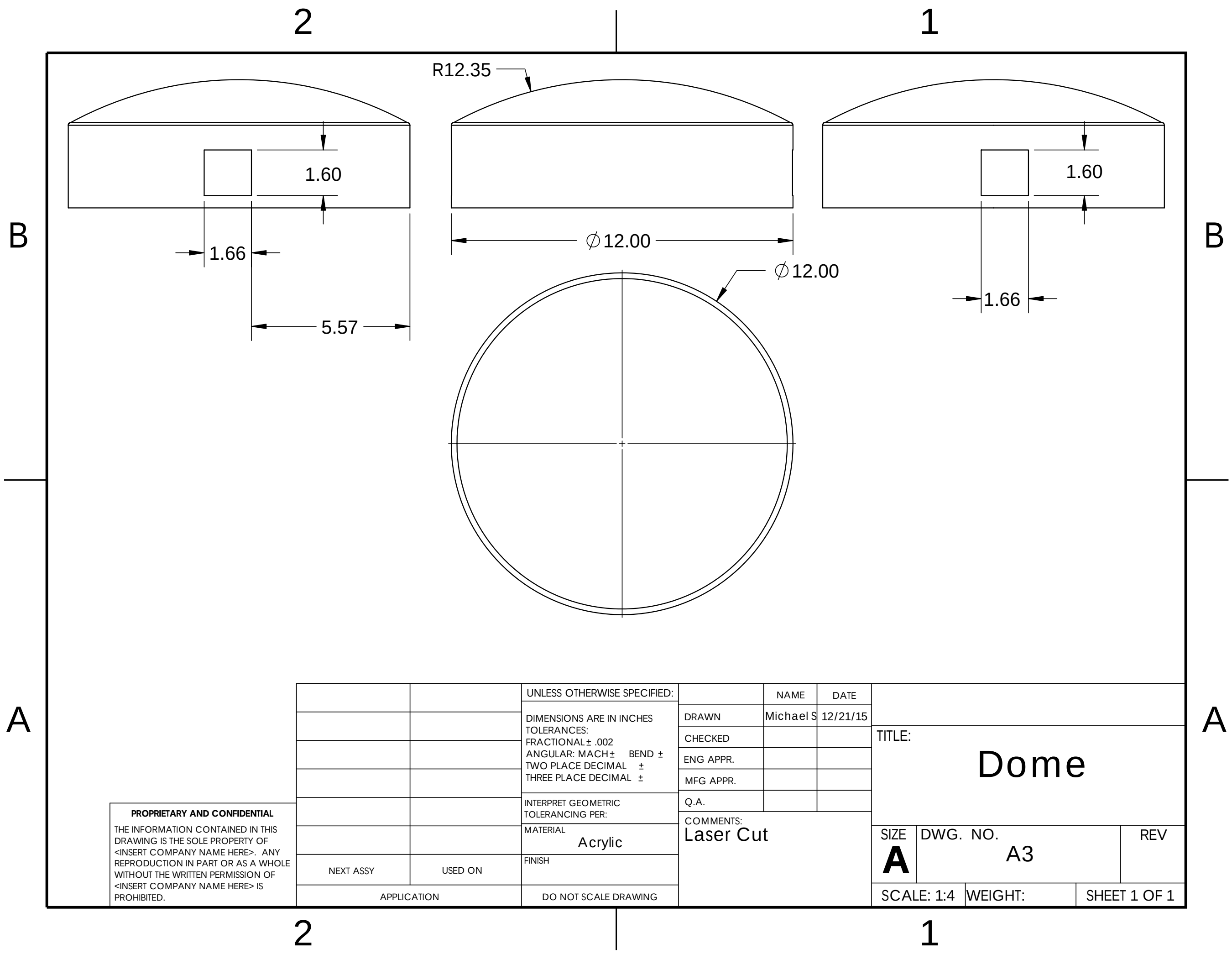


Figure H.4: Dome Housing Design By: Michael Simmons

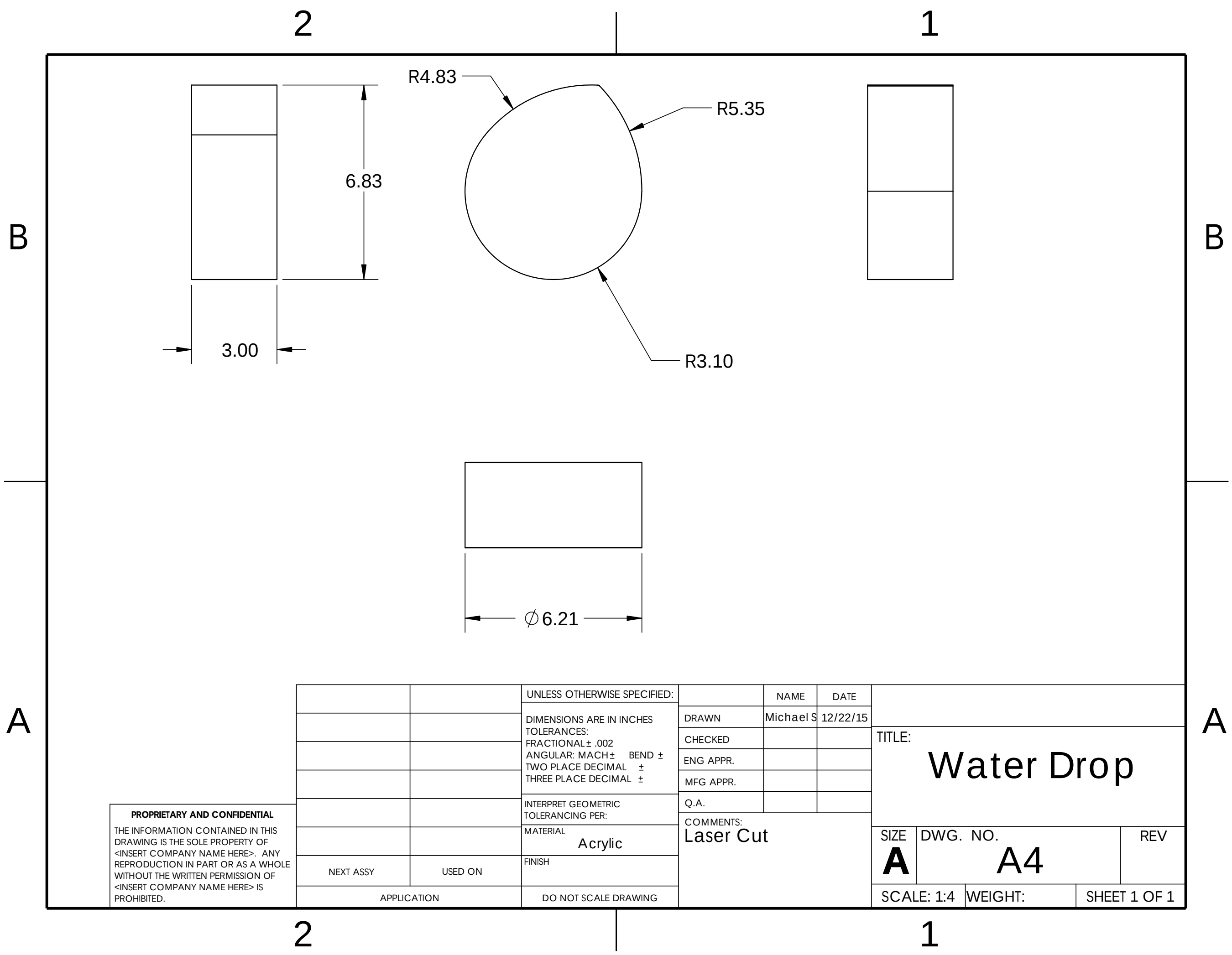


Figure H.5: Water Drop Housing Design By: Michael Simmons

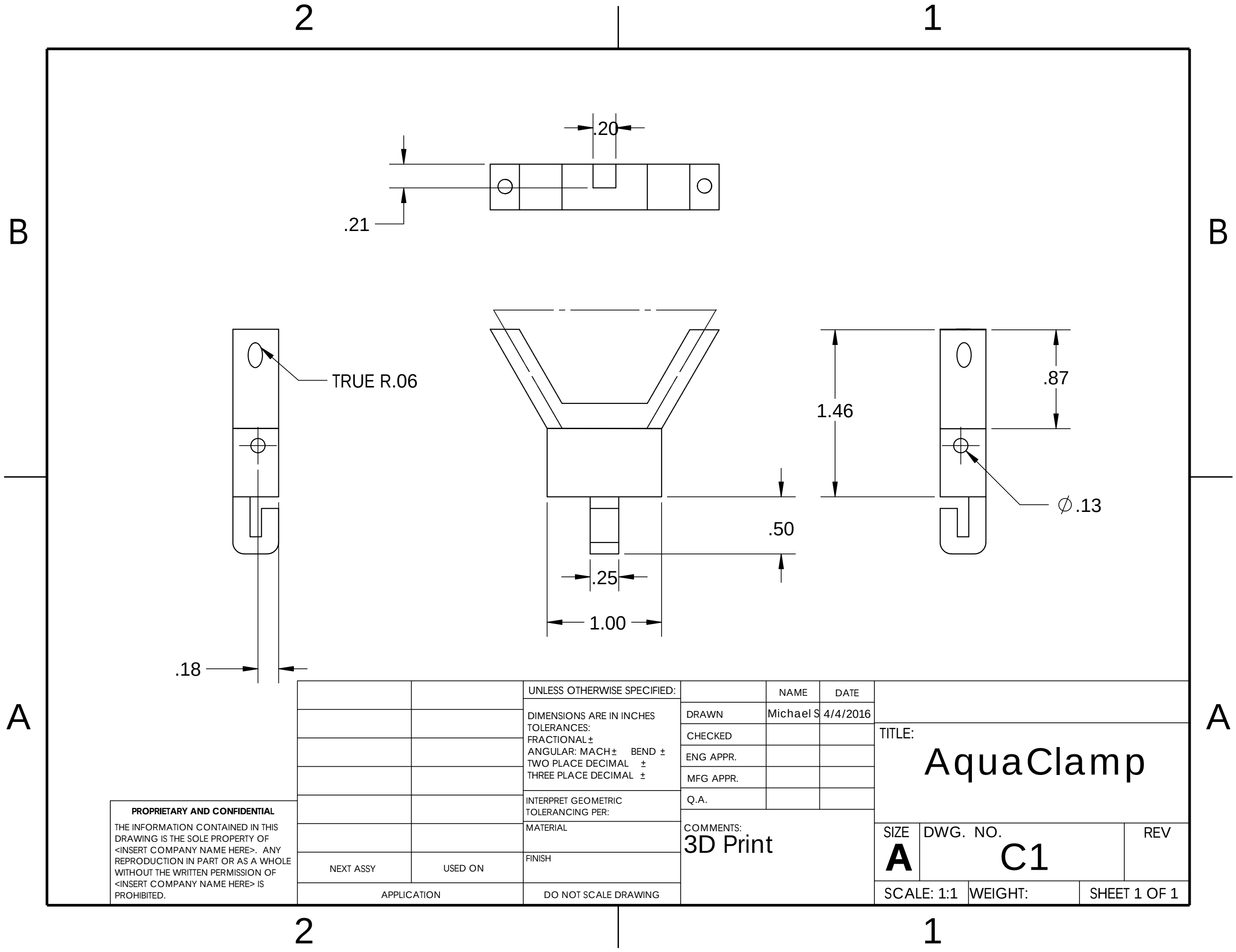


Figure H.6: Clamp Design with Hook By: Michael Simmons

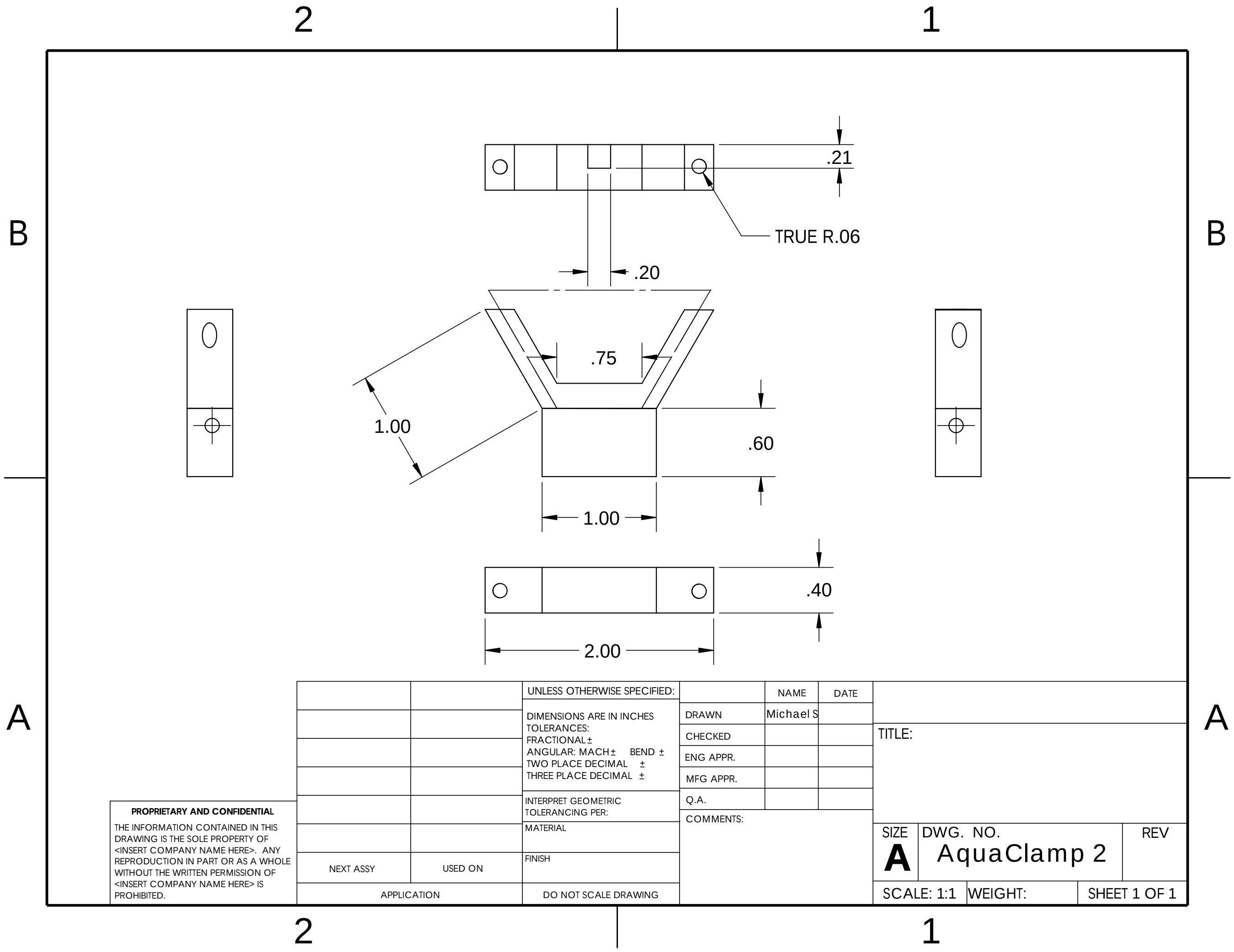
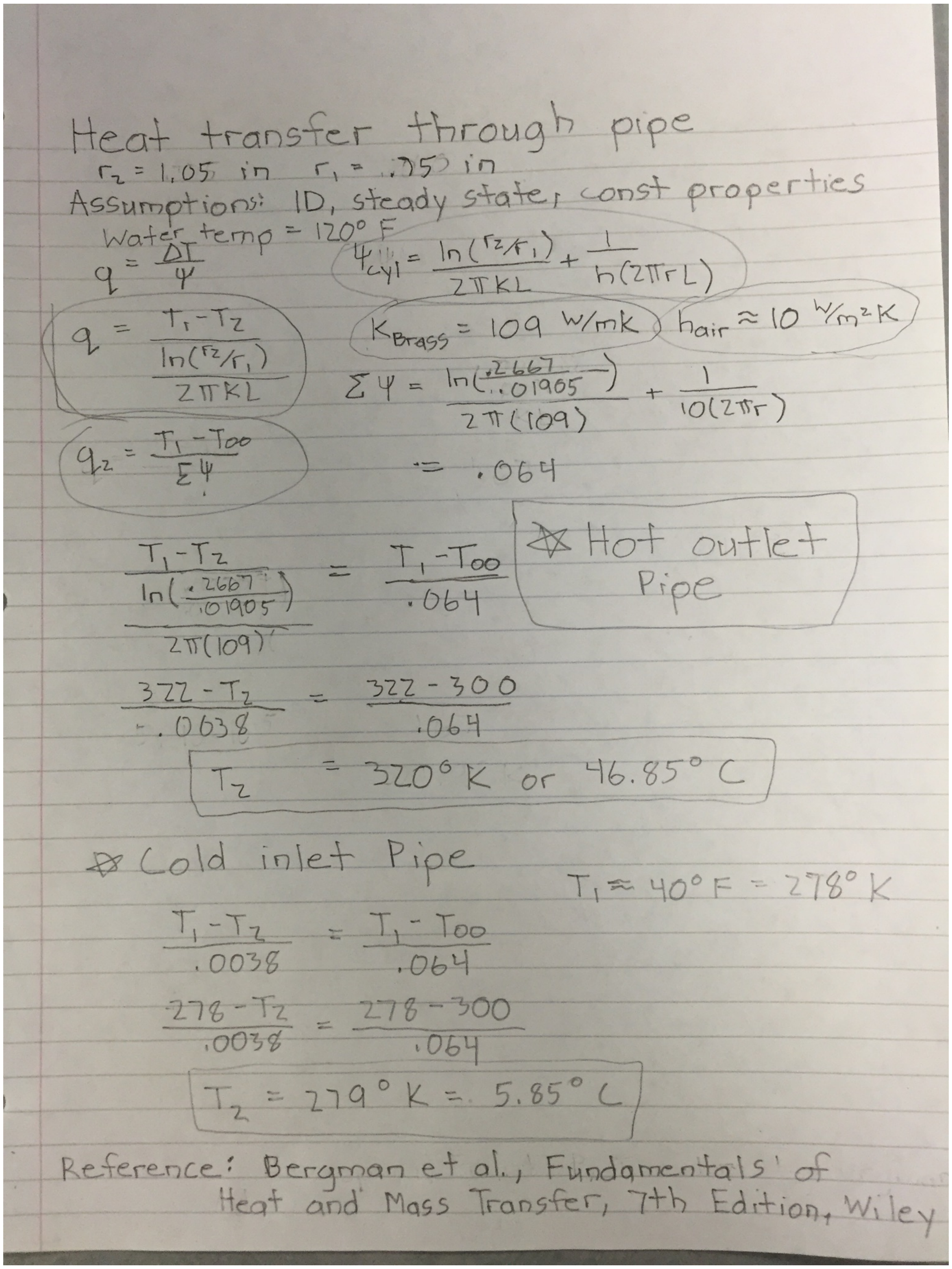


Figure H.7: Clamp Design without Hook By: Michael Simmons

I Hand Calculations for Pipe Computational Analysis



Heat transfer through pipe

$r_2 = 1.05$ in $\quad r_1 = .75$ in

Assumptions: 1D, steady state, const properties

Water temp = 120° F

$q = \frac{\Delta T}{\psi}$ $\qquad \psi_{cyl} = \frac{\ln(r_2/r_1)}{2\pi K L} + \frac{1}{h(2\pi r L)}$

$q = \frac{T_1 - T_2}{\frac{\ln(r_2/r_1)}{2\pi K L}}$ $\qquad K_{Brass} = 109$ W/mK $\qquad h_{air} \approx 10$ W/m²K

$q_2 = \frac{T_1 - T_\infty}{\Sigma\psi}$ $\qquad \Sigma\psi = \frac{\ln\left(\frac{.2667}{.01905}\right)}{2\pi(109)} + \frac{1}{10(2\pi r)} = .064$

$\frac{T_1 - T_2}{\frac{\ln\left(\frac{.2667}{.01905}\right)}{2\pi(109)}} = \frac{T_1 - T_\infty}{.064}$ $\quad$ ☆ Hot outlet Pipe

$\frac{322 - T_2}{.0038} = \frac{322 - 300}{.064}$

$T_2 = 320°$ K or $46.85°$ C

☆ Cold inlet Pipe $\qquad T_1 \approx 40°$ F = 278° K

$\frac{T_1 - T_2}{.0038} = \frac{T_1 - T_\infty}{.064}$

$\frac{278 - T_2}{.0038} = \frac{278 - 300}{.064}$

$T_2 = 279°$ K = 5.85° C

Reference: Bergman et al., Fundamentals of Heat and Mass Transfer, 7th Edition, Wiley

Figure I.1: Hand Calculations for the inlet and outlet pipe computational analysis.

J Prototype Cost Breakdown

Part	Price ($)	QTY Bought	QTY Needed for Single Prototype	Prototype Cost ($)	Estimated Cost of Mass Production ($)
ELECTRIC					
PCB	86	10	1	8.6	3
Relays	72.6	20	2	7.26	5
Current sensors	94.5	15	1	6.3	5
Temp Sensor	63.05	50	3	3.783	1
MOSFET	6.73	25	1	0.2692	0.05
Inverter	17.23	10	1	1.723	1
Photon	19	1	1	19	10
Capacitors	1.71	100	3	0.0513	0.01
Diodes	4.52	100	1	0.0452	0.01
Lrg. Term Blck	55.77	10	2	11.154	5
Power Converters	38.1	10	1	3.81	2
Spacers	1	1	6	6	3
Acrylic	4.5	1	1	4.5	4
TOTAL				**72.4957**	**39.07**
GAS					
PCB	78	10	1	7.8	3
Temp Sensor	63.05	50	3	3.783	1
Photon	19	1	1	19	10
Capacitors	1.71	100	3	0.0513	0.01
Small Term Blk	10.92	20	2	1.092	0.5
Lrg. Term Blck	55.77	10	1	5.577	3
Spacers	1	1	6	6	3
Acrylic	4.5	1	1	4.5	4
TOTAL				**47.8033**	**24.51**

Figure J.1: Breakdown of total cost of the electric and gas prototypes.

K | Senior Design Conference Presentation Slides

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AquAdapt

Michael Simmons
Joe Singer
Scott Jansen

Advisor: Hohyun Lee

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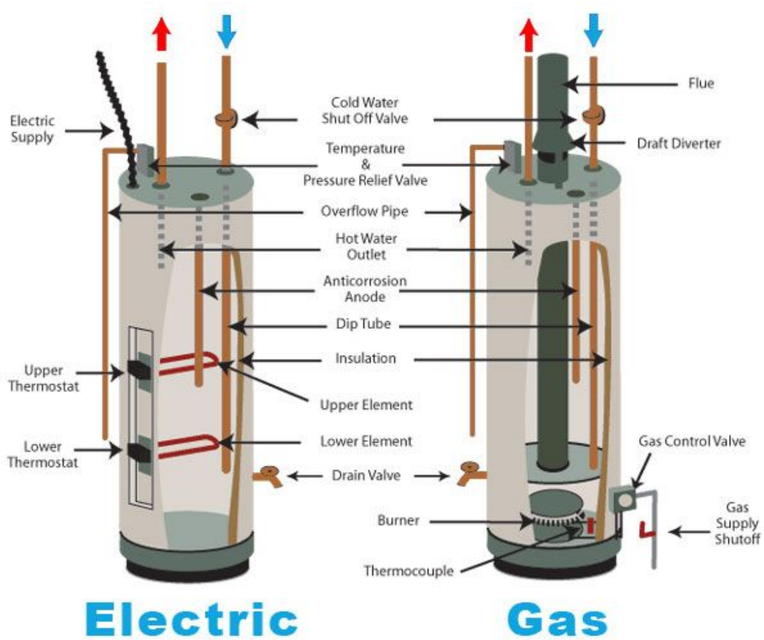
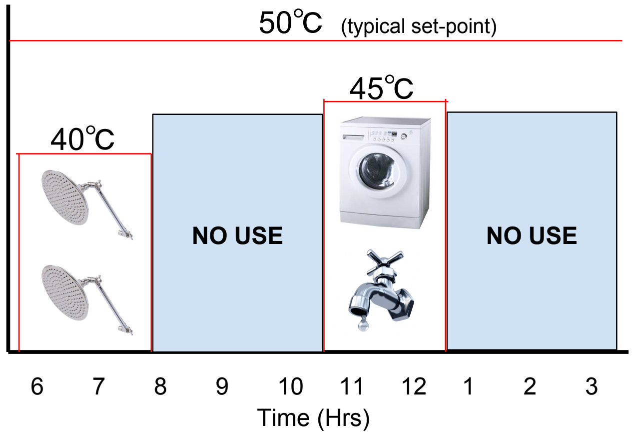
Water Heater Comparison



Why Does the World Need AquAdapt?

- Traditional water heaters waste energy
  - Standby heat loss
  - Improper/mixing hot water temperature



Project Overview

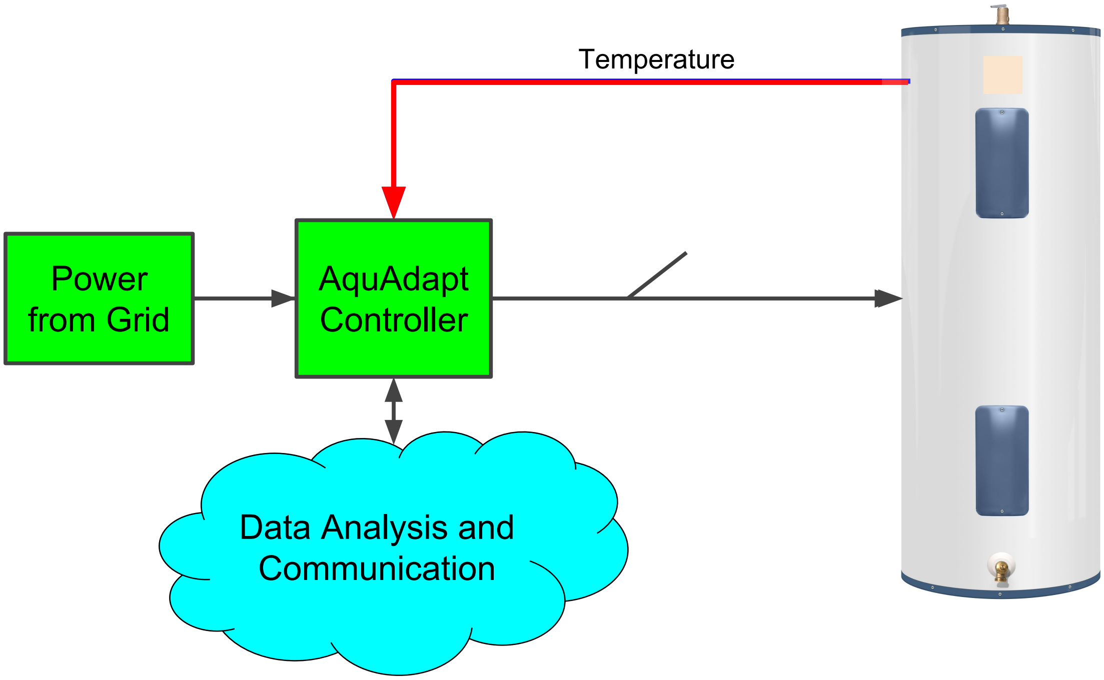
Collects data from water heater

Heats water when needed

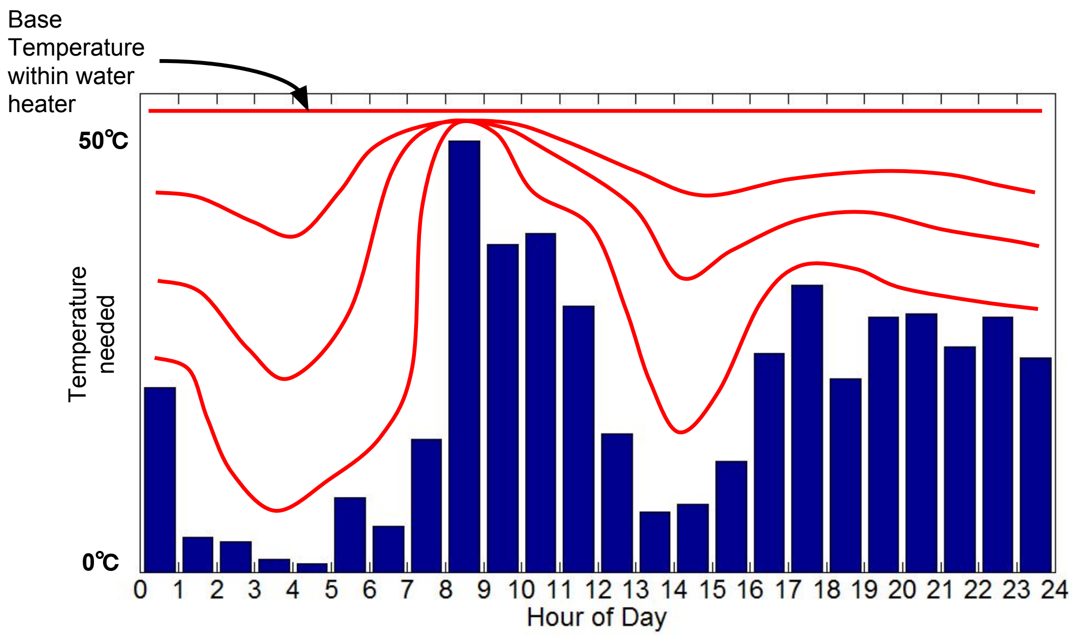
Increase Efficiency

Gas and Electric compatibility

Internet of things



Overall Goal



Technical Challenges

- Minimize sensors used (without flow sensor)
- Variety of water heater configurations
- Reduce need for big data
- Feedback collection



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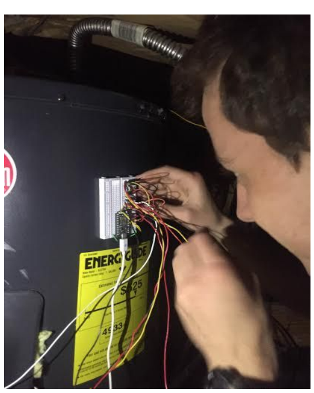
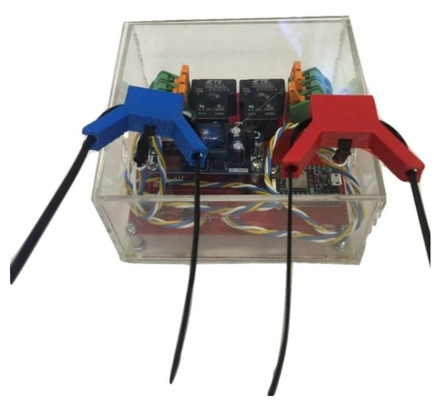
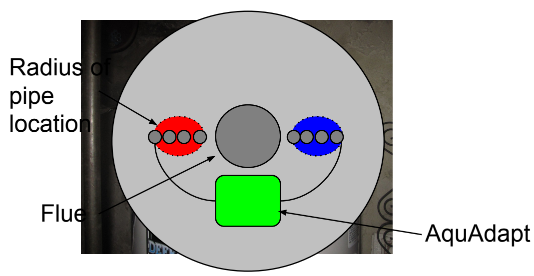
Minimize Sensors Used

- Reduce installation time & cost
- Maximize sensor effectiveness
- No flow rate sensor

Universality

- Make device for all water heaters
  - Gas and Electric
- Place temperature sensors on pipes
- Clamps
- Out of sight out of mind



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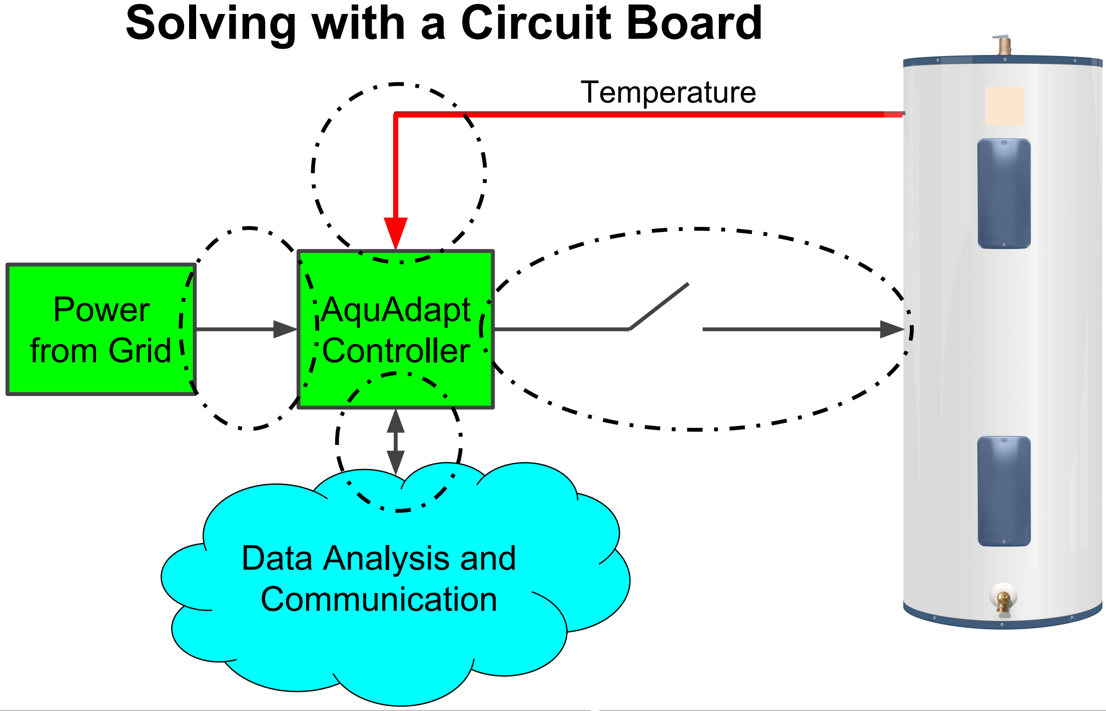
Solving with a Circuit Board



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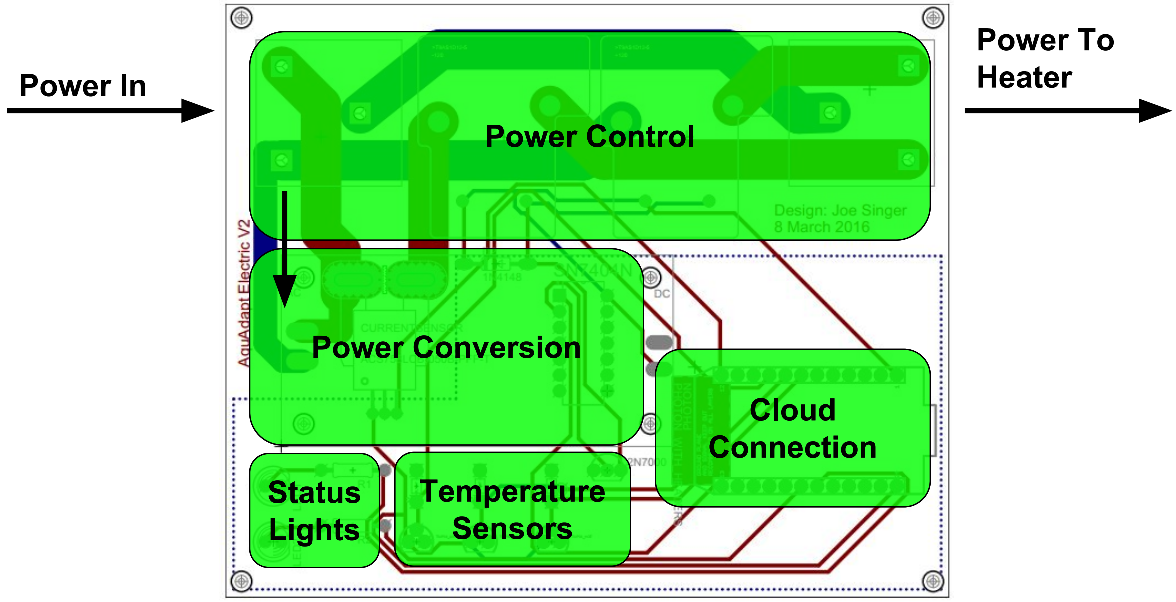
Strategic Circuit Design (Electric)



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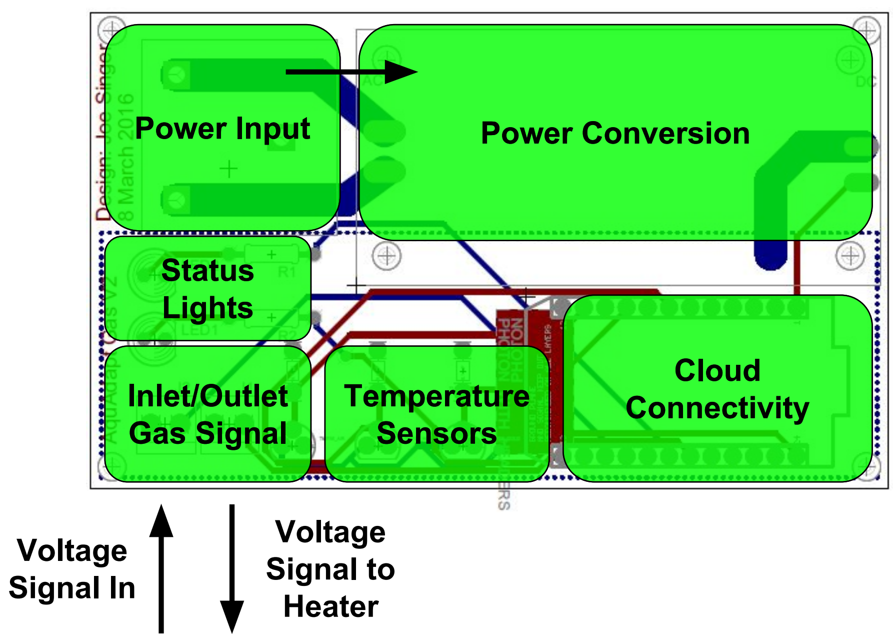
Strategic Circuit Design (Gas)



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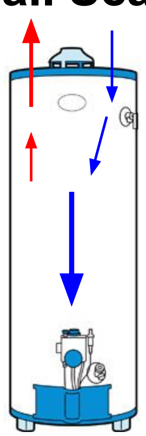
How to Combat the Need for Big Data

Statistical Learning

Mass Flow Rate

Small Scale

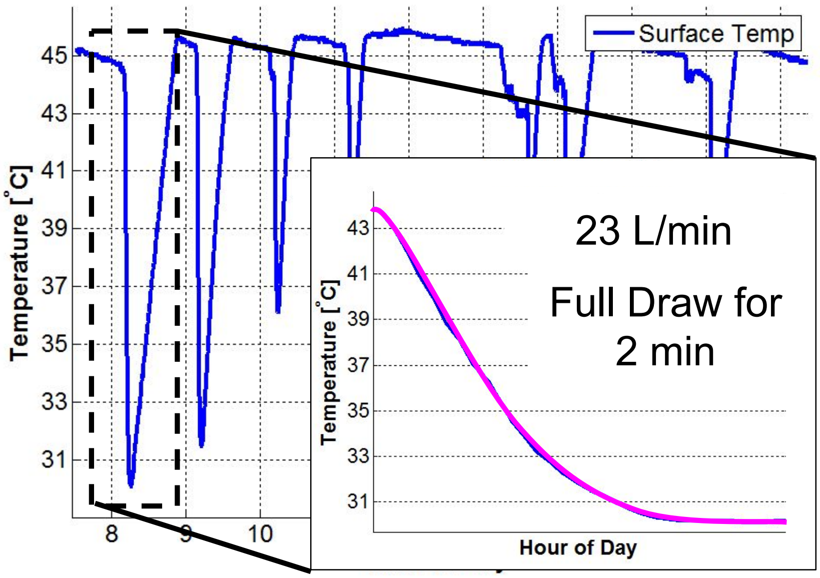


$$e^{-\frac{t}{\dot{m}C_p}\left(\frac{1}{\varphi}+\dot{m}C\right)} = \frac{T_{tank}(t) - T_\infty \frac{1}{1+\varphi\dot{m}C} + (5 - T_{cold})\frac{\dot{m}C}{\left(\frac{1}{\varphi}+\dot{m}C\right)} - \frac{\dot{W}}{\left(\frac{1}{\varphi}+\dot{m}C\right)}}{T_{tank}(t=0) - T_\infty \frac{1}{1+\varphi\dot{m}C} + (5 - T_{cold})\frac{\dot{m}C}{\left(\frac{1}{\varphi}+\dot{m}C\right)} - \frac{\dot{W}}{\left(\frac{1}{\varphi}+\dot{m}C\right)}}$$

Small Scale Analysis

Hot 100%

Cold 0%



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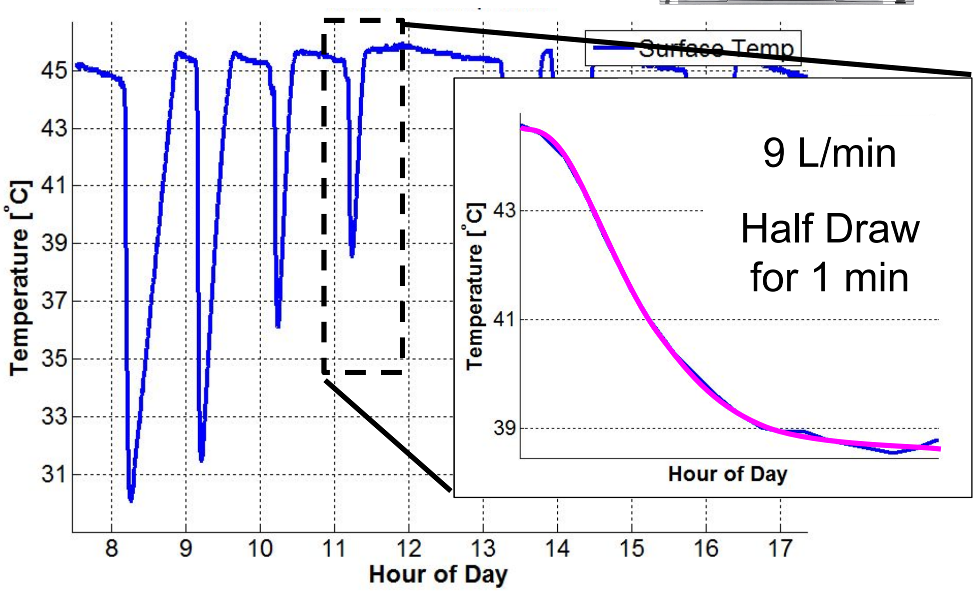
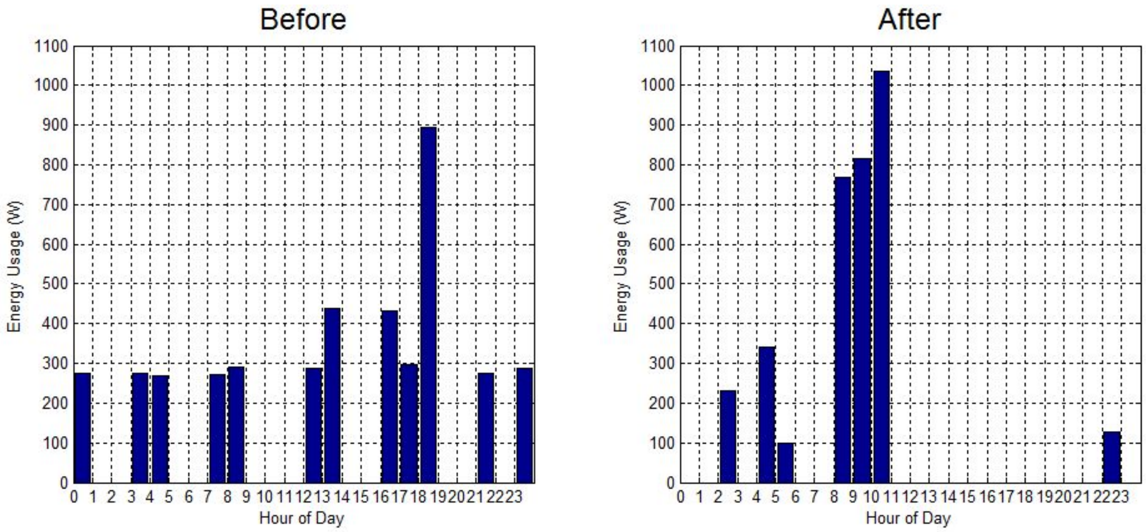
Small Scale Analysis

Hot 50%

Cold 50%



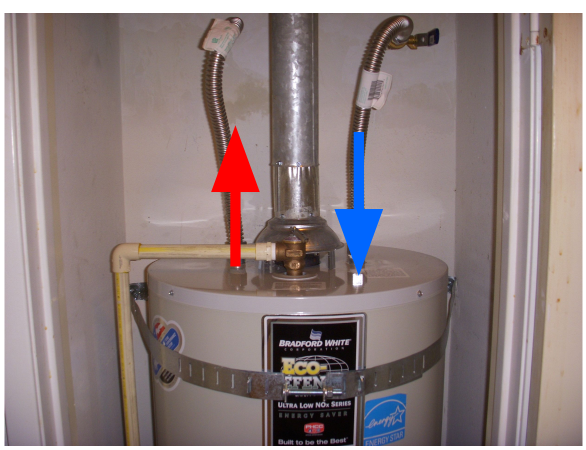
Small Scale Energy Savings



33% Savings!

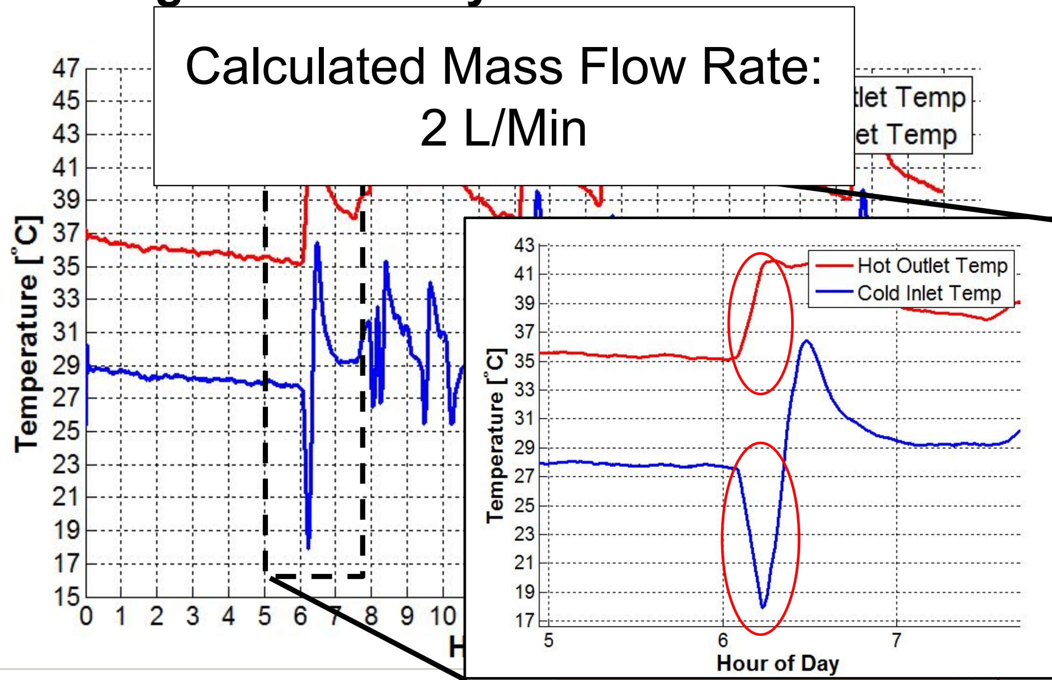
Large Scale

- Hot and cold water pipe temperature

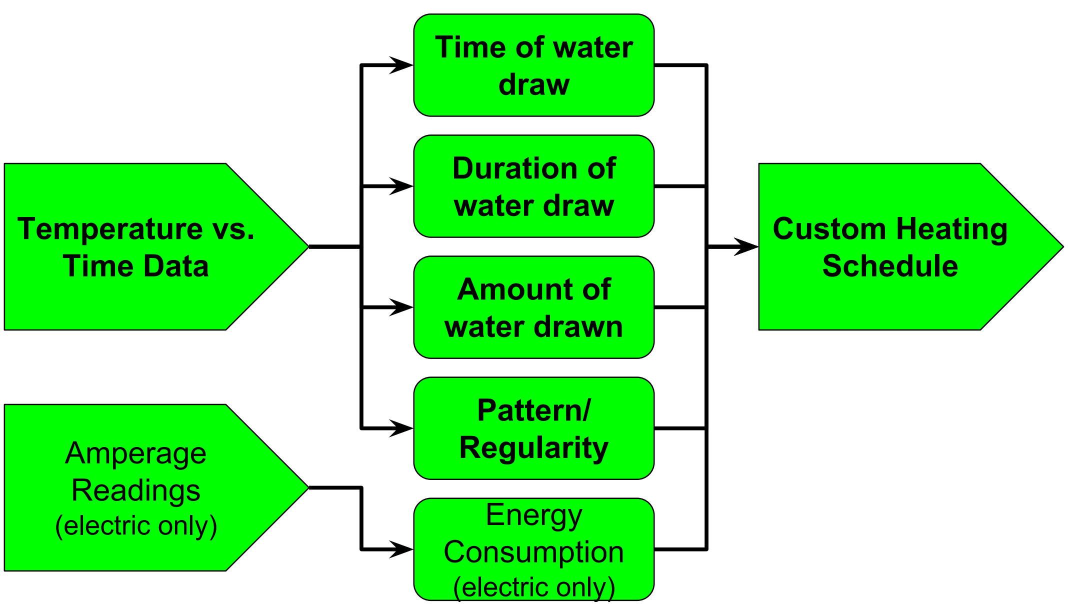


$$\frac{dT_h}{dt} - \frac{dT_c}{dt} = \tau_{o,h}((X_h T_{w,h} - T_\infty) - T_h(1+X_h)) - \tau_{o,c}((X_c T_{w,c} - T_\infty) - T_c(1+X_c))$$

Large Scale Analysis

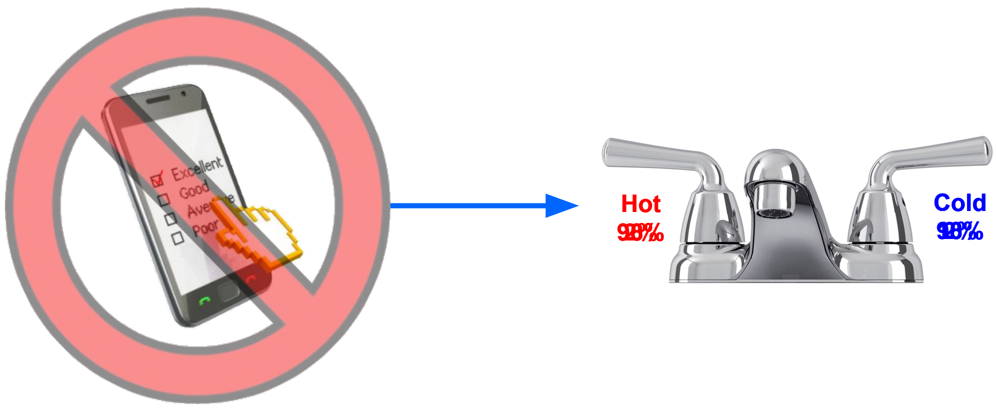


Software Data Analysis



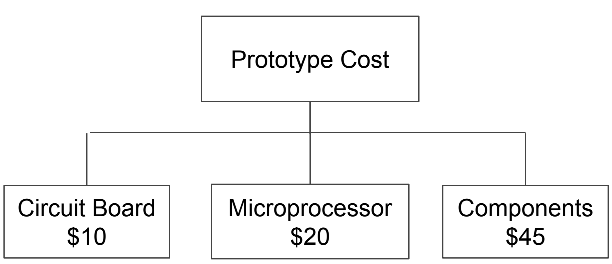
System Feedback

- Less water drawn = Less needed heat
- Utilizes Sensors
- “Out of sight, out of mind”

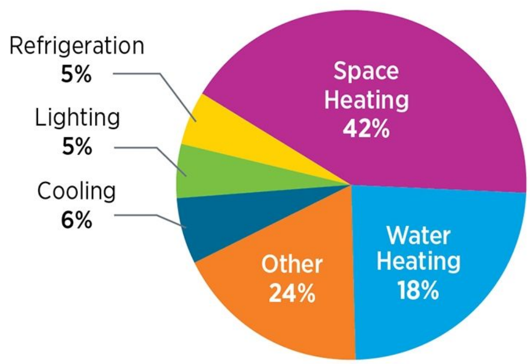


Cost Analysis

- Prototype Cost: $75
- Final Product Cost: $40
- **Market Price: $60**



Societal Impact



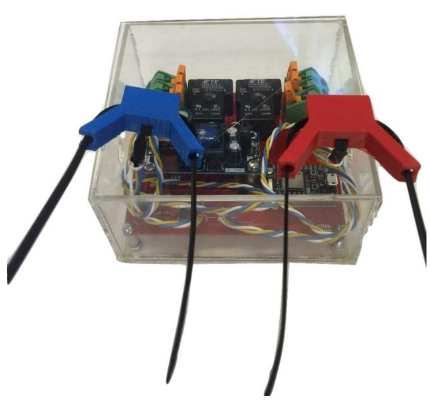
Annual Water Heating Energy Consumption:
2200 (kWh)

Average Annual Cost of Water Heating:
$264 @ $0.12 per kWh

With 33% savings,
Return on Investment:
8 Months!

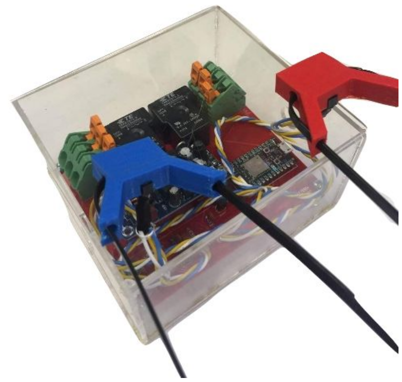
Future Work

- Incorporate further machine learning
- Appliance detection
- Improve ease of use



Conclusion

- Low cost non-invasive sensor
- 33% Energy Savings
- Detect water draw with temperature
- Anticipate usage
- Universal



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Acknowledgements

- Roelandts, Miller Center
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- Russell Williams
- Maker Lab

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Thanks! Questions?

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