Mechanical Engineering Design Methodology
Submitted to:
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Final Report

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Spring 2019

Phase I: Project Proposal

Our Design Methodology Project this semester was based on a challenging prompt of utilizing our engineering knowledge to prototype and create a machine that boils 1 cup of water using human energy. This prompt has a broad range of applications, but our target customer base is located in developing nations in Southeast Asia, where there is scarce access to potable water and electricity. This report will comprehensively compile our design process into three discrete stages: Task Clarification, Conceptual Design, and Embodiment and Fabrication of said design.

The first stage of this report will break down the purpose of the task, compile background information, and walk through interpreting this information to best approach the challenge at hand. This will require tools such as Customer Needs Analyses and House of Quality to shed light on our specific task requirements and clearly outline the problem statement. This is a focus on quality and customer needs, and relates these needs to engineering specifications. This section also references interviews we conducted as a team and background research we collected to gain better insight across the design process and customer needs.

The second stage of this report will focus on the overall design process. In this stage, we explore various concept generation methods and functional modeling. Some tools we utilize include Morphological Analysis, 6-3-5 sketching, and Pugh chart comparisons of our design variants.

The third stage explores the embodiment design and fabrication process of the previously mentioned design concepts. This aspect of the paper goes into detail describing the ways these designs were simulated, tested, prototyped, and presented.

Problem Statement

Limited access to clean water for millions around the world has warranted the need for a clean solution, constrained in our case by the limits of human energy (CDC). We aim to create an easily accessible, reliable clean water station for a developing urban area such as Southeast Asia that harnesses human energy to first boil water from the surrounding area, filter the water, and provide an internally powered light source.

Background Information

Worldwide, 780 million people do not have access to a clean water source. More than 35% of the world's population, an estimated 2.5 billion people, lack access to sanitized water (CDC). Access to potable water is extremely important in developing countries. Unclean water in developing countries can house viruses, bacteria, and protozoa that can cause serious illnesses such as dysentery, cholera, typhoid and gastroenteritis (Pandit 218). These diseases can range from mild to even fatal. The World Health Organization estimates that nearly 1.6 million people die every year from diarrhea, with 90% of those deaths occurring among children younger than the age of five, mostly in developing countries (Pandit 219). Improving water quality can in turn improve health, productivity, well being, and reduce infant mortality. Developing countries with poor access to clean water are usually ranked low in their metrics when compared to more developed industrial countries (Gadgil 254). According to Water.org, nearly 1 billion people world wide live without access to clean water, leading to around a million deaths per year from waterborne diseases like typhoid (Water.org).

Our goal, achieving potable water, is defined as being safe to use for drinking and cooking. The average man needs roughly 3 liters while women need about 2.5 liters per day. A maximum of 8 liters of water daily is estimated to satisfy an individual (Starkey 5). Actual water needs can vary by culture, location, and the level of physical activity. People in developing countries are at risk of exposure to biological, chemical, and physical contaminants when they use unclean water for cooking or consumption.

The most common pollutants in unclean water are biological. It is estimated that just 10 water borne diseases are responsible for over 128 billion disease episodes annually. Of these 10 diseases, diarrheal diseases are particularly fatal. As stated above, nearly 1.6 million people die per year from diarrhea, most being children (Gadgil 257). It is estimated that practicing good hygiene and having access to clean water can reduce deaths by 2.4 million globally each year. (Bartram 257). These pathogens are usually spread when contaminated water is consumed or used to wash and prepare food. These microbes enter through runoff from human waste or nearby farms. Shared water sources become a main medium for pathogens to spread between infected humans.

Inorganic chemical pollutants can also be a serious challenge in achieving clean water supplies. For example, arsenic is a major water pollutant that can cause hyperkeratosis, lung cancer, and liver disorders. This pollutant can be fatal and can also stunt the intellectual and neurological growth in infants and children, leading to defects. There are also chemicals such as fluoride and nitrates that can leach into the water supply, causing problems in infants such as blue baby syndrome. Other chemical contaminants such as heavy metals can cause cancer and upset the hormonal balance in the human body (Pandit 221).

Despite the abundance of water on earth, only a very small percentage of the water is clean enough to drink or use around food. The problem facing those without clean water today is how to sufficiently clean water so that it is potable. Currently there are several commercial technologies to create potable water.

One strategy to create potable water is to employ filtration techniques using slow sand filtration. Slow sand filters are the most applicable filters for our target consumers, due to its extremely low cost and easy maintenance. Slow sand filtration is one of the oldest and most effective ways to filter water. It consists of passing contaminated water through a sand or gravel bed. After roughly 30 days, a layer of biological material forms on the filter which will then achieve a higher rate of 90 to 98% of pollutant removal. The ripening period of the layer (called schmutzdecke) can vary from 17 to 30 days (Pandit 225). The layer develops in the sand a few centimeters below the surface of the sand filter and can be scraped off and restarted when the layer becomes too thick and begins to clog the filter. However the schmutzdecke must be reestablished after that. Water seeps through slow sand filters at a rate of only 0.1 to 0.2 meters per hour, meaning the slow sand filter is only efficient when it has sufficient surface area. Slow sand filters also cannot filter water with high concentrations of pollutants such as suspended solids. If the water has too many solids or algae, the filter will quickly clog and must be restarted. Therefore, slow sand filters prove their value in regards to low maintenance and cost, but have several shortcomings in regards to surface area and filter efficiency (Gadgil 271).

Another technology prevalent in water purification is SODIS (Solar Disinfection), also called solar pasteurization. SODIS functions by exposing the microorganisms in contaminated water to direct solar rays leading to the inactivation of the pathogens. Sunlight can also form hydrogen peroxide in the water leading to damage of the proteins, cell membranes, and DNA of pathogens. The thermal effects also causes further inactivation of the pathogens. SODIS works by filling a transparent glass with water that is treated by exposing it to sunlight for several hours (Pandit 225). SODIS however has several pitfalls. SODIS can be difficult because of the need to manage several bottles daily to meet water needs. Each bottle usually holds 1-2 L, and must be aerated then placed in the sun for several hours. To meet daily needs, a certain number of bottles are required, and they must be managed throughout the day to be accessible. The average household would require 10-20 bottles per day in order to meet a standard 20 liters of daily household water usage. SODIS is also ineffective against turbid water which will decrease the solar penetration of the UV rays. These complications make users unwilling to use SODIS bottles. In a study following the implementation of SODIS bottles into a Nepal village only 9% of the households continued to use SODIS bottles after a few months. (Sobsey 4264). The SODIS method of disinfection is a low cost way of producing clean water, but it severely limited by its capacity and shortcomings.

Another common disinfectant method is chlorination of unclean water. Chlorination is the process of adding chlorine to unclean water in the form of concentrated liquids or tablets. This allows users to treat large volumes of water and is relatively simple. A bottle of chlorine solution can treat over 1000 L of water for only one dollar. However, chlorination will not function as well with water with high turbidity and concentrations of organic matter. It can also lead to changes in taste and odor that cause user skepticism about the cleanliness of the water. (Sobsey 4262). Another significant disadvantage of chlorine is the difficulty of maintaining a supply chain to source the chlorine and transport it to the treatment location. The chlorine solution has a half life usually on the magnitude of either months or weeks. These supply chains require skilled operators to maintain and operate the infrastructure of the supply chain. (Gadgil 259). While the use of chlorine is the most common way of producing potable water today, it has many drawbacks that leave room for improvement of the current supply chain.

Our research into human energy found that the most efficient ways to capturing energy would be through the elliptical or stationary bicycle. Other gym equipment such as the treadmill actually consume energy and use up to 2.2 kWh per hour per machine (Haji 5). Whereas we see that most stationary bicycles are self powered and ellipticals can generate 10,000 kWh for 28 ellipticals (Haji 5). We see that there are clear differences in the efficiencies of each way of capturing human methods.

Our main design strategy is to maximize the efficiency of the energy a person can create in order to minimize the time required to bring the cup of water to a boil. This is important because we need to offset the simultaneous heat loss of the system. A couple ways to achieve high efficiency would be to make sure that our system is well insulated, or to lower the pressure within the system, thus lowering the boiling point of the water. Using the known heat capacity of water given ambient pressure, we determined how much energy would be required using the equation $q = mc\Delta T$. Given ambient pressure, we would require approximately 75 kJ, or 18 kcal of energy to boil a cup of water, neglecting losses. That is about the same amount of energy it would take to lift two full grown male hippopotami a meter off of the ground. To put this in perspective, it would take a cyclist producing 250 watts about 5 minutes to boil the cup of water. However, with the average person more likely producing less than 200 watts of power, we are faced with the issue of the operator becoming exhausted before the water is boiling. Our challenge thus becomes creating a solution that could realistically be used by the general public and not only an olympic cyclist.

Customer Needs Analysis

Given the importance of access to clean water, it is crucial that we identify our customer base and meet their tailored needs accordingly. Potential customers for our product will be attracted to an intuitive machine that is quick to boil water, easy to use, and comfortable. Weather resistance and durability are important concerns of ours as we want our station to be environmentally beneficial and a reliable source of clean water. Our specific target customer base will be in Southeast Asia. As a result, we have to account for monsoon season, higher rainwater rates, and durability to higher humidity and temperatures. Similarly, our machine could also be applied to similar climates such as in South America. As discussed above, there are many mechanical methods of purifying water, but each has their pitfalls, whether it be time constraints or availability of energy. Our team consulted a colleague who organized a Projects with Underserved Communities (PUC) project through UT's Engineering and Social Work schools, and partnered with the NGO CASA (Church's Auxiliary for Social Action). Their project focused on providing a Community Learning and Resource Center for a small village in Packianathapuram, India. The village was experiencing a drought at the time of the project, and there were multiple environmental and infrastructural challenges behind the construction. Infrastructurally, one challenge they encountered was "traveling into the city to acquire last-minute materials. Because of the infrastructure, [they] had to plan for the materials that were needed well in-advance, in order for the materials to be ready and at the construction site on-time”. Due to this challenge, it was recommended “that future teams do their research into their community’s living conditions, because it really does have an affect on their lifestyle” (Ramachandra). The village was experiencing periods of monsoon rains, which led to design changes that had to “account for water pooling in front of the building and on top of the building. We simply made design changes to the roof to allow for water to be dispersed (prevent pooling) and sent away from the building” (Ramachandra). This has inspired our tertiary function: collection of rainwater. Rainwater is clean and safe to drink, so adding collection containers for rainwater will increase the total supply of potable water of our station.

After identifying Southeast Asia and areas with similar climates as our target audience, specific customer needs must be considered. The first and most fundamental customer need is the ability to produce clean usable water through boiling. The energy used to boil the water must be derived from human mechanical energy, and from this requirement stems the rest of the customer needs for this machine. From personal interviews conducted with frequent gym goers, comfortability and adjustability of workout machines were main factors in our decision making process. One interviewee stated that the “stationary bike is the easiest [for me] to use. I can sit down and focus on my cardio. It's also easily adjustable for my long legs” (Schaberg). The energy efficiency of the bike provides for the most productive and quickest way to boil water with human energy. The adjustability and the comfortability of the machine allows Schaberg to work out for extended periods of time without getting uncomfortable or adding extra stress on his body which will be an important factor as human mechanical energy will be used to boil the water.

In Southeast Asia, the climate is highly tropical, meaning temperatures are usually warm. This, along with volcanic and earthquake activity provide for a tough native infrastructural challenge (Andaya). To account for this, durability of our device is our priority. We want our device to be durable and withstand large loads, specifically under 250 pounds of force. Countries such as Vietnam and India have obesity rates of 1.7% and 1.9%, respectively. As one of the least obese regions in the world, our upper weight limit of 250 pounds should be more than enough to accomodate everybody (Andaya). Additionally, we want our device to be accessible regardless of climate conditions such as rainfall, wind, humidity and corrosion. Aruna Ghatak-Roy, a patent attorney for the Dickinson Wright law firm, stated that "accessibility is the most important aspect of an invention that helps other people. No matter how ingenious, if a device is not accessible, it cannot help anybody" (Ghatak-Roy). In our case, this applies to our device being near an urban area, easy to access, and utilizable regardless of weather or time of day. Intuitive use is essential for this project. One interviewee stated "I dislike the user interfaces. It's difficult to use and the buttons are not intuitive" (Schaberg), when referring to workout equipment in the gym; therefore, we want our device to be simple and avoid complicated startup procedures and jumbled instruction manuals. Retainability of clean water is important, as water that is purified might not always be readily transportable. In our interview with Arvind Ramachandra, a member of the PUC India team last summer, he noted that during times of drought, "a father and son from the village would ride on a motorcycle to collect the water and on the way back, the kid sitting at the back would hold on to the water container, as the father rode" (Ramachandra). This inefficient way of transporting water for a whole village can be avoided by providing an onsite location for producing clean water, and one with ample storage will cement our device as a societal landmark. We want our device to have external storage capabilities, so that clean water can be produced and additional water can be stored for later use. Additionally, we want our device to be able to start up and run quickly, providing a short down time and quick, easy access to clean water. Safety and ease of repairs are important to the practicality and marketability of our device. We want our customers to be able to use and easily repair our devices if anything is to go wrong, no matter where they are in the world. Verification of cleanliness of the water is a final attribute that our customers will be comforted by. First Alert WT1 water test strips that identify the cleanliness of water will verify and assure our customers that the water they purified is safe to drink.

Engineering Requirements

Our engineering requirements validate our House of Quality and are supported by our decision making process (Fig. 34). Our target temperature output is 100 degrees Celsius, as that is the temperature water boils at. We estimated that the time that it would take to boil the water is under 15 minutes. This estimation is based off of a couple assumptions. First, we assumed an average human can generate 250 Joules per second of power on the machine for an extended period of time. We also assumed that the container would not be perfectly insulated and the conversion efficiency would be below 100%. The heat calculation yielded 74 kJ of energy necessary to boil water, assuming perfect conditions, which resulted in around a 5 minute boil time; however, it must be noted that these calculations do not account for heat loss and assume 100% efficiency. Our corrosive resistance figure of less than 100 μm per year was gathered from data on the effects of corrosion on different materials in different environments around the world. Our coverage surface area of 18 square feet was gathered from average wingspan and will accommodate free movement and comfortability in the given space. A storage capacity of 6 Liters is targeted, as a maximum of 8 Liters of daily water is estimated to cover cooking, cleaning and general consumption needs. Our target particle level, which we refer to as total dissolved solids or TDS after the water is boiled and filtered is less than 500 mg/L. This information was retrieved from the FDA regulations for cleanliness of water.

Proposal Conclusion

The next step after researching customer needs is to begin the design process. While designing our solution, it is crucial that we take into account the customer needs for our target audience of developing nations in Southeast Asia. We identified that our top priority is to thoroughly boil and filter the water. While cleaning the water may seem of highest importance, it turns out that meeting the less important needs like comfort and safety can help achieve our major needs. For example, a machine that is very comfortable and safe for the operator would allow them to work more quickly and for longer periods of time without risk of injury. With this in mind, we need to consider many different aspects of our design beyond the basic requirement of bringing a cup of water to boil. We have translated the customer needs identified through extensive background research into engineering specifications, which we will use to guide our thoughts as we enter the technical design stage (Fig. 35).

Phase II: Design Review

Concept Generation

We started our concept generation using search engines online to research prior art, existing patents and open-source projects which could inspire some new concept generation for our project. Patent number 9,556,408 is what inspired the idea of using a bicycle to import energy for heating our water. This patent, filed on September 13, 2003 and published on March 19, 2015, includes bicycle driven generators to supply the electricity used in the brewing process. This system utilizes a HERMS (Heat Exchange Recirculating Mash Systems) process, where a heat exchanger is immersed in a Hot Liquor Tank that a pump circulates water through. This system is a great example of harnessing bicycle power to generate electricity, and utilizing this electricity to generate heat for the brewing process (Grose). Additionally, the electricity is used to power a computer for monitoring and recording the electricity generated, and to power a video monitor that displays real-time statistics of the electricity produced by the bicycle. The power generated by the technology detailed in this patent drew us to the idea of using bicycles. The generator attachment in this patent produces enough DC power to fuel the brewing process, and power an electrical monitoring system.

Patent number 10,081,556 highlights a method for water reclamation and purification. This system receives contaminated water and passes it through a heat exchanger that converts a portion of the water into steam and collects a portion of the contaminants in the exchanger. A steam engine is coupled to a generator that is powered by the steam produced from the exchanger, which in turn powers the system (Schubert). This self-sustaining recycling of energy helped inspire a bicycle design concept. However, in this system, the power is provided from runoff steam, and in our project, we will most likely not reach a high enough temperature to achieve steam. Our source of energy will come from the bicycle pedals, but they will similarly be coupled to a generator to power our device.

After finding background information and familiarizing ourselves with existing technologies, we utilized mind-mapping and the 6-3-5 (brainwriting) method in order to jumpstart our idea generation process. We began with a mind-map with “Boil Water” as our focal point. Branching out are different possible methods, with the actual systems and subsystems branching out from there. Our mind-map can be viewed in the appendix (Fig. 25). While this process helped us consider many different solutions, we found that the 6-3-5 method was even more beneficial because we have all been thinking about possible design variations since we were introduced to the problem. After completing our individual rough sketches, we passed them around the circle several times so that the other group members could make suggestions. These marked up sketches can also be found in the appendix. As a group, we found this exercise the most beneficial for idea generation because it allowed us to gain valuable insights into our own designs through observance of the development of our peers’ designs. After completing the 6-3-5 exercise, we refined our rough ideas into four distinct design variations (Fig. 26, 27, 28, 29).

Pugh Chart

In accordance with our problem statement, our team has utilized many of the aforementioned mechanisms and background research to generate concepts for our potential designs. We devised four discrete concept variants and compared them using a Pugh Chart analysis. The Pugh chart presents our concept variants and compares each datum with a set criteria (Fig. 31, 32). This allows for direct comparison of our different models and relates them to customer needs. We broke our chart down into 13 different categories and evaluated each concept variant's performance in regard to these categories. Our categories were energy output, adjustability, comfortability, boil time, durability, storage capacity, operational tasks, bacteria levels, safety, costs, shelter area, operational time, and training time. These criterium draw from our customer needs analysis, House of Quality, and specifications sheet. Our four different concepts are Concept 1, a detachable bike with a bike pump, Concept 2, a covered pedal chair, Concept 3, a detachable bike with rainwater collection, and Concept 4, a rowing machine. For our Concept 1 datum, we compared our detachable bike with bike pump to our 3 other concepts. The power output of a bike was highest compared to a rowing machine and covered pedal chair. A rowing machine produces 68 Joules of energy per second, whereas a bike produces around 250 Joules per second of power. The covered pedal chair is estimated to produce slightly less power than the bicycle as well, as you trade a decrease of power output for comfortability. Adjustability for the bicycle was similarly higher for Concept 1 and Concept 3 as compared to Concepts 2 and 4, as bicycles have adjustable seats, wheels, and handlebars, and are detachable from the machine mount in our designs. The rowing machines and covered pedal chair are both fixed objects, so lost points on adjustability. For comfortability however, both Concept 2 and 4 gained positive points when compared to the bikes, as you can sit down and have back support for both the pedal chair and rowing machines. Boil time is better for the bicycle design than Concepts 2 and 4, as can be seen in our calculations below. Both of the bicycles have the lowest energy requirements to reach a boil, and therefore the lowest boil time. The covered pedal chair will require the second most energy and boil time, and the rowing machine will require the highest energy input as it has the least amount of available power and does not incorporate a pressure reduction, and therefore will take the longest to reach a boil. Our storage capacity for the detachable bike was the lowest, as it is a simple design that essentially only features a mount for the bicycle. In this regard, the rainwater collection bicycle, rowing machine, and pedal chair all excelled as they offered higher amounts of storage for water. However, as the detachable bike with the bike pump (Concept 1), requires the fewest components and is the simplest design, it also has fewer components to break, and is therefore the most durable in terms of lifespan. It is important to find a balance between maximizing storage capacity, comfort and safety, and reliability for our designs. For the bicycle, our operational tasks are an ability to mount the bike to the stand, and understanding how to use the pumps. This increases the number of operational tasks for the bicycle designs, Concepts 1 and 3. For the rowing machine and covered pedal chair, the tasks are reduced to getting on the machine and operating the rowing and pedal mechanics, so are intuitively easier to use, and therefore scored higher in the operational task categories. This in turn resulted in lower training times -- our last category -- for the covered pedal chair and rowing machine, as they are intuitive machines and require less prior knowledge and training to use. For safety, the covered pedal chair scored higher than our detachable bike, as the bike features a heating element directly under the seat of the bike, a potential health hazard, and the pedal chair protects the user from outside elements due to the cover, and has a safe seating arrangement. Similarly, the bike with rainwater collection scored positively in this category, as the heating elements are detached from the bicycle, and the water flows through to an insulated thermos. The rowing machine has more exposed moving parts and for extended periods of use poses a potentially dangerous strain to the user's back and body, and so scored a negative for this safety category. Bacteria levels were compared using concept variants that included water filters, and which types of filters they used. The cost of the detachable bike Concept 1 was lowest, as it required no cover, utilized no electric pump, and was the simplest design requiring the fewest number of components. For our shelter area category, the covered pedal chair was by far the best concept variant, as it has a covered roof with flaps that drop down on both sides, whereas Concepts 1 and 3 were inferior in this regard, given they provide no coverage or protection from the elements. The operational times for Concepts 2 and 4 were the best, as the detachable bike mechanic in Concepts 1 and 3 require more time to mount and set up, as opposed to just sitting down on a pedal chair or rowing machine. Following this initial comparison with Concept 1 as our datum, we created 3 more Pugh Charts comparing all of our concepts to each other, with Concept 2, 3 and 4 as our datum, respectively (Fig. 31, 32).

After comparing all of our Datum, we have overall leading aspects from our concepts that we intend to utilize in our final design. These important aspects are a detachable bicycle design with a cover, large amounts of storage, roll down flaps, a pump to reduce pressure, and a rainwater collection device. In our concept generation steps, we were able to illuminate weak spots in our designs through our 6-3-5 sketches, where we all drew our envisioned designs and combined our ideas and feedback to highlight possible improvements to our designs (Fig. 21, 22, 23, 24). 6-3-5 sketching and functional modeling resulted in illuminating weaknesses such as lack of rainwater collection devices and the necessity to reduce pressure and allow for less total energy requirement for the water to reach a boil. Our final vision for our research, design process, and production is chronologically laid out in four discrete phases in our Task Chart, with group members assigned to specific tasks that they will be responsible for carrying out (Fig. 18). Our Gantt Chart compiles the task list and phase chronology from our Task Chart in order to illustrate our project schedule and individual tasks (Fig. 19). This, combined with our Pugh chart comparison, allowed us to generate a comprehensive final vision of our design that maintains a stable timeline, and combines the strengths and minimizes the weaknesses from our different concept designs. By compiling these concept generation methods, evaluating existing technologies, and conducting background interviews, we can highlight the desired traits and strengths we wish our project to exhibit.

Function Structure

The morph matrix is a tool used to compile a list of possible components that can be used to satisfy the different required functions from the function structure model (Fig. 30). The function structure model decomposes our design problem into a set of simpler problems by representing the components of our project in a form-independent manner. By defining our functions, we can then define the forms that can carry these functions out. By using a black box model to establish our functions and overall inputs and outputs, we incorporated flows of energy, material, and information to develop our function structure. This structure model helped identify our driving functions, system boundaries, and energy flows. This helped address our customer needs while representing each significant component with one or more functions. Once complete with our function structure, we can move on to our morph matrix. The matrix can be used to identify different components that can be used in different design variations. The morphological analysis will numerate functions as a list of rows in the matrix. We populated the solutions for each function according to our classification scheme. The classification scheme was the energy domain sorted by whether each solution was a mechanical, fluid, electrical, or miscellaneous solution. Our Morph Matrix can be found in the appendix (Fig. 30).

Design Proposal Conclusion

After weighing the strengths and weaknesses of each our different design variations for developing concepts, we will be moving onto the embodiment process and detailing to bring our concepts to life. This concept will address a target customer base in a developing nation, with limited access to clean water and electricity. We will start building CAD models of our design and creating technical drawings for fabrication. The CAD models will also be used to generate a Bill of Materials (BOM) to document the cost, function, and planned source of each component. To properly embody our task, we need to develop a prototype. Dr. Rylander mentioned in lecture that if a picture is worth a thousand words, then a prototype is worth a thousand pictures. Hence, we will start with our “unbelievable part”; our water storage container. This container will hold our heating element and a constant vacuum pressure. We will build an experimental prototype of this container out of acrylic and test the vacuum sealing and heat retention. We will also create an assembly plan to create steps that should be followed during the assembly. This will conclude the embodiment phase of our design, which is the final step following clarifying our task and developing our concepts in the design review process.

Phase III: Final Report

Leading Concept

The leading concept from our design review process relied on a combination of information from our sketches and Pugh charts from our design review process. This concept design will include a mounted bicycle with a belt attached to the rear wheel to power a heating element. Our unbelievable task, the acrylic container, will house the heating element that is powered by the electricity generated by the bicycle. This container will be attached to a reversed bike pump, which will facilitate a constant vacuum pressure. In order to develop a successful prototype, we continued to play around with the water loading mechanism for the container. We decided to slightly modify the top lid of the container to allow for quick refilling with a removable lid with clamps to ensure our vacuum will remain depressurized. Additionally, we will secure a water filter to a PVC pipe system that we can pour our freshly boiled water into for a final refinement step to remove harmful particulates. After refining our design and objectives, our final design concept included a 20W halogen light bulb as our internal lighting source. This will also be connected to our belted motor, but will be attached to a switch to allow for functional lighting when necessary, and improvement of system efficiency. Using a favorable gear ratio on our bicycle and a water container to perfectly fit our heating element, we should be able to ensure a high efficiency in our system.

Detailed Drawings (CAD)

Due to the nature of the many moving parts and the involved friction, we decided to order manufactured parts for any components that would be moving for a majority of the system operation. We wanted to avoid wear and tear from friction on 3D printed parts or shearing from the strong forces that can occur within the system. With this being said, we focussed a majority of our prototyping and CAD efforts on the boiling container design. Our ideas for the container design went through many iterations from a metal can with a large circumference to a metal can with smaller circumference and finally an acrylic can with a smaller circumference. The iterations of these designs can be found in the appendix in figures 1, 2, 6 and 7.

Bill of Materials (BOM)

After completing our initial design, we determined that we need to pay careful attention to the total cost of our design. With a strict $300 budget, we knew that it was very important that every component had a specific function and that there were no unnecessary parts, as detailed in our BOM (Fig 15). After we determined what parts we needed, we ordered them as quickly as possible so that we could have time to order any additional parts that we did not forsee initially. We purchased all of our parts from Amazon, Home Depot and McMaster Carr and made sure that there was a fast shipping process. When we experienced a problem with our sensors the week before the showcase, we were forced to return and order new parts to create a better solution.

Failure Modes and Effects Analysis (FMEA)

As shown in figure 17, we performed FMEA to determine all potential failure modes, and identify which failure modes were most likely and most detrimental to the system.We divided our machine into five subsystems including the front stand, the back stand, the bicycle, the motor, and the water boiling container. Each of these subsystems contained multiple components, which we evaluated across criteria for severity, occurrence and detection, thus allowing us to come up with an aggregate score of the overall failure for easy comparison.

After quantifying the failure modes and effects analysis, we determined the most likely components to break and how we would go about reducing the risk of those specific components and how we would amend a potential failure. We determined that the most likely component of our system to break, based on the Risk Priority Number (RPN) scale, was the pulley with regards to its attachment with the motor. The pulley and its connection with the motor scored an RPN of 441 which is nearly 150 points higher than the second high-risk, failure-prone component. This analysis is validated through the iterations that we ran as we optimized our project to prevent the pulley becoming loose and detaching. As we continued to run iterations on our system, we made sure to tighten the pulley-shaft connection with the hex key after every couple uses. The failure effects of the pulley involve not only total failure of the system, but also potentially dangerous ramifications like damage to the motor or flying debris if the pulley failure goes unnoticed. These factors together with the high likeliness of occurrence combine to give the pulley the highest RPN score. To combat this failure, as stated earlier, the operator needs to ensure that the hex bolt is tightened after every couple iterations of the device. Lastly, if the pulley does indeed fail, specific steps need to be taken to restore the component to its correct operation and get the machine back up and running again. The connection piece needs to be visually inspected to make sure that it is still intact. Secondly, the connection piece will have to be reattached securely to the motor and the pulley will need to be screwed into place. Some additional epoxy application to the connection would be recommended to ensure that the failure does not occur again.

The second highest RPN values came from the analysis of the front and back stand subsystems. The failure of these subsystems is catastrophic because they are used to suspend the bicycle and the rider in the air in order to operate the machine. The likeliness of these failures occurring is significantly lower than the failure for the pulley-motor connection, hence the lower RPN values of 300 for the back stand wheel clamp loosening and 180 for the front stand metal rod fracture. Similarly to the pulley-motor connection, the potential effect of the failure is injury to the operator which carries the most significant penalty when analyzing failure using this method. To combat these failure modes, it is important to do a visual inspection of both the front and back stand before use. If the back stand is inspected and tightened as needed the RPN should stay relatively low, however the more corrosive materials used in the front stand mean that the front stand will not only need to be visually inspected but also replaced once judgement is made that the wear and tear on the device is creating dangerous conditions for the operator.

Simulation (Design, Results, and Validation):

Our single most important subsystem and the one which we decided would have the most uncertainty surrounding it was the container in which we would boil the water. For this cup assembly we focused on different parameters for the walls of the container. It was important to us that we chose a material that would sufficiently insulate the heating element and prevent heat loss, which would reduce our overall efficiency, especially at high temperatures. We looked primarily at two factors when it came to the tubing walls in our cup assembly: the wall thickness, and the tube material.

Our design utilized the cup assembly to pull a vacuum and retain the heat generated by our heating element. It acts as a thermal barrier between the room temperature air and the hot water. As more heat is conducted through the wall, the longer the time to boil, possibly causing us to miss our most important specification. We had to balance reducing the heat loss while staying within our budget guidelines. The material we chose also had to be machinable so it could be tapped for the heating element. With these restrictions in mind, we used our simulations to direct us toward the best possible choice of material and thickness.

We used SolidWorks Flow Simulation to see the effects that material and thickness would have on our design. We simplified our CAD model to allow for faster simulation time while keeping results realistic. We removed threading on pipe fittings and suppressed unnecessary parts in the simulation. Unnecessary parts were any parts that were far removed from the heat source and would unlikely affect the heat loss or generation, such a the clamps used to hold down the lid of the cup assembly. We ran the flow simulator as time transient so we could analyze the heat loss over a period of time. We also made sure that other important factors such as gravity and the fluid subdomain was properly applied. The cup assembly contained a fluid subdomain of water, while the rest of the computational domain was filled with air at room temperature. We applied a constant power output to the heating element of 20W. The mesh geometry was applied using the SolidWorks automatic setting and a level of 3 for mesh refinement. We found that varying mesh size did not significantly affect our results of the simulation. The simulation was run with the heating element having the input thermal properties of nickel/chromium 80/20, the most common alloy used in heating elements. We started the water at 89.85° celcius so we could see the heat loss at the point at which it would be the highest, when the water was near boiling and had the greatest difference compared to the surrounding air temperature. From there, we ran our simulation on the model for 120 seconds, generating a cut plot on the XY plane with temperature contours overlaid on the CAD model. We also created graphs of the max fluid temperature over time. These simulations allowed as to visualize the heat loss of our two main factors, material choice and wall thickness.

To validate our simulation we compared our simulation results to our experimental results. For our experimental results we had a control where we attached the heating element to a DC power supply with an output of about 20 W and measured the temperature change over time. For the experiment we used ¼” acrylic with no insulation. Comparing figure 9 from our simulation, we see that it is similar to our experimental results in Figure 33 with a rise of roughly 6 degrees celsius over a normalized time scale. Using this comparison we were more confident in our simulation results and validated the simulation.

We chose material choice as one of our main factors to simulate as we were prototyping due to the fact that we could not decide on a good material for our container. This was due to the fact that our tube had many design restrictions that made it difficult to find the right material. We wanted a material that could be machined and threaded, yet lightweight and resistant to corrosion from water exposure. We also wanted the material to be available in extruded piping that would be narrow and long enough to submerge the entire heating element. After several iterations of CAD prototyping and concept sketches, we decided to use either stainless steel 302 (SS 302) or acrylic. The simulations gave us insight as to which material would be the correct choice of material for our design.

The results from our simulations showed that using stainless steel 302 resulted in much more heat loss then acrylic. Comparing our acrylic designs to our SS 302 results we see that for cups with same thickness, stainless steel is much more unstable and has rapid and drastic temperature drops. We can see in Figure 12, 13 and 14 that the temperature of the water will rise much slower compared to their acrylic counterparts and when it reaches a similar peak temperature as the acrylic walls, the steel cups will suddenly drop in temperature. This is most likely due to the fact that stainless steel has a much higher thermal conductivity than that of acrylic. This higher thermal conductivity allows for heat to travel much faster out of the container, causing the extreme heat loss through the walls of the container. We also can see the effects in our cut plots in Figure 9, 11, 13 and 14, when compared to the cut plots of the acrylic wall.. For example in analysing the cut plots for a ½ inch acrylic and SS 302 wall, the difference is enormous. The acrylic container has its high temperature area isolated solely to the container walls, while the SS 302's high temperature area is extremely out of bounds. The more of the high temperature area outside the cup and in the air reflects on poor insulation. From these results, it was no question that acrylic was the correct material choice.

For our second factor we chose the thickness of the walls. This was a difficult factor to manage as we were severely limited in budget as to the thickness of material we could buy. As the thickness of the hypothetical design's walls increased, the cost of the stock would drastically increase as well. We also had another concern with the thermal properties. We believed that increasing the wall thickness would increase the thermal insulation of the walls; however, we also theorized this would come at a cost. As the walls of the cup increased, so would the heat capacity of the walls. If the cup wall thickness was greatly increased, we would be losing heat to the walls. Instead of heating the water, we would also have to heat the walls, decreasing our efficiency. We were deciding between ¼" and ½" thick walls for our prototype. To find the optimal wall thickness for our two materials, we utilized our simulation to choose the best choice.

From our simulations we saw that increasing the wall thickness in acrylic greatly improved our thermal insulation. Looking at Figure 8 and 10 of ½" and ¼" thick acrylic walls, the heat of the heating element is much better confined within the cup assembly's walls for the ½" heating element. However, when looking at the ¼" simulation, the high temperature area is not well confined to the heating element. We can also see on the temperature vs time for both walls we see that the peak temperature was higher for the ½" walls and dropped to a higher final temperature than the ¼" walls. Due to these results, we saw that a thicker acrylic container wall of ½" would be superior.

For the SS 302 walls, we saw that varying the wall thicknesses had unpredictable results. It seemed that the thicker ½" SS 302 wall actually had worse performance than the ¼" SS 302 walls. Looking at the time plot graphs we saw that we had massive drops in both SS 302 containers, however the ½" had a larger drop and lower peak temperature. These simulation results confirmed our original fears that increasing our wall thicknesses could result in lower efficiency. Because of SS 302's extremely high specific heat capacity and thermal conductivity increasing the wall thickness causes the SS 302 walls to act as a thermal sink instead of an insulator. We do not see this issue with the acrylic walls due to the extremely low thermal conductivity and specific heat capacity. From these results from our simulation we saw that a thicker acrylic wall would serve the best purpose for our design.

Experimentation (Design and Results)

With the ultimate goal of boiling water, we want to minimize energy losses in our system so that our goal can be accomplished efficiently. Considering all the different forms of energy loss in our system, we decided that heat dissipation would be the most important type of energy loss to try and reduce. We knew that with our airtight heating chamber, the only way heat could escape the system is through the acrylic walls. The cylindrical acrylic piece of our heating chamber is only ⅛” thick, while the top and bottom plates are ¼” thick. For these reasons, our group utilized a factorial experiment with 3 design variables and 2 responses in order to investigate the effects of insulation on our system. For each trial of the experiment, we altered the thickness, material, and coverage area of a layer of insulation, wrapped snugly around the cylindrical piece. After some research, we decided that rubber and aluminum foil were the best two possible materials to test due to their functionality and low cost. We wanted to also test an air insulator, but that would require a lot more acrylic which was surprisingly expensive. We used 2 layers of foil as our thin aluminum insulator, and 8 layers to make the thick version. The aluminum foil that is sold in most stores, like the one where we bought ours, has a different finish one each side. On one side is a more shiny and reflective appearance, while the other side appears more matte and less reflective. We used the shiny side facing inwards for each layer of foil. Meanwhile, we found ¼” and 1” thick rubber piping insulation at our local hardware store. For our first response, we chose to measure the time to reach 150℉, because that was one of the lowest temperatures that we could realistically boil water at after creating a vacuum. Additionally, we did not want to add any more time to our experimentation which requires two runs of 8 different trials, each of which takes at least 20 minutes. Our second measured response is the external surface temperature of the insulator. We believe this metric will be a good way of determining whether the heat is mainly being reflected, absorbed or conducted through the insulation.

In order to reduce the effect of extraneous factors, we implemented measures of replication and randomization. For replication, we wanted to have the power supplied to the system in each trial to be exactly the same. For this, we eliminated the use of human generated power and simply wired our heating element to a DC voltage source. Additionally, we started the system at around 70℉ and supplied power, but did not start recording data until the system hit exactly 80℉. This helps ensure that the initial conditions of each trial had minimal variance. To further eliminate noise factors between the independent trials, we removed the heated water from the previous experiment, allowed 10 minutes for the heating element to go back to steady state at room temperature, and finally added in new room temperature water and waited for the thermocouple reading to stabilize. Performing this exact process in between every trial allowed us to eliminate noise factors which could be caused by residual or stored heat within the system. Randomization was satisfied by randomizing the order of trials and not running the same trial back to back. We also rotated who recorded data to remove any bias associated with data collection.

The results of our experiment turned out to be non trivial and extremely insightful. As shown in figure 33, our experimental results yielded the fastest boiling time when we used the thin aluminum insulator and the thick rubber insulator. With these results, we ran an additional experiment combining our efficient combinations of insulation material, thickness and coverage area. As expected, full coverage of the acrylic tube has less heat loss than partial coverage. Our initial test before we started the two cubed factorial test was a control that tested the tube temperature with no added insulation. For this trial, it took 1630 seconds for the water to reach 150 degrees Fahrenheit using the constant power setup. After running all the iterations of the factorial experiment, full coverage was across the board better than partial coverage, with the water reaching 150 degrees fahrenheit a minute and a half faster on average. Additionally, we quickly saw that the insulation was making a significant difference as we compared the trials to the control trial. The best insulation combination yielded a temperature increase of close to 10 degrees fahrenheit over the course of the experiment compared to the control trial.

Statistical analysis of our experimental results indicated that these insulation design variations were indeed statistically significant. As pictured in figure 16, we concluded that the main effect on the boil time was the insulation thickness and coverage area, while the main effect on the exterior temperature of the insulation was the material type. We concluded that the thin aluminum is a better insulator than the thick aluminum because the heat is reflected back into the heating chamber instead of conducting through more layers of foil. The insulation material was the main effect for the exterior temperature of the insulation. The thick rubber insulation performed the best because very little heat escaped all the way to the exterior. To summarize, our experiments were statistically significant and allowed us to optimize our prototype design to maximize efficiency.

Use Experiments and Simulations to Optimize

Both the simulation and experimental results provided important insights that we were able to implement into our design to optimize the efficiency and usability of the overall system. The design which we were most uncertain about involved the creation of the water boiling container, therefore we decided to run both the simulation and experimentation on different aspects of the container. The simulation helped us determine material selection by running tests that would give us an idea which materials would optimize efficiency at different thicknesses. Through this process, the ½" acrylic simulation was by far the best of the four simulations, however, after assessing the associated costs and looking through the bill of materials, we decided to reduce the thickness, but still retain the acrylic material idea. Later, after performing some functional iterations on our completed system, we determined that the insulation provided solely by the acrylic container would not be enough, so we agreed to base the factorial experiment around adding additional insulation. As described in the experimental results section above, this additional insulation helped optimize the system further with the best insulation combination providing a 10 degree fahrenheit increase over the uninsulated system. The thick rubber outer layer of the insulation which we settled on for our final iteration due to the experimentation not only insulated the system, protecting from heat loss, but also protected the user from coming in contact with hot surfaces which could cause pain or injury. Finally, we ran an informal experiment to determine the speed that we needed to pedal to optimize the efficiency of the motor. The motor was rated for a max of 2650 RPM and the type of motor that we used runs most efficiently at an RPM around 90% of the max value. Through some basic calculations involving our gear ratio, we were able to determine that the optimal speed was around 25 kilometers per hour which could be read off the digital meter positioned on the bicycle itself.

Design for Manufacturing and Assembly

One of our main concerns for our device is the manufacturability and assembly ease. Our goal is to reduce the difficulty and amount of labor required to manufacture and assemble the device. For the Design for Manufacturing (DFM), we wanted to use as many off-the-shelf parts in order to minimize the number of parts that actually needed to be manufactured. Using off-the-shelf parts also allows us to quickly and easily replace any parts that fail. For other parts that could not be purchased from a manufacturer, we specifically designed them to make the manufacturing process simple and cost effective. In our design only two subsystems require manufacturing. The first subsystem is our front wheel stand requires sawing the 2x4 planks into smaller lengths. These square cuts can be made by a hand saw or simply table saw, and don’t require a tight tolerance. Due to the fact that the wood screws can bridge gaps in under tolerance parts the tolerance on the wood pieces for our front wheel stand are comparatively high. We also dimensioned our through holes for the wood screws at standard dimensions and placed the holes at a minimum 1.5 x hole diameter from corners and edges. The flat planks of wood make for easy fixturing whether the manufacturer is using a bandsaw or another wood working tool.

The more difficult aspect of our manufacturing process is the cutting, drilling and tapping of acrylic plates. The acrylic is much more brittle than the wood, thus can crack more easily during the machining process. A bandsaw is required to cut out the top and bottom plates, along with the lid. These cuts must be made at a slow feed rate per minute to avoid cracking. However, since the dimensions of the base and top are non essential, the tolerance is plus or minus .1” . To drill the holes into the acrylic on the top and bottom plates, we had to start with a ⅛” drill bit, and gradually increase the drill bit size by 1” until reaching 10 thousandths of an inch under our desired diameter. At the desired diameter a reamer is used to expand the hole to an exact size. We also further reduced the risk of cracking by positioning every hole that needs to be drilled into the acrylic plates away from all edges. The bottom plate is then tapped for a 1” NPT. The top plate is chamfered using a chamfer end mill to give the rubber O-ring a notch to sit in. This part of the manufacturing process could be improved with the use of a water jet cutter, which would speed up the cutting of the acrylic and reduce the risk of cracking. In a larger scale production several plates clamped together, drilled, then cut at all at once using a waterjet cutter.

One of our main goals for DFM was to avoid having to use any expensive or long turnover manufacturing processes. We avoided processes such as 3D printing and CNC machining due to the time intensive processes and the fact that it is ill suited for large scale manufacturing. We focused our DFM efforts on inexpensive and quick manufacturing methods that would benefit the design the best.

For our Design for Assembly (DFA) we wanted to make sure that all of our components were in open space and accessible via hand tools to make the assembly process easier and faster. Avoiding tight enclosures gives more freedom to the assembler to work with their tools and our assembly pieces. We also designed our machine to have as many of our assembly procedures in the same axis direction. Given our large flat base, and easy access from above, we were able to have almost all of our tasks oriented in the -y direction, and all of the tasks oriented so that the assembly is never required to be lifted and turned over.

Standardization of parts was another aspect we wanted to implement. Every assembly procedure that involves joining a wood piece, is done so using a standard screw size. We wanted to standardize these steps by allowing the assembler to use the same tool for the process. Besides the eight shorter screws used to attach the bike trainer to the plywood, we designed all other screw attachments the same way. One way to possibly improve our DFA would be to consider eliminating as many of the fasteners as possible. For example, some subsystems such as the front wheel stand could also have been designed to fit together using less screws. However, eliminating fasteners in our case would dramatically complicate the manufacturing process by having to cut the wood in a way it could be joined without screws.

The cup assembly is also easily assembled since most of the parts are simply standard NPT threads and can be hand tightened. The acrylic container is joined using a simply acrylic glue that can be applied using a small bottle. The assembler has ease of access to the entire joint where the glue must be applied. After that, the insulation is simply wrapped and tied onto the cup assembly. These simple steps to make our design easily manufacturable and assembled, greatly reducing both our cost and turnover time per unit.

Assembly Plan

Given the above information covering design for assembly and manufacturing, we have attached a specific assembly plan in figure 36 of the appendix which takes a detailed step by step look at how our device is intended to be assembled. The assembly plan starts with preparing the base for the front and back wheels of the bicycle to sit in. Once the front and back stands are assembled, the modifications to the bicycle can be made, involving removing the front wheel and tread from the back wheel to expose the track which the band will sit in. Through these quick and simple steps, the bulk of the human interaction components are setup which leaves the more technical assembly including the motor and container assembly. Of the assembly steps involving the motor, the tasks of primary importance involve aligning the motor pulley system with the track of the back bicycle wheel. This carries a great deal of importance to the system because even a slight misalignment can be the root cause of several failure modes that we introduced in the FMEA. A misalignment with the band can cause massive frictional losses due to friction on the band from the tire and the pulley system. This misalignment can also cause the pulley to wobble after several uses which allows it to work its way loose from the motor shaft which can put undue stress on the motor shaft or the motor connection to the base board itself. Lastly, after all the other physical components are assembled, the container assembly is put together and connected with the other subsystems. The container assembly is the most time intensive assembly due to the nature of our design. We originally implemented a pump system which meant that the container had to be airtight. This means that lots of acrylic glue, epoxy, and silicon needed to be used to secure all the assembled pieces of the container. The presence of acrylic glue, epoxy, and silicon means that drying times were necessary before continuing onto the next step of the assembly. We tried to create a relatively basic assembly process that would not require a lot of specific tools, however we wanted the fasteners and connections to be permanent because its primary use would be a water cleaning station that does not need to be removed or disassembled until the end of its life.

Final Discussion and Recommendation

Through our performance at the design showcase, we were able to prove the effectiveness of our human powered water boiling device. We were able to boil 1 cup of water in just 6 minutes while using a vacuum to reduce pressure and were able to reach 100 degrees celsius in just shy of 15 minutes without the vacuum. As the water boiled, we demonstrated how we engineered specific components of the device in order to meet the engineering specifications that we laid out in the project proposal. It was crucial to hit as many of these engineering specifications as possible because hitting these specs would lead to high customer satisfaction as each of the specifications was initially derived from the customer needs developed in the first phase of the project.

We were able to achieve the three main specifications relating to the primary, secondary, and tertiary functions of the device laid out in the problem statement. We were also able to hit a majority of the other specifications while only failing to achieve one of the many specifications. With regard to the three main functions of the water boiling device, we were able to boil water in under 15 minutes while achieving a water temperature of above 80 degrees celsius. We were also able to design a filtration system that would allow the boiled water to be passed through a filter to achieve a particulate level of less than 500 mg/L of total dissolved solids (TDS). Finally, we were able to install a light source which was powered by the bicycle and wired in parallel with the heating element in order to provide light to make the system functional anytime of the day or night. With the three main specifications achieved, we moved on to other specifications with lesser relative importance.

Most of the secondary specifications involved customer comfort and ease of operation in order to make the device as user friendly as possible. We aimed to maximize the comfort and adjustability of the system by making sure the seat was adjustable and was comfortable to sit on while exerting the high amount of effort needed to boil the water as quickly as possible. Additionally, we wanted to develop a design which would be simple, quick, and safe to operate so that more time could be spent boiling water instead of setting up a confusing system. We accomplish these goals by reducing the amount of setup and operational tasks needed before pedalling, reducing the downtime between iterations, and making sure that no heating elements were exposed to direct contact with the operator. We set a goal of less than two and a half operational and setup tasks which we achieved through the simple setup process which only involved filling the cup with water and clamping the lid to the top plate before pedaling. The downtime between operations specification was achieved as it almost always took less than 1 minute to unclamp the lid, pour the water into the filtration device, refill the container with new water, and start pedalling again. Lastly, we protected the user from hot surfaces through our outer layer of rubber insulation on the container. We knew that this thick rubber was not a conductor so any heat that would be generated on the inside of the rubber would not pose a hazard to someone attempting to handle the container even while it was boiling on the inside. Unfortunately, we were unable to hit our specification pertaining to weather proofing the system. We initially had plans to build a setup that would provide cover to both the operator and the device in order to keep it out of the weather and reduce corrosion and wear and tear, but after running into a couple unanticipated design problems throughout the process, we were unable to find room in the budget to fulfil this final specification. The steps that would need to be taken to hit this specification would require us to build a stand with a tarp that could be used to keep the device out of the elements, or at the very least we could have purchased slightly more expensive treated wood which would last longer while exposed to the outdoor elements.

Overall, we were satisfied with our ability to hit all of our most important specifications, but after spending so much time developing this prototype, we feel that there are always recommendations that can be made to improve the prototype. One of the major things that would have made the system more functional is adding a battery or capacitor in connection with the light source that charged from the bicycle operation so that the operator could have the light switched off while pedalling, but could switch the light on while performing setup or down time tasks. Additionally, we would recommend creating a plug that would more easily attach and detach the motor wiring to the heating element. A plug would allow the water boiling container to completely detach from the system which would allow the container to be manipulated unencumbered by the short motor wires. This would allow the operator to more easily perform the second function of the device, pouring the water into the filtration system.

Conclusion

Using the engineering design processes enumerated above, this paper comprehensively illustrates our methods by sectioning the design process into three distinct steps: Clarifying the Task, Developing Concepts, and finally Embodying these Concepts. We have excruciatingly detailed the methods behind these three steps above, and utilized these processes to research, conceptualize, and generate our ideas into a functional machine that addresses our task at hand: boiling water using human energy.

The Task Clarification stage entailed us researching and learning more about the problem statement in order to facilitate discussion and general ideas on what our solution should look like. This phase helped expose us to effective ways of collecting, interpreting, and translating this information into engineering requirements that work in conjunction with people's distinct needs.

The Conceptual Design phase provided the opportunity to expand upon our ideas generated during the clarification stage. The ideas generated in this stage were more problem-specific and technically oriented to provide a list of concepts to draw a final design from. These concepts were sifted through and compared using various selection tools to ensure the most effective and appropriate elements from our designs were being considered.

The final stage, Embodiment Design and Fabrication, chronicles the endeavors that led to the manifestation of our design concepts into tangible, physical solutions to our problem statement. Through use of methods such as prototyping, experimentation and simulation, we were able to properly optimize our design concept to ensure that the best possible solution was being brought to fruition. The interdependence of these three design stages synthesizes individual results and helps bring about a cohesive and well-engineered final product that we are very proud of.

Appendix:

CAD DRAWINGS

Figure 1:

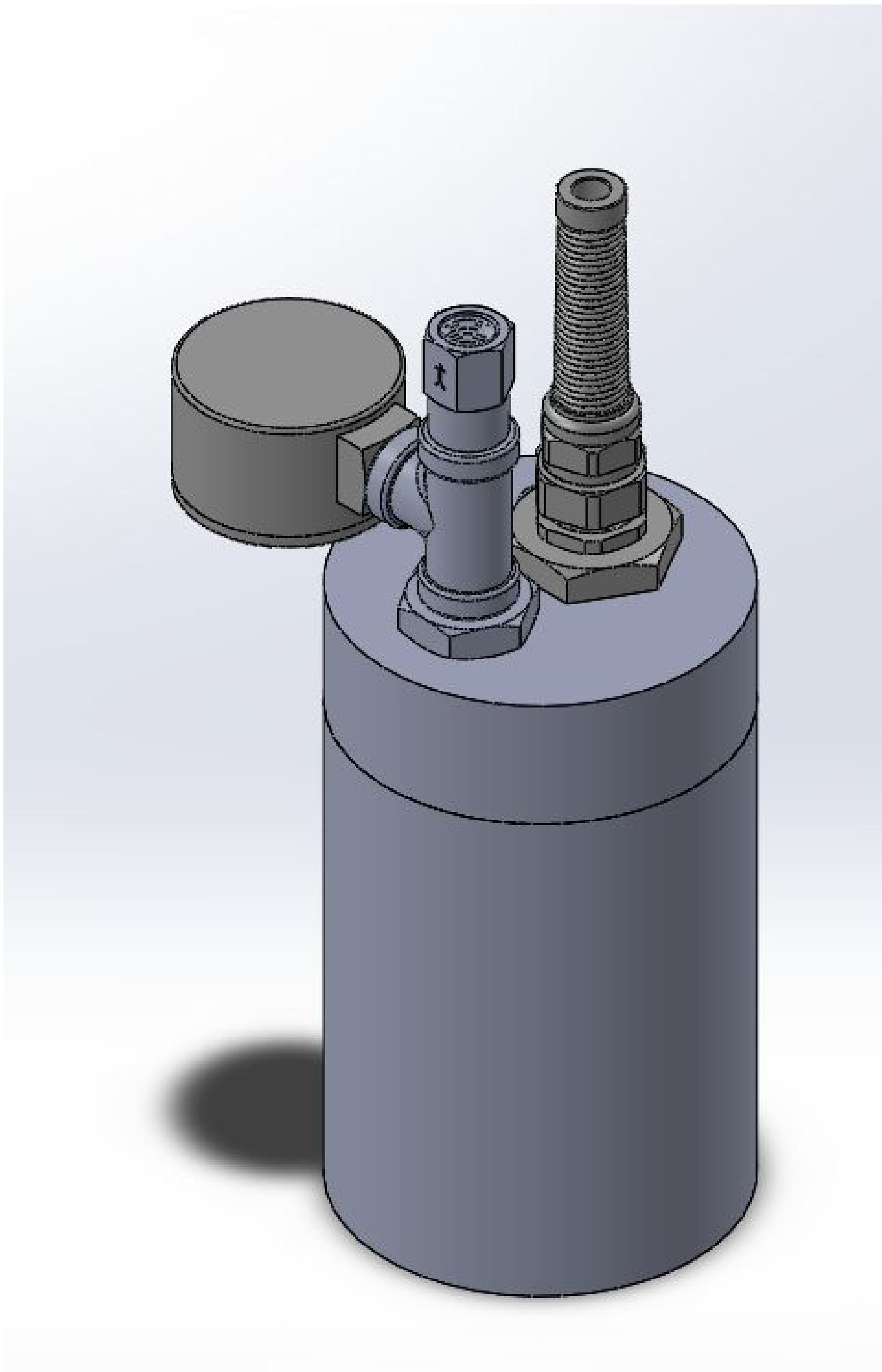


Figure 2:

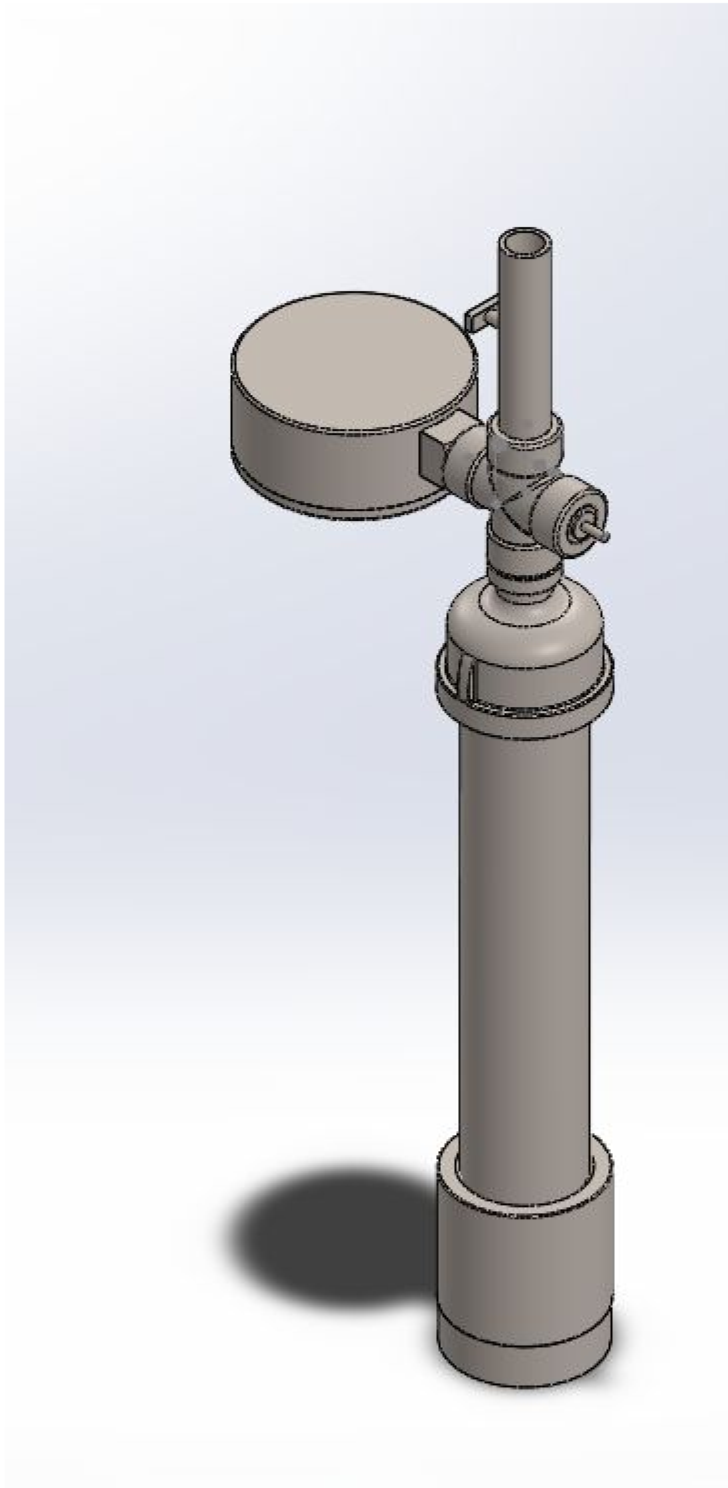


Figure 3:

Figure 4:

Figure 5:

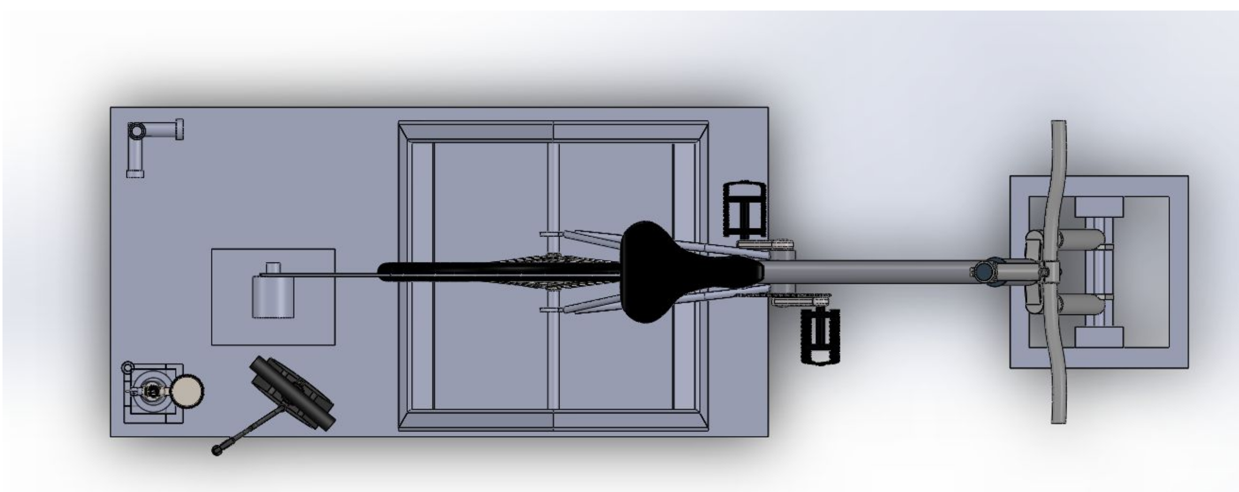
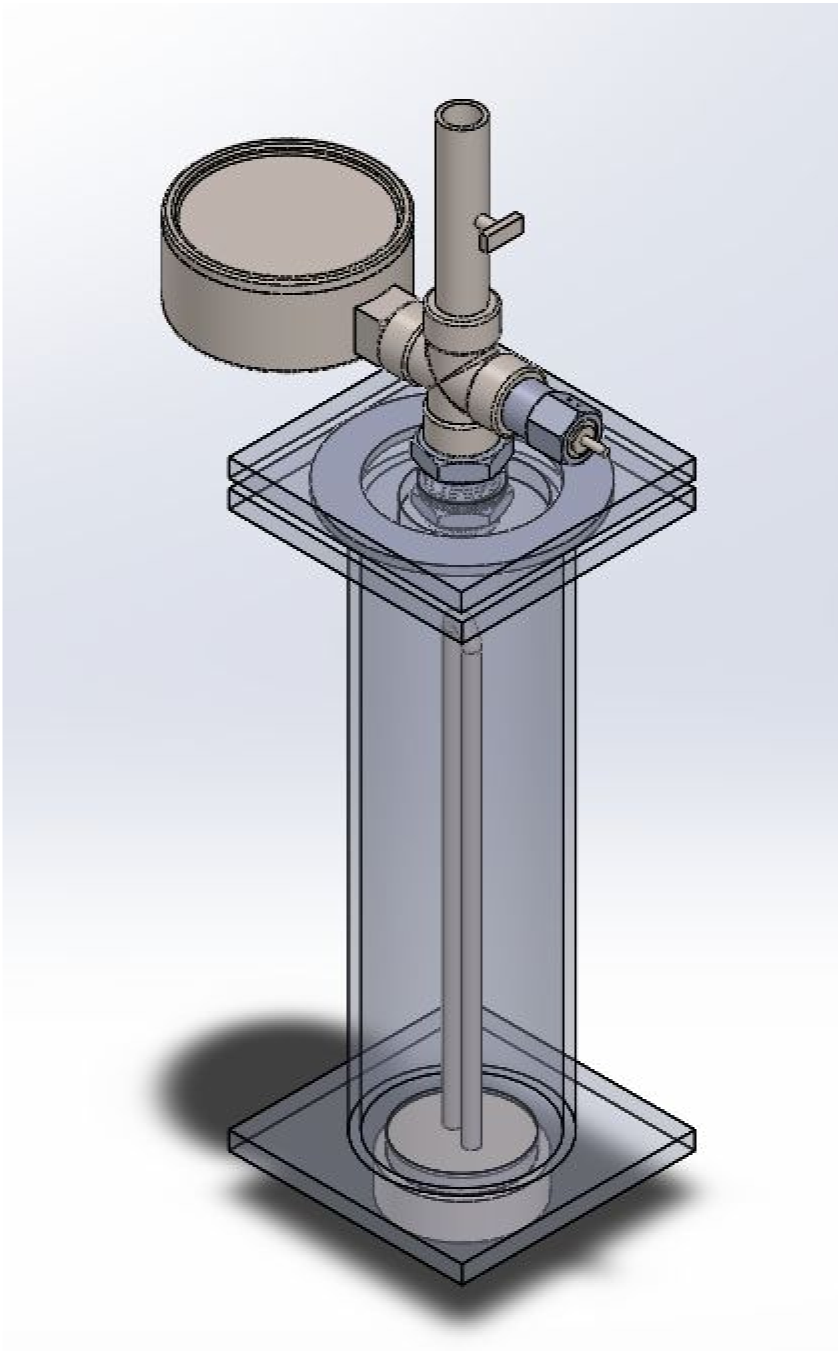


Figure 6:



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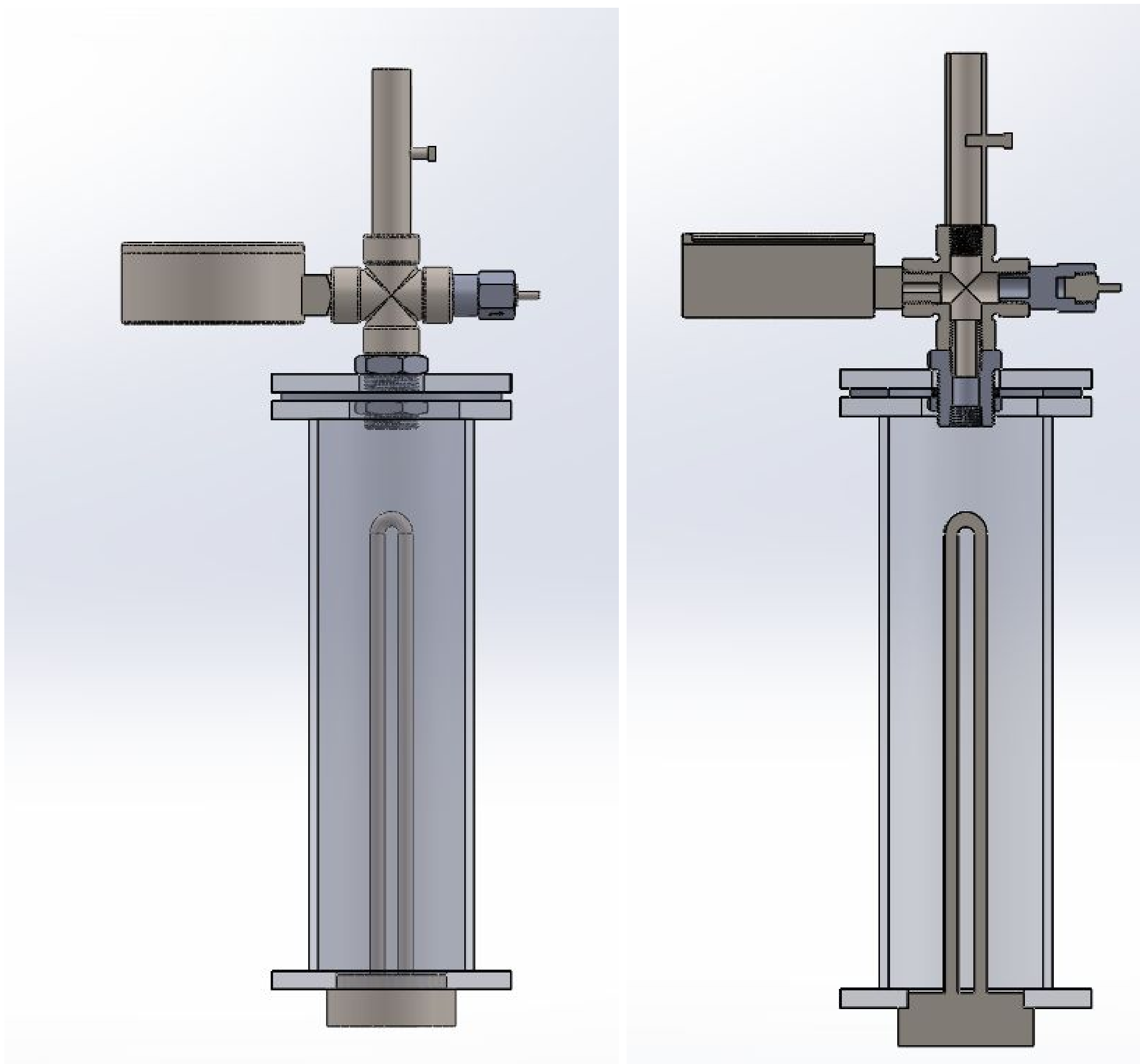


SIMULATIONS

Figure 8:

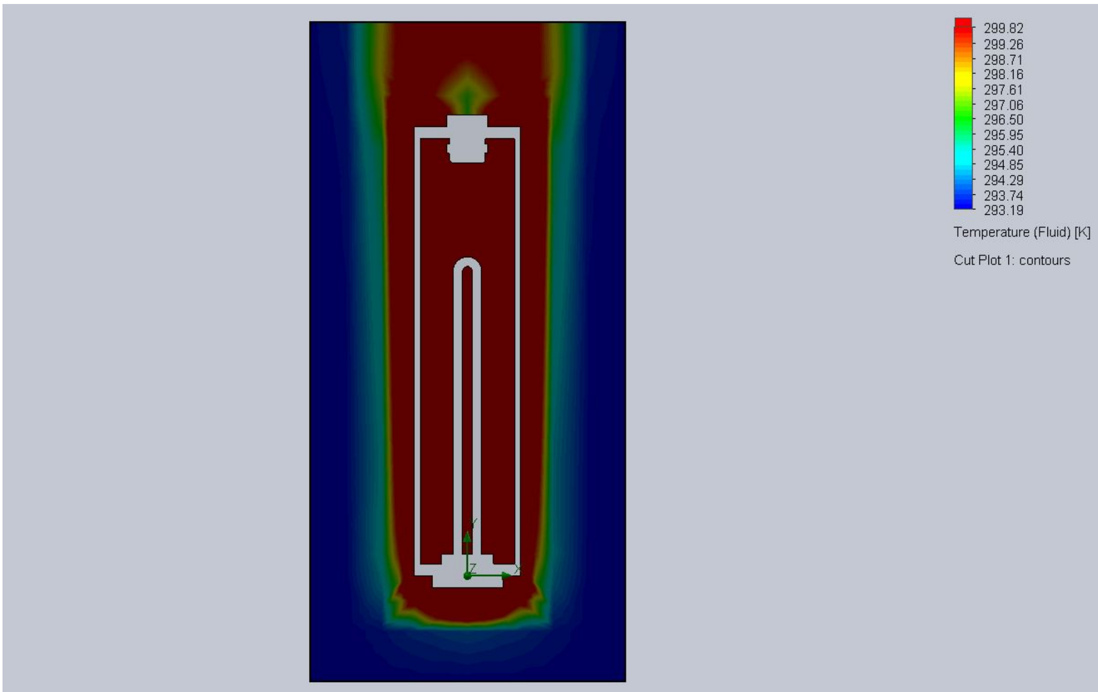
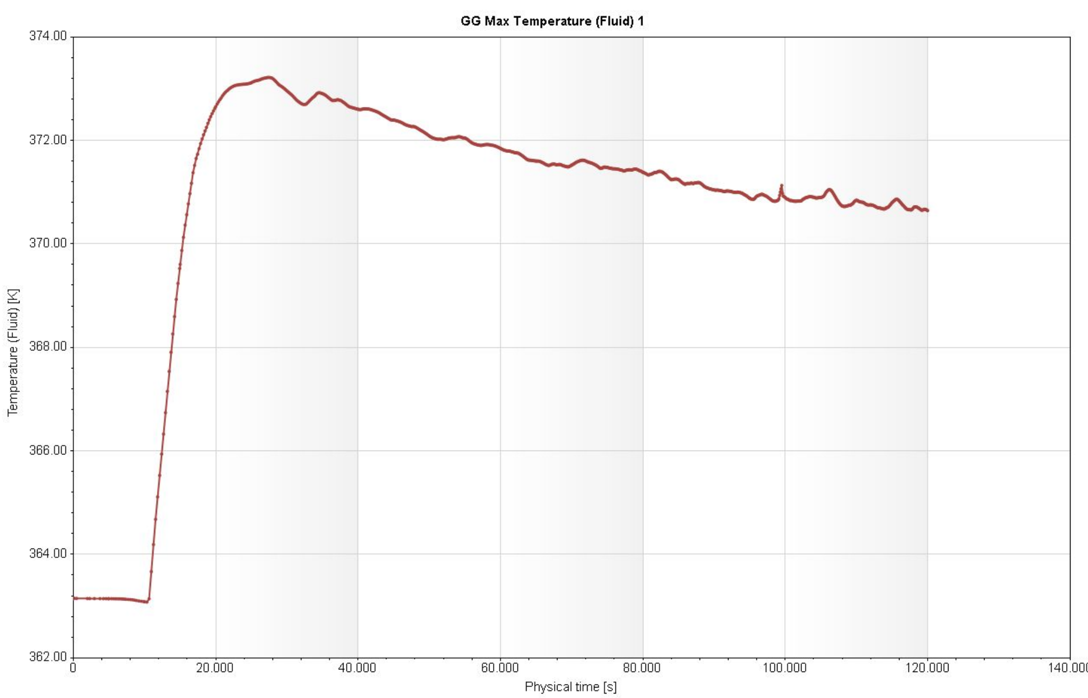


Figure 9:



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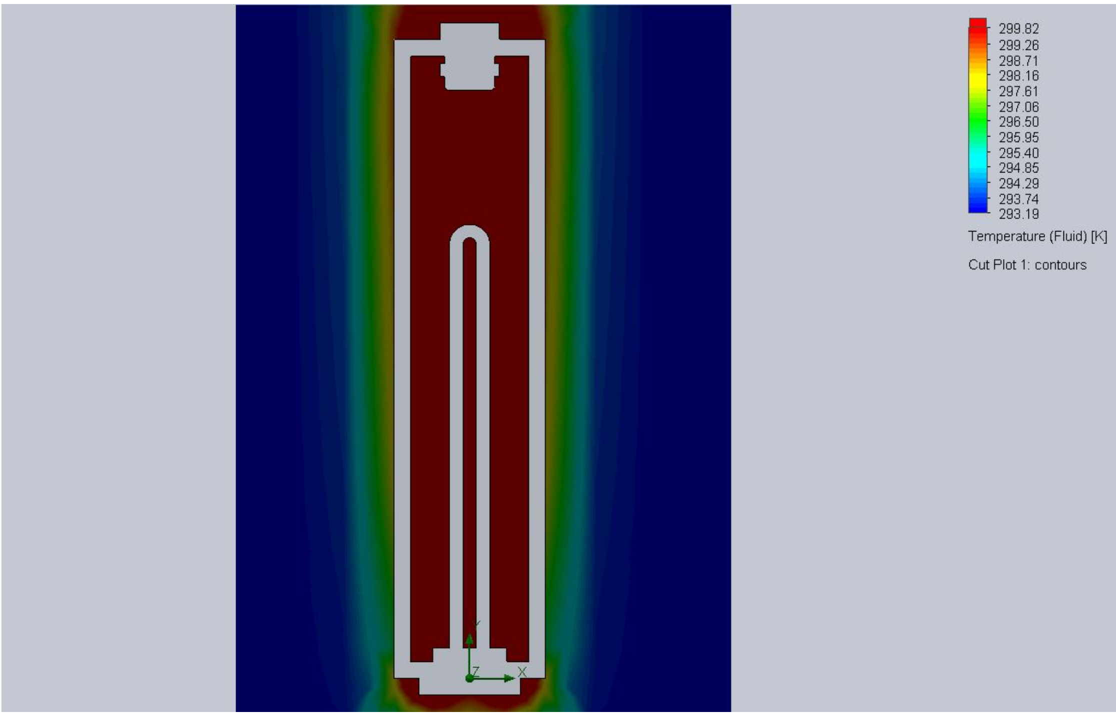

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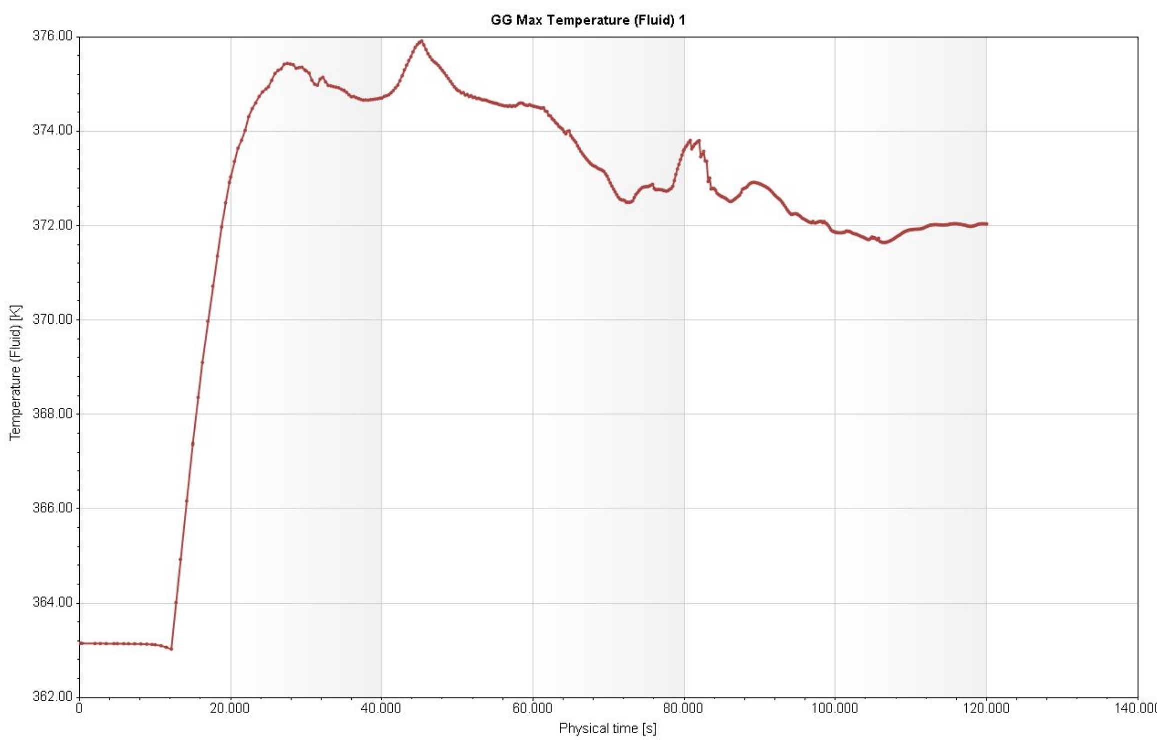


Figure 12:

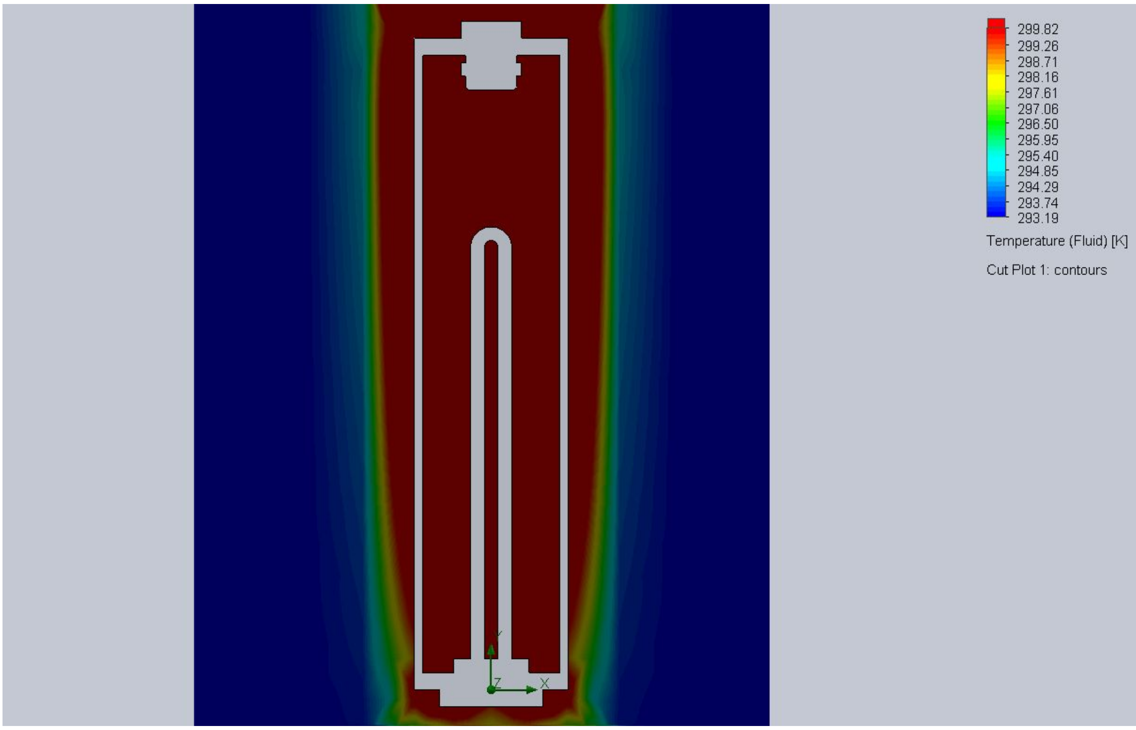
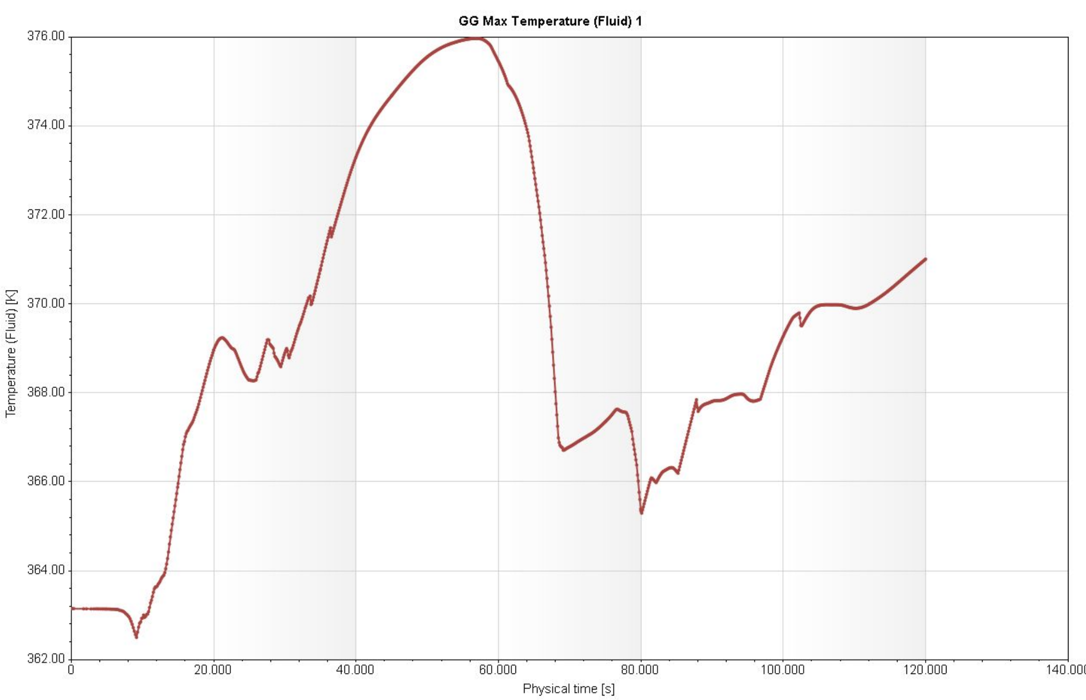


Figure 13:



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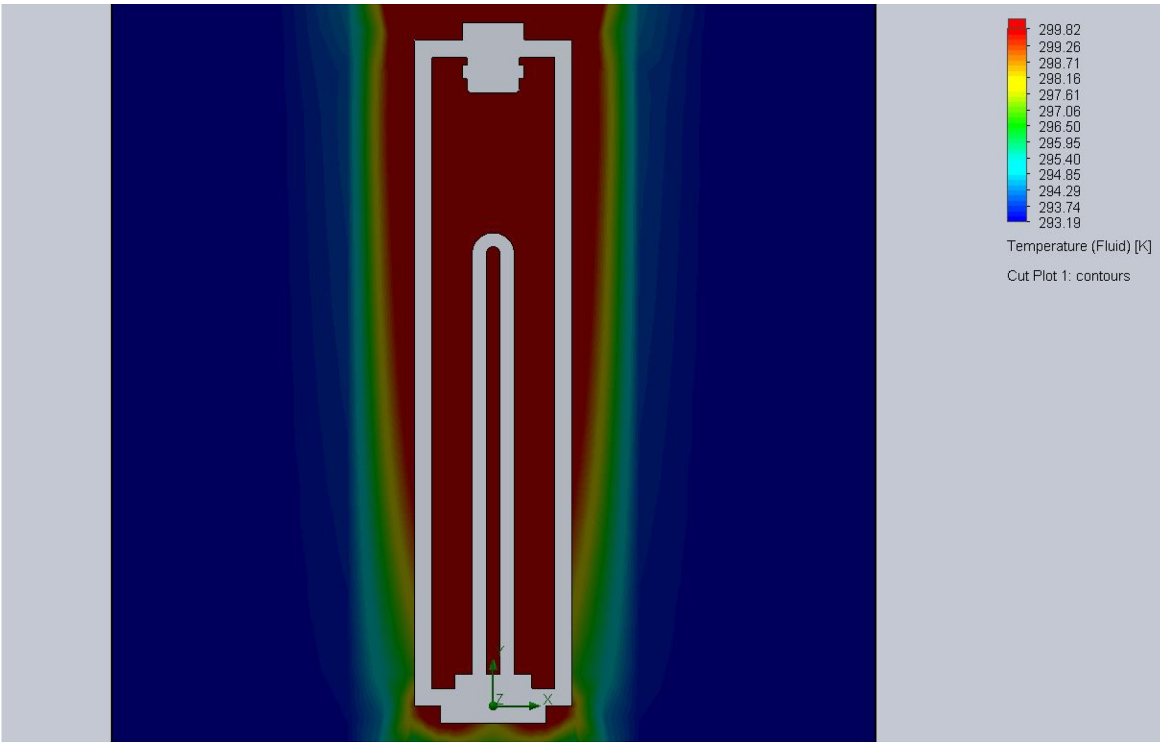
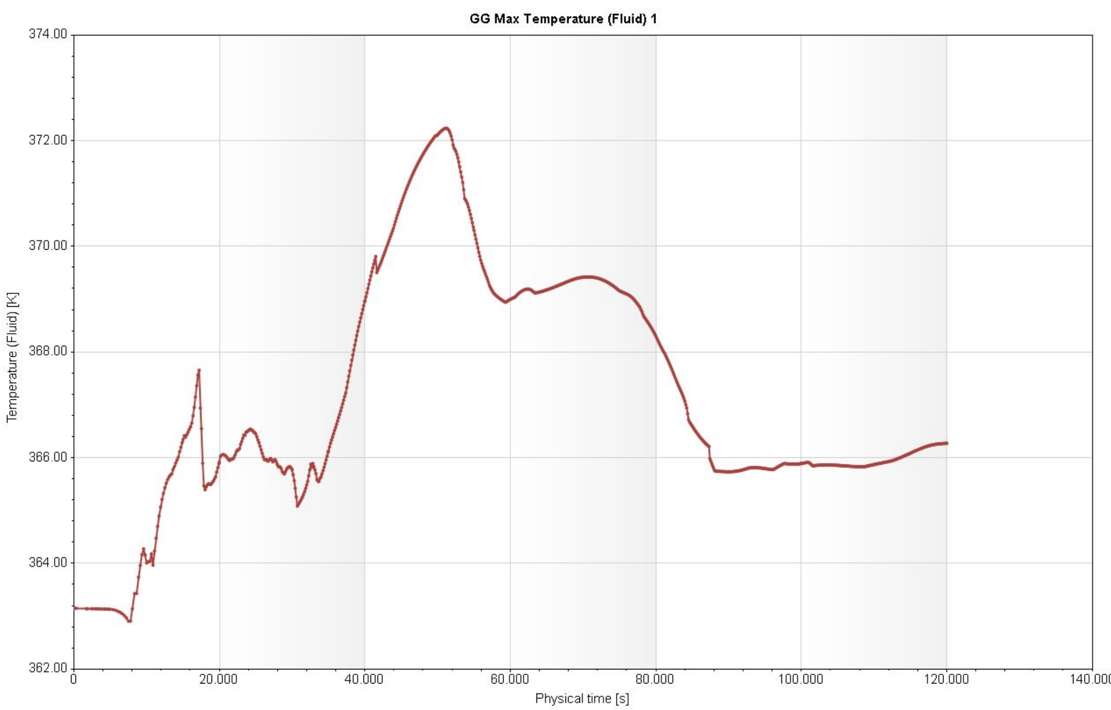


299.82
299.26
298.71
298.16
297.61
297.06
296.50
295.95
295.40
294.85
294.29
293.74
293.19
Temperature (Fluid) [K]
Cut Plot 1: contours
Y
Z
X



GG Max Temperature (Fluid) 1
374.00
372.00
370.00
368.00
366.00
364.00
362.00
Temperature (Fluid) [K]
0
20.000
40.000
60.000
80.000
100.000
120.000
140.000
Physical time [s]

BILL OF MATERIALS

Figure 15:

ITEM NO.	PART NAME	DESCRIPTION	QTY.	TOTAL COST
1	ACRYLIC PLATES	6" X 12" X 1/4"	2	$2.79
2	ACRYLIC TUBE	12" LENGTH (1" DIA & 1/2" THICK)	1	$12.49
3	DERNORD 24V 900W SS HEATING ELEMENT	HEATING ELEMENT	1	$26.99
4	MOTOR	24V DC	1	$30.96
5	BELT	TIMING BELT	1	$29.99
6	3/8" THREADED ROD	24" LONG	1	$0.99
7	WELD ON ACRYLIC	GLUE (4 OZ)	1	$1.34
8	PRESSURE TREATED PLYWOOD	2' X 4' X 3/4"	1	$13.49
9	2X4 LUMBER	4FT LONG	2	$5.26
10	RUBBER GASKET	2 PIECES	1	$1.49
11	METAL SPRING CLAMP	1"	2	$1.98
12	THICK RUBBER PIPING INULATION	6' LONG	1	$0.79
13	ALUMINUM FOIL	50 SQ FT	1	$0.14
14	BIKE	26" MOUNTAIN BIKE	1	$78.00
15	BIKE TRAINER	REAR WHEEL STAND	1	$20.99
16	2-HOLE STRAPS (4 PACK)	1-1/4"	1	$2.59
17	DIGITAL THERMOMETER	COOKING TEMPERATURE PROBE	1	$19.99
18	BIKE ODOMETER	HALL-EFFECT SENSOR	1	$13.49
19	LIGHT BULB	20W HALOGEN BULB (12V)	1	$5.74
20	ELECTRICAL TAPE	EXTREME TEMPERATURE RESISTANT	1	$1.97
21	1" PVC PIPE	24" LONG	2	$4.39
22	3/4" PVC PIPE	24" LONG	1	$0.80
23	3-WAY PVC ELBOW (4 PACK)	1" DIAMETER	1	$2.00
24	PVC SOCKET CAP	1" DIAMETER	3	$2.16
25	2-HOLE STRAPS (2 PACK)	1-1/2"	1	$1.49
26	EPOXY	2 OZ	1	$1.00
27	WIRES	40'	1	$2.20
28	NUT AND WASHER PAIR	3/8"	2	$1.20
29	ELECTRICAL SWITCH (15 PACK)	ON/OFF SWITCH	1	$0.43
30	WOOD SCREWS (4 PACK)	1-1/4"	3	$3.89
		TOTAL:		**$291.03**

STATISTICAL ANALYSIS

Figure 16:

Trial	d1	d2	d3	d123	yh1	yh2	yhbar	syh^2	syh	xh1	xh2	xhbar	sxh^2	sxh	
1	-	-	-	-	1440	1460	1450	200	14.14214	99	97	98	2	1.41421356	
2	+	-	-	+	1460	1450	1455	50	7.071068	103	108	105.5	12.5	3.53553391	
3	-	+	-	+	1490	1470	1480	200	14.14214	85	84	84.5	0.5	0.70710678	
4	-	-	+	+	1350	1370	1360	200	14.14214	104	101	102.5	4.5	2.12132034	
5	-	+	+	-	1430	1420	1425	50	7.071068	87	89	88	2	1.41421356	
6	+	-	+	-	1450	1480	1465	450	21.2132	108	111	109.5	4.5	2.12132034	
7	+	+	-	-	1470	1460	1465	50	7.071068	78	77	77.5	0.5	0.70710678	
8	+	+	+	+	1410	1430	1420	200	14.14214	76	79	77.5	4.5	2.12132034	
							B0	S^2	S	S.E.		B0	S^2	S	S.E.
							1440	175	13.22876	3.307189139		92.875	3.875	1.96850197	0.492125
	Main Effect	on yh	on xh												
	MEd1	22.5	-4												
	MEd2	15	-22						variables	Represents:	postive (+)	negative (-)		Responses	Represents:
	MEd3	-22.5	-0.75						d1	Insulation Thickness	thick	thin		yh	time to reach 150 degrees (sec)
									d2	Insulation material	Rubber	Foil		xh	Exterior temperture of insulation at 150 degrees
									d3	Insulation coverage	Full	Partial			

FMEA

Figure 17:

					Current Situation				
Subsystem	Component	Failure Mode	Failure Effect	Failure Cause	Current Detection Methods	S	O	D	RPN
Front Stand	Wood Stand	Warping of wood	Decrease in stability	Repeated use/Wear and tear	Visible test for wobbling, rotating	5	2	3	30
		Shearing of screws	System inoperable/Safety Issue	Repeated use/Improper operation	Failure - no preemptive determination method	10	1	10	100
	Metal Rod	Fracture due to Oxidation	System inoperable/Safety Issue	Improper use of machine/Improper maintenance	Visible test for excessive bending	10	3	6	180
Back Stand	Wheel Clamp	Loosening	Safety Issue/Minimal functionality damage - easy repair	Vibration/Shock	Check tightness on wheel before use	10	5	6	300
Bicycle	Seat	Material cracking	Customer discomfort	Material selection/Wear and tear	Visual Test - put cover on seat to protect from damage	3	1	2	6
	Frame	Oxidation/Corrosion	Potentially hazardous for operator	Improper maintenance	Examine metal surfaces	10	1	8	80
	Pedals	Fracture	System inoperable	Improper use of machine	Visual Examination	7	1	10	70
		Loose/Wobbling	Decrease in efficiency of system/Decrease in comfort of usablility	Improper maintenance	Jiggle bike pedals	5	2	6	60
	Chain/Gears	Grinding from friction	Decrease in efficiency	Improper maintenance	Measure force used to turn wheel - lubricate for maintenance	4	3	7	84
		Misalignment	System temperarily inoperable - fixable	Resonance/system vibration	Visual examination	5	4	6	120
		Slippage	Decrease in system efficiency	Torque too high	Check the tightness of the seat clamp before use	5	2	3	30
	Back Wheel	Unstable	Loss of energy to vibrations	Fastener becomes loose	Jiggle rear wheel				0
	Band	Misalignment	Efficiency loss to friction	Wrong fastener usage	Ensure band is centered in wheel rail	4	5	6	120
		Inelastic stretching	Loss of efficiency of the system	Wrong fastener usage	Rotate band checking for overly stretched portions	7	2	6	84
Motor	Pulley	Loose - connection with motor	Range from efficiency loss to temperarily inoperable	High torque applied over time	Manually tighten with the hex key between uses	7	9	7	441
		Misalignment	Efficiency loss to friction	Wrong fastener usage	Ensure band is centered in wheel rail	4	5	6	120
	Band	Misalignment	Efficiency loss to friction	Wrong fastener usage	Ensure band is centered in wheel rail	4	5	6	120
		Inelastic stretching	Loss of efficiency of the system	Wrong fastener usage	Rotate band checking for overly stretched portions	7	2	6	84
	Motor Circuit	Open circuit	System temperarily inoperable - fixable	Vibration/Shock	Visual Examination of wire connections	6	5	6	180
		Motor shaft fracture	System inoperable/Safety Issue	High Stress	Ensure Pulley is secure to motor shaft	10	1	10	100
		Overshooting	System inoperable	Pedaling too fast/too much torque	Multimeter voltage/current readings	8	1	4	32
Container	Top/Bottom Plate	Shearing	System inoperable	improper operation	Visual examination for cracks	8	1	10	80
	Thermocouple	Loosening	Temperary loss of temperature readout	Vibration/Shock	Touch to ensure probe is secure	3	5	6	90
		Open Circuit	Temperary loss of temperature readout	Vibration/Shock	Visual Examination of wire connections	3	3	1	180
		Fracture	Permanent loss of temperature readout	Improper or careless setup or operation	Visual examination	6	4	8	72
	Heating Element	Open circuit	System temperarily inoperable - fixable	Vibration/Shock	Visual examination of the wire connection	6	5	6	0
		Thermal Fatigue	System inoperable	improper operation	Digital thermal output readings	8	1	9	0

TASK CHART

Figure 18:

Task Chart

PROJECT DETAILS					
STATUS	START DATE	END DATE	TASK OWNER	DESCRIPTION	% DONE
PROJECT PHASE 1					**100%**
Project Statement	1/25/19	2/14/19	Basab	A general project statement/introduction	100%
Background Information	1/25/19	2/14/19	Harrison	Gather background information to educate yourself and your reader	100%
Customer Identification/Needs	1/25/19	2/14/19	Harrison	Identify the target customer group/determine a list of their needs	100%
Product Requirements/HOQ	1/25/19	2/14/19	Kevin	Fill out the house of quality with customer needs and corresponding engineering specs	100%
Gantt Chart/Task List	1/25/19	2/14/19	Weston	Fill out these documents for scheduling purposes	100%
Interviews	1/25/19	2/14/19	All	Conduct interviews to help gather background information and customer needs	100%
PROJECT PHASE 2					**100%**
Update Project Proposal	2/11/19	2/27/19	Harrison	Implement critique received from project proposal	100%
Black Box Design	2/14/19	2/27/19	Weston	Create black box design focusing on the input-output response	100%

Function Structure Model	2/15/19	3/4/19	Weston	Make a function structure model that organizes the device into subsystems	100%
Reference Prior Art	2/18/19	3/4/19	Basab & Weston	Identify prior patents, publications, design catalogs, ect. as additional candidate solutions	100%
Create four design variation sketches	2/18/19	3/4/19	Kevin & Weston	Each team-member will sketch a different design variation	100%
Design Concept Generation Summary	2/18/19	3/6/19	Kevin	Talk about results and insights gained from mind-mapping and 6-3-5.	100%
Create Morph Matrix	2/18/19	3/5/19	Weston	Make a morph graph to compare the different subsystems from variant designs	100%
Pugh Chart	2/20/19	3/5/19	Basab & Harrison	Create a chart comparing design ideas to the design criteria	100%
Back-of-the-envelope Calculations	2/25/19	3/6/19	Basab & Harrison	Complete and list all calculations used	100%

PROJECT PHASE 3 100%

CAD Design	3/6/19	3/13/19	Kevin	Create a computer-aided design via SolidWorks	100%
Mechatronics Design	3/6/19	3/13/19	Weston	Design the electric circuits	100
Prototype Budgeting	3/6/19	3/13/19	Harrison	Create a detailed budget for the prototype	100%
Bill of Materials	3/6/19	3/13/19	Basab	Compile a list of materials	100%
Component Sketches	3/6/19	3/13/19	All	Sketch each individual part	100%
Final Design Budget	3/6/19	3/13/19	Harrison	Determine the budget based on the bill of materials	100%
50% Functional Prototype	3/7/19	4/1/19	All	A 50% completion of device	100%

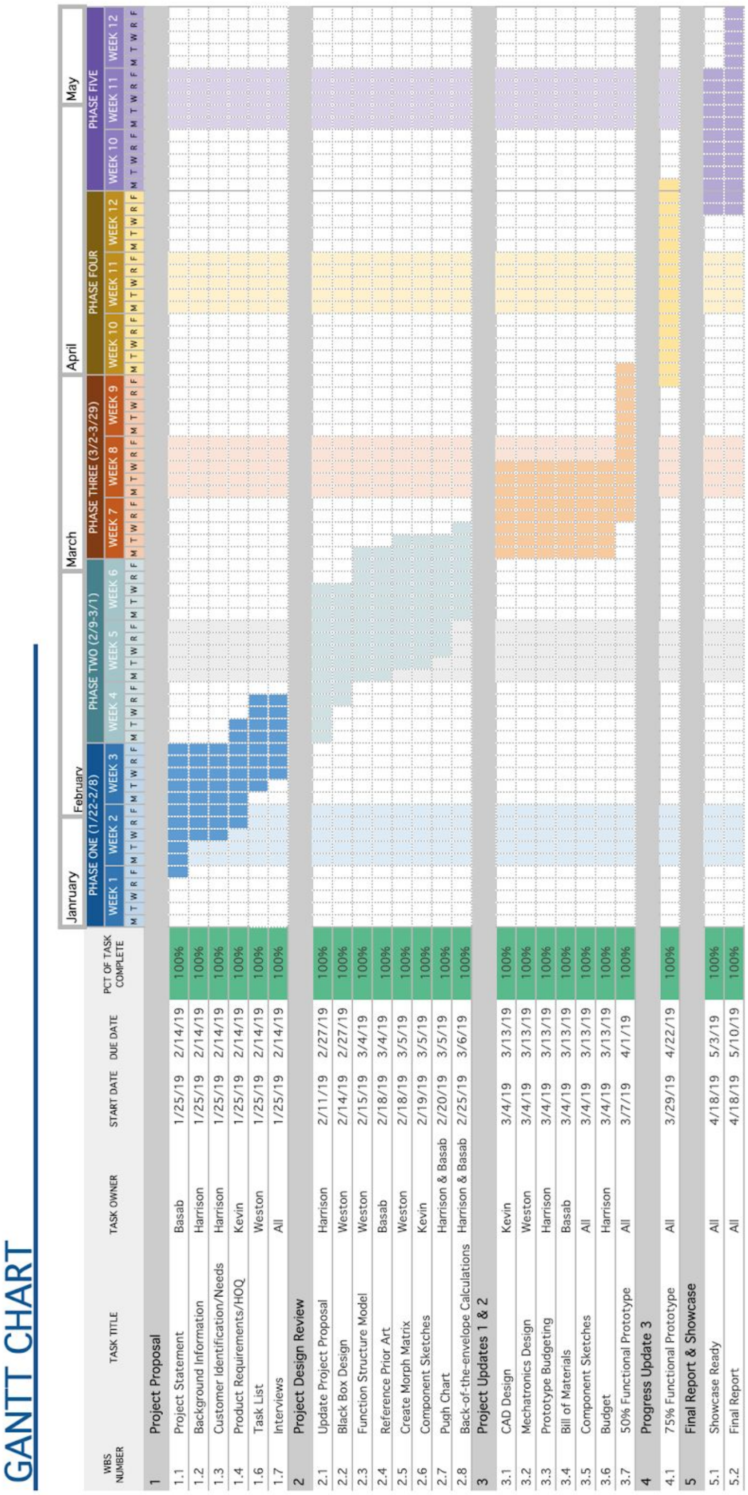
75% Functional Prototype	3/29/19	4/22/19	All	A 75% completion of device	100%

PROJECT PHASE 4 100%

Review & Revise Pugh Chart and Design requirements	4/18/19	4/20/19	All	Return to parts from the design proposal and design review	100%
Create New Task List and Gantt Chart	4/18/19	4/21/19	Weston	Have an updated and detailed plan for the rest of the semester	100%
Provide final sketches	4/18/19	4/28/19	Kevin	Using CAD or by-hand, create a production ready illustration	100%
Perform FMEA	4/18/19	4/30/19	Basab	Failure modes and Effects Analysis	100%
Fabrication and Assembly	4/18/19	5/1/19	All	Build the device	100%
Design & Conduct Experiment of a High-Risk Component or Sub-System	4/20/19	5/1/19	Harrison	Include at least 3 design variable and 2 responses	100%
Run Simulations using a Computer Model	4/22/19	5/6/19	Kevin	Simulate wear and tear on a likely mode of failure	100%
Create FEA	4/22/19	5/6/19	Weston	Use finite element model to evaluate robustness	100%
Perform DFMA	4/25/19	5/7/19	Basab	Create a design for manufacturing and assembly and verify that the parts are manufacturable	100%
Showcase Ready	4/18/19	5/3/19	All	A fully functional device ready for display at the showcase	100%
Final Report	4/18/19	5/10/19	All	Have everything completed and organized	100%

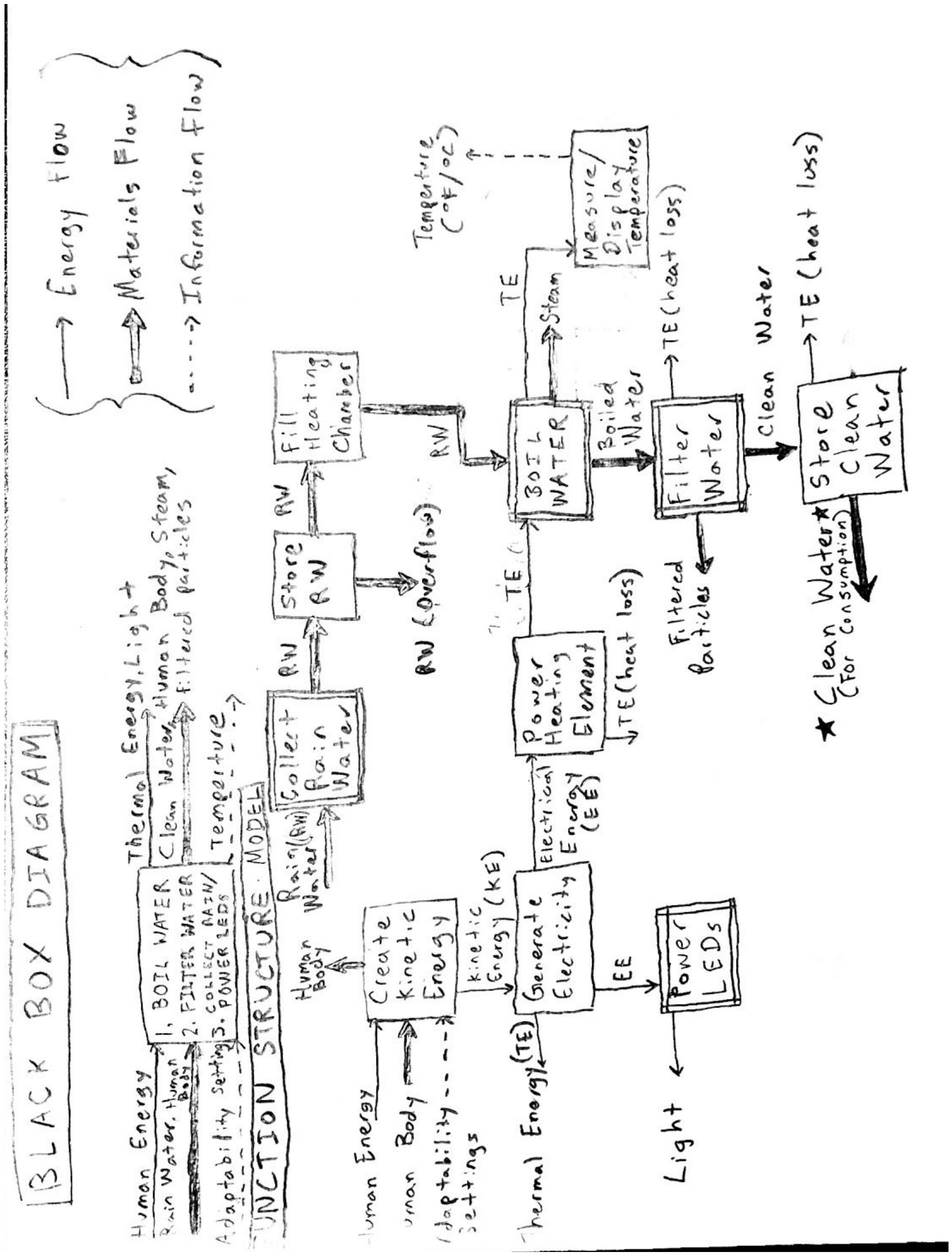
GANTT CHART

Figure 19:



FUNCTION STRUCTURE

Figure 20:



6-3-5 SKETCHES

Figure 21:

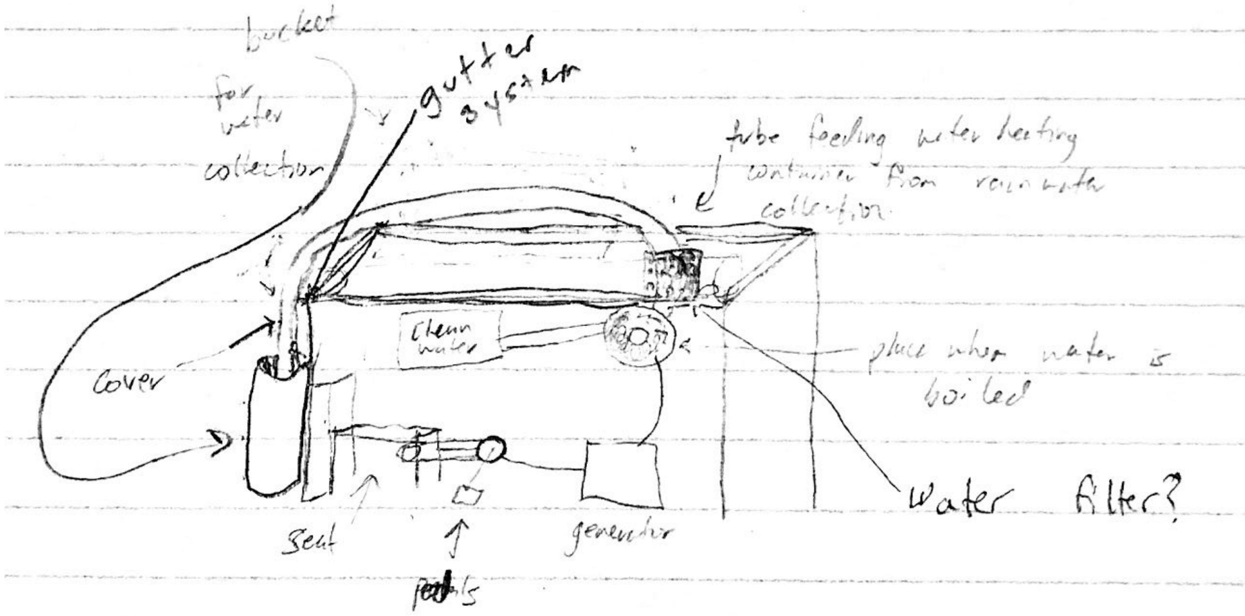


Figure 22:

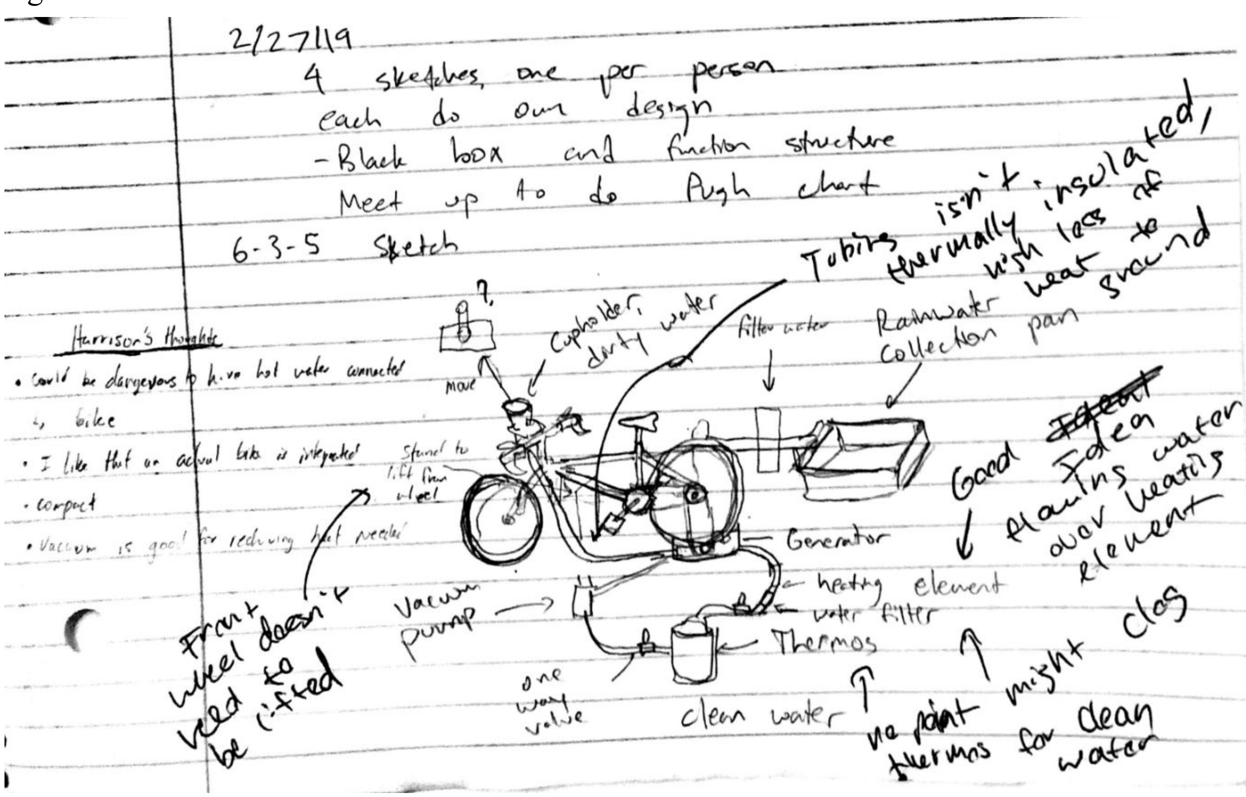


Figure 23:

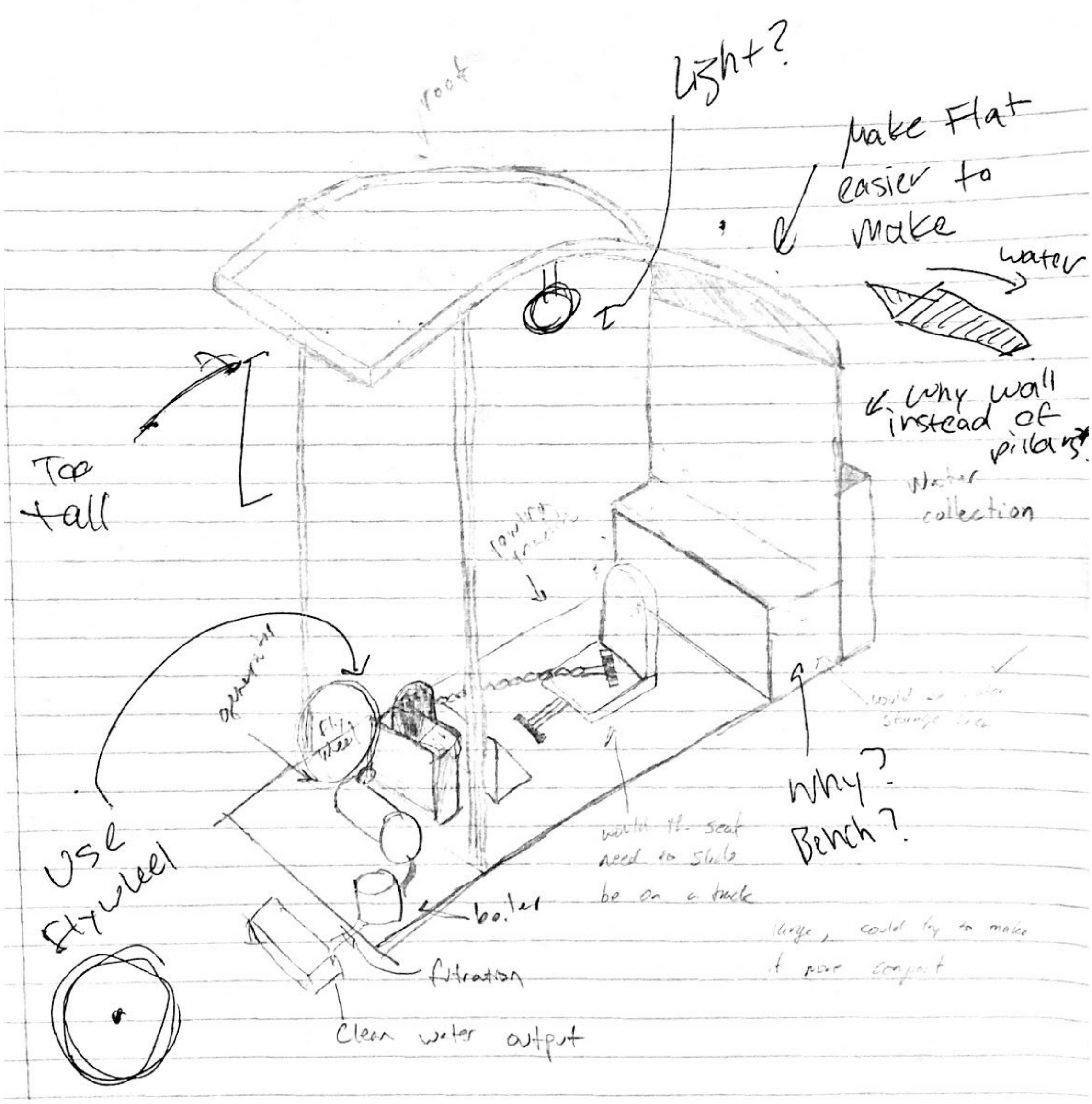
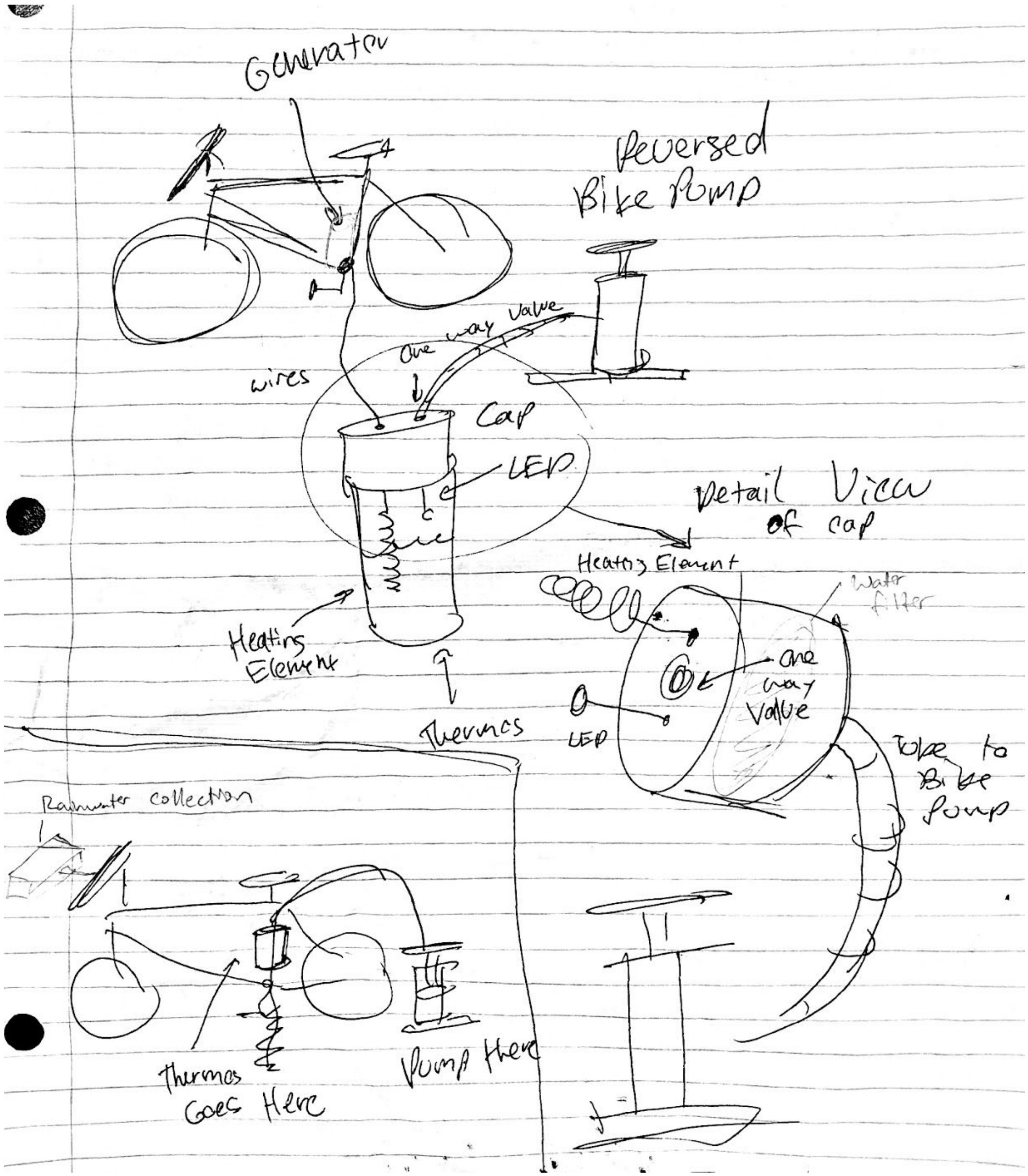
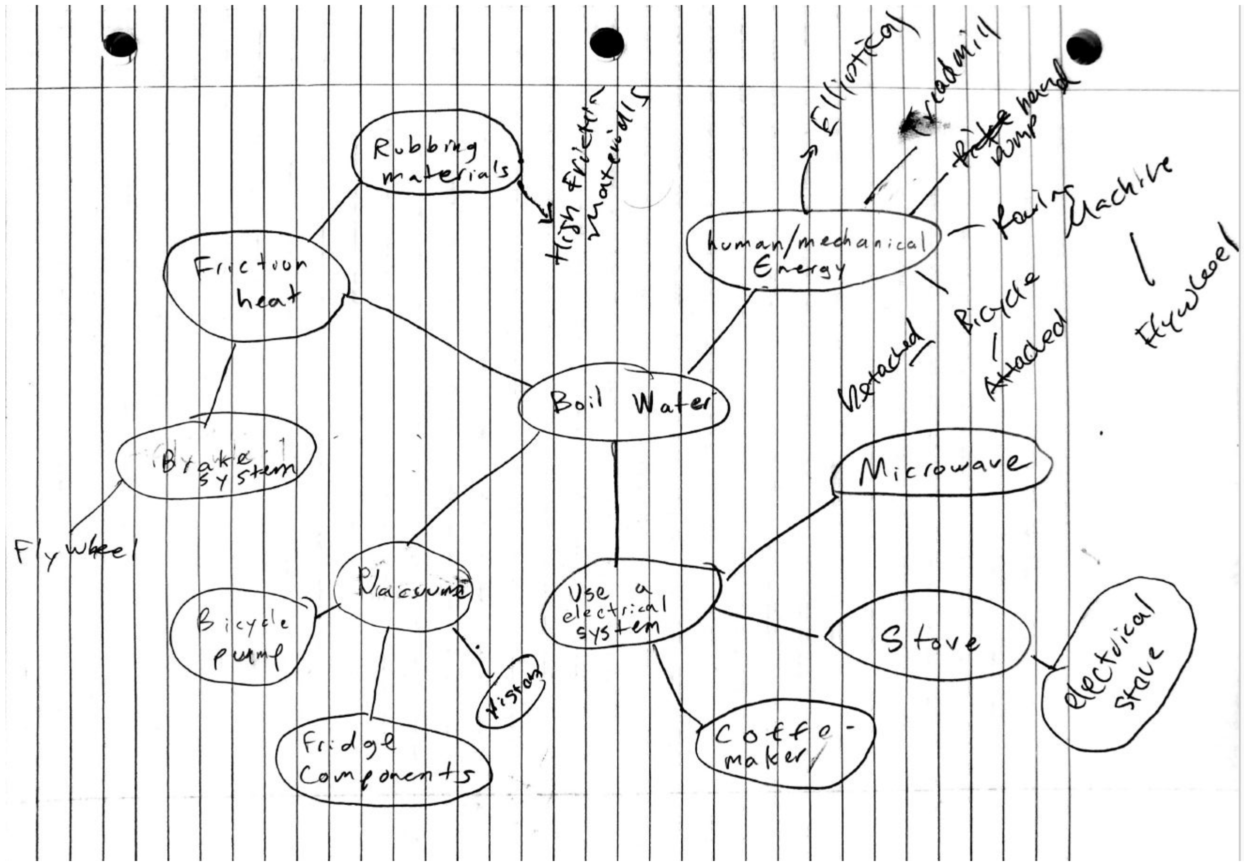

roof
Light?
Make Flat
easier to
make
water
why wall
instead of
pillars?
Too
tall
Water
collection
Use
flywheel
Fly
wheel
would the seat
need to slide
be on a track
why?
Bench?
large, could try to make
it more compact
boiler
filtration
Clean water output

Figure 24:


Generator
Reversed
Bike Pump
One way Valve
wires
Cap
LED
Detail View
of cap
Heating Element
Water
filter
Heating
Element
one
way
Valve
Thermos
LED
Tube to
Bike
Pump
Rainwater collection
Thermos
Goes Here
Pump Here

MIND-MAPPING

Figure 25:



CONCEPT SKETCHES

Figure 26:

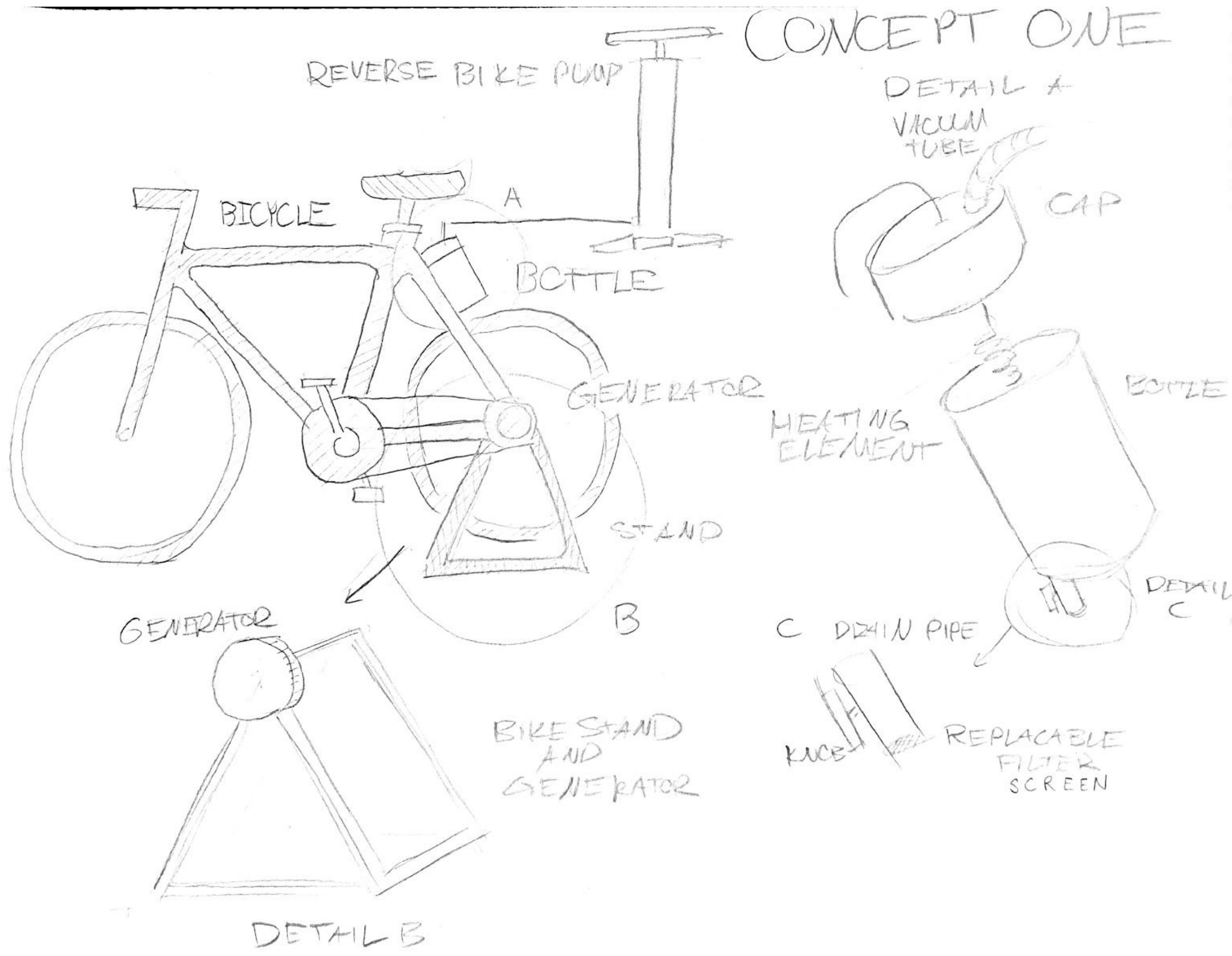


Figure 27:

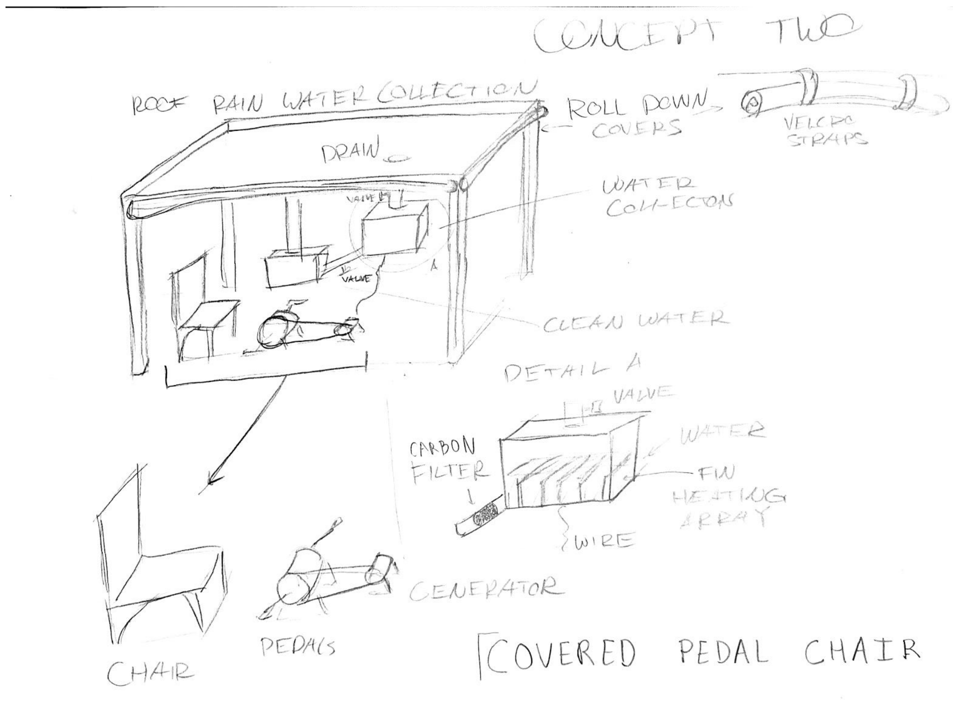


Figure 28:

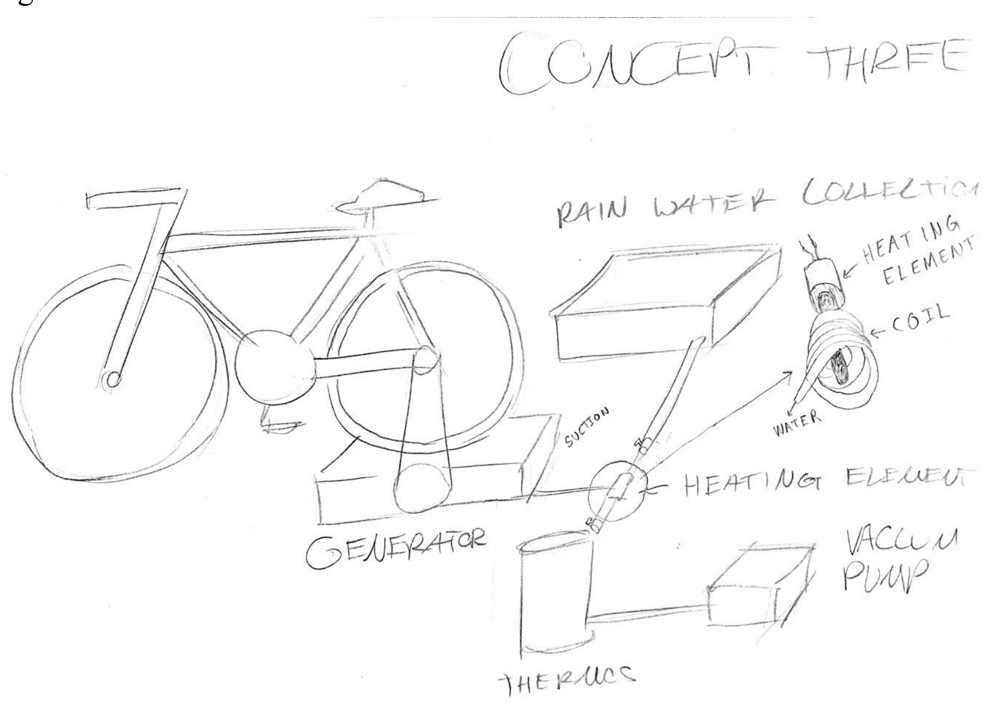
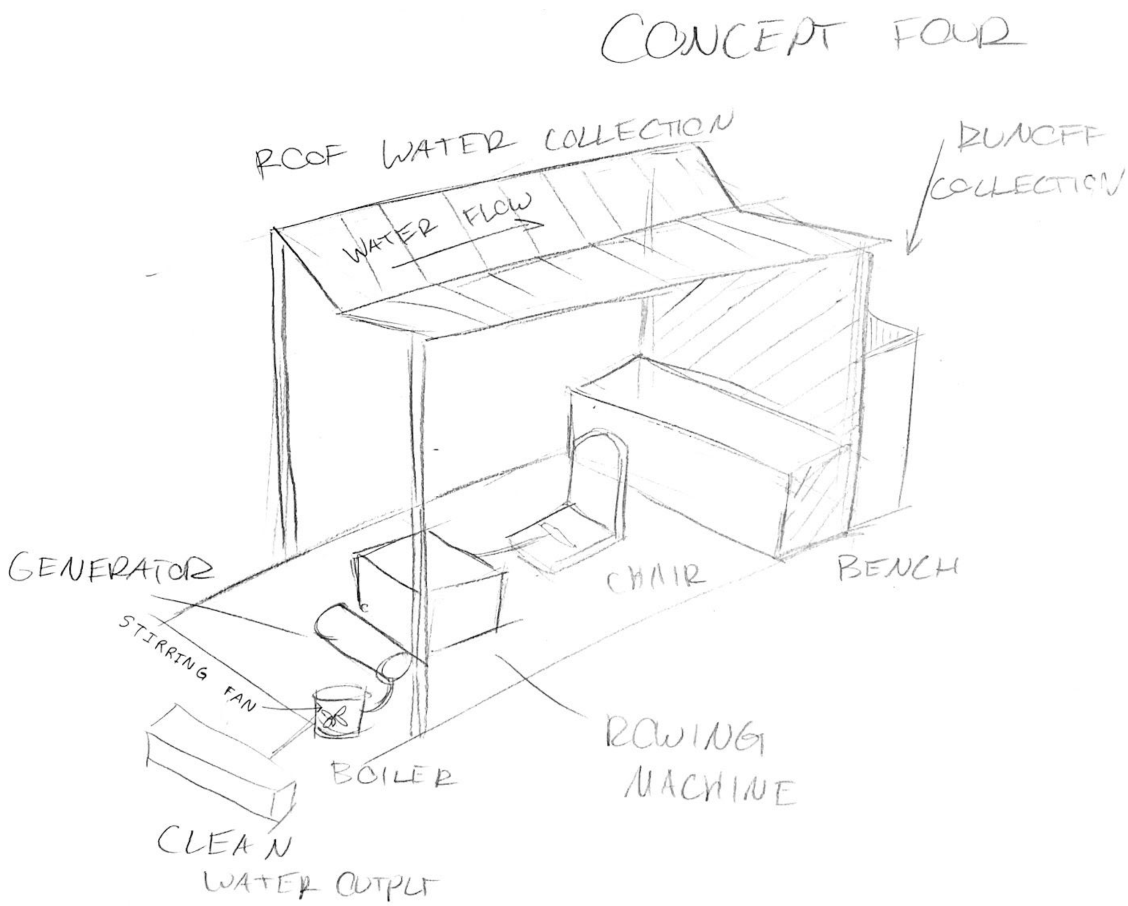


Figure 29:


CONCEPT FOUR
ROOF WATER COLLECTION
RUNOFF COLLECTION
WATER FLOW
GENERATOR
STIRRING FAN
CHAIR
BENCH
ROWING MACHINE
BOILER
CLEAN WATER OUTPUT

Morph Matrix

Figure 30:

		Energy:				
		Mechanical	**Fluid**	**Electrical**	**Misc.**	
Sub-Functions:	**Generate Kinetic Energy**	Crank	Turbine	Electromagnetics	Gravity	Concept #1
			Water mill	Electric Motors	Magnets	Concept #2
		Springs	Wind Vanes			Concept #3
		Pedulum	Propeller			Concept #4
		Rollers				
		Seesaw				
	Generate Electricity	Homopolar generator (DC)	Hydroelectric Turbine		Solar Panels	
		Linear Electric generator (AC)	Salter Duck		Ground Source Heat Pump	
		Variable-speed constant-frequency generators (AC)				
		Magnetohydrodynamic (MHD) generator (DC)				
	Boil Water	Friction	Pressure	Heating Resistor	Conduction	
					Convection	
					Chemical Reactions	
				Microwaves	Radiation	
	Collect Rain Water	Funnel				
		Gutters				
		Open-tank				
		Concave Roof				
	Fill Heating Chamber	Syphon			Manually	
		Valve				
		Pump				
		Piston				
	Filter Water	Cotton			UV light	
		Carbon				
		Wool/Floss/Cloth				
		Screen				
		Sponge/Foam				
		Permiable Membrane				
		Sand				
	Store Water	Tank				
		Bottles				
		Bladder				
		Heating chamber				
		Pipes				
	Measure/Display Temperture	Bimetallic Strips	Glass thermometer	Thermistor	Eye-ball test	
			Gas Thermometer	Thermocouple	Chemical Strips	
					Infrared	

PUGH CHART

Figure 31:

Concept 1 Datum					
	Concepts	Concept 1	Concept 2	Concept 3	Concept 4
Criteria		Detachable bike w/ hand pump	Covered Pedal Chair	Detachable bike w/ electric pump	Rowing Machine
Energy output (J)	X3 weight	0	---	0	---
Adjustability		0	-	0	-
Comfortability		0	+	0	+
Boil time (min)	X3 weight	0	---	---	---
Durability (years)		0	-	-	-
Storage Capacity (L)	X2 weight	0	++	++	++
Operational tasks (#)		0	+	+	+
Bacteria levels (mg/L)	X2 weight	0			
Safety		0	+	+	-
Costs ($)	X2 weight	0	--	--	--
Shelter area (m^2)		0	+	0	+
Operational time (% of day)		0	+	-	+
Training time (hrs.)		0	+	+	+
Sum Positives		0	8	5	7
Sum Negatives		0	-10	-7	-11
Sum Total		0	-2	-2	-4

Concept 2 Datum					
	Concepts	Concept 2	Concept 3	Concept 4	Concept 1
Criteria		Covered Pedal Chair	Detachable bike w/ rainwater collection	Rowing Machine	Detachable bike w/ hand pump
Energy output (J)	X3 weight	0	+++	---	+++
Adjustability		0	+	+	+
Comfortability		0	-	-	-
Boil time (min)	X3 weight	0	+++	---	+++
Durability (years)		0	+	-	+
Storage Capacity (L)	X2 weight	0	--	++	--
Operational tasks (#)		0	-	-	-
Bacteria levels (mg/L)	X2 weight	0			
Safety		0	-	-	-
Costs ($)	X2 weight	0	++	--	++
Shelter area (m^2)		0	-	-	-
Operational time (% of day)		0	-	0	-
Training time (hrs.)		0	-	-	-
Sum Positives		0	10	3	10
Sum Negatives		0	-8	-14	-8
Sum Total		0	2	-11	2

Figure 32:

Concept 3 Datum

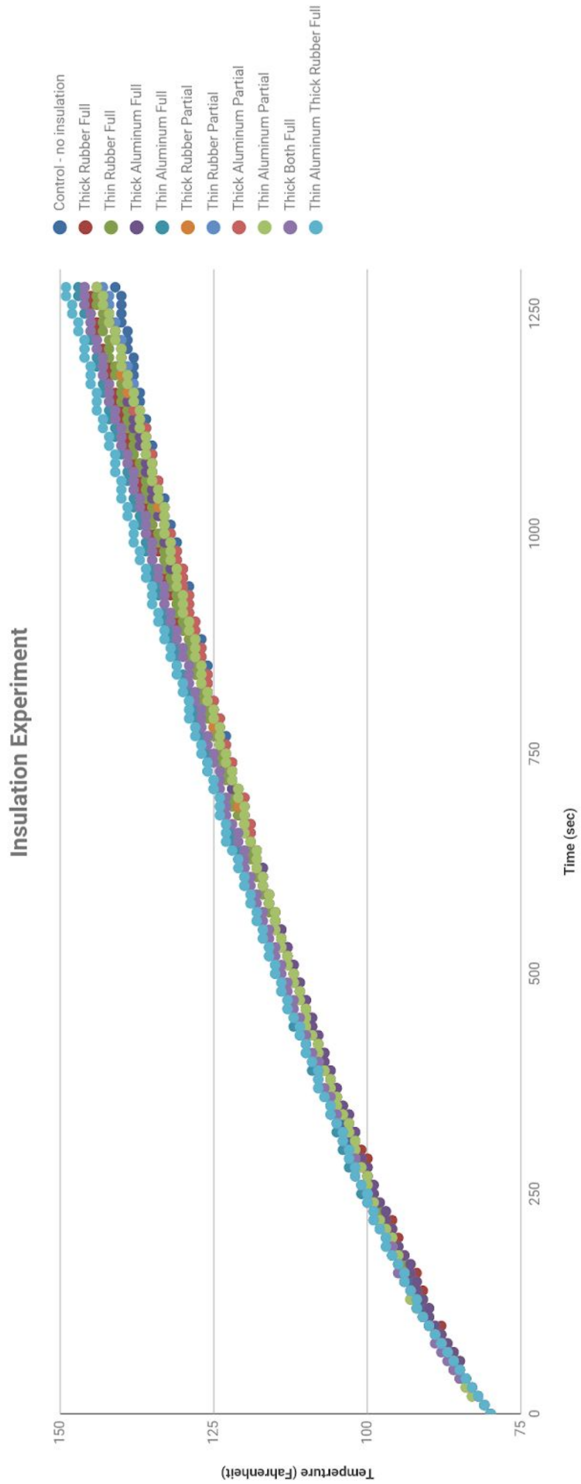
Criteria	Concepts	Concept 3 Detachable bike w/ rainwater collection	Concept 4 Rowing Machine	Concept 1 Detachable bike w/ hand pump	Concept 2 Covered Pedal Chair
Energy output (J)	X3 weight	0	---	0	---
Adjustability		0	-	0	-
Comfortability		0	+	0	+
Boil time (min)	X3 weight	0	---	+++	---
Durability (years)		0	-	+	-
Storage Capacity (L)	X2 weight	0	++	--	++
Operational tasks (#)		0	+	-	+
Bacteria levels (mg/L)	X2 weight	0			
Safety		0	-	+	+
Costs ($)	X2 weight	0	--	++	--
Shelter area (m^2)		0	++	0	++
Operational time (% of day)		0	+	+	+
Training time (hrs.)		0	+	-	+
Sum Positives		0	8	8	9
Sum Negatives		0	-11	-4	-10
Sum Total		0	-3	4	-1

Concept 4 Datum

Criteria	Concepts	Concept 4 Rowing Machine	Concept 1 Detachable bike w/ hand pump	Concept 2 Covered Pedal Chair	Concept 3 Detachable bike w/ rainwater collection
Energy output (J)	X3 weight	0	+++	+++	+++
Adjustability		0	+	-	+
Comfortability		0	-	+	-
Boil time (min)	X3 weight	0	+++	+++	+++
Durability (years)		0	+	+	+
Storage Capacity (L)	X2 weight	0	--	--	--
Operational tasks (#)		0	-	+	-
Bacteria levels (mg/L)	X2 weight	0			
Safety		0	+	+	+
Costs ($)	X2 weight	0	++	++	++
Shelter area (m^2)		0	-	+	-
Operational time (% of day)		0	-	0	-
Training time (hrs.)		0	-	+	-
Sum Positives		0	11	14	11
Sum Negatives		0	-7	-3	-7
Sum Total		0	4	11	4

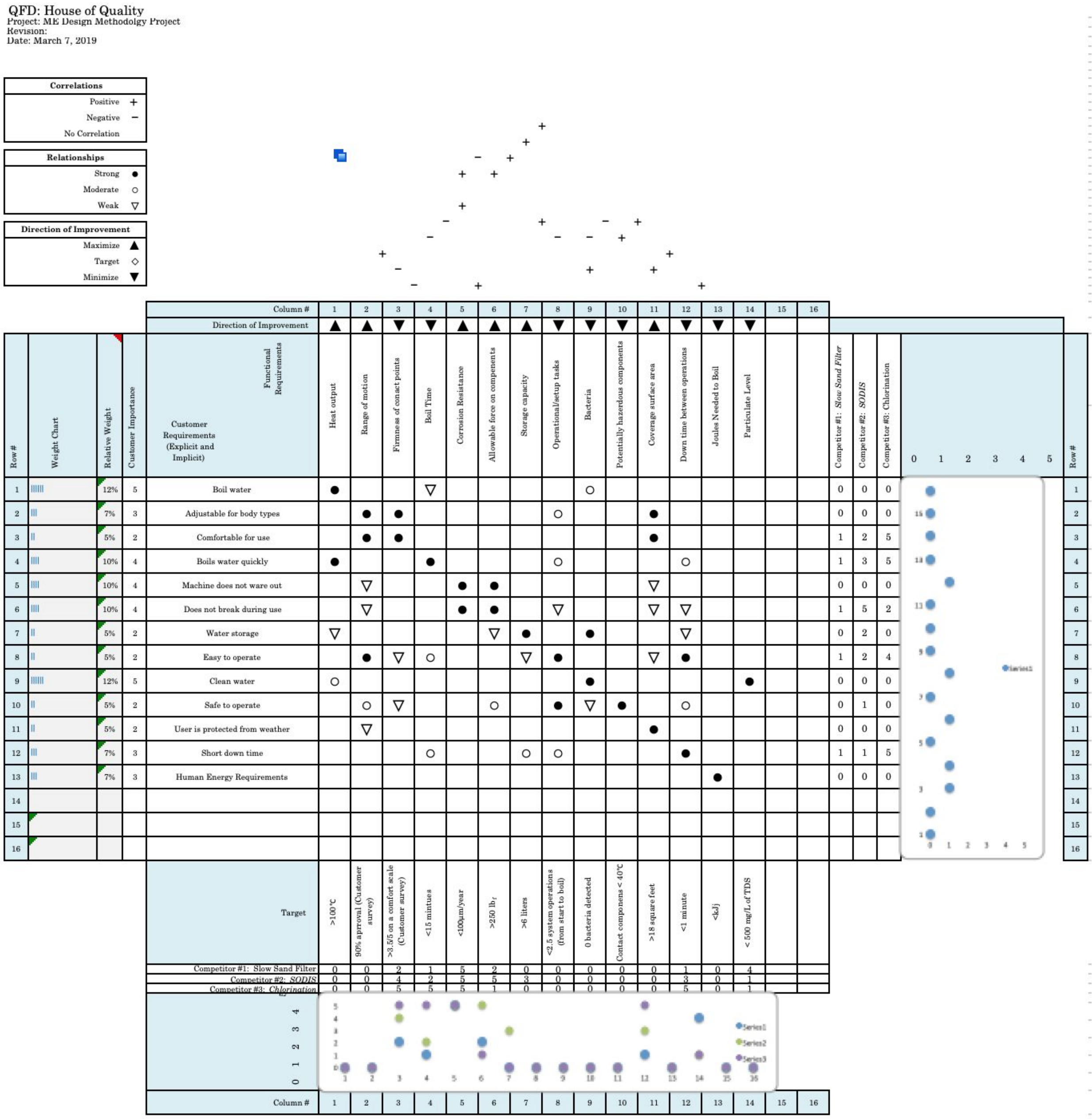
EXPERIMENTAL RESULTS

Figure 33:



HOUSE OF QUALITY

Figure 34:



QFD: House of Quality
Project: ME Design Methodolgy Project
Revision:
Date: March 7, 2019

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

Row #	Relative Weight	Customer Importance	Customer Requirements (Explicit and Implicit) / Functional Requirements	1 Heat output	2 Range of motion	3 Firmness of conact points	4 Boil Time	5 Corrosion Resistance	6 Allowable force on compenents	7 Storage capacity	8 Operational/setup tasks	9 Bacteria	10 Potentially hazerdous components	11 Coverage surface area	12 Down time between operations	13 Joules Needed to Boil	14 Particulate Level	15	16	Competitor #1: *Slow Sand Filter*	Competitor #2: *SODIS*	Competitor #3: Chlorination	Row #
			Direction of Improvement	▲	▲	▼	▼	▲	▲	▲	▼	▼	▼	▲	▼	▼	▼						
1	12%	5	Boil water	●			▽					○								0	0	0	1
2	7%	3	Adjustable for body types		●	●					○			●						0	0	0	2
3	5%	2	Comfortable for use		●	●								●						1	2	5	3
4	10%	4	Boils water quickly	●			●				○				○					1	3	5	4
5	10%	4	Machine does not ware out		▽			●	●					▽						0	0	0	5
6	10%	4	Does not break during use		▽			●	●		▽			▽	▽					1	5	2	6
7	5%	2	Water storage	▽					▽	●		●			▽					0	2	0	7
8	5%	2	Easy to operate		●	▽	○			▽	●			▽	●					1	2	4	8
9	12%	5	Clean water	○								●					●			0	0	0	9
10	5%	2	Safe to operate		○	▽			○		●	▽	●		○					0	1	0	10
11	5%	2	User is protected from weather		▽									●						0	0	0	11
12	7%	3	Short down time				○			○	○				●					1	1	5	12
13	7%	3	Human Energy Requirements													●				0	0	0	13
14																							14
15																							15
16																							16

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Target	>100°C	90% aprroval (Customer survey)	>3.5/5 on a comfort scale (Customer survey)	<15 mintues	<100μm/year	>250 lb_f	>6 liters	<2.5 system operations (from start to boil)	0 bacteria detected	Contact componens < 40°C	>18 square feet	<1 minute	<kJj	< 500 mg/L of TDS		
Competitor #1: Slow Sand Filter	0	0	2	1	5	2	0	0	0	0	0	1	0	4		
Competitor #2: *SODIS*	0	0	4	2	5	5	3	0	0	0	0	3	0	1		
Competitor #3: *Chlorination*	0	0	5	5	5	1	0	0	0	0	0	5	0	1		

ENGINEERING SPECIFICATIONS:

Figure 35:

Specification	**Metric**	**Importance**	**Target**	**Test/Verification**
Heat output	Temperature (Celcius)	5	> 80℃	Measure using thermometer
Filtration	Particulate level	4	< 500 mg/L of TDS	Test particulate level using fine filter
Range of motion	% interviewed who could adjust machine to fit body type	3	> 90%	Introduce consumer to prototype then interview them
Firmness of contact points	Comfort scale rating (0-5)	2	> 3.5	Introduce consumer to prototype then interview them
Boil time	Time (min)	4	< 15 minutes	Have 10 timed trials and average time of the 10
Corrosive Resistance	Corrosion (µm per year)	4	< 100 µm per year	Choose materials based on known corrosiveness values
Allowable force on operating components	Force (lbs)	4	< 250 lbs	Physical test
Vacuum	Pressure (Inches of Hg)	4	> 10 inches	Pressure gauge

			of Mercury	
Operational/ Setup tasks	Number of tasks	2	< 2.5 tasks	Quantify tasks
Potentially hazardous components (to touch during setup or down time)	Temperature (celcius)	2	< 40℃	Infrared laser
Down-time between operations	Time (min)	3	< 1 minute	Have 10 timed trials and average time of the 10
External light source	Watts	2	>20 Watts	Measurement of voltage * current

ASSEMBLY PLAN

Figure 36:

Step	Part	Task	Tool	Access Direction
	Bicycle Modifications			
1	Front Wheel	Remove bolts	Wrench	+/-z
2	Front Wheel	Remove front wheel	Hands	+y
3	Back Wheel	Remove bolts	Wrench	+/-z
4	Back Wheel	Remove chain	Hands	+/-z
5	Back Wheel	Remove back wheel	Hands	+y
6	Back Wheel	Remove Tread	Knife	-y
7	Back Wheel	Insert belt	hands	+z
8	Back Wheel	Replace back wheel	hands	-y
9	Back Wheel	Replace Chain	Hands	+/-z
10	Back Wheel	Replace bolts	Wrench	+/-z
	Front Wheel			

	Stand			
11	Stand Base	Insert screws to attach the base	Drill	+z, +x
12	Stand Arms	Drill holes for rod	Drill	+z
13	Stand Arms	Feed rod through holes	Hands	+z
14	Bicycle + Stand	Set bicycle on rod	Hands	-y
	Back Wheel Stand			
15	Back Wheel	Set back wheel into stand	Hands	-y
16	Stand	Tighten knob to secure wheel	Hands	-z
17	Stand	Secure stand to base board	Screw Driver	-y
	Container			
18	Bottom Plate	Screw in heating element	Hands/Wrench	+y
19	Bottom Plate	Attach to tube	Hands/Glue	+y
20	Top Plate	Attach to tube	Hands/Glue	+y
21	Tube	Insert thermocouple	Hands/Silicon	+z
22	Tube	Wrap with aluminum foil	Hands	+x, +z
23	Tube	Wrap with rubber insulation	Hands	+x, +z
24	Tube	Secure insulation with zip tie	Hands	+x, +z
25	Tube	Secure tube to base board	Screwdriver	-y
26	Top Plate	Place gasket on top place	Hands	-y
27	Top plate	Place lit on top of gasket	Hands	-y
28	Lid	Clamp lid to top plate	Hands/Clamp	+/-z
	Filtration device			
29	PVC Pipe Filter Tube	Attach Filter	Hands/Tape	-y
30	PVC Pipe Filter Tube	Connect the 3 PVC pieces	Hammer	-y
31	PVC Pipe Base	Secure filter stand to board	Screwdriver	-y
32	PVC Pipe Filter Tube	Place filter tube into stand	Hands	-y
	Motor			
33	Motor	Attach pulley bearing to motor	Hammer	-z
34	Pulley	Attach pulley to bearing	Hex Key	-y
35	Pulley	Attach belt around pulley	Hands	+z
36	Motor	Secure motor to baseboard	Screwdriver	-y

37	Motor/Container	Attach wires from motor to container	Hands/Wires/Screwdriver	+y
	Halogen Light			
38	Wires	Wire the light in parallel with the heating element	Hands/Clamps	-y
39	Light	Attach light to the base board	Hands/Tape	-y
40	Switch	Wire switch into light	Hands	-y

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