# THERMAL ENERGY STORAGE FOR LOAD SHIFTING FINAL DESIGN REVIEW

Prepared for Prof. Pete Schwartz

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## *Statement of Disclaimer*

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**Abstract**

The following document accounts for the progress made in the prototype development of our design solution since the Critical Design Review, and our group's response to recent world events which greatly impacted planned activities. Our design challenge is to develop a thermal energy storage system which will sequester the energy from a photovoltaic (PV) array during the day and allow for its dispersal at night in the form of near boiling water. Looking at our user's needs, we broke our design solution into four components: water heating, storage, distribution, and controls. Research of all components was conducted to ascertain which systems should be developed and which system components could be purchased. Engineering specifications were developed to directly address customer needs and to create performance goals which our final solution can be measured against. During this phase, our group was tasked with procuring all required materials, manufacturing our prototype, and conducting verification testing. The system configuration was selected in the previous phase, and lists of components were compiled, along with manufacturing steps. We have constructed our prototype, and we have completed some preliminary testing, however there is more work to be completed by our sponsor. The selected system composition is outlined, including supporting documentation for testing procedures. Our Final Design Review outlines all final development activities which have taken place and next steps required for further iteration of our prototype.

## 1.0 Introduction

Our team is a collection of three Mechanical Engineering Seniors from California Polytechnic State University, San Luis Obispo. Our names are Taylor Harms, Jordan Lopez Corley, and Weston Montgomery. For our senior project, we chose to design and build a system which will store the energy produced by a photovoltaic (PV) array during the day within an insulated water reservoir, heated to as close to 95 °C as possible. The stored energy will be utilized to heat the hot tub of our sponsor, Dr. Peter Schwartz. This project will serve as a case study in the use of residential level thermal energy systems, as well solar powered electric heaters.

California has a goal of 100% clean energy usage by 2045 [1]; this translates to the banning of carbon-based fuels in household cooking and water heating. This legislation, coupled with a resurgence in anti-nuclear power regulations, has created a growing movement to shift to renewable energy sources such as solar, wind, and geothermal systems. At the domicile level, solar is the most effective method of energy independence. Naturally, solar energy is only reliable during daylight hours, and it is concentrated in a narrower time span from 9:00 am until 3:00 pm. This is the same time span as the lowest residential energy demand, as most of the nation follows an 8:00 am to 5:00 pm work/school schedule. The issue arises in the evening when energy costs peak in response to demand. For renewable energy to be more attractive to the average customer, a storage system is needed. Looking at residential energy consumption, various heating appliances compose the majority of energy utilized in the evening; thus, the development of a thermal storage system would be a valuable asset in reducing evening non-renewable power usage [2].

Figure 1.1 displays a days-worth of electrical demand, taken for the state of California, on October 18, 2019, from the California Independent System Operator, a non-profit organization which monitors the operation of California's bulk electricity production. Beginning at noon, there is a steady increase in demand as the state heats in the afternoon sun. It is important to note a sharp rate of change increase between 6:00 and 7:00 pm, when most families are at home cooking and doing laundry. Our system aims at shifting that load to earlier in the afternoon.


Figure 1.1: Typical California electricity demand (CAISO)

The remaining sections of this report will be broken down into the following sections:

- **Background:** Establishes the needs and wants of our customer and provides a background for the technical challenges being solved and the current products addressing the issues at hand.
- **Objectives:** Establishes the goals and criteria that will be used to judge the performance of our final design solution. The scope of the final design solution is also described.
- **Concept Design:** Overview of concept design process and chosen design path
- **Final Design:** Overview of selected components and final assembly, and discussion of how they will meet our project specifications
- **Manufacturing Plan:** Overview of construction of verification prototype with full instructions on component procurement, construction, and assembly procedures
- **Design Verification Plan:** Discussion of testing plan which will verify that our prototype meets all specifications, and how well
- **Project Management:** Establishes the process that has been followed to reach this point of our work and outlines the practices that will be adopted throughout the remainder of the project.
- **Conclusion:** Summarizes the topics covered in the Scope of Work (SOW) document.

### *1.1 COVID-19 Pandemic Project Change in Scope*

On March 19, 2020, an executive order from the government of California declared a 'Shelter in Place' order, which instructed all non-essential workers to stay home, and non-essential activities to cease. This would delay the beginning of our Spring Quarter by one week and restrict the completion of our senior project to an online-only format. Spring Quarter, or the third quarter in the senior project series, is focused on final prototype construction, and design testing. We will no longer be constructing any piping systems, modifying a water heater, or wiring solar panels to a form of heating element. To this end, as a final deliverable for our sponsor, our team has decided to focus heavily on the design, construction, and testing of a control system, which will automate all operations of the thermal storage system. This will include constantly monitoring temperatures throughout the system, executing commands to turn on/off the pump, and deactivating the heating elements to prevent the tank from overheating. This document will still outline all of the necessary tasks to construct the entire thermal storage system, which could be completed at a later date.

Fortunately, one of the team members, Taylor Harms, will be able to remain in San Luis Obispo, as will our sponsor, Pete Schwartz. He will carry out all assembly and manufacturing operations for the control panel, as well as design verification. After delivery of the control panel, or box, it will then be incumbent on our sponsor to install piping, a pump, and all wiring operations, should he continue to be interested in this project.

This has certainly been a major change to our project scope, however our group is still interested in the greater cause of thermal energy storage, and we look forward to delivering a final product.

## 2.0 Background

Our end user for this project will be our sponsor, Dr. Pete Schwartz. Our design solution will attempt to serve as a viable device for an average hot tub consumer but will ultimately be tailored to Dr. Schwartz's requirements. These requirements have shaped the nature of the solutions we have considered, thus shaping the topics we have studied while conducting our research.

*2.1 User* requirements

When we met with Dr. Schwartz to discuss the project, we gleaned that he requires a water heating system which is functional, affordable, reliable, and – most importantly – able to be completely run by solar power. Additionally, Dr. Schwartz wanted to integrate within our design solution the use of a DC diode chain: a technology he has previously developed to serve as a heater for research he has conducted on solar cooking [3]. Although this technology has desirable energy storage potential, at low cost, due to manufacturing concerns which are fully discussed in Section 5.0, the final design will only use a commercially available resistive heater. Previous analysis using DC-Diode immersion heaters is still valuable for future projects, and it is referenced throughout this report.

Currently, Dr. Schwartz's hot tub is being heated using commercially available resistance heaters, which are wired to his PV-array. This solution is hazardous to the user through risk of burns from directly contacting the heating tubes and electrocution from any possible loose connections. To mitigate these risks – and to provide a better insulated system than the tub itself – Dr. Schwartz recommended that we utilize a separate tank for heating. Our final design will now be centered on safely removing the resistive heater from the tub, into the tank

*2.2 Design Research*

Breaking down the task at hand, our group quickly realized there are five components our solution will cover: a heater, a storage system, a heat exchanger system, a distribution system, and a control system. It will be difficult for our team to develop detailed solutions for all three systems, so we have had to carefully consider which components (if any) we will develop and which components may be adapted simply or purchased as a complete part. In order to determine where our efforts would be most useful, we researched patents, products, research papers and standards related to all of these systems.

Below we have documented the articles relevant to our paper in a list format. Following that, Table 2.1 lists of all of the patents related to our topic, Table 2.2 lists all of the products relevant to our product, and Table 2.3 complies all of the codes we have considered while conducting our research thus far.

*List of Research Documents*

- "Hot Diodes!: Dirt Cheap Cooking and Electricity for the Global Poor?"
  This case study prompted our sponsor's interest in the usage of a diode-chain heater, as our primary heat source. The study evaluated the applications of diodes in cooking. The diodes were found to be successful for numerous trials. The experiments proved the diodes were capable of sustaining high operating temperatures and operate well with the DC power provided from solar panels. An economic study is included, indicating a low cost, especially in mass quantities.

- “Recent Investigations of Phase Change Materials Use in Solar Thermal Energy Storage System”
  This paper evaluates the thermodynamic performance of multiple inorganic phase change materials (PCMs), specifically for energy storage. The materials under investigation were selected based on preferable properties such as high specific heats and relatively low melting temperatures, which are beneficial for building service applications
- “Performance Analysis of Shell and Tube Heat Exchangers: Case Study”
  This paper evaluated the thermodynamic performance of a particular heat exchanger that utilized plastic components and turbulence-inducing components in its design. The paper would serve as a good jumping-off point for our own design, and for how we might evaluate the effectiveness of a heat exchanger
- “On the performance of ground coupled seasonal thermal energy storage for heating and cooling: A Canadian context”
  This journal article discusses the energy storage potential of groundwater in a bayonet tube heat exchanger for winter heating and summer cooling. The research was completed in Canada.
- “Smartbath: Water temperature control system”
  This article covering a conference proceeding discusses a control system which was developed to aid the elderly by making their baths easier to regulate. A system was developed to control the bath temperature, water flow-rate and light intensity (with particular attention on the bath temperature control). The discussion surrounding this system would likely be relevant to us as we develop our own control system for our sponsor’s hot tub.
- *“A Golden Thread: 2500 Years of Solar Architecture and Technology.”*
  This book provides a great historical context for the different solar architectural and engineering solutions people have used for the past two millennia. Most advancements in the field of solar energy collection were sparked by a lack of resources (e.g. deforestation in Ancient Greece led to the conception of Western solar homes). Innovation was also inspired by solar warfare. Progress was held back by the Church in a few instances.

Table 2.1: List of Relevant patents

| Patent Name | Patent Number | Filing Date | Description |
|---|---|---|---|
| Portable spa heater | US20060260036A1 | 2006-05-19 | Comprised of casing, a heater, a pump, hosing & a thermostat. Heats & circulates water to/from a spa. |
| Photovoltaic DC heater systems | US9518759B2 | 2013-10-10 | Solar immersion heater intended for a pressurized or non-pressurized tank |
| Apparatus for collecting and thermally storing energy | US4200783A | 1977-07-18 | Converts solar energy to electrical energy and then uses a resistive heater to store thermal energy in a ferrous core at temperatures of at least 1000 °F. |
| Solar heating system including freeze protection | US4207866A | 1978-12-21 | Pressurized solar water heating tank which can operate in low temperature climates. |
| Heat exchanger and drain down for solar collector | US4257479A | 1979-04-02 | Pumps water from the bottom of a tank to pass through a heat exchanger which runs gravity fed solar heated water. |

The portable spa heater (US20060260036A1), will be an important template to use when we design our piping system to and from the hot tub along with auxiliary equipment. It will also be useful to use the schematic diagrams provided in the Photovoltaic DC heater system patent (US9518759B2) to guide our wiring system, since we have little experience with circuits. This will also be a good design stepping-stone for the diode immersion heater. Patent US4200783A serves as a positive case study in the implementation for high temperature applications of solar energy, and shows the amount of potential success available.

Table 2.2: List of Existing Products

| Product Name | Company Name | Cost | Description |
|---|---|---|---|
| 560WP WATERPROOF IMMERSION HEATER | Ulanet | $134.99 | "500 to 1500 Watt high quality waterproof (IP67) immersion heater w/ 1" NPT threads, set to 190°F provides easy solutions for those seeking a controlled heat source in laboratories and kitchens, as well as a control method for general lab liquids." |
| Sunbank Solar Hot Tub Heater Kit | Sunbank Solar | $1,799.00 | "The kit comes with an SRCC certified glazed flat plate solar collector, heat exchanger (drop in or integrated version), mounting bracket (roof mount or ground mount), and the components of a solar controlled pump station including solar photovoltaic (PV) panel. You provide PEX piping and fittings as those are custom for each project." |

| | | | |
|---|---|---|---|
| Solar GeoThermal Water Storage Tank- SolarStor 50 gallon SCE - Single Exchanger | Northern Lights Solar Solutions | $1,895.40 | High capacity 7.8 square foot bottom Internal Heat Exchanger, Back Up 4.5 kW Heating Element, 2" thick foam insulation |
| Eco | The Alternative Energy Company | Unknown (NZ company) | Uses evaporation, condensation, and compression to heat a refrigerant (and subsequently water for a tank) 24/7 |
| BriskHeat Metal Drum Heater — 55-Gallon, 1,200 Watt, 120 Volt, Model# DHCS15 | BriskHeat | Sale $149.99 | "two extra-thick layers of fiberglass-reinforced silicone rubber for excellent strength and durability" Heated externally, so probably not well insulated. |

This research has bolstered the design constraint of insulation. Each system, regardless of heating methodology emphasizes that the systems overall efficiency is dependent on the amount of thermal resistance preventing heat loss.

Table 2.3: Relevant Codes and Standards to be considered

| Agency | Standard Number | Description |
|---|---|---|
| California Energy Code (CEC) | 110.4, 110.5 | All electrical codes for hot tubs |
| ASME | BPVC | Boiler and pressure vessel design guidelines |
| ASHRAE | 90.1 | Pipe sizing guidelines |
| AHRI/ANSI | 401 | Performance rating standard for liquid heat exchangers |
| NEC | 690 | All PV system wiring standards |

*2.3 Diode Testing Research*

The initial design which was to be constructed needed to be tested for the best method of heat sinking the diodes to the aluminum tubing. Although we have since changed our final design to not include the diode immersion heater technology, a series of tests were still planned. They are highlighted in Appendix L: Diode Chain Testing.

*2.4 Conclusions from research*

From our research into the various products, patents, and journal articles surrounding each component, our team was able to make preliminary decisions regarding solution development. We believe that although it would be possible to eventually use the diode technology promoted by Dr. Schwartz through further optimization, it will not be feasible for this project. We have however explored the topic appropriately as shown in section 5.0, and made an objective determination that it is not optimum for our project.

## 3.0 Objectives

The overall goal of our senior project can be summarized in the following problem statement:

> *Current heating processes for hot tubs require large amounts of energy to be produced through the combustion of fossil fuels or utilization of electricity which is likely to originate from non-renewable sources (especially in the evening, when hot tubs are more likely to be used). Environmentally conscious hot tub owners need a separate, carbon-neutral way to heat the water in their spas at any time of the day. Our specific sponsor, Pete Schwartz, has encouraged us to utilize his previously obtained photovoltaic array and diode chains as a heat source for our particular solution.*

A visual representation of the "solution space" afforded to us by our problem statement can be seen in a boundary diagram of our problem setup (see Figure 2).

The breadth of the design will be an auxiliary product which will connect between the customer's existing solar panels and the domestic water supply. It will be a self-contained system, with its own pumps, heating elements, etc. Prof. Schwartz will provide the heating elements and PCM (if utilized), which will be permanently embedded within the system. Our team will design and build the storage tank, heat exchanger, diode chain, and control system, along with connections to the hot tub. From our customer, a list of important design needs are listed:

- Sustainably sourced and operated components (no chemical batteries)
- Heating is completely solar powered, within capacity of existing panels
- Ability to provide sufficient flow of hot water to allow customer control of hot tub temperature, duration of use, at a selectable time
- Exposed components are thermally and electrically insulated, and free from sharp edges/pinch points
- Entire system fits within a reasonably sized shed
- Entire system is easily serviceable, with affordable replacement parts

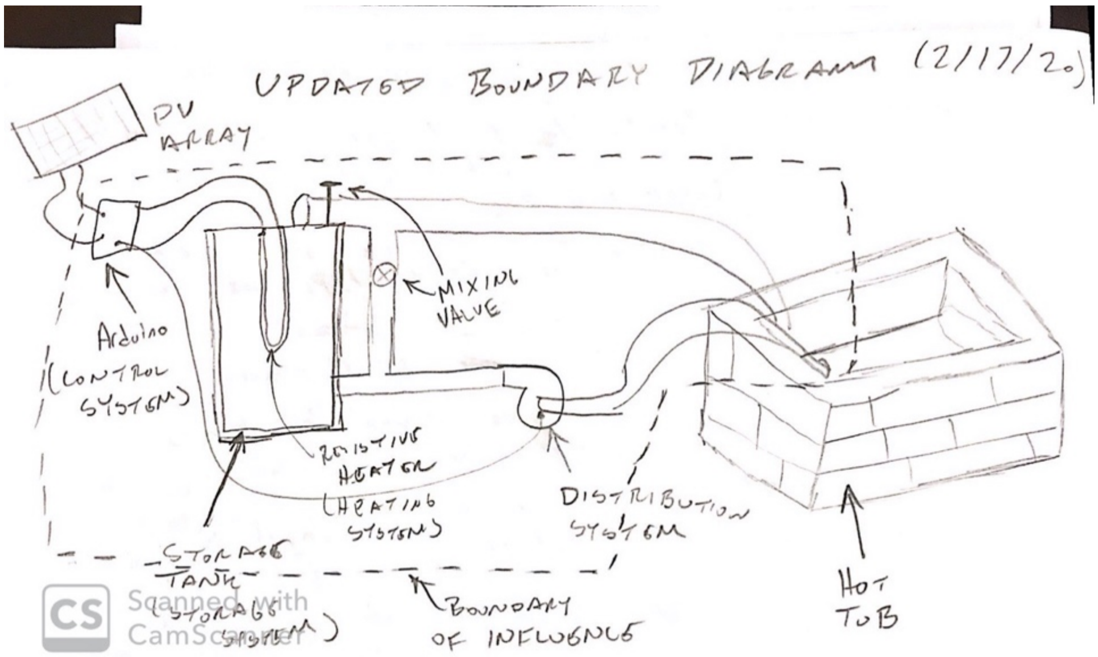



Figure 3.1: Boundary Diagram Showing the Problem Setup

The area contained by the dashed line in Figure 3.1 represents the solution space available to us as designers – everything outside of the line cannot and/or should not be controlled by us.

In order to ensure that these customer needs and wants are met, our team has utilized the Quality Function Deployment (QFD) approach for our design. This has included making engineering specifications – specific technical goals that correspond to one or more customer needs. These goals are what link our engineering problem to the task at hand. A complete list of the engineering specifications was produced for our design solution (see Table 3.1).

Our full QFD house contains all of these specifications and their relationships to the user needs/wants of the user, as well as showing how these relate to devices already available on the market (see Appendix B). The HOQ also explains the processes in which we will be compliant with our specifications: we will test specifications 1-7 and ensure our design will account for specification 7.

Looking at the specifications listed in Table 3.1, we can elaborate on the testing procedure for each.

- **Stable Temperature over time:** We will utilize a data acquisition system (or even handwritten data logs if necessary) to document the average tub temperature over time. This will allow us to monitor the duration of the heat provided by our system, with a goal of reaching 38-40°C for 3 hours.
- **Desired Hot Tub Temperature:** We will utilize thermocouples to record tub temperature. This will allow us to record the temperature range achieved, to compare this value with the temperature requested, and to ensure the temperature is spread as uniformly as possible throughout the tub. We want our tub to have an average temperature of 40°C.

- **BOM Total cost:** This will allow us to record whether we remain within budget or not. Our goal is to spend close to $1000; we were not given a hard budget cap, as our sponsor was more in favor of communicating about purchases.

Table 3.1: Engineering Specifications Table

| Spec. # | Specification Description | Requirement or Target (units) | Tolerance | Risk | Compliance |
|---|---|---|---|---|---|
| 1 | Stable temperature over time | Maintains 38-40° C for 3hrs | ±1° C | M | T |
| 2 | Desired Hot Tub Temperature | Reaches 40° C | ±2° C | H | T |
| 3 | BOM total cost | $500 | ±$500 | H | T |
| 4 | Desired HWS Temperature | Reaches 80° C | -4° C +19° C MAX | M | T |
| 5 | Time to assemble | 8 hours | ±2h | M | T |
| 6 | Visual Inspection of component insulation | No components which can come into contact with skin will reach 50 ° C | ±1° C | H | T |
| 7 | Does not scratch foam test strip | No visual scratches | N/A | H | D, T |
| 8 | Durability | No visible corrosion after 1 month of usage. Heater fully functional. | N/A | M | T |
| 9 | Mixed Water Proportions | Supply mixed water does not exceed 46C | 0 C | H | T |
| 10 | Control System Operational | All components are fully automated, system turns on by itself | N/A | M | T |
| 11 | Maximum Tank Temperature | Tank reaches but doesn't exceed 95 C | -1 C | H | D,T |

- **Time to assemble:** This will allow us to record whether the system could easily be implemented in an average user's home (presumably after "purchase"). Our goal is to install the system in its position next to the tub in less than 8 hrs.
- **Desired HWS Temperature:** We will utilize thermocouples to record the temperature of the hot water system, which will be useful in maintaining a safe outlet temperature while

achieving the desired overall temperature, as well as in establishing a control system for our solution. Our goal is to hit 80°C, with a high of 99°C and a low of 76°C.

- **Visual Inspection of component insulation:** All components passing dangerous levels of voltage or heat must be visually verified to be sufficiently insulated, in order to prevent users from coming to harm through direct contact.
- **Does not scratch foam test strip:** All of the project components which may cut or puncture through physical contract must be dulled or padded. Sharp edges will be rounded as well. To test this, a foam test strip may be bumped into the component, and should escape without being deformed.
- **Durability:** Since we are designing a functional prototype, it is not critical that the immersion heater lasts for years. Yet, the longer it lasts, the better it will be for our sponsor and for future consumers. Therefore, we will ensure the prototype is able to at least sustain 1 month of use without corroding. In addition, it shall be able to reach the maximum diode temperature for at least 30 cycles before burning out.
- **Mixed Water Proportions:** The greatest safety feature for our system is that the incoming water does not exceed 46C so there isn't a risk of scalding any users. During commissioning, valves will be adjusted such that at the greatest temperature difference between the tank and the tub, the mixed water will not exceed 46. At all other times, the mixed temperature will be lower, with locked mixing proportions.
- **Control System Operational:** Control system needs to reliably give the appropriate commands to the pump and heater to make sure that the tub nor tank exceed their set temperatures. The TES system should also be able to automatically heat itself every evening, as commanded by the microcontroller.
- **Maximum Tank Temperature:** In order to prevent boiling, pressurizing the storage vessel, and deteriorating plumbing materials, it is crucial that the tank does not ever exceed 95C. This will be regulated by a power switch, attached between the solar panels and the heater. If the temperature is approaching 95, and the tub is at 40, then the control system will open the solar panel circuit, preventing further heating.

Following the change in scope, our objectives remain the same. We still strive to construct a safe, efficient, and effective thermal management system, for the use of storage of daily electrical energy. Following a full-scale test after construction, these objectives will be able to be accomplished.

## 4.0 Concept Design

Due to the abundance of research from Dr. Schwartz's previous projects, our primary strategy for energy collection and conversion was already determined from the beginning. Our sponsor's primary requirement is to further develop the usage of the diode chain immersion heater technology, including its manufacturing process. Our team still had to select the storage method, heat transfer strategy to the hot tub, and piping configuration.

The concept design process began with large scale ideation regarding how best to fulfill the primary functions of the system, with as little direction given as possible to promote creativity. We held two separate brain writing sessions, in which each person wrote as many relevant ideas down for five minutes straight and passed the notebooks to the other members who would write additional ideas inspired by the first. A few pages from these sessions are given in Appendix C. During these sessions, we determined it would be advantageous to design a system which utilizes the DC diode immersion heater, a thermal energy storage system, and a distribution system. This design will meet all of the sponsor's requirements and needs in a manner which is safe and cost efficient.

From the brainwriting sessions, we determined the three critical subsystems for this project are thermal energy storage, heating, and distribution. We created separate Pugh Matrices (Appendix D) for each subsystem. The thermal energy storage Pugh matrix compares barrels, insulated tanks, underground tanks, no tank, and PCMs against one another. Based on the results, the insulated tank appears to be the best result. Digging a large underground trench would not be feasible because of the time and expense of such an endeavor. Using a phase change material may not be the best approach either because most PCMs have a melting point far higher than the max temperature of our system. The heating element Pugh matrix compares resistive heaters, direct solar radiation, diode heaters, and combustion. Overall, the diode heating element outperformed the other options. This is reassuring because our sponsor greatly prefers using a DC diode immersion heater. Lastly, we compared PVC, copper, stainless steel, and garden hose for the distribution system of our device. PVC is the clear winner here; the two metals are much too expensive and are about as easy to manufacture. Hose may be used for some components, as it allows flexibility in the design, but its lack of durability and need for thermal insulation make it a poor primary building material.

Looking at the systems described in the Weighted Decision Matrix (Appendix E), it becomes clear the best options include similar components: drum barrels, insulated tanks, DC Diode IH, insulated piping, PVC piping and/or hose. Therefore, we have determined it is critical to include a DC diode IH as the heating subsystem for our project. The storage subsystem will be a drum barrel or tank, and our distribution system will be PVC piping or hose. We will ensure our storage and distribution subsystems are properly insulated to prevent heat loss. The ultimate factor in choosing between the listed components are cost and availability. Since we are dealing with a limited budget, the more cost efficient the storage and distribution systems are, the better. In addition, selecting a second-hand storage subsystem would be ideal because it would be more cost efficient and more sustainable.

In order to determine the overall size of the storage system, we first needed to determine the maximum size allowable for the storage tank. The tank would be sized based on the amount of water able to be heated from 20-100 °C, from the PV array to be used. Prof. Schwartz had previously recorded electrical output data for a single, 100-W solar panel on his roof, and numerically integrated all time from morning, until the evening, to obtain a total energy value. The setup to be used is an array of four, 425-W panels. To do this, the power data was scaled 4.25x times, and total energy values multiplied by 4. From this analysis, it was found that 10.4 kWh were available; thus, we expect to be able to heat 30 gallons of water per day.

Another important subsystem would be the coil heat exchanger. The absolute minimum length required for the copper tubing was found by approximating the system as a straight, copper tube surrounded by constant temperature water at 95 °C. A resistance network analysis was used with an assumed heat transfer rate based on a performance parameter of raising the hot tub water temperature from 30 to 40 °C, within 30 minutes. The minimum length needed was found to be 3.5 feet. Our coil will be 9 feet, coiled in a pitch of 4 inches, and diameter of 1 foot. Full preliminary calculations are included in Appendix E.

From these calculations, it was also determined that heating the hot tub (which holds 219 gallons of water) from 20-40 °C would not be possible with the nominal tank size previously found. Luckily, we will be able to charge our system over the course of a few days, so we are planning to expand our tank size to 50 gallons to increase the amount of heat it will be able to discharge once fully charged. Additionally, we plan to also use the hot tub as a thermal storage reservoir; we will dump heat into it to get as close to a starting temperature of 30°C water.

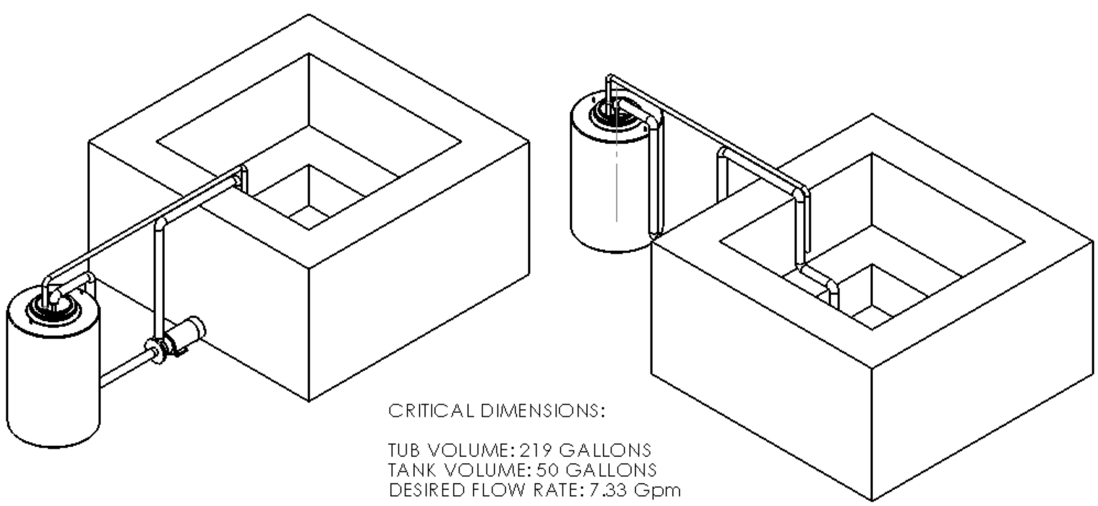



Figure 4.1: Concept Prototype Isometric View

All of the major systems are included; the storage vessel, the heat exchanger, and the distribution system are shown in Figure 4.1. Critical system dimensions are included. The tub water will then be able to be heated to the preferred operating temperature when the system is activated at night. As long as the user allows a couple of days for the system to charge, this is not to be a major performance issue.

Our concept prototype design, which can be seen in Figures 3 and 4, shows these design parameters incorporated into a 3D CAD model. The tank shown is a 50-gallon tank model that is available from McMaster-Carr; any tank selected will have the same volumetric capacity, though its actual dimensions may vary. All of the tubing shown is coplanar to better illustrate system functionality in a section view (see Figure 4.2). The actual distribution system will have a similar inlet and outlet position, but the tubes will be routed to be as unobtrusive as possible to the hot tub users. The pump was modeled off pool pump dimensions; while a large size was preferable to better illustrate system functionality, our pump will likely have a lower demand (7.33 gpm vs 100+ gpm for a typical pool system) and thus will be a bit smaller. The dimensions of the tub are accurate and fixed; they came from our sponsor's own measurements of his hot tub.

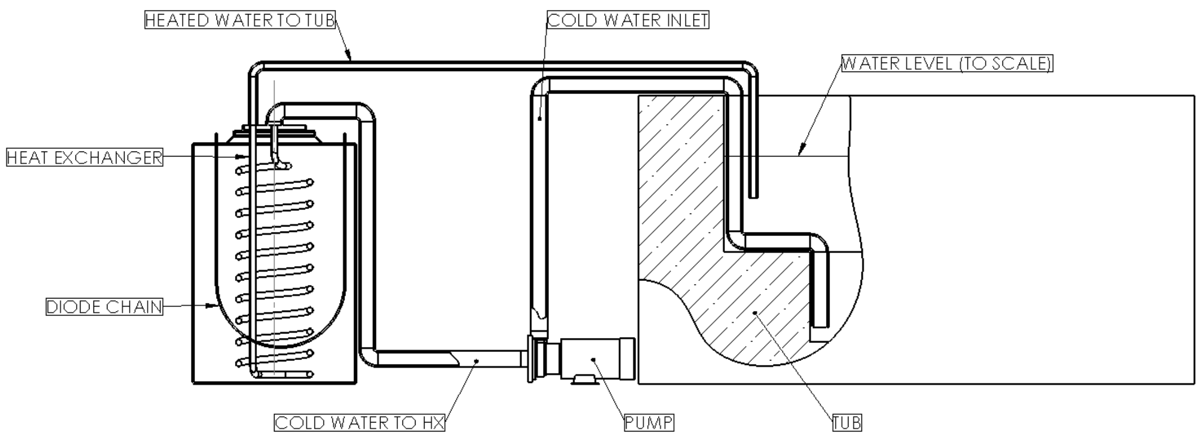



Figure 4.2: Section View of Concept Prototype. All system components are labeled. The heat exchanger and diode chain components are clearly visible.

Other unknowns which remain include the total pressure drop through the coiled heat exchanger. This will likely be the greatest contributor to our pump selection. A combined major/minor loss coefficient will be determined experimentally and from consultation with professors. Also included is the transient response of the temperature drop in the reservoir, which will impact the heat transfer to the hot tub water. We will compensate for this by allowing ample contact surface area from the piping and decreasing fluid velocity as much as allowable.

Hazards found with our system include thermal and electrical shock, and any sharp edges. Thermal shock could occur when first turning on the circulation pump. Water in the heat exchanger will be in equilibrium with the reservoir, and thus be at least 95 °C. To ensure this temperature of water does not reach any person, a bypass valve will be installed, which will mix incoming hot tub water, lowering the risk of thermal shock. Sufficient insulation will also be installed on all piping and storage elements. Lastly, we will ensure we use non-corrosive materials to limit the chance of component failure during the operation of our system. Additional hazard information can be found in Appendix G.

## 5.0 Final Design

Our overall design has had many major changes since our Preliminary Design Review:

- The heat exchanger element was removed.
- The tank was finalized as a 40-gallon domestic water heater.
- The distribution system saw the addition of a bypass, finalization of pipe diameter, and selection of materials. Several fittings were added to regulate temperature. The pump has been selected.
- A 3800 W, 240 VDC resistive immersion heater was selected to be used as the heating element.

Our overall design saw a few minor changes since our Critical Design Review:

- Our 40-gallon water heater(s) could not accommodate our selected heating element, so we opted to switch to a 50-gallon electric water heater (not reflected in the CAD model).
- The structural supports for the water heater and piping was finalized and is included in the attached appendix Assembly Instructions
- The detailed design work for the enclosure was finalized and is outlined in Section 6.6

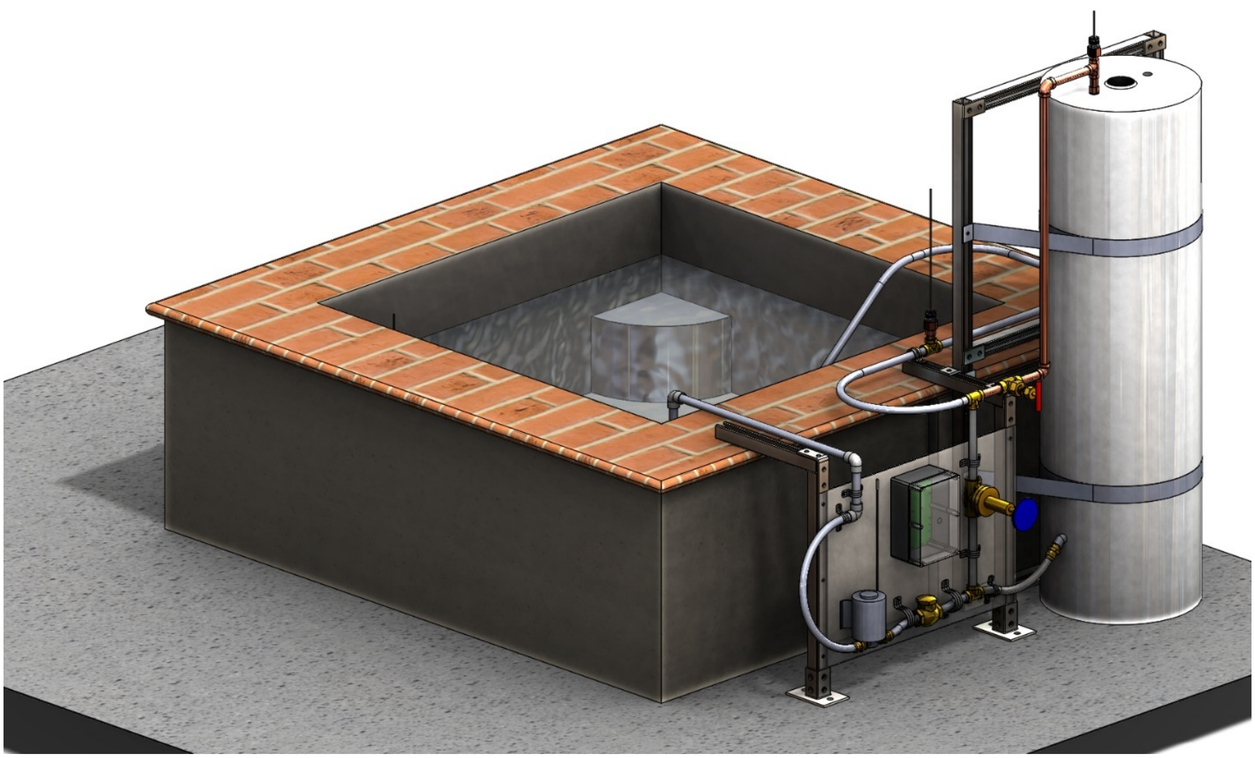


Figure 5.1: Overall Final Design Layout

In the next few paragraphs, we will explain the finalized design of each subsystem and its critical components, along with the design considerations that lead to its configuration.

### *5.1 Heating Element*

Our team decided to completely redesign the heating element since PDR from a diode-chain immersion heater to a commercially available resistive heater for three primary reasons: manufacturing feasibility, cost, and first principles.

### *5.1.1 Heating Element Manufacturing Feasibility*

We calculated 130 diodes would be necessary for our immersion heater by assuming a 70V drop across the panels and a 0.53V drop across each diode. After building a few prototype immersion heaters which were either five or ten diodes in chain size, we calculated an approximate tubing length per diode of 1.04 in. After factoring in an additional 2.1 in. for the end leads, we approximated 11.4 ft of aluminum tubing would be necessary for 130 diodes. In order to fit 11.4 ft of aluminum tubing into a 4 ft deep tank, we would need to perform a triple bend with the aluminum tubing. Each bend increases the risk of tube cracking which would make the immersion heater not waterproof. To limit the risk of burning out the diodes, we would only run 6A of current through each chain. Therefore, to get 850 W of heating, we would need to manufacture two diode chain heaters. It would take us over 37 hours of labor to manufacture two 11.4', 130-diode chain heaters. This is assuming it would take 387 minutes to make 258 diode braids, 90 minutes to apply thermal paste and heat shrink to 260 diodes, 60 minutes to pull the diode chains through the two tubes, 10 minutes to solder, 5 minutes to bend the tubing. It would also take three hours to install fittings which make the heaters compatible with the tank. This also assumes a time safety factor of three. A common issue faced with previous projects of Dr. Schwartz with diode chain immersion heaters is that they are very sensitive to high temperatures, and should any electrical connection fail, the entire chain also fails. For this method to be feasible, there would need to be great care taken during the manufacturing and assembly process to ensure uniform thermal connection and complete electrical insulation. This degree of quality control required for two, 130-diode long immersion heaters is not feasible with our team and current manufacturing methods.

### *5.1.2 Heating Element Cost*

25' of aluminum tubing would cost $40.48, 260 diodes would cost about $91, ten tubes of thermal paste would cost about $71.10, and twenty feet of heat shrink tubing would cost $47.98. Assuming the cost of copper wire and solder is negligible, the total price would be about $159.56 to manufacture two 130-diode immersion heaters. The 3800 W resistive heater we purchased only cost $11.87.

### *5.1.3 Heating Element First Principles*

Our sponsor, Dr. Schwartz, has current-voltage data for a 100 W panel. One series of data is for a resistive heater used on March 25, 2019 and another series is for a diode chain used on March 28, 2019. We took both sets of data and scaled both from 100 W to 1728 W. The results can be seen in Figure 5.2 and 5.3.

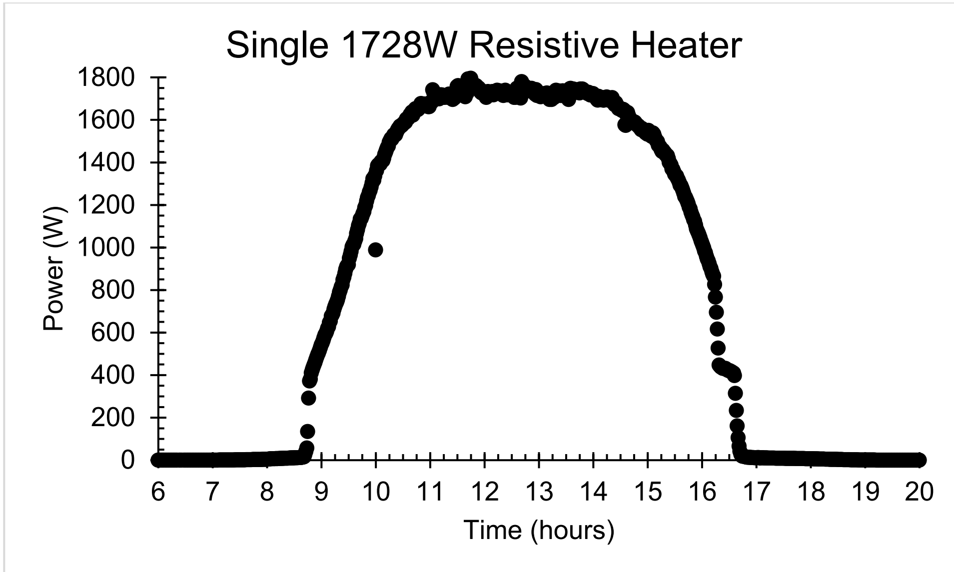



Figure 5.2: Scaled Power Data from March 25, 2019

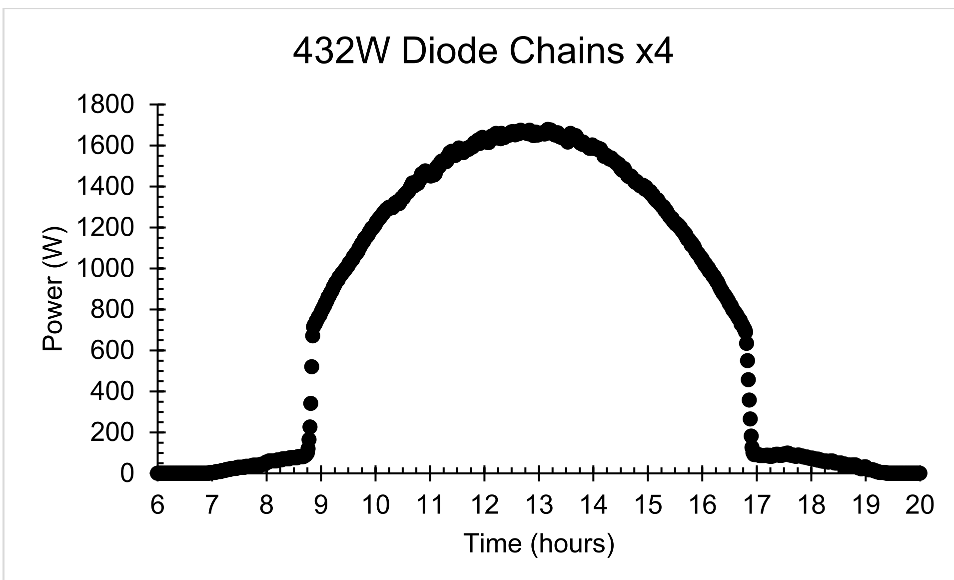
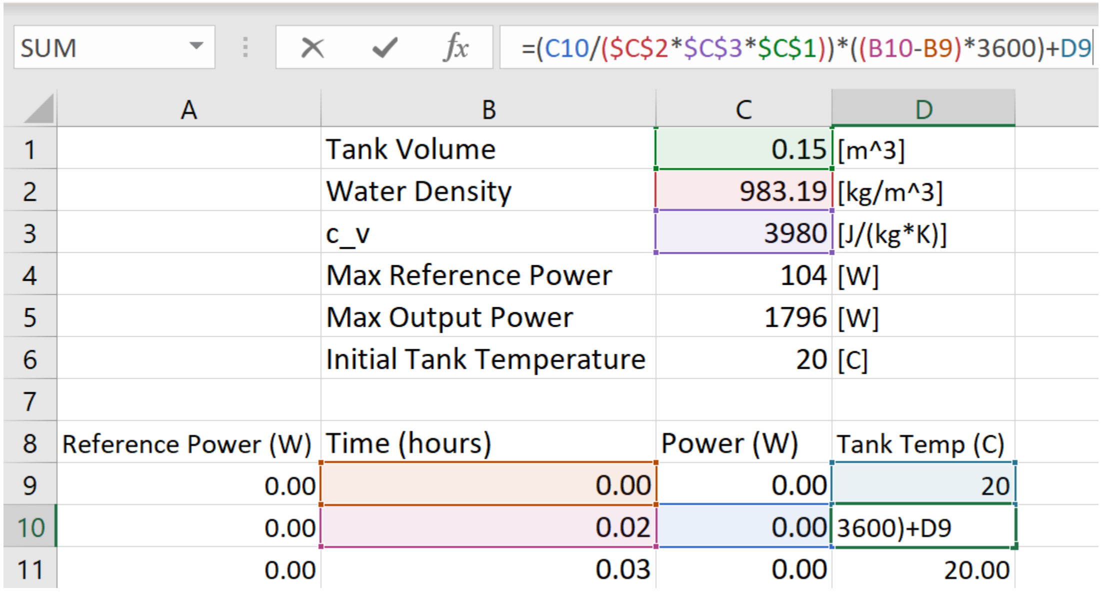



Figure 5.3: Scaled Power Data from March 28, 2019

From here, the scaled power data was used with transient first law of thermodynamics to calculate the change in temperature of the tank as a function of time. This calculation (Eq 5-1) was made assuming an insulated tank, constant volume, constant density, and constant specific heat. After a day's worth of heating, a 40-gallon tank of water would increase from 20 °C to 87.9 °C using a resistive heater, but it would only increase from 20 °C to 87.0 °C using a diode chain. The method used for numerical integration can be seen in Figures 5.4 and 5.6 and their results can be seen in Figures 5.5 and 5.7.

$$T_{i+1} = \frac{\dot{E}_{heater}}{\rho c V} \Delta t + T_i \qquad \text{(Eq 5-1)}$$



SUM =(C10/($C$2*$C$3*$C$1))*((B10-B9)*3600)+D9

| | A | B | C | D |
|---|---|---|---|---|
| 1 | | Tank Volume | 0.15 | [m^3] |
| 2 | | Water Density | 983.19 | [kg/m^3] |
| 3 | | c_v | 3980 | [J/(kg*K)] |
| 4 | | Max Reference Power | 104 | [W] |
| 5 | | Max Output Power | 1796 | [W] |
| 6 | | Initial Tank Temperature | 20 | [C] |
| 7 | | | | |
| 8 | Reference Power (W) | Time (hours) | Power (W) | Tank Temp (C) |
| 9 | 0.00 | 0.00 | 0.00 | 20 |
| 10 | 0.00 | 0.02 | 0.00 | 3600)+D9 |
| 11 | 0.00 | 0.03 | 0.00 | 20.00 |

Figure 5.4: Resistive Heater Final Tank Temperature Estimate using Euler's Method with Transient, 1st Law of Thermodynamics, with resistive heating element

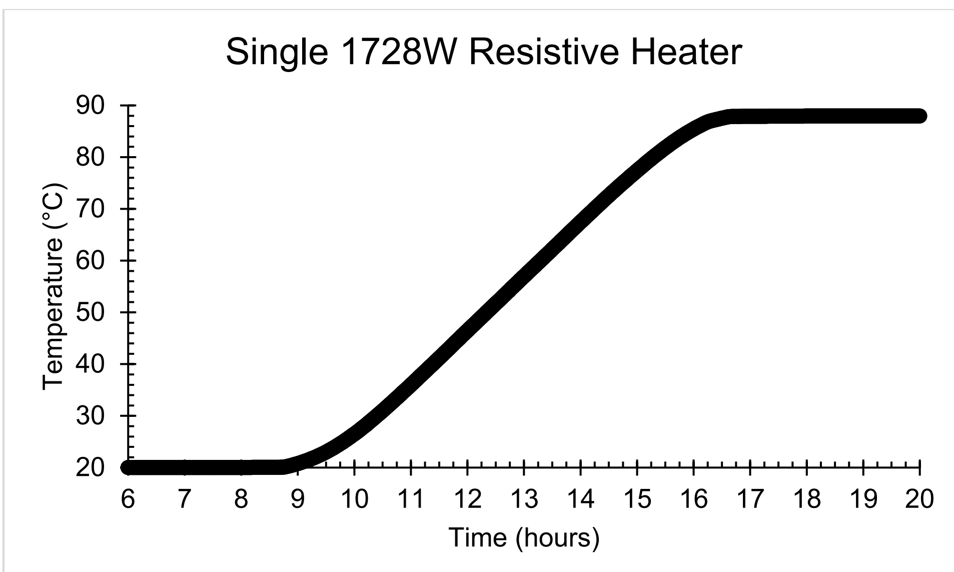
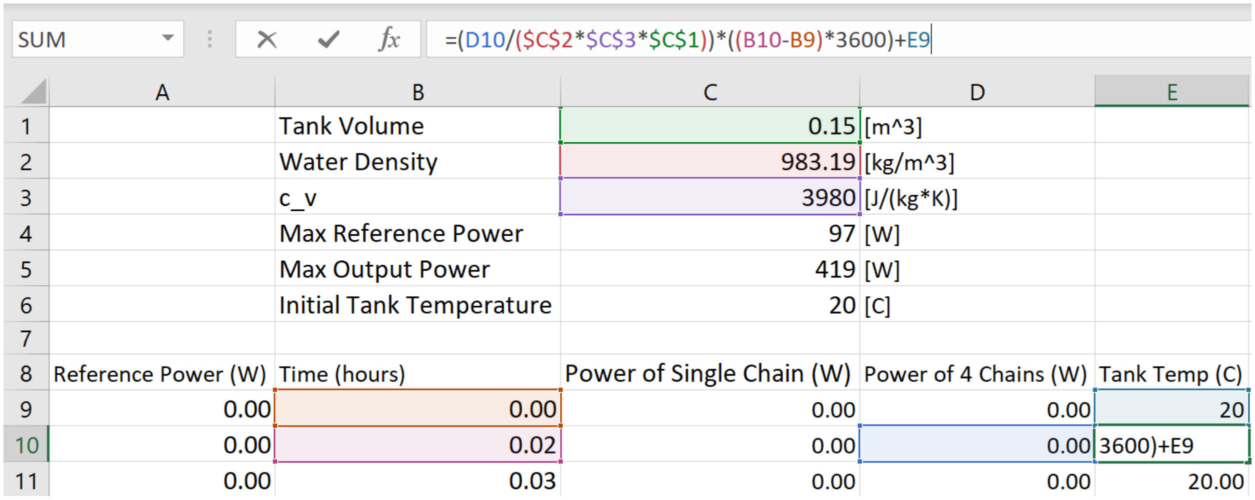



Figure 5.5: Resistive Heater Water Tank Temperature vs. Time

Using Euler's Method for calculating temperature as a function of time in the tank, we find that using a comparable 1728W resistive heating element the 40-gallon water tank will come to the same final temperature as that gained from using diodes only, this scan be seen by Figure 5.7. This analysis assumes a constant power output from the heater, and a uniform temperature throughout the tank, thus the plot is linear. This would be a best-case scenario for our heating system.



SUM | =(D10/($C$2*$C$3*$C$1))*((B10-B9)*3600)+E9

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | | Tank Volume | 0.15 | [m^3] | |
| 2 | | Water Density | 983.19 | [kg/m^3] | |
| 3 | | c_v | 3980 | [J/(kg*K)] | |
| 4 | | Max Reference Power | 97 | [W] | |
| 5 | | Max Output Power | 419 | [W] | |
| 6 | | Initial Tank Temperature | 20 | [C] | |
| 7 | | | | | |
| 8 | Reference Power (W) | Time (hours) | Power of Single Chain (W) | Power of 4 Chains (W) | Tank Temp (C) |
| 9 | 0.00 | 0.00 | 0.00 | 0.00 | 20 |
| 10 | 0.00 | 0.02 | 0.00 | 0.00 | 3600)+E9 |
| 11 | 0.00 | 0.03 | 0.00 | 0.00 | 20.00 |

Figure 5.6: Diode Chain Immersion Heater Final Tank Temperature Estimate

Euler's method (linear approximation) performed for a transient case of First Law of Thermodynamics to estimate final tank temperature when using a diode chain heating element.

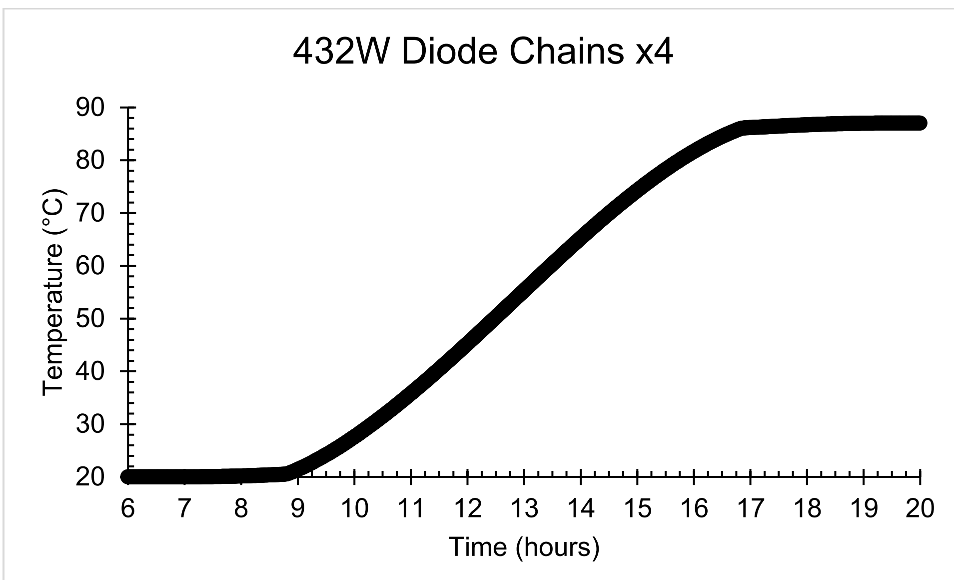



Figure 5.7: 40-gallon water tank analysis with four 432W diode heaters

To emphasize the benefit of resistive heating over diode chain heating, we directly compared a single 1728 W resistive heater to four 432 W diode chains. To reiterate, it would be nearly impossible to install four 432 W diode chains into our tank. Table 5.1 shows the summarized comparison between building two diode heaters vs purchasing a single resistive heater.

Table 5.1: Heating Element Summarized Comparison

| **Diode Heater** | **Resistive Heater** |
|---|---|
| Labor Time: 37 hours | Labor Time: 1 hour |
| Max Power: 864 W | Max Power: 1728 W |
| Total Cost: $159.56 | Total Cost: $11.87 |

The vast difference in direct cost and labor time, which has a monetary value, was the greatest differentiator when making the decision to use the Resistive heating elements are more cost effective, and have more consistent performance. Electric water heaters have used this technology for decades, so this has greatly driven down their cost, making them an economic choice.

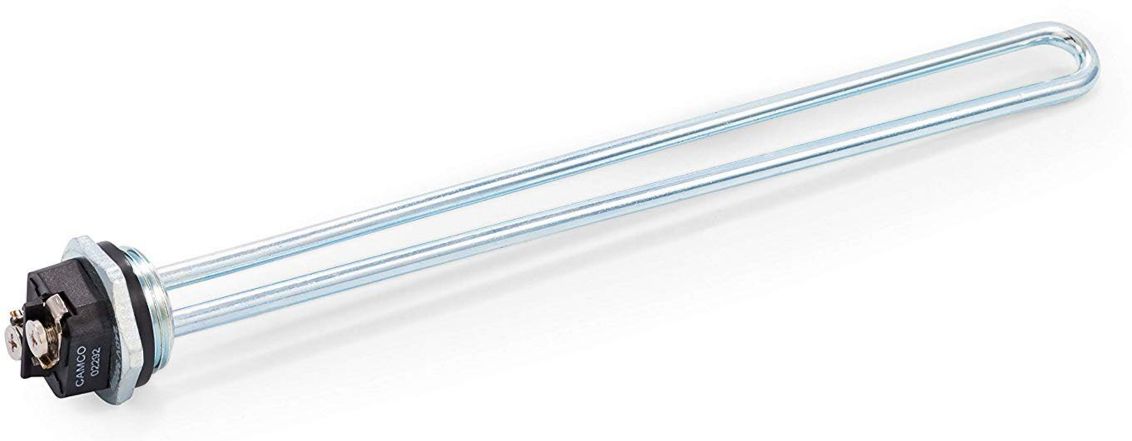


Figure 5.8: 3800 W, 240 V Camco Immersion Heater

Figure 5.8 shows the initial heating element we selected. This heating element was chosen to be compatible with a used 40-gallon gas water heater and the 4 panels wired in parallel and in series.

The next few sections outline why we chose to instead use a 50-gallon electric water heater and two separate circuits of 2 panels wired in parallel. Based off this final design, we selected two 2000 W, 120 V Camco Immersion Heaters (Figure 5.9). These heating elements provide about 7.2 Ohms of resistance. With our panel configuration, we would be able to achieve a maximum heat input of 1476 W

Figure 5.9: 2000 W, 120 V Camco Immersion Heater

*5.2 Thermal Storage System*

For our storage system, we have selected a commercially available 50-gallon electric water heater (Rheem Model XE50T06ST45U1). Before, we had been considering a 40-gallon gas water heater (Whirlpool Model BFG1F4034T3NOV). The following sections will detail the design considerations associated with our storage system selection.

*5.2.1 Storage Syste*m Initial Considerations

The 40-gallon capacity was selected as the result of a calculation performed to determine the number of gallons of 95ºC water needed to raise 219 gallons of 30ºC water to our selected operating temperature of 40ºC (See calculations in Appendix N). We knew that we wanted to convert a water heater for our purposes so we could take advantage of its pre-installed insulation and connection points. Our specific model was the result of local availability; we were able to source our heater for free using Craigslist, details provided in Section 6.1. We will still fill the chimney with insulating foam to limit heat loss through the middle of the tank. Other than that, the only modifications performed were removing the dip pipe from the cold-water outlet and replacing the threaded outlets for the hot and cold water with copper fittings. To reduce the corrosion seen by our system, we recommend our sponsor change out the anode rod in the heater at the rate recommended by the manufacturer.

Figure 5.9: Whirlpool Water Heater

The Whirlpool water heater was selected for our final prototype because it was in the best condition and it was the most aesthetically pleasing. Notice the pressure relief valve (PRV) also shown; this will be a primary means of safety against system over-pressurization. The PRV is designed to relieve pressure at 150 PSIG and to drip water out at 98.9 °C The white drain valve will be the entry point for the cold water from the tub, to replace the hot water coming out. The vertical pipe near the top will be the hot water outlet.

*5.2.2 Storage System Final Considerations*

Our final thermal storage device was changed as the result of component sizing and conversations with our project sponsor. As we switched our design to utilize a resistive heating element, we discovered that the element would not be able to fit within the water inlet and outlet ports of our chosen water heater. We briefly considered altering the geometry of those components, but a conversation with our sponsor revealed two things: first, altering the geometry of water heater resistive elements (something he had experience with) is difficult, and second he would be willing to spend the money on an electric water heater to better suit our system's needs. The latter of these two revelations also allowed us to upgrade our tank size from 40 gallons to 50 gallons. While this change would increase the total time it would take to "charge" the system, it would give our heater additional capacity. This additional capacity was desirable so that our system would have a small safety factor with respect to heating the tub from 30ºC to 40ºC.

*5.3 Distribution System*

Our distribution system has seen perhaps the most change since our Preliminary Design Review. Overall, the heat exchanger has been removed and a bypass has been added. The material we will be using to pump water on the cold side has been selected to be 3/4" PEX pipe. Our hot water piping will be 3/4" copper pipe, type L. Copper pipe will be used in the parts of the system exposed to up to 95 °C water and PEX will be used in the parts of the system exposed to up to 46 °C water. We made this decision because Copper piping can handle up to 150 °C steam and PEX can handle up to 93.3 °C water.

Perhaps the most notable of the design changes, we have elected to remove our heat exchanger. This decision was prompted by a question from our sponsor and justified by examining a number of different factors. First, a heat exchanger was mismatched with our chosen storage medium. The largest benefit of a heat exchanger would be the ability to have disparate storage and "cooling" materials, but because high temperature thermal storage liquids / PCMs are expensive, we elected not to use them. Additionally, we reasoned that increasing the temperature of our storage medium would increase the hazards posed by the system and increase energy losses through the walls of the thermal storage container. For all those reasons, we elected to use water as our thermal storage medium, so the best benefits of a heat exchanger were lost to us. Couple this with the difficulties in manufacturing/installing a heat exchanger within our storage unit, and the decision seemed obvious.

Without a heat exchanger, however, we would need a way to control the outlet temperature of our pipe; this design consideration led to the inclusion of a bypass in our system. The bypass allows for the mixing of the tub water with the hot tank water before the two streams combine in the outlet pipe. Building codes regulate that water leaving a hot outlet must be below 49ºC; we have calculated that with the tank water at its hottest temperature of 95ºC and the tank water at its "idle" temperature of 30ºC, having a 1/3.33 ratio of hot to cold flowrate will provide a stream whose temperature is 45ºC (see calcs in Appendix J). We plan to regulate this temperature using two control valves; one placed along the hot water line, and the other along the bypass line. The method for maintaining a safe temperature as the tub and tank temperature vary is discussed in 5.1.4: Control System.

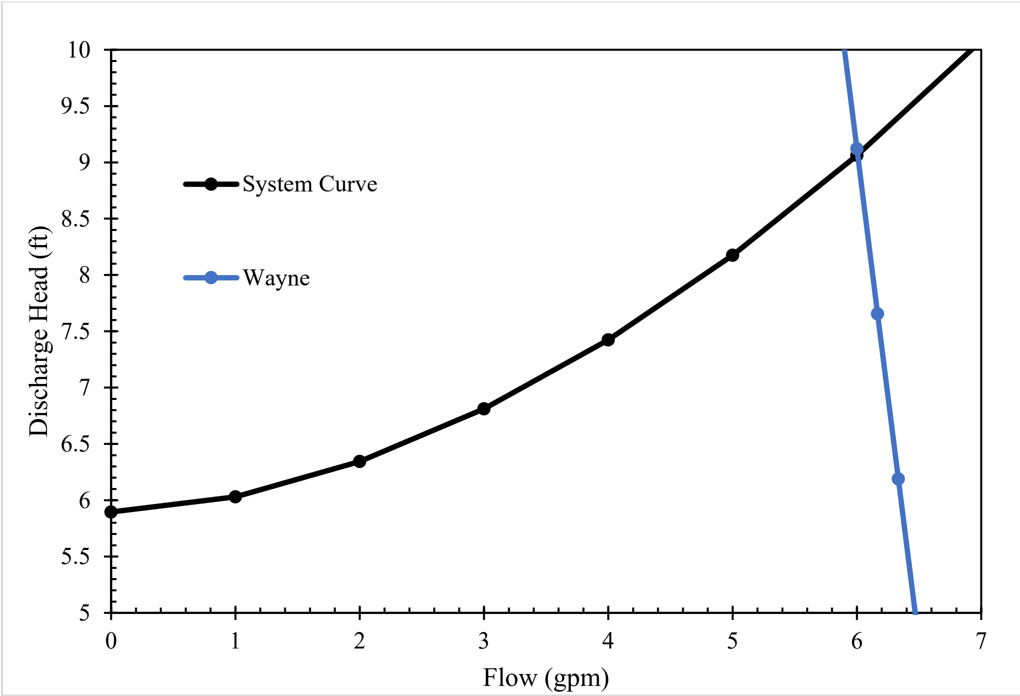



Figure 5.10: Piping System Curve

We have selected a 0.1 hp pump based on the following specifications: 7.3 GPM flowrate (Tub water replaced in 30 minutes) at 17 ft of head. From figure 5.10, the system will likely operate at 6 gpm, and 9 ft of head. The selected pump offered the smallest deviation from our desired operating point without exceeding the desired flowrate. Exceeding the desired flowrate would potentially create safety and controllability issues, and on the other hand a slightly lower flowrate was not a major concern of our sponsor. A check valve has been included directly after our pump to prevent backflow which could damage it.

In order to accommodate our selected flowrate, we selected 3/4" nominal pipes. PEX pipe was chosen for the cool water lines for a few considerations: PEX is flexible, making its installation easier, PEX is much cheaper than metal alternatives (especially considering PEX can be bent, eliminating many fittings), PEX has better thermal properties than CPVC (more robust at higher temperatures), plastic is corrosion-resistant. For the hot water portions of our piping system, we determined copper would be the best material. This is because copper is more corrosion-resistant and cheaper than galvanized steel. All our piping will be insulated to reduce heat loss through the pipes, to protect the pipes from the environment, and to protect users from coming into contact with hot pipes.

*5.4 PV Panel Electrical System*

All resistive heating elements which produce over 1728 W of power can only support a voltage drop up to 240 VDC. In order to maximize the peak power of the four panels, we decided it would be best to wire two in parallel and two in series. This would produce a total of 144 VDC and 12 A for the system. With these specifications in place, we selected a 3800 W, 240V resistive water heater. Figure 5.8 shows the configuration in which the panels are wired to the heating element. This element can dissipate over twice the expected power from our system; therefore, our heating element will not burn out even under prolonged periods of use. The red tie points (TP) in figure 5.8 show where our system will tie into our sponsor's system which an electrician will wire.

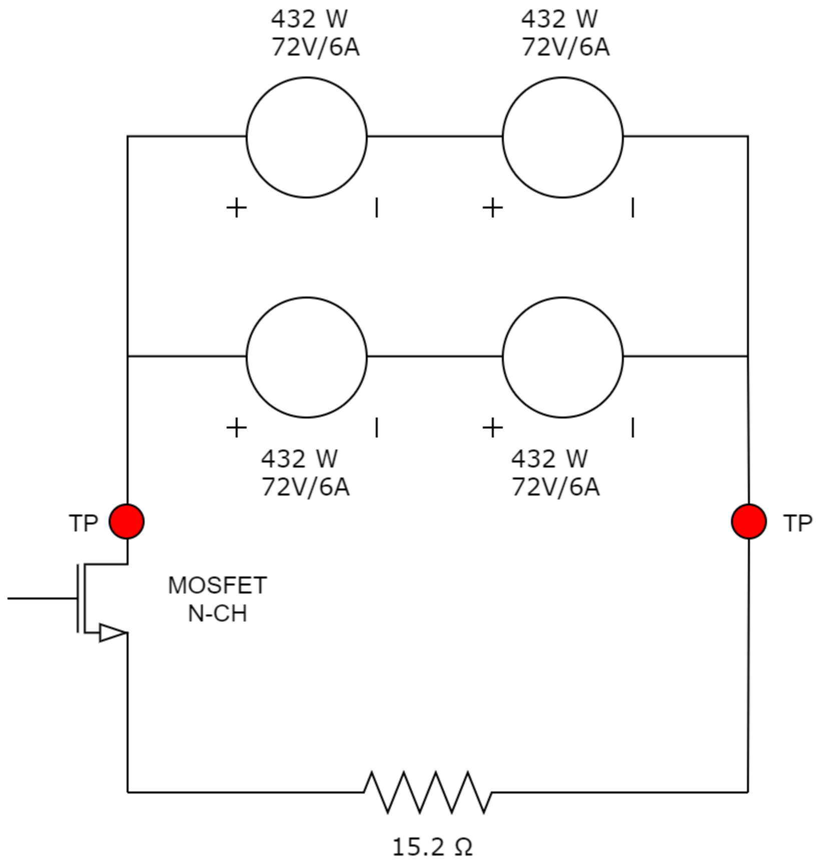



Figure 5.10: Old Panel Wiring Diagram

Our sponsor felt uncomfortable with a 144 VDC system, so we decided to redesign the wiring of our panels. The new design (Figure 5.11) utilizes two separate, yet identical, circuits which power and control the two heating elements. The voltage drop across each heating element is half the original design, making the new design twice as safe.

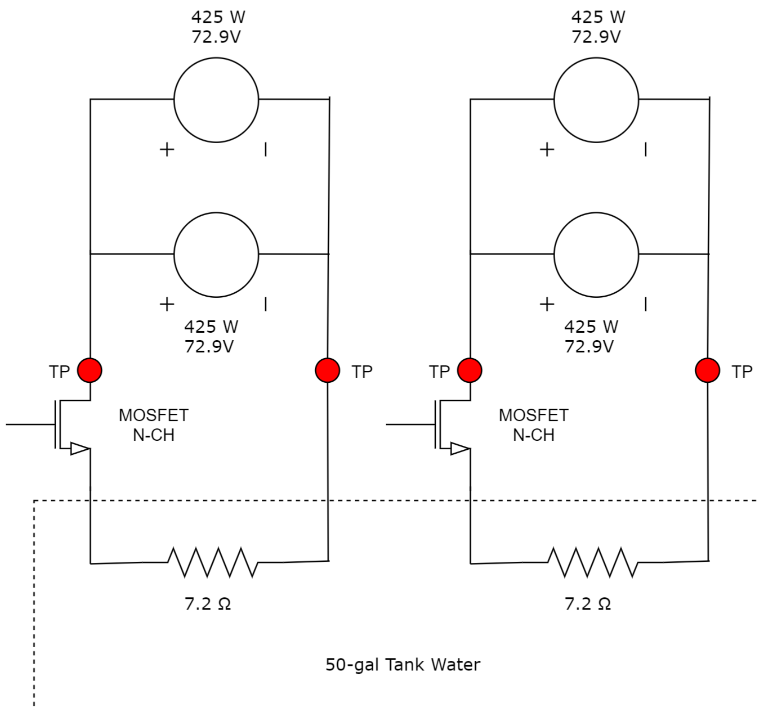


Figure 5.11: New Panel Wiring Diagram

With the incorporation of the additional MOSFET, for two separate circuits, the maximum voltage drop in any one circuit would be 72.9 V. Additionally, the MOSFETs can be wired such that they will receive the same signal from the Arduino microcontroller, and will always operate simultaneously. With minor wiring modification, this also allows the ability to control each heater independently in the future, if our sponsor decides to only use one of the circuits (i.e., 2 solar panels) only.

*5.5 Control System Overview*

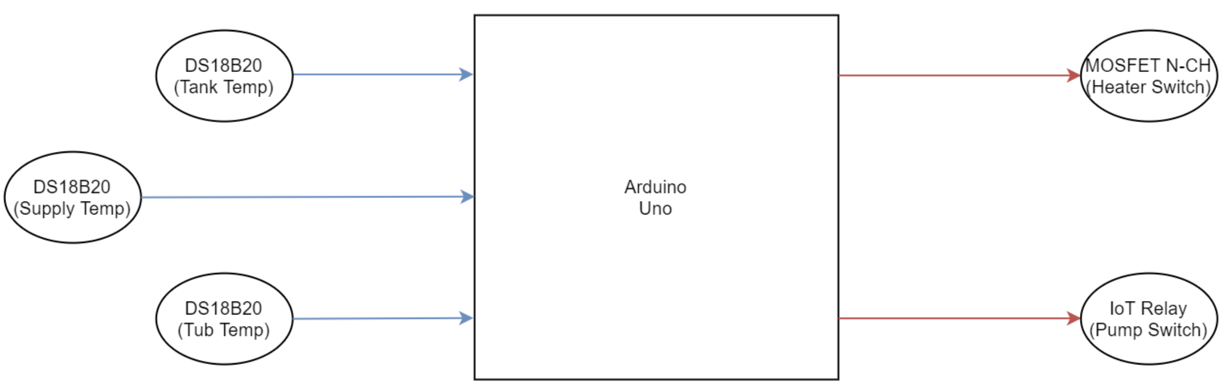


Figure 5.12: Arduino I/O Wiring Diagram

Figure 5.12 is a simplified wiring diagram for our microcontroller, with the three primary sensors as inputs, and our two switches as outputs. As-built wiring diagrams which reflect the final electrical architecture are shown in Appendix S. Our system has two modes of operation: standby mode and active mode. Our system's setpoint is always 95 °C for the tank and 40 °C for the tub. In passive mode, our system prioritizes the tank setpoint, while in active mode, our system prioritizes the tub setpoint.

To properly illustrate how our control system works, we will look at our system over the span of two days. Based on the first law transient analysis we performed using Euler's method and the scaled data from our sponsor, our 40-gallon tank would be at about 95 °C around 11AM of sunny day two. This is assuming a starting tank temperature of 20 °C on sunny day one and a 10 °C overnight temperature drop inside the tank between sunny day one and sunny day two. Once the tank reaches 95°C the pump will turn on and the tank will begin heating the hot tub. Assuming a starting tank temperature of 95 °C, a starting tub temperature of 20 °C, a volumetric flowrate of 1.875 GPM, constant density, constant specific heat, we would have a heat loss of about 33,970 W. This would drop the tank temperature quickly. After roughly 1.5 minutes, the tank will drop from about 95 to 90 °C. From here, the pump would shut off and the tank would continue to heat back up to 95 °C (this would take roughly half an hour). This process would continue until both the tank and tub reach their setpoints. The time it takes for the tank to drop from 95 to 90 °C will slowly increase each time as the tub temperature increases from 20 to 40 °C. Please refer to equations 1-3.

$$\Delta t = \frac{\rho c V (T_2 - T_1)}{\dot{E}_{st}} \qquad \text{(Eq 1)}$$

$$\Delta t_{drop} = \frac{\left(979 \frac{kg}{m^3}\right) * \left(4190 \frac{J}{kg * K}\right) * (0.152\ m^3) * (95℃ - 90℃)}{(33970 - 1728)\ W} * \frac{1\ min}{60\ sec} \qquad \text{(Eq 2)}$$

$$\Delta t_{drop} = 1.53\ min$$

$$\Delta t_{rise} = \frac{(979\ kg/m^3) * \left(4190 \frac{J}{kg * K}\right) * (0.152\ m^3) * (95℃ - 90℃)}{(1728)\ W} * \frac{1\ min}{60\ sec} \qquad \text{(Eq 3)}$$

$$\Delta t_{rise} = 30.1\ min$$

When our system is in active mode, it will prioritize heating the tub above heating the tank. It will continuously run the pump until the tub reaches its setpoint of 40 °C. During heating mode, there is 33.97 kW entering the tub, which will heat it from 20-40 ºC over 32 minutes, which is close to our desired time of 30 minutes. To recover the heat loss to the tub, for every 5 degrees that the tub loses, it will take approximately 30 minutes to heat it back up; this would occur during passive mode during the day, when the tub is not in use. These calculations are outlined in Appendix P.

*5.5.1 Heating Element Control*

We will control the resistive heater by using enhancement mode N-CH MOSFETs as switches. We selected an N-CH MOSFET rated for 500V, 100A, and 2500W. We never expect this much power/voltage to dissipate through the MOSFET, but we oversized the component in case the heating element shorts. When we run a 5V signal to the MOSFET, it will act in the "on" state and allow the panels to provide power to the resistive heating element. When we run no signal to the MOSFET, it will act in the "off" state and the resistive heating element will be off.

*5.5.2 Pump Control*

We will use an IoT power relay to control our 120VAC pump. The pump will be plugged into the "normally off" socket, so that the default operation for the pump will be off. When our Arduino sends a 5V signal to the IoT relay, it will turn the pump on. When we send no signal to the IoT relay, the pump will turn off. It is important that the pump is plugged into the correct socket, because the controls programming is based on this design constraint.

*5.5.3 Additional Controls Safety Measures*

Safety is our number one priority, so we will enable additional checks to account for potential failure modes. In addition, the pump will turn off if the tub reaches 40 °C or if the hot water supply exceeds 46 °C. The pump will only be able to turn back on if it has been off for at least two minutes. This will prevent the pump from cycling on and off.

*5.6 Structural Supports*

The design of the structural supports for our system came late in this project's life. Our original plan after CDR was to directly secure our water heater to the side of our sponsor's hot tub with earthquake bracing straps, and to utilize a plywood board supported by triangular plywood feet to support our piping components. More detailed measurements of our sponsor's hot tub revealed that its sides were not tall enough to provide adequate bracing for the water heater, and further consideration led to the dismissal of any plywood elements due to the water damage those wooden elements would encounter.

Our final structural design utilizes Unistrut metal framing and connections to build scaffolding of galvanized steel to support both the water heater and the acrylic board to which the piping components can be secured. The framing is secured to the concrete of the hot tub side and the concrete skirt surrounding the hot tub using concrete anchors.

*5.7 Safety*

A full breakdown of safety concerns and plans to mitigate risks and hazards are provided in Appendix O. The control system subsystem was implemented solely because of safety concerns with our previous design in PDR, and further changes in IDR.

Our team also had safety meetings with campus electrician, Ben Johnson, and ME technical support, Jim Gerhard. For both meetings we presented our proposed wiring diagrams for all electrical connections and both professionals were confident in its safety and efficacy.

While the design of our structural support has been selected using the California Guidelines for Earthquake Bracing [13] and the strapping requirements established by the County of San Diego [14] as a guide, we were not able to perform analysis to validate the structural loading our design would be able to withstand. As a result, while we would intuit that our design should withstand the forces subjected to it during regular use, it cannot be said to be truly earthquake rated or able to withstand intentional misuse.

*5.8 Cost*

A major driver for our final design was mitigating cost. Moving away from a copper heat exchanger and an aluminum tubed diode immersion heater brought down costs considerably. Our hesitation to purchase an electric water heater at the onset of this project was an attempt to keep our project costs down.

Our total estimated project cost (which includes a component-level breakdown) is provided in the Indented Bill of Materials (iBOM), Appendix M. All costs shown in appendix are final costs, which include estimated taxes and shipping costs. More details on the costs of this system are presented in section 8.3.

*5.*9 Future Recommendations

From our field site visits, we have determined that the solar panels are not oriented in the optimum configuration. Using measurements from Google Earth and photo telemetry, we have determined that they are pointed with an azimuth angle (deviation from South) of 45º West, and an altitude angle (tilt from horizontal) of 20º. To, capture more energy at any time of year, we recommend that our sponsor increase the tilt angle to 35º and point the panels as close to south as possible.

We also recommend that our sponsor utilizes an electrical engineering student next year to upgrade our system to maximize the power output of our heating element. In theory, both methods should increase the maximum power output as the current drops during the day. There are two main design directions the EE student could choose between:

- Design a variable resistance heating element which changes resistance based on the I-V curve for the solar panels throughout the day.
- Design a DC-AC-DC buck converter which increases the current and decreases the voltage supplied by the panels throughout the day.

## 6.0 Manufacturing

Per the previous CDR report, our final prototype will feature relatively few parts. It will now be divided into four subsections labeled storage, distribution, heating, and control system. After PDR, we realized that due to safety concerns associated with near boiling water, and possibility of thermal runaway in the case of extraordinarily sunny days, a passive control system was required. The control system will be responsible for starting the circulation pump, and ensuring temperature set points are achieved. It will consist of thermocouples, electrical switches, and an Arduino microcontroller. Storage will include all parts relevant to the holding of hot water, including the hot tub and water heater. Distribution will include all pipe, connections, the pump, and any submerged diffuser devices within the tub. Heating will include the immersion heater and appropriate electrical connections to the existing photovoltaic array. This manufacturing plan will serve as a step-by-step guide to the construction of all manufactured parts, full assembly, plan for procurement, and any outsourced manufacturing operations.

### *6.1 Procurement*

The two most expensive components, and two of the most critical ones, were the hot water tank and circulation pump. The greatest hurdle came from securing a hot water tank which balanced price, water capacity, and quality in materials. Fortunately, our system did not require the full utility of a typical domestic water heater and was only needed for its insulative and water holding capabilities; the heating element was not required to be operational. The pump needed also only required single speed operation, which could be controlled by a power switch.

For our purposes, we searched numerous used appliance online forums, centering our search to San Luis Obispo County. From *craigslist.com* we found two 40-gallon natural gas water heaters made by GE and Whirlpool. They were being offered for free, and they are in an acceptable condition. The seller was only getting rid of them as he was switching to a tankless hot water heating system. The two tanks were picked up by our team, and they are being stored in a senior project space, in the Bonderson Project Center on Cal Poly SLO campus. We had planned to use the Whirlpool model in our final prototype, as its connections were in better condition and it has a cleaner outer appearance. We switched to using a purchased 50-gallon electric water heater to better accommodate our heating elements. If this TES system were to be widely manufactured, a storage tank could be built inexpensively using stamped and rounded metals, with injectable foam insulation.

For the distribution system, sourcing a properly sized pump was of primary concern for safety and efficiency. We set a performance goal to be able to adequately heat the tub from 30-40°C, over a course of 30 minutes, thus exchanging the entire tub volume, over the same duration. This gave a flowrate of 7.5 GPM. The operating head required, however, has drastically changed from PDR, as we have opted to replace a single loop, heat exchanger strategy, with a hybrid pipe, bypass system which will mix hot tank water with cooler tub water, modulated by two valves. This presents a different system curve which the pump must be fitted for. A transfer pump from Wayne has been selected with a rated flow rate of 20 GPM, which will adjust to match the amount of pressure drop throughout the system. The pump is available through *Amazon.com* and can be delivered to campus. All associated piping supplies will also be purchased at a local Home Depot so returns and professional advice will be nearby. They supply both the ¾" copper L type piping and PEX piping which will be used to transport the mixed water, and be the ultimate inlet into the tub. The mixing valves, which will be globe valves, will also be purchased from Home Depot.

The heating system will only require the purchase of a 3800 W resistive immersion heater, also available through *Amazon.com*.

The control system consists of a N-CH MOSFET, an Arduino microcontroller, an IoT relay, and three DS18B20 digital temperature probes. The primary function of this sub-system is to monitor temperatures in the tub, tank, and mixed supply feeding into the tub. The Arduino microcontroller and mandatory features such as a power source will be purchased through *Amazon.com* and the DS18B20 probes will be purchased through *adafruit.com*. The Arduino programming community has provided extensive literature regarding integration of digital temperature sensors. The MOSFET can be purchased on *digikey.com*.

### *6.2 Drawing Package*

A drawing package containing all of the custom parts to be manufactured for our assembly has been included as Appendix T. This package includes an exploded drawing of the distribution piping, cut sheets for the Copper, PEX, and Unistrut, and manufactruing instructions for the Acrylic sheet which will serve as a mounting spot for the piping components and the enclosure.

### *6.3 Component Manufacturing*

Although our team has opted to purchase a commercially available resistive heater, a step-by-step guide for diode chain immersion heater will still be provided as Table 6.2. Our final design will feature only off the shelf components, to be assembled in a customized way. Theoretically, diodes can offer greater power extraction from the panels during cloudier weather and suboptimal sun angles. Future endeavors can explore this option further and use this as a starting point.

Table 6.2: Detailed Diode Chain Manufacturing

| Diode Chain Immersion Heater | | | | | |
|---|---|---|---|---|---|
| **Major Step** | **Process Step** | **Process** | **Tools** | **Dimensions** | **Comments** |
| 1 | 1 | Select 10 diodes | | | |
| | 2 | Hold Diodes atop one another and horizontal | | Edge of lead halfway across diode body of other diode | Make sure they are linked + to - |
| | 3 | Twist diode leads together until immovable | Needle nose Pliers | Tight braid, horizontal | |
| | 4 | Clip excess lead | Wire clippers | | |
| | 5 | Repeat for 13 Chains x 10 Diodes Each | | | |
| 2 | 1 | Repeat Steps 2-4 to create single chain 90 diodes | Wire clippers, needle nose pliers | | Again, make sure they link + to - |
| 3 | 1 | Mix two-part JB weld epoxy | Plate, popsicle stick | | |
| | 2 | Generously coat metal leads | Popsicle stick | | Try to prevent getting on diode body |
| 4 | 1 | Clip 2 ft long purple lead wire | Wire cutters | | |
| | 2 | Solder to positive lead of chain | Soldering iron, tin solder | | Wrap copper wiring around diode lead |
| | 3 | Clip 2 ft long black lead wire | Wire cutters | | |
| | 4 | Solder to negative lead of chain | Soldering iron, tin solder | | |
| 5 | 1 | Get string and 11’ aluminum tube | | | |
| | 2 | Tightly secure string to positive lead | | | |
| | 3 | Thread string through aluminum tube | | | |
| | 4 | Carefully pull diode chain through until all diodes are inside tube | | | |
| | 5 | Bend into double U-shape | | Three sides 2 inches apart | |
| | 6 | Set aside to dry, with leads vertical | | | |

*6.4 Prototype Assembly*

Due to the size of our system, it will need to be assembled as an installation at our sponsor's residence, it its final location. A breakdown of the major steps, which should be completed in consecutive order is as follows:

Table 6.3A: Preparatory Steps and Time Estimates

| Step | Description | Estimated Time (minutes) |
|---|---|---|
| 1 | Pipe cutting | 60 |
| 2 | Pipe soldering | 60 |
| 3 | Immersion heater and MOSFET wiring | 30 |
| 4 | Arduino programing | 480 |
| 5 | Component (e.g. sensors and switches) testing and verification | 240 |
| | Total On-Site Time = | ~14.5 hours |

Table 6.3B: Onsite Installation Guide and Time Estimate

| Step | Description | Estimated Time (minutes) |
|---|---|---|
| 1 | Safely transport water heater, plumbing, and all electronic components to project site | 90 |
| 2 | Fill chimney with foam insulation | 15 |
| 3 | Install resistive heater into water heater port. Do NOT connect it to solar panels yet. | 30 |
| 4 | Place pump in correct location in front of tank | 5 |
| 5 | Install all piping, fittings, and sensors shown in the assembly drawings | 240 |
| 6 | Fill tank and tub with clean water | 120 |
| 7 | Function test pump by plugging in to house power. There may be some vibration as air leaves the piping system. Check for leaks. | 5 |
| 8 | Unplug the pump | 1 |
| 9 | Have an electrician connect the heating element to the PV panels | 15 |
| 10 | Install the microcontroller: connect the three temperature inputs and the two switch outputs | 15 |
| 11 | Allow system to heat, monitor tank temperature | 60 |
| 12 | When tank has reached 95C, heater will stop. Manually activate pump, and adjust globe mixing valves until the mixed water temperature reads 46C going into the tub. Lock valves in this position. | 60 |
| 13 | Plug the pump into the "normally off" socket in the IoT relay | 1 |
| 14 | Now that the tank is in the proper orientation, secure the tank to the tub by using concrete bolts and a strap | 60 |
| | Total On-Site Time = | ~12 hours |

Using a x3 time safety factor, we predict it will take about 80 hours of prep and on-site work to fully assemble and install the system.

### *6.5 Outsource Operations*

Per *Cal Poly ME Senior Project Success Guide*, to protect the safety of students or otherwise untrained personnel, we are not allowed to complete and energize any system using over 50 Volts. Our system will nominally operate at 144 Volts, and 12 amps of current. A campus approved electrician will need to construct a grounded port which allows a safe connection between the solar panels, and our immersion heater. Our sponsor, or electrician, will be required to be the one to "plug in" the system, making the final connections. Outside of the scope of this senior project, it is still recommended that a professional electrician inspect all electronic connects for this system or similar, to ensure it is safe for use.

### *6.6 Control Panel Enclosure Modification*

Our final deliverable will be a control panel, which will have a pre-programmed Arduino Uno microcontroller, which will conduct all major safety and heating operations, autonomously. All electronics will be mounted to the side of the hot tub, drilled into a wooden base, secured to its cinder block exterior. We purchased a waterproof enclosure; however, it was completely sealed. In order to allow inputs from the four temperature sensors, and power from the solar panels, and outputs to turn on the pump, we needed to create numerous penetrations into the enclosure.


Figure 6.1: Modified Control Panel Enclosure

Plastic electrical cord grommets were used as the splash-proofing mechanism, which radially tighten on the inserted cord to protect from water infiltration. Each hole was made using a ½” through-hole drill bit, and then gradually sanded down about their circumference using a high RPM rotary tool, until the selected grommet was able to fit through.

The enclosure will be oriented inverted to the orientation shown in figure 6.1. Relative to the figure, on the top right are single, ½” grommets for each temperature sensor. Top left shows a 5/8” grommet for the IoT relay power supply, which will also power the Arduino at all times, and a power plug for the pump. On installation, the power plug for the pump will have to be cut, and reconnected in order to fit through the whole. On the left side is the stainless-steel push button, which has a waterproofing rubber gasket, is the button which will be used to switch the system in between active, and passive mode. These modes will be discussed in detail in Section 7.6. The other holes are described in Appendix Q: Enclosure Hole Management Diagram.

Black Velcro was secured to the enclosure bottom, with mating side attached to the bottom of the IoT relay, Arduino, and PCB’s in order to secure the components, when it is mounted vertically, and to make sure that upon reassembly with maintenance, components will be returned to the proper locations.

*6.7 Soldered Connections*

Although all electrical connections will be inside the enclosure, to prevent sparking, and to make sure that all physical connections for the controller allow clear signal, all connections must be soldered. To this end, a lead-free solder was used, which featured 2.2% flux core, 0.8mm in diameter. The best performance was achieved when the soldering iron was used on its highest setting, 480ºC.

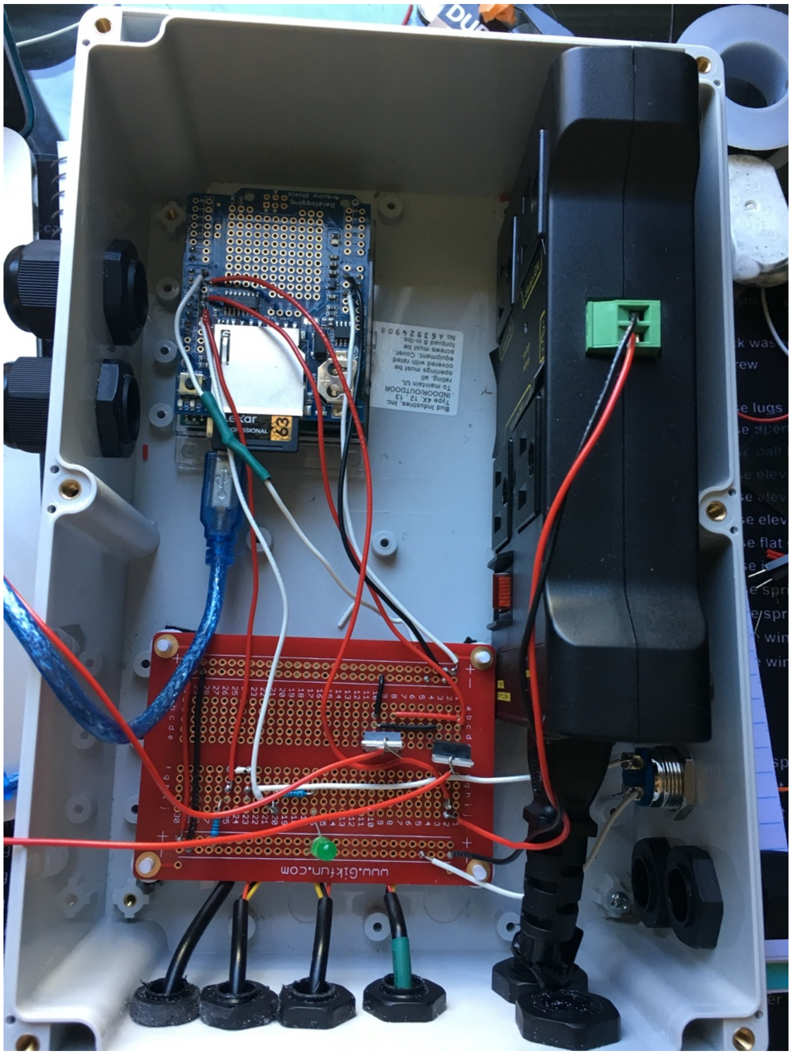


Figure 6.2: Filled Control Panel Enclosure

The PCB boards were the first components to be soldered. The circuit to be made, was formed on a solderless breadboard, and pre-tested so that it would work. Wires, resistors, and LEDs were loosely placed into the through holes, and tape was attached to hold components in place, The board was flipped, and soldered on the bottom, for a clean top surface. In order to have enough space for all wiring, two PCB boards were used, stacked atop one another using 3D printed spacers, which snap into each other. The top and bottom boards share the same 5V voltage source from the Arduino, and the same grounding plug. Essentially, they operate in parallel. To attach them in parallel, the main power and grounding wire from the microcontroller attach to a single power and ground rail on the top PCB. All circuits will attach to these main rails as their power supply.

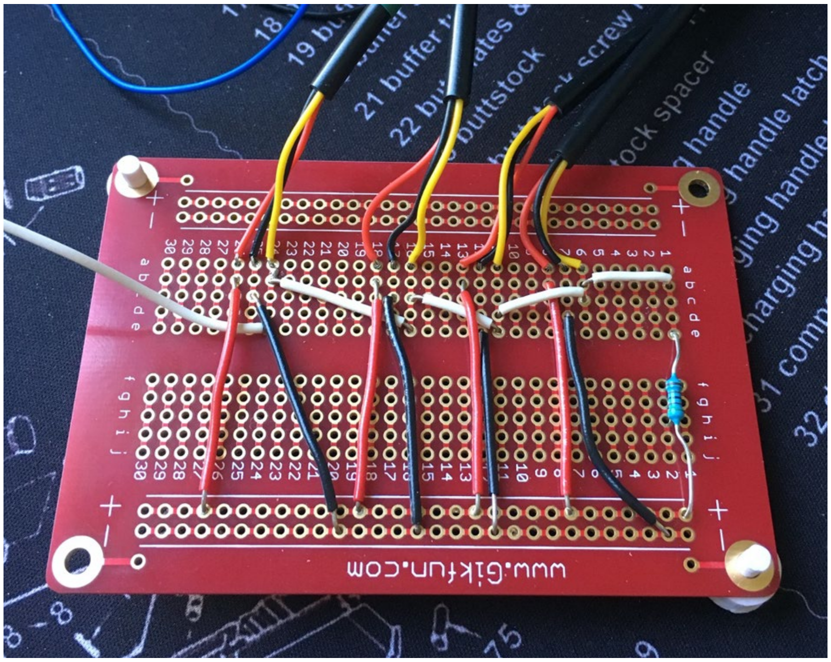



Figure 6.3: Bottom PCB Board

The bottom board held all wiring for the four temperature sensors, which includes 4 of each data wire (yellow in Figure 6.3), power wire (red) and grounding (black), along with a single 5kΩ resistor, intended to smooth the voltage signal from the temperature sensors. Each signal is added in parallel, and then parsed at the microcontroller, since the sensors operate on a digital signal.

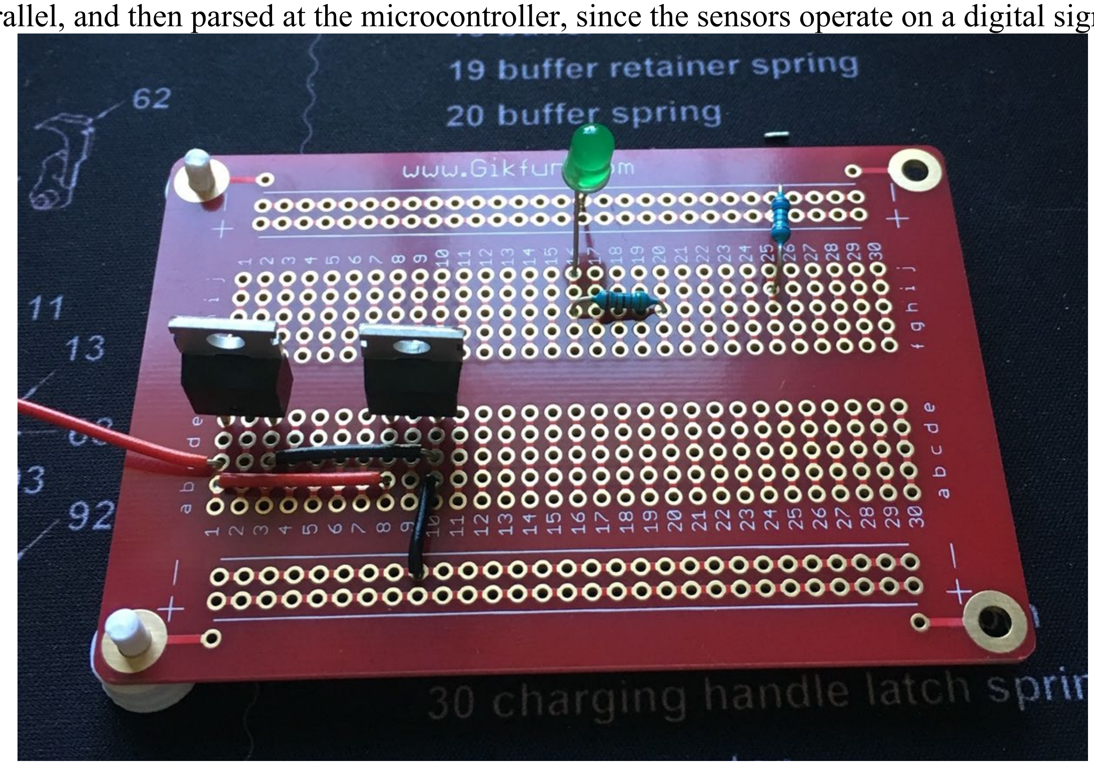



Figure 6.4: Top PCB Board

The top PCB board contains all wiring for the MOSFET switches between the heating elements and solar panels, wiring for the button mode selector and mode LED light, and the IoT relay. The LED uses a 5kΩ resistor to moderate current, and receives a voltage from pin13 on the Arduino.

The drain segment for the MOSFET, which was the center pin, was clipped. The top flange serves the same purpose, and will be used as the wiring point between the solar panels, and microcontroller. After installation into the enclosure, wires for the IoT relay were connected to this board, as was the main power connection for both power rails, the remaining button wires, and grounding. The completed build of the top PCB orientation can be seen in Figure 6.2. Easier to read, as-built wiring diagrams are shown in Appendix S. For the datalogger shield, wires were loosely placed in a similar fashion, since it has similar through holes. Those wired connections were soldered on top, as that was the only accessible point.

## 7.0 Design Verification

There are four major tests which may be completed to ensure the system performs to our design specifications. The system tests are also highlighted in the attached DVPR document.

1. Photovoltaic power verification
2. Hot tub operating time
3. HWS mixed temperature
4. Tub heating time

### *7.1 Photovoltaic Power Verification*

A major assumption made during the development of the system was the amount of time required to initially heat the tank water starting from room temperature, or 20ºC to 95ºC, and from 40ºC to 95ºC. This was made off of the total amount of energy available over the course of one day, with solar panel power data recorded in March on a 100W panel. The data was adjusted to match four 432W panels to give an estimation of the system's performance. This was a large assumption, and it will need to be verified. We estimate that the tank will be fully charged after about 9 hours of sunlight: approximately a day and a half of typical solar insolation. This test does not require a full assembly of the system, only a data logger which will record the total amount of power during each time step. This data can then be further processed, to give an estimation of total energy throughout the day.

Table 7.1: Photovoltaic Power Verification Data Types

| Sensor | Type of Data | Units | Uncertainty |
|---|---|---|---|
| Panel Ammeter | Current | Amps | +/- 0.5A |
| Panel Voltmeter | Voltage | Volts | +/- 1V |

Considering uncertainty propagation, we will be able to calculate the total instantaneous wattage to +/- 0.5 W. Numerically integrating via Euler's Method and using a suitably small time step will offer good accuracy.

### *7.2 Hot Tub Operating Time*

This test will confirm that at operating hours, the control system will maintain the tub temperature at 38-40ºC for three hours. This will require a full build of the system, including an operational heating system, and a fully charged tank beforehand. For three hours, we will monitor the three temperatures to ensure that none of them reach below 38ºC, which would ensure that the tub also is at the ideal temperature. It would also be important to visually monitor the system, to watch for when the pump turns on in reaction to a dip in temperature.

Table 7.2: Hot Tub Operating Temperature Data Points

| Sensor | Type of Data | Units | Uncertainty |
|---|---|---|---|
| Tub Thermocouple | Temperature | ºC | +/- 2ºC |
| Hot Water Tank Thermocouple | Temperature | ºC | +/- 2ºC |
| Mixed Water Thermocouple | Temperature | ºC | +/- 2ºC |

*7.3 HWS Mixed Temperature Verification*

One of the key safety features of our system is the restriction of mixed water entering the tub to a maximum of 46 ºC, which is the threshold for human injury. A thermocouple embedded in a probe pipe fitting will measure the centerline temperature of the incoming water. A simple test will be conducted which will involve allowing the tank water at 95 ºC to mix with tub water at 30 ºC, to ensure that the mixed water will not exceed 46 ºC. At all other times, the tank temperature will be lower, and the mixed temperature will also be lower. If this temperature is exceeded, a command will be sent to shut off power to the pump.

*7.4 Tub Heating Time*

A specification which was necessary for the selection of our pump was the ability to heat the tub +10 ºC over the course of 30 minutes, by cycling the entire volume of the tub within that amount of time. This test can be recorded by allowing the system to run, with the tank starting fully charge, and the tub at 30 ºC. A timer will be set and stopped when the tub reaches 40 ºC.

*7.5 Design Verification Test Estimates*

Table 7.3: Design Verification Time Estimates

| Test # | Test Description | Onsite Time |
|---|---|---|
| 1 | Record data from panel voltmeter and ammeter to determine daily energy | 6 hours |
| 2 | Test the effectiveness of control system. Temperatures at three locations will be monitored over 2 days to function test all states of system | 12 hours (6 hours of sunlight, days) |
| 3 | Monitor mixed water inlet temperature when tank is fully charged during first heating period | 10 Minutes |
| 4 | Record tub average temperature over 30-40 minutes to determine heating time | 35 Minutes |
| | **Total** | 18.75 Hours |

Assuming a 3x factor of safety for time, we estimate a time budget of 56.25 hours will be appropriate to verify all systems are operational. However, the only tests which must be conducted with a full build of the system are tests 2-4. Test #1, which verifies our modeling assumptions for the total amount of energy available by linearly scaling data from a different panel, can realistically be conducted at any time. Ideally it can take place any time during March, so that it can match previously recorded data from our sponsor. This decreases the amount of testing time on site to 38.25 hours. Tests 3 and 4 can happen simultaneously, we would just need to use two data loggers in order to monitor times and temperatures. Test #2 should be the final test conducted, since it will be a final verification for the full system package: testing all processes involved, from energy capture to activating/deactivating components.

*7.6 Completed Testing*

The change in scope due to state restrictions halted all large-scale construction of our project, so the associated verification tests were also cancelled. The available design verification tests diminished to only two tests which would verify the effectiveness of our control system. They would include temperature sensor validation, which would ensure that our sensors would work as intended, and a bench top style test of control system outputs, modeling the pump and resistive heaters as a string of Christmas lights and blue LEDs respectively.

*7.6.1 Temperature Sensor Validation*

The first step towards the control system verification was to make sure that the input signals to the controller were accurate. After soldering, each temperature sensor was simultaneously placed in an ice bath, allowed to sit at room temperature, and then placed into a bottle of hot water.

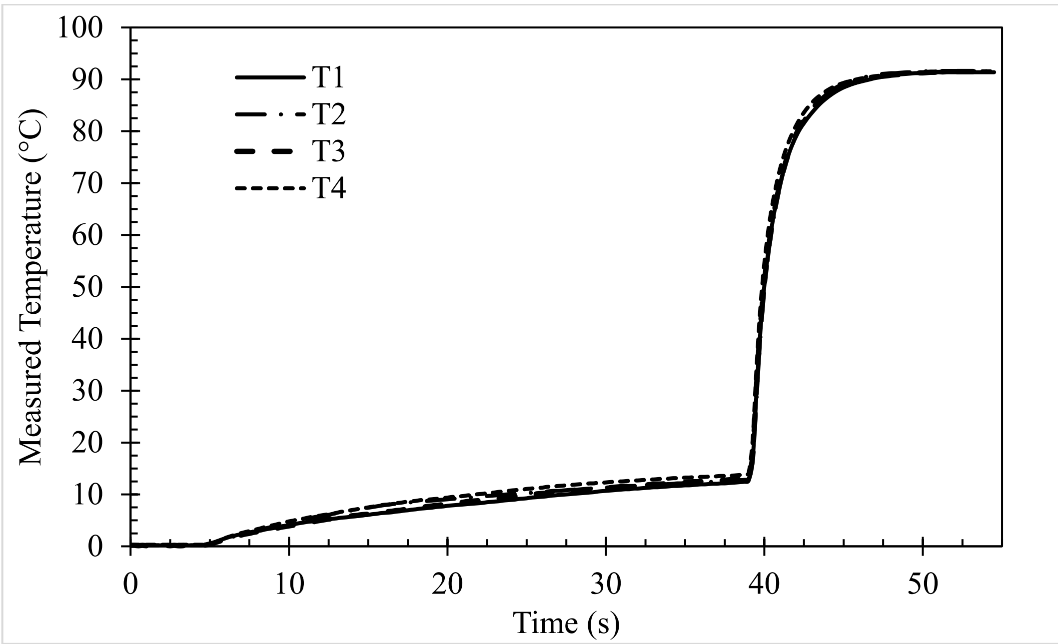



Figure 7.1: Temperature Sensor Validation Plot

Although the upper limit of temperature could not be verified with actively boiling water reading 100ºC, the lower limit was able to be validated, with a reading of 0ºC when allowed to sit in ice water for a few minutes. A plot of temperature vs time for each sensor is shown on Figure 7.1, and they are all in agreement. The greatest variance would be about 2 ºC, which occurred when removed from the ice bath. This can be due to uneven convection on the individual sensors. From the temperature variation plot, it appears that the sensors are a first-order system. The response time is inversely proportional to the temperature differential between the measurement and the environment, and the heat capacity of the sensor. During full scale operation, temperature change will occur on a larger time scale, and variation between sensors will be reduced to $\pm 0.5°C$, as stated by the manufacturer.

*7.6.2 Controller Logic Test*

Table 7.4: Passive Mode Truth Table

| Case # | Tank Temp. > 93ºC = 1 | Hot Tub Temp. > 40ºC = 1 | Mixed Water Temp. > 46ºC = 1 | Pump 1 = On 0 = Off | Heater 1 = On 0 = Off |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 1 |
| 2 | 0 | 1 | 0 | 0 | 1 |
| 3 | 0 | 0 | 1 | 0 | 1 |
| 4 | 0 | 1 | 1 | 0 | 1 |
| 5 | 1 | 0 | 0 | 1 | 0 |
| 6 | 1 | 1 | 0 | 0 | 0 |
| 7 | 1 | 0 | 1 | 1 | 0 |
| 8 | 1 | 1 | 1 | 0 | 0 |

The table above summarizes the logic to be executed by the microcontroller. During passive mode, the tank will try to leave the heater on, and pump off, as much as possible in order to maximize storage. However, to protect the water tank and those in the area, the maximum temperature allowed for the tank is 95ºC, however, the set point to begin turning off the heaters is 93ºC, to account for a -1ºC error in the temperature sensor. The pump will activate to mix hot water into the tub, to use that as additional thermal storage. However, if the tub becomes too hot, then all components have the ability to shut off, and the system will naturally cool until safe operation is achievable. For the Active mode, a similar table to Table 7.4 was constructed, however the pump will by default be running, and it will only turn off if the mixed or hot tub temperatures become too hot, or the controller is again placed into passive mode.

Figure 7.2a: Experimental Setup

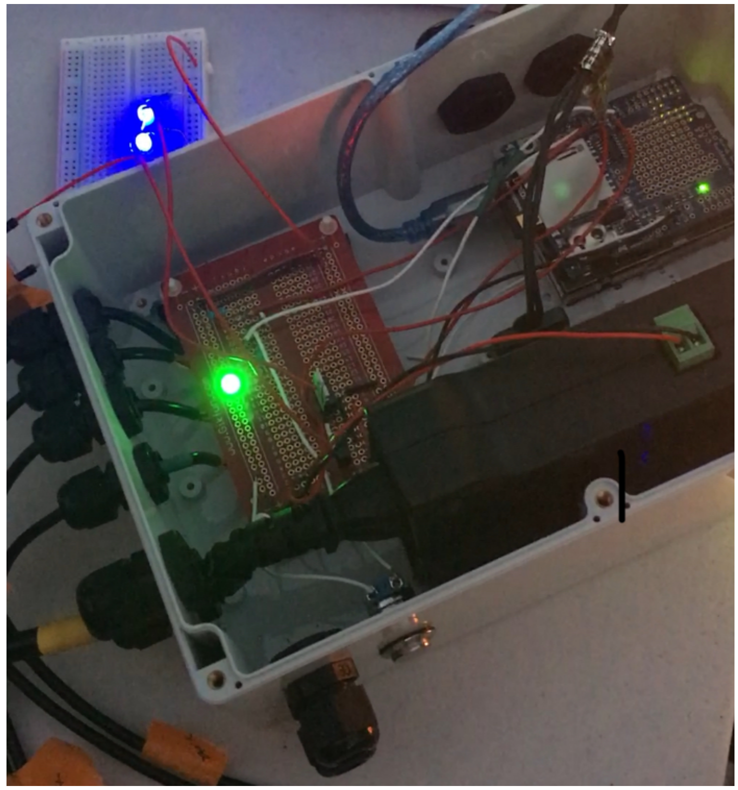


Figure 7.2b: Confirmation of Heating Elements On

After all components were assembled, each combination of “hot” (1) and “cold” (0) temperature sensors, outlined in Table 7.4, were completed, and the output was observed. Simultaneously, the temperatures were read in real time, as an additional check of when signals were being sent. Due to the COVID-19 pandemic, a full-scale construction, and control system implementation, was unable to be completed. However, close approximations were allowed with household elements. The Christmas lights shown in figure 7.2a will use the same 3-prong outlet on the IoT relay, as the pump will use, and is a direct stand in.

The heating elements will be connected through the drain segment on the MOSFETs. For testing, they were simulated as a pair of blue LEDs, shown in Figure 7.2b, electrically connected to the same drain segment on the MOSFET. The camp stove was implemented to simulate the water heater, as it can achieve boiling temperatures. It was also used as a means to quickly heat other temperature sensors during testing.

The temperature sensors were marked “Tub”, “Tank”, “Mixed”, and “Ambient”, to symbolize their respective locations. The sensor names matched those used in the code. Case by case, sensors were placed in hot, or cool water to simulate the different test cases, and each one passed. Minor adjustments were required for the programming, to ensure that the pump or heating elements would turn back on or off, after receiving an off or on command, and to make sure that ‘flickering’ would not occur in the pump, which could lead to inefficient operation.

*7.7 Testing Conclusions*

From the outlined completed tests, we found that the programming for the Arduino controller was successful. All components functioned as predicted, and we would feel comfortable placing this controls enclosure onto the full-scale system, when it is constructed. Although we were unable to complete full scale testing of the entire system, this should be a goal of a future project team.

## 8.0 Work to Be Completed

As a result of the COVID-19 pandemic, not all of our work was able to be completed before the end of our senior project. Specifically, the manufacturing, assembly, and design verification of all of the components other than the control system will have to be completed by another project group or by our sponsor. To that point, we have developed detailed manufacturing, assembly, and verification plans to be utilized for our project.

### *8.1 Manufacturing Plans*

Our project does not contain many custom components; the majority of our custom components are piping elements, metal frames, and mounting plates. The schematics needed for the manufacturing of these components can be found in Appendix T.

### *8.2 Assembly Instructions*

Detailed instructions have been provided for the assembly of our structure. These instructions can be found in Appendix U. While it was our intent to provide as much detail as possible to aid in the construction of this system, there were certain limitations to this goal. Plumbing components, in particular, are often vague in their part descriptions from online retailers, so it is highly recommended that each component used for this project be checked before purchase to ensure that all of the parts will join together as specified.

Financially, it should be noted that the iBOM presented as Appendix M represents an estimate of assembly costs more than an exact ledger of prices. Certainly, economic stresses could cause prices to change in the future in unpredictable ways, and additionally the builder of this system may have access to in-person retailers of plumbing components, scrap parts from the university, and other means of acquiring materials that are unavailable to us at this time. In short, we recommend price hunting to seek out the lowest cost for all components.

### *8.3 Design Verification*

After our system has been built, it will still need to be verified as we had planned. We recommend that the verification plans outlined in sections 7.1 through 7.4 be followed to measure whether the system performs as expected. It should be noted, however, that the verification recommended in section 7.1 could possibly be circumvented with analytical methods previously unknown to our group. Textbooks such as *Renewable and Efficient Electric Power Systems* by Gilbert M. Masters offer analytical methods for estimating the power produced by solar panels, given the manufacturer data sheet of the panels and the spatial positioning of the panels.

## 9.0 Project Management

The overall design process our team implemented throughout the course of our senior project is the same design process that we have been taught throughout our years at Cal Poly. Broadly speaking, the steps are:

- **Empathize** with our user so we may better understand the problems they face, to then take their concerns and distill the deeper needs behind their comments.
- **Define** the problem, framing it in such a way as to capture the insights gleamed from our user interviews.
- **Ideate** to generate as many possible solutions to the problem as possible; this process is where any innovations that are to be made can be found.
- **Evaluate** the different solutions using a variety of methods such as weighted decision matrices and analytical reasoning, in order to focus on one solution.
- **Design** the solution by drafting the critical components and assemblies; ensure detailed analysis is performed so the final product meets the specifications.
- **Build** the solution using the resources available in Cal Poly's many machine and research labs.
- **Test** the design solution based off the technical requirements that were specified.

To keep our group on task as we progressed through these steps, we utilized a mixture of Weekly Status Review (WSR) documents and a Gantt chart to track progress – though we may transition to solely one or the other in the future. On the WSR documents, the weekly tasks we accomplished are listed in an upper table, and tasks for the upcoming week are listed in a table below. The Gantt chart has a similar level of detail to the WSR's, though some tasks which are quickly assigned and accomplished during the week may be omitted. A detailed picture of our project Gantt chart may be seen in Appendix C.

Throughout the final phase of the project, our team was required to work remotely. Although much of the testing verification could not be completed, there were still resources for control system simulation. Using TinkerCAD, a free software from Autodesk, we were able to wire breadboards with actual components, connect the components to an Arduino, and write code to simulate the system. This served as an indispensable tool for quickly prototyping and organizing the electrical system. Screen captures of the electrical schematics are given in Appendix S; these images directly reflect the configuration for the actual system. Although this was not by choice, having one dedicated person for manufacturing procedures proved to be more efficient. One team member would research how the components should be wired, while another would assemble and test to ensure the researched methods worked. Similarly for all CAD, one dedicated person to handle it proved to work well for us, since they would have their own organizational scheme, and know where everything is.

All of these team management decisions allowed each person to focus on work that played well into their strengths, resulting in a streamlined approach which ensured all activities were accomplished well and within acceptable deadlines. For future projects, we will consider this same setup.

## 10.0 Project Conclusions & Recommendations

The purpose of this document was to serve as a step by step guide to allow the construction of our verification prototype, which we believe was the best solution to our sponsor's need to reduce his photovoltaic system's dependency on local weather patterns. During the entire design process, our team was constantly inspired by our sponsor's household DIY approach to alternative energy. This prevented over-engineered systems which only gave marginal improvements. It includes some history of past design ideas and logic for why our final chosen design is what it is. This document will allow any build team to be able to procure, assemble, and test the final assembly to assure that it means all specifications, and will also serve as a jumping off point for future improvements to the design.

*Project Achievements*

As we discovered during the research phase of the project, there is no similar system to ours that has been constructed and tested with any degree of legitimacy. In practice, most current systems which use thermal storage utilize phase change materials to take advantage of high latent heat of fusion and densities. As we found from our sponsor's previous research, the only PCM which had a safe melting temperature was Erythritol, but it undergoes major volumetric variation with melting and solidification, leading to logistical issues. Systems which use solar thermal energy storage require massive collectors, and they do not use photovoltaic panels. Our sponsor wanted us to use PV panels, since they were already on site. However, these were not the greatest technological hurdles to overcome.

We had entered the project optimistic for the usage of diodes because, on paper, they can offer greater performance than current resistive heating elements. Also, our sponsor had experienced success on a small scale with diodes as heating elements in previous endeavors, however at our scale, it would not be suitable due to manufacturing concerns. Despite the fact that we ultimately did not utilize diodes in our verification prototype, our project did a thorough job of further exploring the usage of diodes by posing questions and concerns which had not been considered before. This ultimately led to the realization that the technology was not quite ready for this application, at this scale.

The primary achievement of our project was completing a lot of the groundwork necessary to have a successful project for thermal energy storage. This project began relatively blind to how the design and construction would happen. This consumed a lot of time, which is still a necessary part of a research project, which is how this should be described. We confirmed the usefulness of simplistic modeling, back-of-the-envelope calculations which serve as a compass for which direction to go, where to dedicate analysis and design efforts. The simple calculation of determining the number of diodes necessary to complete our project was what gave us direction to a more realistic approach. The final deliverable was a major achievement in itself. Developing a fully functional control system in just two months during the middle of a pandemic is not an easy feat. Very quickly, we achieved rapid verification of software and hardware, and we optimized the system through testing with a simple, realistic setup.

*What This Project Did Not Achieve*

While the achievements of this project had the potential to go further or possibly even fall short of our expectations, ultimately our project's scope was cut short by the COVID-19 pandemic.

The shelter-in-place order halted all of our ongoing and planned construction operations for our project. Unfortunately, this included the vast majority of our manufacturing and assembly options. In order to meet as many of our initial goals as possible, we had to scale back our manufacturing and produce what we could – the control system for our project.

We were not able to conduct a full-scale test of the system. Most importantly, we were not able to verify the operating point for the pump. The piping analysis shown only features pipe sizes and lengths that were selected for CAD, and will likely differ for the actual system. A change in the operating point could cause the tub to heat too slowly. On the full-scale system test, the commissioning for the mixing valves, which would control the proportion of water from the tank to mix with cool water from the tub, can only take place after completion. This is a safety concern, and our group wanted to be responsible for ensuring the system is safe. A full-scale test would also allow the verification of modeling assumptions, which would benefit future analysis for similar systems. This would include the scalability of one solar panel's output, to predict output of numerous panels, which was the basis for our heating element selection. Another major issue with this type of energy storage, is the lack of resources to assist low level design and calculation. Our data which would have been collected, and analyzed for trends, would have been an indispensable resource for future designers. Our team hopes to see residential scale thermal energy storage systems expand in popularity, and that begins with a reliable basis of predictability.

We were also unable to test the control logic and component behavior using the real components such as the PV-panels and resistive heaters. The design verification chapter highlights the series of tests which were conducted, and the control system, as a whole, completed all tests, and refined the code to work more efficiently. These tests would be described as bench tests, or logic tests. Even though the tests' successes were encouraging, they do not replace viewing output on real solar panels instead of a battery, and real resistive heaters instead of LEDs. As we had found during testing use diode-heaters, conducting real hardware tests highlights their respective problems, and doing so system wide, could very well lead the project in another direction, and this would make it an appropriate starting point for another project team.

*Sponsor Next Steps*
Our sponsor, Professor Pete Schwartz, will be tasked with coordinating the following construction activities, which can occur asynchronously.

*Assembly of the System*
The system should be assembled in the manner specified in the *Assembly Instructions* section of this document (8.2).

*Wiring of PV Panels*
The success of our project is dependent upon the usage of four 432W photovoltaic panels, 2 circuits with 2 panels wired in parallel. This is an unusual configuration, and the installation should be completed by a licensed professional. Our team refrained from giving precise schematics which must be followed, because we wanted to leave the installation instructions to the discretion of those more knowledgeable. Instead, we opted to provide a detailed description of what we need, and the general location of ports which will tie in to our controller. A major concern would be the grounding for the solar panels.

The MOSFETs which will be used as switches between the heaters and panels are rated for the current expected, however, we would like to see an external grounding so that high energy wires have a safe discharge route. Again, this will be at the discretion of a professional. Following a safety test of the panels, it can be wired to the control system.

*Future Project Group*

It will be incumbent on the next group to first verify that the full system operates as intended. This includes all tests mentioned in the *What this Project Did Not Achieve* section above as a starting point. Improvements to the code can be conducted, which includes utilization of the attached data logger to view temperature trends, and use that to make predictions based on weather, date, etc.

We also recommend that an electrical engineering student could upgrade our system by designing and building an electrical gyrator capable of dynamically decreasing the voltage supply from the panels and increasing the current supply to provide the maximum possible heat output from the resistive heating elements. This would be a low-cost, yet effective way to achieve a dynamic heating solution without having to use less reliable diodes. They could even install the upgrade for one heating elements and use the original system as a control to compare results.

The future group has this entire report as a starting point, and they should work to improve the system, making it more approachable for the average homeowner.

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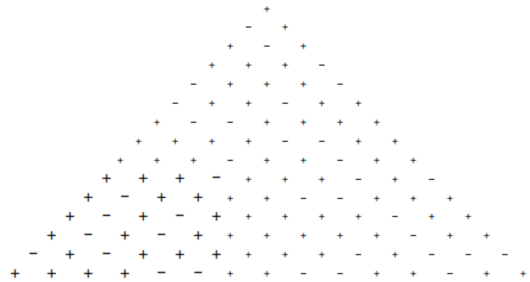
**Appendices List**

# Appendix A: QFD House of Quality

| Correlations | |
|---|---|
| Positive | + |
| Negative | − |
| No Correlation | |

| Relationships | |
|---|---|
| Strong | ● |
| Moderate | ○ |
| Weak | ▽ |

| Direction of Improvement | |
|---|---|
| Maximize | ▲ |
| Target | ◇ |
| Minimize | ▼ |

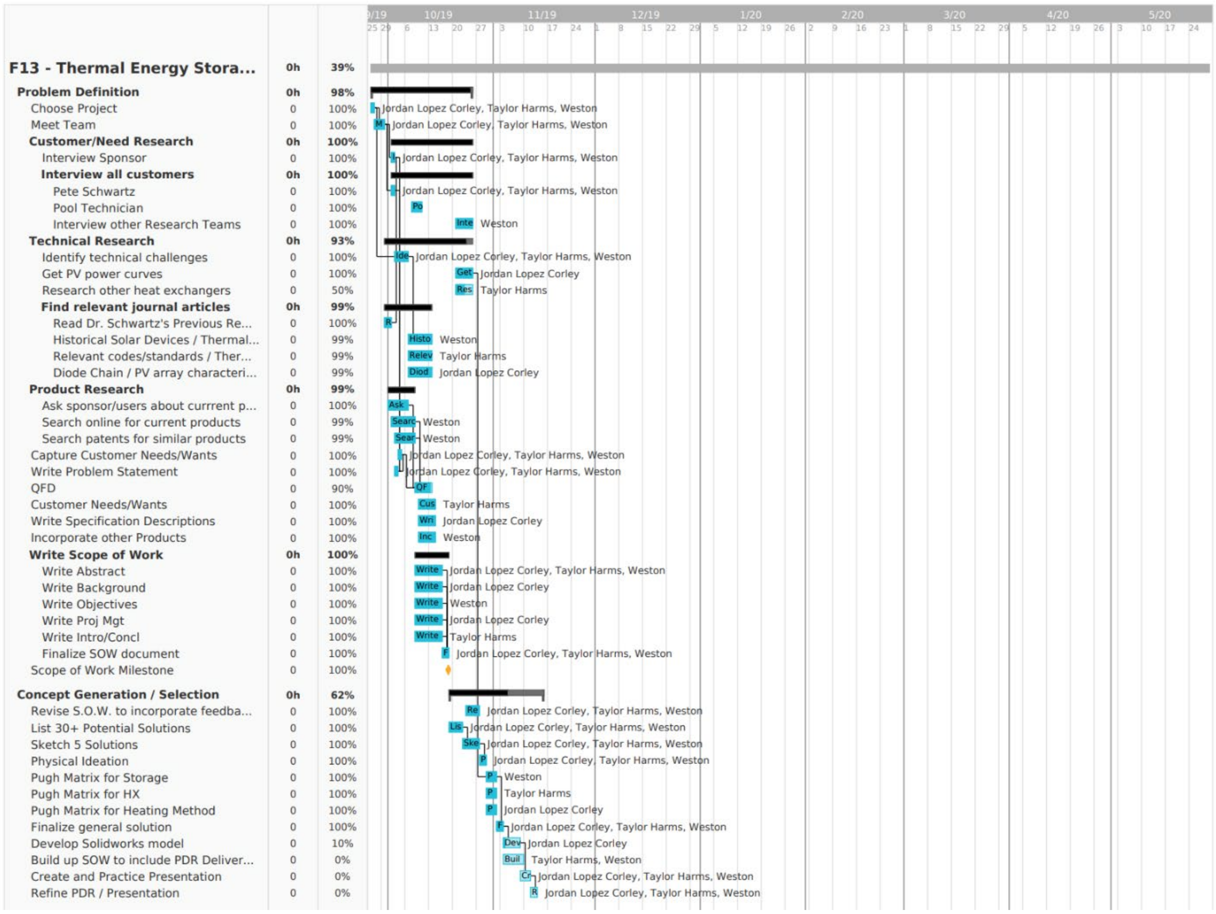


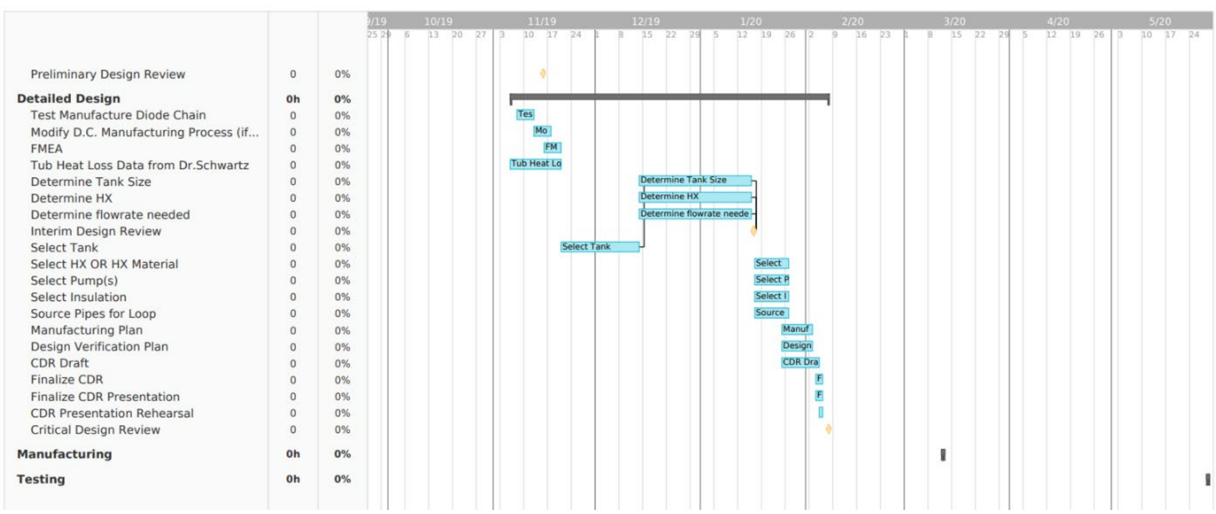
| Row # | WHO: Customers Weight Chart | Relative Weight | Pete | Maintenance | Average Tub User | | Maximum Relationship | WHAT: Customer Requirements (Needs/Wants) |
|---|---|---|---|---|---|---|---|---|
| 1 | IIII | 9% | 9 | 7 | 10 | | 9 | Hot water after sunset |
| 2 | IIII | 8% | 8 | 7 | 8 | | 9 | Temperature Control in range |
| 3 | III | 8% | 8 | 6 | 8 | | 9 | Hours of use |
| 4 | III | 7% | 3 | 9 | 9 | | 9 | Safe Electrical |
| 5 | III | 7% | 3 | 9 | 9 | | 9 | Safe Thermal |
| 6 | III | 7% | 3 | 7 | 9 | | 9 | Safe physical |
| 7 | III | 7% | 7 | 4 | 10 | | 9 | Can be used 1 hour after sunset |
| 8 | IIII | 9% | 8 | 8 | 8 | | 9 | Compact in shed |
| 9 | IIII | 9% | 7 | 10 | 9 | | 9 | Serviceable (cheap parts, easy to s\ |
| 10 | I | 3% | 3 | 1 | 6 | | 9 | Aesthetically pleasing |
| 11 | IIII | 9% | 8 | 7 | 9 | | 9 | Water supply temp modulation |
| 12 | IIII | 8% | 8 | 6 | 9 | | 9 | Even temperature dist. |
| 13 | III | 8% | 10 | 5 | 6 | | 9 | Sustainability |
| 14 | | 0% | | | | | | |
| 15 | | 0% | | | | | | |
| 16 | | 0% | | | | | | |

| Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction of Improvement | ▲ | ▲ | ▼ | ▲ | ▼ | ▲ | ◇ | | | | | | | | | |
| HOW: Engineering Specifications (Tests) | Data Logger verifies stable tem | Thermocouple - Tub | BOM total cost | Thermocouple - HWS | Time to assemble | Visual Inspection of componen | Round sharp edges, padding lo | | | | | | | | | |
| Hot water after sunset | ● | ● | ▽ | ● | ▽ | ▽ | ▽ | | | | | | | | | |
| Temperature Control in range | ● | ● | ▽ | ● | ▽ | ▽ | ▽ | | | | | | | | | |
| Hours of use | ● | ▽ | ▽ | ▽ | ○ | ▽ | ▽ | | | | | | | | | |
| Safe Electrical | ▽ | ▽ | ▽ | ▽ | ▽ | ● | ● | | | | | | | | | |
| Safe Thermal | ○ | ● | ▽ | ● | ▽ | ● | ● | | | | | | | | | |
| Safe physical | ▽ | ● | ▽ | ● | ▽ | ● | ● | | | | | | | | | |
| Can be used 1 hour after sunset | ○ | ○ | ▽ | ○ | ▽ | ● | ▽ | | | | | | | | | |
| Compact in shed | ▽ | ▽ | ▽ | ▽ | ▽ | ● | ▽ | | | | | | | | | |
| Serviceable (cheap parts, easy to s\ | ▽ | ▽ | ● | ▽ | ▽ | ○ | ○ | | | | | | | | | |
| Aesthetically pleasing | ▽ | ▽ | ▽ | ▽ | ○ | ● | ● | | | | | | | | | |
| Water supply temp modulation | ● | ● | ▽ | ● | ▽ | ○ | ▽ | | | | | | | | | |
| Even temperature dist. | ● | ● | ▽ | ● | ▽ | ○ | ▽ | | | | | | | | | |
| Sustainability | ● | ● | ○ | ● | ▽ | ▽ | ▽ | | | | | | | | | |
| HOW MUCH: Target Values | Maintains 38-40C for 3hrs | Reaches 40C | $500 | Reaches 80C | 8 hours | Nothing seen can burn or electrocute | Does not scratch foam test strip | | | | | | | | | |
| Max Relationship | 9 | 9 | 9 | 9 | 3 | 9 | 9 | | | | | | | | | |
| Technical Importance Rating | 528.5 | 562.7 | 190.1 | 562.7 | 122.5 | 478.4 | 317 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Relative Weight | 19% | 20% | 7% | 20% | 4% | 17% | 11% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Curr. Products: Our Current Product | 2 | 3 | 5 | 0 | 4 | 3 | 5 | | | | | | | | | |
| WP Waterproof Immersion Heater | 2 | 4 | 4 | 1 | 5 | 5 | 5 | | | | | | | | | |
| Sunbank SB-80G | 3 | 4 | 3 | 0 | 2 | 5 | 5 | | | | | | | | | |
| Portable spa heater | 5 | 5 | 2 | 1 | 2 | 5 | 5 | | | | | | | | | |
| Photovoltaic DC heater systems | 2 | 4 | 4 | 1 | 4 | 3 | 5 | | | | | | | | | |
| Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |

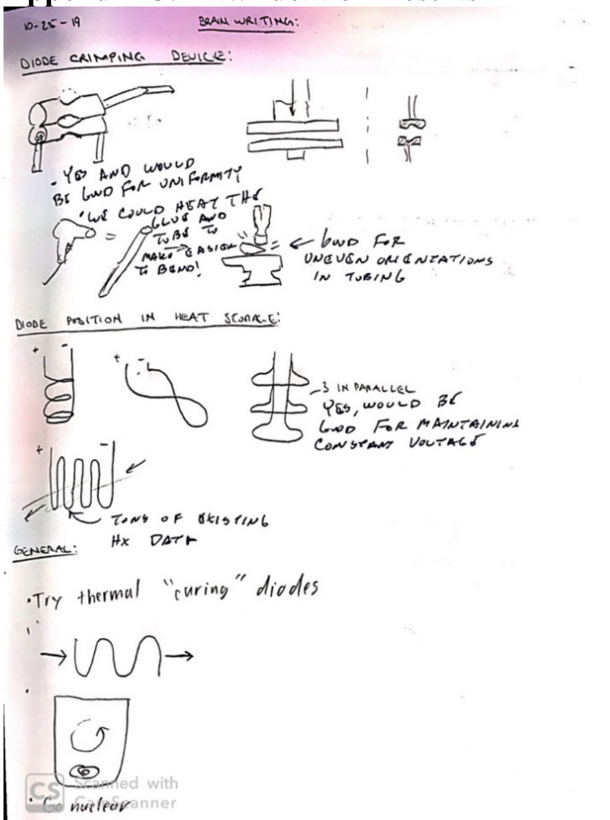
| NOW: Curr. Products | Our Current Product | 560WP Waterproof Immersion | Sunbank SB-80G | Portable spa heater | Photovoltaic DC heater system | Row # |
|---|---|---|---|---|---|---|
| | 2 | 5 | 2 | 5 | 2 | 1 |
| | 0 | 1 | 2 | 5 | 2 | 2 |
| | 1 | 5 | 1 | 5 | 1 | 3 |
| | 2 | 2 | 5 | 5 | 3 | 4 |
| | 2 | 2 | 4 | 4 | 3 | 5 |
| | 4 | 4 | 5 | 5 | 4 | 6 |
| | 4 | 5 | 4 | 5 | 4 | 7 |
| | 5 | 5 | 5 | 5 | 5 | 8 |
| | 3 | 5 | 5 | 4 | 3 | 9 |
| | 0 | 2 | 3 | 3 | 2 | 10 |
| | 0 | 1 | 2 | 5 | 1 | 11 |
| | 0 | 0 | 1 | 4 | 1 | 12 |
| | 4 | 0 | 4 | 0 | 4 | 13 |
| | | | | | | 14 |
| | | | | | | 15 |
| | | | | | | 16 |

## Appendix B: Gantt Chart As Of 11/11/19



## Appendix C: Raw Ideation Results


10-25-19

BRAIN WRITING:

DIODE CRIMPING DEVICE:

- YES AND WOULD BE GOOD FOR UNIFORMITY

WE COULD HEAT THE GLUE AND TUBE TO MAKE EASIER TO BEND!

← GOOD FOR UNEVEN ORIENTATIONS IN TUBING

DIODE POSITION IN HEAT STORAGE:

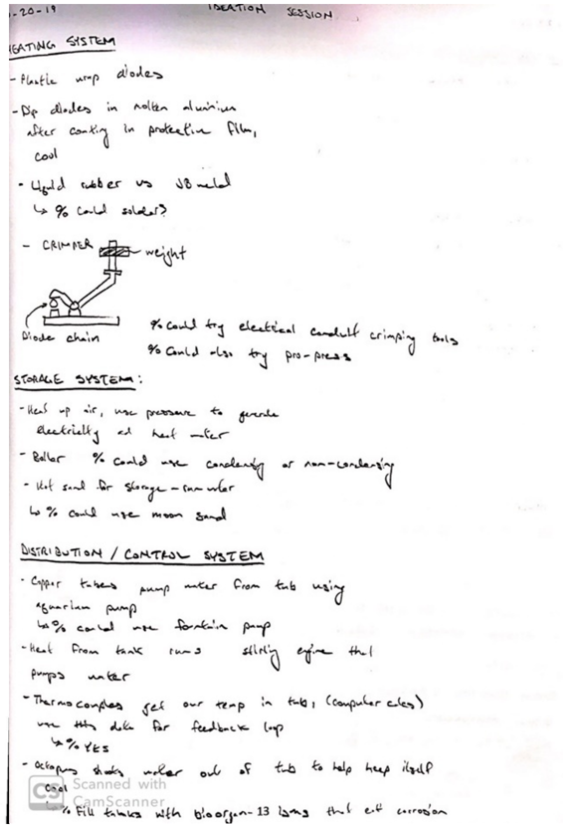
3 IN PARALLEL YES, WOULD BE GOOD FOR MAINTAINING CONSTANT VOLTAGE

TONS OF EXISTING HX DATA

GENERAL:

- Try thermal "curing" diodes
- Go nuclear




-20-19 IDEATION SESSION

HEATING SYSTEM

- Plastic wrap diodes
- Dip diodes in molten aluminum after coating in protective film, cool
- Liquid rubber vs JB weld
  - ↳ % Could solder?
- CRIMPER — weight, Diode chain
  - % Could try electrical conduit crimping tools
  - % Could also try pro-press

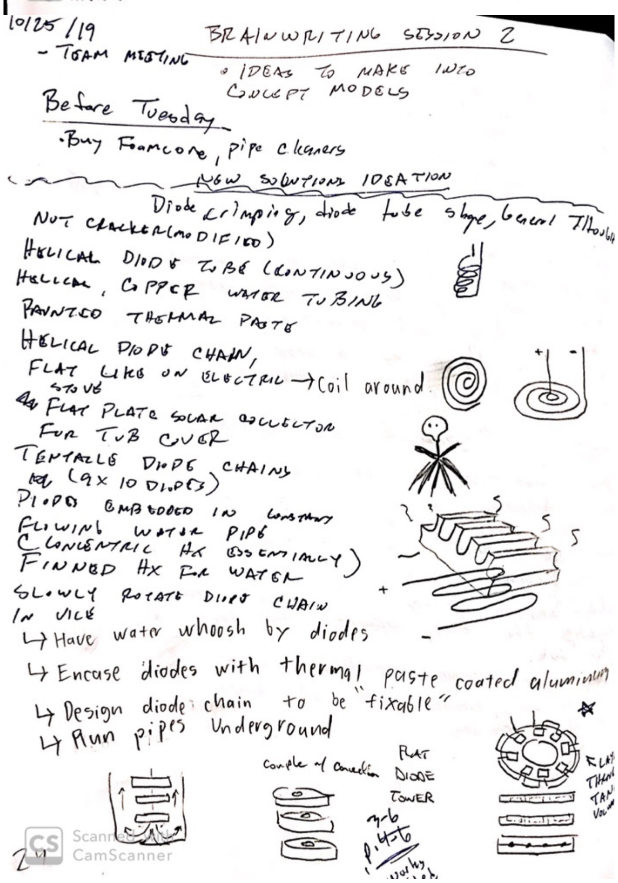
STORAGE SYSTEM:

- Heat up air, use pressure to generate electricity at heat water
- Boiler % could use condensing or non-condensing
- Hot sand for storage – run water
  - ↳ % could use moon sand

DISTRIBUTION / CONTROL SYSTEM

- Copper tubes pump water from tub using aquarium pump
  - ↳ % could use fountain pump
- Heat from tank runs stirling engine that pumps water
- Thermocouples get our temp in tub, (computer codes) use this data for feedback loop
  - ↳ % YES
- Octopus sucks water out of tub to help keep itself cool
  - ↳ % Fill tanks with bioorgan-13 bugs that eat corrosion




10/25/19 BRAINWRITING SESSION 2

- TEAM MEETING
- IDEAS TO MAKE INTO CONCEPT MODELS

Before Tuesday

- Buy Foamcore, pipe cleaners

NEW SOLUTIONS IDEATION

Diode crimping, diode tube shape, general thoughts

NUT CRACKER (MODIFIED)

HELICAL DIODE TUBE (CONTINUOUS)

HELICAL COPPER WATER TUBING

PAINTED THERMAL PASTE

HELICAL DIODE CHAIN, FLAT LIKE ON ELECTRIC STOVE → Coil around

FLAT PLATE SOLAR COLLECTOR FOR TUB COVER

TENTACLE DIODE CHAINS (9 x 10 DIODES)

DIODES EMBEDDED IN CONSTANTLY FLOWING WATER PIPE (CONCENTRIC HX ESSENTIALLY)

FINNED HX FOR WATER

SLOWLY ROTATE DIODE CHAIN IN VICE

↳ Have water whoosh by diodes

↳ Encase diodes with thermal paste coated aluminum

↳ Design diode chain to be "fixable"

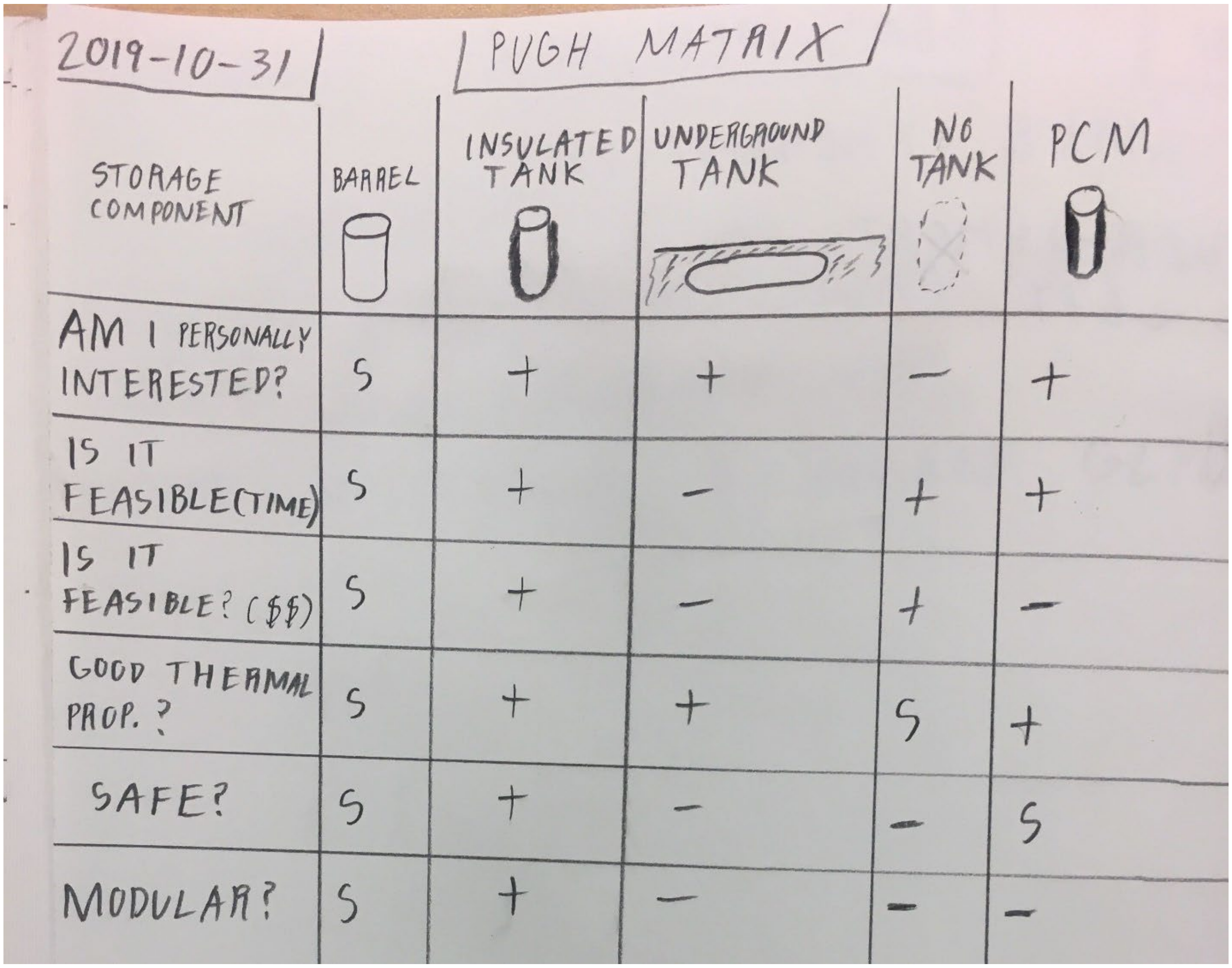
↳ Run pipes Underground

Couple of Convection

FLAT DIODE TOWER

FLAT THERMAL TANK VOLUME

**Appendix D: Pugh Matrices**



2019-10-31

PUGH MATRIX

| STORAGE COMPONENT | BARREL | INSULATED TANK | UNDERGROUND TANK | NO TANK | PCM |
|---|---|---|---|---|---|
| AM I PERSONALLY INTERESTED? | S | + | + | − | + |
| IS IT FEASIBLE(TIME) | S | + | − | + | + |
| IS IT FEASIBLE? ($$) | S | + | − | + | − |
| GOOD THERMAL PROP.? | S | + | + | S | + |
| SAFE? | S | + | − | − | S |
| MODULAR? | S | + | − | − | − |

10/31/19

PUGH MATRIX - WATER HEATING

| STORED WATER HEATING METHOD | Resistive Heater | DIRECT SOLAR RADIATION | PUMP HEATER | NATURAL GAS |
|---|---|---|---|---|
| AM I PERSONALLY INTERESTED? | S | + | + | − |
| FEASIBLE? | S | − | S | + |
| THERMALLY EFFECTIVE? | S | − | + | + |
| SAFE? | S | S | S | − |
| EASY TO FIX? | S | − | S | − |
| CHEAP? | S | − | + | S |
| TOTAL CAPACITY? | S | S | + | + |

10-31-19

PUGH MATRIX

| DISTRIBUTION SYSTEM | PVC | Copper | STAINLESS STEEL | HOSE | POOL NOODLE |
|---|---|---|---|---|---|
| AM I PERSONALLY INTERESTED? | S | − | − | S | + |
| IS IT FEASIBLE (TIME)? | S | S | − | + | + |
| IS IT FEASIBLE (COST)? | S | − | − | + | + |
| SAFE? | S | − | − | − | − |
| DURABILITY/ OXIDIZE RESIST | S | − | S | − | − − |
| THERMAL INSULATION? | S | − | − | − | + |

## Appendix E: Weighted Decision Matrix

| | | Options | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Criteria | Weighting | System A | | System B | | System C | | System D | | System E | | System F | | System G | | System H | |
| | | Score | Total | Score | Total | Score | Total | Score | Total | Score | Total | Score | Total | Score | Total | Score | Total |
| Cost | 4 | 5 | 20 | 4 | 16 | 0 | 0 | 5 | 20 | 4 | 16 | 2 | 8 | 2 | 8 | 4 | 16 |
| Time | 4 | 4 | 16 | 5 | 20 | 0 | 0 | 5 | 20 | 4 | 16 | 2 | 8 | 2 | 8 | 4 | 16 |
| Safe Electrical | 5 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 4 | 20 |
| Safe Thermal | 5 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 4 | 20 | 5 | 25 | 4 | 20 |
| Safe Physical | 5 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 3 | 15 |
| Reliability | 4 | 5 | 20 | 4 | 16 | 5 | 20 | 3 | 12 | 4 | 16 | 3 | 12 | 4 | 16 | 4 | 16 |
| Hot Water After Sunset | 5 | 5 | 25 | 4 | 20 | 5 | 25 | 4 | 20 | 4 | 20 | 3 | 15 | 3 | 15 | 4 | 20 |
| Temp Control in Range | 4 | 5 | 20 | 5 | 20 | 5 | 20 | 5 | 20 | 5 | 20 | 4 | 16 | 3 | 12 | 3 | 12 |
| Serviceable | 4 | 5 | 20 | 4 | 16 | 0 | 0 | 5 | 20 | 5 | 20 | 2 | 8 | 4 | 16 | 4 | 16 |
| Aesthetically Pleasing | 2 | 3 | 6 | 4 | 8 | 5 | 10 | 3 | 6 | 3 | 6 | 5 | 10 | 3 | 6 | 2 | 4 |
| Even temp. disp. | 3 | 3 | 9 | 4 | 12 | 5 | 15 | 4 | 12 | 3 | 9 | 3 | 9 | 3 | 9 | 4 | 12 |
| Sustainability | 5 | 0 | 0 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 5 | 25 | 4 | 20 | 4 | 20 |
| Water Sup. Temp Modulation | 3 | 2 | 6 | 4 | 12 | 5 | 15 | 4 | 12 | 3 | 9 | 4 | 12 | 4 | 12 | 3 | 9 |
| | | | | | | | | | | | | | | | | | |
| | **TOTAL:** | | **217** | | **240** | | **205** | | **242** | | **232** | | **193** | | **197** | | **196** |

| System | Storage | Heating | Distribution |
|---|---|---|---|
| A | Drum Barrel | Natural Gas | PVC piping |
| B | Insulated Tank | DC Diode IH | Insulated Piping |
| C | Underground Tank | DC Diode IH | SS Piping |
| D | Insulated Tank | DC Diode IH | Hose |
| E | Drum Barrel | DC Diode IH | PVC piping |
| F | Underground Tank | Solar Radiation | Copper Pipe |
| G | Insulated Tank | Natural Gas | SS Piping |
| H | Drum Barrel | Solar Radiation | Insulated Piping |

## Appendix F: Preliminary Calculations

TOTAL ENERGY AVAILABLE & TANK SIZE

FROM PETE'S PREVIOUS RESEARCH...

BY 6:00 PM, TOTAL ENERGY GAINED WAS 0.6387 kWh, FOR A SINGLE 100-W PANEL

OUR SET UP INVOLVES 4, 425 WATT PANELS

$$E_{TOT} = 4 \text{ PANELS} \times 425\ W \times \frac{0.6387\ kWh}{100\ \text{WATT} \cdot \text{PANEL}}$$

$$\boxed{E_{TOT} = 10.86\ kWh}$$

MAXIMUM TANK SIZE...

LET $T_i = 20°C$, $T_f = 100°C$

$E = m C_p \Delta T$ $\quad \rho = \rho(T = 20°C) = 998.21\ kg/m^3$ ← SEALED SYSTE.

$E = \rho \forall C_p \Delta T$ $\quad C_p = C_p(T = 20°C) = 4.1955\ kJ/kg \cdot K$

$$\forall = E / \rho C_p \Delta T$$

$$= \frac{10.86\ kW \cdot h}{(998.21\ \frac{kg}{m^3})(4.1955\ \frac{kJ}{kg \cdot K})(100 - 20\ K)} \times \frac{1\ kJ/s}{1\ kW} \frac{3600\ s}{h}$$

$$\forall = 0.117\ m^3 \times \frac{264.172\ gal}{1\ m^3}$$

$$\boxed{\forall_{TANK} = 30.91\ gal}$$

## MINIMUM HX COIL LENGTH

TUB VOLUME = $0.8294\ m^3$

PERFORMANCE GOALS: 1 TUB CHANGE, 30 MINUTES

$T_{i,c} = 30°C \quad T_{o,c} = 40°C,\ V = 5\ ft/s$

$$Q = \frac{0.8294\ m^3}{30\ \text{minutes}} \times \frac{1\ \text{min}}{60\ s} = \underline{4.60778 \times 10^{-4}\ m^3/s}$$

$= 7.3\ gal/min$

FOR COPPER TUBING, $V_{rec} = 5\ ft/s$

SELECT 3/4" TYPE L, 0.785" ID, $t = .045"$

$$V = 7.3\ gal/min \times \frac{1}{\frac{\pi}{4}(.785\ in)^2} \times \frac{1\ ft^3}{7.481\ gal} \times \frac{144\ in^2}{1\ ft^2} \times \frac{1\ min}{60\ s}$$

$V = 4.84\ ft/s = 1.47523\ m/s$

ID $0.785" = 0.019939\ m$

OD $0.785" + 2(.045") = .022225\ m$

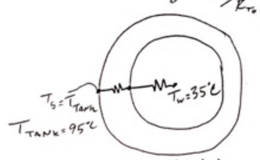

ASSUME LINEAR HEAT EXCHANGE INTO TUB

$$\dot{q} = \rho_{TANK} V_{TANK} C_{P_{TANK}} \Delta T_{TANK} / t$$

$$\dot{q} = \frac{(994.03\ kg/m^3)(0.8294\ m^3)(4.18\ kJ/kg \cdot K)(40-30°C)}{30\ \text{mins} \times 60\ s}$$

$\dot{q} = 19.1455\ kW$

$$q = \Delta T / R_{TOT}$$




$$R_{TOT} = \frac{\ln(r_o/r_i)}{2\pi L K_{cu}} + \frac{1}{h_i A_i}$$

NUSSELT NUMBER CORRELATIONS

$$Re_D = \frac{\rho V D}{\mu}$$

$$= \frac{(994.03\ kg/m^3)(1.47523\ m/s)(.019939\ m)}{0.6\times10^{-3}\ N/m^2 \cdot s}$$

$$Re_D: 48732$$

$$Nu_D = 0.023\,Re_D^{4/5}\,Pr^n \quad n = 0.4\ (\text{Heating})$$

$$= 0.023(48732)^{4/5}(4.495)^{0.4}$$

$$= 236.1$$

$$Nu_D = hD/k$$

$$h_i = \frac{Nu_D\,k_{water}}{D_i}$$

$$= \frac{(236.1)(0.635\ W/m\cdot k)}{(.019939\ m)}$$

$$h_i = 7519.1\ W/m^2\cdot k$$

$$R_{TOT} = \frac{\ln\left(\frac{.022225}{.019939}\right)}{2\pi L(399\ W/m\cdot k)} + \frac{1}{(7519.1\ \frac{W}{m^2 k})(\pi\cdot .019939\ m\cdot L)}$$

$$R_{TOT} = \frac{1}{L}\cdot 2.1664\times10^{-3}\ \frac{m}{W\cdot k}$$

$$q = \Delta T/R_{TOT}$$

$$R_{TOT} = \Delta T/q$$

$$= 2.1664\times10^{-3}/L = \Delta T/q$$

$$L = \frac{2.1664\ m\cdot k}{\Delta T\ W}\cdot q$$

$$L = \frac{(2.1664\times10^{-3})\frac{m\cdot k}{W}\cdot 19.1455\times10^{3}\ W}{(95-35)\,k}$$

$$L = 0.6913\ m$$

$$\boxed{L_{MIN} = 2.27\ ft}$$

VERY SMALL, POOR ASSUMPTIONS
MAXIMIZE SURFACE AREA!

## Appendix G: Design Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: Ra Energy________________________________ Advisor: Dr. Schwartz______ Date: 2019/11/07___

| Y | N | |
|---|---|---|
| ☐ | × | 1. Will the system include hazardous revolving, running, rolling, or mixing actions? |
| ☐ | × | 2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions? |
| ☐ | × | 3. Will any part of the design undergo high accelerations/decelerations? |
| ☐ | × | 4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces? |
| ☐ | × | 5. Could the system produce a projectile? |
| ☐ | × | 6. Could the system fall (due to gravity), creating injury? |
| ☐ | × | 7. Will a user be exposed to overhanging weights as part of the design? |
| ☐ | × | 8. Will the system have any burrs, sharp edges, shear points, or pinch points? |
| ☐ | × | 9. Will any part of the electrical systems not be grounded? |
| ☐ | × | 10. Will there be any large batteries (over 30 V)? |
| ☐ | × | 11. Will there be any exposed electrical connections in the system (over 40 V)? |
| × | ☐ | 12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases? |
| ☐ | × | 13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system? |
| ☐ | × | 14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design? |
| ☐ | × | 15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing? |
| ☐ | × | 16. Could the system generate high levels (>90 dBA) of noise? |
| × | ☐ | 17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use? |
| × | ☐ | 18. Is it possible for the system to be used in an unsafe manner? |
| ☐ | × | 19. For powered systems, is there an emergency stop button? |
| × | ☐ | 20. Will there be any other potential hazards not listed above? If yes, please explain on reverse. |

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

| Description of Hazard | Planned Corrective Action | Planned Date | Actual Date |
|---|---|---|---|
| 12. There will be stored thermal energy which could burn someone | Fully insulating the tank | March 10, 2019 | |
| 17. The system will be placed outdoors in San Luis Obispo where there is fog, humidity, and cold/high temperatures | We will select non-corrosive materials to avoid the tank corroding and leaking boiling water. | March 10, 2019 | |
| 18. Someone could remove the lid of the tank and touch the water. | We will make sure all the potential users are properly educated. If the sponsor requests a padlock, we will use one. | March 10, 2019 | |
| 20. When the water in the tank is at 100°C, and the water in the heat exchanger is not moving for a long period of time, the water in the heat exchanger will eventually reach 100°C. | We will utilize some sort of bypass valve or diffuser to make sure the 100°C water never contacts the user. | March 10, 2019 | |

## Appendix H: Design Verification Plan and Report

| Senior Project DVP&R | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date: 2/16/2020 | | Team: Ra Energy | Sponsor: Dr. Pete Schwartz | | | | Description of System: Hot Tub Thermal Energy Storage | | | | | DVP&R Engineer: | | |
| TEST PLAN | | | | | | | | | | TEST REPORT | | | | |
| Item No | Specification # | Test Description | Acceptance Criteria | Test Responsibility | Test Stage | SAMPLES Quantity | SAMPLES Type | TIMING Start date | TIMING Finish date | TEST RESULTS Test Result | TEST RESULTS Quantity Pass | TEST RESULTS Quantity Fail | NOTES | |
| 1 | 0001 | Maximum Hot Tub Usage | Maintains 38-40C Water for 3 Hours | Weston | FP | 1 | Sys | | | | | | | |
| 2 | 0002 | Maximum Hot Tub Temperature | Tub reaches 40C | Jordan | FP | 1 | Sys | | | | | | | |
| 3 | 0003 | Tub HWS | Reaches, but does not exceed 46C | Jordan | FP | 1 | Sys | | | | | | | |
| 4 | 0004 | Maximum Tank Temperature | Tank reaches 95C after 9 hour sunlight | Taylor | FP | 1 | Sys | | | | | | | |

## Appendix I: Tank Charge Feasibility Calculation

AVAILABLE ELECTRICAL ENERGY

FROM NUMERICALLY INTEGRATING SOLAR PANEL DATA

- SCALED x4 FOR 4 PANELS
- SCALE 4.25 SINCE TESTING USED 100 W PANELS, PETE HAS 425 W.

$E = 10.75 \text{ kWh} \times 3600$

CHARGE TIME OF 40 Gal TANK FROM 40 TO 90°C

CAPACITY REQU'D

$E = (40 \text{gal})(.003785 \frac{m^3}{gal})(1000 \frac{kg}{m^3})(4.184 \frac{kJ}{kg \cdot k})(50k)$

$= 31672.88 \text{ kJ} \times \frac{1 \text{ kwh}}{3600 \text{ kJ}}$

$E = 8.8 \text{ kWh}$ REQUIRED

TANK CAN CHARGE WITHIN 1 CYCLE

FROM 20 TO 90°C (VERY START)

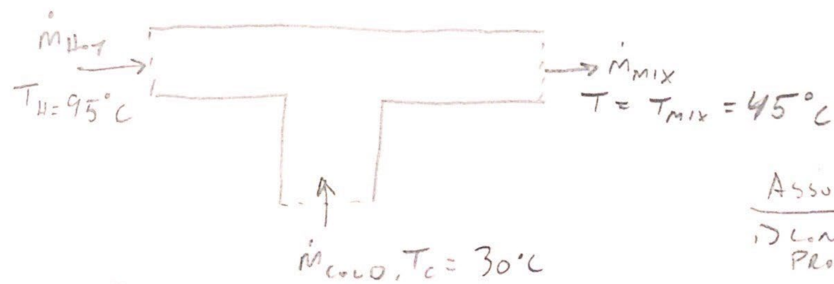
$E = 12.32 \text{ kwh}$

FULLY OPERATIONAL AFTER 1.5 DAYS.

**Appendix J: Valve Mixing Proportion Calculation**

VALVE MIXING PROPORTIONS

MOST EXTREME
TEMP DIFFERENCE : TANK = 95°C
TUB = 30°C




ASSUMPTIONS
1) CONSTANT PROPERTIES

$$E_{in} = E_{OUT}$$

$$(\dot{m} c_p T)_{COLD} + (\dot{m} c_p T)_{HOT} = (\dot{m} c_p T)_{MIX}$$

$$(Q \rho T)_{COLD} + (Q \rho T)_{HOT} = (Q \rho T)_{MIX}$$

$$Q_{COLD} T_C + Q_H T_H = (Q_C + Q_H) T_{MIX}$$

$$Q_C (T_C - T_{MIX}) + Q_H (T_H - T_{MIX}) = \emptyset$$

$$\frac{Q_H}{Q_C} = \frac{T_{MIX} - T_C}{T_H - T_{MIX}}$$

IF $T_H = 90°C$

$Q_H / Q_C = 0.\overline{33}$ $(1/3)$

$$\boxed{\frac{Q_H}{Q_C} = \frac{45 - 30}{95 - 45} = 0.3}$$

## Appendix K: Failure Modes and Effects Analysis

### Design Failure Mode and Effects Analysis

Product: ____________________________ Prepared by: ____________________________

Team: ____________________________ Date: ________________(orig)

| System / Function | Potential Failure Mode | Potential Effects of the Failure Mode | Severity | Potential Causes of the Failure Mode | Current Preventative Activities | Occurence | Current Detection Activities | Detection | Priority |
|---|---|---|---|---|---|---|---|---|---|
| Immersion Heater / Heats Water | 1. Corrosion<br>2. Thermal failure<br>3. Electrical failure<br>4. Mechanical failure | 1,2,3,4. Lukewarm or cold tub<br>2. Scorching hot tub | 9 | 1,4. Broken Diode<br>3. Bad soldering/braiding<br>3. PV supply disconnect<br>2,3. Too much JB Weld | 1,4. Stress testing<br>3. Soldering/braiding inspection<br>2,3. Practice manufacturing | 5 | Voltmeter across leads<br>Tank temp data log | 3 | 135 |
| Water Storage Tank / Stores Water | 1. Leakage<br>2. Eruption<br>3. Tipping<br>4. Large Heat Loss | 1. Tank supply too cold<br>2. Matl leaches chemicals into water<br>1,2. Loss of circuit water | 6 | 1. Bad pipe connections<br>2. Overheating water<br>3. Too top heavy<br>4. Poor insulation | 1. Proper o-ring integration<br>2. Proper material selection<br>3. Platform<br>4. Insulation | 6 | Visual Inspection<br>Temp data log for tank | 3 | 108 |
| Distribution / Water and Energy Distribution | 1. Large pipe heat loss<br>2. Pipes leak<br>3. Pump cant handle head<br>4. Pump uncontrolled<br>5. No dT<br>6. Valve Failure | 4 Fluid velocity too fast<br>2,3,4 Pump stops working<br>1,2,5, 6 Return temp too low<br>6 Return temp to high | 9 | 2,6. Bad pipe gluing<br>6. Valve rupture | 1,2 Pipe insulation<br>3,4 Single function pump<br>5. Select pump for good flow rate 6. Select good mix valve | 4 | Visual Inspection<br>Temp data log for tank<br>Auditory inspection<br>Monitor inlet/outlet Temps<br>Monitor pipe velocities | 5 | 180 |
| Control System | 1. Temperature Unregulated | 1. Tub too hot/cold, tank too hot, boiling | 9 | 1. Coding error 2. Thermocouple failure<br>3. Pump loss of power | 1. Thorough testing | 3 | Monitor system during startup and comissioning | 4 | 108 |

Page 1 of 1 Revision Date:

**Appendix L: Diode Chain Testing Data**

Before our team made the decision to change to a commercially available resistive heater, there was a series of thermal tests ready to be conducted to determine the most effective method of thermally connecting the diodes to the tubing. We wanted to compare the widely accepted method of JB weld to ensure electrical insulation, to a thermal paste applied to diode surface, no additive, and no additives, but with the aluminum tubing uncrimped. Previous experimentation has proved the effectiveness of crimping the diode chain, we wanted to verify that result.

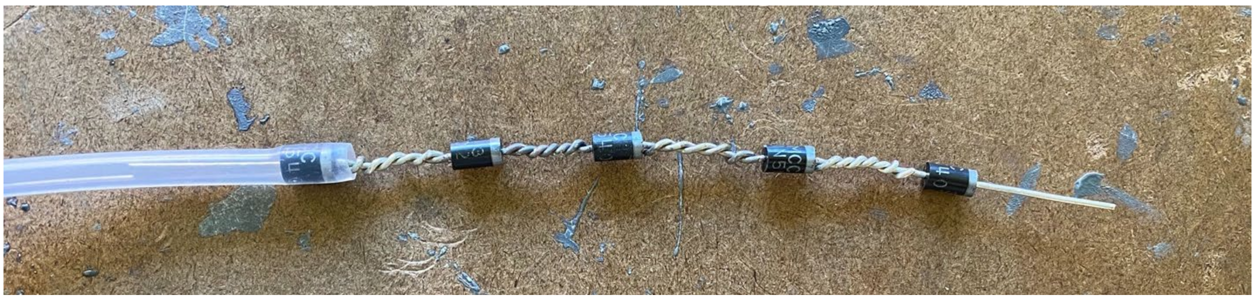


Figure L.1 Bare Diode Chain

The bare diode chain is shown before application of any JB weld or thermal paste. This would be inserted into the aluminum tubing, shaped, and crimped as shown in figure L.2.


Figure L.2 Diode Immersion Heater Test Setup

To ensure proper heat sinking during testing, each test immersion heater would be placed in water. Thermocouples would then be placed on the outer surface of a diode in the center of the heater, and another firmly secured to the outer surface of the tubing. As current is applied, the two temperatures are measured, and subtracted to see the temperature differential across the tube. A more efficient thermal connection will be resembled as a smaller differential. This protects the diodes from overheating and improves the efficiency of the heater.

For the testing to be conducted, we wanted to attach the test chains to the same power source, shown connected in Figure L.2. Due to the nature of diodes, they would all exhibit the same voltage drop across the chain, and the power output will adjust to the applied current. The solar panels to be used have a maximum nominal current of 6 amps, so we wanted to see the performance of each heat sinking method at a range of currents, up to their maximum operating state.

Table L.1 Thermal Performance Test Data Sheet

| **Nominal Current** | **Bare Diodes** | **Bare Diodes (Uncrimped)** | **JB Weld** | **Thermal Paste** |
|---|---|---|---|---|
| **1.50 A** | $\Delta T =$ ºC | $\Delta T =$ ºC | $\Delta T =$ ºC | $\Delta T =$ ºC |
| **2.50 A** | $\Delta T =$ ºC | $\Delta T =$ ºC | $\Delta T =$ ºC | $\Delta T =$ ºC |
| **3.50 A** | $\Delta T =$ ºC | $\Delta T =$ ºC | $\Delta T =$ ºC | $\Delta T =$ ºC |
| **6.00 A** | $\Delta T =$ ºC | $\Delta T =$ ºC | $\Delta T =$ ºC | $\Delta T =$ ºC |
| **Average** | $\Delta T =$ ºC | $\Delta T =$ ºC | $\Delta T =$ ºC | $\Delta T =$ ºC |

## Appendix M: Indented Bill of Materials

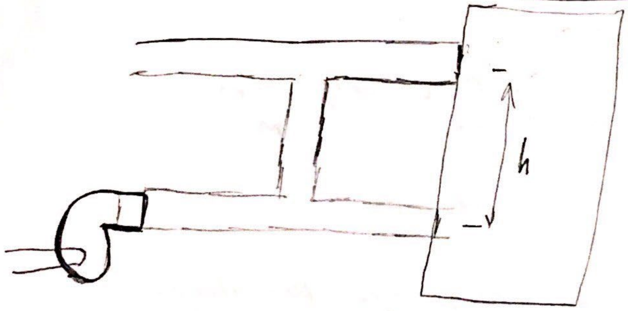
**Indented Bill of Materials (iBOM)**
**Thermal Energy Storage for Load Shifting**

| Assembly Level | Part Number | Description: Level 0 | Level 1 | Level 2 | Level 3 | Vendor | Quantity | Cost | Total Cost | Purchased? |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.00.00.00 | Final Assembly | | | | | | | | |
| 1 | 1.01.00.00 | | Heating System | | | | | | | |
| 2 | 1.01.01.00 | | | 2000W Immersion Heater | | Amazon | 2 | $7.85 | $15.70 | Y |
| 1 | 1.02.00.00 | | Storage System | | | | | | | |
| 2 | 1.02.01.00 | | | 50-GAL Water Heater | | Home Depot | 1 | $408.37 | $408.37 | N |
| 2 | 1.02.02.00 | | | Water Heater Sleeve | | Home Depot | 1 | $32.13 | $32.13 | N |
| 2 | 1.02.03.00 | | | Retaining Straps | | Home Depot | 1 | $20.37 | $20.37 | N |
| 1 | 1.03.00.00 | | Distribution System | | | | | | | |
| 2 | 1.03.01.00 | | | 5ft, 3/4" Pipe, Copper Type L | | Home Depot | 1 | $11.00 | $11.00 | N |
| 3 | 1.03.01.01 | | | | Cu_L_i | | 1 | | | N/A |
| 3 | 1.03.01.02 | | | | Cu_L_1 | | 1 | | | N/A |
| 3 | 1.03.01.03 | | | | Cu_L_2 | | 1 | | | N/A |
| 3 | 1.03.01.04 | | | | Cu_L_3 | | 2 | | | N/A |
| 3 | 1.03.01.05 | | | | Cu_L_Sensor | | 1 | | | N/A |
| 2 | 1.03.02.00 | | | 25ft, 3/4" Pipe, PEX | | | 1 | $20.84 | $20.84 | Y |
| 3 | 1.03.02.01 | | | | PEX_-2 | | 1 | | | N/A |
| 3 | 1.03.02.02 | | | | PEX_-1 | | 1 | | | N/A |
| 3 | 1.03.02.03 | | | | PEX_0 | | 1 | | | N/A |
| 3 | 1.03.02.04 | | | | PEX_1 | | 1 | | | N/A |
| 3 | 1.03.02.05 | | | | PEX_2 | | 1 | | | N/A |
| 3 | 1.03.02.06 | | | | PEX_3 | | 1 | | | N/A |
| 3 | 1.03.02.07 | | | | PEX_4 | | 1 | | | N/A |
| 3 | 1.03.02.08 | | | | PEX_Bypass | | 2 | | | N/A |
| 3 | 1.03.02.09 | | | | PEX_5 | | 1 | | | N/A |
| 3 | 1.03.02.10 | | | | PEX_6 | | 1 | | | N/A |
| 2 | 1.03.03.00 | | | 6ft, Pipe Insulation | | Home Depot | 5 | $1.77 | $8.85 | N |
| 2 | 1.03.04.00 | | | 3/4 PEX 90 Elbows | | Home Depot | 3 | $5.29 | $15.87 | N |
| 2 | 1.03.05.00 | | | 3/4 Garden to 3/4 PEX | | Dripworks | 3 | $2.85 | $8.55 | N |
| 2 | 1.03.06.00 | | | 3/4 PEX Check Valve | | Home Depot | 1 | $17.97 | $17.97 | N |
| 2 | 1.03.07.00 | | | 3/4 PEX to 3/4 NPT, F | | Home Depot | 1 | $5.61 | $5.61 | N |
| 2 | 1.03.08.00 | | | 3/4 PEX Tee Connection | | Supply House | 1 | $2.13 | $2.13 | N |
| 2 | 1.03.09.00 | | | 3/4 PEX Ball Valve | | Home Depot | 1 | $10.81 | $10.81 | N |
| 2 | 1.03.10.00 | | | 3/4 PEX and 3/4 Cu, F Tee Connection | | Home Depot | 2 | $3.47 | $6.94 | N |
| 2 | 1.03.11.00 | | | 3/4 NPT, M to 3/4 Cu, F | | Home Depot | 1 | $2.33 | $2.33 | N |
| 2 | 1.03.12.00 | | | 3/4 Cu 90 Elbows | | Home Depot | 2 | $1.47 | $2.94 | N |
| 2 | 1.03.13.00 | | | 3/4 Cu Globe Valve, solderable ports | | Home Depot | 1 | $9.50 | $9.50 | N |
| 2 | 1.03.14.00 | | | 3/4 Cu,F to 3/4 NPT, F | | Home Depot | 1 | $4.26 | $4.26 | N |
| 2 | 1.03.15.00 | | | 3/4 Cu, M to 3/4 NPT,F | | Home Depot | 1 | $4.26 | $4.26 | N |
| 2 | 1.03.16.00 | | | 3/4 Cu Tee Connection | | Home Depot | 1 | $3.32 | $3.32 | N |
| 2 | 1.03.17.00 | | | 0.10 hp Wayne PC2 Pump | | Home Depot | 1 | $85.00 | $85.00 | N |
| 2 | 1.03.18.00 | | | 3/4 NPT, M to 4mm Cord Grip | | McMaster Carr | 1 | $9.80 | $9.80 | N |
| 2 | 1.03.19.00 | | | ProPEX Rings | | Home Depot | 17 | 0.54 | $9.18 | N |
| 1 | 1.04.00.00 | | Control System | | | | | | | |
| 2 | 1.04.01.00 | | | Enclosure | | Polycase | 1 | $40.35 | $40.35 | Y |
| 2 | 1.04.02.00 | | | 0.170-0.450" Cable Glands | | Polycase | 2 | $2.64 | $5.28 | Y |
| 2 | 1.04.03.00 | | | 0.115-0.250" Cable Glands | | Polycase | 4 | $1.95 | $7.80 | Y |
| 2 | 1.04.04.00 | | | Mouting Screws | | Polycase | 1 | $3.82 | $3.82 | Y |
| 2 | 1.04.05.00 | | | Mixed Cable Glands | | Amazon | 1 | $14.99 | $14.99 | Y |
| 2 | 1.04.06.00 | | | Arduino | | Amazon | 1 | $18.00 | $18.00 | Y |
| 2 | 1.04.07.00 | | | Arduino Charger | | Amazon | 1 | $6.49 | $6.49 | Y |
| 2 | 1.04.08.00 | | | Data Shield | | Amazon | 1 | $16.08 | $16.08 | Y |
| 2 | 1.04.09.00 | | | Solderable Breadboard | | Amazon | 1 | $20.89 | $20.89 | Y |
| 2 | 1.04.10.00 | | | IoT Relay | | Amazon | 1 | $19.95 | $19.95 | Y |
| 2 | 1.04.11.00 | | | Heating Element Mosfet | | Mouser | 4 | $1.88 | $7.52 | Y |
| 2 | 1.04.12.00 | | | DS18B20 (5pack) | | Amazon | 1 | $15.31 | $15.31 | Y |
| 1 | 1.05.00.00 | | Structure | | | | | | | |
| 2 | 1.05.01.00 | | | 24"x36"x0.177" Acrylic Sheet | | Home Depot | 1 | $40.70 | $40.70 | N |
| 2 | 1.05.02.00 | | | 0.5"x3.75" Concrete Anchors (10 pack) | | Home Depot | 1 | $24.45 | $24.45 | N |
| 2 | 1.05.03.00 | | | Unistrut P1000T (5') Metal Framing | | Gordon Electric | 5 | $52.80 | $264.00 | N |
| 3 | 1.05.03.01 | | | | Upright Posts | | 2 | | | N/A |
| 3 | 1.05.03.02 | | | | Crossbeam | | 3 | | | N/A |
| 3 | 1.05.03.03 | | | | Leg Horizontal | | 2 | | | N/A |
| 3 | 1.05.03.04 | | | | Leg Vertical | | 2 | | | N/A |
| 2 | 1.05.04.00 | | | Unistrut P1924 Flat Plate Connector | | Gordon Electric | 6 | $3.78 | $22.68 | N |
| 2 | 1.05.05.00 | | | Unistrut P1325 L Bracket Connector | | Amazon | 2 | $6.97 | $13.94 | N |
| 2 | 1.05.06.00 | | | Unistrut P2942 Post Base | | Unistrut Ohio | 2 | $14.91 | $29.82 | N |
| 2 | 1.05.07.00 | | | Unistrut P1006-1420 | | Unistrut Ohio | 31 | $0.74 | $22.94 | N |
| 2 | 1.05.08.00 | | | Routing Clamps 1.25" Diameter (10pc) | | Amazon | 1 | $10.95 | $10.95 | N |
| 2 | 1.05.09.00 | | | Routing Clamps 2" Diameter (5pc) | | Amazon | 1 | $7.50 | $7.50 | N |
| 2 | 1.05.10.00 | | | 1/4-20x0.75 Bolts (100pc) | | Miner's Ace | 1 | $24.99 | $24.99 | N |
| 2 | 1.05.11.00 | | | 1/4-20 Nuts (100pc) | | Miner's Ace | 1 | $3.69 | $3.69 | N |
| 2 | 1.05.12.00 | | | Fast-Setting Concrete | | Miner's Ace | 3 | $9.21 | $27.64 | N |
| 2 | 1.05.13.00 | | | Unistrut P2343L Fitting | | Unistrut Ohio | 1 | 11.89 | $11.89 | N |
| 2 | 1.05.14.00 | | | One-Sided Routing Clamps (1.25") | | Unistrut Ohio | 1 | 2.99 | $2.99 | N |
| Total: | 68 parts | | | | | | | Grand Total: | $1,400.39 | |

**Appendix N: Tank Size Calculation**

- Contact junk yard

TANK SIZE CALC




$$\frac{219.13 \text{ gal}}{30 \text{ minutes}} = 7.3 \text{ gpm}$$

For 5 gpm, t= 44 minutes

$\Delta E = m c_p \Delta T \qquad \Delta T = 10°C$

$$= (219.13 \text{ gal})\left(\frac{.003785 \text{ m}^3}{1 \text{ gal}}\right)\left(4.184 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)\left(1{,}000 \frac{\text{kg}}{\text{m}^3}\right)(10 \text{ K})$$

$$\boxed{\Delta E = 34702.4 \text{ kJ}}$$

$\Delta E = \rho V c_p \Delta T \qquad \Delta T = 95 - 40 = 55$

$$V = \frac{\cancel{34702.4 \text{ kJ}}\,(10 \text{ K})(219.13 \text{ gal})}{55 \text{ K}}$$

$$\boxed{V_{TANK} = 39.8 \text{ gal}}$$

$40(95 - T_{TANK}) = 220(40-30)$

$\cancel{T_{TANK} = 40(95)}$

$95 - T_{TANK} = \frac{220}{40}(10)$

$95 - \frac{220}{40}(10) = T_{TANK}$

$T_{TANK} = 40$

$V_{TANK}(95) + V_{TUB}(30) = 40(V_{TANK} + V_{TUB})$

$55\, V_{TANK} = 10\, V_{TUB}$

$V_{TANK} = \frac{10}{55} V_{TUB}$

$V_{TANK} = \frac{\Delta T_{TANK}}{\Delta T_{TUB}} V_{TUB}$



*The tank volume was calculated to be 39.8 gallons. It is covered by the CamScanner watermark.

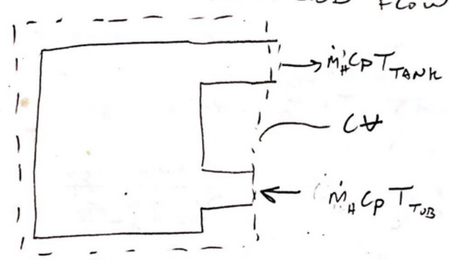
# Appendix O: Safety Considerations

| Hazard Type | Specific Hazard | Risk | Severity | Poses Risk To | Method of Prevention | Risk after Prevention |
|---|---|---|---|---|---|---|
| Thermal | Scalding water from outlet | High | High | User | Control system to prevent outlet temperature above 46C, valves to adjust mixture of hot/cold water, warning lables to not occupy tub while warming up. | Very low |
| | Boiling water in tank | Medium | High | User, passerby | Tank is a refurbished water heater with Temperature Pressure Relief valve. Expansion of water can be accomodated by the tub. | Very low |
| | Tank becomes pressurized | Low | Very high | User, passerby, technician / maintainence | Tank is a refurbished water heater with Temperature Pressure Relief valve | Very low |
| | Burns from hot piping | Medium | High | User, passerby, technician / maintainence | Thermal insulation will be applied to all exposed pipes. | Very low |
| | Pipe leaking hot water | Low | Medium | Passerby | All pipes will be attached to standard plumbing specifications. | Very low |
| | Pipe bursting | Very low | Very high | User, passerby, technician / maintainence | All piping material will be rated for expected operating temperatures, flowrate, and pressure. | Very low |
| Electrical | Electricution from solar panel leads | High | Very high | User, technician / maintainence | A certified electrician will wire solar panels into desired configuration and install the leads for the heater. High voltage warning labels will be placed near the leads. | Very low |
| | Shock from user interface | Low | High | User, technician / maintainence | The user interface will be electrically insulated. Warning labels will be placed to warn against operating while wet. | Very low |
| | Replacing resistive heater | High | Very high | Technician, maintenence | Warnings will be placed to disconnect the heater from the solar power source at night. | Low |
| | Shock from custom wiring of mosfat for resistive heater | High | Very high | Technician, maintenence | Our high-voltage wiring will be reviewed by an electrician before installation. | Very low |
| | Shock from wiring for pump and Arduino power | Medium | High | User, technician / maintainence | Visual inspection of all wiring to ensure all wiring has been insulated. | Very low |
| Mechanical | Water heater tipping | Low | High | User, passerby, technician / maintainence | Water heater will be strapped into side of tub using concrete bolts. | Very low |

## Appendix P: Tank Temperature Loss Over Time

STANBY CONTROL STATE

- TANK AT 95
- TUB AT 20°C – 40°C (HEATING SEQUENCE)
- ASSUMING 1:3, HOT: COLD FLOW




FOR ENERGY CONTROL VOLUME SURROUNDING TANK

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_g}^{\,0} = \dot{E}_{ST}$$

$$\dot{m}_H C_p T_{TUB} - \dot{m}_H C_p T_{TANK} = \dot{E}_{ST}$$

$\dot{m}_H$ = 25% TOTAL SYSTEM MASS FLOW

$$0.25 \cdot 7.5\,gpm \times \frac{1\,m^3/s}{15850.3\,gpm} \times 995\,\frac{kg}{m^3} \cdot 4190\,\frac{J}{kg \cdot k}\,(20°c - 95°c) = \dot{E}_{ST}$$

$\dot{E}_{ST} = -33.97$ kw → TANK IS LOSING 33.97 kw



THE MINIMUM HEAT LOSS OCCURS WHEN $T_{TANK} = 90°C$, $T_{TUB} = 40°C$

$$\underline{\dot{E}_{ST} = -24.66\ kw}$$

FOR THE TANK TO DROP FROM 95 – 90°C, ASSUMING CONSTANT HEAT LOSS

$$\Delta t = \frac{979\,kg/m^3\,(4190\ J/kg \cdot k)(.152\,m^3)(95°c - 90°c)}{33.97 - 1.728\ kw}$$

← FROM HEATER

$\Delta t$ = 1.53 minutes

TIME FOR THE TUB TO GO FROM 30 – 40 CONSTANT HEATING

$$\Delta t = \frac{(979\,kg/m^3)(4190\ J/kg \cdot k)(0.833\,m^3)(40 - 30\ °c)}{33.97\ kw} \times \frac{1\,min}{60\,s}$$

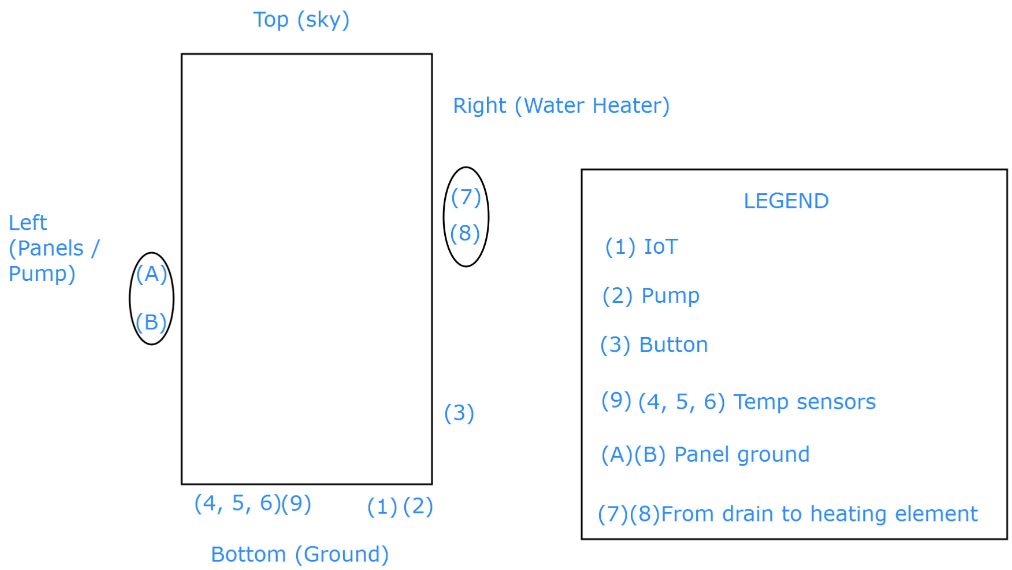
$\Delta t$ = 33.5 minutes

FOR THE TANK TO INCREASE FROM 90 – 95 (REGAIN PREVIOUS LOSS)

$$\Delta t = \frac{979\,kg/m^3\,(4190\ J/kg \cdot k)(.152\,m^3)(95c - 90c)}{1728\ w} \times \frac{1\,min}{60\,s}$$

$\Delta t$ = 30 minutes

## Appendix Q: Enclosure Hole Management Diagram




Numbers withing parenthesis or circles can potentially be fed through the same hole

## Appendix R: Arduino Code

```
//ds18b20 code reference:

//https://lastminuteengineers.com/multiple-ds18b20-arduino-tutorial/

//button code reference:

//https://www.arduino.cc/en/tutorial/switch

//how to use IoT relay:

//https://www.digital-loggers.com/iotfaqs.html

//pin locations

int outPin = 13;       // the number of the output pin to LED

int inPin = 12;         // the number of the input pin (button)

int heater = 11; // heating element output

//digital pin 10 is reserved for SD card writing

int relay = 9; //iot relay pin


int state = HIGH;      // the STARTING state of the output pin

int reading;           // the current reading from the input pin

int previous = LOW;    // the previous reading from the input pin

long time = 0;         // the last time the output pin was toggled

long debounce = 50;   // the debounce time, increase if the output flickers

int pump_delay = 2000; //delay time to turn pump on/off to prevent flickering

//1 = Active Mode

//0 = Passive

//Temperature sensor setup

//https://lastminuteengineers.com/multiple-ds18b20-arduino-tutorial/

#include <OneWire.h> //include digital signal, one wire library

#include <DallasTemperature.h> //include Temperature Conversion library

#define ONE_WIRE_BUS 8 // pin number for temp input

OneWire oneWire(ONE_WIRE_BUS);
```

```
DallasTemperature sensors(&oneWire);

void setup(void)

{

  pinMode(inPin, INPUT);

  pinMode(outPin, OUTPUT);

  pinMode(heater, OUTPUT);

  pinMode(relay, OUTPUT);

  sensors.begin(); // Start up temp library

  Serial.begin(9600);

digitalWrite(relay,LOW);

digitalWrite(heater,HIGH);

}


void loop(void)

{

  previous = reading;

  reading = digitalRead(inPin);

  //button and state toggling, do not touch

  if (reading == HIGH && previous == LOW && millis() - time > debounce)

  {

  digitalWrite(heater,HIGH); //Let heater be on

    if (state == HIGH) //Passive

     {

      state = LOW;

     }

    else

    {

      state = HIGH; ////Active

    }
```

```
    time = millis();
  }
  //button and state toggling, do not touch
  //Measure temperature
  sensors.requestTemperatures();
  int T_mix = sensors.getTempCByIndex(0);
  int T_tub = sensors.getTempCByIndex(1);
  int T_amb = sensors.getTempCByIndex(2);
  int T_tank = sensors.getTempCByIndex(3);

  //Show temperatures on serial monitor
//  Serial.print("T_tub  ");
//  Serial.print("T_tank  ");
//  Serial.print("T_mix ");
//  Serial.println("T_amb");
//  Serial.print(T_tub);
//  Serial.print(" ");
//  Serial.print(T_tank);
//  Serial.print(" ");
//  Serial.print(T_mix);
//  Serial.print(" ");
//  Serial.println(T_amb);
  //Serial.println(state);
  //Control Logic
if (state == HIGH) //active
{
 // Serial.println("Active");
  digitalWrite(outPin, state);
```

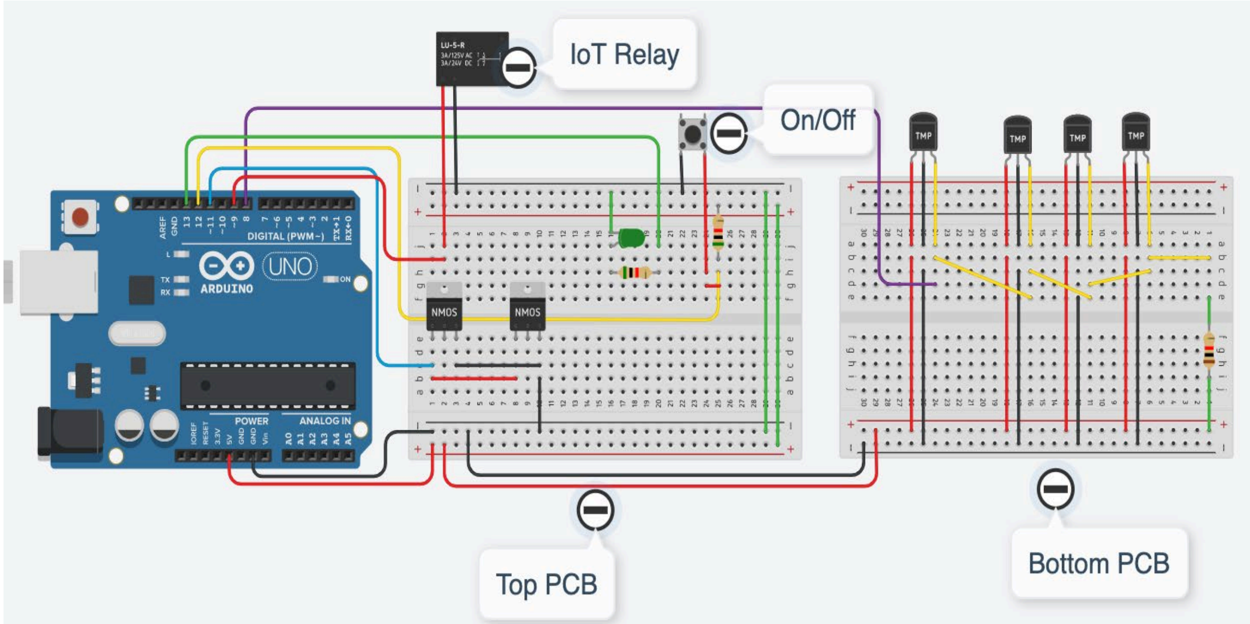
```
//     digitalWrite(relay,HIGH); //pump on
//      digitalWrite(heater,HIGH); //heater on
      if (T_tank > 93) //tank too hot
      {
        digitalWrite(heater,LOW); //turn off heater
        if ((T_tub > 40) || (T_mix >= 46)) // Tub too hot or mix too hot
        {
          delay(pump_delay);
          digitalWrite(relay,LOW);//pump off
        }
        else
        {
         delay(pump_delay);
         digitalWrite(relay,HIGH); //pump on
        }
      }
    else if ((T_tub > 40) || (T_mix >= 46)) // Tub or mix too hot, tank not
hot
      {
       digitalWrite(heater,HIGH);
       delay(pump_delay);
      digitalWrite(relay,LOW); //Pump off
      //delay(50);
      }
    else
    {
      digitalWrite(heater,HIGH);
      delay(pump_delay);
      digitalWrite(relay,HIGH);
```

```
    }
  }
  else
  {
   //Serial.println("Passive");
    digitalWrite(outPin, state);
        //Serial.print(state);
        if (T_tank > 90) //tank approaching too hot
       {
         if(T_tank >= 93) //tank too hot
         {
         digitalWrite(heater,LOW); //turn off heater
         if((T_tub <= 40) && (T_mix < 46))
         {
           delay(pump_delay);
           digitalWrite(relay,HIGH);
         }
         else
         {
           delay(pump_delay);
           digitalWrite(relay,LOW);
         }
         }
        else if((T_tub <= 40) && (T_mix < 46))
       {
         delay(pump_delay);
         digitalWrite(heater,HIGH);
         digitalWrite(relay, HIGH); // pump on
       }
```

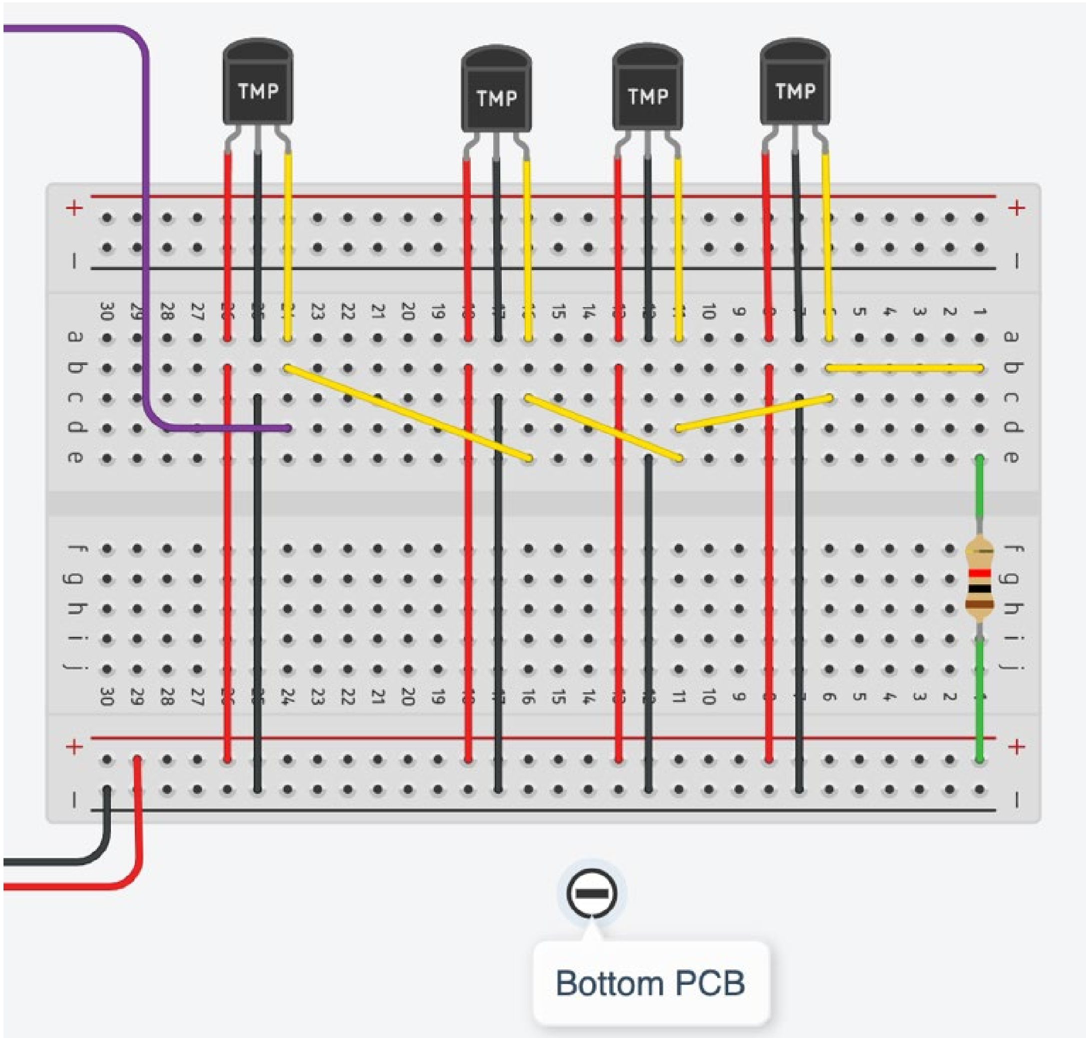
```
        else
       {
        delay(pump_delay);
        digitalWrite(heater, HIGH); //heater on
        digitalWrite(relay, LOW); //turn off pump
       }
     }
    else // tank is cool, establish idle temp 30C
      {
        digitalWrite(heater,HIGH);
       if((T_tub <= 30) && (T_mix < 46))
        {
          delay (pump_delay);
          digitalWrite(relay, HIGH); // pump on
        }
       else //tub or mix too hot
        {
        delay(pump_delay);
        digitalWrite(relay, LOW); //turn off pump
       }
      }
   }
 }
```

**Appendix S: Wiring Diagrams**

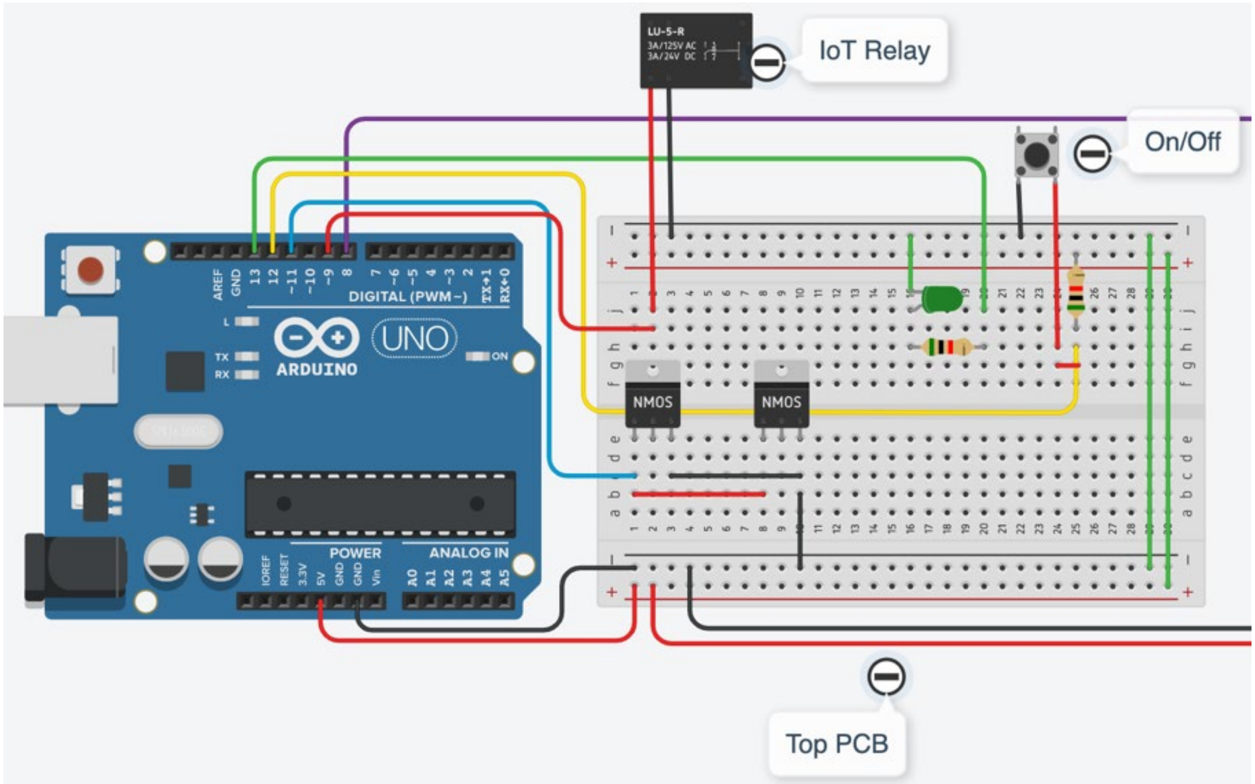
Note: Wire colors may be different than those in actual controls enclosure, colors have been adjusted to improve diagram clarity.



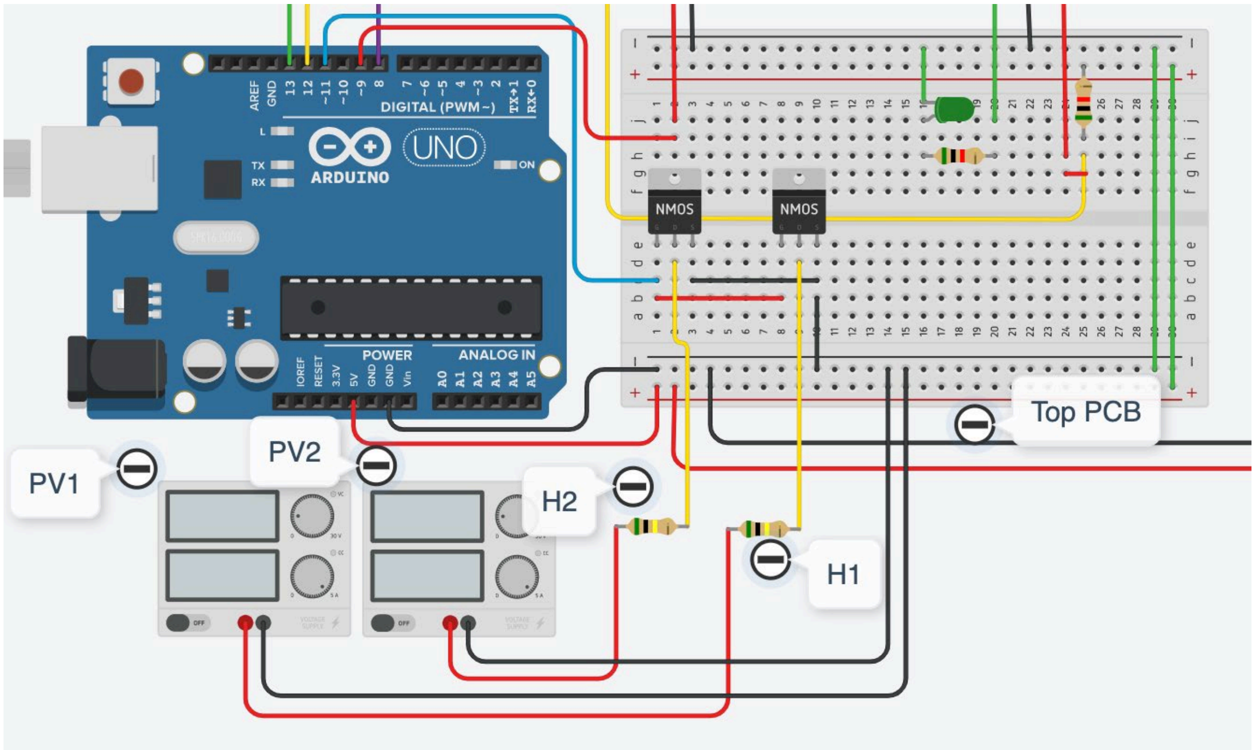

Full Electrical As-Built Wiring Diagram



Bottom PCB As-Built Wiring Diagram

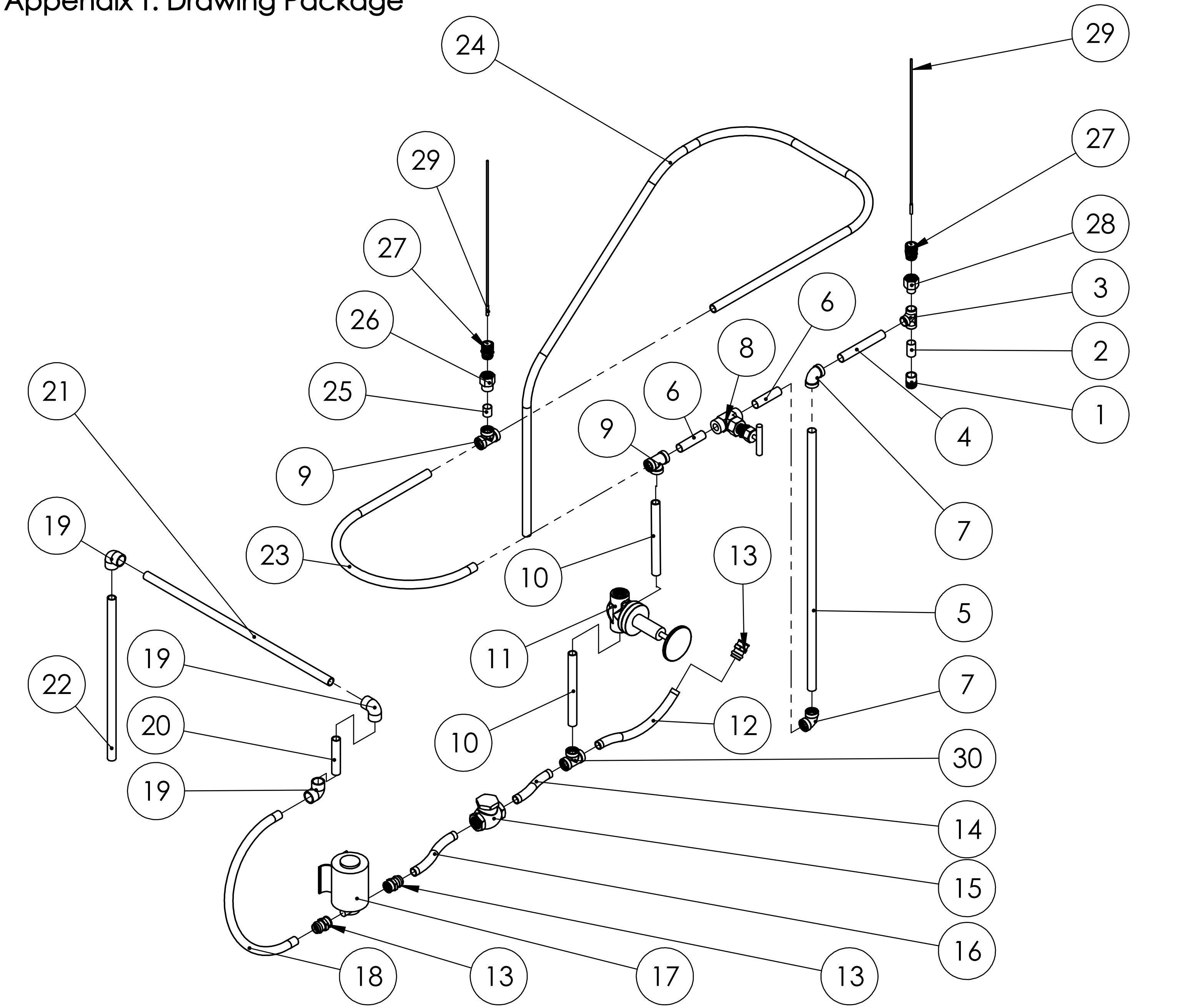


Connection to Arduino and Top PCB As-Built Wiring Diagram




Planned wiring diagram to include PV arrays (PV1, PV2), to resistive heaters (H1, H2) respectively. Grounding to external source may also be necessary for safety of solar panels.

# Appendix T: Drawing Package

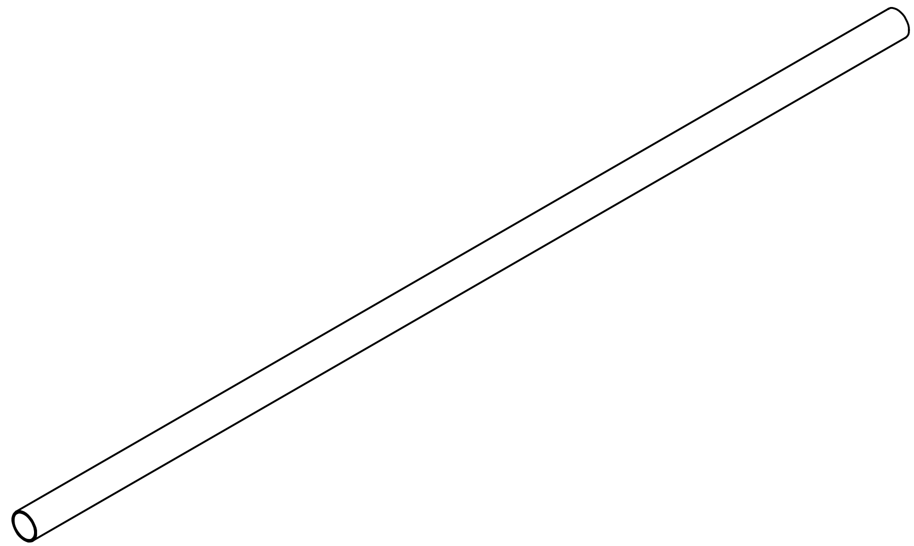


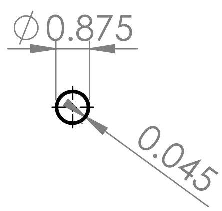

| ITEM NO. | PART NUMBER | QTY. |
|---|---|---|
| 1 | 1.03.11.00 | 1 |
| 2 | 1.03.01.01 | 1 |
| 3 | 1.03.16.00 | 1 |
| 4 | 1.03.01.02 | 1 |
| 5 | 1.03.01.03 | 1 |
| 6 | 1.03.01.04 | 2 |
| 7 | 1.03.12.00 | 2 |
| 8 | 1.03.13.00 | 1 |
| 9 | 1.03.10.00 | 2 |
| 10 | 1.03.02.08 | 2 |
| 11 | 1.03.09.00 | 1 |
| 12 | 1.03.02.07 | 1 |
| 13 | 1.03.05.00 | 3 |
| 14 | 1.03.02.06 | 1 |
| 15 | 1.03.06.00 | 1 |
| 16 | 1.03.02.05 | 1 |
| 17 | 1.03.17.00 | 1 |
| 18 | 1.03.02.04 | 1 |
| 19 | 1.03.04.00 | 3 |
| 20 | 1.03.02.03 | 1 |
| 21 | 1.03.02.02 | 1 |
| 22 | 1.03.02.01 | 1 |
| 23 | 1.03.02.09 | 1 |
| 24 | 1.03.02.10 | 1 |
| 25 | 1.03.01.05 | 1 |
| 26 | 1.03.14.00 | 1 |
| 27 | 1.03.18.00 | 2 |
| 28 | 1.03.15.00 | 1 |
| 29 | 1.04.12.00 | 2 |
| 30 | 1.03.08.00 | 1 |

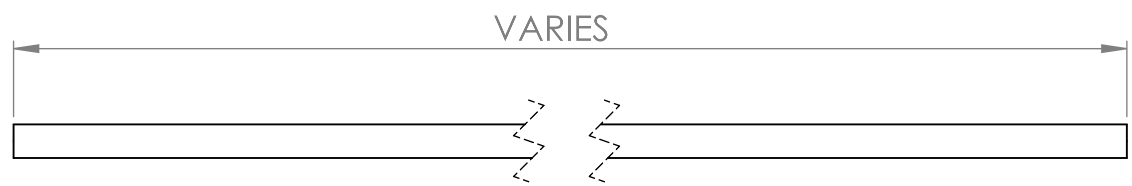
| | | | | |
|---|---|---|---|---|
| Cal Poly Mechanical Engineering | Lab Section: 01 | Assignment # | Title: EXPLODED DISTRIBUTION ISO | Drwn. By: JORDAN LOPEZ CORLEY |
| ME 430 - SPRING 2020 | Dwg. #: | Nxt Asb: | Date: 6/8/20 — Scale: 1:15 | Chkd. By: ME STAFF |

CUT SHEET FOR TYPE L 3/4" COPPER PIPING

UNLESS OTHERWISE SPECIFIED:
ALL DIMENSIONS IN INCHES
TOLERANCES:
.XXX = ±.125





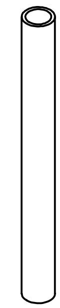



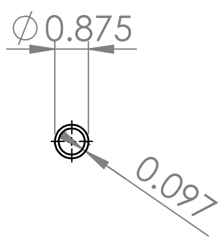

| PART NO. | CUT LENGTH | DESCRIPTION | QTY. |
|---|---|---|---|
| 1.03.01.01 | 1.500 | Cu_L_i | 1 |
| 1.03.01.02 | 6.000 | Cu_L_1 | 1 |
| 1.03.01.03 | 32.125 | Cu_L_2 | 1 |
| 1.03.01.04 | 3.375 | Cu_L_3 | 2 |
| 1.03.01.05 | 1.000 | Cu_L_Sensor | 1 |

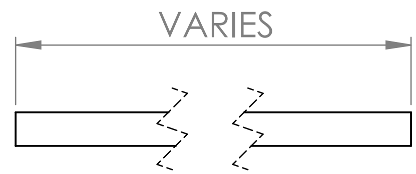
| | | | | | |
|---|---|---|---|---|---|
| Cal Poly Mechanical Engineering | Lab Section: 01 | Assignment # | Title: COPPER TYPE L CUT SHEETS | | Drwn. By: JORDAN LOPEZ CORLEY |
| ME 430 - SPRING 2020 | Dwg. #: | Nxt Asb: | Date: 6/8/20 | Scale: 1:5 | Chkd. By: ME STAFF |

CUT SHEET FOR 3/4" PEX PIPING

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ± .125





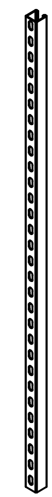



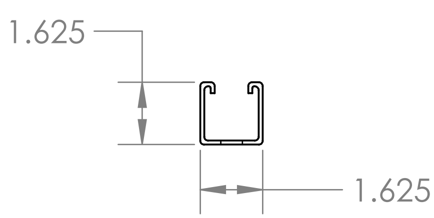

| PART NO. | CUT LENGTH | DESCRIPTION | QTY. |
|---|---|---|---|
| 1.03.02.01 | 20.000 | PEX_-2 | 1 |
| 1.03.02.02 | 26.500 | PEX_-1 | 1 |
| 1.03.02.03 | 4.250 | PEX_0 | 1 |
| 1.03.02.04 | 24.063 | PEX_1 | 1 |
| 1.03.02.05 | 7.825 | PEX_2 | 1 |
| 1.03.02.06 | 5.850 | PEX_3 | 1 |
| 1.03.02.07 | 12.000 | PEX_4 | 1 |
| 1.03.02.08 | 8.813 | PEX_Bypass | 2 |
| 1.03.02.09 | 25.625 | PEX_5 | 1 |
| 1.03.02.10 | 98.625 | PEX_6 | 1 |

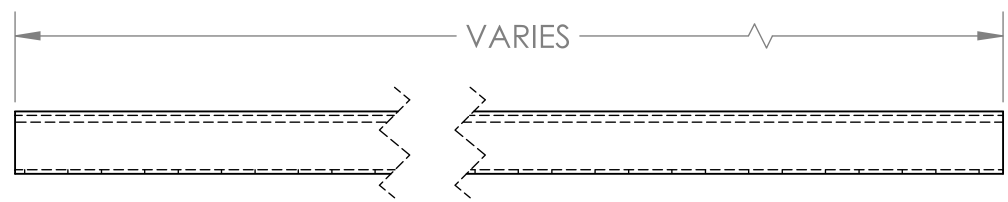
| | | | | | |
|---|---|---|---|---|---|
| Cal Poly Mechanical Engineering | Lab Section: 01 | Assignment # | Title: EXPANSION PEX CUT SHEET | | Drwn. By: JORDAN LOPEZ CORLEY |
| ME 430 - SPRING 2020 | Dwg. #: | Nxt Asb: | Date: 6/8/20 | Scale: 1:5 | Chkd. By: ME STAFF |

CUT SHEET FOR 1 5/8" UNISTRUT P1000T METAL FRAMING

UNLESS OTHERWISE SPECIFIED:
ALL DIMENSIONS IN INCHES
TOLERANCES:
.XXX = ±.125





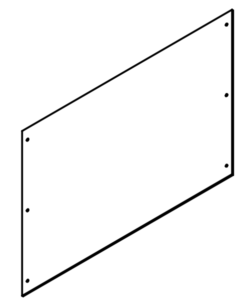



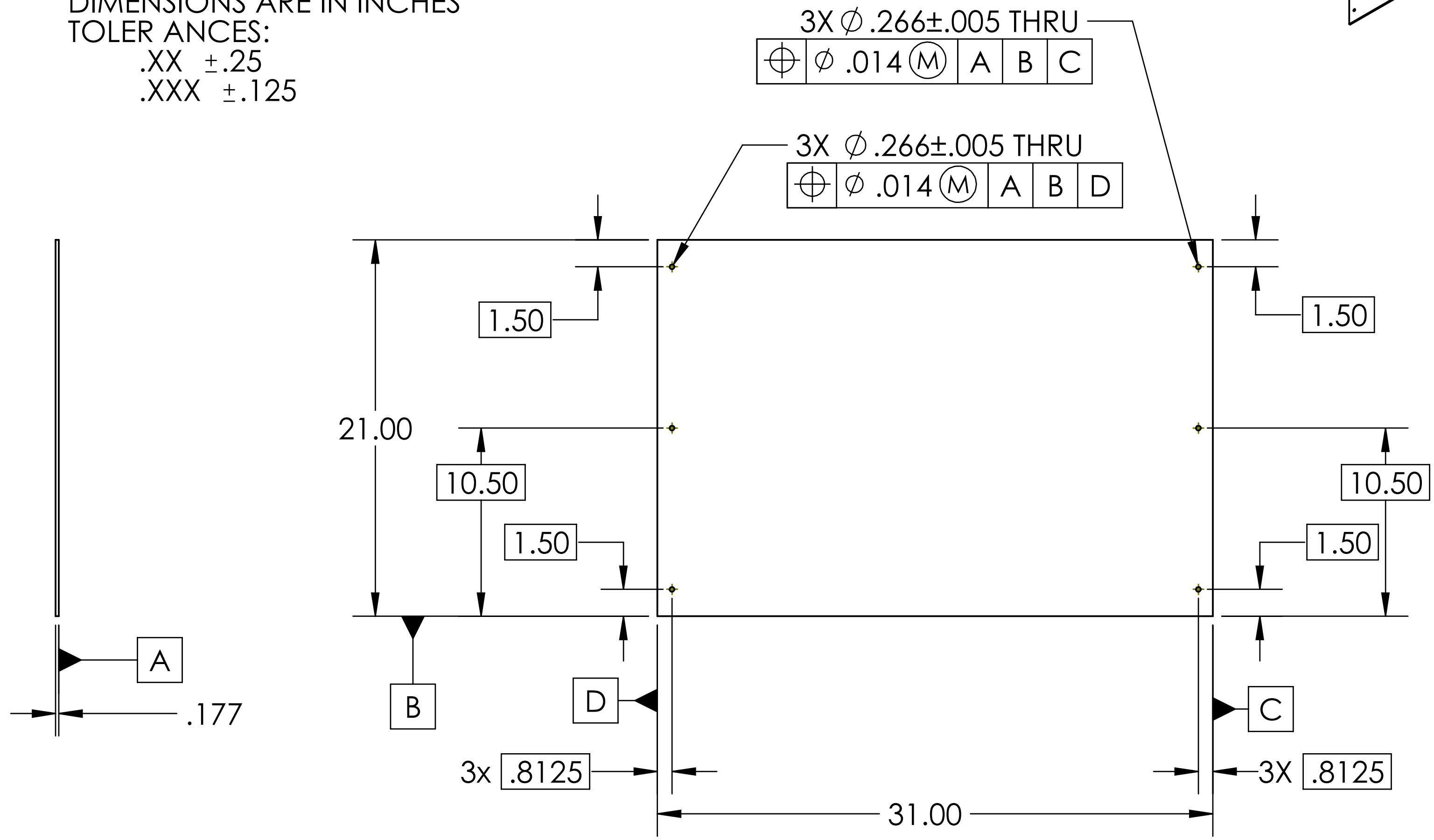

| PART NO. | CUT LENGTH | DESCRIPTION | QTY. |
|---|---|---|---|
| 1.05.03.01 | 60.000 | UPRIGHT POSTS | 2 |
| 1.05.03.02 | 28.375 | CROSSBEAM | 3 |
| 1.05.03.03 | 15.750 | LEG HORIZONTAL | 2 |
| 1.05.03.04 | 26.500 | LEG VERTICAL | 2 |

| Cal Poly Mechanical Engineering | Lab Section: 01 | Assignment # | Title: UNISTRUT CUT SHEET | | Drwn. By: JORDAN LOPEZ CORLEY |
|---|---|---|---|---|---|
| ME 430 - SPRING 2020 | Dwg. #: | Nxt Asb: | Date: 6/8/20 | Scale: 1:5 | Chkd. By: ME STAFF |

CONTROL PANEL ACRYLIC BOARD
3/16" ACRYLIC
ALL OTHER MODIFICATIONS TO BE MADE ON-SITE

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLER ANCES:
.XX ±.25
.XXX ±.125






| Cal Poly Mechanical Engineering<br>ME 430 - SPRING 2020 | Lab Section: 01 | Assignment # | Title: JORDAN LOPEZ CORLEY | | Drwn. By: JORDAN LOPEZ CORLEY |
|---|---|---|---|---|---|
| | Dwg. #: | Nxt Asb: | Date: 6/8/20 | Scale: 1:10 | Chkd. By: ME STAFF |

**Appendix U**

# Assembly Instructions

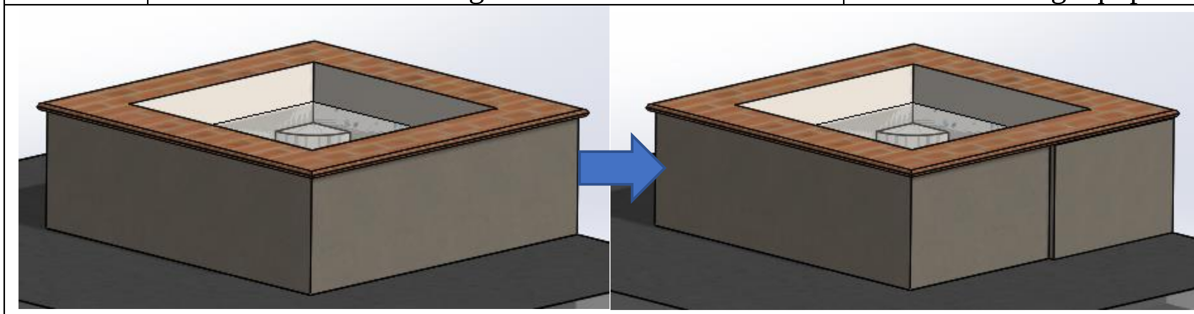
<u>Preparation:</u>
Cut the piping and metal framing to length, following the cut sheets in Appendix T. Drill the six mounting holes needed into the acrylic sheet.

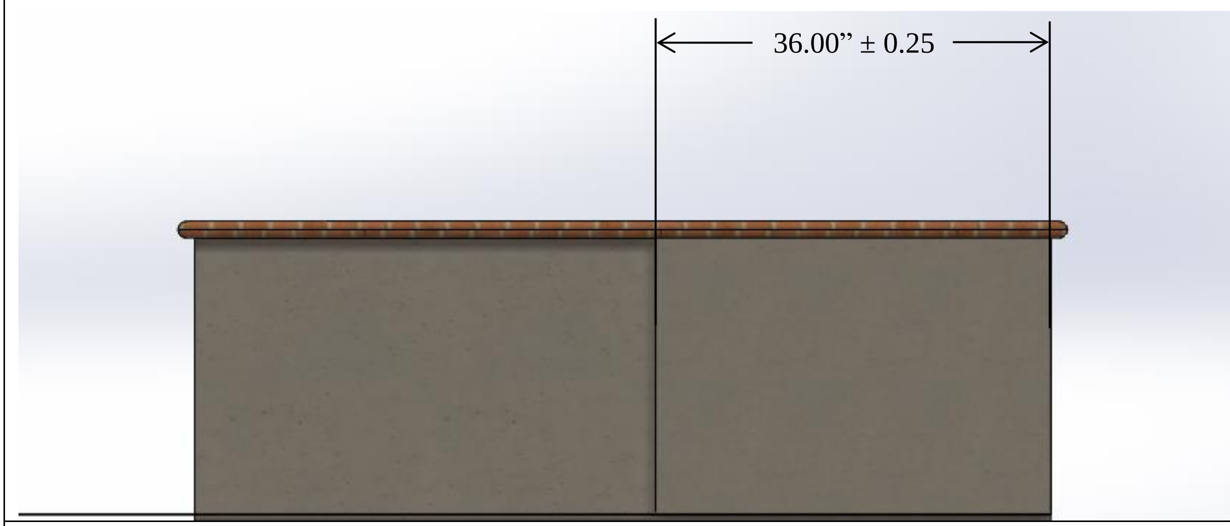
This installation will require all the parts outlined in the iBOM, as well as the following tools:

- Concrete setting equipment
  - Plywood
  - 5-gallon bucket
  - Mixing attachment for hand drill
  - Hand Trowel
- Copper pipe toolkit
  - Handheld torch
  - Lighter
  - Sandpaper
  - Lead-free flux
  - Lead-free solder (95-5)
- PEX piping equipment
  - PEX expander tools
  - ProPEX rings
  - 14” Diameter Plywood Circle for forming bends (optional)
- Wire splicing tools
  - Wire cutter / stripper
  - Wire matching or similar in gage to the wire being replaced.
  - Soldering iron
  - Solder
  - Electrical tape
- Hammer drill with 0.5” bit OR suitable replacement
- Socket wrench
- Long hex socket (matching concrete anchors)
- Phillips head screwdriver
- Measuring tape
- Monkey wrench
- Needle nose pliers
- Hand drill (powered)
- ¼ drill bit
- Wrench for ¼-20 nut OR crescent wrench
- Marker
- Calipers
- Crescent wrench
- Heating element wrench
- Tools recommended by water heater manufacturer for replacing the heating element

Optional:
- Marking chalk
- Box knife

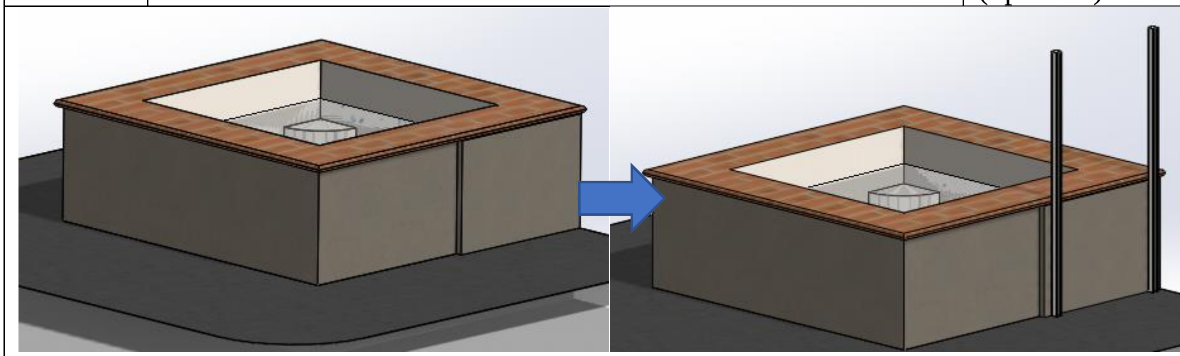
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 1 | 1.05.12.00 Fast-Setting Concrete | Concrete setting equipment |

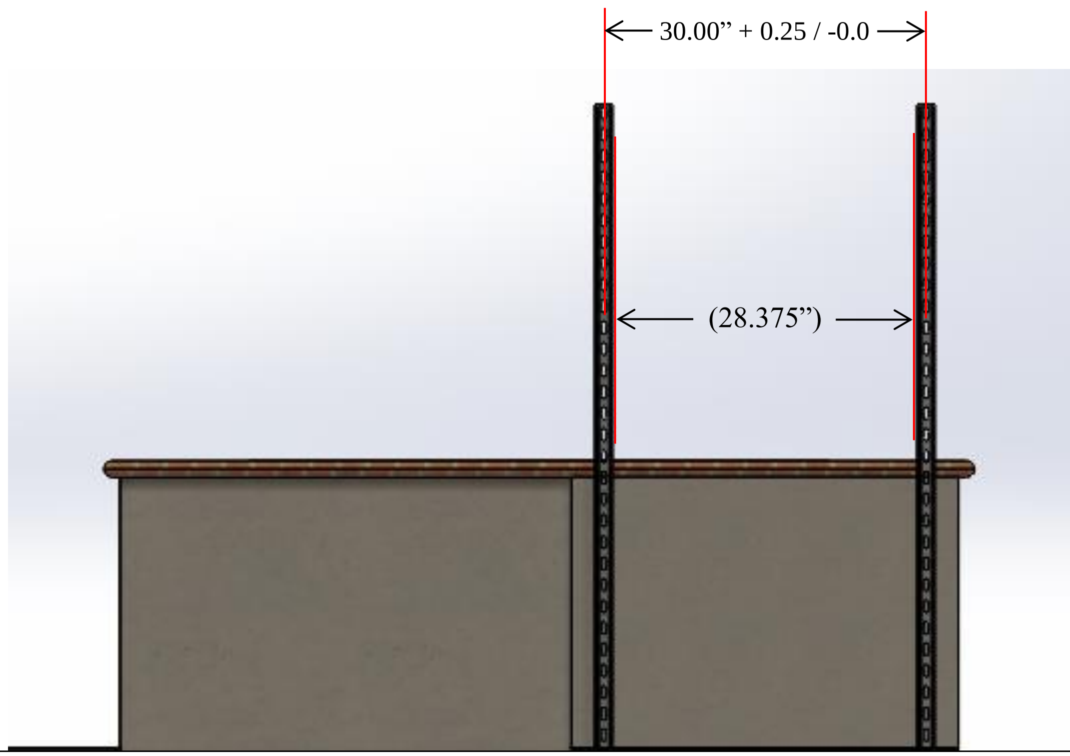




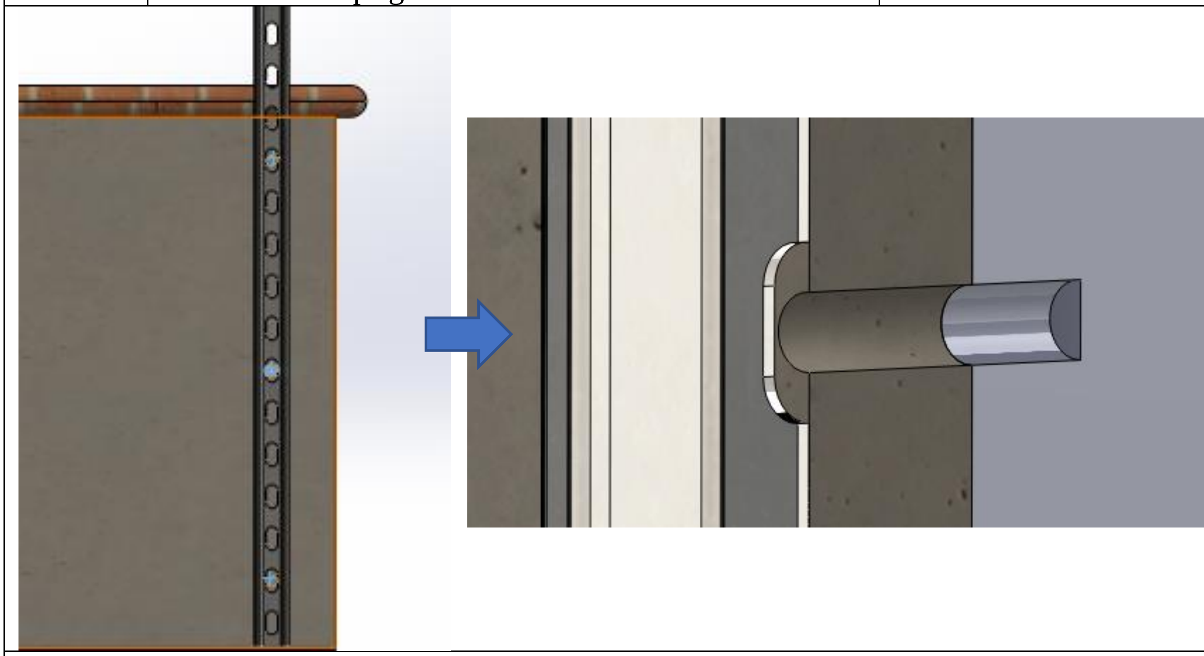

Instructions: Using the quick-setting concrete, fill in the front face of the hot tub such that the surface is as smooth as possible, even with the lip of the tub. This addition should start at the existing corner of the tub and extend 36 inches inward.

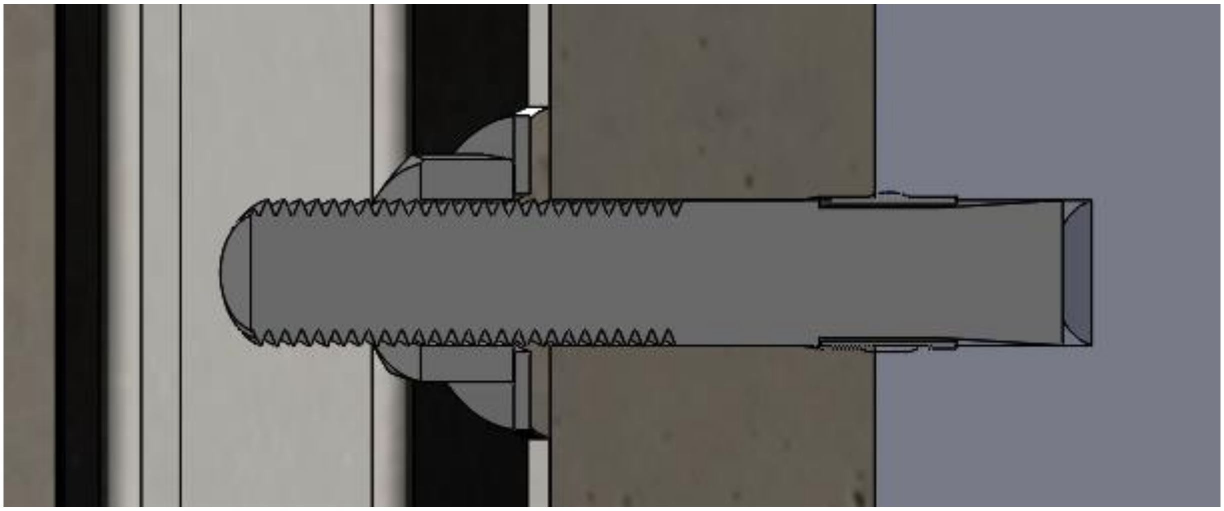
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 2 | 1.05.03.01 Upright Posts<br>1.05.03.02 Crossbeam | Marking chalk (optional) |



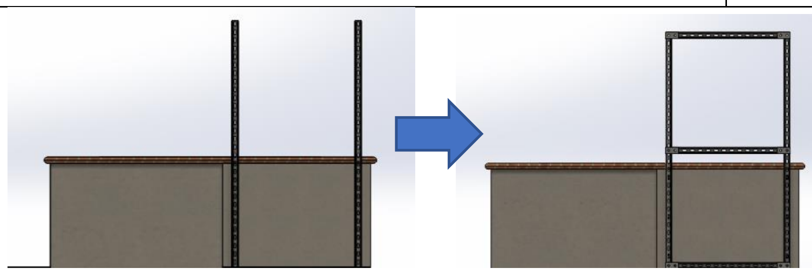


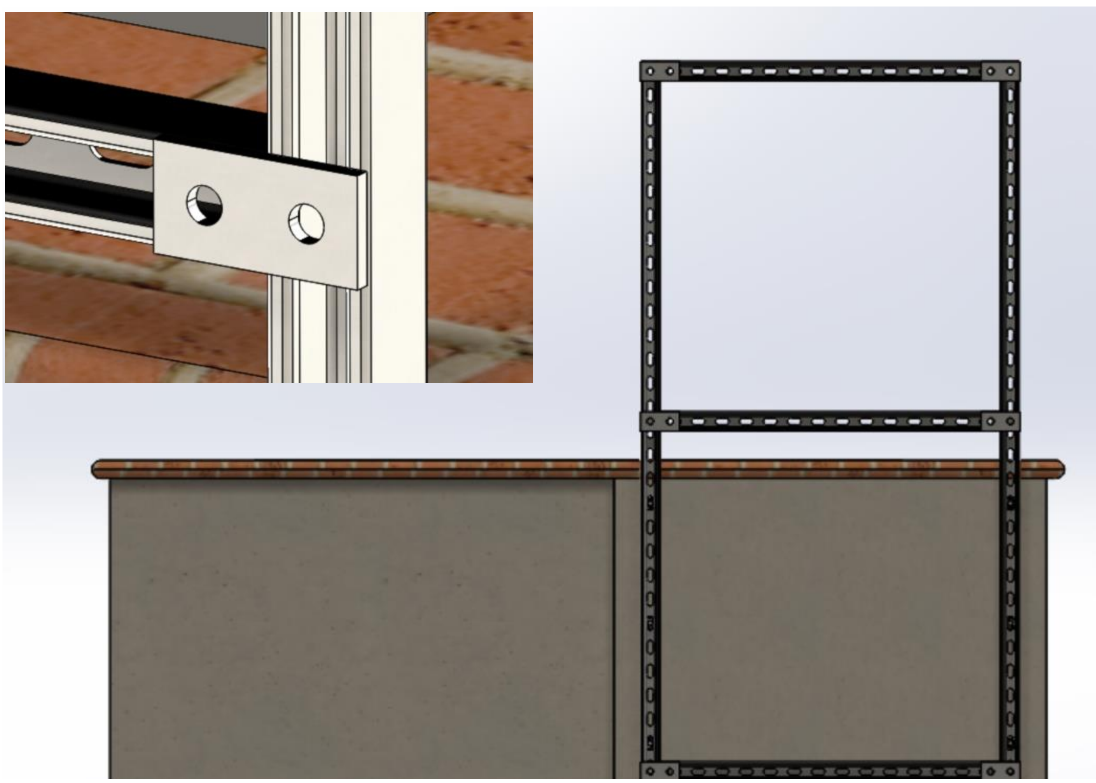

Instructions: After the concrete has set, the Unistrut posts should be centered on the newly filled-in concrete and spaced such that the center of the left post is 30” from the right post (This will leave 28.375” of space between the inside face of each post). It may be helpful to use a Crossbeam (part no. 1.05.03.02) to get accurate spacing. Mark this position with chalk, if able.

<table>
<tr><td>Step No.</td><td>Parts Needed:</td><td>Equipment Needed:</td></tr>
<tr><td>3</td><td>1.05.03.01 Upright Posts</td><td>Hammer drill with 0.5” bit</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">Instructions: Using the metal framing as a guide, place three 0.5” holes in each of the two uprights (It may be necessary to mark the positions of these holes and move the framing out of the way before drilling). The exact spacing of the holes is left to the discretion of the installer, as the exact dimensions of the slots for the metal framing may vary, but we recommend spacing out the holes so that one hole is closer to the top of the side of the hot tub, another is close to the middle, and the third is close to the bottom of the side of the hot tub, as shown. Each hole must have a depth of at least 2.5 inches.</td></tr>
</table>

<table>
<tr><td>Step No.</td><td>Parts Needed:</td><td>Equipment Needed:</td></tr>
<tr><td>4</td><td>1.05.03.01 Upright Posts<br>1.05.02.00 0.5”x3.75” Concrete Anchors (x6)</td><td>Long hex socket,<br>socket wrench</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">Instructions: The California Guidelines for Earthquake Bracing recommend that anchor bolts securing bracing to concrete or concrete masonry walls be 3/8s diameter, with a minimum embedment of 2 inches. We have prescribed that 0.5 diameter bolts be embedded 2.5” within the holes created in Step 3. OUR DESIGN SHOULD NOT BE CONSIDERED RESISTANT TO EARTHQUAKES. While we have done our best to follow the guidelines available to us, a structural analysis of our framing structure and anchoring technique would need to be performed to ensure our system could sustain the loading experienced during seismic events. Our intent is to provide a system robust enough to prevent unintentional tipping caused through normal use.</td></tr>
</table>

| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 5 | 1.05.03.02 Crossbeam (x3)<br>1.05.04.00 P1924 Flat Plate Connector<br>1.05.07.00 Unistrut P1006-1420<br>1.05.11.00 ¼-20x0.75 Bolts | Phillips head screwdriver, measuring tape |

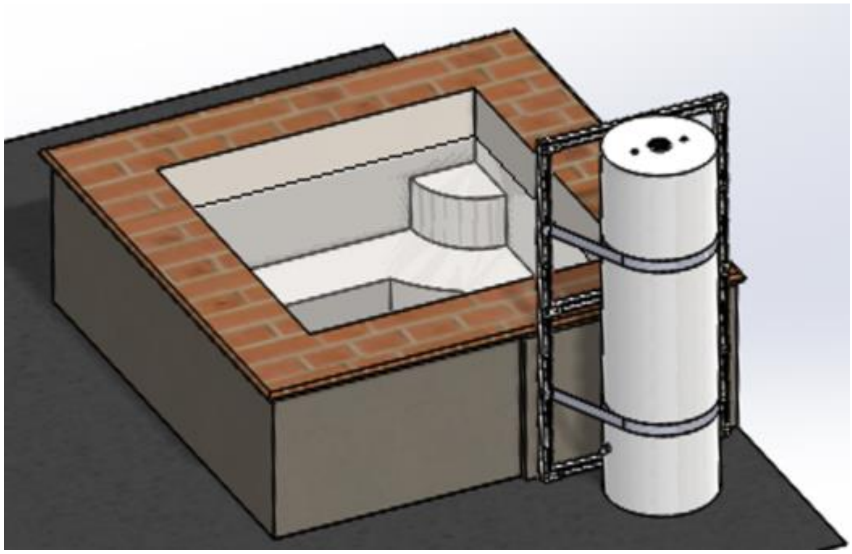


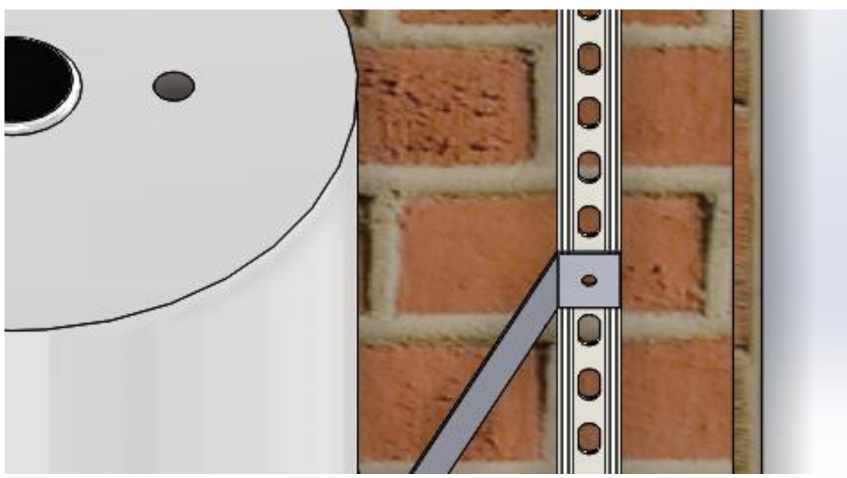


Instructions: Attach the Crossbeams to the Uprights by threading the ¼-20 bolts through the Flat Plate Connectors into Unistrut P1006-1420 spring-loaded channel nuts located on the inside tracks of both the Crossbeam and Upright members*. Online resources should be available from Unistrut to assist with this procedure. The Crossbeams should be positioned at the top, middle, and bottom of the uprights, as shown.

*NOTE: the bolts and spring-loaded channel nuts have been omitted from our CAD to reduce the amount of hardware depicted.

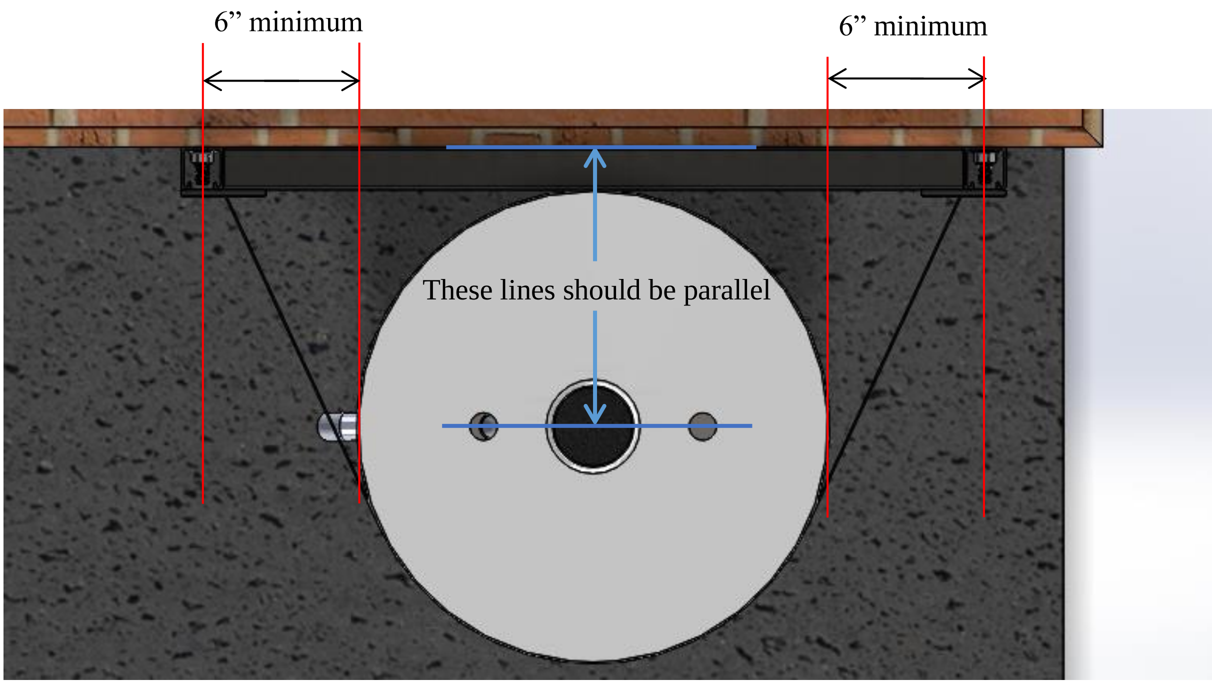
| Step No. | Parts Needed: | Equipment Needed: |
| --- | --- | --- |
| 6 | 1.02.01.00 50-GAL Water Heater<br>1.02.03.00 Retaining Straps (x2)<br>1.05.07.00 Unistrut P1006-1420 (x4)<br>1.05.11.00 ¼-20x0.75 Bolts (x4) | Phillips head screwdriver, measuring tape |

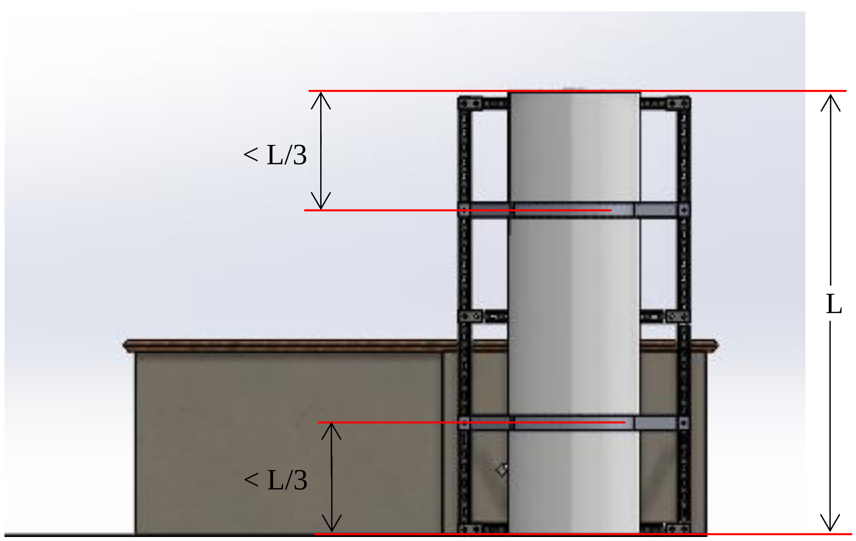




Instructions: Next, set the 50-GAL Water Heater in place with the Retaining Straps affixing the heater to the Upright Posts. Follow the dimensions for positioning the Retaining Straps as shown on the following page: these dimensions follow the recommendations from the California Guidelines for Earthquake Bracing. OUR DESIGN SHOULD NOT BE CONSIDERED RESISTANT TO EARTHQUAKES. While we have done our best to follow the guidelines available to us, a structural analysis of our framing structure and anchoring technique would need to be performed to ensure our system could sustain the loading experienced during seismic events. Our intent is to provide a system robust enough to prevent unintentional tipping caused through normal use. (INSTRUCTIONS CONTINUED ON FOLLOWING PAGE)

| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 6 (Continued) | 1.02.01.00 50-GAL Water Heater<br>1.02.03.00 Retaining Straps (x2)<br>1.05.07.00 Unistrut P1006-1420 (x4)<br>1.05.11.00 ¼-20x0.75 Bolts (x4) | Philips head screwdriver, measuring tape |

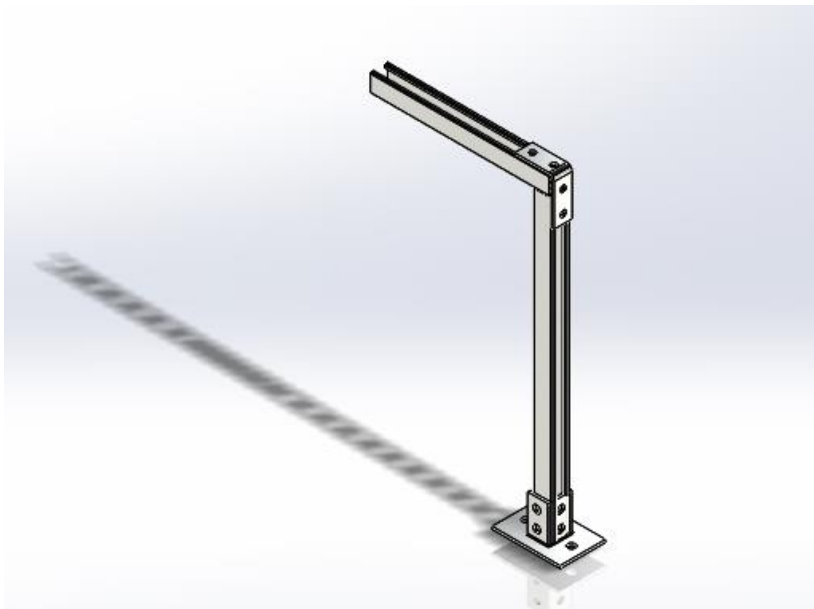


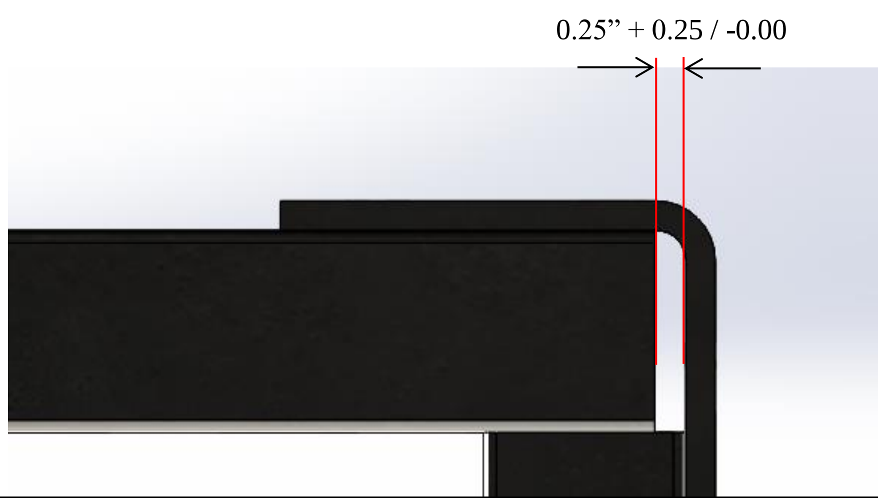




Instructions (Continued): It is important that the hot and cold outlets be installed so that a line collinear with both diameters of the outlets will run parallel to the plane describing the front side of the hot tub. The drain position is of secondary importance; if the drain is not in line with the hot and cold water ports, the heater should be positioned such that the drain is in the closest accessible position to the rest of the piping system. PEX_4 can be cut and bent to accommodate the positioning of this outlet.
If water from the TPR valve cannot be properly routed to a safe location, install a drain pan for the water heater at this time.

| Step No. | Parts Needed: | Equipment Needed: |
| --- | --- | --- |
| 7 | 1.02.02.00 Water Heater Sleeve | Box knife (optional) |
| (This part was not included in the CAD model of the design.) | | |
| Instructions: Install the Water Heater Sleeve (not pictured). Cut the insulation with a box knife (if necessary) to allow the sleeve to fit over the retaining straps. | | |

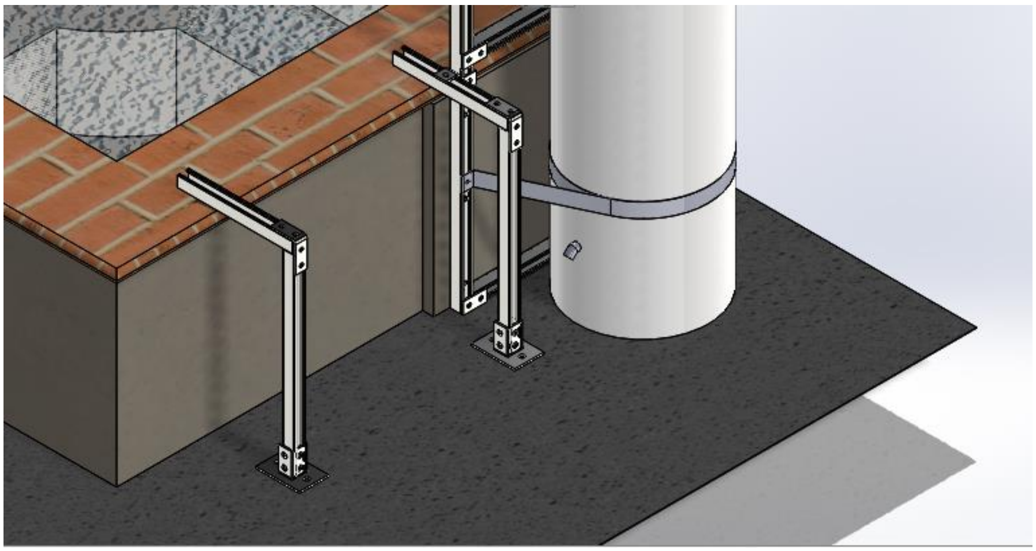
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 8 | 1.05.03.03 Leg Horizontal (x2)<br>1.05.03.04 Leg Verticle (x2)<br>1.05.05.00 Unistrut L Bracket Connector (2x)<br>1.05.06.00 Unistrut P2942 Post Base (2x)<br>1.05.07.00 Unistrut P1006-1420 (x6)<br>1.05.11.00 ¼-20x0.75 Bolts (x6) | Philips head screwdriver, measuring tape |

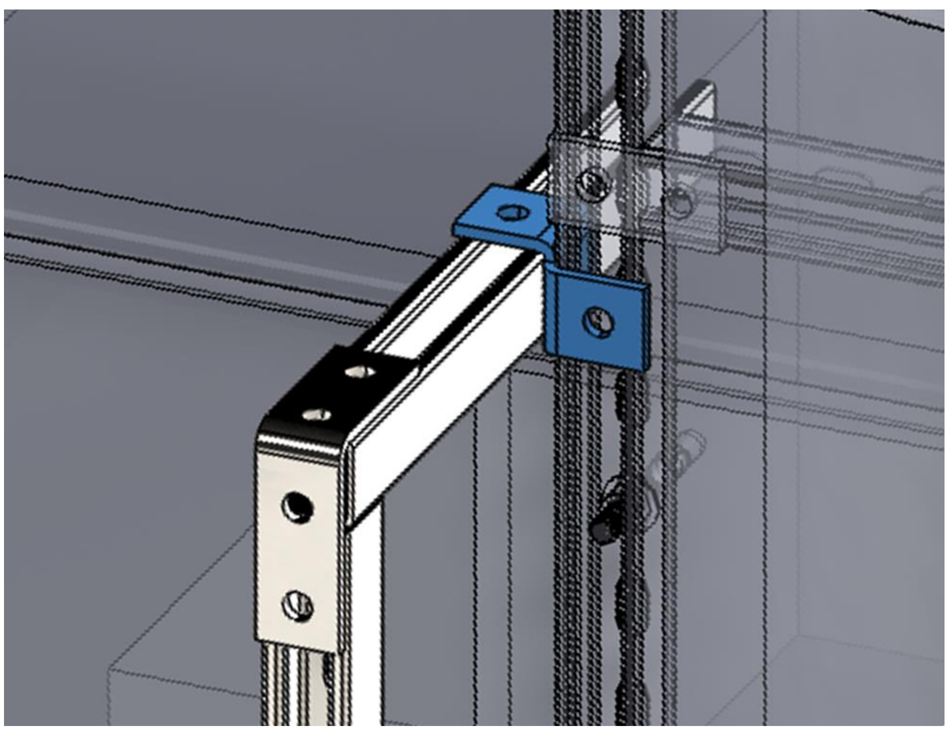





Instructions: Assemble two legs as shown. Make sure to leave a 0.25” gap in the connection between the lengths of Unistrut to account for the curvature of the L Bracket Connector. The positioning of the Vertical Leg within the Post Base can be adjusted up if necessary so that the bottom of the Horizontal Leg is even with the top of the hot tub.

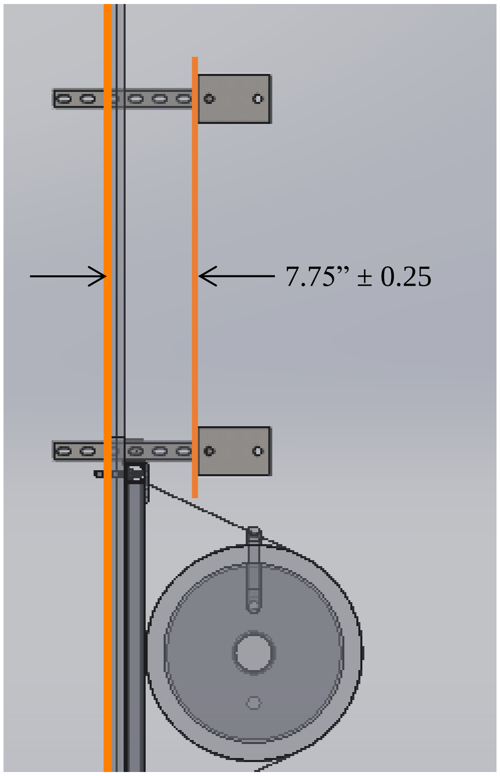
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 9 | 1.05.13.00 Unistrut P2343L Fitting<br>1.05.07.00 Unistrut P1006-1420 (x2)<br>1.05.11.00 ¼-20x0.75 Bolts (x2) | Philips head screwdriver, measuring tape |

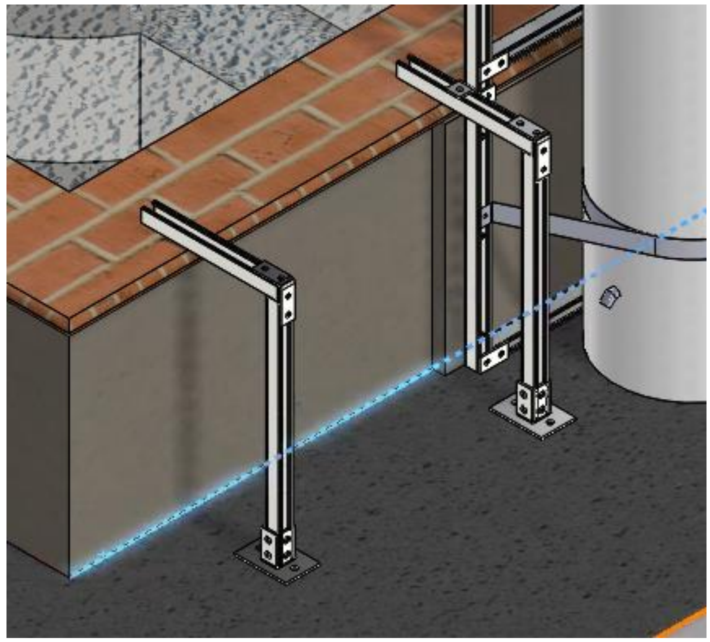


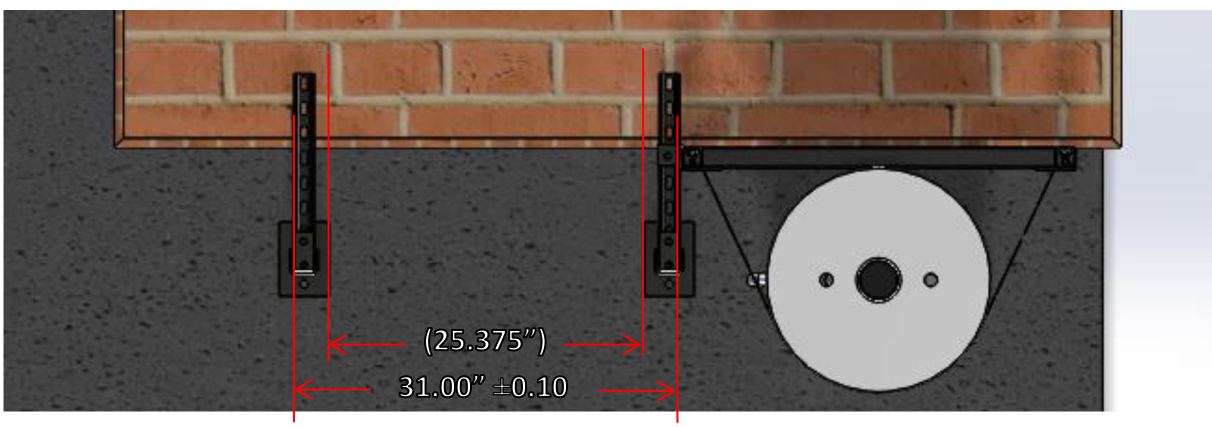


Instructions: Next, we will position the legs. The top photo shows the general arrangement; the following slides will help to describe the position exactly. First, locate the right leg side-to-side by firmly attaching the P2343L Fitting to the Upright Posts and loosely attaching the fitting to the Horizontal Legs. CONTINUED ON NEXT PAGE

| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 9 (Continued) | 1.05.13.00 Unistrut P2343L Fitting<br>1.05.07.00 Unistrut P1006-1420 (x2)<br>1.05.11.00 ¼-20x0.75 Bolts (x2) | Philips head screwdriver, measuring tape |

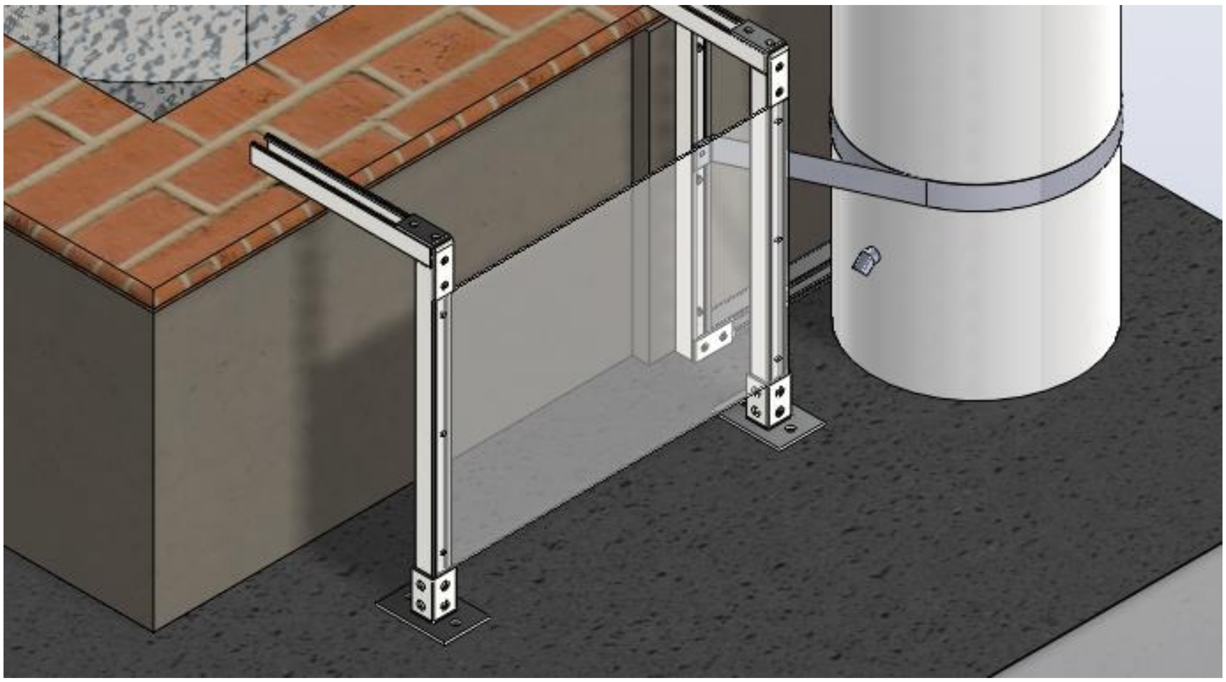




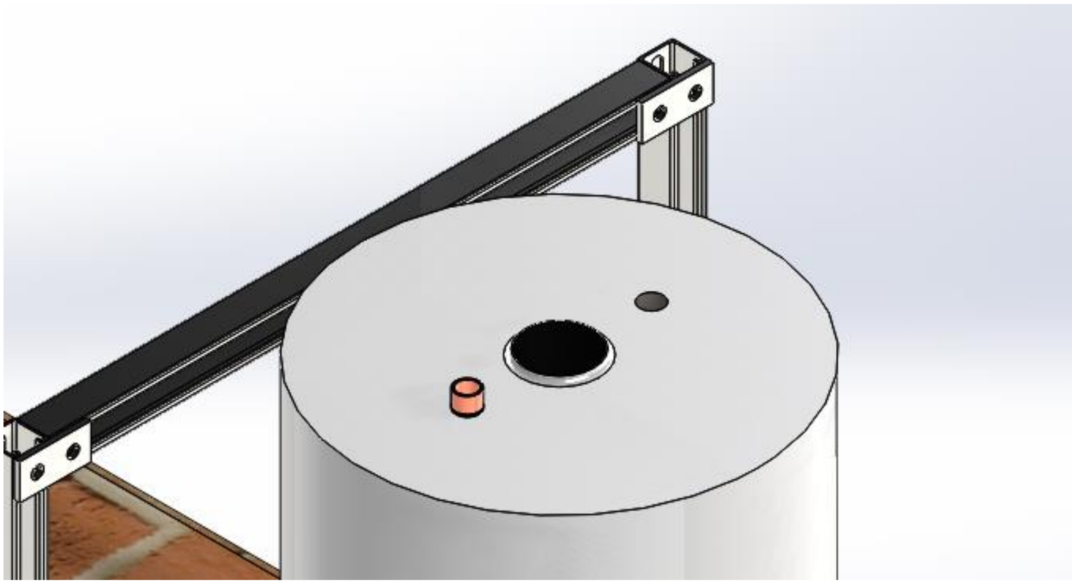

Instructions: The legs should be located front-to-back by placing the back edge of the P2942 Post Bases 7.75 inches from the bottom edge of the hot tub.
The left leg is located from the right leg. The two inside edges of the P2942 Post Bases should be 25.375” apart; this places the two outside edges of the Vertical Legs 31” apart. It may be helpful at this time to position the Vertical Legs using the Acrylic Sheet.

| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 10 | 1.05.02.00 0.5”x3.75” Concrete Anchors (x4)<br>1.05.13.00 24”x36”x0.177” Acrylic Sheet<br>1.05.07.00 Unistrut P1006-1420 (x6)<br>1.05.11.00 ¼-20x0.75 Bolts (x6) | Philips head screwdriver, hammer drill with 0.5” bit, long hex socket, socket wrench. |



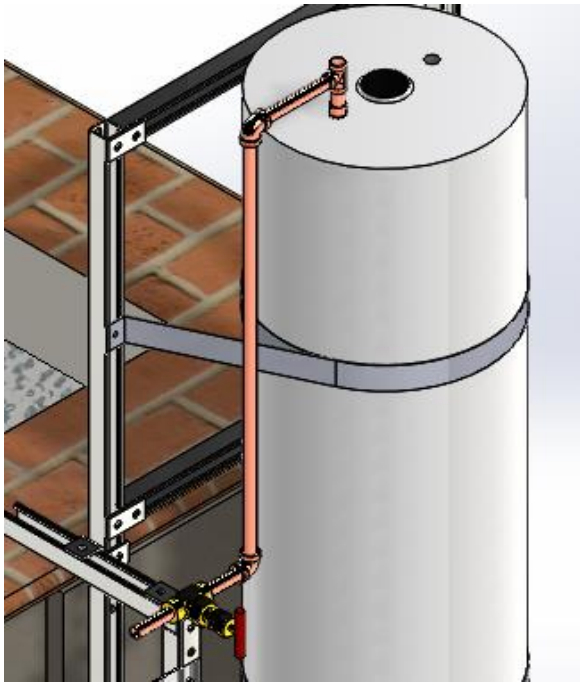
Instructions: Connect the two posts by affixing a 3/16” thick piece of acrylic plastic to their fronts. Secure the posts to the ground following the same methods by which the Unistrut was secured to the side of the tub; drill two 2.5 inch holes into the concrete for each post holder, and secure with 0.5”x3.75” Concrete Anchors.

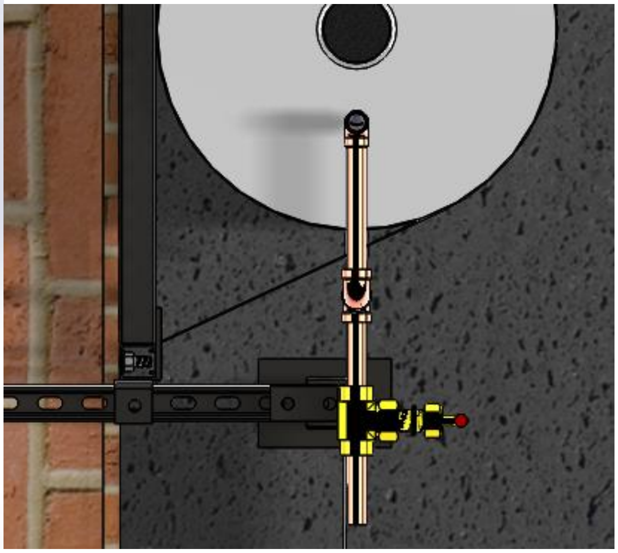
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 11 | 1.03.11.00 ¾ NPT, M to ¾ Cu, F | Monkey wrench, needle nose pliers |



Instructions: Install a female copper outlet for use with ¾ Type-L copper piping into the leftmost outlet. It is likely that a threaded pipe nipple for this outlet will have to be removed at this time. If this outlet was the cold water connection, then it will be necessary to remove the dip tube. If the other connection is not plugged, it will be necessary to purchase an additional plug for this connection. Plug the water connection that is not in use.

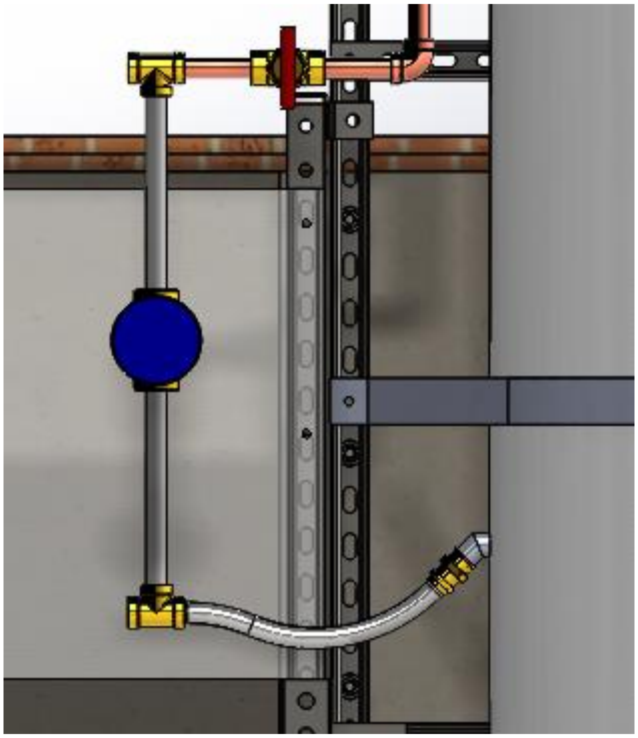
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 12 | 1.03.01.01 Cu_L_i<br>1.03.15.00 ¾ Cu Tee Connection<br>1.03.01.02 Cu_L_1<br>1.03.04.00 ¾ Cu 90 Elbows (x2)<br>1.03.01.03 Cu_L_2<br>1.03.01.04 Cu_L_3 (x2)<br>1.03.13.00 ¾ Cu Globe Valve, Solderable Ports | Copper pipe soldering toolkit |



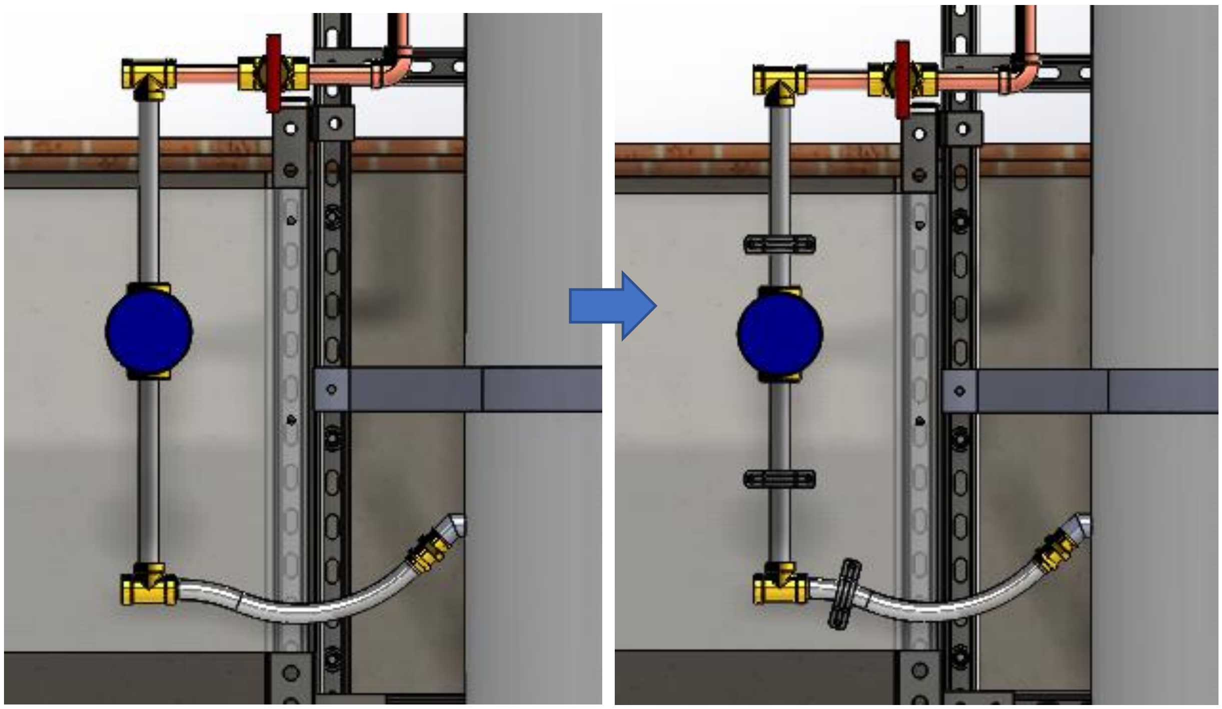


| |
|---|
| Instructions: Solder together the new components first, keeping all of the components coplanar and following the instructions from the Exploded Distribution document within the Drawing Package (Appendix T). Attach the whole assembly to the ¾ NPT to ¾ Cu, F adaptor from step 12. |

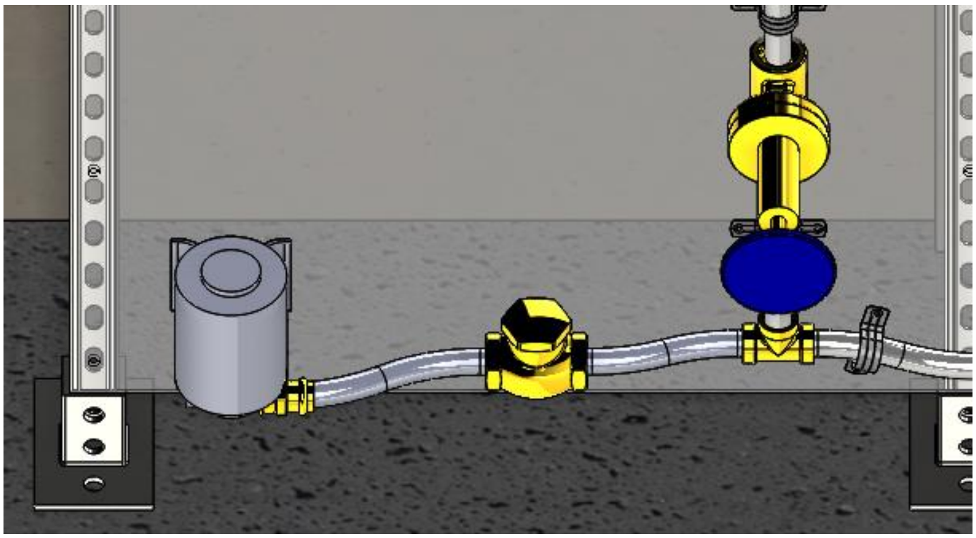
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 13 | 1.03.10.00 ¾ PEX and ¾ Cu Tee Connection (x2)<br>1.03.02.08 PEX_Bypass<br>1.03.09.00 ¾ PEX Ball Valve<br>1.03.02.07 PEX_4<br>1.03.07.00 ¾ PEX to ¾ NPT, F<br>1.03.03.00 Pipe Insulation<br>1.03.05.00 ¾ Garden to ¾ PEX | PEX piping equipment |

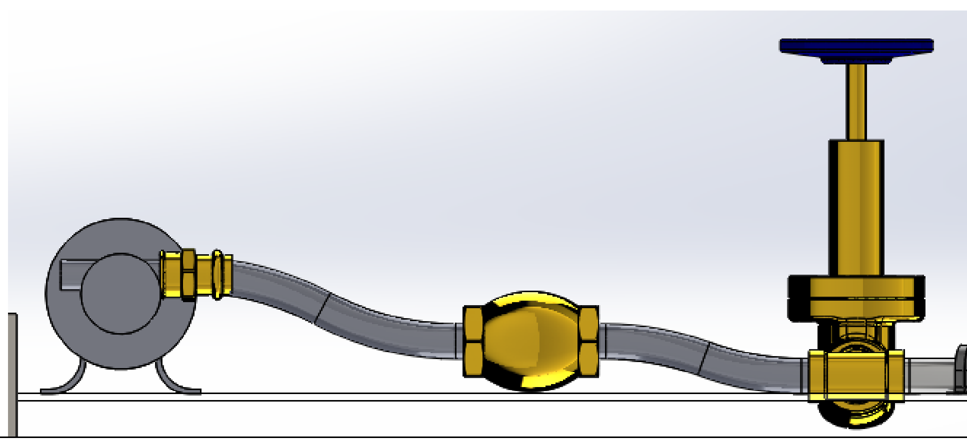


Instructions: Attach the components as shown, following the instructions from the Exploded Distribution document within the Drawing Package (Appendix T). PEX_4 may need to be cut to a longer length to accommodate the positioning of the water heater drain. Ensure the radius of curvature for the PEX piping is greater than 7 inches. Insulate all of the newly added piping after assembly.
NOTE: Part 1.03.05.00 may need to be exchanged with a ¾ PEX to ¾ NPT adaptor, depending on the drain pipe of the water heater purchased.

<table>
<tr><td>Step No.</td><td>Parts Needed:</td><td>Equipment Needed:</td></tr>
<tr><td>14</td><td>1.05.08.00 Routing Clamps 1.25” Diameter (x3)<br>1.05.10.00 ¼-20x0.75 Bolts (x6)<br>1.05.11.00 ¼-20 Nuts (x6)</td><td>Hand drill, 0.25” bit, wrench for ¼-20 nut, marker</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">Instructions: Attach Routing Clamps to the piping. The recommended positioning is shown, but the exact positioning is left to the discretion of the installer. It is recommended that the Routing Clamps be positioned, their holes marked, and then subsequently drilled.</td></tr>
</table>

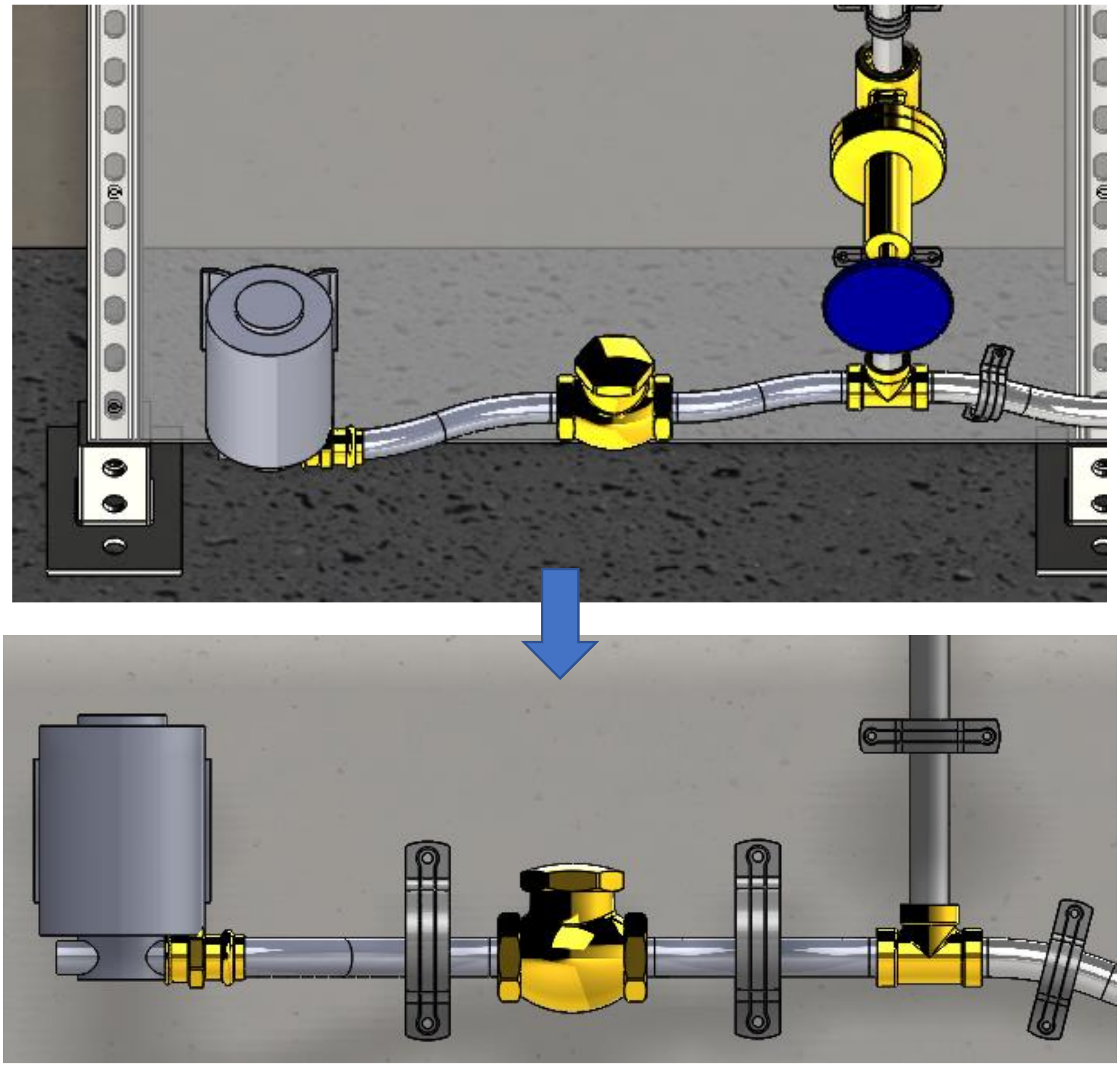
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 15 | 1.03.17.00 0.10 hp Wayne PC2 Pump<br>1.03.02.05 PEX_2<br>1.03.06.00 ¾ PEX Check Valve<br>1.03.02.06 PEX_3<br>1.05.10.00 ¼-20x0.75 Bolts (x4)<br>1.05.11.00 ¼-20 Nuts (x4)<br>1.03.03.00 Pipe Insulation<br>1.03.05.00 ¾ Garden to ¾ PEX | Hand drill, 0.25" bit, wrench for ¼-20 nut, PEX piping equipment |





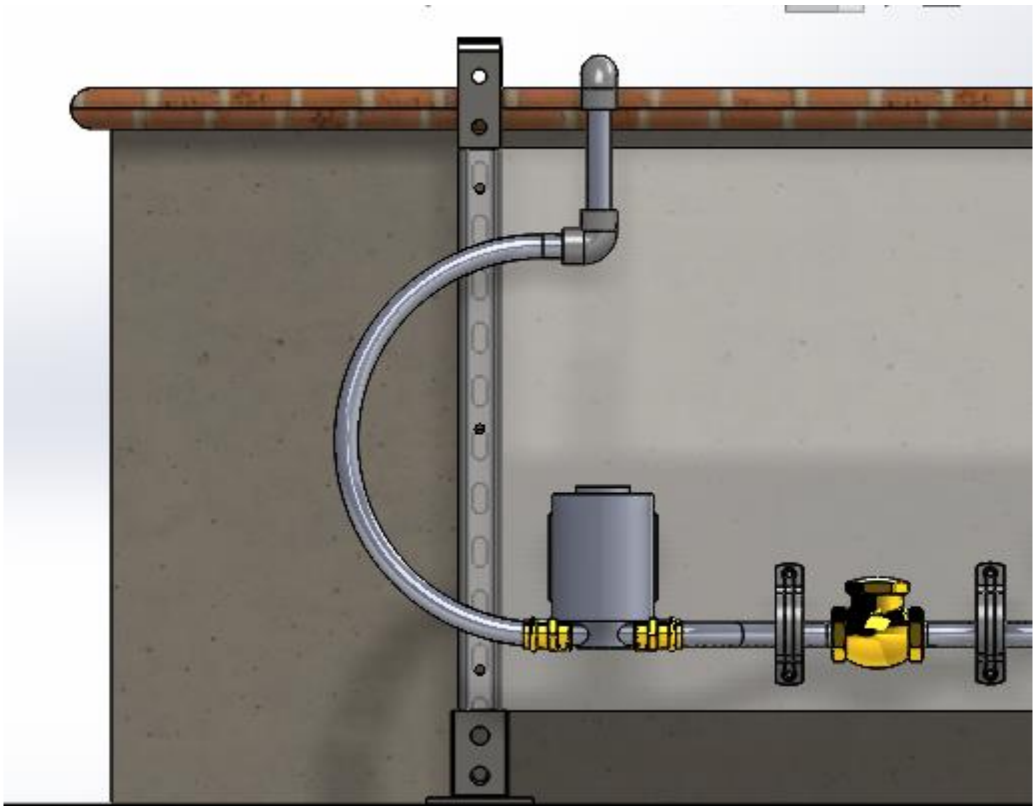
Instructions: Attach the components as shown, following the instructions from the Exploded Distribution document within the Drawing Package (Appendix T). We recommend mounting the pump first and then the other components. The exact positioning of the pump is left to the discretion of the installer, but the components should be installed such that the radius of curvature of the PEX piping is greater than 7 inches

| Step No. | Parts Needed: | Equipment Needed: |
| --- | --- | --- |
| 16 | 1.05.09.00 Routing Clamps 2” Diameter (x2)<br>1.05.10.00 ¼-20x0.75 Bolts (x4)<br>1.05.11.00 ¼-20 Nuts (x4) | Hand drill, 0.25” bit, wrench for ¼-20 nut, marker |

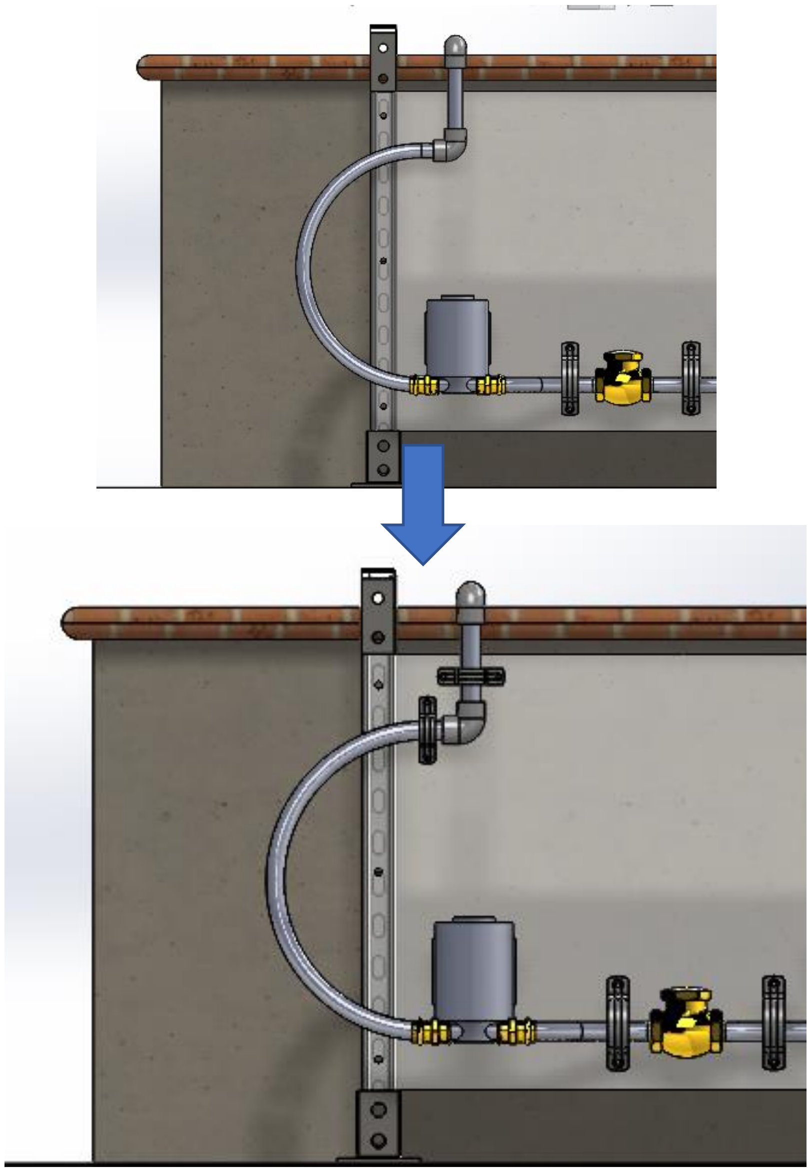


Instructions: Attach Routing Clamps to the piping. The recommended positioning is shown, but the exact positioning is left to the discretion of the installer. It is recommended that the Routing Clamps be positioned, their holes marked, and then subsequently drilled.

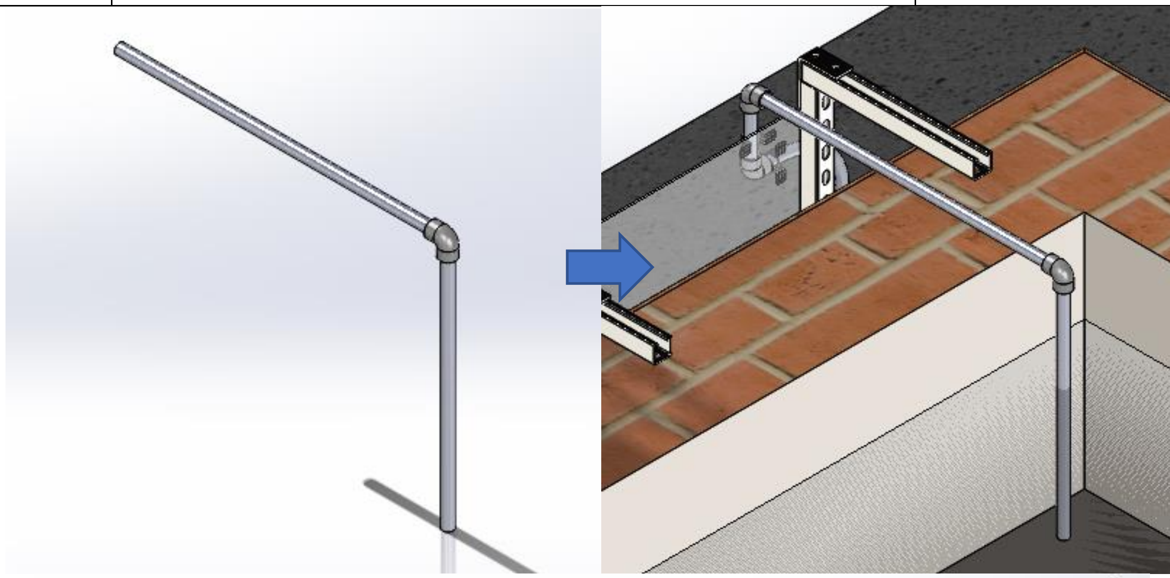
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 17 | 1.03.02.04 PEX_1<br>1.03.04.00 ¾ PEX 90 Elbows<br>1.03.02.03 PEX_0<br>1.03.03.00 Pipe Insulation<br>1.03.05.00 ¾ Garden to ¾ PEX | PEX piping equipment, measuring tape |

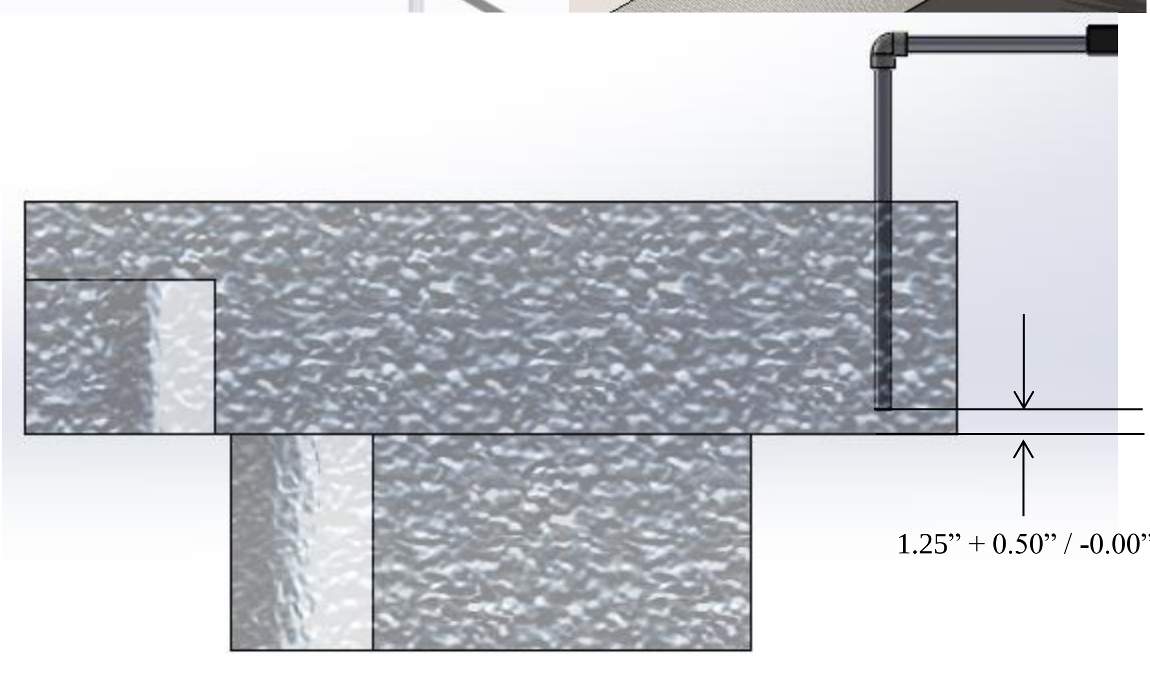


Instructions: Attach the components as shown, following the instructions from the Exploded Distribution document within the Drawing Package (Appendix T). The ends of the PEX piping should be placed at least 14.5” apart to prevent a radius of curvature damaging to the PEX. The newly installed pipes should be insulated after assembly.

<table>
<tr><td>Step No.</td><td>Parts Needed:</td><td>Equipment Needed:</td></tr>
<tr><td>18</td><td>1.05.08.00 Routing Clamps 1.25” Diameter (x2)<br>1.05.10.00 ¼-20x0.75 Bolts (x4)<br>1.05.11.00 ¼-20 Nuts (x4)</td><td>Hand drill, 0.25” bit, wrench for ¼-20 nut, marker</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">Instructions: Attach Routing Clamps to the piping. The recommended positioning is shown, but the exact positioning is left to the discretion of the installer. It is recommended that the Routing Clamps be positioned, their holes marked, and then subsequently drilled.</td></tr>
</table>

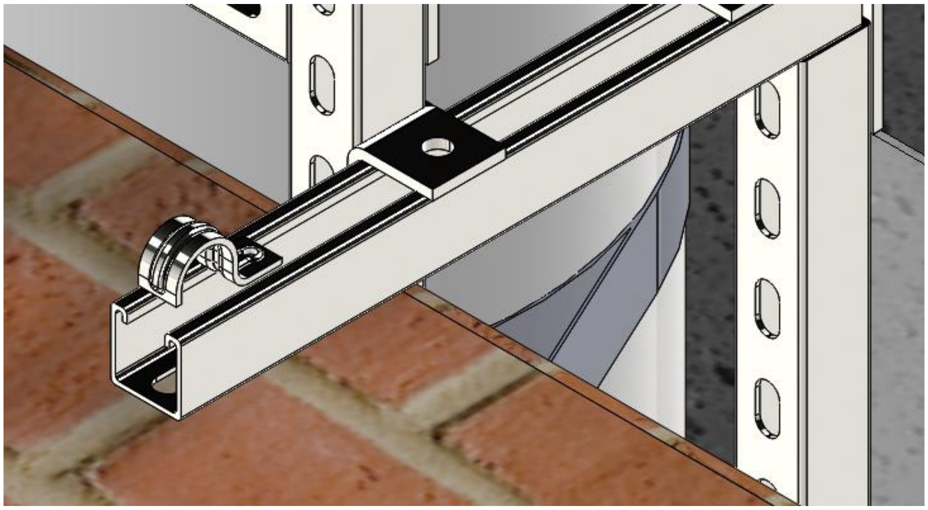
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 19 | 1.03.02.02 PEX_-1<br>1.03.04.00 ¾ PEX 90 Elbows<br>1.03.02.01 PEX_-2 | PEX piping equipment, measuring tape |

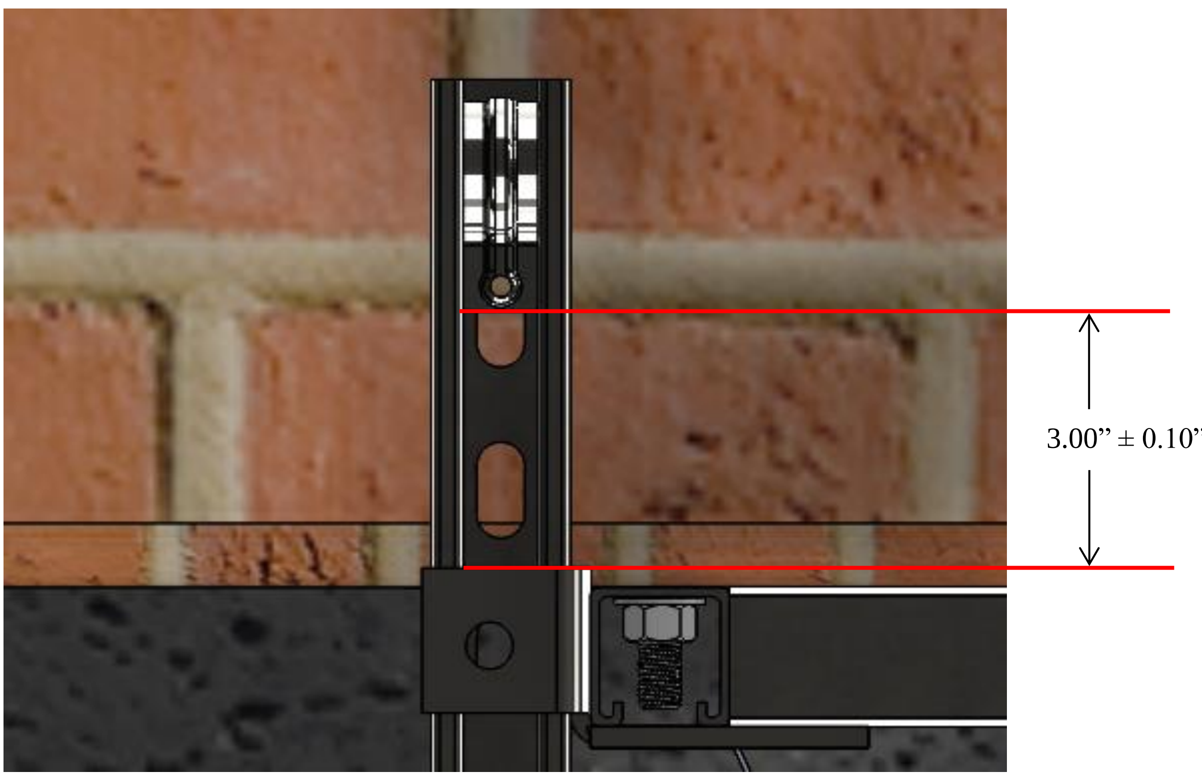





Instructions: Assemble PEX_-1 and PEX_-2 as shown, following the instructions from the Exploded Distribution document within the Drawing Package (Appendix T). After these components are connected, connect with the rest of the assembly, ensuring the bottom of the inlet pipe is approximately 1.25” from the local bottom of the tub.

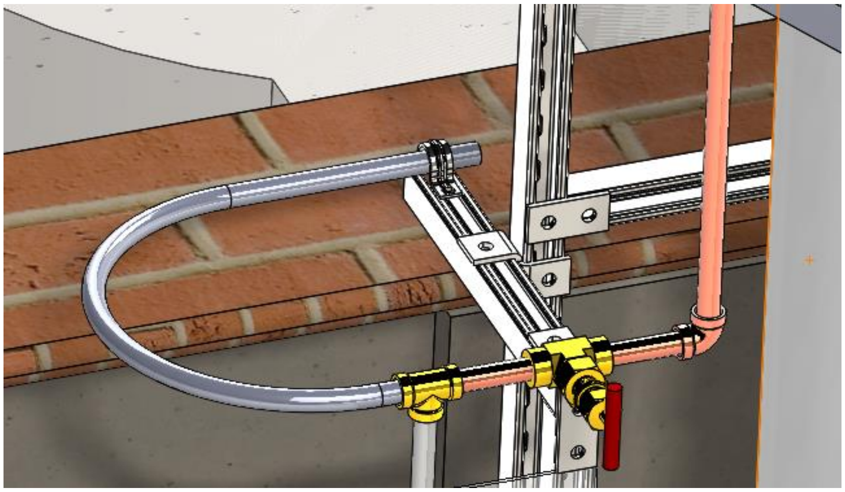
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 20 | 1.05.14.00 One-Sided Routing Clamps<br>1.05.07.00 Unistrut P1006-1420<br>1.05.10.00 ¼-20x0.75 Bolts | Philips head screwdriver, measuring tape |

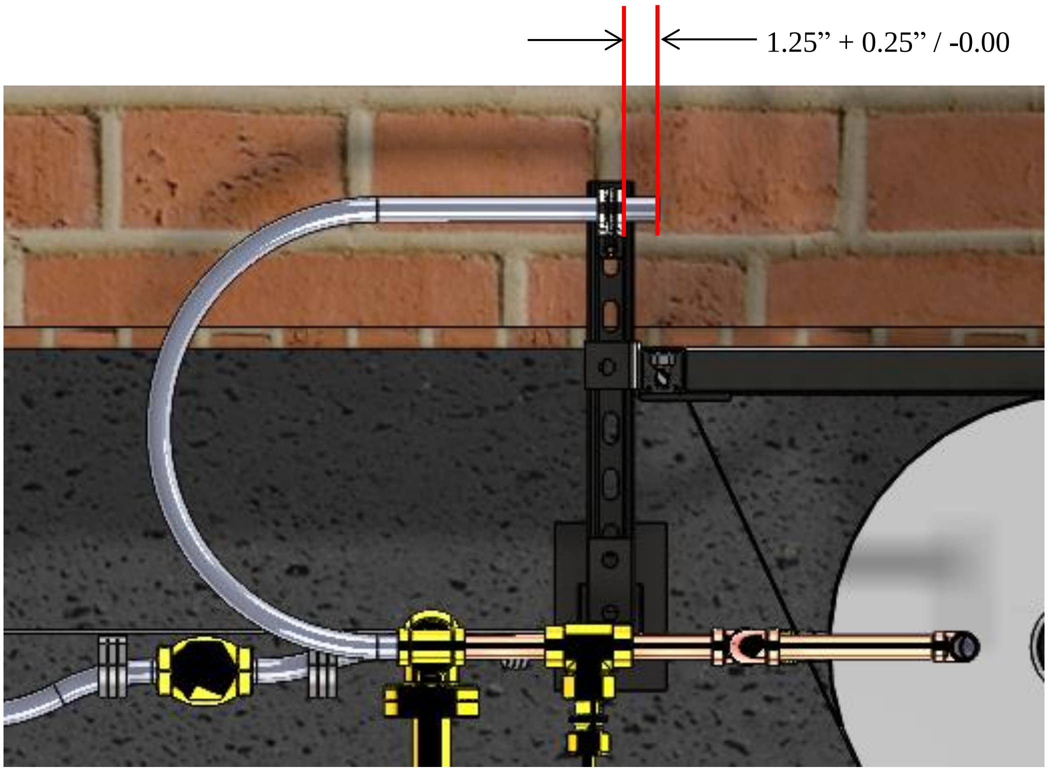





Instructions: Affix a One-Sided Routing Clamp to the right Horizontal Leg so that the edge of its base is approximately 3” from the closest side of the Unistrut P2343L fitting.

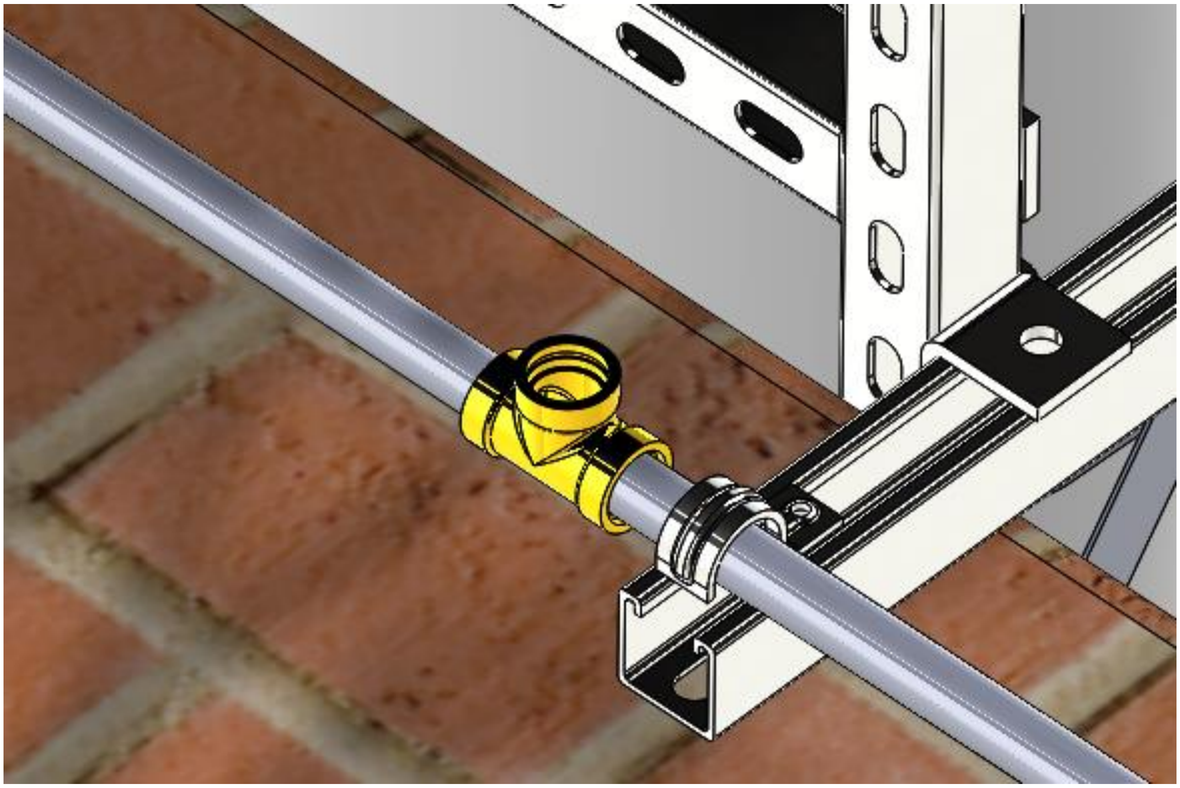
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 21 | 1.03.02.09 PEX_5 | PEX piping equipment, measuring tape |





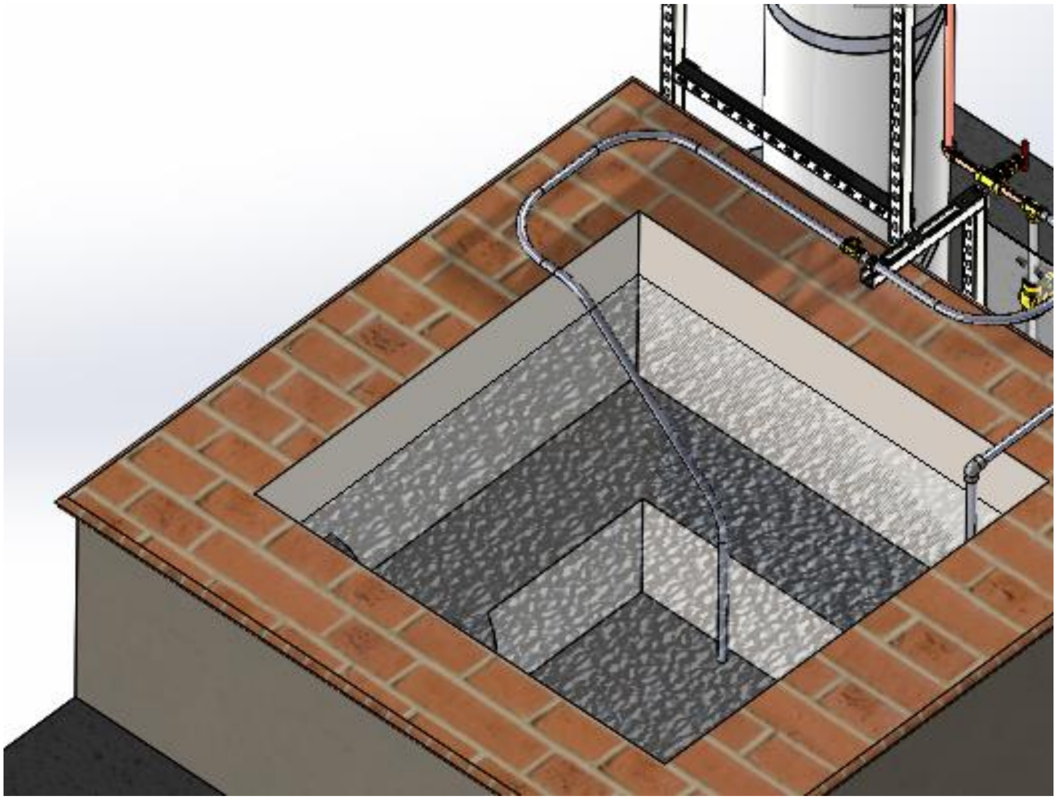

Instructions: Attach PEX_5 through this One-Sided Routing Clamp to the tee connection at the bypass junction. Ensure that at least 1.25” of piping sticks out past the routing clamp.

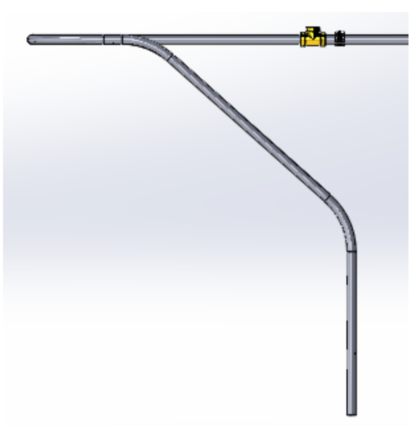
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 22 | 1.03.10.00 ¾ PEX and ¾ Cu, F Tee Connection | PEX piping equipment |

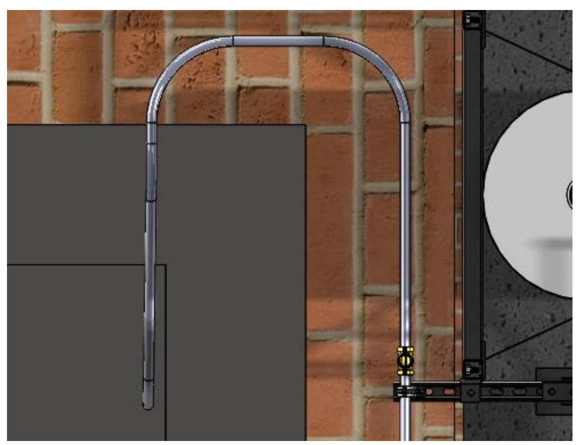


Instructions: Attach the component as shown. Ignore the pictured PEX_6 piping until Step 23.

| Step No. | Parts Needed: | Equipment Needed: |
| --- | --- | --- |
| 23 | 1.03.02.10 PEX_6 | PEX piping equipment, measuring tape. |

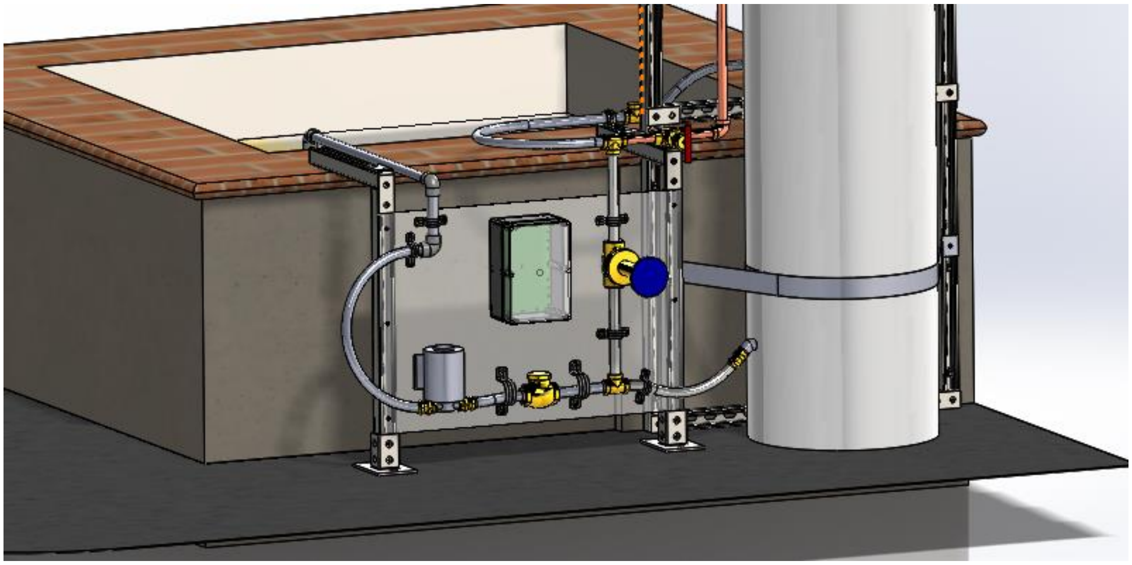


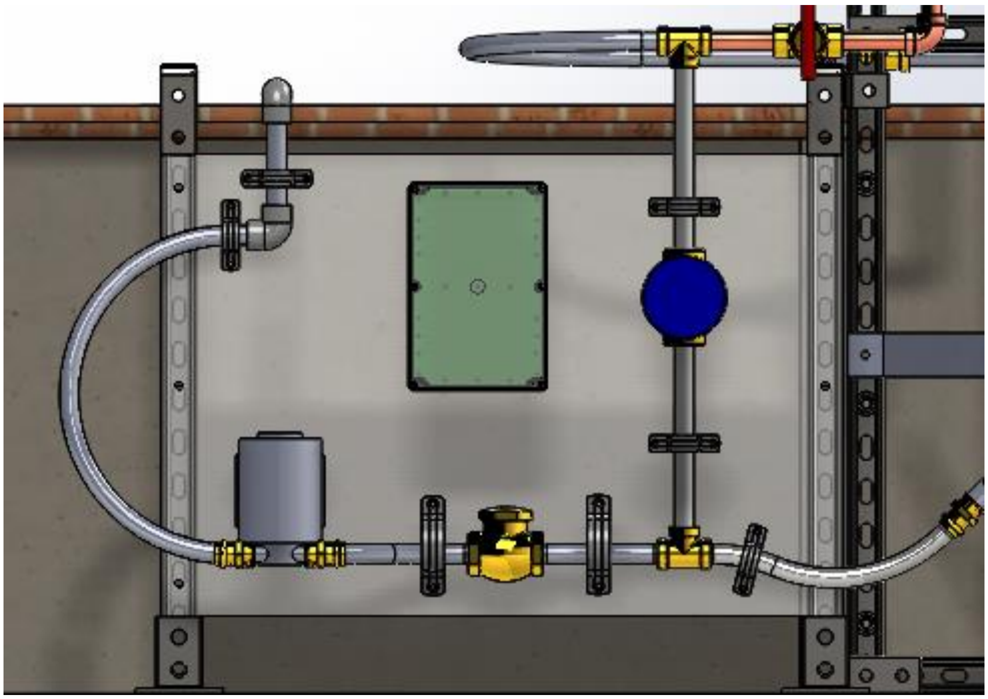




Instructions: Attach the component as shown. Ensure that no portion of the pipe has a radius of curvature less than 7 inches, and that the bottom of the inlet pipe is approximately 1.25” from the absolute bottom of the tub.

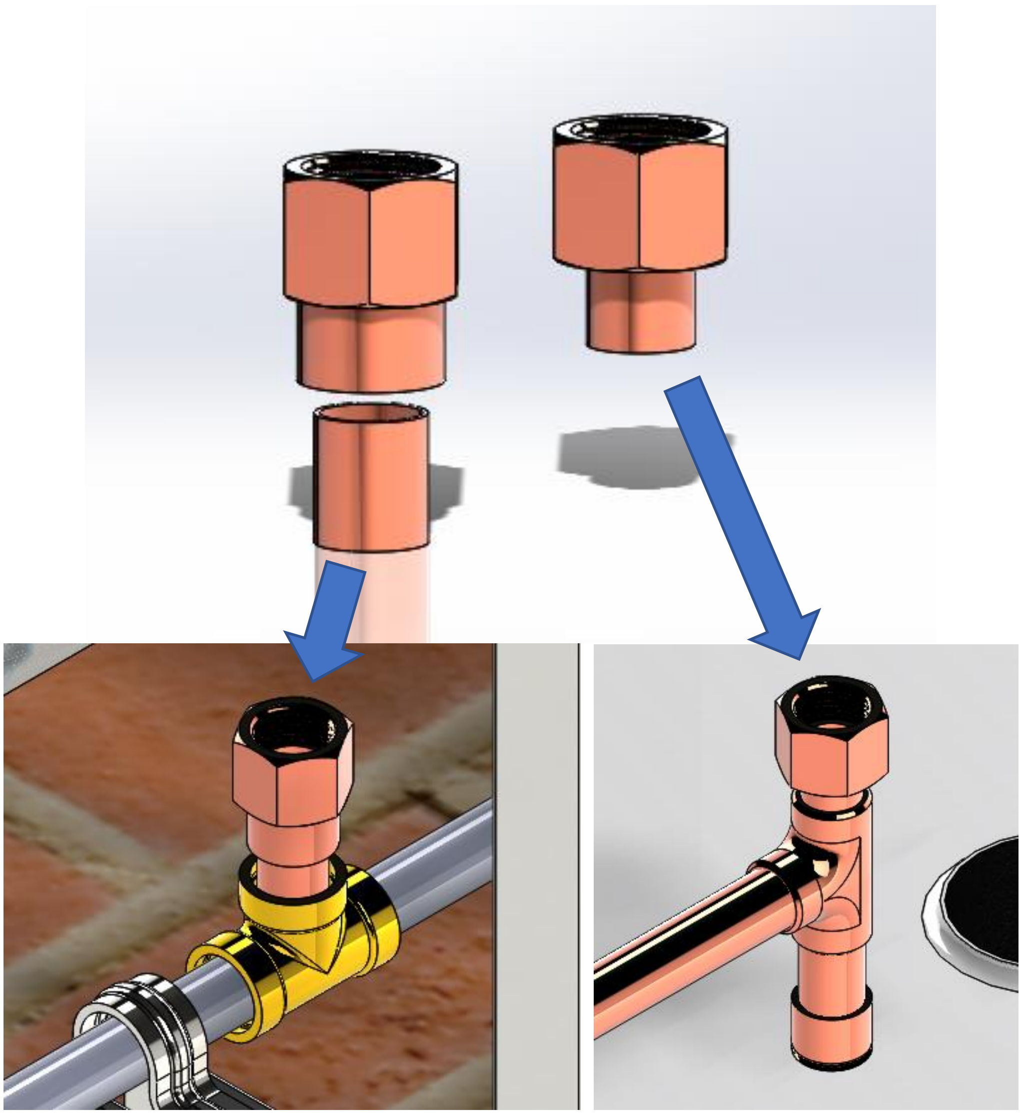
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 24 | 1.04.00.00 Control System<br>1.05.10.00 ¼-20x0.75 Bolts (x4)<br>1.05.11.00 ¼-20 Nuts (x4) | Hand drill, 0.25” bit, wrench for ¼-20 nut, marker |





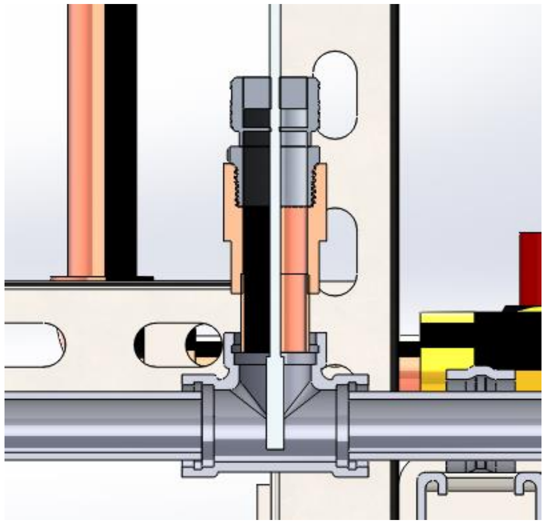
Instructions: Mount the Control System. The recommended positioning is shown, but the exact positioning is left to the discretion of the installer. It may be desirable to mount it further up on the acrylic support in order to reduce the length of the temperature sensor and MOSFET lines. NOTE: the CAD model shown does not display the components contained within.

| Step No. | Parts Needed: | | Equipment Needed: |
|---|---|---|---|
| 25 | 1.03.01.05<br>1.03.14.00<br>1.03.15.00 | Cu_L_Sensor<br>¾ Cu,F to ¾ NPT,F<br>¾ Cu,M to ¾ NPT,F | Copper pipe soldering toolkit |

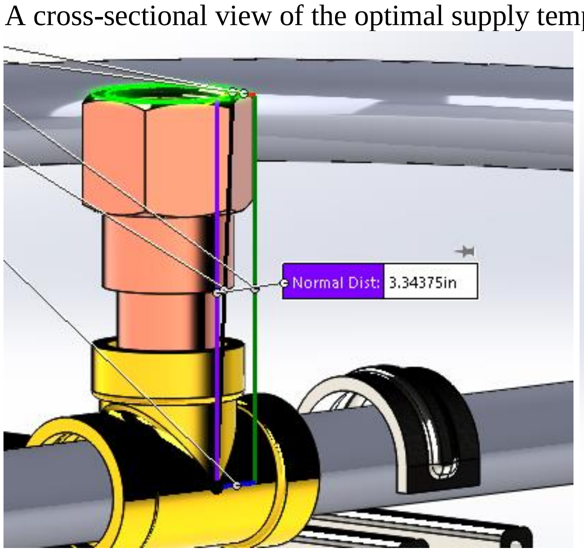


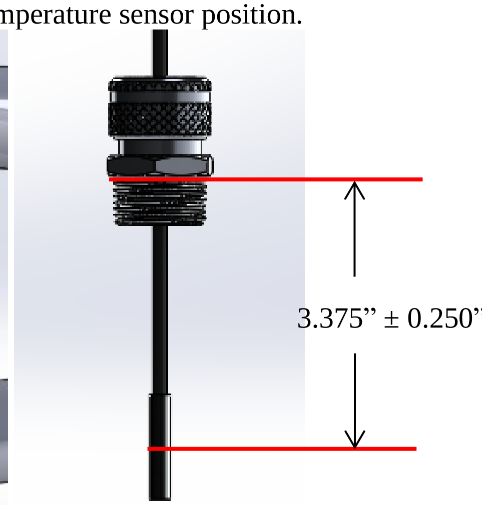
Instructions: Solder the ¾ Cu,F to ¾ NPT,F connector to Cu_L_Sensor. Attach that to the ¾ PEX and ¾ Cu,F Tee connection. Solder the ¾ Cu,M to ¾ NPT,F adaptor directly to the ¾ Cu Tee Connection.

| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 26 | 1.03.18.00 ¾ NPT,M to 4m Cord Grip<br>1.04.12.00 DS18B20 (Temperature Sensor) | Crescent Wrench, wire splicing tools, calipers |



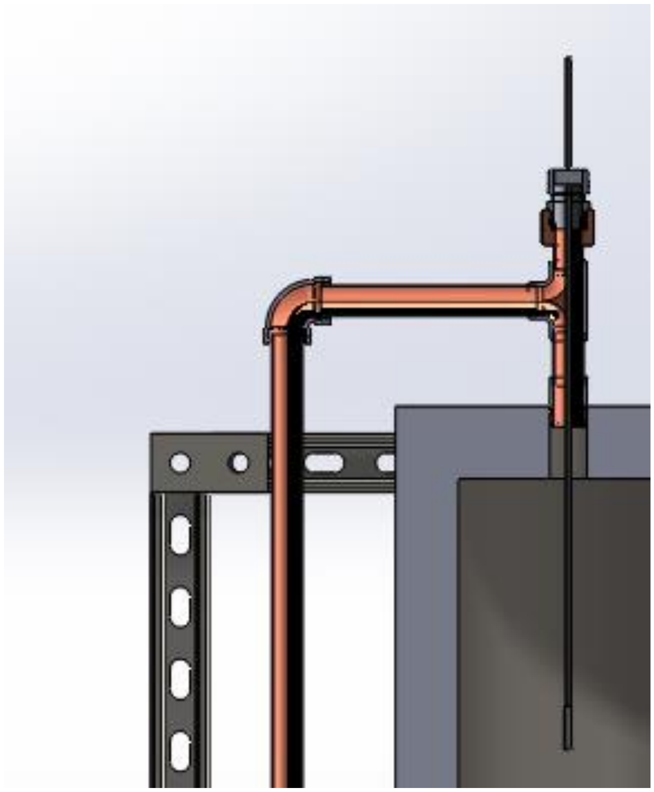
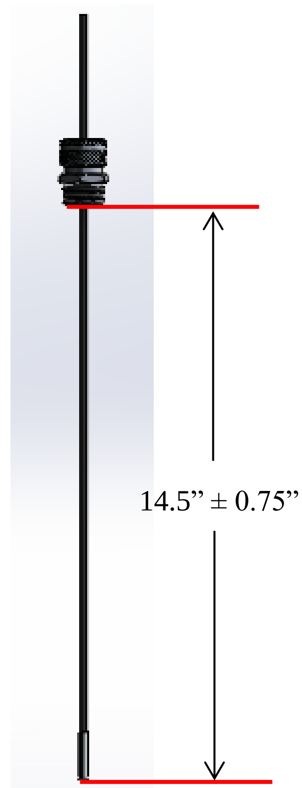
A cross-sectional view of the optimal supply temperature sensor position.



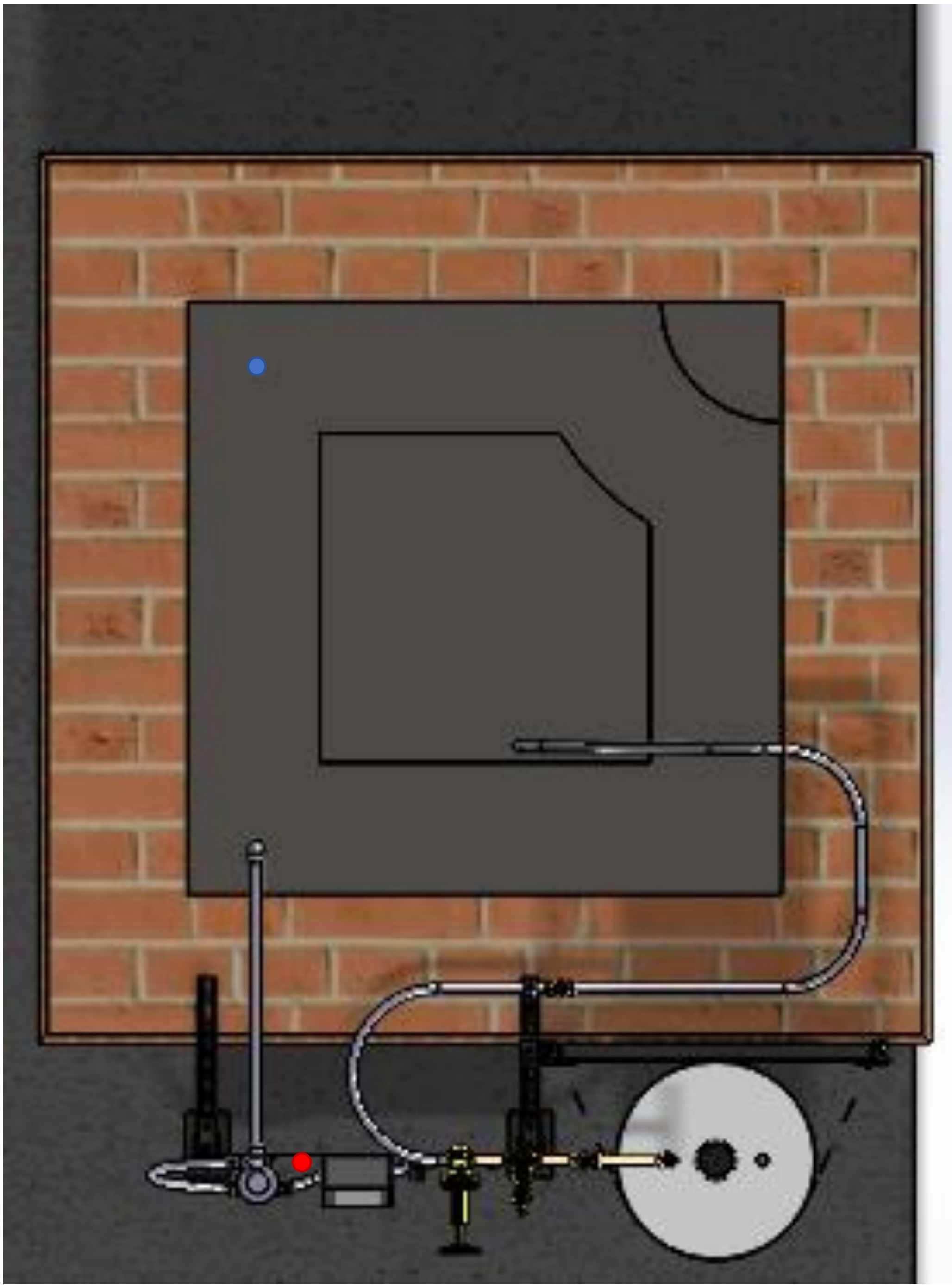




If the caliper reading on the left were to be obtained, the dimension on the left would be the proper positioning.

Instructions: The midpoint of the supply temperature sensor should fall approximately at the midpoint of the ¾ PEX and ¾ Cu,F Tee Connection along the supply water line.
Using calipers, measure the depth from the top of the copper adaptor fitting to approximately the midpoint of the Tee Connection. The midpoint of the supply temperature sensor should be secured at a similar distance from the top of the threaded section of the cord grip.
Thread the Cord Grip into the ¾ Cu,F to ¾ NPT,F adaptor, splicing the cord if more length is necessary.

<table>
<tr><td>Step No.</td><td>Parts Needed:</td><td>Equipment Needed:</td></tr>
<tr><td>27</td><td>1.03.18.00 ¾ NPT,M to 4m Cord Grip<br>1.04.12.00 DS18B20 (Temperature Sensor)</td><td>Crescent Wrench, wire splicing tools</td></tr>
<tr><td colspan="3"> </td></tr>
<tr><td colspan="3">Instructions: The midpoint of the temperature sensor for the tank should be submerged at least 8 inches beneath the top of the tank.<br>To achieve approximately this depth, secure the tip of the temperature sensor approximately 14.5 inches from the bottom of the threads on the cord grip.<br>Thread the Cord Grip into the ¾ Cu,F to ¾ NPT,F adaptor, splicing the cord if more length is necessary.</td></tr>
</table>

| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 28 | 1.04.12.00 DS18B20 (Temperature Sensor) | None |



Instructions: Place the tub (blue) and ambient (red) temperature sensors in locations approximately matching the positions shown.

| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 29 | 1.01.00.00 2000W Immersion Heater (x2) | Phillips screwdriver, heating element wrench, other tools recommended by manufacturer. |
| (This part was not included in the CAD model of the design.) | | |
| Instructions: Following the water heater Manufacturer's instructions, install the two 2000W Immersion Heater elements to the water heater. | | |

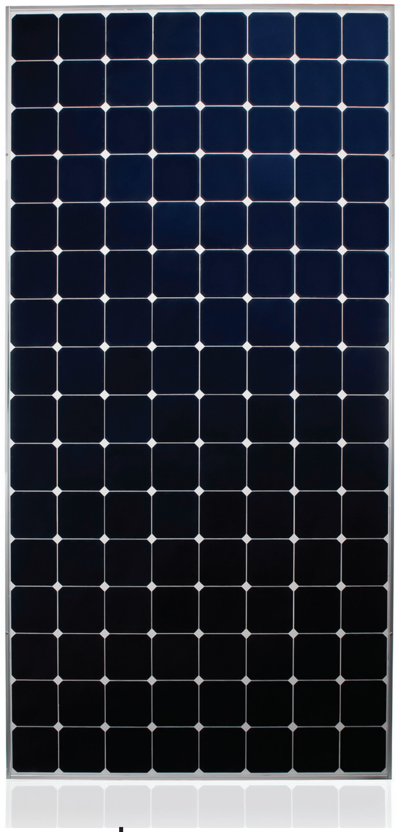
| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 30 | N/a | N/a |
| (This part was not included in the CAD model of the design.) | | |
| Instructions: Hire an electrician or other licensed professional to connect the solar panel wire lines to the control system, consistent with the wiring diagrams in Appendix S. Keeping the function of our wiring schematic in mind, they are free to (and encouraged to) add any additional safety features to the system that they see fit. The electrical safety of our system is of parmount importance to our team. | | |

| Step No. | Parts Needed: | Equipment Needed: |
|---|---|---|
| 31 | N/a | N/a |
| (This part was not included in the CAD model of the design.) | | |
| Instructions: Ensure that the TPR valve can discharge safely in the event of water heater overheating. | | |

SUNPOWER

# E19 / 425 SOLAR PANEL

MAXIMUM EFFICIENCY AND PERFORMANCE



E19 SERIES

## BENEFITS

**Highest Efficiency**
SunPower™ Solar Panels are the most efficient photovoltaic panels on the market today.

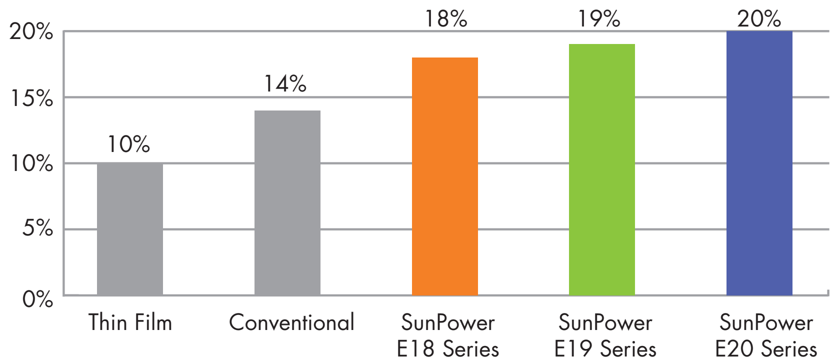
**More Power**
Our panels produce more power in the same amount of space—up to 50% more than conventional designs and 100% more than thin film solar panels.

**Reduced Installation Cost**
More power per panel means fewer panels per install. This saves both time and money.

**Reliable and Robust Design**
Proven materials, tempered front glass, and a sturdy anodized frame allow panel to operate reliably in multiple mounting configurations.

**A new standard for power plants.**
The SunPower® 425 Solar Panel provides today's highest efficiency and performance. Utilizing 128 back-contact solar cells, the SunPower 425 delivers a total panel conversion efficiency of 19.7%. The panel's reduced voltage-temperature coefficient, anti-reflective glass and exceptional low-light performance attributes provide outstanding energy delivery per peak power watt.

**SunPower's High Efficiency Advantage**




SPR-425E-WHT-D

# E19 / 425 SOLAR PANEL

SUNPOWER

MAXIMUM EFFICIENCY AND PERFORMANCE

## Electrical Data

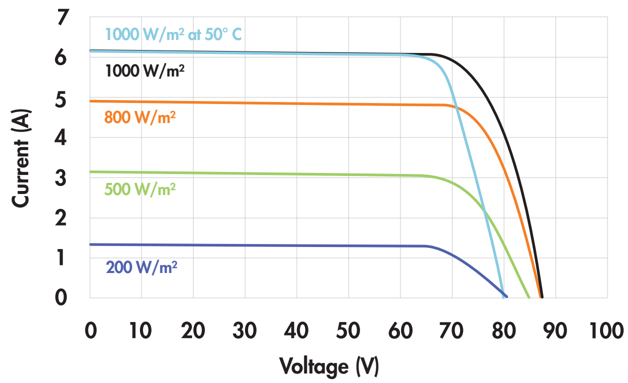
Measured at Standard Test Conditions (STC): irradiance of 1000W/m², AM 1.5, and cell temperature 25° C

| | | |
|---|---|---|
| Peak Power (+/-5%) | $P_{max}$ | 425 W |
| Efficiency | η | 19.7 % |
| Rated Voltage | $V_{mpp}$ | 72.9 V |
| Rated Current | $I_{mpp}$ | 5.83 A |
| Open Circuit Voltage | $V_{oc}$ | 85.6 V |
| Short Circuit Current | $I_{sc}$ | 6.21 A |
| Maximum System Voltage | UL | 600 V |
| Temperature Coefficients | Power (P) | -0.38% / K |
| | Voltage ($V_{oc}$) | -235.5mV / K |
| | Current ($I_{sc}$) | 3.5mA / K |
| NOCT | | 45° C +/-2° C |
| Series Fuse Rating | | 20 A |

## Mechanical Data

| | |
|---|---|
| Solar Cells | 128 SunPower all-back contact monocrystalline |
| Front Glass | High transmission tempered glass with anti-reflective (AR) coating |
| Junction Box | IP-65 rated with 3 bypass diodes Dimensions: 32 x 155 x 128 (mm) |
| Output Cables | 700 mm cables/ Multi-Contact (MC4) compatible connectors |
| Frame | Anodized aluminum alloy type 6063 (silver); stacking pins |
| Weight | 56.0 lbs. (25.4 kg) |

## I-V Curve




Current/voltage characteristics with dependence on irradiance and module temperature.

## Tested Operating Conditions

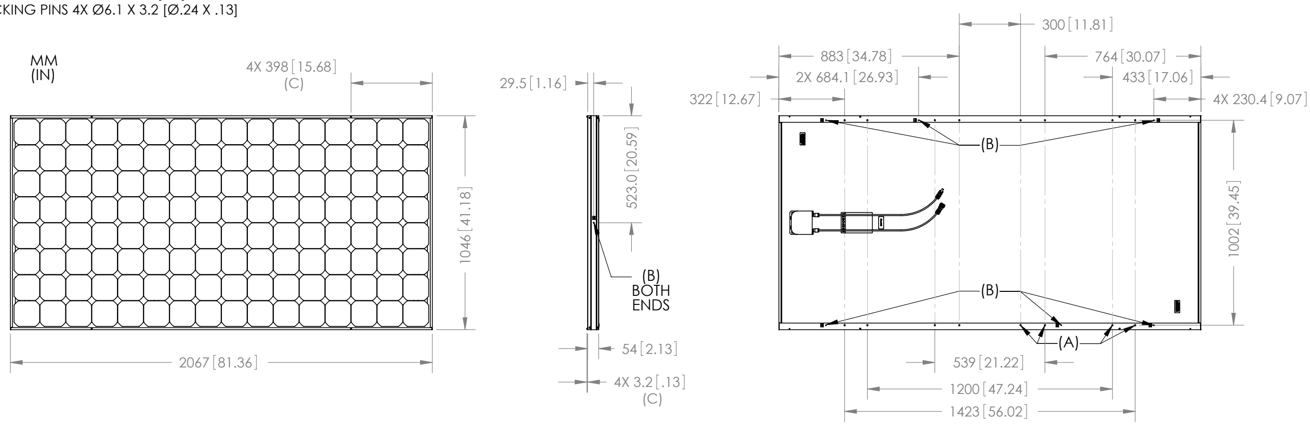
| | |
|---|---|
| Temperature | -40° F to +185° F (-40° C to + 85° C) |
| Max load | 50 psf (245 kg/m² ) (2400 Pa) front and back – e.g. wind |
| Impact Resistance | Hail 1 in (25 mm) at 52mph (23 m/s) |

## Warranties and Certifications

| | |
|---|---|
| Warranties | 25 year limited power warranty |
| | 10 year limited product warranty |
| Certifications | Tested to UL 1703. Class C Fire Rating |

## Dimensions

(A) - MOUNTING HOLES 16X Ø6.6 [.26]
(B) - GROUNDING HOLES 8X Ø4.2 [.17]
(C) - STACKING PINS 4X Ø6.1 X 3.2 [Ø.24 X .13]




**CAUTION: READ SAFETY AND INSTALLATION INSTRUCTIONS BEFORE USING THE PRODUCT.**

Visit sunpowercorp.com for details





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Document #001-67015 Rev*A / LTR_EN

## APPENDIX W: OPERATOR'S MANUAL

### Safety Hazards

As with any hot tub, or water heating system, there is a risk associated with prolonged exposure to very hot water, and *any* exposure to water which is nearly boiling. The hazards which were determined during the design phase can be found in the Design Hazard Checklist document, or Appendix G.

In addition to those mentioned, there are additional hazards due to the intricate control system. All electrical components are enclosed in an IP65 rated splash proof housing, and all power should be disconnected before opening enclosures for maintenance. Any maintenance on the primary power supply from either the house or solar panels should only be done by the user and will not be conducted by students.

### System Startup

Step 1: Controls verification

All programming work shall be done by the senior project design team, and the delivered package will arrive to the customer pre-tested and verified. However, to make sure the system is able to correctly work on the field, further verification is needed. First, place the control module (splash-proof enclosure) in a safe area where it cannot be knocked over. Attach the temperature sensors into their different locations as specified in the Assembly section of the Final Design Report. Ensure that microcontroller is plugged into the "ALWAYS ON" port on the IoT relay and the Arduino data logger shield has a pill battery installed. Check that the temperatures are being recorded properly and that the ranges make sense.

Step 2: Valve Commission

It is important to achieve the correct mixing ratio which will allow safe temperature for the mixed water inlet. The system does not need to be fully charged for this to work, however there should be at least a 20°F temperature differential between the storage tank and tank water. Allow both water sources to flow, and adjust valves until mixed temperature fits the following equation:

$$T_{mix} = \frac{3 * T_{Tub} + T_{Tank}}{4}$$

*(this should have the same effect as a 3:1, tub:tank mixing ratio)
Once the valves are in this position, the system will be set up so that the ideal mixing temperature is reached at operating temperatures. Lock valves in position.

Step 3: Final Securing

Set microcontroller into passive mode (green LED should be off). Ensure that all components are secured, and in appropriate enclosures. At different times for the proceeding days, check by hand the temperature of the tub, and ensure that it is comfortable.

**System Operation**

Using the Ra Energy hot tub heating system is a straightforward process. The microcontroller works diligently to ensure that the water temperature of the tub and supply lines is maintained at a comfortable temperature. Follow the listed steps to use your system:

1. Ensure that the power cable leading to the control box is plugged in and insulated from splashing water.
2. Looking through the clear cover of the control box enclosure, ensure all the wires within are secured (no loose connections are visible)
3. Follow the four temperature sensor wires from the control box to their respective locations (water heater, submerged in tub, supply line to tub, open air). Ensure that no temperature sensors have been pulled/removed from their appropriate enclosures.
4. Visually inspect the water heater and its supply lines, looking for leaks. If a leak is found, do not use the water heating system until the system has been repaired.
5. After verifying that all the cables, sensors, and plumbing are appropriately connected, push the button on the side of the control box to set the system to Active Mode. The Green LED will indicate that the system has entered Active Mode.
6. Wait approximately 30 minutes for the heating system to bring the tub to its desired temperature. We recommend that the user remain outside of the tub while it is heating.
7. After enjoying the hot tub, the Ra Energy hot tub heating system will automatically re-enter Standby Mode
8. For best results, wait 2-3 sunny days before utilizing the system again.

The Ra Energy hot tub heating system should not be used during inclement weather. During inclement weather, please remove the Pump from the rest of the system and place it in a dry location.

**Maintenance/Troubleshooting**

Maintenance of the Ra Energy hot tub heating system is potentially hazardous and should be attempted with caution. ANY REPAIRS ASSOCIATED WITH THE POWER SUPPLY SHOULD ONLY BE ATTEMPTED BY AN A CERTIFIED ELECTRICIAN OR A SOLAR POWER INSTALLER.

| PROBLEM | SOLUTION |
|---|---|
| The pipes are leaking | Turn off the heating system. Wait 2-3 days for the water heater temperature to drop to safe levels. Disconnect the leaking components, examine the connections. Replace any faulty connections and re-attach using fresh components. If a pipe has split open, replace the pipe length with an identical portion of pipe. |
| The water heater is leaking | DO NOT ATTEMPT TO REPAIR THE WATER HEATER. Contact a licensed plumber / water heater installation professional to have them troubleshoot and repair the water heater in the event of a malfunction. |
| The water heater temperature and pressure valve is leaking | TURN OFF THE WATER HEATING SYSTEM. Hire an electrician to **safely** disconnect one of the heating elements from the power supply. |
| The supply water keeps tripping the pump shut-off | Being cautious of hot pipe connections, close the hot-water supply valve slightly and re-enter Active Mode. If shut-off occurs again, repeat the process. |
| The water temperature is not hot enough | 1. <u>Heating element corrosion.</u> Hire an electrician to disconnect the power supply from the water heater heating elements. Allow 2-3 days for the water heater to cool, then remove the heating elements to check for corrosion. Replace heating elements as necessary.<br>2. <u>Improper insulation.</u> Visually inspect all piping and water heater insulation, ensuring that no piping is exposed. Ensure that the hot tub is covered during the day. Purchase insulation and repair as needed.<br>3. <u>Covered panels</u>. Ensure that the solar panels are clear of dust and debris. |
| The LED won't turn on during Active Mode | Remove the enclosure. Looking at the wiring diagram found in Appendix S, ensure that all of the connections are going to the proper pins / elements / sensors. |