INSULATED SOLAR ELECTRIC COOKER (ISEC) IMMERSION HEATER
Final Design Review

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Abstract

This report is the final design review (FDR) report for our team completing the Insulated Solar Electric Cooker (ISEC) Immersion Heater mechanical engineering senior project. The goal of this project is to standardize and perform analysis on a preexisting, inexpensive solar-powered immersion heater for cooking use in developing countries, reducing the adverse effects presented by traditional biomass cooking fires. We also designed a manufacturing process to improve repeatability and to reduce labor investment of heater production. The ISEC research team from the California Polytechnic State University Physics Department have been working on the development of this immersion heater and have produced working prototypes. Our task was to improve upon this design with a focus on conductive filler material and proper diode chain manufacturing, and to develop a manufacturing process that will allow these heaters to be made more efficiently and with fewer people in order to reduce manufacturing costs. As a result, we created specifications for the heater that that impacted the design and use of our manufacturing jig, which was created to aid the manufacture of the heater. Our preliminary analysis suggests that in order to extend heater lifetime and promote more effective heating of food, the temperature difference between the inside and the outside of the heater should be below 100℃. We were not able to produce heaters to meet this specification, but were able to make recommendations for how to proceed based on our findings. More detailed design specifications are included in this report, as well as background research and details regarding the manufacturing process for the immersion heater. With our manufacturing jig, our team was able to reduce the heater manufacturing time to approximately a quarter of the time taken previously. Additionally, our manufacturing jig allows for one person to perform the most cumbersome steps of the process alone. Also included are the final design, manufacturing plan, and cost analysis for a manufacturing jig to aid in heater manufacturing.

1 Introduction

This senior project team consists of four mechanical engineering students at California Polytechnic State University in San Luis Obispo (Cal Poly), and will be working with our sponsor, Dr. Peter Schwartz, to continue research and development of inexpensive solar cookers as a senior project. Because household fires and indoor air pollution due to traditional biomass stoves are a growing concern in developing countries, our team hopes to provide an inexpensive and clean solution that alleviates these problems. The proposed Insulated Solar Electric Cookers (ISECs) are, therefore, anticipated to bring significant positive change in many developing countries where a large amount of energy is consumed by cooking food. By substituting our ISECs for the biomass stoves, we can reduce the danger involved with cooking over open flames. Additionally, it will provide a clean and inexpensive source of electricity for important functions such as charging cellular phones and lights in communities that otherwise could not afford it.

Our team was involved with the immersion heater project as a whole, but we chose to focus on the manufacturing method as we believed that would have the greatest impact on the heater's function and efficiency. Our specifications directly pertain to the heater, but impacted the design and use of the manufacturing jig.

This report contains background research on the existing immersion heaters, as well as potential improvements to the design and manufacturing processes. Our research includes information on diodes and filler materials in the context of improving heater function, as well as streamlining the manufacturing process and increasing ease-of-manufacturing. It also contains the plan of development we expect to follow through the 2018-2019 academic year, which should yield valuable data, a functional prototype of an immersion heater derived from the research already conducted by the ISEC student research team, and a semi-automated manufacturing process by the project's end date of June 2019.

2 Background

Note: More relevant information and additional patent research has been added since the previous submission of the Critical Design Review report.

A growing concern in underdeveloped countries is the adverse health effects caused by biomass cooking fires. An estimated 600,000 Africans die each year as a result of dangerous or inefficient cooking fuels and methods, and many more are affected by chronic illnesses including bronchitis and lung cancer [1]. Several solutions to this problem currently exist, but many have significant drawbacks. An inexpensive immersion heater has been developed by collaborators in Cal Poly's physics department as a solution to this issue. However, there are problems with the current manufacturing processes which result in unrepeatable results, specifically variance in size and shape of the heater, and non-functioning heaters. Our initial research for this project consisted of customer research, technical research, patent research, and project research.

2.1 Customer Research

The customers that our team is considering are women residing in underserved rural villages in Africa. Because cultures can vary greatly among these villages, we will likely consider people in Uganda where some ISEC units have already been deployed by Cal Poly students, or Malawi where the ISEC research collaborator Dr. Robert Van Buskirk is currently working on the implementation of ISEC devices.

Our team must also keep in mind who is intended to manufacture the heaters. In order to create jobs in underserved communities and decrease shipping costs, the heaters will be manufactured in Africa with materials and equipment available in nearby cities. With this in mind, we must design our manufacturing process to consist of less-advanced methods and equipment.

2.2 Technical Research

To gain a better understanding of the current manufacturing process and its setbacks, our senior project team participated in an immersion heater manufacturing demonstration. The ISEC collaborators from the physics department originally used a variety of processes for inserting the diode chain into the heater tube while inserting the filler material. When the process was demonstrated to us, a plastic container was filled with the filler material and we taped the heater tube to a part of the container that had a hole in it. The diode chain was then fed through the tube and filler material was simultaneously scooped into the tube. We applied vibrations to the tube by impacting it with a scrap piece of tubing. This process was cumbersome and there were evidently opportunities for improvement.

Technical research regarding the manufacturing of the ISEC immersion heater was centered on the materials used and design decisions made by previous designers in order to understand how ISEC has been developed up to this point. One critical element that Dr. Schwartz has stressed is the use of appropriate filler material inside of the immersion heater tubing. The previous ISEC research teams have found that mortar, which is cement mixed with sand, has worked better than many other materials with which they have experimented. Further research was done on the motivation for using diodes as heating elements as opposed to traditional heaters, as well as on effective manufacturing methods, with results listed below.

2.2.1 Diodes as Heating Elements

This project is unique in using diodes as heating elements. Typically, DC powered electric heaters consist of some resistive metal, such as nickel chromium (Nichrome) as the primary heat source. Previous iterations of heaters have been built using Nichrome, but this has since been abandoned in favor of the diode chain. The reason for this becomes evident when one takes into account how solar panels operate. Figure 1 shows a typical voltage-current output plot for a solar panel. There are three curves representing the output at different times of day. The lines starting at the origin and extending to the solar panel curves represent various resistors selected to optimize power dissipation for each of the three power curves; where they intersect the solar panel curves is the operating point of the system. However, when supplying DC power directly from a solar panel to a resistance heater, you must be able to vary the resistance of the heater in order to maximize power output because of the sun’s variations in position.

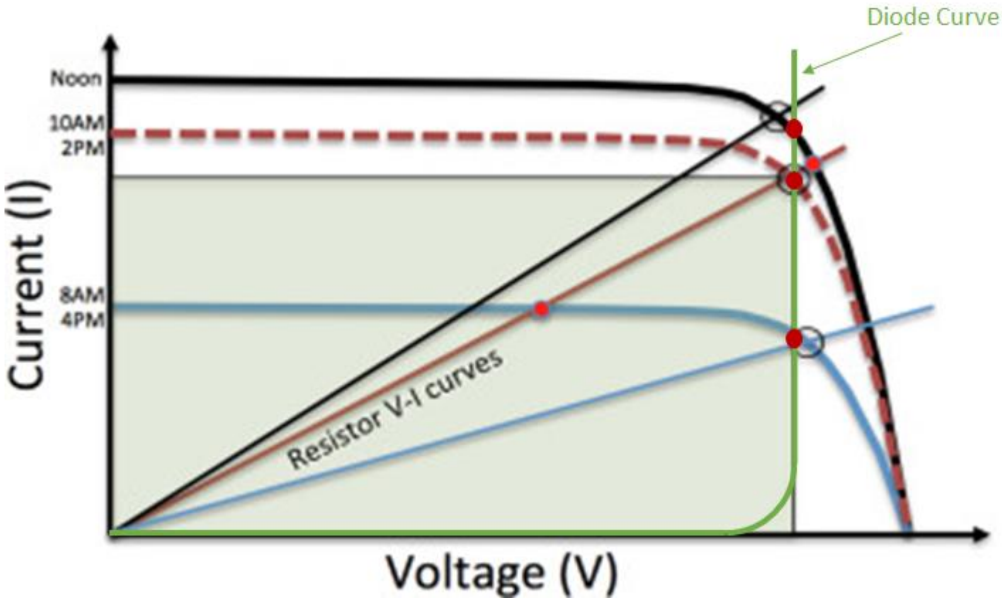


Figure 1. Current vs voltage curve [3]

A diode is an electrical component comprised of semiconductor material that only allows current to flow in one direction. Another convenient property of diodes is that they exhibit roughly uniform “voltage drop” as current flows, mostly regardless of the amount of current being conducted.

In this application, diodes are being used to generate heat, much like the resistive heaters. Where they excel however, is in the fact that you can string several diodes together in series to correspond to a specific voltage drop. This is represented on the solar panel curve as a exponential line, as is shown by the imposed green line on Figure 1. If the voltage drop across the diode chain is near the voltage of the optimal operating points, but not above, then the solar panel will be able to conduct current through the heater. Because the voltage drop and the current is the same across each diode in the series, this arrangement is conducive to even heat generation throughout the chain. You can see that the diode chain operates at near optimum power throughout the day from the diode chain curve added to Figure 1. Continued development is currently being done to allow adjustment of the heater for improved operation over a small range of voltages corresponding to solar panel power output variation at different times of day.

2.2.2 Soldering Methods

By twisting the leads of diodes together before soldering them into a chain, our team found that the diode chain was much more durable and easier to feed through the heater pipe during manufacturing. In addition, if the diode chain inside a finished heater was to become too hot and release the solder holding the leads together, the twisting of the leads would allow the diodes to maintain strong contact and prevent any issues associated with electrical shorting.

2.2.3 Pipe Bending Methods

Currently, the only way our team bends the filled heaters is with pipe benders. Though this method generally works, it is not easily repeatable or standardized. Also, the heater pipes can buckle in some cases through this method. We have found that the cracking and buckling of pipe is less common when the pipes are preheated as this makes the metal more malleable.

2.3 Product Research- Vibration Motors

Our team researched different products used to set concrete or help improve concrete flow, with a focus on vibrating components. Figure 2 below contains information on the vibration characteristics of vibrators used in various fields.

CHARACTERISTICS, PERFORMANCE, AND APPLICATIONS OF INTERNAL VIBRATORS

Group	Diameter of head, inches	Recommended frequency, vibrations per minute, while vibrator is in concrete	Recommended amplitude, inches*	Approximate radius of action inches**†	Approximate rate of placement, cubic yards per hour per vibrator‡	Use of vibrator
1	¾—1½	10,000—15,000	0.015—0.03	3—6	1—5	Plastic and flowing concrete in very thin members and confined places. May be used to supplement larger vibrators, especially in prestressed work where cables and ducts cause congestion in forms. Also used for fabricating laboratory test specimens.
2	1¼ —2½	9,000—13,500	0.02—0.04	5—10	3—10	Plastic concrete in thin walls, columns, beams, precast piles, thin slabs, and along construction joints. May be used to supplement larger vibrators in confined areas.
3	2—3½	8,000—12,000	0.025—0.05	7—14	6—20	Stiff plastic concrete (less than 3-inch slump) in general construction such as walls, columns, beams, prestressed piles, and heavy slabs. Auxiliary vibration adjacent to forms of mass concrete and pavements. May be gang mounted to provide full width internal vibration of pavement slabs.

* Measured or computed as described in Reference 1. This is the average of the values at the tip and back end, with the vibrator operating in air.
** Distance from vibrator over which concrete is fully consolidated.
† Assumes insertion spacing is 1½ times the radius of action, and vibrator operates two-thirds of time concrete is being placed.
‡ These ranges reflect not only the capability of the vibrator but also differences in workability of the mix, degree of deaeration desired, and other conditions experienced in construction.

Figure 2. Table showing common frequencies for application of vibration motors in various industries and fields

One concept employed in the construction industry is the use of internal vibration motors to help set large quantities of concrete [18]. By using large vibration motors that are inserted into the wet concrete, it is possible to “liquify” the concrete, pushing out all air bubbles and allowing it to set far better than without the added vibration. Our team plans to use this principle to aid in the insertion of filler material into the heater tube during the manufacturing process in order to reduce the need for several people during heater manufacturing.

While there are many applications of internal vibration motors in construction, external vibration motors can be used with similar results for different projects. External vibration motors are generally used in scenarios where concrete must settle within a shaped mold [17]. Because the inside of the heater tube is similar to the inside of a mold, our team believes an external vibration on the heater housing could result in improved settling of concrete, allowing less air to be trapped inside the heater tube.

2.4 Patent Research

Research was focused on patents relating to technologies relevant to the manufacture and implementation of ISEC. One patent our team observed was for a concrete vibration table [14], which also applied the concept of vibration as a viable way to remove air from concrete, allowing it to settle into the desired shape. In this patent, an external vibrator is applied to a surface of concrete, causing the concrete to compact into the desired shape.

In another similar patent, a suction apparatus is used to cinch a vibration motor directly onto a mold [15]. The purpose of this apparatus was for civil and architectural engineering usage, as a way to improve the settling of concrete within molds. This gave our team the idea to have an external vibratory motor that could easily clamp onto the housing of the heater during manufacture, allowing the mortar filler material to fill all voids of the heater tube.

Though many patents are not readily available for vibration-induced concrete settling, our team found the ideas listed in the patents above to be very informative and will adapt concepts into the final manufacturing design. After reviewing the uses of both internal and external vibration motors in different scenarios, our team believes a hybrid design containing both types of vibration motors could increase mortar flow through the tube and induce settling of mortar within the tube.

2.5 Academic Research

Part of our team’s project research involved looking at academic publications related to ISEC directly. Although there is no documentation of the immersion heater manufacturing processes or comprehensive designs, information could be obtained from the senior project: Development of an Insulated Solar Electric Cooker (ISEC) with Thermal Storage for Use in Developing World Countries [16]. This report contains information on diodes as heating elements, insulated solar electric cookers, and preliminary immersion heater tests.

3 Objectives

Note: This section has been refined and clarified to better portray the scope of our project since the original submission of the Preliminary Design Review report.

This project builds upon the successful development of ISEC iterations developed by previous design teams and undergraduate researchers. Our project sponsor has requested the further development of an immersion heater unit which can be used with the 100W photovoltaic panel systems used for previous ISEC designs. Additionally, the sponsor requested a repeatable manufacturing process and a functioning prototype for this immersion heater unit, placing emphasis on minimizing the cost of materials and time required to manufacture. With these goals in mind, we looked at the requirements of our sponsor, as well as the needs of the end user of this device. The two have slightly different metrics for successful development, as the sponsor is likely going to be more concerned with efficiency and refinement of manufacturing, while the African villager will be most concerned with ease of use and low cost. Our group used a Quality Function Deployment (QFD), located in Appendix B for reference, to organize customer needs in simple terms. We then took each need and developed a corresponding measurable engineering specification that we can use to gauge the effectiveness of our future solutions. Each specification is addressed below.

3.1 Customer Wants

We interviewed Dr. Schwartz to get a better understanding of the requirements of the system. Table 1 below lists his wants and needs summarized from the meeting with him:

Table 1. Sponsor wants and needs

Needs	Wants
Refined manufacturing process for building the heater	Materials available within 50 mile radius of deployment
Working prototype	Can charge a cell phone and lights
Sufficient thermal conduction to dissipate heat	Optimize design of diode chains
Runs with 100-200 W solar panel	Investigate cookware options and lid-heater interface configurations
Design for ease-of use	

3.3 Boundary Diagram

The boundary diagram shown in Figure 3 below is a visual representation of the scope of the project, with the red dotted line depicting the boundary of the scope. Our senior project team will determine a suitable filler material for the heater with thermal conductivity and ease of manufacturing as key parameters. We will also standardize the heater shape, dimensions, and materials using information from our sponsor and results from research and testing conducted by our senior project group. Our senior project team will also design a comprehensive manufacturing plan to improve repeatability, decrease manufacturing person-hours, and decrease waste. The key focus of the improved manufacturing plan is getting the filler material into the aluminum tube, but stretch goals include improving the diode chain manufacturing and pipe bending methods.

All objects outside of the boundary in Figure 3 are factors we must consider when designing our product, and our team will be responsible for ensuring the relationship between the immersion heater and its environment is satisfactory; the immersion heater must successfully connect and draw power from the solar panel while transfering heat to the surrounding enclosure where the food will be located.

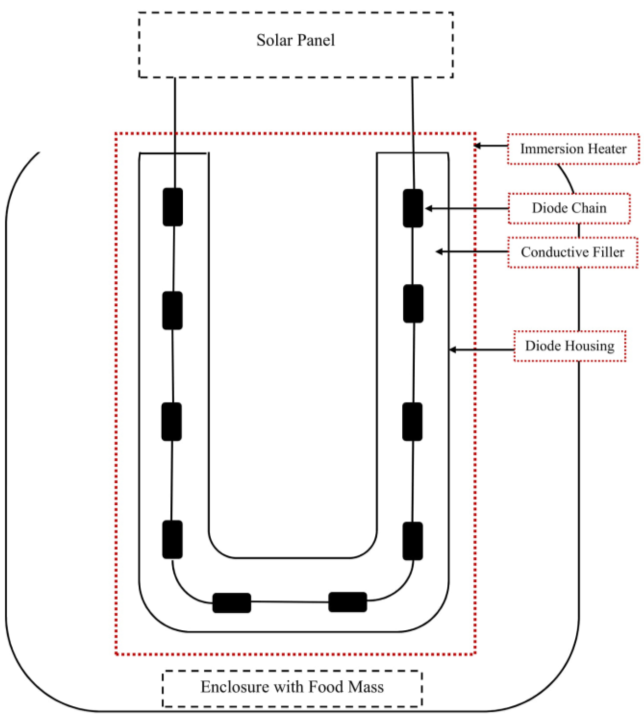


Figure 3. Boundary diagram illustrating scope of project

3.4 Quality Function Deployment

The Quality Function Deployment is a tool used for defining the key elements of a project including who the customer is, what they need and want, how useful current products are, and what engineering specifications must be met for the product to be successful. Our senior project team created a QFD, which can be found in Appendix B. We used the needs and wants list generated through customer research to fill in our QFD. The products listed in the product research section were then compared using the needs and wants list. Engineering specifications were generated with the design considerations and customer needs in mind.

3.5 Specifications

With the customer wants and needs in mind, the following design specifications have been determined as the group's major concerns.

3.5.1 Cost to Manufacture

The material cost of one ISEC immersion heater unit should not exceed $15. Given that about 73% of Sub-Saharan Africans live on less than the equivalent of $2 US per day [2], the cost of any device being provided is of critical concern. The end goal in the development of ISEC is to begin manufacturing them in the countries where they will be used. This will cut the amount of capital spent on labor while providing jobs to the customers we are trying to reach. Being that labor costs are both low and difficult to calculate, our engineering specification refers only to the material costs required to produce one immersion heater unit.

3.5.2 Man-Hours to Manufacture

The amount of time to manufacture one ISEC unit should not exceed 1 man-hour. As mentioned in Section 4.1, the cost of labor is going to vary depending on the location of the work being done, but as part of refining the manufacturing process, we need to consider the amount of time required to build this device.

3.5.3 Local Material Availability

Materials required to build an ISEC unit should be available for purchase in an urban area near the site of deployment if possible. To minimize material costs, it would be preferable if all materials required to build an ISEC unit were readily available in the areas it will be used. Naturally-occurring materials present a particular advantage being that they are potentially free of charge, or extremely inexpensive. However, as our sponsor noted to us, "The globalization of commerce is nearly complete," so if we need to source some materials from outside of the immediate area, that may be acceptable.

3.5.4 Power Input Requirements

Nominal power supplied by solar panel(s) should be 100-200W. ISEC units of the past have used a 100W solar panel to supply power to the heating element, however as the cost of solar panels falls rapidly, a 200W panel may become feasible in the near future. The mechanical engineering senior project team of 2017 notes that during their trip in Uganda, they bought a 120W solar panel for use with their device [3].

3.5.5 Heater Temperature Difference

To ensure safe diode operating temperatures, the temperature difference between the heater and the foodmass being cooked should not exceed 100℃, but preferably would not exceed 75℃. This metric is a measurable way to qualify the thermal conductivity of the heater, and it may depend on parameters such as diode spacing, filler material, lead standoff method, etc.

3.5.6 Predominant Dimension

The immersion heater should not exceed 20 cm in its predominant dimension. Although the immersion heater will likely not be "one-dimensional," the largest dimension should not exceed 20 cm in order to fit in a two to six liter pot.

3.5.7 Pot Size

The immersion heater should be compatible with a pot between two to six liters. Our team must decide whether or not to include a standard size pot in the sale of ISEC or to design the unit to be usable with a range of pot sizes that villagers may already have. As mentioned by the sponsor, a two to six liter pot allows the device to maximize the power to food-mass ratio, so this is a preferable range for cooking pot size.

3.5.8 Electrical Short Prevention

The chain of diodes should be electrically insulated from the metal immersion heater casing. Our team must develop a solution to the problem of grounding occurring at some point along the diode chain. This has been an issue in some of the previous ISEC designs, and must be avoided to ensure functionality of the immersion heater unit. Covering the diode leads with an electrical insulator may be a bad solution if it also prevents conduction of heat from the diode leads through the heater. Further analysis will be done to weigh the potential benefits of insulating materials.

3.5.9 Heater-Foodmass Interaction

The heater must be sealed in such a way that food is not allowed to enter the heater. Additionally, this should prevent any contents of the heater, such as stray filler material, from interacting with or entering the food. This is critical for sanitary operation and food safety.

3.6 Specification Risk and Compliance Assessment

The specifications mentioned above have been compiled into Table 2 below, where the targets, tolerances, and risk have been listed. We plan to ensure compliance through analysis (A), testing (T), or inspection (I). The risk of the specifications have been evaluated and listed as either high (H), medium (M), or low (L). We have also listed how we will ensure compliance.

Table 2. Specifications, compliance, and risk assessment

Spec. #	Parameter Description	Requirement or Target	Tolerance	Risk	Compliance
1	Cost to Manufacture	$15	Max	L	A
2	Man-Hours to Manufacture	1 hour	Max	M	T
3	Material Availability	Available in nearby city	-	L	A
4	Power Input Requirement	100W	-	L	A
5	Temperature Difference	100℃	Max	M	A,T
6	Maximum Heater Dimension	20 cm in predominant dimension	Max	L	I
7	Compatible with Minimum Pot Size	2 liter	Min	L	I
8	Protection from Shorts in Circuit	Electrical insulation covering wires	-	H	I
9	Heater-Food Mass Interaction	Food mass and heater contents shall not contact	-	H	I

We have concluded that the highest risk specification is Specification 10: protection from shorts in circuit. It is necessary to ensure that the diodes are properly isolated from electrical contact with the body. If this specification is not met, the bypassed diodes will not produce heat, rendering the heater ineffective.

4 Concept Design Development

Concepts were developed through brainstorming and ideation sessions. Our team used brainstorming, SCAMPER, and brainwriting methods to create ideas and concepts corresponding to each function. In the SCAMPER method, a preexisting idea is altered using the following actions: substitute, combine, adapt, modify, put to another use, eliminate, and reverse. All ideas were encouraged during the ideation phase, with an emphasis on producing a large quantity of concepts. Once the ideas were developed, they were evaluated using Pugh matrices. Pugh matrices are a tool for formatting concept evaluation and expressing ideas through the use of controlled convergence. Pugh matrices are used by comparing each concept, represented in the matrix by a concept sketch, to a current product or datum. Positive or negative signs are assigned to each concept based on whether they are better or worse than the datum for specific criteria. New ideas can be generated by combining features of concepts. Pugh matrices are an asset to the design process because of this generation of new ideas. Pugh matrices used for this project are located in Appendix C and are organized by the function which the concepts correspond to. Our team evaluated concepts for producing heat and improving the manufacturing process, which are the two main goals of the project. The top concepts are compiled in Tables 3 and 4.

Table 3. Heat production concept sketches

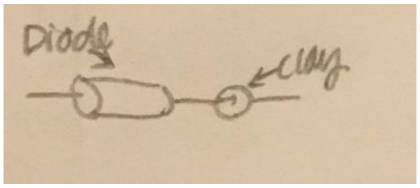
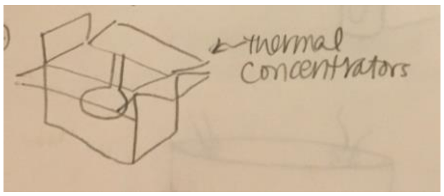
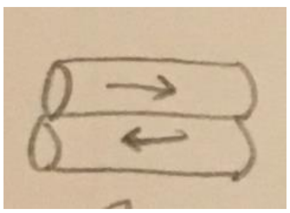
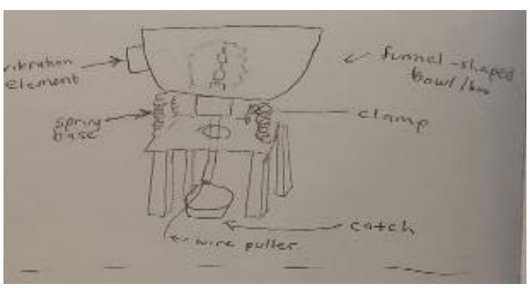
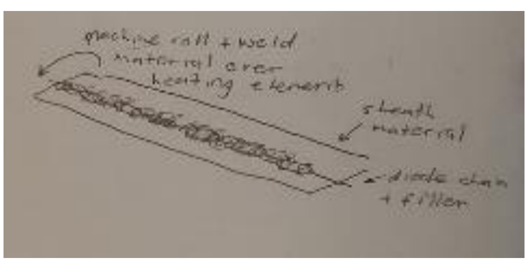
Concept Sketch	Concept Description
	One feasible mode of heat production would be to make improvements to the current immersion heater design. One idea for this is to improve the spacers to prevent shorting by molding clay balls onto the wires instead of pieces of wood.
	An alternate heat production method was the use of a solar thermal concentrator in addition to the current immersion heater design.
	The image depicts a heat exchanger, which our team theorized would be a good alternative heat transfer method.

Table 4. Manufacturing improvement concept sketches

Concept Sketch	Concept Description
	This idea consists of a "shake table" meant to reduce the amount of human effort required to make an immersion heater device. The device consists of a filler material container at the top that is excited by a vibrating motor and is allowed to move freely on springs. This vibration is intended to remove air pockets from the mortar material as it is fed into the immersion heater.
	This idea for manufacturing consists of rolling a diode chain with filler material in metal and welding the metal to form a pipe. This was modeled to imitate the process of how much piping is commercially produced, however this process we determined would be much too involved for this application.

The concepts were then arranged into three groups according to Pugh matrix results, with one concept from each function selected per group. The decision matrix can be seen in Figure 4 along with a key for the groupings. The first group contains the top concepts, while the third group contains the lowest scoring concepts. The groups in the decision matrix were then evaluated against the design specifications and a score was calculated after assigning weights to each criteria. The highest scoring concepts in the decision matrix were the diode heating element and shake table manufacturing process.

Group 1: Produce heat- diodes
Improve manufacturing- shake table machine

Group 2: Produce heat- solar concentrator/diode hybrid
Improve manufacturing- funnel

Group 3: Produce heat- heat exchanger
Improve manufacturing- rolling and welding pipe

Criteria	Weights	Group 1		Group 2		Group 3	
Cost to Manufacture	5	5	25	3	15	3	15
Hours to Manufacture	4	5	20	2	8	2	8
User Satisfaction Surveys	2	4	8	4	8	3	6
Heat Transfer from Heating Element	3	4	12	4	12	2	6
Material Availability	4	5	20	3	12	2	8
Power Input Requirement	2	5	10	5	10	5	10
Maximum Termperature Difference	3	3	9	3	9	2	6
			104		74		59

Figure 4. Decision matrix

For improving the manufacturing process, we weighed two concepts against the datum of the current manufacturing processes in place. One alternative our team came up with during brainstorming was to create diode chain and filler material that could then be wrapped with metal, which would be welded in place. This idea did not stand up to scrutiny in the Pugh matrix for manufacturing, as it would be too costly and require much more complex operations than the existing process. The other idea for manufacturing consisted of the creation of a device that would hold the pipe during manufacturing, apply vibrations, and catch excess filler material. This would drastically reduce the amount of hands needed to complete this process, allowing one person to make heaters easily on their own. Our senior project team also utilized failure modes and effects analysis (FMEA), included as Appendix I, in order to evaluate possible failure modes of the idea. This analysis led to the concept prototype, as seen in Figure 5, which was developed and presented at a senior project preliminary design review.

4.1 Concept Prototype

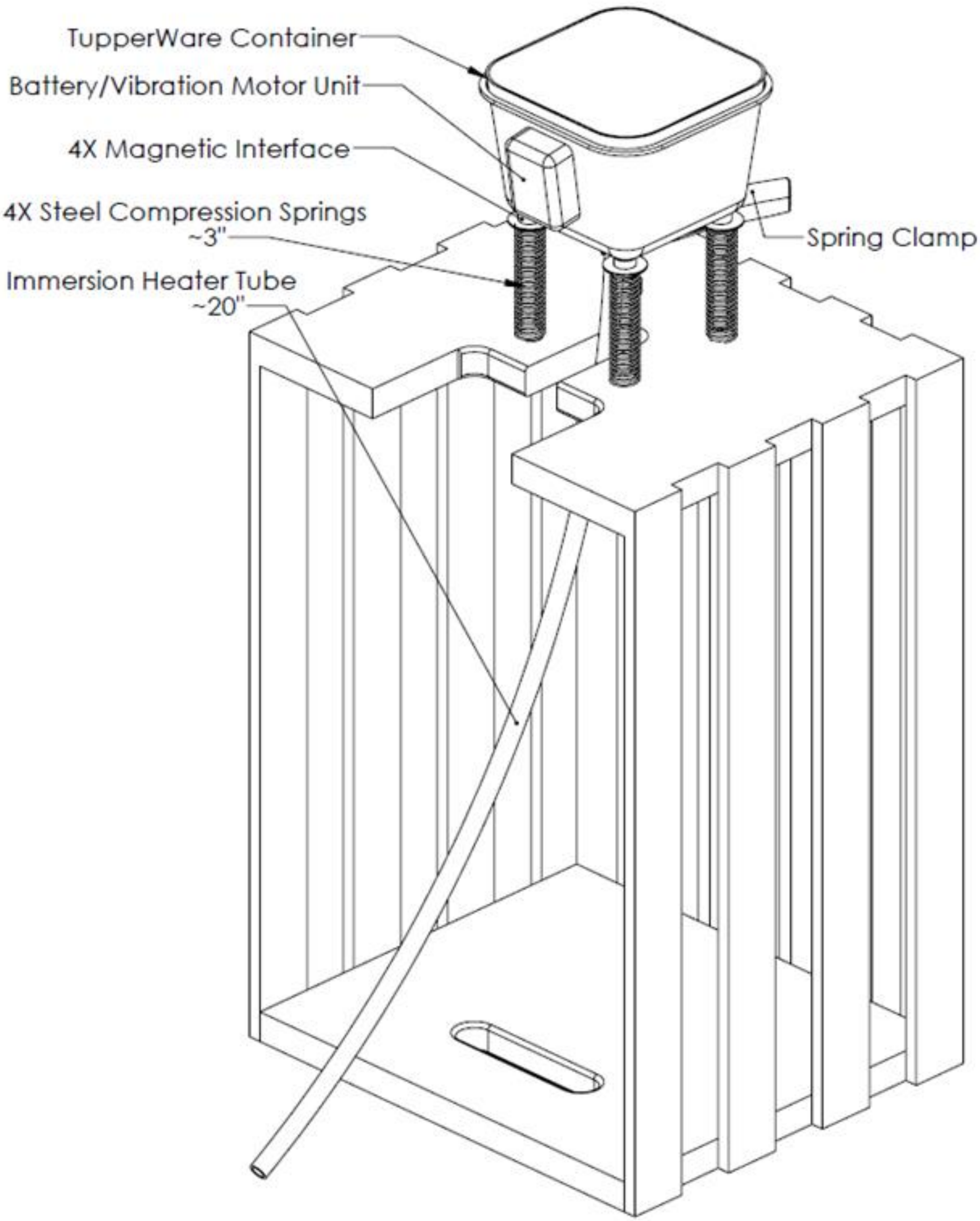


Figure 5. Concept prototype drawing

Being that the main goal of this project is to improve the manufacturing process used to create these immersion heaters, it is important to understand the process currently being performed. The ISEC research team has tried a variety of ways to make immersion heaters, and the method we were shown consists of the following steps:

1. Construct diode chain by twisting leads of diodes together, adding wooden standoffs between each diode. (These standoffs currently consist of sections of popsicle sticks shaped in a way that will prevent shorting of the heater).
2. Solder a thermal switch to the end of the diode chain, and then solder leads (lengths of wire) to either end of the chain, including the thermal switch.
3. Apply dielectric tape to locations of soldered joints, completely insulating areas that may cause shorting.
4. Mix mortar material in plastic container according to specified material ratio.
5. Tape empty heater tubing to plastic container so that the hole in the container is roughly concentric with the tubing.
6. Simultaneously scoop mortar mixture into the tube while feeding the diode chain into the tube. Apply vibrations to the plastic container as necessary to allow the mortar mixture to settle. Catch mortar material that may fall all the way through heater tube.
7. Bend heater to shape, and apply current to ensure proper function of heater, allow mortar to cure.

The point of this process we targeted for improvement thus far is Step 6. This step requires four people to simultaneously interact with the heater manufacturing process with each of them doing fairly simple tasks. The biggest problem with this process is that it requires too many hands to manage. This is the biggest improvement we attempted to implement with our concept prototype.

The concept prototype that we created consists of a stable base with springs to isolate the vibrations exerted on the filler container from the base itself. The container has a hole and a clamp for holding the aluminum tube enclosure in place during manufacturing, as well as an attached vibration motor and batteries for applying vibrations to the container. This is in hopes that the vibration will allow the filler material to settle more easily into the heater tube. The whole container is attached to the springs with magnets to make it easy to remove and clean the container. Future improvements to this design include possibly adding a catch to contain any excess filler material that may fall through the heater tube during manufacture. An image of the completed concept prototype is shown in Figure 6.

Our initial observations lead us to believe this design will be an improvement upon the method formerly in use. We learned from construction practices that vibrations applied to wet mortar will help remove voids from the material, and we hope to use this method to improve the flow of mortar into our immersion heater as we feed the diode chain through. Along with the addition of the tubing clamp, we expect that our shake table will result in a far simpler assembly method requiring only a single person, rather than four.

Figure 6. Concept prototype

4.2 Concept Preliminary Analysis and Testing

Preliminary analysis shows that the current ISEC immersion heater design is a feasible solution to the problem of clean, safe cooking. The primary energy transfer calculation, shown in Appendix A, demonstrates that the available solar panels are capable of supplying enough energy to cook the required amount of food. In addition, the tests we have performed on diodes in open air can operate at temperatures of around 170°C before failure, as seen in Figure 7. The diodes used in the tests (IN4001) are considerably smaller than the diodes being used to create heaters (IN5408), so this temperature of failure is likely to be different across different diode specifications. A datasheet for IN5408 has been included in Appendix D for reference. As stated, the testing performed was meant to be more qualitative in nature, and thus varying failure temperatures and currents in ambient air are not of the utmost importance. What is important to note is that in every case of testing, all diodes were able to dissipate much more energy than they were rated for, which is fortunate for our application.

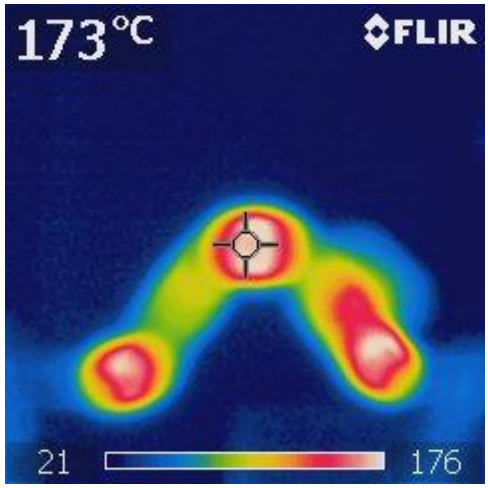


Figure 7. Infrared image showing upper limit of diode temperature before failure

4.3 Potential Hazards of Concept

Potential user hazards were analyzed through use of a Design Hazard Checklist, as seen in Appendix E. One risk to user safety was improper use of the immersion heater. Our senior project team plans to write an Operator's Manual for users which will include cautions regarding safety concerns. Generally, powered systems would incorporate an emergency stop directly in the circuit design, but we will not be including that as the on/off switch of the power supply acts as an emergency stop of this system. Finally, there are significant burn risks to the user if they touch the hot section of the heater. A section will also be included in the Operator's Manual with personal protective equipment (PPE) recommendations.

5 Final Design

Note: Final Design information and CAD drawings have been updated to reflect design changes since it was last submitted for the Critical Design Review report.

Our final design consists of a manufacturing jig similar to that presented in the concept prototype section above (Section 4.1) with some modifications. The manufacturing jig, shown in Figure 8, is now intended to act more as a heater-making fixture rather than a vibration table. This will allow a single person to do all of the tasks associated with filling the heater tube with the heating element and filler material. The manufacturing jig works by firmly holding the heater tube in place while allowing the user to easily feed the diode chain and filler material into the tube. It also applies vibration to the tube, as opposed to the filler container, allowing filler material to be displaced throughout the tube more effectively. The part/assembly details can be found in the drawing package in Appendix G.

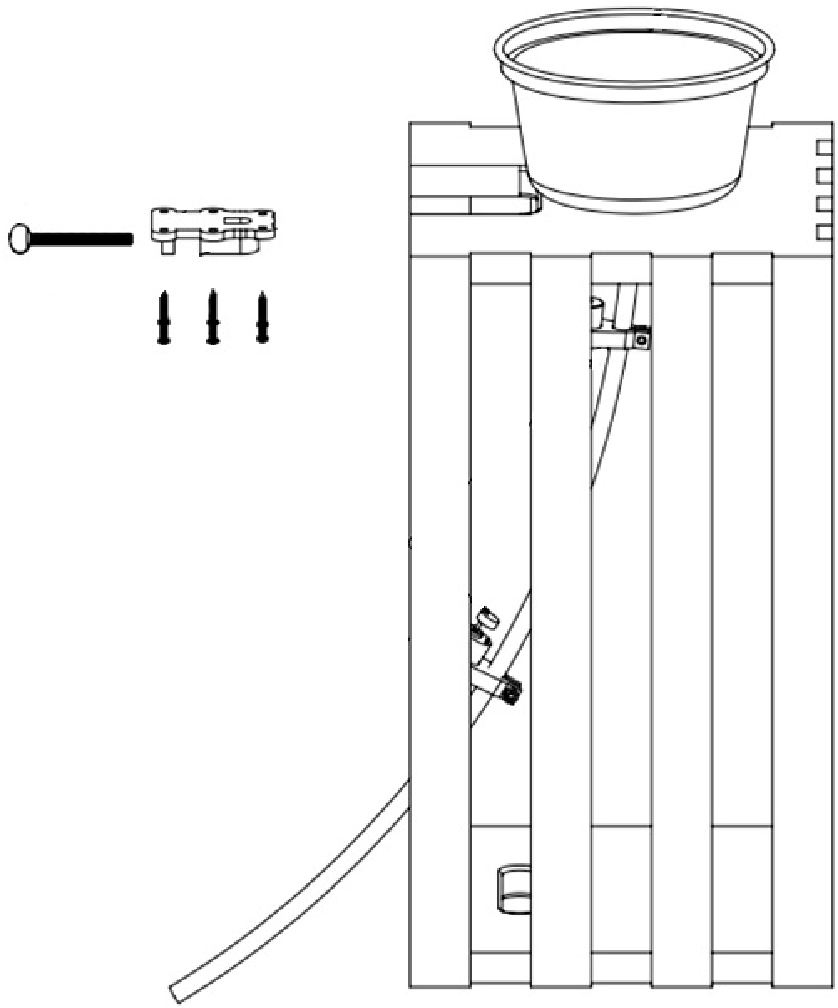


Figure 8. Exploded assembly view of manufacturing jig

5.1 Manufacturing Jig Subsystems

The manufacturing jig consists of the following subsystems: manufacturing jig structure and clamp, filler containment, and vibration.

5.1.1 Manufacturing Jig Structure and Clamp Subsystem

The manufacturing jig's structure is primarily made of a wooden crate which was purchased off-the-shelf at a hardware store. This was chosen for simplicity of assembly and for likelihood of being able to find a similar component in the regions where ISEC will be deployed. Minor modifications are made to the

crate, including one hole drilled in the top to accept the heater tube, a slot cut out of the top to allow easy access to the clamp/vibration area, and holes for securing the clamp to the crate.
The tube clamp is a custom part designed by our team to firmly hold the immersion heater tube in place. It consists of a 3D printed part, as shown in Figure 9, made to accept a square nut (press fit) and a thumb screw used to actuate the clamping action. This was designed and implemented due to a lack of off-the-shelf solutions for tightly clamping small diameter tubes.

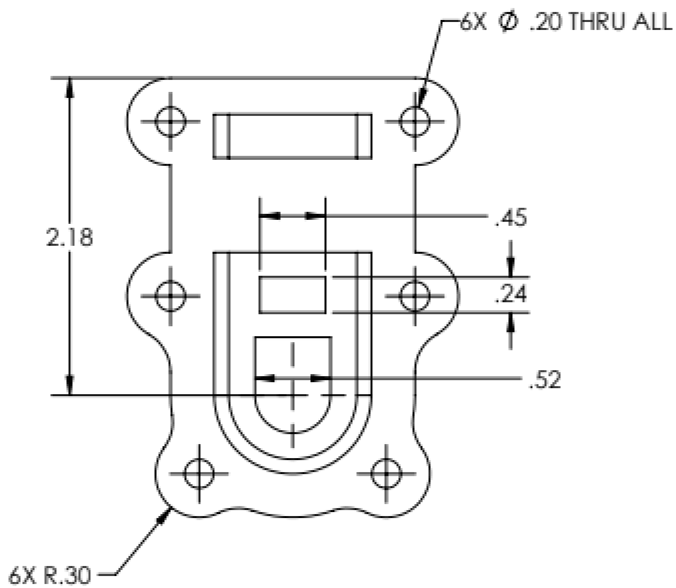


Figure 9. Drawing of clamp part, critical dimensions shown

5.1.2 Filler Containment Subsystem

The filler containment subsystem is intended to hold the heater filler material during production of an immersion heater. This subsystem consists of a small plastic container attached to the top of the manufacturing jig structure. There is a hole cut in the middle of the bottom of the container that is intended to fit around the top of a heater tube during use.

5.1.3 Vibration Subsystem

The vibration subsystem currently consists of an eccentrically weighted vibration motor. Currently, our team has found success by using the weighted portion of the motor to apply impacts directly to the outside of the heater tube beneath the clamp. This process will require further development, but preliminary testing has indicated that this method of applying vibration is effective in depositing filler material throughout the heater tube. We designed clamps, shown below in Figure 10, which hold the motors to the outside of the tube. These clamps are to be 3D printed.

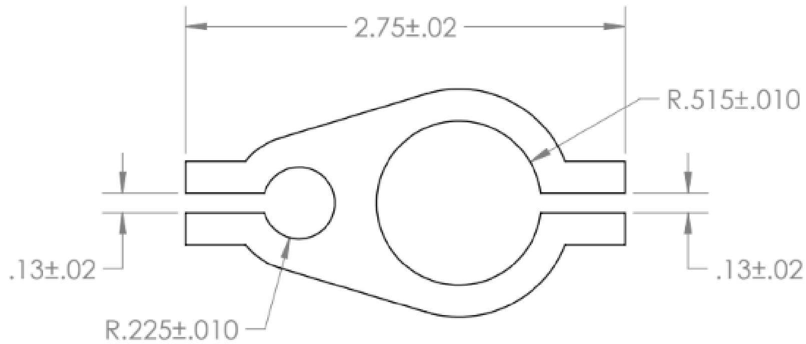


Figure 10. Vibration motor clamps

5.2 Manufacturing Jig Function

As stated above, the purpose of the manufacturing jig is to firmly hold an immersion heater tube while one operator feeds the diode chain and filler material through the tube to make a functioning heater. Additionally, the table allows the user to apply vibrations to the filler material through the metal tube to eliminate any voids present in the filler. In this process, the operator would insert a heater tube into the clamp and actuate the clamp in order to hold the pipe firmly. They would then place the filler material container on top of the crate, ensuring that the top of the heater tube protrudes through the hole in the container. The soldered diode chain is then fed through the heater tube so that one lead of the chain extends out the bottom of the heater tube. Note that the lead should be a section of wire long enough such that the lead comes out the bottom of the heater tube before the first diode enters the tube. Mixed filler material is then added to the plastic container to surround the diode chain. Vibrations are applied to the tube via a vibration motor, and filler material should begin to "flow" through the pipe. As this happens, the operator would gently begin to pull the diode chain by the bottom lead as to surround the diode chain with filler material. Only a small amount of filler material surrounding the pipe should be expected to flow, so the operator would also be tasked with scooping the remaining filler material towards the tube. Once the diode chain is fully inside of the tube, the operator may want to remove the heater from the table, plug the end that was being filled, and flip the heater over, clamping it in place by what was formerly the bottom of the heater. Filler material can now be added to this side to fill any remaining gaps. Further detail on the heater manufacturing process can be found in Section 6 of this report.

5.3 Vibration Motor Electrical Circuit

The electrical circuit used to drive the vibration motor simply consists of a power supply (currently a 9V battery), a SPST ON/OFF switch, and the vibration motor itself as shown in Figure 11. Further considerations of this circuit may necessitate the use of a potentiometer speed controller and a more refined power source, such as a DC power supply, or some method to draw power from a solar panel.

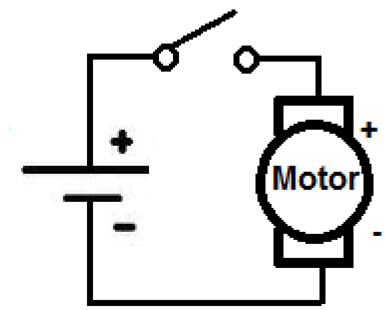


Figure 11. Electrical schematic representation of vibration motor circuit

5.4 Safety, Maintenance, and Repair Considerations

The manufacturing jig presents little in the way of safety hazards. There are no major pinch points, all voltages present are low, and there is no concern of high temperatures, spinning parts, etc. The only concern we foresee is the risk of splinters from wooden components. There are few safety concerns for the heater as there will be low voltage and current running through the system. There are safety concerns for burns due to the high temperatures, but this has been addressed in the design hazard checklist. This is reflected in the design hazard checklist in Appendix E.

Maintenance may be of significant concern, however. The greatest foreseeable issue is keeping the key components free of any mortar buildup. There are several places where excess or stray mortar could be allowed to harden and build up, such as the clamp, the inside of the hole in the wooden crate, and in the filler container. After each use, the user should take care to wash any stray mortar away from these locations. Too much build-up could lead to impaired function of any parts affected.
Repair of the manufacturing jig is likely to consist of simply repairing any damaged components. The system design incorporates inexpensive and widely available pieces for this reason.

5.5 Heater Subsystems

The immersion heater consists of the following subsystems: aluminum tubing, diode chain/wiring, and filler material.

5.5.1 Aluminum Tubing

The aluminum tubing of the heater is used as a containment vessel. The diode chain and filler material are inside of the aluminum tubing. This allows the immersion heater to be food safe as aluminum is a food safe metal and no filler material will get into the food.

5.5.2 Diode Chain/Wiring

The diode chain consists of eighteen diodes, a thermal switch, and wire leads. When the leads are connected to a power source, current runs through the chain and causes the diodes to produce heat. The thermal switch is attached in series with the diode chain to prevent the diodes from overheating and cracking.

5.5.3 Filler Material

A mixture of cement, sand, and water is funneled down into the aluminum tubing, around the diode chain. This mixture is called mortar and the cement to sand to water ratio is 2:1:1. The mortar is used to improve the thermal conductivity of the heater, compared to a heater without any filler material. The mortar takes the heat away from the diodes and helps to conduct that heat into the food.

5.6 Heater Function

The heater is designed to be submerged into the user's water and/or food to heat and cook the contents of the pot. The immersion heater is powered by a 100W solar panel to allow for inexpensive deployment in underserved communities.

5.7 Heater Electrical Circuit

The electrical circuit used to produce heat in the immersion heater simply consists of a power supply (100W solar panel), a thermal switch, and the diode chain as shown in Figure 12. The full-sized diode chain will consist of 18 diodes.

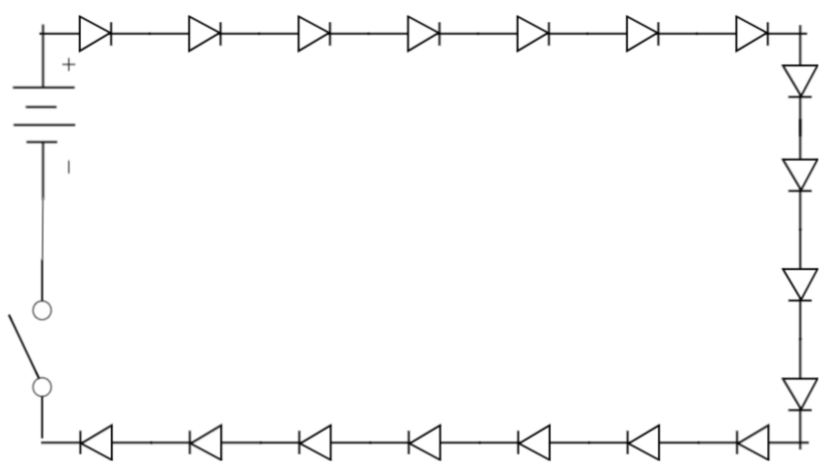


Figure 12. Heater electrical schematic

5.8 Final Design Cost Summary

Given that the goal of this project is to bring cooking solutions to people who have very little money to spend, we have tried to minimize the cost of the heater and its manufacturing jig. As you can see in Table 5 below, the crate we have purchased is the most expensive component and accounts for over half of the total cost of the manufacturing jig. This crate was selected with the idea that in the areas where the immersion heaters will be deployed, some other similar implement may be easily accessible. This may include something as simple as a sheet of plywood supported such that the clamp and other components could be simply mounted to it.

Table 5. Cost summary of final design (* denotes modified component, ** denotes custom part)

Part	Part No.	Quantity	Cost/Unit	Cost
Crate*	110T	1	$15.00	$15.00
Plastic Container*	111T	1	$1.00	$1.00
Vibration Motor	121T	2	$4.00	$8.00
Clamp Nut	112T	1	$0.10	$0.10
Clamp Screw	113T	1	$0.50	$0.50
Wood Screws	114T	6	$0.20	$1.20
Clamp**	115T	1	$2.00	$2.00
Motor Clamp**	122T	2	$1.00	$2.00
Motor Clamp Screw	123T	4	$0.11	$0.44
Total Cost				$30.24

One of the specifications of the project is that the heater must cost below $15 for materials. We have verified that our design will meet this specification by performing a cost analysis of the heater. The results are shown below in Table 6. We found that the heater would cost about $10, which is well below the specification of $15.

Table 6. Cost summary of heater design

Part	Part No.	Quantity	Cost/Unit	Cost
Diode	121	18	$0.08	$1.44
Aluminum Tubing	111	2 feet	$0.81	$1.62
Mortar	112	0.66 lb	$4.28	$2.82
Thermal Switch	122	1	$1.11	$1.11
Wires	123	12 inches	$0.08	$0.96
Dielectric Tape	124	4 inches	$0.01	$0.04
Total Cost				$7.99

6 Manufacturing

Note: Since the submission of the Critical Design Review report, manufacturing information has been updated for the Final Design Review.

The team refined our ideas from the structural prototype to construct our confirmation prototype. The confirmation prototype is based off of the final design. Below are the details of material procurement and manufacturing process for this design. The Operator's Manuals for both the manufacturing jig and immersion heater can be found in Appendix H. Please refer to Appendix H before attempting to operate the products.

6.1 Procurement

Currently, most of the parts for the manufacturing jig are purchased and then slightly modified to fit the project's needs. The crate, washers, clamp nut, clamp screw, and wood screws are all purchased through Home Depot. Of those items, only the crate gets modified to fit our design. The plastic container, magnets, and vibration motor are purchased through Amazon. The only item purchased from Amazon that is modified is the plastic container. When the parts for the manufacturing jig are being purchased out in Africa, there probably will not be a Home Depot but there will be similar hardware stores in the nearby cities that have comparable products. There are a few pieces for the manufacturing jig that are 3D printed: the clamp and the motor clamps. There may be 3D printer access in some of the larger cities around Africa; if not, the parts are small enough to be printed domestically and sent to Africa with Dr. Schwartz's collaborator, Dr. Van Buskirk. All of the heater components can be purchased from Amazon (diodes, filler material, and thermal switch) or Home Depot (aluminum tubing, wires, and dielectric tape), so our team is confident that the parts will be available for purchase from a store in a nearby city in Africa.

This project was given a budget of $300 by our sponsor Dr. Schwartz. Even though this is our budget, Dr. Schwartz stated that the project should not need to use most of the budget. Based on Table 7, it is clear that Dr. Schwartz was correct. All materials for this project have been purchased and the team has only spent $52.03. The indented bill of materials (BOM) in Appendix G also shows the cost breakdown for this project, and it shows where each item was purchased.

Table 7. Budget status summary

Description	Quantity	Unit	Cost/unit	Total Cost
Aluminum Tube	2	feet	$0.81	$1.62
Diode	18	piece	$0.08	$1.44
Filler Material	0.66	lb	$4.28	$2.82
Thermal Switch	1	piece	$1.11	$1.11
Wires	12	inches	$0.08	$0.96
Dielectric Tape	4	inches	$0.01	$0.04
Crate	1	piece	$15.00	$15.00
Plastic Container	1	piece	$1.00	$1.00
Vibration Element	4**	piece	$4.00	$16.00
Square Nut ¼-20	1	piece	$0.10	$0.10
Screw ¼-20	1	piece	$0.50	$0.50
Wood Screw #6x3/4”	4	piece	$0.20	$0.80
Clamp	1	piece	$2.00	$2.00
Motor Clamps	4**	piece	$1.00	$4.00
Screw #8-32	8**	piece	$0.11	$0.88
*Magnets	4	piece	$0.74	$2.96
*Washers	4	piece	$0.10	$0.40
			Total Cost	$51.63

*These items were removed from the final design after they had been purchased.
**These quantities have been reduced for the final design after the parts were made/purchased. Through testing, the final design only uses two motors and motor clamps and four screws to hold the motor clamps onto the pipe.

The changes related to the asterisks in Table 7 are reflected in the indented BOM in Appendix G.

6.2 Manufacturing

There are two separate manufacturing processes for this project. One procedure describes how the manufacturing jig is made. The manufacturing jig must be manufactured before the heater because the manufacturing jig is used to help manufacture the heater. The second process describes how the heater is made, and it includes the use of the manufacturing jig. Both processes are described below and the steps are in the recommended order for manufacture.

Manufacturing Jig Production

- Build stand to specifications or source wooden crate in drawings
  - Equipment: Hacksaw and Drill
  - Must have a flat, wooden top that is approximately 1 ft x 1 ft
  - Cut wood pieces to size and screw together
  - Drill hole in wood for heater tube to go through
- 3D print clamp, see Figure 9 for the part drawing

- Equipment: Access to 3D printer, Drill
    - Insert square nut and screw into clamp
    - Mark and drill holes for clamp screws, aligning clamp hole with hole drilled in wood for tube
    - Attach clamp to stand with wood screws so that the clamping screw is accessible at the front of the stand
- 3D print motor clamps, see Figure 10 for the part drawing
    - Equipment: access to 3D printer
- Cut 1/2 inch hole in plastic container
    - Equipment: X-acto knife or similar, hot glue gun
    - Glue magnets to bottom of container, at each corner
    - Glue washers to top of wood surface to align with each magnet

Heater Manufacturing

- Create diode chain by twisting diode leads together and soldering joint, solder extra wires and thermal switch to ends of diode chain (see Figure 13 and Figure 14 below)
    - Equipment: Soldering iron, pliers

Figure 13. Soldering over the twisted diode leads

Figure 14. Completed diode chain with thermal switch and wire leads

- Mix mortar: 2 parts sand, 1 part cement, 1 part water (see Figure 15)
    - Equipment: Spoon or similar to mix

Figure 15. Separated parts of mortar mixture

- Cut aluminum pipe to length using pipe cutter, determining the length is shown in Figure 16. The cutting process is shown in Figure 17.
  - Equipment: Pipe cutter

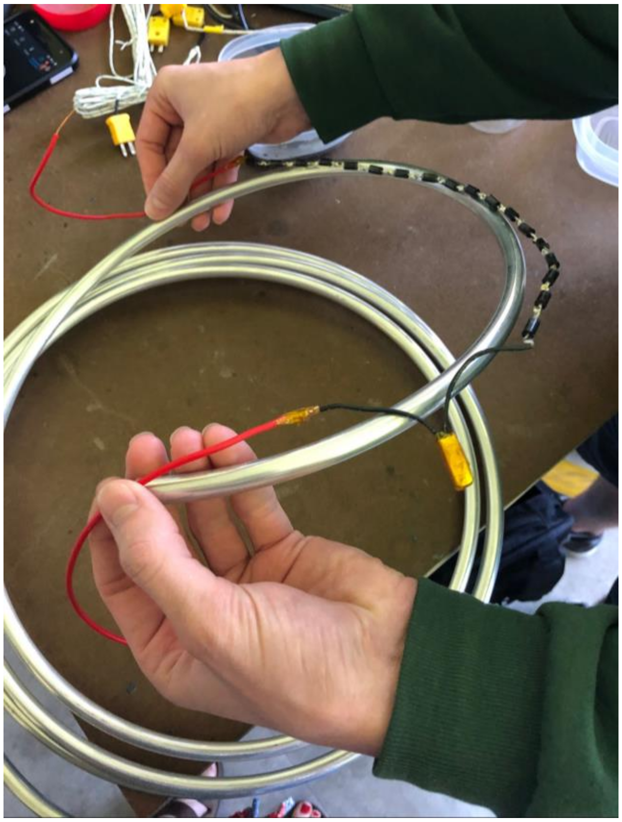


Figure 16. Determining approximate length of tubing needed for the diode chain

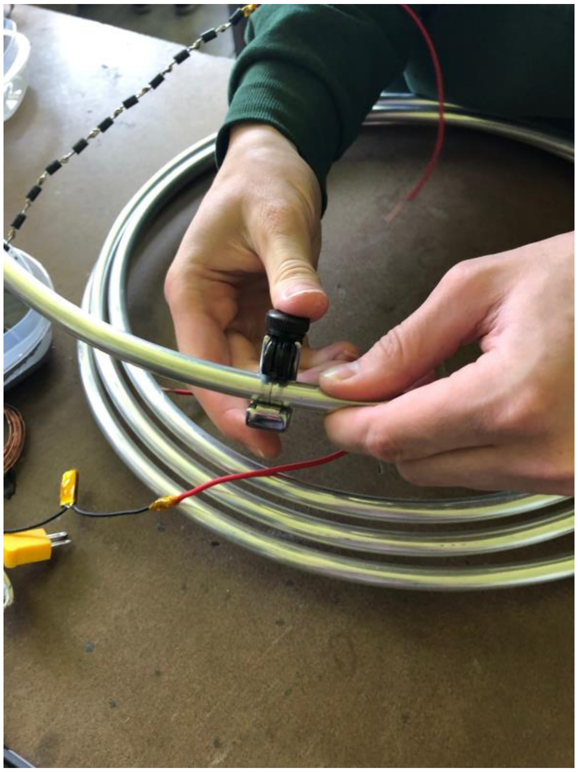


Figure 17. Use pipe cutter to cut heater tube to length

- Flare end of pipe (see Figure 18)
  - Equipment: hole deburring tool

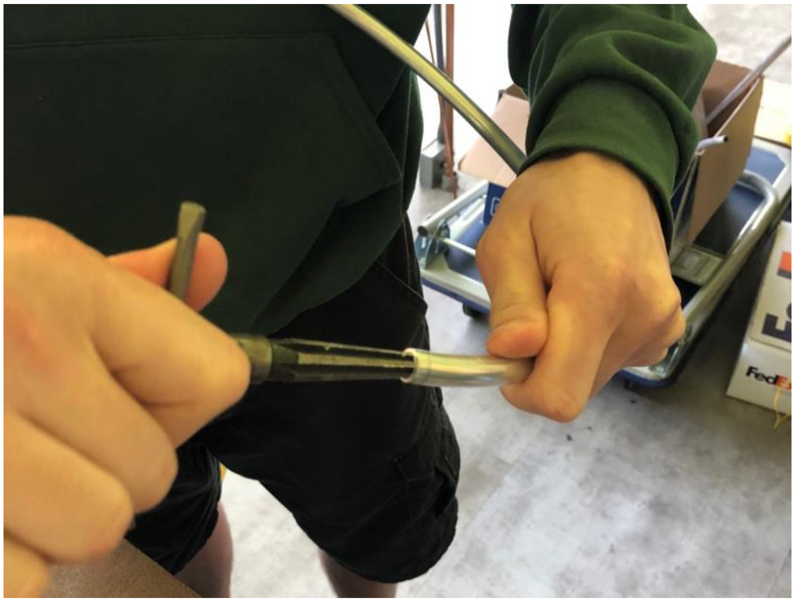


Figure 18. Flare end of pipe using hole deburring tool

- Attach one end of pipe to manufacturing jig via clamp (see Figure 19)
  - Equipment: manufacturing jig

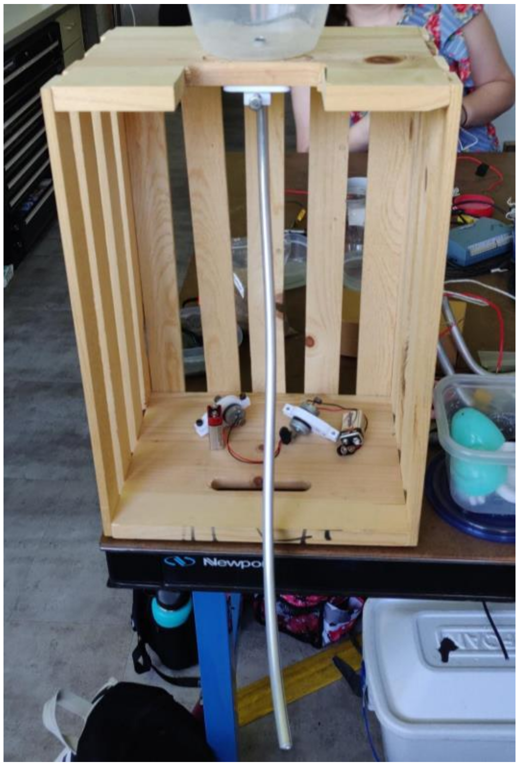


Figure 19. Tube gets attached to manufacturing jig as shown

- Attach motor clamps to pipe at varying distances along length, with one close to the top of pipe and one near the middle or bottom of pipe (see Figure 20)
    - Equipment: motors, motor clamps, screws

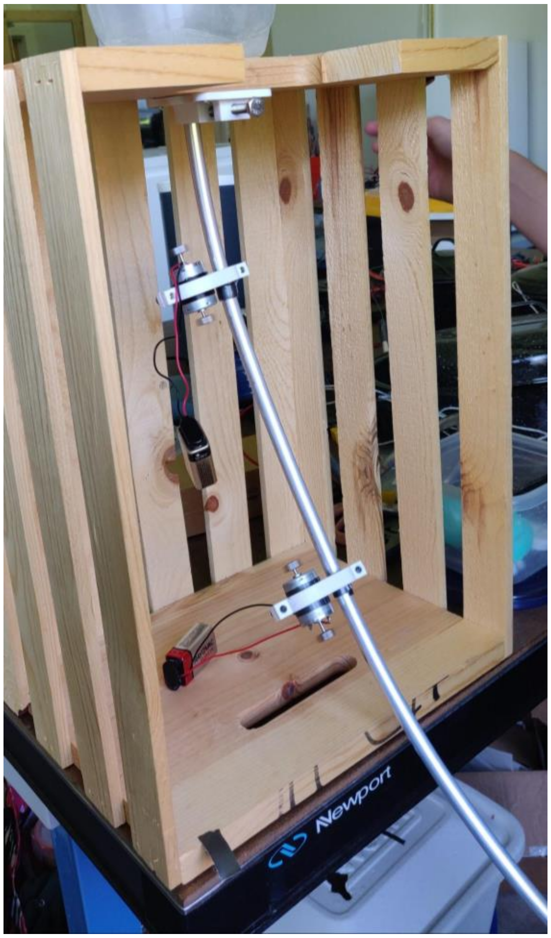


Figure 20. Motor placement

- Place tape over open ends of pipe to prevent mortar leakage (see Figure 21)

Figure 21. End of tube taped closed to prevent mortar leakage

- Feed diode chain and mortar through pipe (see Figure 22)

Figure 22. Feeding diode chain and mortar through pipe using manufacturing jig

- Bend heater to specified shape with the pipe bender (see Figure 23 and Figure 24)
    - Equipment: Pipe bender

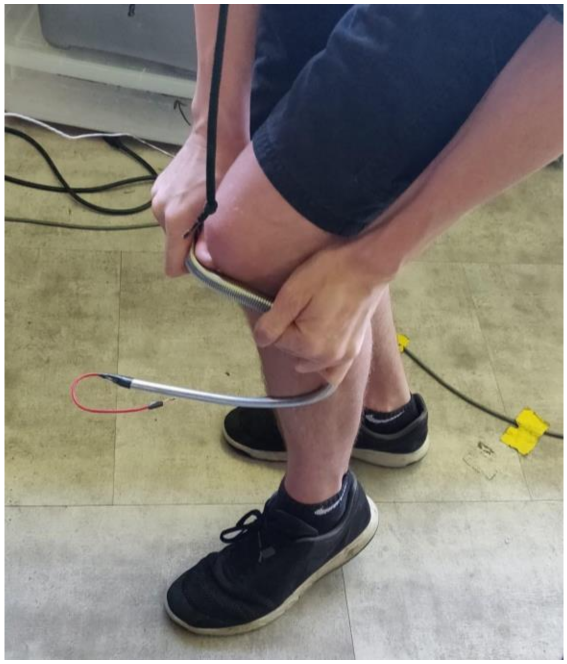


Figure 23. Bend pipe using pipe-bending equipment

Figure 24. Final shape of heater

- Allow mortar to cure for 24 hours

6.3 Assembly

Once the manufacturing jig components are manufactured, it should be relatively simple to assemble. Press fit the square nut into the slot in the clamp. Then thread the screw into the clamp through the guide hole and into the square nut. The tip of the screw should protrude into the pipe holding hole. The clamp needs to be screwed onto the underside of the top surface of the table so that the hole lines up with the pipe holding hole drilled through the top surface of the table. Finally, make sure the hole in the bottom of the plastic container lines up with the pipe holding hole of the table. That completes the assembly of the manufacturing jig, as seen in Figure 25 below. The heater assembly is the same as the heater manufacturing plan. There is no need to outsource any manufacturing for this project.

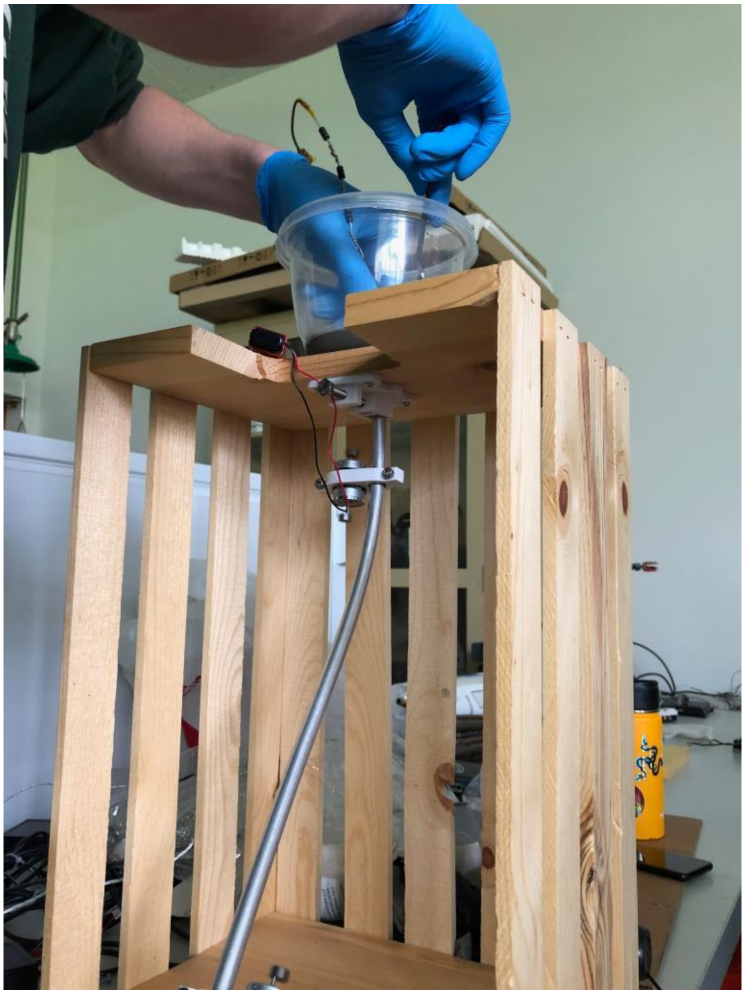


Figure 25. Assembled manufacturing jig including clamp and plastic container

One challenge that the team encountered while manufacturing the heater was the thermal switch on the diode chain did not fit into the aluminum tubing. This was because the pipe cutter slightly crimped in the end of the tubing when it was cut to length. Using a deburring tool to flare out the cut end of the pipe was a very simple and effective solution to that problem.

A recommendation for future production is to manufacture smaller heaters. Dr. Van Buskirk suggested to our team that the heater design could potentially be modified to fit inside an insulated thermos. It could theoretically heat up water or broth for soup quicker than the current immersion heater can heat water in a pot. Our team liked the idea and thought it could be very useful, however Dr. Van Buskirk talked to our team about this idea at the end of our second quarter. It was much too late for our team to pick up a completely new/different task for this senior project. So, our team recommends redesigning the heater to fit into a thermos to the next team that does work with immersion heaters.

7 Design Verification

Note: Design Verification section has been updated with new information and test results since its last submission in the Critical Design Review report.

While compliance with our specifications can be determined through observation or simple analysis, our team created a design verification plan and report (DVP&R) to ensure that comprehensive testing is complete to verify completion of requirements. Our team's DVP&R can be found in Appendix F. The specifications not listed in the DVP&R and Sections 7.1-3 include cost to manufacture, power input requirements, and material availability which have already been confirmed as met through analyses. A cost breakdown was completed which showed that the cost of the heater was $10, well below our $15 specification. We also designed our heater and manufacturing jig with materials which are readily accessible in larger, nearby cities meeting our availability specification. We designed our heater to be smaller than 20 cm in its predominant dimension, which guarantees that we met our maximum heater dimension specification, and designed the loop of the heater to be small enough in diameter such that it will fit with the minimum pot size of 2 liters as listed in our specifications in Section 3.5 and Appendix B. We chose the number of diodes for our heater to be 18, which will work for a 100 W solar panel based on analysis. Our final two specifications: protection from shorts in circuit and no heater-foodmass interaction can be confirmed through observation.

7.1 Man-Hours to Manufacture Verification

In order to verify that we are able to meet our manufacturing time limit specification of one person-hour, our team conducted several manufacturing time trials. This test was performed in the D13 lab facility in Cal Poly building 52. During this time trial, one full heater was manufactured by a single team member using our manufacturing jig. This process was timed, discluding mortar cure time. Necessary equipment includes a stopwatch, heater materials, a soldering iron, mortar mixing equipment, and the manufacturing jig. The data collected over the course of four tests is recorded in Table 8 below.

Table 8. Data acquired from timed tests

Date	Trial	Time to Manufacture
April 11th	1	40 min 23 sec
April 16th	2	45 min 55 sec
May 2nd	3	42 min 33 sec
May 23rd	4	43 min 44 sec

Our senior project team found the statistical uncertainty using the values in Table 9 below. We performed the statistical analysis at 95% certainty and found our time to manufacture a heater to be 43.15 ± 3.21 minutes (highlighted rows in Table 9).

Table 9. Statistical analysis of timed test data

Parameter	Value
Average (min)	43.15
Average (sec)	2588.75
t	2.776
n	4
Standard Deviation (sec)	138.60
Uncertainty (sec)	192.38
Uncertainty (min)	3.21

From the data presented in the tables above, we concluded that our design and build process meets our design specification of being manufactured in one person-hour.

7.3 Temperature Difference Verification

The temperature difference between the center of the heater and the outside surface of the heater must be less than or equal to 100℃, listed as a project specification. In the Bonderson Projects Center at Cal Poly, our team performed two trials of a test using a full scale heater and thermocouples in order to verify this. One heater contained our standard cement and sand mixture as the conductive filler material while the other utilized a cement and aluminum oxide mixture. This was done to test the differences in the conduction of heat through various filler materials. Both of these heaters were manufactured by our team with a thermocouple installed in the middle of the diode chain within the heater core. In addition, another thermocouple was placed on the outside of the tube in the middle of the heater. We then submerged our heater in water and applied an input power from a power supply, recording the steady state temperature as current was increased.

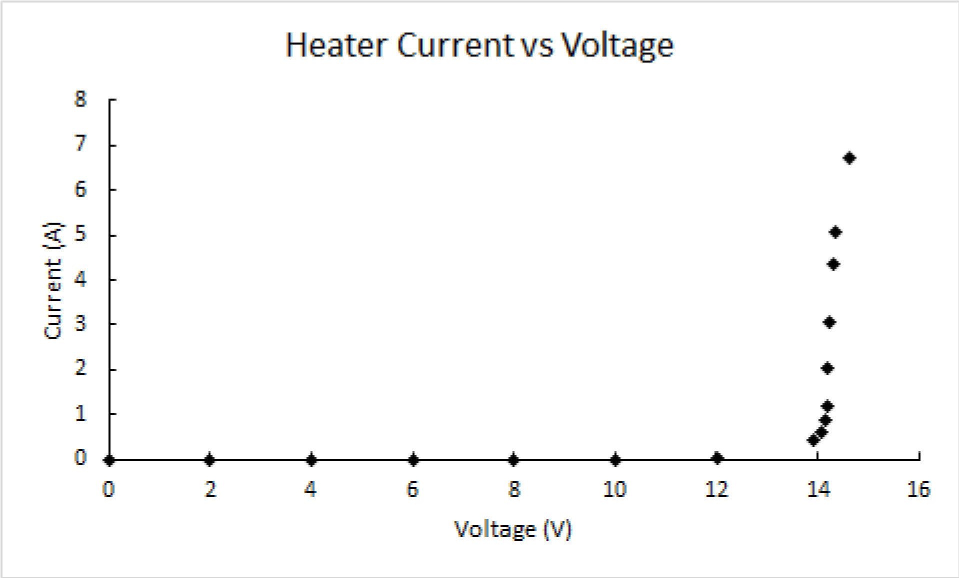


Figure 26. Current and voltage response for the diode chain within the test heater.

Figure 26 above shows the voltage and current response of the diode chain within our heater and behaves as we expected it to, with a near constant voltage once current is applied.

Figures 27 and 28 below are plots of temperature as a function of power input for the sand heater and aluminum oxide heater, respectively. The temperatures plotted include the temperature on the outside of the heater, on the inside of the heater, and most importantly: the temperature difference between the inside and the outside of the heater. The equations displayed on both plots represent the linear relationship between the heater's temperature difference and the input power.

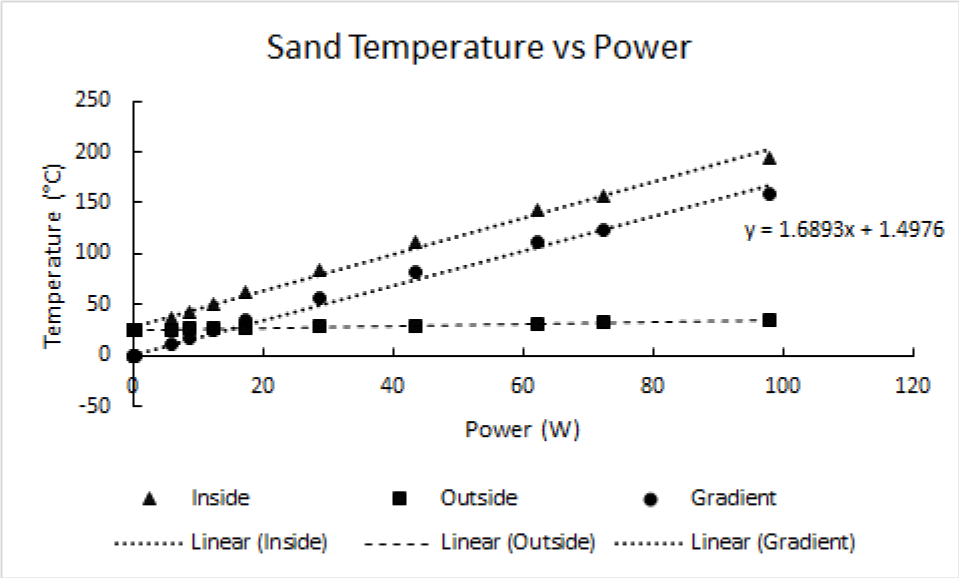


Figure 27. Temperature data for cement and sand filled heater

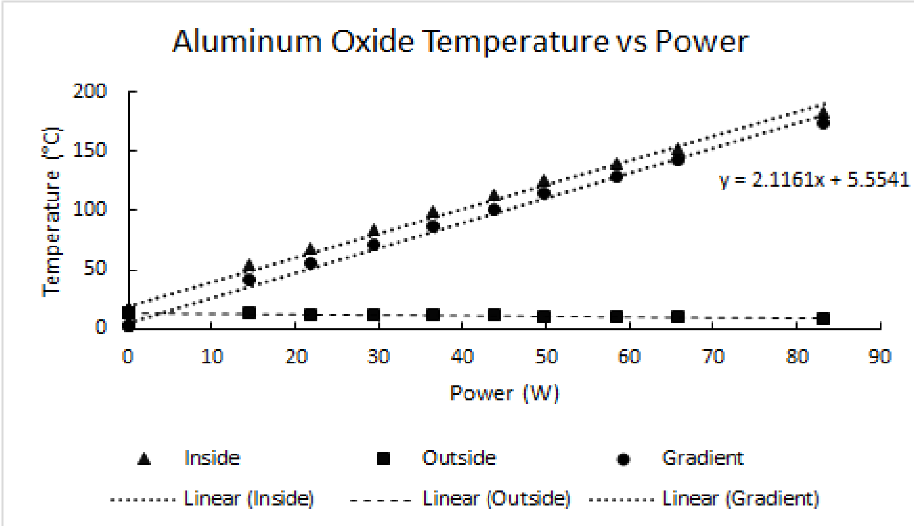


Figure 28. Temperature data for cement and aluminum oxide filled heater.

As can be seen from Figures 27 and 28, we observed a smaller temperature difference for the sand heater, which was not expected. Because aluminum oxide has a better heat transfer coefficient than sand, we expected the opposite to occur. At this time, we do not have an explanation for the cause of this. In addition, the temperature difference of both heaters is greater than 100°C, and thus fails our specification. The temperature difference for the sand heater grows to 159.0°C, while the temperature difference for the aluminum oxide heater reaches 174.7°C. After testing, our team has concluded that though it fails our specification, cement and sand is currently the best option for filler material as alternatives with better performance would be too expensive to be effective.

Table 10. Uncertainty propagation data for sand-filled heater.

Power	Voltage	Current	U_V	U_I	U_P
0.0	0.0	0.0	0.0005	0.005	-
0.0	2.0	0.0	0.0005	0.005	-
0.0	4.0	0.0	0.0005	0.005	-
0.0	6.0	0.0	0.0005	0.005	-
0.0	8.0	0.0	0.0005	0.005	-
0.0	10.0	0.0	0.0005	0.005	-
0.4	12.0	0.0	0.0005	0.005	0.0600
6.0	13.9	0.4	0.0005	0.005	0.0696
8.7	14.1	0.6	0.0005	0.005	0.0703
12.3	14.1	0.9	0.0005	0.005	0.0707
17.2	14.2	1.2	0.0005	0.005	0.0709
28.7	14.2	2.0	0.0005	0.005	0.0710
43.4	14.2	3.1	0.0005	0.005	0.0711
62.3	14.3	4.4	0.0005	0.005	0.0715
72.5	14.3	5.1	0.0005	0.005	0.0718
98.0	14.6	6.7	0.0005	0.005	0.0732

Table 11. Uncertainty propagation data for aluminum oxide-filled heater.

Power	Voltage	Current	U_V	U_I	U_P
0.0	0.0	0.0	0.05	0.05	-
0.0	2.0	0.0	0.05	0.05	-
0.0	4.0	0.0	0.05	0.05	-
0.0	6.0	0.0	0.05	0.05	-
0.0	8.0	0.0	0.05	0.05	-
0.0	10.0	0.0	0.05	0.05	-
14.5	14.5	1.0	0.05	0.05	0.7267
21.8	14.5	1.5	0.05	0.05	0.7289
29.4	14.7	2.0	0.05	0.05	0.7418
36.5	14.6	2.5	0.05	0.05	0.7406
43.8	14.6	3.0	0.05	0.05	0.7453
49.6	14.6	3.4	0.05	0.05	0.7495
58.4	14.6	4.0	0.05	0.05	0.7569
65.7	14.6	4.5	0.05	0.05	0.7639
83.2	14.6	5.7	0.05	0.05	0.7837

As shown in Tables 10 and 11, we performed uncertainty propagation for P=VI using resolution uncertainty of the power supply.

7.4 Testing Summary

Our team conducted several trials of two different tests in an attempt to prove that our final design meets our projected specifications. The first of the two tests, our timed manufacture test, was very successful, showing that we easily meet our specification of manufacture in less than one person-hour. We conducted four trials of this test, and found that our manufacturing time for a single person working is 43.15 ± 3.21 minutes.

Conversely, our specification to have a temperature difference lower than 100°C between the inside and outside of our heater was not met. In the first trial with our sand-filled heater, our temperature difference had a maximum of approximately 159°C, while our aluminum oxide-filled heater had a maximum temperature difference of approximately 175°C. While these tests did fail our specification, our group concluded that cement and sand combination's low cost outweighed the poor performance and is still the best known option for heater filler material. In addition, we did encounter some issues while attempting these tests. First, we had difficulties with a malfunctioning thermocouple reader, which resulted in us using two separate readers to monitor the inside and outside temperatures of the heater. We also had difficulties with our power source in the D13 lab space, which caused us to use the power source in the Bonderson Projects Center for the second trial with our aluminum oxide-filled heater. These issues did not cause problems with our final data collection, but did slightly delay our tests.

8 Project Management

Note: Project Management section has been updated since the Critical Design Review to provide the most current information and plan available. In addition, current information and schedule can be found in the updated Gantt chart found in Appendix J.

Our design project spanned over three key segments: design, build, and test. Our process was highly iterative, putting emphasis on building and testing prototypes. The overall project spanned from September 2018 to June 2019, and had many major project milestones to reach during that time, which are listed in Table 12 below.

Table 12. Major project milestones

Due Date	Deliverable
10/19/2018	Scope of Work Document
11/16/2018	Preliminary Design Review Report and Presentation
1/17/2019	Interim Design Review Presentation
2/8/2019	Critical Design Review Report and Presentation
3/14/2019	Manufacturing and Test Review
5/31/2019	Final Design Review Report
5/31/2019	Senior Project Expo

Major deliverables that our team completed over the course of this project included creating the quality function deployment, concept models, failure modes and effects analysis, structural and confirmation prototypes, and writing the Operator's Manual.

The tasks for this project were organized in the Gantt charts found in Appendix J. Our team used the TeamGantt website to manage and update our Gantt charts, which we found to be a very useful tool for organizing our project and one that we would use for future projects.

Our team followed a design-build-test process where we evaluated the wants and needs of the sponsor and end user in fall quarter, built prototypes in the winter and spring quarter, and tested in the spring. This process may not have been the best for this project because the nature of the project was more research oriented. A process more centered around building and testing from the very beginning would likely have been helpful, as many of the pieces of the project were already in place upon our entry. We also had difficulties with defining the scope of the project, which affected our progress and focus in the beginning. This process would certainly fit projects which are more design-oriented, so we would use this process for a design project in the future.

9 Conclusions and Recommendations

The Insulated Solar Electric Cooker senior project sponsored by Dr. Peter Schwartz is outlined in this document. This report summarizes all relevant analyses and prototypes as well as the results and final design of our immersion heater manufacturing jig. At this time, a complete working manufacturing jig and a complete immersion heater design are ready to be handed off to Pete Schwartz for use by his ISEC researchers or the community members in Africa. We are confident that the findings of our project will meet the needs of our sponsor, as well as those manufacturing heaters in Africa by streamlining the immersion heater manufacturing process.

The goal of this project was to standardize and perform analysis on a preexisting, inexpensive solar-powered immersion heater for cooking use in developing countries, reducing the adverse effects presented by traditional biomass cooking fires. We accomplished these goals, and specifically, we have supplied our sponsor with a viable manufacturing plan for producing immersion heaters in approximately one fourth the amount of time that was previously possible. This includes a functional manufacturing jig that allows one user to perform the most challenging and time consuming steps in the production process.We will also deliver plans to the sponsor for the production of more heater jigs if duplicates are determined to be necessary. We have also contributed our general findings to the research group's overall understanding of how heaters can be made and implemented. Our senior project team only failed to meet one of our specifications: filler material temperature difference. Although the overall effectiveness of the heaters is not yet sufficient in relation to the specifications of our sponsor, we have contributed all of our findings for future contributors to the project.

Of the materials that we tested, we would recommend using mortar comprised of cement and sand as a filler material even though it has a higher temperature difference at operating conditions than requested by the sponsor. We believe that the incredibly low cost of this mortar mixture makes it a viable option, even though it does not meet the desired temperature difference, since the outside of the heater will reach cooking temperatures and the cost for mortar is well within the project budget. We recommend that future groups do further research into filler materials if a smaller temperature difference is still desired. The sponsor has mentioned the possibility of adding more thermally conductive materials to the inside of the heater such as copper wire. If we had more time to build and test heaters, we would have tested this sort of arrangement. We recommend moving forward with investigation of promoting heat conduction and electrical insulation of the heater tube and/or diode chain leads.

Further development of the heater should take advantage of the manufacturing processes developed in this project to expedite production of prototypes.As further development and testing is done in the future, some statistical reliability analysis will become pertinent. We would suggest that this would be best left to research assistants, considering that we felt we did not have sufficient time to produce and test a large sample of prototypes. We were instead tasked with producing a small number of prototypes, making improvements, while completing all necessary documentation, presentations, etc.

Based on our experience with this project, we feel that it would be beneficial for both the ISEC research group and mechanical engineering senior project students to collaborate in the future. We found that this project was research-focused, which is a new experience for mechanical engineering students who are used to design projects. As mechanical engineering students, we were able to bring design and manufacturing expertise to the research group.

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Appendix A: Preliminary Analysis

Energy Transfer Calculations

Maximum possible cooking energy to verify spec 3.1.4 can be met:
Assume:
8 hr cook time
Constant 100W solar panel output
Lossless transmission of power

Analysis:

$$E_{max} = P_{panel} \times t$$

$$E_{max} = (100W) \times (8hrs) \times (\frac{60\ min}{1\ hr}) \times (\frac{60\ sec}{1\ min})$$

$$E_{max} = 2{,}880{,}000\ J$$

Although the above assumptions assume ideal circumstances, this puts us well above the amount of energy required to cook 4 kg of rice or beans (1600 kJ).

Thermal Conductivity Analysis

Table A.1. Thermal Conductivity of Readily Available Materials

Material	Thermal Conductivity (W/mK)
Dry Sand	0.25
JB Weld	0.59
Dry Earth	1.5
Mortar	1.7
Dry Clay	1.8
Emery	11.6

Appendix B: Quality Function Deployment

Correlations	
Positive	+
Negative	−
No Correlation	

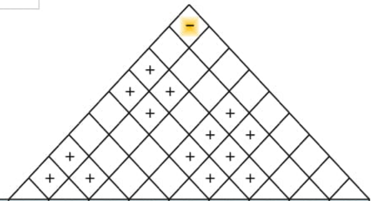
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: ISEC

Revision Date: October 26, 2018

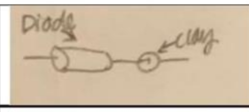
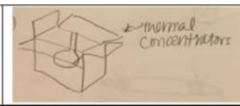
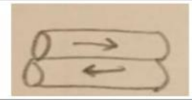


Row #	Weight Chart	Relative Weight	African Women	Pete Schwartz	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) \ HOW: Engineering Specifications (Tests)	Cost to manufacture	Man-hours to manufacture	Material availability	Power input requirements	Temperature difference	Maximum heater dimension	Compatible with minimum size pot	Protection from shorts in circuit	Heater-food mass interaction	Biomass stoves	Improved cook stove (ICS)	Solar thermal cookers	Full electric range	Row #
						Column #	1	2	5	6	7	8	9	10	12	NOW: Curr.				
						Direction of Improvement	▼	▼	◇	▼	▼	▼	◇	◇	◇					
1		20%	6	9	9	Low operation pollution	▽	▽	▽	▽	▽	▽	▽	▽	●	0	3	5	2	1
2		17%	4	9	9	Refined manufacturing process	○	●	○	●	○	▽	▽	●	●	5	3	2	0	2
3		20%	9	6	9	Maintains desired temperature	▽	○	○	○	●	▽	▽	●	▽	3	4	0	5	3
4		21%	8	8	9	Low power use	▽	▽	▽	●	●	▽	▽	●	▽	1	3	5	0	4
5		19%	7	7	9	Comprised of local materials	●	▽	●	○	○	▽	▽	▽	▽	5	0	0	0	5
6		27%	10	10	9	Inexpensive purchase price	●	●	●	○	▽	▽	▽	▽	○	5	4	2	1	6
7		23%	10	7	9	Easy for consumer to use	▽	▽	▽	▽	○	●	●	○	○	3	4	1	5	7
8		13%	4	6	9	Safe for consumer to use	▽	▽	▽	▽	▽	○	○	○	●	0	4	4	3	8
9		21%	9	7	9	Heats food for up to 10 people	▽	▽	▽	○	●	○	●	●	▽	5	3	3	3	9
10		19%	8	6	9	Compatible with varying pot size	▽	▽	▽	▽	▽	●	●	▽	▽	5	1	1	1	10

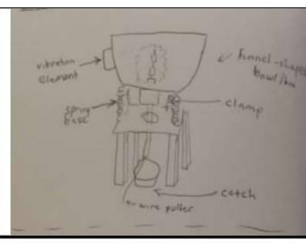
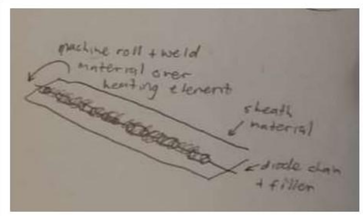
		1	2	5	6	7	8	9	10	12
	HOW MUCH: Target Values	$15	1 hour	Available in nearby city	100, 120, 200 W	100 °C	20 cm in length	Compatible with 2 liter pot	Electrical insultion covering wires	No contact
	Max Relationship	9	9	9	9	9	9	9	9	9
	Technical Importance Rating	597.3	592	637.3	682.7	818.7	600	728	912	704
	Relative Weight	10%	9%	10%	11%	13%	10%	12%	15%	11%
Curr. Products	Biomass stoves	5	5	5	1	3	0	5	0	3
	Improved cook stove (ICS)	3	1	2	4	5	0	3	5	4
	Solar thermal cookers	1	2	2	5	5	0	2	5	4
	Full electric range	1	1	2	3	5	0	3	5	4
	Column #	1	2	5	6	7	8	9	10	12

Appendix C: Pugh Matrices

Function: Produce Heat

Criteria \ Concepts	Datum: Diode Chain			
Cost to Manufacture	S	+	-	-
Hours to Manufacture	S	+	+	-
Power Input Requirements	S	+	+	-
Maximum Heater Dimension	S	+	-	-
Safe to Use	S	+	+	+
Maintains Desired Temperature	S	+	+	-

Function: Improve Manufacturing

Criteria \ Concepts	Datum: Four Person Manufacturing Team		
Cost to Manufacture	S	+	-
Hours to Manufacture	S	+	-
Material Availability	S	-	-
Power Input Requirements	S	+	+
Maximum Heater Dimension	S	+	+
Protection from Shorts	S	+	+
Safe to Use	S	+	+

Appendix D: Datasheets

Component Datasheet- Diode

1N5400 THRU 1N5408

3.0 AMP SILICON RECTIFIERS

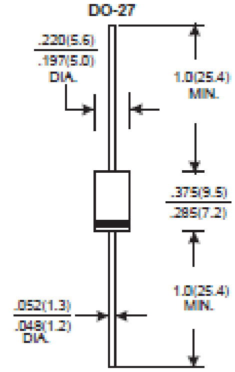
FEATURES

* Low forward voltage drop
* High current capability
* High reliability
* High surge current capability

MECHANICAL DATA

* Case: Molded plastic
* Epoxy: UL 94V-0 rate flame retardant
* Lead: Axial leads, solderable per MIL-STD-202, method 208 guranteed
* Polarity: Color band denotes cathode end
* Mounting position: Any
* Weight: 1.10 grams

VOLTAGE RANGE
50 to 1000 Volts
CURRENT
3.0 Amperes



MAXIMUM RATINGS AND ELECTRICAL CHARACTERISTICS

Rating 25°C ambient temperature unless otherwies specified.
Single phase half wave, 60Hz, resistive or inductive load.
For capacitive load, derate current by 20%.

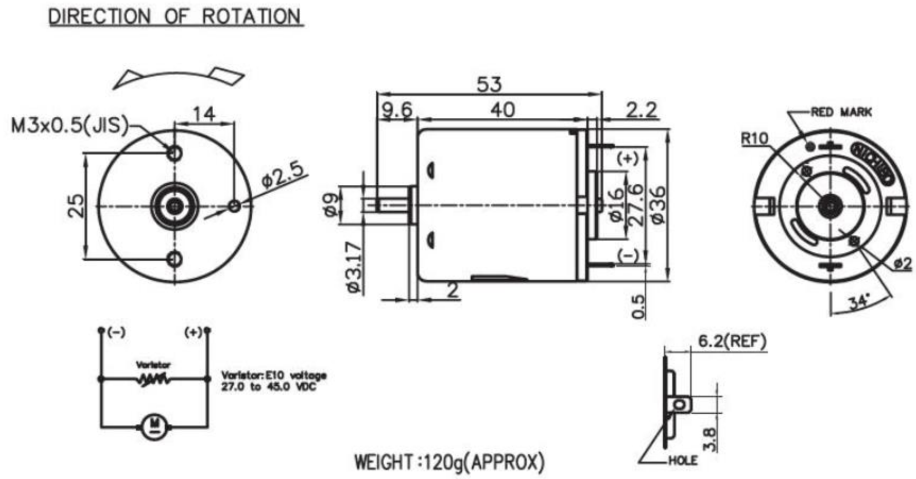
TYPE NUMBER	1N5400	1N5401	1N5402	1N5404	1N5406	1N5407	1N5408	UNITS
Maximum Recurrent Peak Reverse Voltage	50	100	200	400	600	800	1000	V
Maximum RMS Voltage	35	70	140	280	420	560	700	V
Maximum DC Blocking Voltage	50	100	200	400	600	800	1000	V
Maximum Average Forward Rectified Current .375"(9.5mm) Lead Length at Ta=75°C				3.0				A
Peak Forward Surge Current, 8.3 ms single half sine-wave superimposed on rated load (JEDEC method)				200				A
Maximum Instantaneous Forward Voltage at 3.0A				1.0				V
Maximum DC Reverse Current Ta=25°C				5.0				μA
at Rated DC Blocking Voltage Ta=100°C				50				μA
Typical Junction Capacitance (Note 1)				40				pF
Typical Thermal Resistance RθJA (Note 2)				30				°C/W
Operating and Storage Temperature Range T_J, T_{STG}				-65 — +150				°C

NOTES:

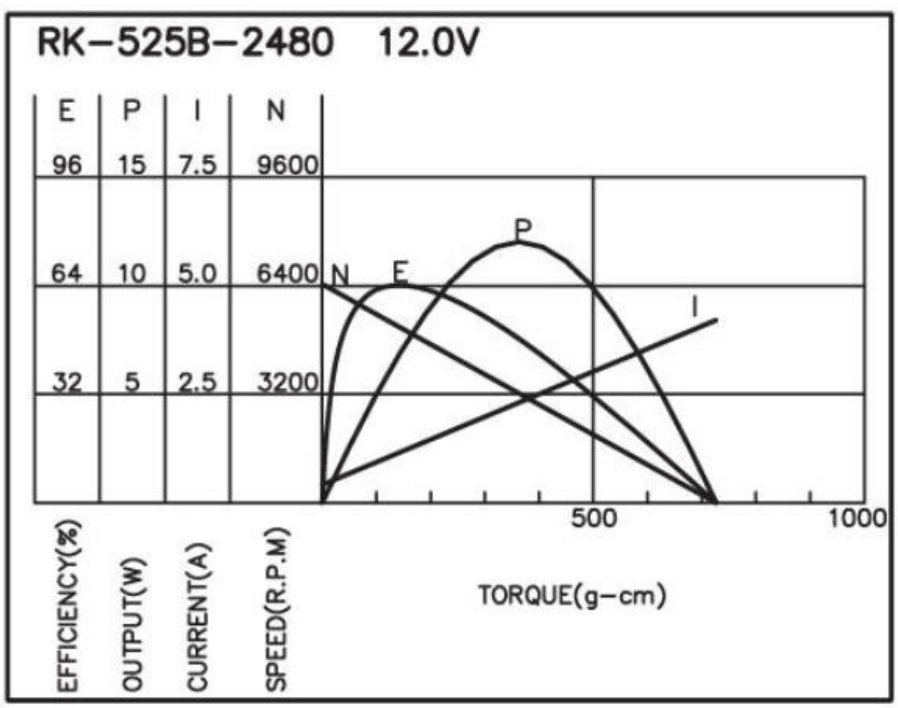
1. Measured at 1MHz and applied reverse voltage of 4.0V D.C.

2. Thermal Resistance from Junction to Ambient .375" (9.5mm) lead length.

Component Datasheet- Vibration Motor



MODEL	VOLTAGE		NO LOAD		AT MAXIMUM EFFICIENCY						STALL		
	OPERATING RANGE	NOMINAL	SPEED	CURRENT	SPEED	CURRENT	TORQUE		OUTPUT	EFF	CURRENT	TORQUE	
			rpm	A	rpm	A	g-cm	mN-m	W	%	A	g-cm	mN-m
RK-525B-15180S	6.0-36.0	24.0V CONSTANT	5700	0.11	4613	0.39	118	11.57	5.59	63	1.81	688	67.45
RK-525B-2480	6.0-36.0	12.0V CONSTANT	6450	0.42	5131	0.96	136	13.33	7.15	64	4.21	727	71.72



Appendix E

Design Hazard Checklist

Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: Toto (ISEC) Advisor: Rossman Date: 11/15/2018

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.

Corrective Action Plans

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
It is possible for the device to be used in an unsafe matter, resulting in burns	User manual will recommend PPE (gloves/mitts) to user	4/2/2019	4/20/2019
Uncured mortar can irritate skin	Manufacturing instructions will include recommendation to wear gloves and avoid contact with irritant	4/8/2019	4/20/2019

Appendix F

Design Verification Plan and Report

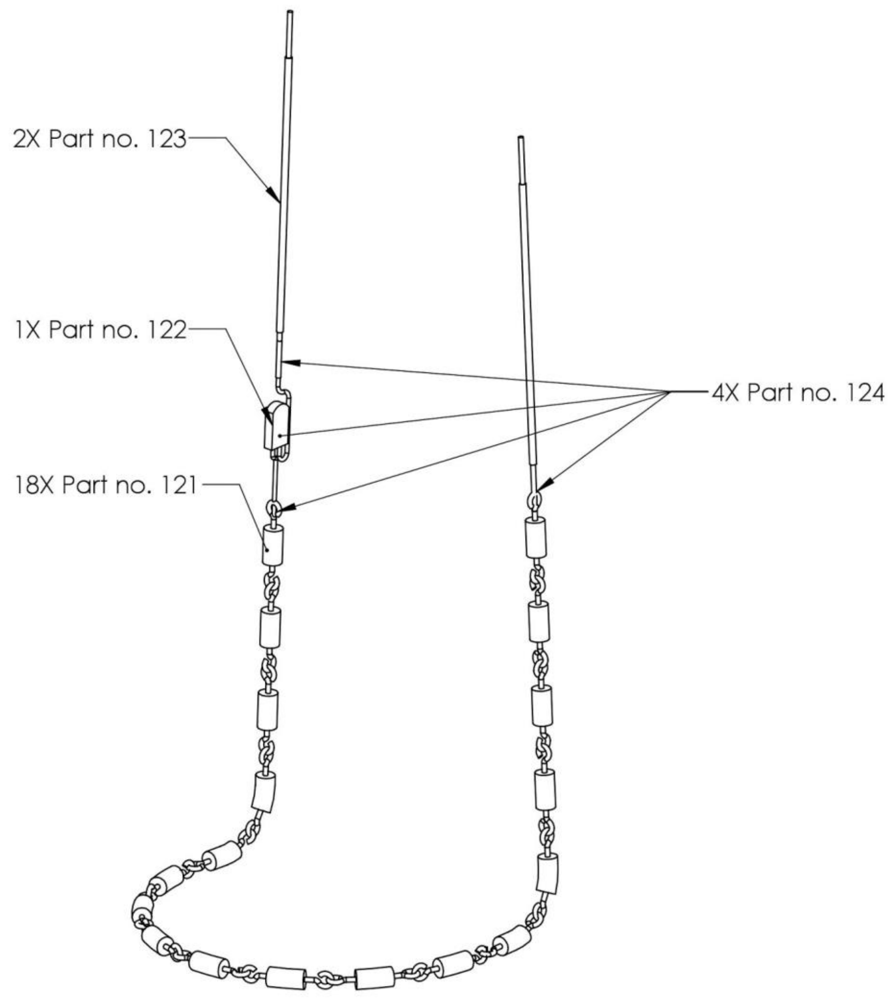
Senior Project DVP&R														
Date: 2/5/2019		Team: ISEC, Toto	Sponsor: Dr. Pete Schwartz			Description of System: Heater to be used in cooking food, and manufacturing jig for heater						DVP&R Engineer: Emily Burnside		
TEST PLAN											**TEST REPORT**			
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	5	Filler Material Temperature Difference	Temperature difference less than 100 °C	Brady Banks	CP	1	Sub	2/3/2019	5/14/2019	ΔT_{min} = 159	0	2	
2	2	Man Hours to Manufacture Qualification	Less than 1 hour to manufacture	Josh Stevens	FP	1	Sys	4/4/2019	4/16/2019	45 mins	2	0	

Appendix G

Drawing Package and Bill of Materials

Heater BOM

Assembly Level	Part Number	Description Lvl0	Lvl1	Lvl2	Vendor	Qty	Unit	Cost/Unit	Ttl Cost
0	100	**Final Assy**			------				
1	110		**Diode Chain Assy**						
2	121			Diode	Amazon	18	# of Diodes	0.08	1.44
2	122			Thermal switch	Amazon	1	# of Switches	1.11	1.11
2	123			Wires	Home Depot	12	inches	0.08	0.96
2	124			Dielectric Tape	Home Depot	4	inches	0.01	0.04
1	111		Tube		Home Depot	2	feet	0.81	1.62
1	112		Filler material		Amazon	0.66	lb	4.28	2.82
	Total Parts					**37**			**7.99**

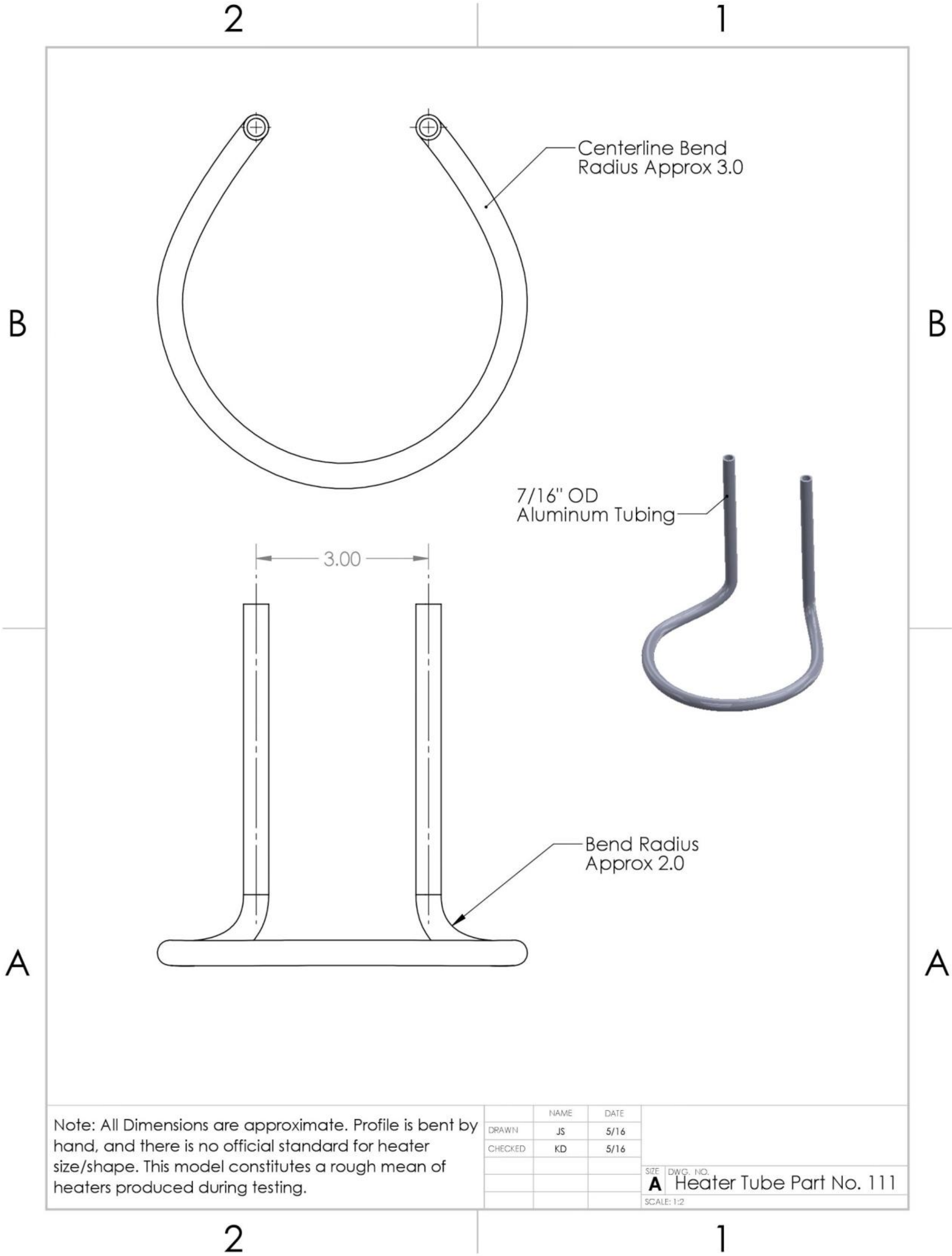


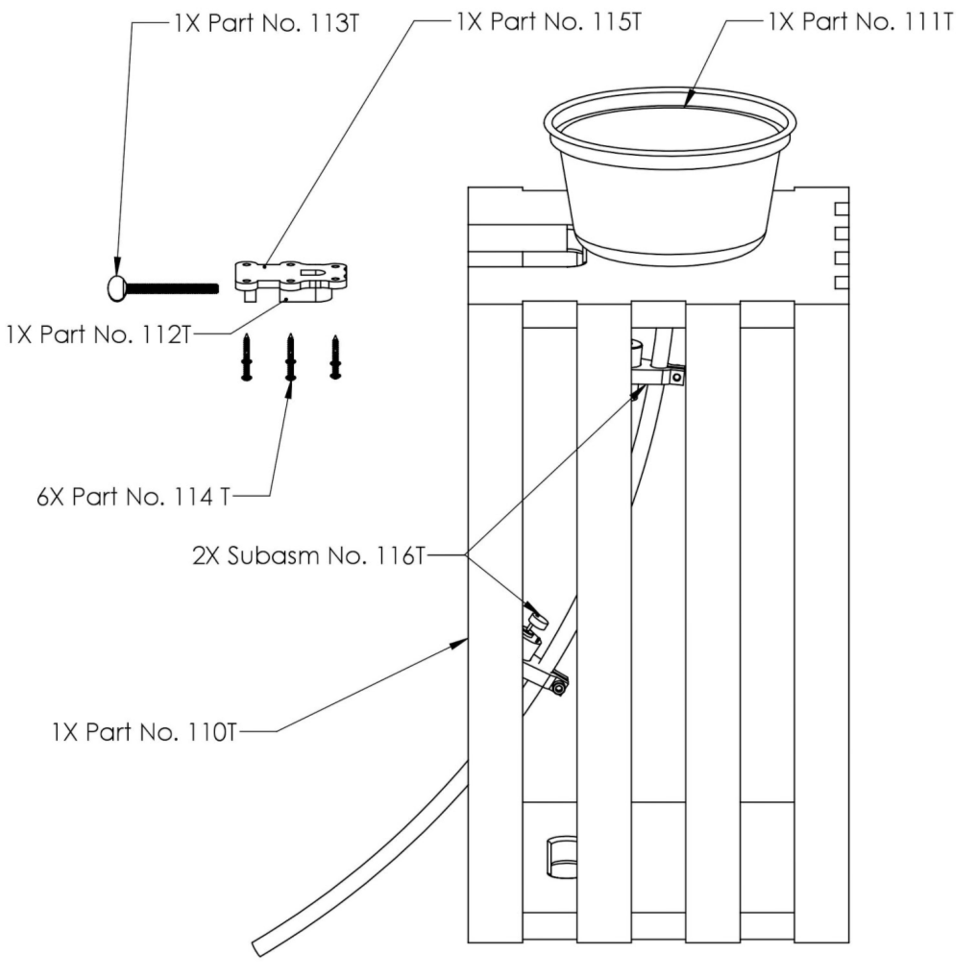
Part no.	Qty.	Description
121	18	1N5400 Rect. Diode
122	1	Bimetallic Thermal Switch 120° C
123	2	Approx 6" Stranded Copper Wire
124	4	Kapton Dielectric Tape Insulation

	NAME	DATE
DRAWN	JS	5/16
CHECKED	KD	5/16

SIZE A DWG. NO. Subasm 110 (Diode Chain)

SCALE: 2:3


Centerline Bend
Radius Approx 3.0
7/16" OD
Aluminum Tubing
3.00
Bend Radius
Approx 2.0
Note: All Dimensions are approximate. Profile is bent by hand, and there is no official standard for heater size/shape. This model constitutes a rough mean of heaters produced during testing.
NAME
DATE
DRAWN
JS
5/16
CHECKED
KD
5/16
SIZE
DWG. NO.
A
Heater Tube Part No. 111
SCALE: 1:2



Part no.	Qty.	Description
110T	1	Wooden Crate
111T	1	Plastic Container
112T	1	1/4-20 Square Nut
113T	1	1/4-20 Thumb Screw
114T	6	#6-3/4" Wood Screw
115T	1	3D Printed Pipe Clamp
116T	2	Motor Subasm

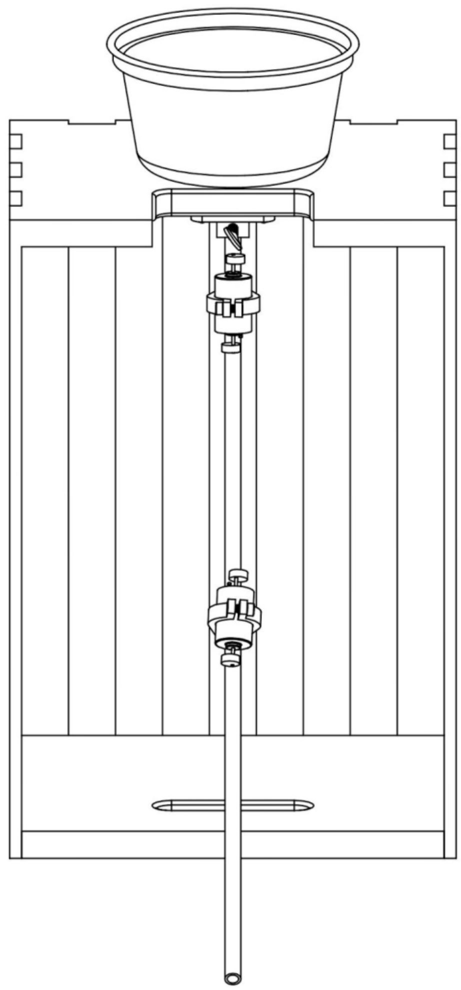
	NAME	DATE
DRAWN	JS	1/29
CHECKED	KD	1/29

SIZE A DWG. NO. Assembly 100T - Exploded

SCALE 1:4

2 1

B B



A A

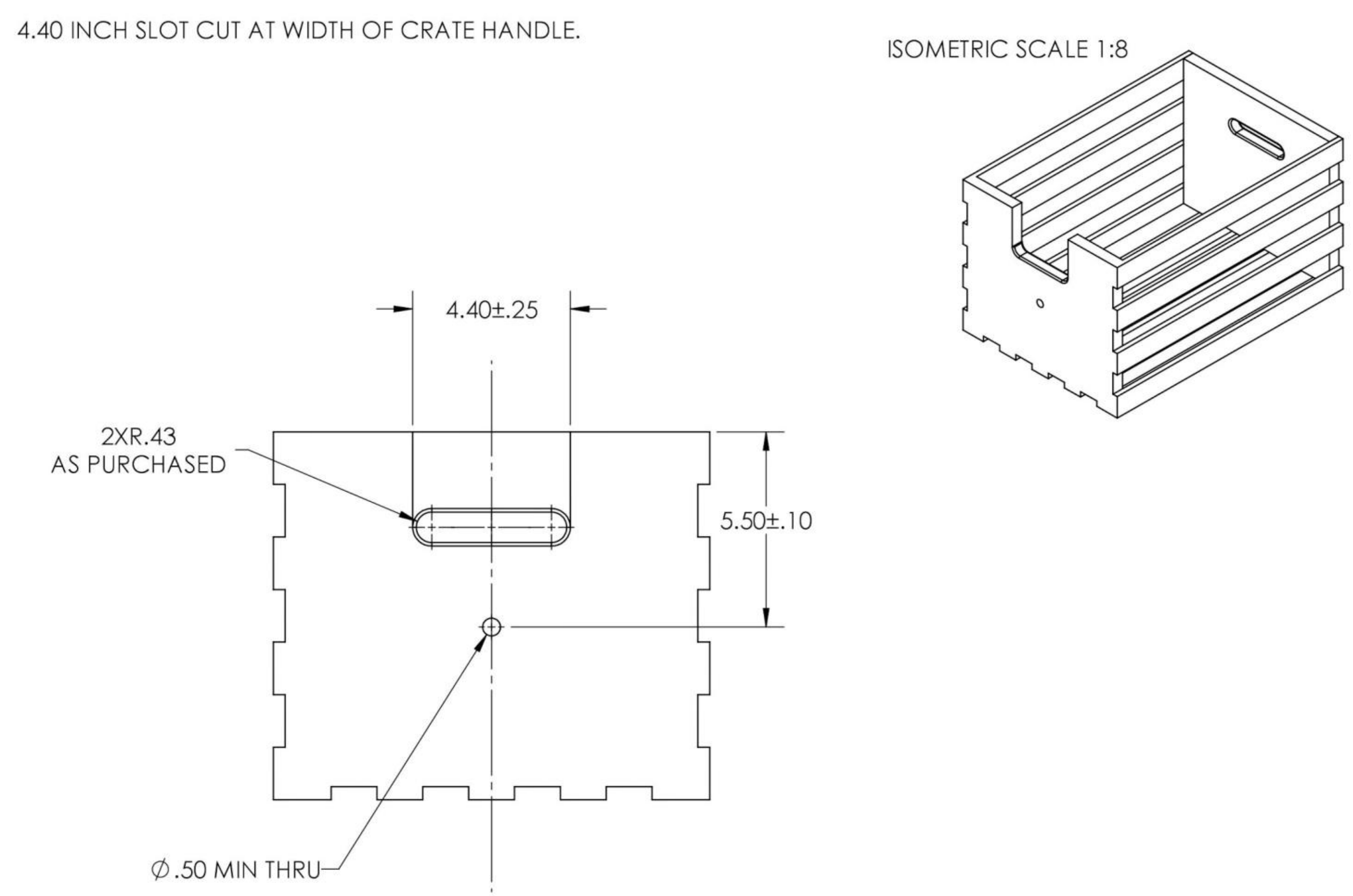
Part no.	Qty.	Description
110T	1	Wooden Crate
111T	1	Plastic Container
112T	1	1/4-20 Square Nut
113T	1	1/4-20 Thumb Screw
114T	6	#6-3/4" Wood Screw
115T	1	3D Printed Pipe Clamp
116T	2	Motor Subasm

	NAME	DATE
DRAWN	JS	1/29
CHECKED	KD	1/29

SIZE A DWG. NO. Assembly 100T

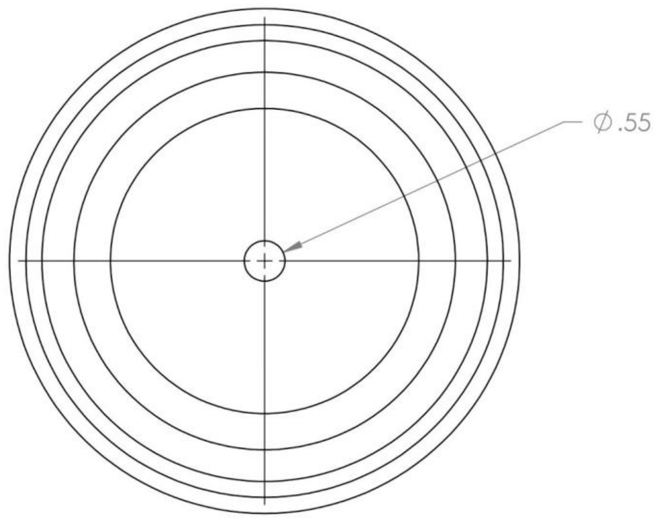
SCALE 1:4

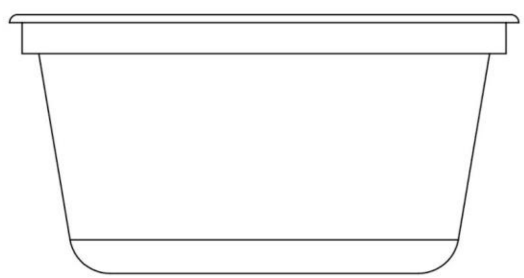
2 1



Cal Poly Mechanical Engineering	Lab Section:05	Assignment #	Title: CRATE	Drwn. By: JOSH STEVENS
ME 429 - WINTER 2019	Part #: 110T	Nxt Asb:	Date: 1/29/19 — Scale: 1:4	Chkd. By: ME STAFF

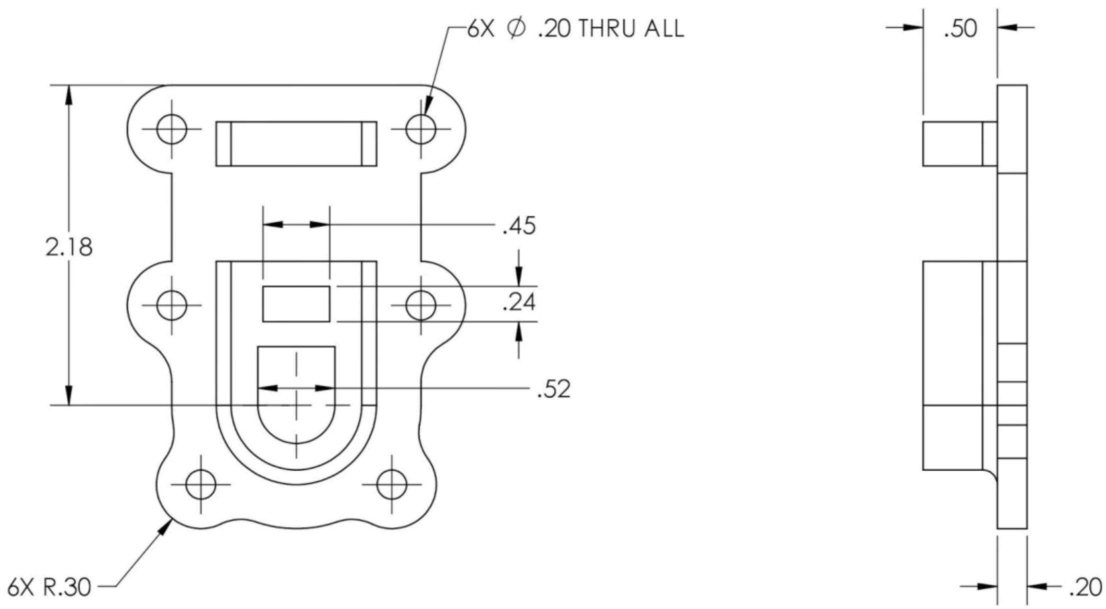
HOLE IS ONLY CRITICAL DIMENSION.
SIZE AND SHAPE OF CONTAINER IS TRIVIAL SO LONG AS CONTAINER
IS OF SUFFICIENT CAPACITY TO CONTAIN FILLER MATERIAL FOR A HEATER.



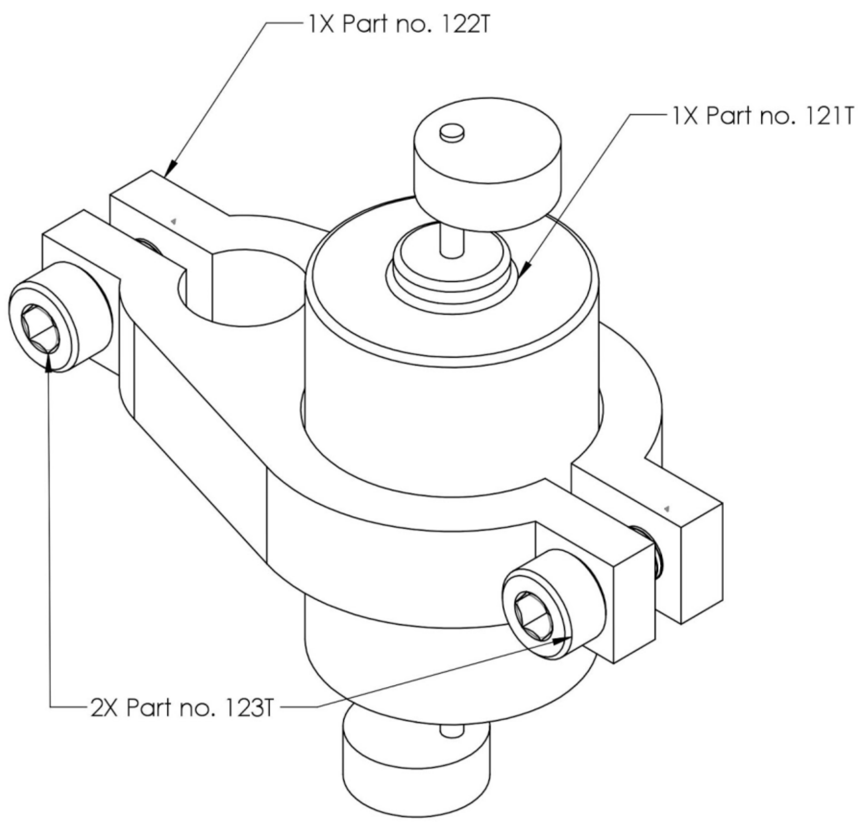


Cal Poly Mechanical Engineering	Lab Section: 05	Assignment #	Title: PLASTIC CONTAINER	Drwn. By: JOSH STEVENS
ME 430 - SPRING 19	Dwg. #:111T	Nxt Asb:	Date: 5/21/19 / Scale 1:2	Chkd. By: ME STAFF

PART IS 3-D PRINTED. CRITICAL DIMENSIONS ARE SHOWN.
OUTER PROFILE SHAPE/SIZE AND HOLE SPACING ARE TRIVIAL.
HOLES SHOULD HAVE >0.1 INCH OF MATERIAL AROUND.
TOLERANCES OF ALL FEATURES DETERMINED BY PRINTING PROCESS.



Cal Poly Mechanical Engineering	Lab Section:05	Assignment #	Title: Heater Tube Clamp		Drwn. By: JOSH STEVENS
ME 429 - WINTER 2019	Part #:115T	Nxt Asb:	Date: 1/29/19	Scale 1:1	Chkd. By: ME STAFF

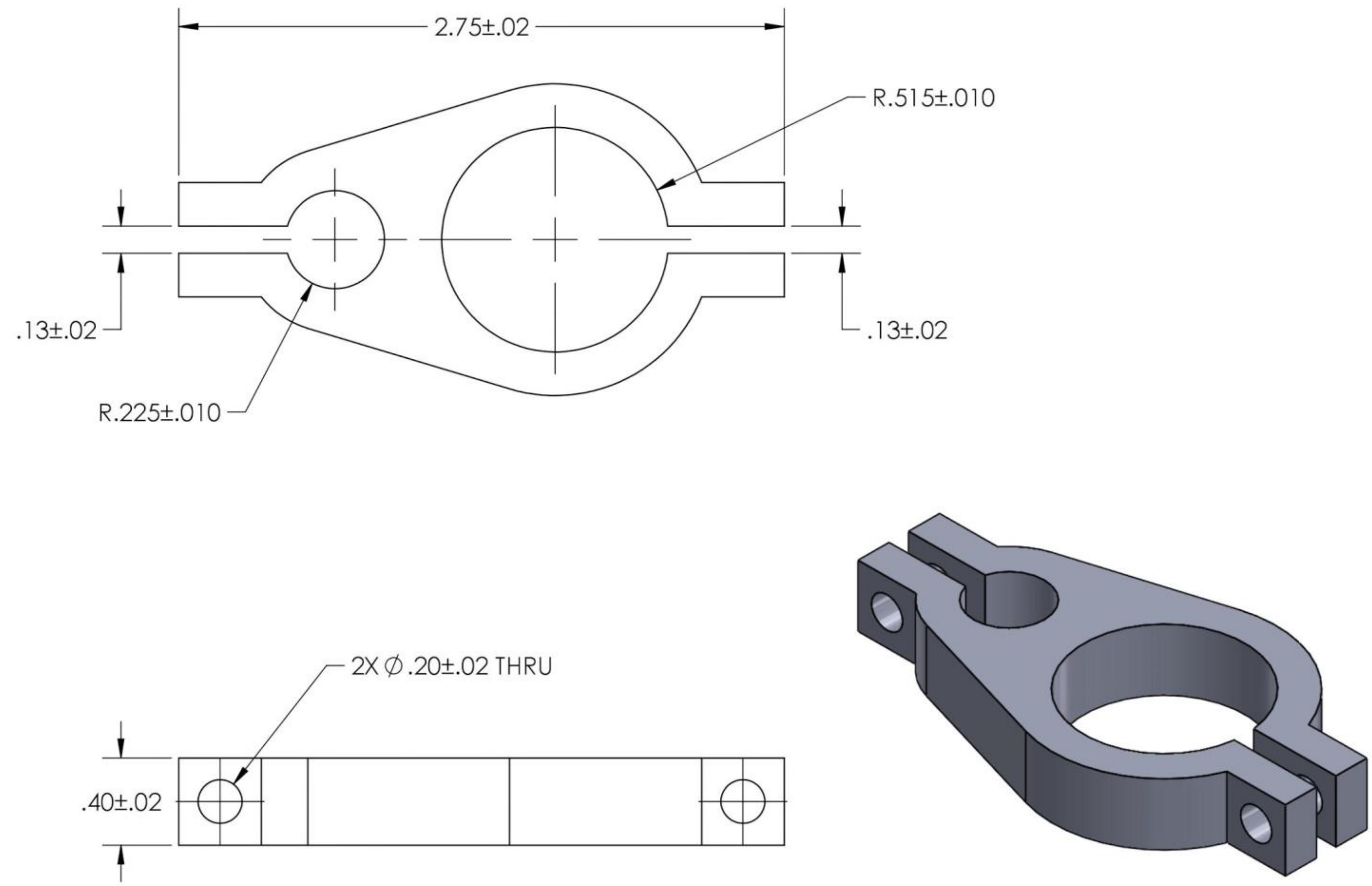


Part No.	Qty.	Description
121T	1	6-12V Vibration Motor
122T	1	3D Printed Motor Clamp
123T	2	#8-32 Hex Head Screw

	NAME	DATE
DRAWN	JS	5/21/19
CHECKED	KD	5/21/19

SIZE A DWG. NO. SUBASM 116T

SCALE:1:1



Cal Poly Mechanical Engineering	Lab Section: 05	Assignment #	Title: Part No. 122T - Motor Clamp	Drwn. By: JOSH STEVENS
ME 430 - SPRING 2019	Dwg. #:122T	Nxt Asb:	Date: 5/21/19 / Scale 3:2	Chkd. By: ME STAFF

Appendix H

Operator's Manual

Manufacturing Jig Operator's Manual

Safety/PPE: rubber/latex gloves, safety glasses

Emergency shut-off: on/off switch for motors

Purpose: manufacture immersion heater

To Use:

1. Refer to manufacturing chapter (chapter 6) of the FDR for specifications of immersion heater materials and their preparation
2. Insert cut pipe into clamp, so that a small length of tube (approx. ¼") protrudes above the top of wooden crate. Place hole in plastic container over exposed pipe section (shown in Figures 1-3).

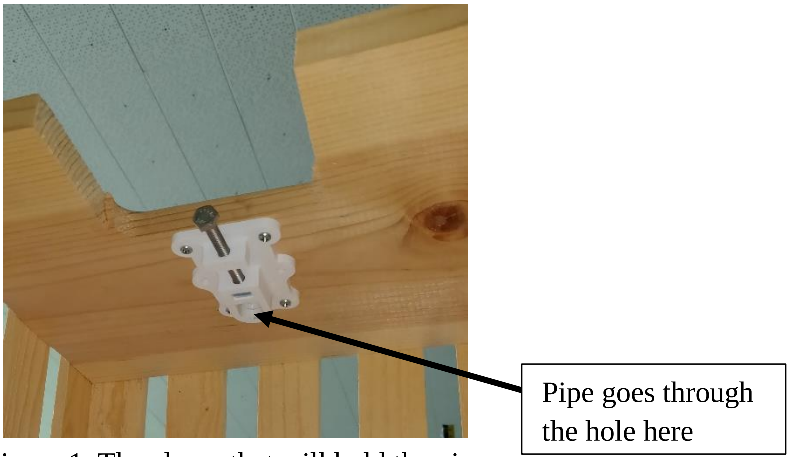


Figure 1. The clamp that will hold the pipe

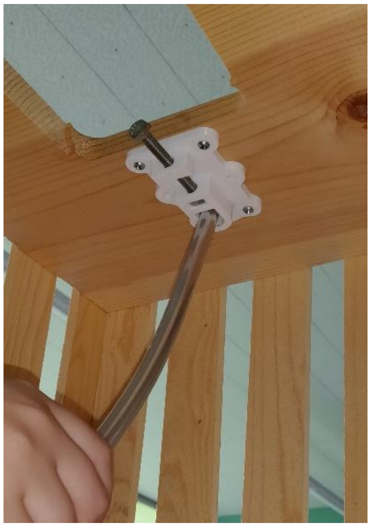


Figure 2. Putting the tubing through the hole of the clamp

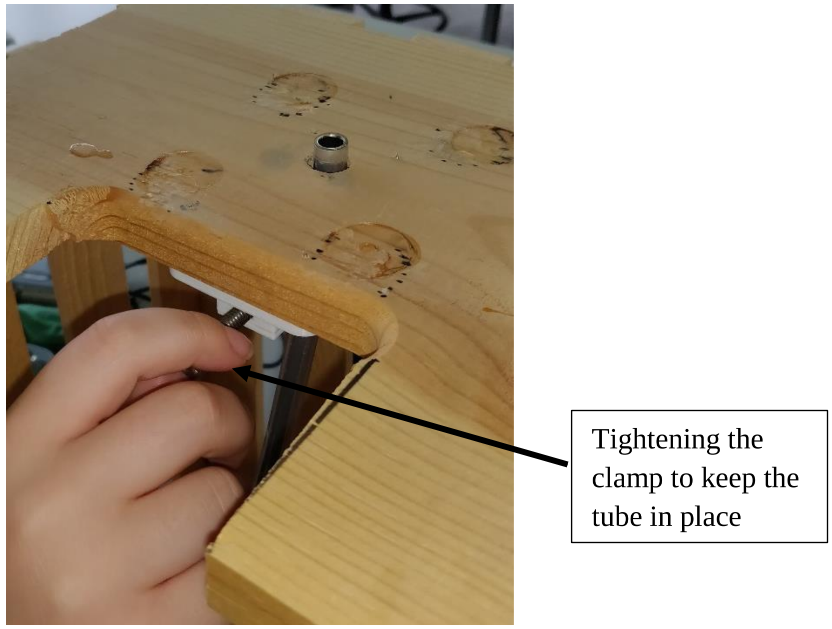


Figure 3. The amount of tubing that should protrude above the table

3. Secure clamp by turning bolt until snug. Verify tightness by gently pulling down on heater tube. **<u>Note:</u>** do not over tighten clamp to avoid deforming the tube
4. Attach motor clamps to the tubing at the approximate locations shown in Figure 4 below. Motor clamps are fastened by tightening clamping screw. Depending on exact tubing diameter, shimming clamp with tape may be necessary.

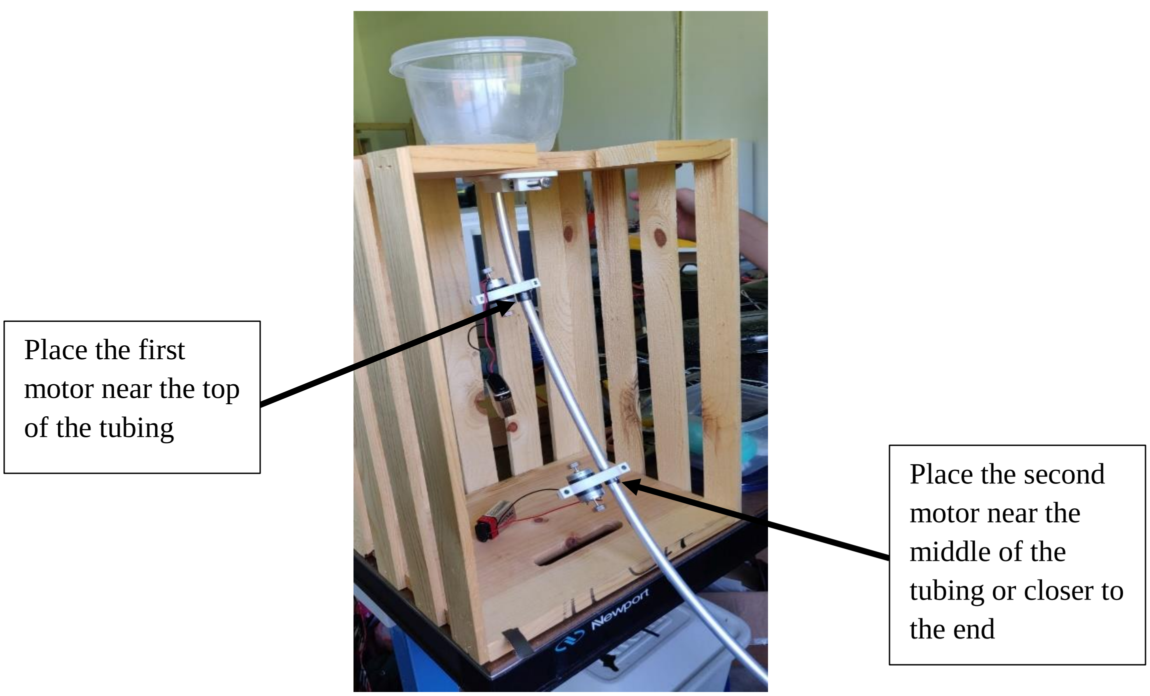


Figure 4. Approximate motor placement

5. Connect motors to desired power source (6-12V)

6. Thread diode chain through tube from the bottom, such that the end of the chain with the thermal switch will be in the bottom end when fully fed through (process shown in Figures 5 and 6).

Figure 5. Showing how the diode chain should go into the tube, and where the tape should be placed

Figure 6. Beginning to put the diode chain through the tubing

7. Stop pulling the diode chain through the tube once the tape stopping point indicator reaches the entrance to the bottom of the tube (shown in Figure 7). Figure 8 shows that the other lead should be coming out of the top of the tubing when you reach the stopping tape.

Figure 7. Stopping when the tape reaches the end of the tube

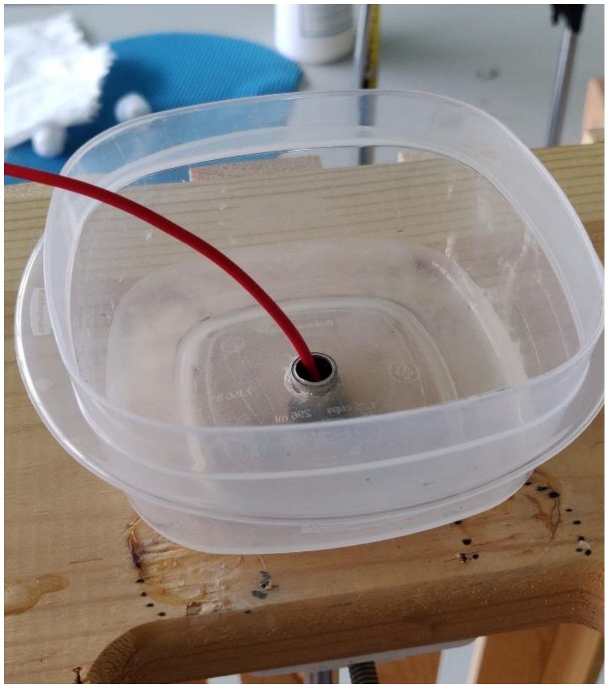


Figure 8. Wire lead coming out of the top of the tubing

8. Once the diode chain is in place in the tube, tape the bottom opening of the tube closed to prevent mortar leakage (shown in Figure 9).

Figure 9. Taping the end of the tubing

9. Turn on vibration motors
10. Pour mortar mixture into plastic container, covering hole of pipe as much as possible (shown in figure 10). Begin pulling/pushing diode chain through pipe (since the bottom end is taped closed, it'll feel more like wiggling the chain around in the tube) while ensuring pipe hole is covered by mortar mixture. Shifting the diode chain around while putting in the mortar mixture helps the mixture flow down evenly.

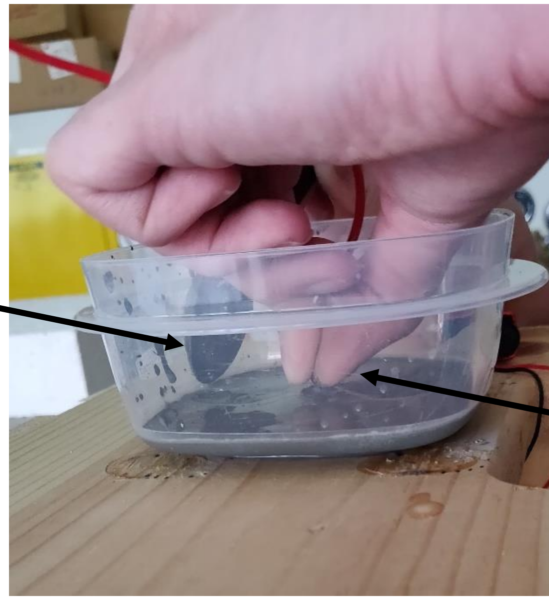


Figure 10. Putting filler material into the tubing

11. Turn off vibration motors once mortar stops flowing down into the tubing.
12. Remove pipe from shake table by loosening shake table clamp and removing plastic container.
13. Cover open end with tape to prevent mortar leakage.
14. Bend heater to shape using pipe bender (shown in Figure 11). It can be helpful to bend heater to near desired shape, remove pipe bender, and bend the heater the rest of the way. If fully bent with tube bender, the bender can become stuck on the heater tube (bending process and result shown in Figures 12-14).

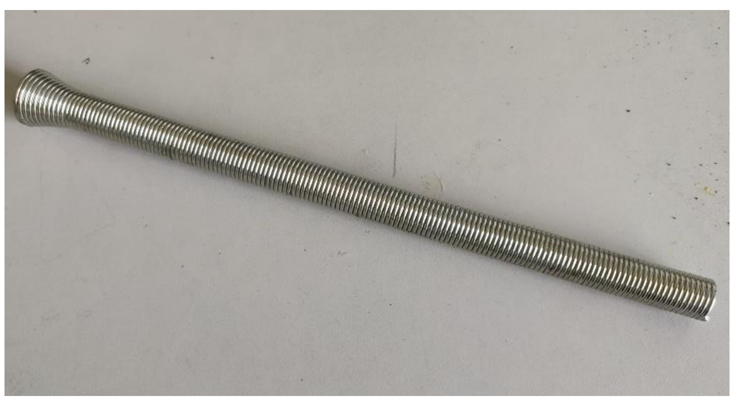


Figure 11. The pipe bending tool

Figure 12. Putting the pipe bender onto the tubing

Using your knee to bend the tubing makes the process easier. It makes it easier to get the curves of the heater.

Figure 13. Bending the tubing

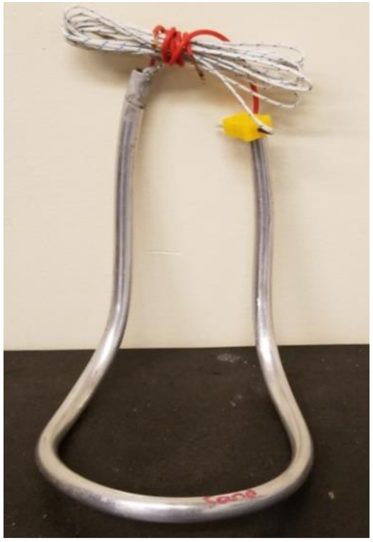


Figure 14. Final shape of the heater

15. Allow mortar to cure for roughly 24 hours before using heater

Maintenance

Table should be cleaned after use. The plastic container and tube clamp should be the only surfaces in contact with the concrete material, and these should be cleaned thoroughly with water after use. If dry concrete begins to build up on the container, attempt to remove it, or replace container.

Parts *Replacement*

For specifications on any parts that need to be replaced, refer to our assembly BOM. Included part drawings and our chapter on manufacturing detail the process used to make any part of the shake table. 3D printed components can be replicated based on part drawings, or STL files can be made available.

Heater Operators Manual
Safety/PPE: oven mitts or heat-safe gloves
Emergency shut-off: Thermal switch on diode chain
Purpose: immersion heater for food or liquids
To Use:

1. Clean surface of heater.
2. Connect heater to power source.
3. Submerge heater in food or water- keep heater submerged until food is thoroughly cooked or water has reached desired temperature.

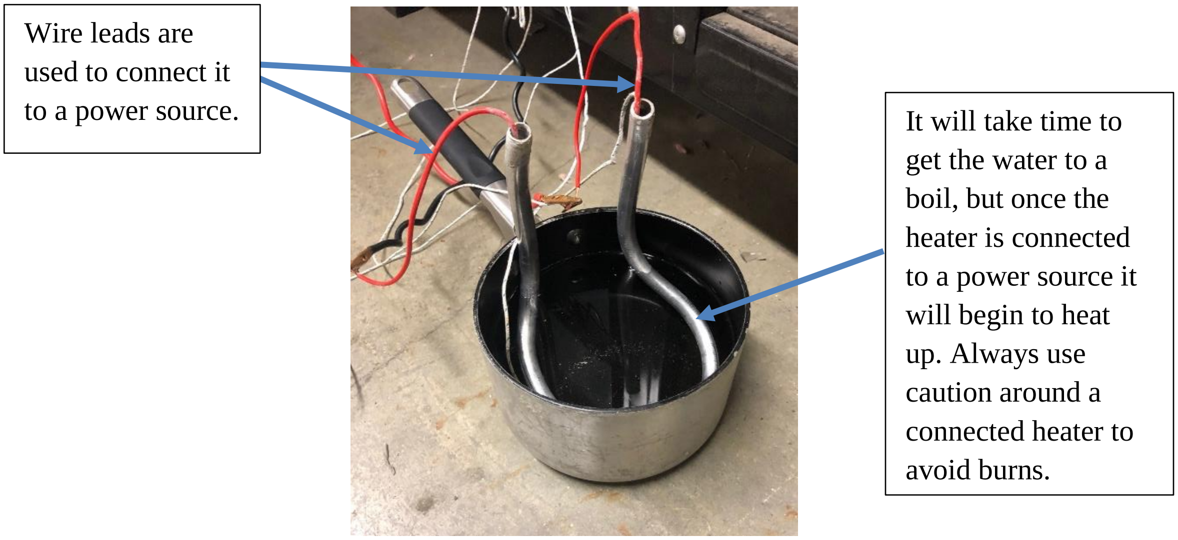


Figure 1. Heater submerged in water

4. Check food temperatures to ensure the food is safe to eat.
5. Disconnect heater from power source.
6. Allow heater to cool, or remove from cooking pot using oven mitts/heat-safe gloves.

Maintenance
Heater should be kept clean. To ensure long heater life, avoid running heater in open air. Heater should be submerged when powered on in order to prevent overheating of diodes. If a diode chain fails inside of a heater, nothing can be done to fix it. Another heater will need to be manufactured in the event of diode chain failure.

Appendix I

Failure Modes and Effects Analysis

Design Failure Mode and Effects Analysis

Product: ____________________________ Prepared by: ____________________________

Team: ____________________________ Date: ________________ (orig)

												Action Results			
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	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
Enclosure/transfer heat	metal isn't thermally conductive	no heat	7	1) too thick 2) poor thermal conductor	1) pipe analysis/selection 2) material analysis	1	thermal imaging	1	7						
Enclosure/transfer heat	metal has insulating coating	a) no heat b) inadequate heat	7	poor thermal conductor	material analysis	1	thermal imaging	1	7						
Enclosure/provide barrier	cracks in metal	filler material isn't contained	8	pipe cracks	heat treatment	5	inspection	1	40	refine manufacturing process	January 22, 2019	Cautious bending			
Enclosure/non-toxic	has harmful coating	releases toxic materials when heated	9	has toxic coating	use aluminum	1	analysis	1	9						
Enclosure/non-toxic	metal rusts	releases toxic materials when heated	9	has toxic coating	use aluminum	1	analysis/inspection	1	9						
Heating/produce heat	no heat produced	no heat produced	6	1) diodes short 2) diodes break 3) defective/DOA diodes	1) spacers 2) thermal switch 3) pre-manufacturing testing procedure	7	thermal imaging	3	126	Twist Diode Leads and Solder	January 9, 2019	Twist leads prior to soldering			
Heating/produce heat	not hot enough	inadequate heat	5	1) diodes short 2) diodes break 3) defective/DOA diodes	1) spacers 2) thermal switch 3) pre-manufacturing testing procedure	7	thermal imaging	3	105	Twist Diode Leads and Solder	January 9, 2019	Twist leads prior to soldering			
Filler/transfer heat	material isn't thermally conductive enough	a) inadequate heat b) overheat c) no heat	6	1) poor thermal conductor 2) air bubbles/impurities	1) material analysis 2) improve manufacturing process	6	testing	3	108	refine manufacturing process, consider different filler materials to improve conductivity and manufacturability	January 22, 2019	Vibration motors to eliminate air bubbles			
Overall system/Reduce time investment	Design is too cumbersome	Time is not reduced by design	3	Poor overall design/process design	Consider ergonomics, time to complete each task	2	Time process	2	12						
Overall system/Improve filler deposition	Tube isn't held at proper angle	Filler falls through tube too quickly	2	Clamp too weak, structure positions tube poorly	Experiment with different tube orientations	4	Inspection	1	8						
Vibration, interface system/Reduce time investment	Interface is too weak	Container falls off	4	Magnet connection not strong enough, user applies too much force to diode chain/tube	Spring deflection analysis/interface disengagement testing	4	Prototype Testing	1	16			Springs Removed			
Vibration, interface system/Improve filler deposition	Vibration is wrong amplitude	Composite is not properly liquified	4	Motor wrong size, applied at poor location	Vibration analysis/spring modeling	3	Inspection	5	60	Research different vibrating elements	Brady/Josh - 12/6	Vibration motors selected			
Vibration, interface system/Improve filler deposition	Power is not supplied	Motor does not spin	6	Batteries die, conection is severed	Investigate backup power options	4	Inspection	1	24	Consider power supply alternatives	Brady/Josh - 12/6	Changed motor system			

Design Failure Mode and Effects Analysis

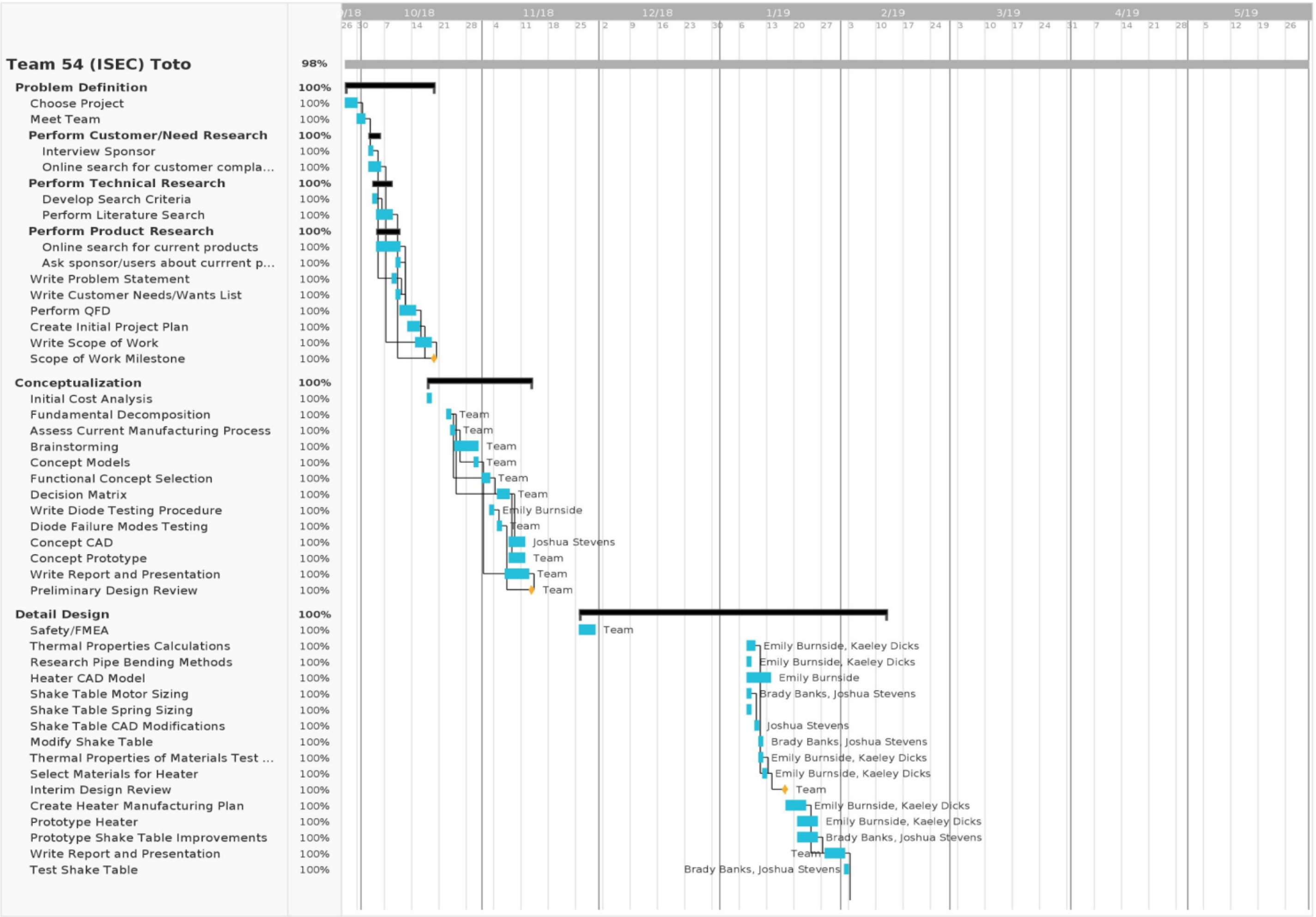
Product: ____________________________ Prepared by: ____________________________

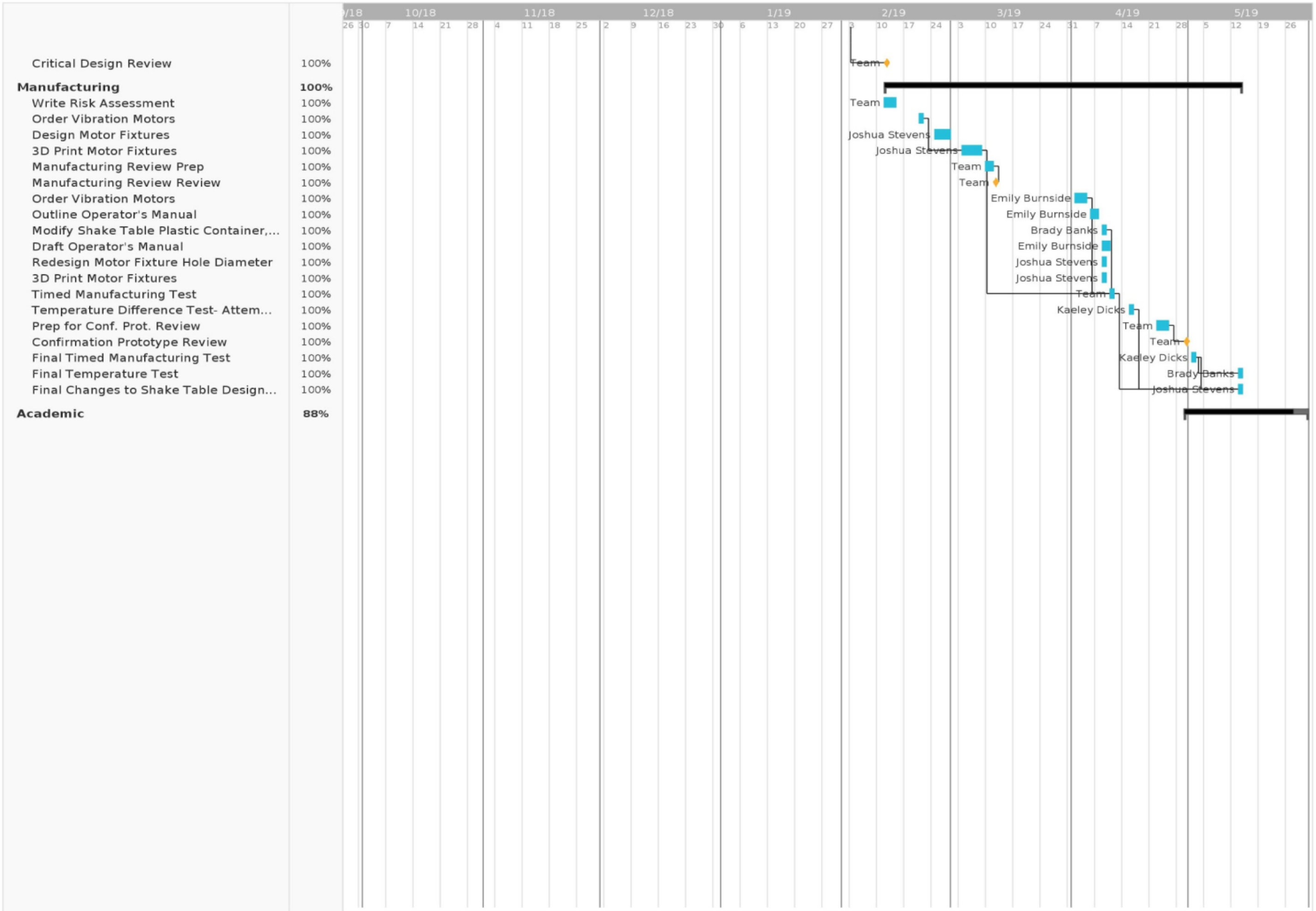
Team: ____________________________ Date: ________________ (orig)

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	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Severity	Action Results: Occurence	Action Results: Criticality
Containment, Fixturing system/Reduce time investment	Container isn't big enough	Doesn't hold enough concrete to make a heater	3	Improper container selected	Select properly sized container	1	Inspection/Analysis	1	3						
Containment, Fixturing system/Reduce time investment	Tube falls out of fixture	Time wasted in refixturing heater	3	Clamp too weak, large force applied to diode chain/tube	Clamping force analysis/testing	4	Inspection during use	1	12			Designed custom clamp			
Containment, Fixturing system/Improve filler deposition	Filler falls through hole around tube	Filler material is lost	2	Hole is too big	Consider rubber grommet	5	Inspection during use	3	30	Cut smaller hole or apply duct tape near gap	Brady/Josh - 12/6	Tape applied around gap			
Containment, Fixturing system/Improve filler deposition	Vibration is dissipated through container	Composite is not properly liquified	2	Container is not stiff material, motor attachment too weak, motor is placed poorly	Consider different locations, containers	1	Observation during use	5	10			Motor held on tubing instead			
Structure system/Reduce time investment	Structure falls over or breaks	Heater is ruined, time wasted	7	Large forces applied to system	Pick robust structure	1	Observation during use	1	7						
Structure system/Improve filler deposition	Structure dissipates vibration energy	Composite is not properly liquified	2	Structure is too weak	Pick robust structure	1	Observation during use	5	10			Apply vibration directly to tube			
Recovery System/Reduce time investment	Recovered material not usable	Time wasted in making more composite	1	Material is too dry/contaminated in container	Investigate rehydrating filler, ensuring container is in good condition	2	Inspection	4	8						
Recovery System/Reduce time investment	Fail to catch filler material	Time wasted in making more composite	1	Container is in wrong position	Design container positioning to catch material	2	Observation during use	2	4						

Appendix J

Gantt Charts




10/18
11/18
12/18
1/19
2/19
3/19
4/19
5/19
Critical Design Review 100%
Manufacturing 100%
Write Risk Assessment 100%
Order Vibration Motors 100%
Design Motor Fixtures 100%
3D Print Motor Fixtures 100%
Manufacturing Review Prep 100%
Manufacturing Review Review 100%
Order Vibration Motors 100%
Outline Operator's Manual 100%
Modify Shake Table Plastic Container,... 100%
Draft Operator's Manual 100%
Redesign Motor Fixture Hole Diameter 100%
3D Print Motor Fixtures 100%
Timed Manufacturing Test 100%
Temperature Difference Test- Attem... 100%
Prep for Conf. Prot. Review 100%
Confirmation Prototype Review 100%
Final Timed Manufacturing Test 100%
Final Temperature Test 100%
Final Changes to Shake Table Design... 100%
Academic 88%
Team
Team
Joshua Stevens
Joshua Stevens
Team
Team
Emily Burnside
Emily Burnside
Brady Banks
Emily Burnside
Joshua Stevens
Joshua Stevens
Team
Kaeley Dicks
Team
Team
Kaeley Dicks
Brady Banks
Joshua Stevens