ANYANWU
COOKWARE

Development of an Insulated Solar Electric Cooker (ISEC) with Thermal Storage for Use in Developing World Countries

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Section 1: Introduction.

According to the World Health Organization, about half of the world's population uses biomass stoves to cook their meals. However, biomass fires can be dangerous. Unattended biomass fires and indoor air pollution are responsible for an estimated 600,000 deaths annually and the creation of approximately 4 million instances of chronic disease. They also release CO_2 and other pollutants into the air, and require the families to gather enough material to keep it burning (WHO 2017). Although cleaner cooking technology seems like a clear solution, often families are either unwilling to change how they cook food or are unable to afford cleaner cooking solutions. In populations where the average daily pay rate is less than $1.25/day, an inexpensive cooking option is crucial.

Our group will work closely with our sponsor, Dr. Pete Schwartz, to follow on the successful prototypes of Insulated Solar Electric Cookers (ISECs) that inexpensively slow cook food over the course of the day for up to 10 people. We wish to add thermal storage to these designs to provide the ability to heat things with higher power and provide use after dark. This report includes the necessary background research we have done on the other ISECs and the design development we plan to follow to come to a solution.

We have decided to name our group Anyanwu Cookware. This name is inspired by the sun god of the Igbo people, Anyanwu.

Section 2: Background.

From 2015-2016 T. Watkins, P. Arroyo, R. Perry, R. Wang, O. Arriaga, M. Fleming, C. O'Day, I. Stone, J. Sekerak, D. Mast, N. Hayes, P. Keller and P.Schwartz began developing the first generation of low cost ISECs. Anywanu Cookware's development of ISECs with thermal storage will build heavily on the work of these students and professors. Watkins et al. published their findings in the document "Insulated Solar Electric Cooking - Tomorrow's Healthy Affordable Stoves?" which appears in *Development Engineering.* It is important to fully understand the successes and shortcomings of previous ISEC models to determine why a new cooker is of necessity to the third world population.

As mentioned in the introduction, cooking with coal and biomass causes 600,000 deaths per year in addition to many more instances of chronic illness. These preventable deaths are caused by lung cancer, bronchitis, and other health complication that are due to the air pollution associated with cooking over an open fire. Not only does cooking over an open fire cause plentiful deaths and instances of chronic disease annually, but it also contributes to forest degradation, biodiversity loss, and deforestation (Kammila et al. 2014). Some places in Africa, women must walk 2 to 3 miles to gather firewood due to the depletion of resources (National Geographic). If the use of new clean cookers is adopted in places where open fires are generally used to cook, life expectancy and quality of life would increase. From the publication, *Clean and Improved Cooking in Sub-Saharan Africa*, clean cooking solutions are defined in tiers of cleanliness as outlined in the table below.

Table 1. Provisional ISO/IWA tier classifications for clean and improved cooking technologies, Kammila et al. 2014.

Proposed ISO tier	Safety rating (Iowa State Univ. Rating System)	Fuel use (thermal efficiency) (%)	Emissions (CO + PM) (stove rating will be based on the lowest score from the four criteria)				Indoor emissions		Illustrative stove type
			CO (g/MJ)	CO (g/min/L)	PM (mg/MJ)	PM (µg/min/L)	CO (g/min)	PM (µg/min)	
Tier 0	<45	<15	>16	>0.2	>979	>8	>0.97	>40	3-stone fire
Tier 1	≥45	≥15	<16	<0.2	<979	<8	<0.97	<40	Improved efficient charcoal stove (KCJ type)
Tier 2	≥75	≥25	<11	<0.13	<386	<4	<0.62	<17	Rocket stove; natural-draft gasifier
Tier 3	≥88	≥35	<9	<0.1	<168	<2	<0.49	<8	Forced-draft "fan"-gasifier stove
Tier 4	≥95	≥45	<8	<0.09	<41	<1	<0.42	<2	LPG stove

The key issues with current clean cooking stoves are poor fits with consumer needs, negative side effects that negate benefits (i.e. long cook times), low awareness of new stove technologies, low appetite for risk, and inability for target customers to afford these technologies (Kammila et al. 2014).

An electric cooker typically requires about 1000W of power, however, this would cost about $800 for the solar panels alone. Watkins et al. found that 100W could bring one liter of water from 20°C to 100°C in about three hours. A 100W panel costs about $100 which is much more affordable. Based on these findings the team used a 100W panel to make their cooker. They also found that the cost of solar panels has decreased in nearly logarithmic fashion over the past 40 years and is expected to continue to decrease. This will make ISECs increasingly affordable in third world countries.

Finding the correct heating element resistance was important for the group because the correct resistance will maximize the power delivery of the solar panel. The team chose to make their own heating element out of Nickel-Chromium wire so they could tailor the resistance of the heating element to the panel and control the shape of the heater.

The resistance needed to optimize power delivery differs with solar intensity. The group examined IV curves for the power output of solar panels in three different circumstances: power output at noon, power output at 8AM or 4PM, and power output at 10AM or 2PM. Their plot is reproduced below from their publication. The straight lines show different resistances: the blue straight line corresponding with the 8AM or 4PM power output, the red line corresponding with the 10AM or 2PM power output, and the black line corresponding with the noon power output. A resistance for the heater was chosen at the 10AM or 2PM power output line to strike a compromise that would maximize power for the greatest proportion of the day.

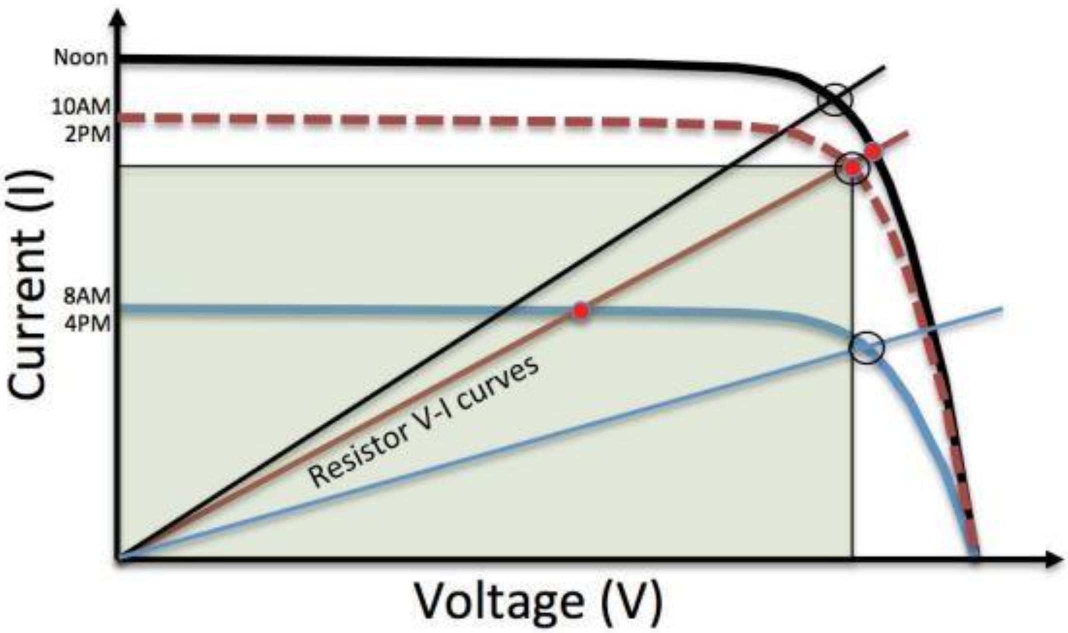

Figure 1. Standard solar panel power curve. The operating point for each time is circled in black. The resistance chosen is the red linear line. The red dots correspond to the operating points at each time with the chosen resistance. (Watkins et al. 2017)

Two prototypes were made at the student experimental farm at Cal Poly. Watkins et al. created a thermal model of their ISEC for analysis purposes, the prototype modeled is illustrated below.

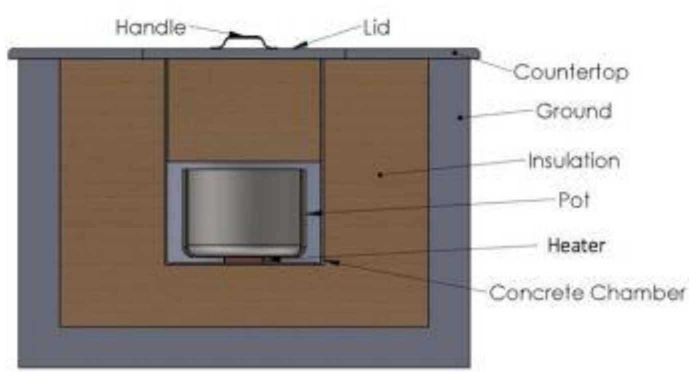

Figure 2. Solid model of an ISEC prototype. A thermal model was produced based on this model. (Watkins et al. 2017)

The group found the heat loss through the insulation by using a thermal resistance model. They used the equation

$$q = \frac{\Delta T}{R} \qquad \text{(Equation 1)}$$

to find the total heat loss through the insulation. Where q represents heat lost to the insulation, ΔT is the temperature difference between the cooking pot and insulation, and R is the thermal resistance. They modeled the heat flow in three sections: a hollow cylinder (in which the cooking pot would be) and two solid disks of insulation. The thermal resistance was calculated for each section and then added in parallel.

The heat loss is then used to find the total energy present in the system by using the equation:

$$E_n = E_{n-1} + (P_{in} - q) * t_{step} \qquad \text{(Equation 2)}$$

In this equation E_n is energy in the chamber, E_{n-1} is the energy at the previous time step, P_{in} is the power from the solar panel, q is the heat loss, and t_{step} is a time step. Finally, the increase in temperature of the contents in the cooking pot is calculated using:

$$E_n = mc\Delta T \qquad \text{(Equation 3)}$$

which is rearranged to

$$\Delta T = \frac{En}{(mc)H20 + (mc)mass} \qquad \text{(Equation 4)}$$

In this equation m is mass, c is specific heat, E_n is total energy calculated previously. Mass of the water and mass of the pot and concrete are included in the equation.

After testing the ISEC prototype described in Figure 2, the group found that their thermal model predicted the system behavior well. The plot reproduced below shows a comparison of the experimental data collected to the temperatures the thermal model predicted.

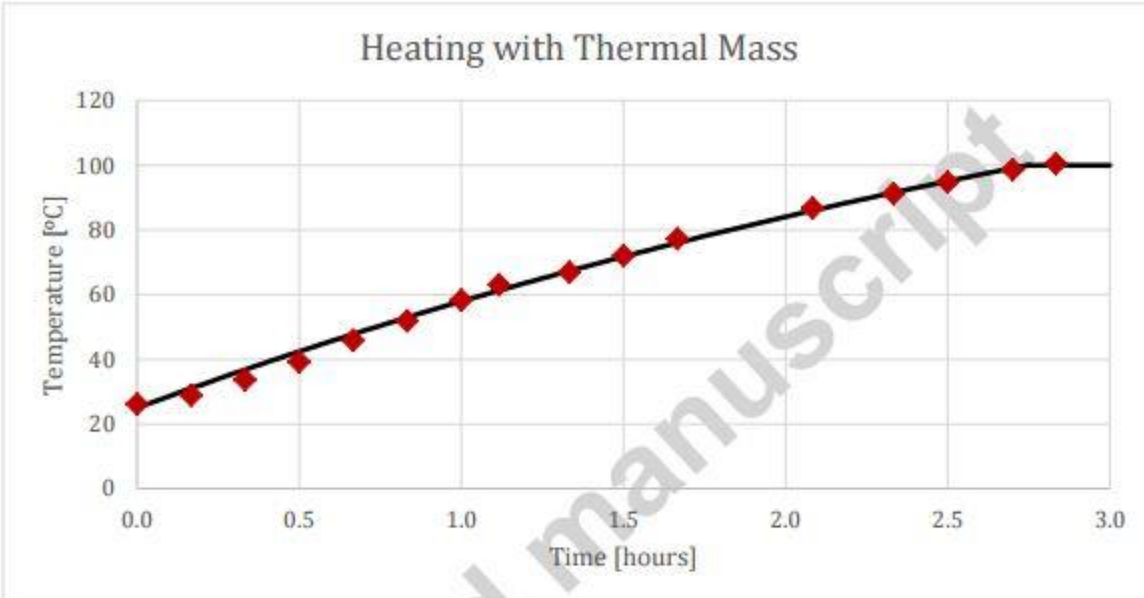

Figure 3. Temperature of water versus time in the ISEC shown in Figure 2. The red diamonds represent experimental data points. The black line represents the thermal model. (Watkins et al. 2017)

This experiment showed that 1L of water took about 3 hours to boil. The group also calculated a maximum temperature the ISEC could reach if no water was present. From the thermal model explained above, they found that a maximum temperature of 185°C could be obtained.

Another prototype was made called an immersion heater ISEC. Figure 4 shows the solid model and the finished prototype of this ISEC.

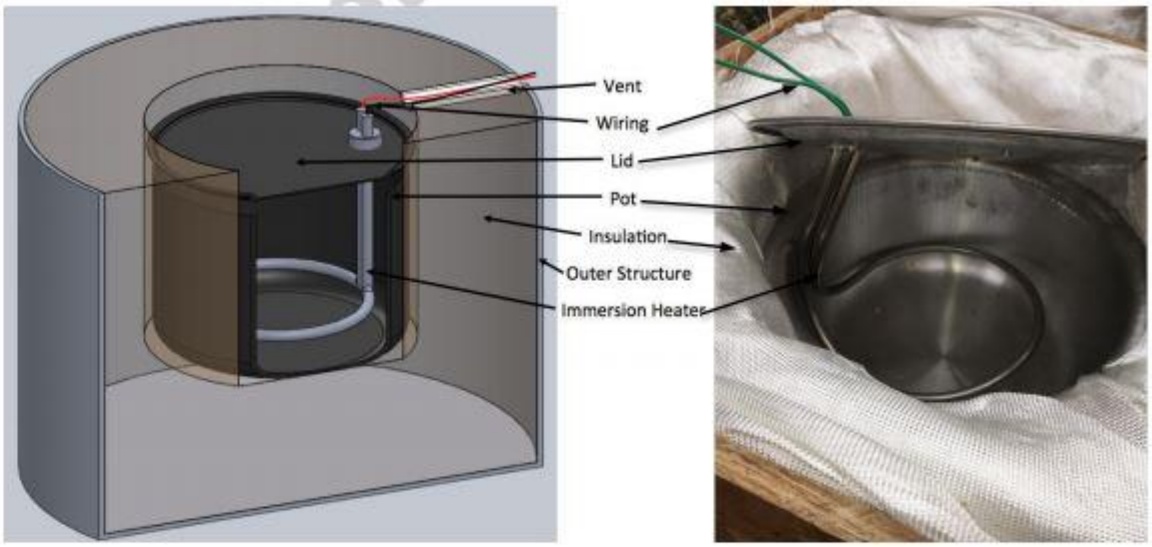

Figure 4. Solid model and finished prototype of immersion heater ISEC. (Watkins et al. 2017)

This ISEC was tested using 2.7 kg of stew (meat, beans, and vegetables) which was brought to a boil and then allowed to cool. This ISEC was able to boil the 2.7 kg of stew in about 4 hours. After a boil was reached, the ISEC was turned off. The temperature loss rate was 6.67°C/hr which corresponds to a heat loss rate of 20.7W. Figure 5 below illustrates how the temperature in the cooker changes over time when the immersion heater is turned on, or allowed to cool.

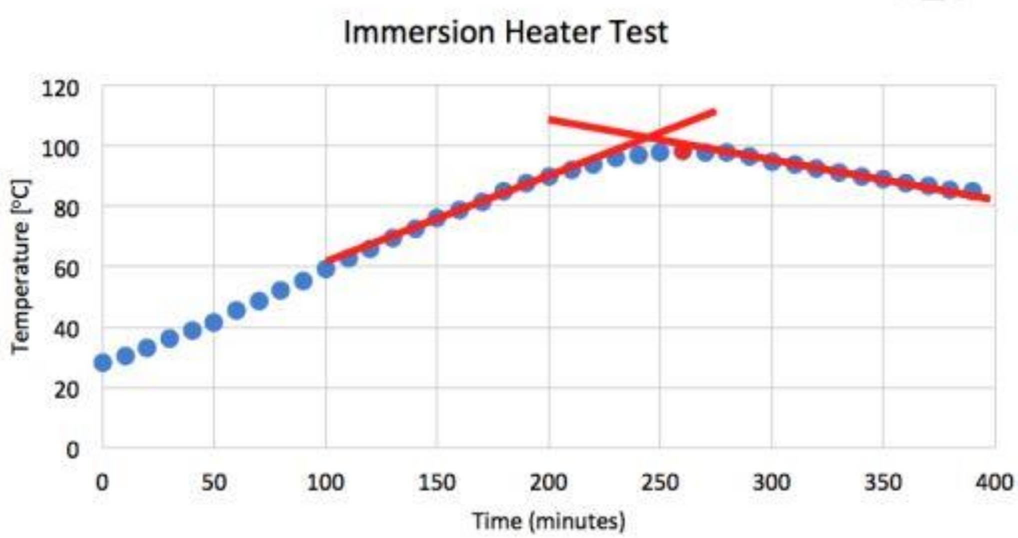

Figure 5. Temperature of 2.7 kg of stew in an immersion heater ISEC. The stew was brought to a boil in 260 minutes and then turned off. Data after 260 minutes shows how the system cools. (Watkins et al. 2017)

Four students were able to travel to Gulu, Uganda to study village life and implement two ISEC prototypes. Both of the prototypes were built using material purchased in Gulu. The first prototype they implemented was dug in the ground. This design was immediately rejected by the villagers. The villagers disliked the appearance and wanted the cooker to be off the ground. Next, an ISEC was built with a reed-mat outer structure and rice hulls for insulation. All of the materials, including a 120W solar panel, were bought for $110.

Figure 6. ISEC implemented in Uganda. The outer structure is made of reed mat and rice hulls are used as insulation. The heater rests inside a larger pot and a smaller pot holding food rests on top the heater. A ceramic tile is placed under the larger pot to insulate rice hulls from hot spot under the heater. (Watkins et al. 2017).

The students made visits to the two families that received the ISECs over the following five weeks. The families continue to use and improve on the ISECs. The ISEC has been used to cook vegetables for short periods of time, or larger meals like beans over the course of the day. The ISEC has also been used to heat bath water if there was a surplus of electricity. The villagers complained that the ISEC had insufficient power to cook in the evening.

Section 3: Objectives.

“We follow on the successful prototypes of Insulated Solar Electric Cookers (ISECs) that inexpensively slow cook food over the course of the day for up to 10 people. We wish to add thermal storage to provide the ability to heat things with higher power and provide use after dark.”

Keeping the above problem statement in mind, we investigated the needs of our different customers; we rated the needs of the impoverished in Africa as the highest priority. We then developed our specifications after an exercise known as quality function deployment (QFD). This procedure began with us writing our customer needs in as simple of terms as possible. Then, we elaborated on those needs and decided how we could measure them. Finally, we researched a provisional clean cooking standard, the heat transfer rates of similar cooking units, and other specific details concerning the implementation of the last iteration of ISECs to generate the specific values we plan to design to. Two iterations of our QFD house can be found in Appendix B as a visual representation of this process.

It is important that every specification is chosen to meet specific customer needs, and that each value is substantiated. Below we offer the reasoning behind each of our specifications.

Specification 1: The total materials cost of the unit shall not exceed 30USD if the solar panels and connectors are not included in cost calculation.

As mentioned in the background section of this report, the end users of this ISEC will be the impoverished in sub-Saharan Africa. Nearly 30% of this population earns less than $1.25/day so this unit must be low cost (Kammila et al. 2014). The previous iterations of this ISEC device cost approximately $110 with solar, and $20 excluding the solar (Watkins et al. 2017). We know our device will likely cost more than the previous iteration due to the added functionality of thermal storage. We placed a conservative cost cap at $30 to account for the cost of thermal storage. This cost does not include the cost of the solar panels, as that is not something we can influence.

Specification 2: Starting from a cool thermal reservoir at a temperature of 20°C, then subjecting the unit to AM1.5G insolation conditions, the unit will be capable of heating 1L of H_20 from 20°C to 100°C in under 3 hours.

To be able to verify our specification, we need repeatable test conditions. The most important parameter for us to control is the power delivered from the solar panels. Because we are unsure of the exact panel model we will be using, it makes sense to define the solar conditions the panels will experience such that the panels perform at their rated power. Most solar panels are rated for AM1.5G insolation conditions, so we will design our specifications around this test condition. For our readers, AM1.5 means that the light from the sun must travel through an air mass 1.5X the air mass normal to the Earth's surface. When accounting for the irradiance scattered through the Earth's atmosphere and the energy of the direct radiation from incident light rays, calculations show that terrestrial solar flux is approximately 970 W/m^2. However, the standard AM1.5G spectrum has been normalized to give 1000 W/m^2 due to the convenience of the round number and the fact that there are inherently variations in incident solar radiation. Finally, the below spectrum is specified as the spectrum of light experienced under normal terrestrial conditions in the AM1.5G test condition. It is important to specify the spectrum because solar cells have varying quantum efficiencies at different wavelengths, and thus their performance is tied not only to the intensity of the light they are receiving, but also the type of light they are receiving (Honsberg, Bowden 2013).

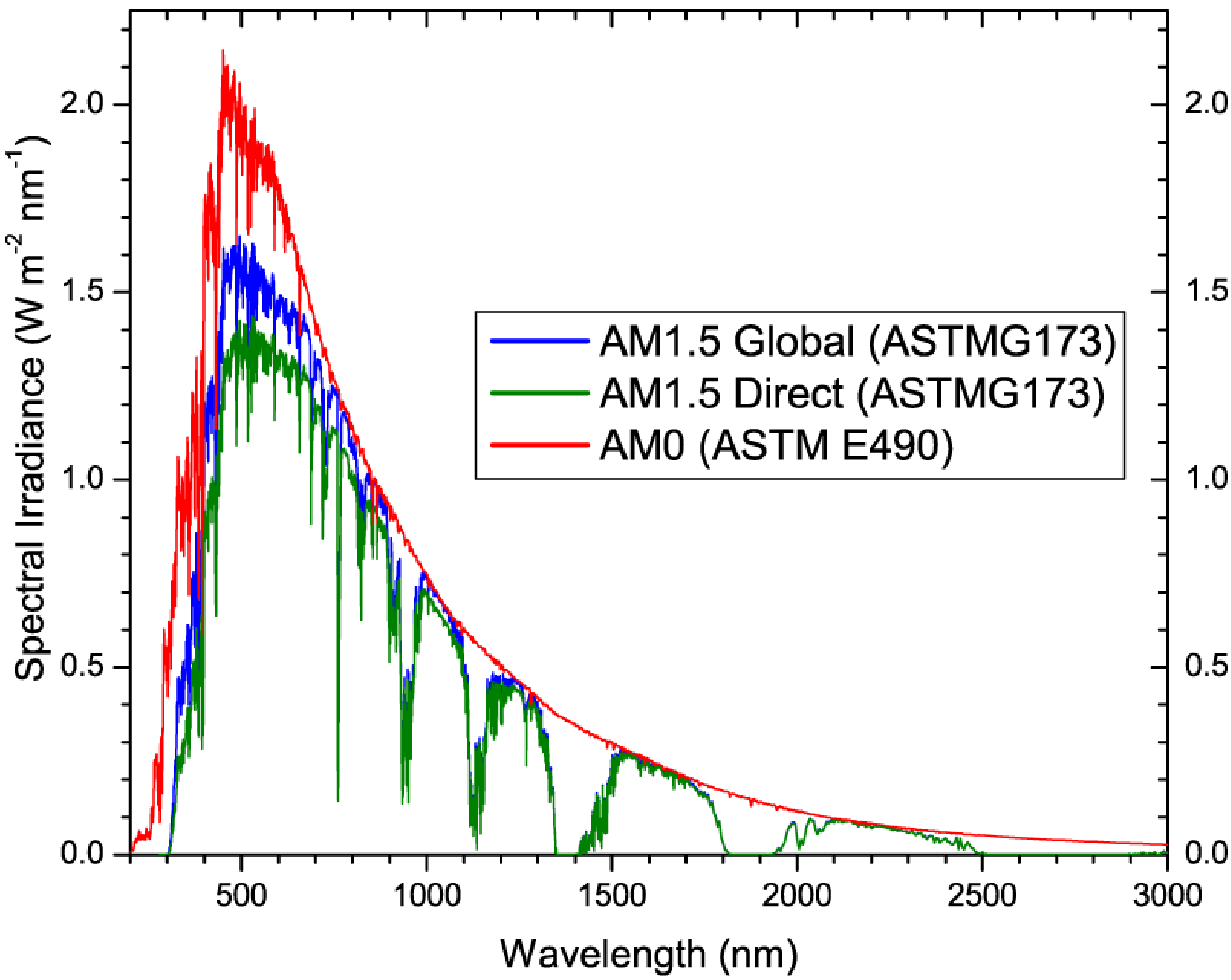

Figure 7. The amount of spectral irradiance across the spectrum of light coming in from the sun at different specified test conditions, AM0, AM1.5D, AM1.5G (Honsberg, Bowden 2013).

To be a solar cooker, our device must be able to raise the temperature of whatever it is cooking. To define how well it achieves this purpose, we decided to mimic a test performed by the ISEC team before us (Watkins et al. 2017). This is the same specification that the previous group designed their ISEC around. It seems logical that the next iteration in a line of products ought to perform at least as well as its predecessor, so we have chosen to also use this metric. Although our ISEC will perform to the same heating standard as the previous unit, this value still reflects growth because of the added functionality our ISEC will provide with thermal storage.

Specification 3: After the ISEC has been subjected to 8 hours of AM1.5G insolation conditions, and thus has heated the thermal reservoir, the magnitude of the average rate of temperature change at the cooking surface of the unit should remain at or below 6.67°C/hr over a 6 hour cooling period.

Thermal storage is going to be what differentiates our ISEC from its predecessors. As such, it is necessary to design a system that loses heat more slowly than the previous system lost heat at

~6.67°C/hr (Watkins et al. 2017). To arrive at the 5°C/hr number, we started with how warm the food needed to be at 10PM. According to the FDA, warm food must maintain an internal temperature of 60°C to be considered safe in a buffet/warm food storage environment (U.S. Food and Drug Administration [FDA] 2017). We decided that if the food reached this temperature at 10PM, the thermal storage would have performed its function, allowing for cooking after dark. Next, we considered that after 4pm (or 4 hours after solar noon, more accurately) the performance of the solar panels drops off significantly, see Figure 1 (Watkins et al. 2017). By treating 4pm as the start time for when the cooker is no longer receiving power, we determined that our cooker would have 6 hours to cool. Assuming that the food had reached a temperature of 100°C before the panel shuts off, and would be warm, 60°C at 10PM, it was some simple algebra to determine that our device would need to lose heat at a rate of 6.67°C/hr or less to perform its thermal storage function.

Specification 4: The unit should meet all energy and emission requirements for a Tier 4 clean cooking technology as outlined in the paper "Clean and Improved Cooking in Sub-Saharan Africa" by Africa Clean Cooking Energy Solutions Initiative. Refer back to Table 1. The thermal efficiency requirement for this standard is defined as (energy absorbed by food)/(chemical energy of the fuel). As our fuel is sunlight, and we are limited by the capabilities of photovoltaic technology, we have chosen to redefine thermal efficiency as (energy absorbed by food + thermal reservoir)/(energy outputted from solar panels).

It may seem a bit redundant to include these specifications. Most of them are centered on emissions, and a solar cooker will not produce any emissions. However, we have chosen to hold ourselves to this standard because the purpose of this project is to reduce the emissions from cooking, thereby safeguarding the health of millions. This goal ought to be reflected in our specifications.

Furthermore, we felt it was important to compare ourselves to other clean cooking technologies. Realistically, this product will be competing with a variety of cooking technologies, not just solid fuel fire or other ISECs. Thus is makes sense to frame the successes of our product, namely its safety on an emissions basis, in terms that would be understood easily by the cooking community. Rather than define our own standards of what constitutes clean, we will design a product that far exceeds that highest tier of already defined clean cook stoves.

Finally, considering that the cooking zone of our unit will be insulated, it is reasonable to assume that the thermal efficiency we have redefined will be significantly higher than the 48% specified in the ISO clean cooking standard. The previous iteration of ISECs were able to demonstrate thermal efficiencies near 75% (Watkins et al. 2017). However, by adding thermal storage to our unit, we fundamentally change how it will behave. Thus it doesn't make sense to create specifications from the last model of ISEC.

Specification 5: The solar panels shall be mounted on a fixed angle rack that may be manually rotated once a day, such that the angle of the rack creates the optimum incident angles of sunlight over the course of a year to maximize the power output from the panel.

The performance of our solar cooker is directly tied to the performance of our solar array. The angle and orientation of a solar array will affect how it performs over the course of time. As the sun travels across the sky the incident angle with which light enters the array will vary, resulting in different light paths through the PV material and ultimately, different amounts of energy produced (Honsberg, Bowden 2013). Below are two images produced using a solar calculator that show how the energy produced by an array varies over the course of a year if the array is located at a certain latitude of the world (in this case 2° North; the same as Gulu, Uganda) oriented equatorially (Northern hemisphere arrays point South, Southern hemisphere arrays point North) at two different tilt angles.

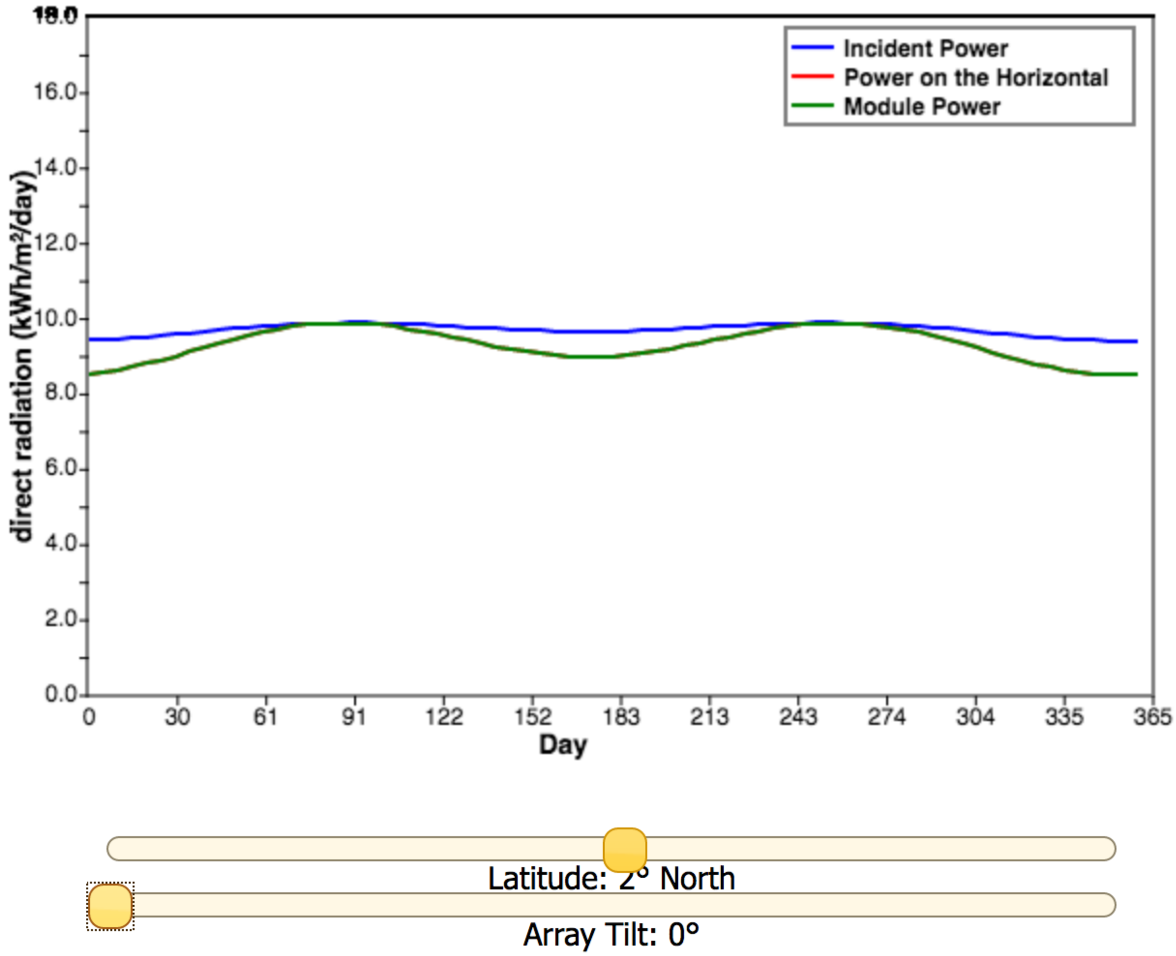

Figure 8. Power generated by a solar array over the course of a year if the array is placed at a tilt angle of 0° at a latitude of 2° North to model Gulu, Uganda (Honsberg, Bowden 2013).

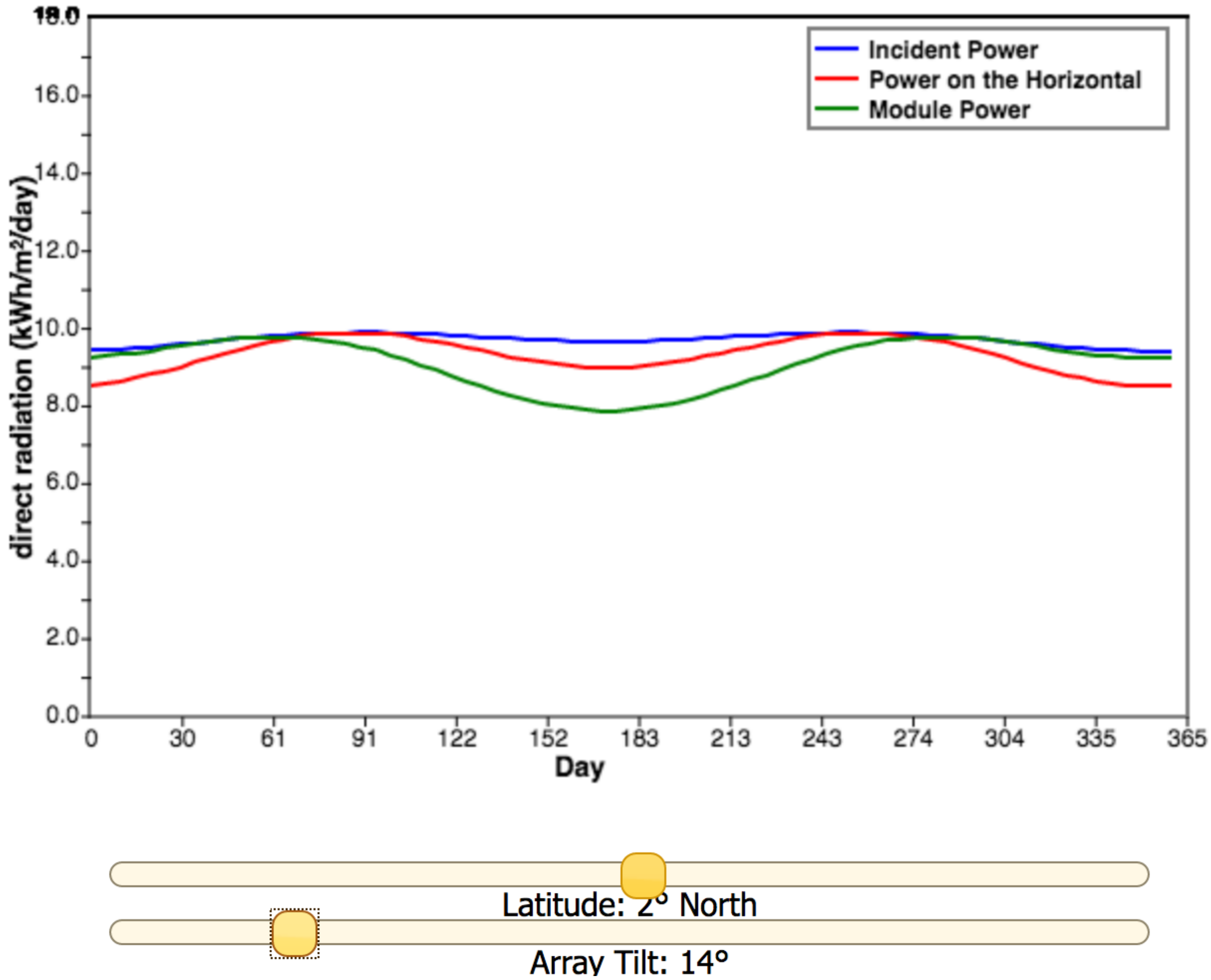

Figure 9. Power generated by a solar array over the course of a year if the array is placed at a tilt angle of 14° at a latitude of 2° North to model Gulu, Uganda. Notice that during winter, the tilt angle helps the array collect more power than a flat array, but during the summer it collects less power. It is important to optimize these changes such that the total area under the module power curve, or the total amount of energy collected, is maximized (Honsberg, Bowden 2013).

It is seen that changing the tilt angle of the array changes how the unit functions during different parts of the year. To produce the most power over the course of a year, we would like to orient our arrays such that the area under the curve of “module power” is maximized.

Specification 6: All manufacturing materials available within 50 miles of implementation zone.

This specification is born of two customer requirements: the unit needs to be low cost, and it must be able to be implemented by the end users. If all the components of the device can be purchased locally, this will make it possible for end users to service their units, or build more units as they accumulate the money to do so. Furthermore, it reduces the cost of the units by reducing shipping costs. Additionally, there is evidence that if end-users of a new technology have a hand in its creation/implementation, they are more likely to report positive experiences with the technology and utilize it more often (Mirza 2015). Again, we looked to the last group's experience in Gulu, Uganda. They were able to purchase all of their materials in Gulu, so we set our purchasing radius to include Gulu and several nearby cities. We determined that a 50 mile radius was sufficiently large such that residents of smaller villages outside of metropolitan areas wouldn't be excluded as potential customers, but also small enough to create a truly local solution.

Specification 7: At no time should the exterior of the ISEC unit reach temperatures above 45°C.

It is always important to consider safety when designing anything. In an ISEC unit, the only real danger is the risk of burns. As such, we needed to create a specification to protect users from the exterior of the unit becoming hot enough to burn. We determined 45°C to be a reasonable temperature limit because first degree burns don't start occurring until 48°C (Thompson 2015). Optimally, our device will operate with a lower exterior temperature, but we decided it was smarter to set our specification high because we are sending this unit to Uganda, where it can get very warm, and it doesn't make sense to set our maximum external temperature lower than the ambient temperature of the environment.

Table 2. Design specifications for Anywanu Cookware ISEC. The compliance column outlines how each specification target will be verified. Specifications will be checked through mathematical analysis (A), testing (T), and visual inspection (I).

Spec Number	Parameter Description	Requirement or Target (units)	Risk	Compliance
1	Unit cost	$30	low	I
2	Bring 1L of H_2O from 20°C to 100°C under AM1.5G conditions	In 3hrs	med	A, T
3	Average rate of temperature loss over an 6 hour cooling period immediately following an 8 hour heating period under AM1.5G conditions	6.67°C/hr	high	A, T
4	Tier 4 ISO/IWA Clean Cookstoves	Thermal efficiency >48% Safety rating >95 (Iowa State University Rating System) Emissions: CO (g/MJ)<8; (g/min/L)<0.09 PM (mg/MJ)<168; (µg/min/L) <1 Indoor Emissions: CO (g/min)<0.42 PM (µg/min)<2	low	A, T
5	Maximize solar output for year	Absolute maximum of total watts generated	low	A
6	Local materials	50 mile sourcing radius	low	I
7	Exterior temperature	<45°C at all times	low	A,T

Section 4: Management Plan.

All members in Anyanwu Cookware have equal responsibility, however, some specific responsibilities are delegated to each team member. These responsibilities are summarized in Table 3.

Table 3. Team member responsibilities.

Person	Responsibility
Kyle Smit	● Primary point of contact ● New concrete prototype lead ● CAD drawings ● Fabrication and assembly instructions
Spencer Davis	● Material coordinator ● Rebar prototype lead ● Cost analysis ● Safety considerations
Amanda Gyokery	● Team treasurer ● Prototype/test scheduling ● Heat transfer modeling

Section 5: Design Development.

The first step in coming up with a solution was to conduct background research on the existing technologies that we can improve on. A summary of this research can be found in the "background" section above. Additionally, we have incorporated numerous brainstorming ideation sessions into our design development process. The purpose of these sessions is to generate as many ideas as possible, such that we can down select to a few strong ideas. Figures 10-15, shown below, contain some ideation sketches from these brainstorming sessions. These sketches are rudimentary and not to scale; they are drawn exaggerated to emphasize ideas and clearly illustrate concepts.

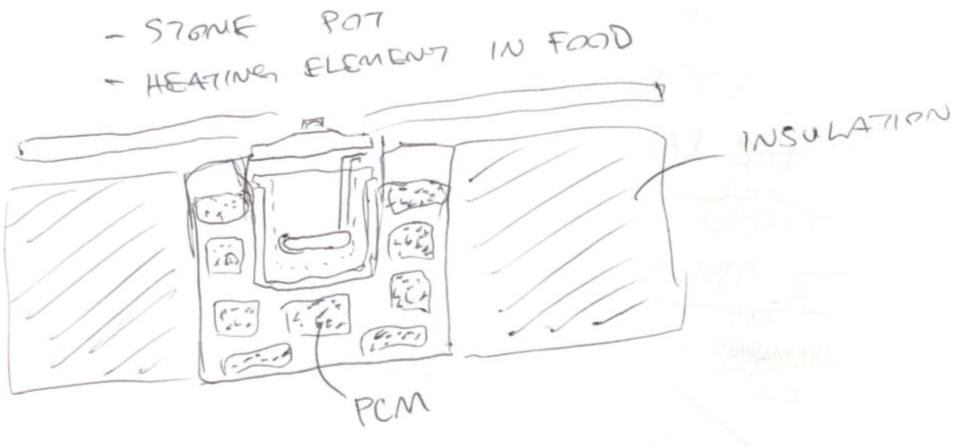

Figure 10. This concept has a pot surrounded by a concrete reservoir with pockets of phase change salt. The logic behind this idea is that the phase change salts would be able store large amounts of energy and release them again at a specific desired temperature.

Figure 11. This concept consists of a cylindrical concrete reservoir with a rebar heater immersed in the center and welded to the cast iron cooking surface. Rice hulls would surround the reservoir and a bag of rice hulls would insulate the top.

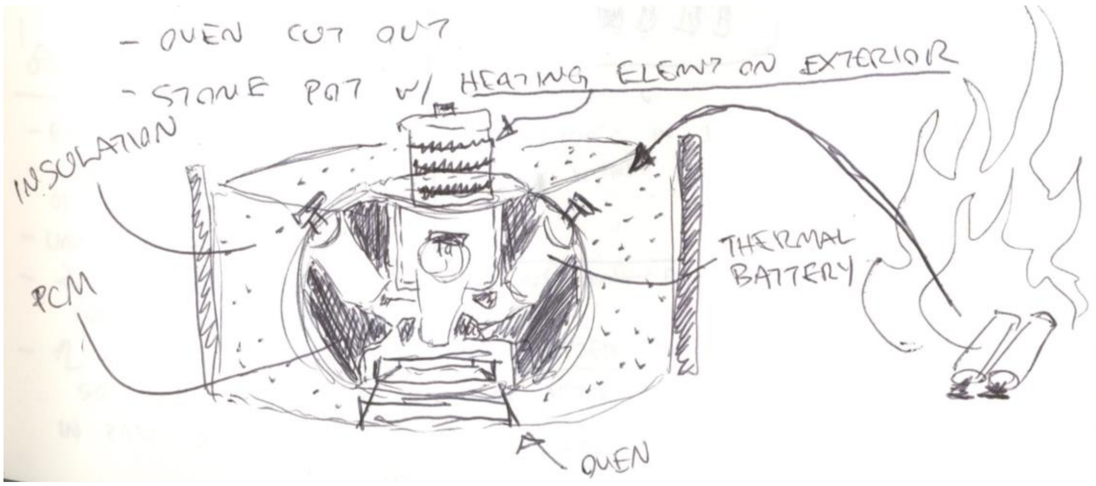

Figure 12. This concepts includes thermal charges, which could be heated separately on a large fire and placed back into the thermal storage to help heat food after the solar panel stops providing power. Alternatively these charges could be removed from a hot thermal reservoir for other uses.

Figure 13. This idea focuses on the heating element and includes a thermal switch to direct the power to a heater either immersed directly in the food or one in the thermal storage.

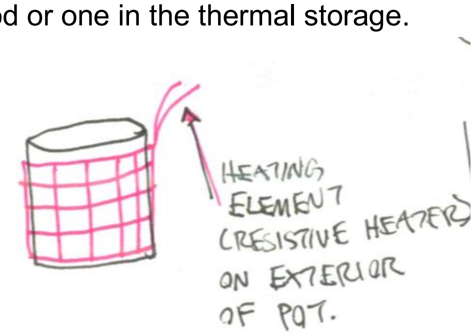

Figure 14. This idea shows a heating element wrapped around the pot. This would provide a large heating surface area and would heat the food quickly, ostensibly. Heat would also flow from the heater into the thermal storage surrounding the pot.

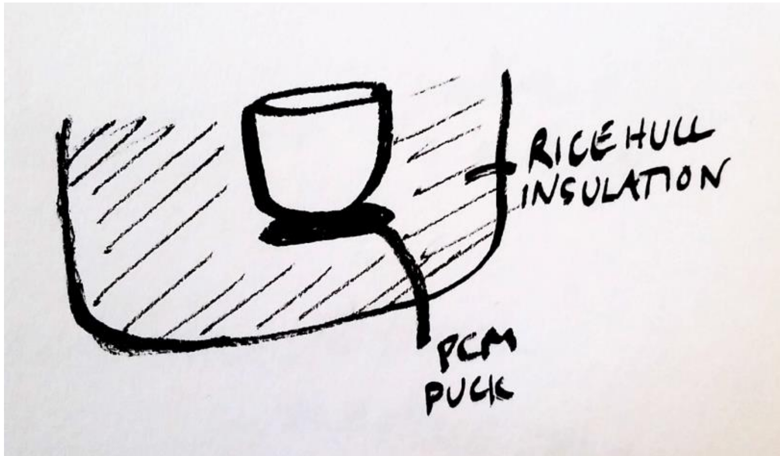

Figure 15. This idea does not use concrete as a thermal storage reservoir, instead it uses a high temperature Phase Chance Material puck surrounded by rice hull insulation.

Moving past the brainstorming phase, it became important to sift through our ideas and select only the ones that could be a feasible solution to our problem. To start, we tossed out nonsensical, overly complicated designs that were unsafe, well outside of our budget range, or "off the wall," zany ideas. The next step in the down selection process was to define the functions our ISEC was expected to perform. Our ISEC needs to have a heating element, a thermal storage element, and an insulation element. We then separated the brainstorm ideas by function, and created decision matrices that ranked each component of an idea on its ability to perform the function. These decision matrices can be seen below in Tables 4-6.

Table 4. Heating element decision matrix. Each idea is ranked on its durability, surface area for heat transfer, ease of assembly, cost, and serviceability. These metrics are also weighted in that order, from most to least important.

	Durability		Surface Area		Ease of Assembly		Cost		Serviceability		Totals
Weight->	5		4		3		2		1		
Outside of pot	2	10	5	20	4	12	3	6	5	5	53
Concentrator	1	5	4	16	1	3	1	2	2	2	28
2 heaters with a switch	2	10	5	20	2	6	2	4	3	3	43
Heater in thermal reservoir	5	25	5	20	3	9	2	4	3	3	61
Immersion Heater	2	10	4	16	4	12	3	6	5	5	49

Table 5. Thermal storage element decision matrix. Each idea is ranked on its cost, ease of assembly, and durability in that order of importance. Durability has been weighted as the least important in this case because we estimate that all thermal storage elements will be similar in durability, and as such it should not be the major deciding factor in ranking.

	Cost		Durability		Design for Assembly		Totals
Weight->	3		1		2		
Concrete w/ PCM Pockets	1	3	3	3	1	2	8
Concrete, rebar, cast iron	2	6	3	3	3	6	15
PCM puck	1	3	2	2	2	4	9
Concrete w/ cores	3	9	1	1	2	4	14

Table 6. Insulation element decision matrix. Each idea is ranked on its cost, ease of assembly, and insulation capacity in that order of importance. Insulation capacity has been weighted as the least important in this case because differences in thermal conductivity can be made up with more/less insulation.

	Cost		Insulation rating		Design for Assembly		Totals
Weight->	3		1		2		
Rice Hulls	3	9	3	3	3	6	18
Reflective	2	6	4	4	3	6	16
PCM-Low Temp	1	3	4	4	2	4	11
Ground	4	12	1	1	2	4	17
Vacuum	1	3	5	5	1	2	10

From this, we were able to generate a list of components of the design that could perform the necessary functions of the ISEC. We then combined the best performing components into fully fledged ideas based on how the components could be assembled to create a final project. That is to say, we made sure to only combine compatible components into full ideas; a solar concentrator heating element would probably not work well with an insulated cook zone, as the two would need to exist in separate environments by their nature. These preliminary designs are illustrated below in Figures 16-19.

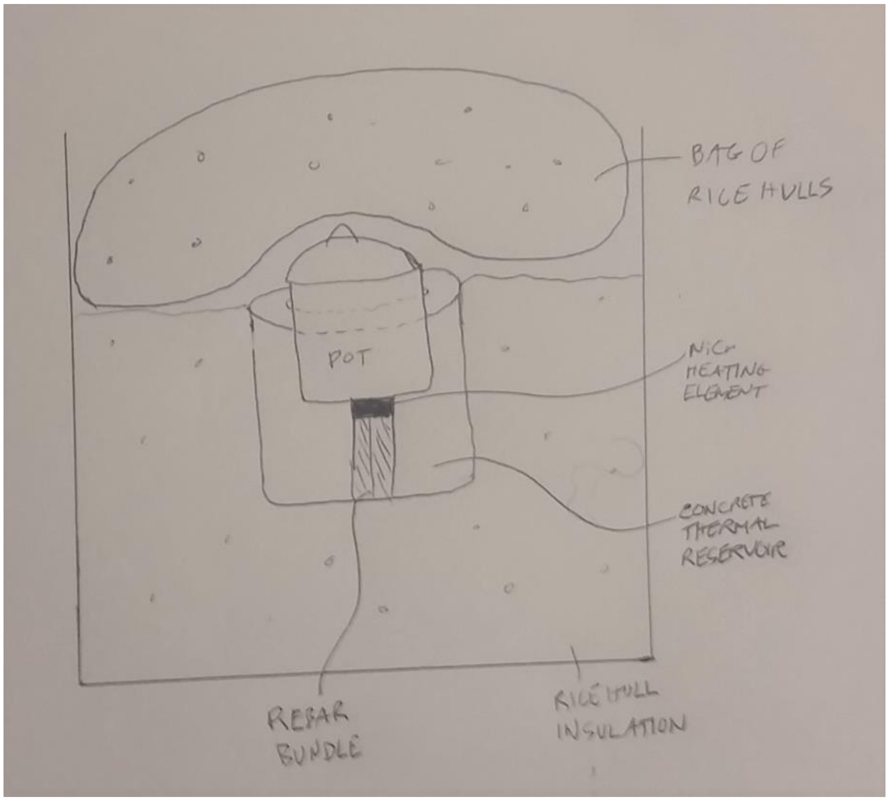

Figure 16. Rebar Cored Prototype. The concrete reservoir idea is to have a thermal reservoir made of concrete with a bundle of rebar in the center. The heater made from nickel-chromium wire will be at the top of the thermal reservoir in the center of the rebar. Surrounding the thermal reservoir and covering the pot will be rice hulls for insulation. Initial heat transfer calculations for this prototype can be found in Appendix A.

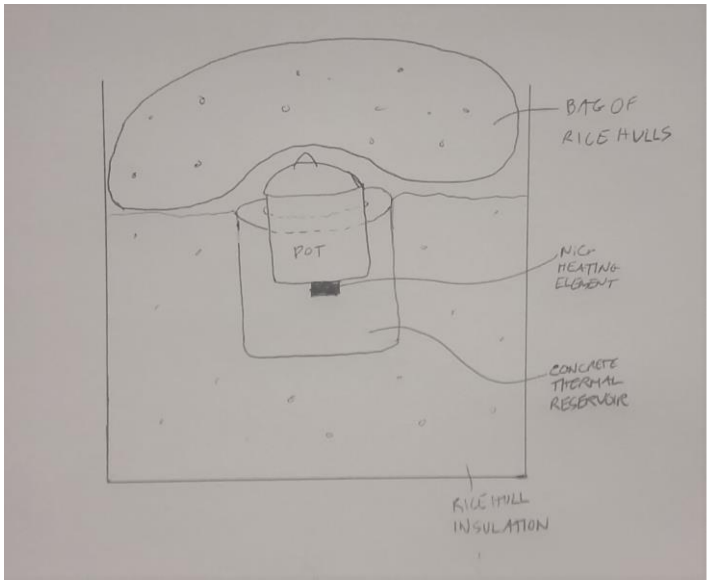

Figure 17. Concrete Sleeve Prototype. This prototype surrounds the pot in a thermal concrete reservoir. This concept includes a NiCr heating element. Initial heat transfer analysis for this concept can be found in Appendix A.

Our group made prototypes of the concrete sleeve design, and the rebar cored design. We then tested the temperatures achieved by the thermal reservoir and food, and the cooling rate of the thermal reservoir. We also assessed the difficulty of manufacturing and assembling this ISEC using only basic tools. After prototyping, we decided to modify the rebar core design for our final design. We eliminated the concrete sleeve around the cooking pot so various pots could be used, and made the top surface of the thermal reservoir a steel plate. Another steel plate extended down from this cook surface into the thermal reservoir to conduct heat preferentially to the food.

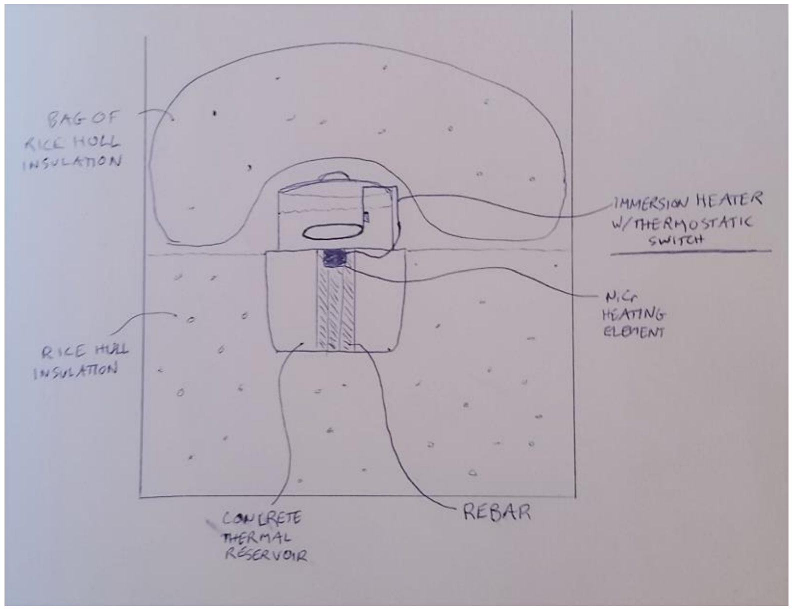

Figure 18. Split Thermal Energy Prototype. The double heater with a thermal switch idea would also have a thermal reservoir made from concrete and rebar, but instead of just one heater at the top of the thermal reservoir, it would also include an immersion heater directly in the pot. To direct the power between the two heaters, a thermal switch would be included so that once the temperature of the food exceeds 100°C.

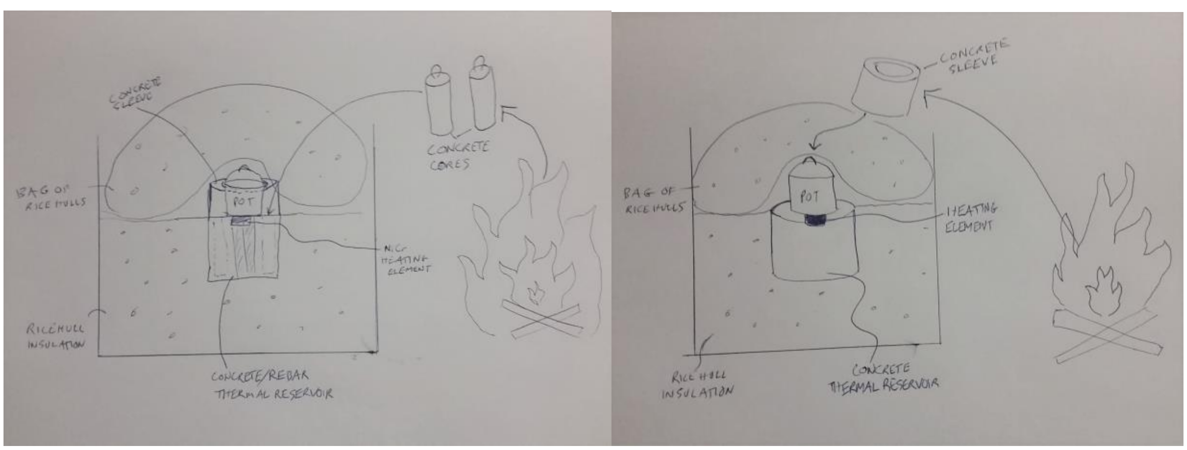

Figure 19. Removable Concrete Sleeve Reservoir Prototype. The third idea is to include thermal cores which could be removed and heated separately over a large fire. These cores could either be small, removable cylinders (left), or a ring that would rest on top of the reservoir and heat it (right). This idea would help keep the cook surface hot after the solar panel stops providing power to the heater. One concern about this idea is that it might not replace using biomass fires for cooking.

Section 6: Initial Analysis

Calculations for the analysis of the Concrete Sleeve Reservoir Prototype and Rebar Cored Prototype can be found in Appendix A.

We started our analysis by trying to estimate possible dimensions of a Concrete Sleeve Reservoir prototype. To begin to assess the feasibility of our design, we made several generous assumptions: we assumed that our cooking zone would be an 8 inch diameter, 8 inch tall cylinder, we assumed our solar panels would provide 100W for an 8 hour window during the day, that all of the energy produced by the panels would be absorbed by our thermal reservoir, that the interior wall temperature of the thermal reservoir would reach 250°C and that the heat flow can be modeled as one dimensional conduction through multiple plane walls. This greatly oversimplifies the reality of the heat transfer involved in this system, because the thermal reservoir is absolutely going to be losing heat on its interior side. That is how the unit cooks. However, we treated the inner wall as adiabatic for this first round of calculations so that we could over design for the amount of rice hulls needed to get an estimate of the maximum size of the ISEC. These calculations uncovered an error in our design. If we expect to reach a 250°C inner wall temperature of the thermal reservoir, we will need to create a thermal reservoir with a wall thickness thinner than what our material can support. Obviously this won't do.

The next step was to create a model of the ISEC with the minimum wall thickness pourable for our type of concrete, 2 inches. Then, using the same assumptions as in the previous analysis, excepting the inner wall temperature of the thermal reservoir, we calculated for the maximum temperature of the inner wall of the thermal reservoir. We determined that the maximum temperature the ISEC might reach would be approximately 194°C. This is still plenty hot enough to quickly boil water, and a value that we see as acceptable to begin moving forward in prototyping. We then recalculated the dimensions necessary to protect users of the ISEC.

If we had designed our first Concrete Sleeve Reservoir Prototype to the dimensions solved in Appendix A, then the ISEC should have posed no safety risk. However, we were limited by our building materials and had to change the wall thickness of the thermal reservoirs. We still used the same amount of concrete in this prototype, which should have yielded very similar results. Additionally, we found that it was possible to form concrete walls thinner than the minimum recommended wall thickness. We believe that this recommended wall thickness is for load bearing structures, which is not the case in the walls of our thermal reservoir. Several tests have already been run on this prototype and are discussed in the Safety Considerations and Testing Plan sections of this report. We believe that an iterative experimental process will yield a more successful end product than if we keep the design of our ISEC on paper longer.

Following this rudimentary analysis on the Concrete Sleeve Prototype, we began a more complicated analysis of the Rebar Cored Prototype. This analysis makes the same assumptions as the Concrete Sleeve Reservoir. The same process was used but an added rebar cylinder was analyzed. If all the energy from the solar panel went into heating the steel, the model predicts that the steel could reach 300°C. We also tried to find the temperature of the concrete surrounding the rebar by modeling it as one-dimensional conduction through cylindrical walls. The model assumes that the rebar is a cylinder located in the center of a larger cement cylinder. The heat flux found in the Concrete Sleeve Prototype was used to calculate the temperature of the concrete. We found the temperature difference between the rebar and the concrete was about 20°C. This temperature difference seems small. We think this was due to not accounting for the thermal storage of the cement and assuming the heat flux is constant through both conduction and convection zones.

This was our first foray into analysis on these designs. We also have utilized actual test data to refine our models and create a more accurate thermal model for further design iteration.

Section 7: First Prototype Assembly Procedure

The assembly process is designed to be flexible with the intent that the end user can adapt the design to their needs. An assembly of the first prototype our group put together can be seen in Figure 20 below. When assembling the concrete sleeve ISEC prototype, we followed the below process guidelines. However, after numerous instances of combustion during testing, we made a number of changes to our final design and manufacturing procedure.

- First, build the outer housing to be 63cm x 63cm x 63cm or larger. Our group used redwood, which has an ignition temperature of 364°C, however a less flammable material such as cement board is recommended.
- Then, follow the instructions on the bag of concrete to get the appropriate proportions when mixing 10 lb of concrete for the thermal reservoir. Dimensions can be based on available mold sizes.
- Prepare insulated copper wire to connect power supply to NiCr wire. For wire lengths between 0-50 ft use a minimum of 16 gauge copper wire.
- Next connect the 32 cm of NiCr wire to the length of insulated copper wire using wire clamps. When pouring the concrete, sink the NiCr wire about an inch from the surface and ensure that the wire is near the center and that none of it is exposed. Any exposed wire causes a high fire risk.
- When installing the pot, place it onto the concrete in the mold immediately after it is poured and fill around the pot with concrete.
- Fill the bottom of the housing with ~20 cm of rice hulls.
- Place the thermal reservoir in the center and surround it with rice hulls.
- Ensure the copper wire leads can reach out the side and connect to a solar panel. Once everything is in place, fill a non-flammable sack with rice hulls to use as an insulation lid.

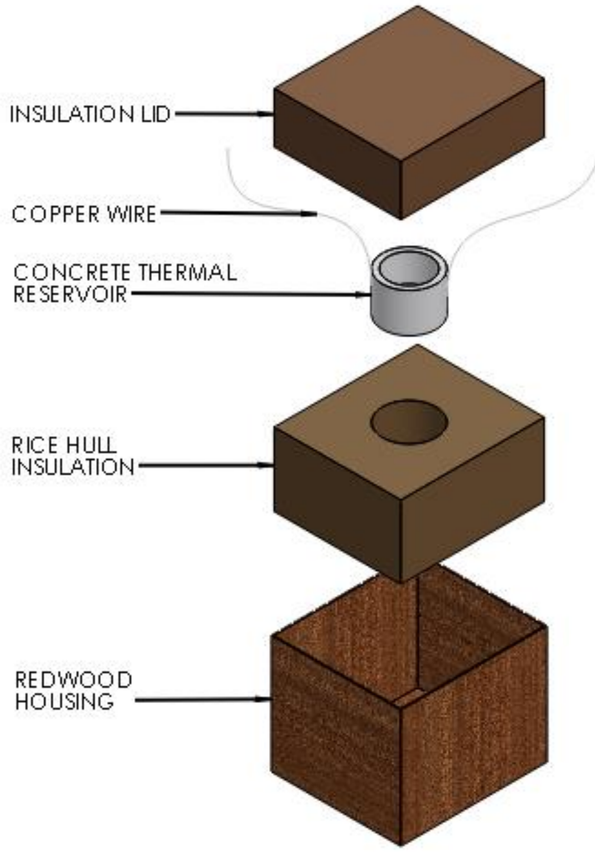

Figure 20. Assembly model of the initial ISEC prototype tested. A complete assembly and drawings of the prototype can be found in Appendix C.

Following these assembly instructions, we built our own first prototype. As maintaining a low unit cost is of the utmost importance to making this technology available, it was important for us to keep close track of all costs associated with manufacturing. We excluded the cost of the mold we used for the concrete because it was not included in the final prototype and could be used to make many more ISECs.

Table 7. Breakdown of costs associated with the materials necessary for Prototype 1, and justifications as to why these materials were selected.

Material	Total Cost ($)	Cost/ ISEC ($)	Justification
60lb bag of Concrete, Quickcrete High Strength	23.16	3.86	This is the essential building material of our thermal reservoir. We cannot do without it. A 60lb bag is a (relatively) large up front investment, but provides enough material to build 6 thermal reservoirs.
Pot with lid	4.00	4.00	Concrete does not work very well for cooking in, and will eventually chip off into food. This provides a food safe surface for our users. In later prototypes we'd like this to be removable, but this will take a little more process control over the thermal reservoir molding.
Rice hulls	9.00	2.25	Rice hulls are a very cost effective insulation solution. They can be purchased at low cost from rural supply stores as we did for convenience, but by asking around it is also possible to get large donations from rice farmers, and people in third world countries will have abundant access to this material for low to no cost.
Screws	5.58	2.79	We needed a way to construct our containment box that would hold the insulation, thermal reservoir, and cook zone. Screws are easy to use, low cost, and robust.
Redwood fence posts	23.34	11.67	We sourced our materials at the Home Depot in San Luis Obispo for this first prototype. The redwood fence posts were some of the most affordable building material available, so we bought them to keep costs down. Additionally, redwood has a high ignition temperature (364℃) and these boards had not been processed with any other chemicals that could introduce new hazards.
26AWG NiCr wire	6.00	0.13	In order to focus on the thermal storage component of our design, we decided to create the same form of resistive heater as our predecessors. There was an existing body of evidence demonstrating the efficacy of NiCr wire as a resistive heater in ISEC units, so we decided to also use NiCr wire. Additionally, we were able to get enough from our sponsor to make several prototypes for free. Our cost analysis is based on a 50ft spool we found on Amazon.
Insulated	2.00	2.00	A low resistance way to connect our resistive heater to our

copper wire			power supply is a necessity for this project. Insulated copper wires are a low cost, easily obtainable way to achieve this.
Wire clamps	1.99	0.38	We needed a way to mechanically join our resistive heater and copper wires. This is the simplest, lowest cost way to do this short of twisting the wires together by hand and calling it good.

Our first prototype cost $27.08 for materials. This is below our target cost of $30/unit, but this prototype is rudimentary. Better materials selection can help to lower costs, for example, if we used a more affordable alternative to redwood for our containment box. Money saved by better materials choice can be reinvested into the project so that we can add complexity to the design. As an example, an easily removable lid will be a necessity for our final design, but was replaced in our first design with unpackaged rice hulls for simplicity of thermal modeling.

Section 8: Safety Considerations

The first, most fundamental canon of the ASME engineering code of ethics is that all “engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties.” Keeping this in mind, it is of utmost importance that any design we hope to introduce to the third world is safe. We began the analysis of our design with a design hazard checklist designed to help identify potential safety hazards. Our checklist can be seen in Appendix F.

Once we’d identified potential sources of danger, we planned a series of corrective actions that could help minimize the impact of these hazards.

Table 8. Detailed description of potential hazards with accompanying planned corrective actions and timelines.

Description of Hazard	Corrective Action(s)
Large amounts of stored thermal energy can lead to smoldering of insulation and combustion of the unit.	Investigate other insulation options. Test unit with intermediate insulation between thermal reservoir and rice hulls.
System will be exposed to a variety of weather conditions.	Choose materials that will not degrade quickly due to elemental exposure. Leave no large gaps in exterior of unit.
System can be used in unsafe manner.	Write detailed use case instructions for end users that outlines potential misuse cases and how and why to avoid them.

We initially believed that the risk of our ISEC combusting was very low as our insulation material (rice hulls) have an ignition temperature of 440°C and our containment box, though made of wood, was made of redwood which has an ignition temperature of 364°C (Watkins et. al; Li & Drysdale). However, in both of the tests we have conducted so far the rice hulls smoldered and started a fire several hours after power supply to the ISEC was cut.

In our first test we supplied the ISECs resistance heater with ~150W for three hours, then disconnected power from the unit and stored it with the thermal reservoir inside the insulation to cool. After nearly six hours without power, the unit caught fire. Cal Poly's Dr. Emberly, a fire protection engineer, examined the scorch marks on the containment unit and informed us that what had most likely happened was the rice hulls began smoldering at a temperature much lower than their ignition temperature. The slowly burned their way to a crack in the exterior wall of the unit. Once at the crack, heat from the rice hulls created a chimney effect, pulling oxygen into the burn, increasing the temperature, and accelerating the rate of heat absorption until the edge of the unit reached ignition temperatures and caught fire. This alerted us to the dangers of smoldering, and we planned another experiment to determine if there were any hot spot localizations in our ISEC.

For our second experiment we fed the ISECs resistance heater ~150W for three hours. After three hours we removed the cooking zone and thermal reservoir from the insulation and took pictures with a thermal camera (Appendix E). These images revealed an exposed portion of our resistance heater that likely led to hot spot localization. We then replaced the thermal reservoir in the insulation, removed the power from the heater, and allowed the reservoir to cool for ninety minutes in the insulation. After ninety minutes, we removed the thermal reservoir from the insulation, and soaked the insulation and containment box with water. Approximately three hours after this, the unit was found smoking by another group of students and was doused with more water.

These tests are especially concerning because of the long smolder times associated with the rice hulls burning. Users in the third world could set the units to heat up in the morning, and return to find their new cook stoves, and potentially their homes, in flames.

In light of these fires, our group decided to use a non-flammable material, stucco, to construct the outer housing. We also decided to include a layer of fiberglass insulation between the thermal reservoir and the rice hulls to prevent the rice hulls from igniting.

Section 9: Testing Plan

To begin testing, we supplied the ISEC’s resistance heater with ~150W for three hours, then disconnected power from the unit and stored it with the thermal reservoir inside the insulation to cool. The purpose of this experiment was to help us characterize the heat loss through our insulation such that we could build a reliable thermal model of our system. Then, we can test design changes using this model instead of actually constructing more prototypes and testing them. The time history of this experiment can be seen below in Figure 21.

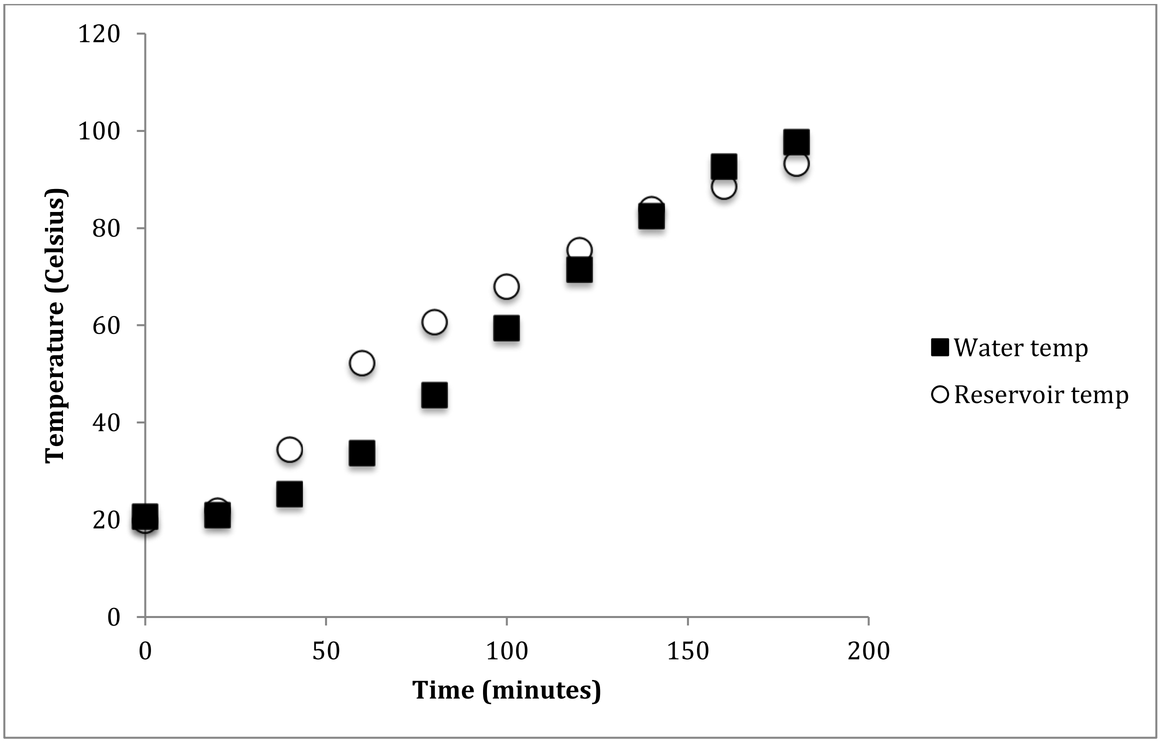

Figure 21. Test 1 time history of the temperatures of the water in the ISEC cook zone and thermal reservoir over the course of three hours. Data was collected at 20 minute increments. Unit was supplied ~150W for the duration of this test.

After nearly six hours without power, and after we stopped collecting data, the unit caught fire. This alerted us to an issue with our rice hull insulation; it is susceptible to smoldering, which can be difficult to notice and to put out. To determine the root cause of the smoldering we planned another, very similar, experiment to determine if there were any hot spot localizations in our ISEC.

Again, we supplied the ISEC's resistance heater ~150W for three hours. As discussed in the Safety Considerations portion of this report, we removed the thermal reservoir and cook zone after three hours and took images with a thermal camera as seen in (Appendix E). These images revealed an exposed portion of our resistance heater that likely led to hot spot localization. This information is valuable because it informs us how the smoldering likely started. We then replaced the thermal reservoir in the insulation, removed the power from the heater, and allowed the reservoir to cool for ninety minutes in the insulation. After this cooling period, we removed the thermal reservoir from the insulation, and soaked the insulation and containment box with water. The time history of this experiment can be seen below in Figure 22, to better understand the thermal profile of our system, we took measurements at more locations within the ISEC than in our first test.

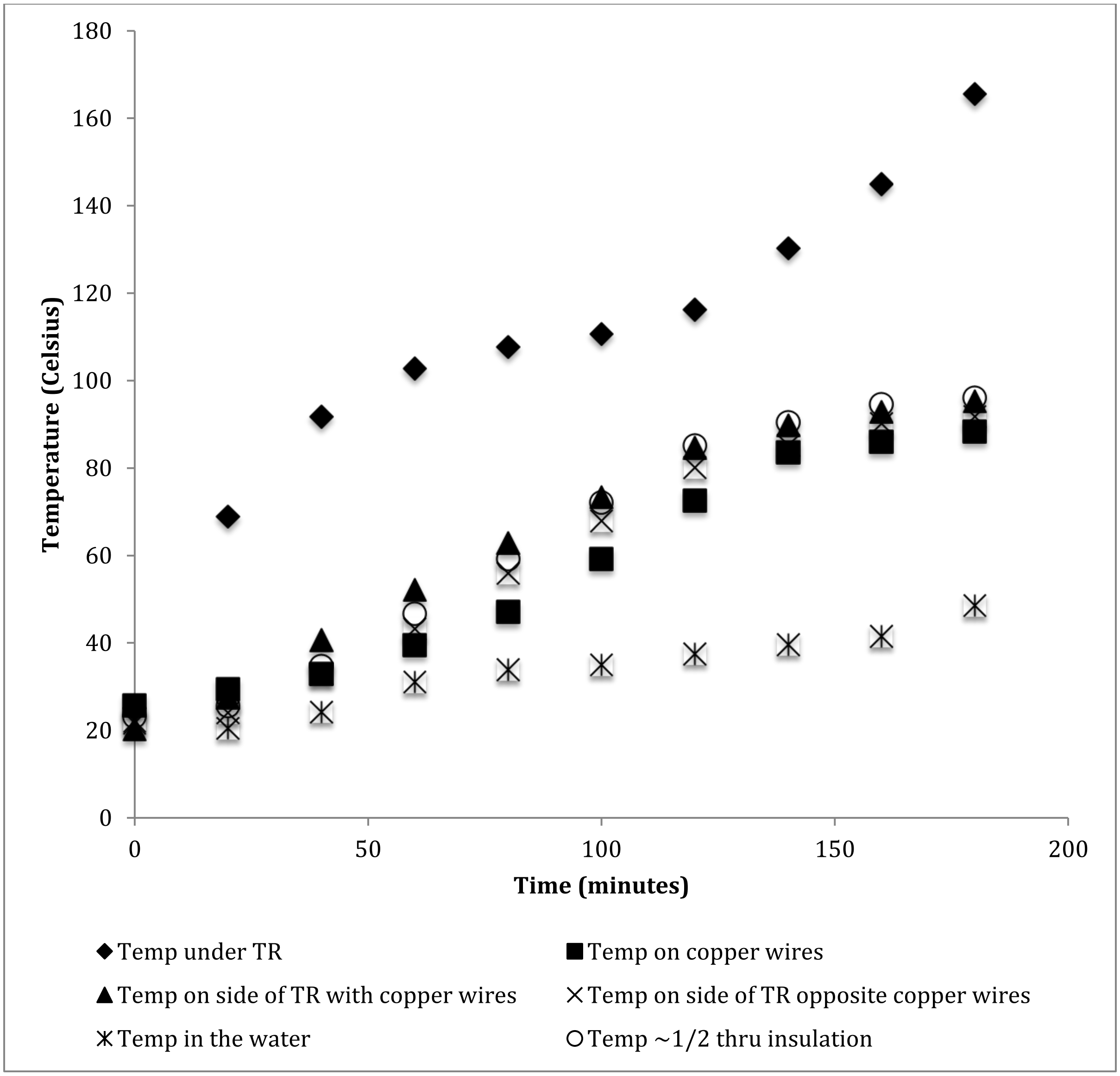

Figure 22. Test 2 time history of the temperature of the water in the ISEC cook zone, temperature on the bottom and sides of the thermal reservoir, temperature of the insulated copper wires, and temperature of the rice hulls approximately half way between the thermal reservoir and exterior wall over the course of three hours. Data was collected at 20 minute increments. Unit was supplied ~150W for the duration of this test.

Approximately three hours after dismantling and soaking the ISEC, the unit was found smoking by another group of students and was doused with more water. While incredible that the rice hulls continued to smolder after being soaked with water, this provides a very important learning outcome: once smoldering, rice hulls are very difficult to extinguish. This means that the safety hazard of smoldering must be avoided at all costs. As such, it is of paramount importance that we understand the characteristics of rice hull smoldering.

After the fires in this first prototype, we built a new unit and began testing it. We performed the same safety verification test, heating test, and heating and cooling test. We then planned a series of tests to check all of the points in our Objectives portion of the report. However, during our final heating and cooling test, a lead wire from the thermal reservoir to the transformer melted, thus breaking the unit. Luckily, this failure did not pose a significant safety hazard, but unfortunately, we did not have time to build and test another prototype.

Section 10: Thermal Modeling

We used experimental data from our second test to create a thermal model. The previous group successfully built an accurate thermal model of their ISEC, so we followed a similar approach. First, we found the thermal resistance of our insulation by modeling the ISEC in three parts: a solid disk for the top section of insulation, a hollow cylinder for the middle section of insulation, and a solid disk for the bottom section of insulation. The thermal resistance for the solid disks were calculated using equation 5, where h is the height of insulation, k is the thermal conductivity of the insulation, and r is the radius of insulation.

$$R = \frac{h}{k*\pi*r^2} \quad \text{(Equation 5)}$$

The thermal resistance for the hollow cylinder of insulation was calculated using equation 6, where r_2 is the radius of the outer surface of the insulation, r_1 is the radius of the inner surface of insulation, k is the thermal conductivity of the insulation, and h is the height of the insulation.

$$R = \frac{ln(r2/r1)}{2*\pi*k*h} \quad \text{(Equation 6)}$$

After finding these three resistances based on dimensions of the prototype, the total resistances was calculated by summing the resistances in parallel. The total resistance and the change in temperature of the inner and outer surfaces of insulation were then used to find the heat loss.

$$q = \frac{\Delta T}{R} \quad \text{(Equation 1)}$$

The outer surface of insulation was assumed to be constant (about 25 C) and the inner surface of insulation was assumed to be the same temperature as the outer surface of the concrete, which we used experimental data for. So, heat loss increased as the temperature of the concrete surface increased.

The heat loss was then used to calculate the total energy in the system which was then used to calculate the temperature change. The total energy in the system was calculated using equation 2, where E is the total energy in the system, E_0 is the energy from the previous time, P_{in} is the power inputted from the source (150W for this test condition), *q* is the heat loss for the given time, and *t* is the time.

$$E = E_0 + (P_{in} - q) * t_{step} \qquad \text{(Equation 2)}$$

After calculating the total energy in the system, we could use find the total temperature change of the thermal mass. To do this, we used equation 4, where *E* is the energy present in the system, *m* is the mass, and *c* is the specific heat.

$$\Delta T = \frac{E}{(m*c)water + (m*c)concrete} \qquad \text{(Equation 4)}$$

From this calculation, the total change in temperature of the system was 175 °C. Detailed calculations can been seen in Appendix H.

This calculation assumes that the water and the concrete start at the same initial temperature and end at the same final temperature, which is not what we see from experimental data. However, the model still does a decent job predicting the average temperature of the system throughout the experiment. Figure 23, shows a comparison of the model prediction and experimental data.

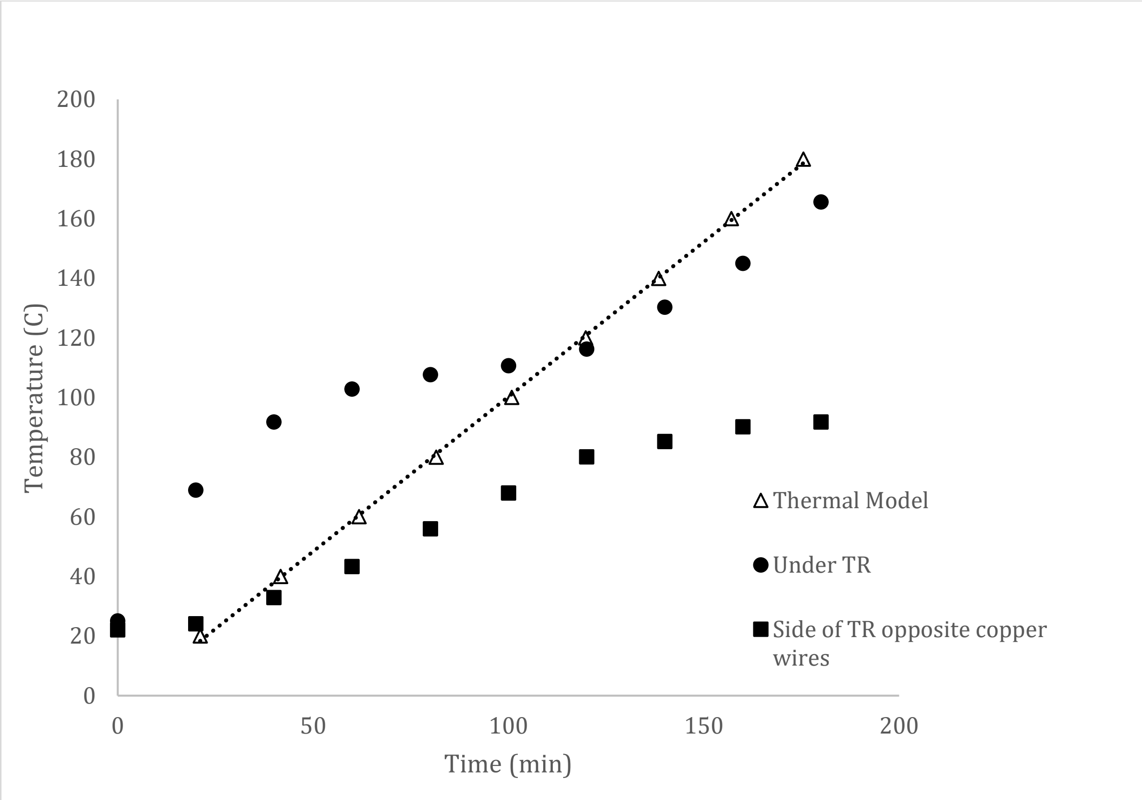

Figure 23. The thermal model and experimental data are plotted above on the same axes. This thermal model represents an average temperature change of the thermal reservoir and water in the cook zone, and as such we've chosen to compare it to the recorded temperatures of the thermal reservoir. This data should most closely match the thermal model because the thermal reservoir will not undergo a phase change (the water in the cook zone will at 100°C which is not accounted for in the thermal model, but will certainly account for some of the temperature disparity seen between the model and test data) but will continue to heat up as more energy is added to the system. The thermal model has also been fitted to a linear trend line.

The experimental data hovers around the thermal model prediction. Underneath the concrete matched closest to the thermal model, towards the end temperatures increase linearly just below where the thermal model predicts. The side of the concrete temperatures are much lower than what the thermal model predicts. We believe this is because an exposed wire on the edge of the concrete allowed heat to escape to the insulation rather than into the concrete thermal storage. Thermal pictures of the prototype after 3 hours of heating are shown in Appendix E. These pictures show that our prototype did not have uniform temperature throughout the concrete. As seen, the hottest parts of the concrete get up to 680°F or 360°C. This may have been caused by issues in pouring the concrete, there were some holes in the cement and part of the heating wire was exposed. These inconsistencies contribute to the inaccuracy of the thermal model.

Section 11: Final Manufacturing Process.

After establishing a final design, we began manufacturing. We began with the thermal reservoir as we already had successfully made two prototypes. Our final design, however, incorporated one more element: the steel plate on the cook surface.

To build this, we bought a steel plate from the Cal Poly Machine Shop and used a chop saw to cut a length of it off.

Figure 24. Spencer cuts what will become the top of the thermal reservoir.

Once we had two pieces of mild steel, we welded them together into a t-joint. Unfortunately we forgot to photograph this t-joint. A large flat portion of it would be the top cooking surface of the thermal reservoir, while a fin inside the reservoir would help to preferentially conduct heat to the top of the cook surface.

With this t-joint constructed, we formed the reservoir around it. We placed the t-joint face down in a cylindrical mold made from scrap foam core we had. This could just as easily be cardboard, reed mat, or any other materials that should be very easy to source in the developing world. We poured a mixture of approximately five pounds of dry concrete and water into the mold, then carefully laid in the heating element, NiCr wire, and the positive and negative wires it was connected to. It is important during this step to not allow the NiCr wire to touch the steel fin of the t-joint. If these come into contact it will change the resistivity of the circuit and significantly affect the heating properties of the thermal reservoir. We then poured another five pounds of dry concrete mix and water onto this set up and allowed it to set for a weekend. The minimum cure time for the concrete mix is only 24 hours. However, we found that using the recommended amount of water in the mixture created an unsatisfactorily lumpy reservoir with poor filling in the corners. So we added enough water to achieve a slurry that could be easily poured then allowed more drying time. This made the concrete much easier to work with and did not seem to impact its final properties.

Next, we needed a housing for the insulation and thermal reservoir. The rest of the unit, if you will. We knew it was imperative that our insulation housing be non-flammable. As such, we decided to manufacture the walls of this housing from cementitious stucco. This also allowed us to easily form a cylindrical housing which better fit our heat transfer model.

To begin, we cut a circular pattern for the base of the housing from plywood using a bandsaw. Although we used power tools for convenience, people in developing world countries could certainly use other methods to shape this base.

Figure 25. Spencer using the bandsaw to cut the housing base while Amanda acts as a human vice to keep the board from bouncing around.

After forming the base, we hammered in a ring of rebar posts. These posts would serve as guide-poles for the interior section of the housing which holds the cook zone and a layer of insulation.

Figure 26. Kyle hammers the rebar poles into the housing base.

With the guides set in the housing base, we wove several layers of chicken mesh around the rebar, and interlaced the mesh with the rebar. We discovered that the lathe on chicken mesh was too large to hold wet stucco, so we compensated by wrapping the mesh around multiple times. This created smaller gaps between each layer that could hold the stucco. These layers tended to come very far apart, though, so we used zip-ties to secure them more closely. The next step was to begin applying the stucco.

Figure 27. Spencer poses with the mesh and rebar backbone of the inner housing ring. Stucco has been applied to the plywood base to prevent the possibility of fire.

With the mesh and rebar backbone complete, we began applying stucco to the housing walls. This was a long, sometimes arduous process. We mixed our stucco by hand in a five gallon bucket, and are very confident that this process could be replicated by people in developing world countries with minimal technology.

Figure 28. Kyle and Amanda mix stucco the old fashioned way.

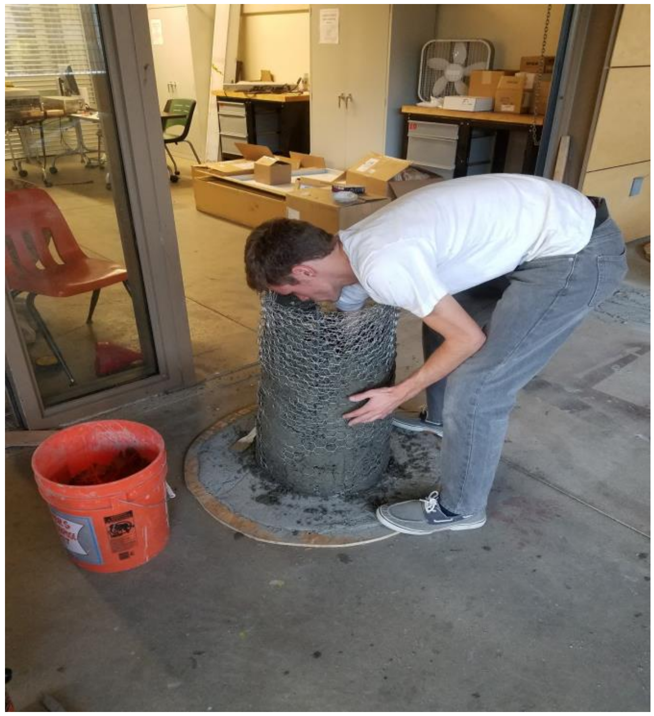

Figure 29. Kyle applies stucco the mesh and rebar backbone.

Figure 30. Finished inner ring of the housing unit. Note the irregular shape of its gaping maw.

After this inner ring had dried, we discovered a problem with our manufacturing process: it was very difficult to maintain cylindricity of a stucco wall using only rebar and mesh. Look at the shape of the inner housing wall in Figure 30. Before moving on to the outer housing wall, we devised a way to combat this issue. We created small tack welds on the rebar guides for the outer wall, and slipped a wooden guide ring, similar to the housing unit's base board, on the rebar, resting on the tack welds. We wove chicken mesh around this outer rebar ring in the same method as the interior walls, then applied stucco over them too.

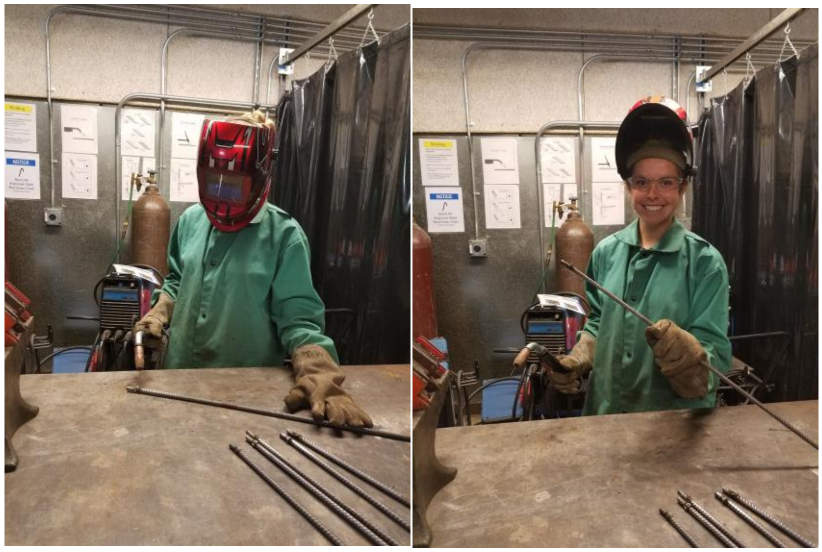

Figure 31. Amanda showing off her tack welding skills. Smile brighter than an arcflash!

Figure 32. Kyle poses with the improved mesh and rebar backbone of the outer housing walls.

Figure 33. Outer walls of the thermal reservoir coated with stucco.
This unit is nearly complete. A final layer of stucco will be added over
the plywood and to patch any gaps before it is finished.

Once the housing unit was fully coated in stucco, we placed the thermal reservoir in the interior ring of the unit and fed the wires to the exterior of the unit. We then added a layer of rice hulls beneath the thermal reservoir and compacted them. With less oxygen the rice hulls are less likely to smolder and become a potential fire hazard. Between the rice hulls and bottom of the thermal reservoir we also included a layer of pink fiberglass insulation used in roofing. This material is even less flammable than the rice hulls. While it added to the BOM cost of our unit, we felt the added safety more than justified the expense.

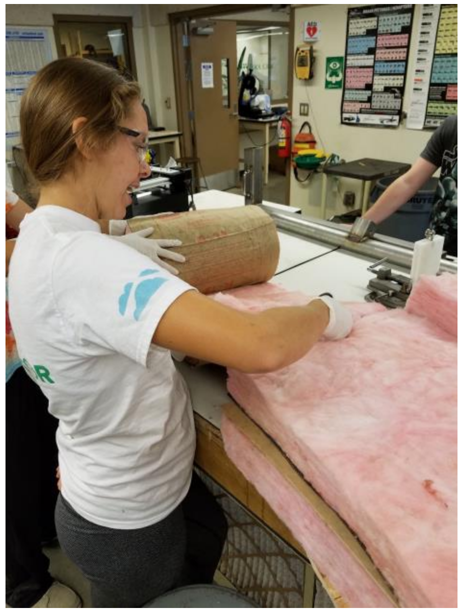

Figure 34. Amanda cheerily cuts fiberglass insulation to be used on the housing unit lid and beneath the thermal reservoir.

After adding the insulation to the inner ring of the housing unit and establishing the cook zone, we added the main bulk of insulation to the outer ring of the housing unit. We compacted rice hulls all within the unit, then poured a very fine stucco slurry over the compacted rice hulls to fill as much open space within the insulation. The goal was to eliminate any chances for smoldering.

Finally, we had to prepare a lid. In the same fashion that we cut the base of the housing unit, we created another plywood disc. Then, we drilled two holes in it and fed rope through the holes to create a handle. We used insulation adhesive to stick a layer of pink fiberglass insulation to the bottom of the lid. This not only further insulates the unit, but also provided a seal to prevent convective heat transfer out of the ISEC. The weight of the lid compressed the insulation against the top of the housing unit preventing a draft from convecting away the heat generated within the cook zone. Finally, before testing, we added more fiberglass insulation over top of the cook pot within the inner ring.

Section 12: Final Test.

To test our final prototype, we followed a similar procedure to the earlier testing. We first connected the ISEC to a transformer which supplied 150W of power. To ensure there were no exposed wires or hot spots on the thermal reservoir, we captured thermal images while the ISEC was connected to power.

After verifying the design had no hot spots, we started our first test of the final prototype. This test provided power to the ISEC for three hours to see if 1L of water was able to boil. Thermocouples were placed in various locations in the ISEC: in the insulation surrounding the thermal reservoir, on the bottom of the thermal reservoir, on the cook surface, and in the water. The data is plotted in the Figure 35. After three hours the water reached a temperature of 85°C. Since the water was not able to boil in three hours so we added fiberglass insulation on top of the pot for our next test.

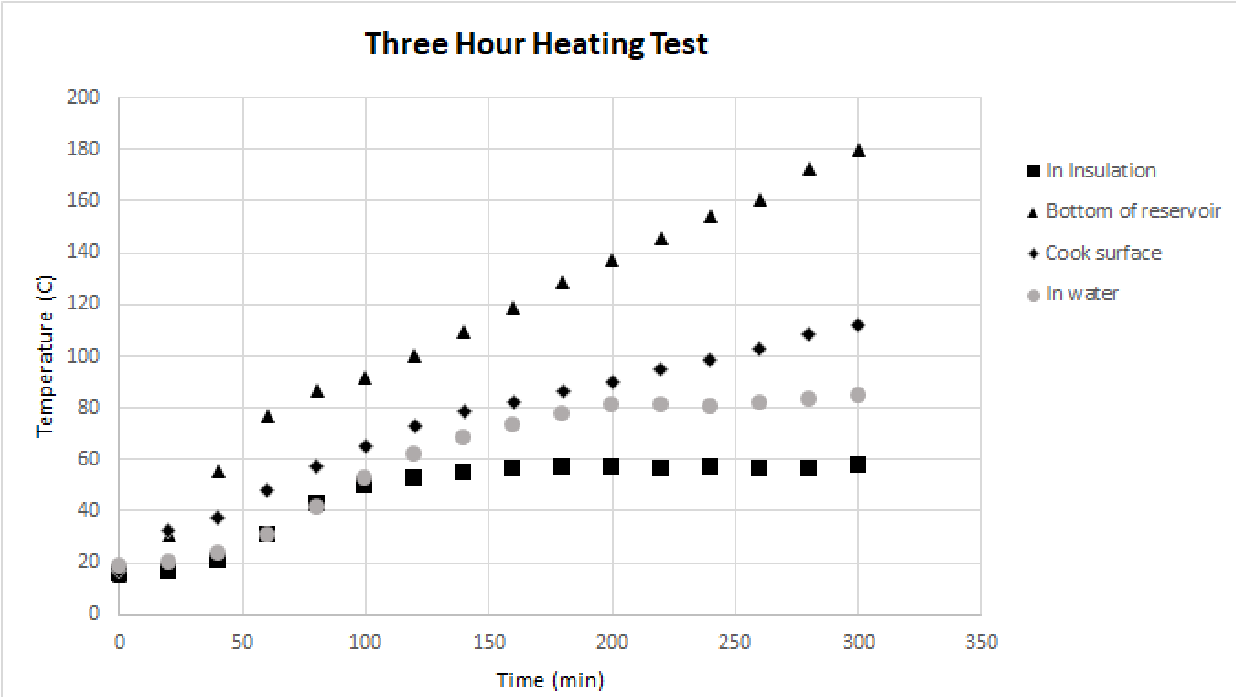

Figure 35. Data from three hour heating test. Temperature measurements were taken of the water in pot, on the bottom of the thermal reservoir, on the cook surface, and in the insulation surrounding the thermal reservoir every 20 minutes for three hours. Unit was supplied 150W for the duration of this test.

This test also provided 150W to the ISEC for three hours. After three hours the power was turned off and cooling data was collected for three hours. With the added insulation, water reached a temperature of 94°C. The bottom of the thermal reservoir reached the highest temperature of 158°C. We suspect that the cook surface did not reach the highest temperature because it also conducts heat into the pot and water. With no pot on the cook surface, we believe the cook surface would reach the highest temperature. After the power was turned off, the water decreased 18.3°C in the three hours we collected data. This corresponds to a cooling rate of 6.1°C/hour, which exceeds our design specification of 6.67°C/hour. Data from both tests can be found in Appendix I.

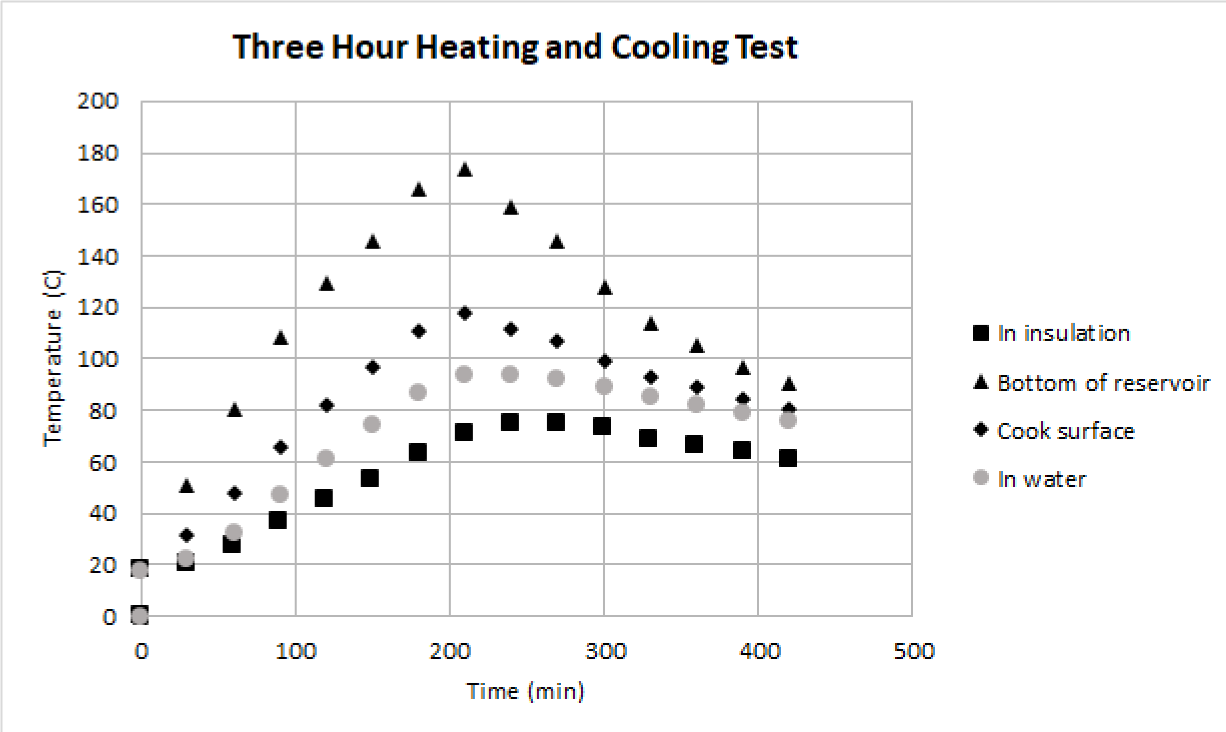

Figure 36. Data from three hour heating and cooling test. Temperature measurements were taken of the water in pot, on the bottom of the thermal reservoir, on the cook surface, and in the insulation surrounding the thermal reservoir every 20 minutes for three hours with ~150W supplied. The unit was then disconnected and temperature measurements were taken every 20 minutes for three hours to see cooling characteristics.

Section 13: Improvements.

For future ISEC prototypes, we recommend using both a resistive heater in the thermal reservoir and an immersion heater with a switch to direct power between them. This way if the user was needing to cook something quickly they could switch the heat directly into their food for quicker results, and if they were away from periods of time, they can switch the heat back into the reservoir for storage. We also recommend using a non-flammable, inexpensive material for the housing. The latest prototype was built using stucco, but clay or some other locally sourced material is acceptable. Our prototype could have been improved with better building practices as well. Our center cylinder was lopsided and should be constructed using a guiding ring, similar to the one used for the outer rebar ring, to ensure a straight, cylindrical housing.

Further testing on materials should be done to prevent fires and melting materials. We used the appropriate gage wire but a wire still melted during our test due to the high temperatures of the reservoir. We also suggest a chimney test on the rice hulls to more accurately determine what temperatures they ignite and begin to smolder at. For this test we would pack a cylinder with rice hulls, supply heat at the bottom such that the rice hulls begin to smolder, and then monitor the temperature wave that flows through the chimney as the rice hulls smolder. This would allow us to determine how much lower than the ignition temperature rice hulls smolder, and thusly set new temperature parameters for the interface between the rice hulls and thermal reservoir, or more likely, an intermediate insulation layer. These tests will help improve the safety of the ISECS.

Our final recommendation is to construct a new lid that is food safe. A non-flammable material should cover the fiberglass insulation to prevent any contamination of the food. We recommend continuing research of ISECs with these improvements before implementing them in the developing world.

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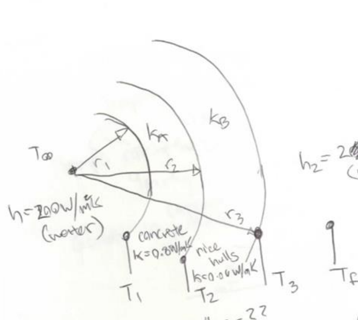
Appendix A. Initial analysis hand calculations and MATLab code.



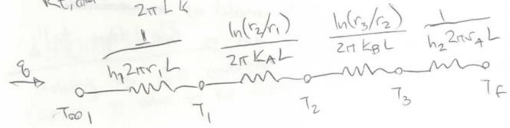
LET $r_1 = 4''$, $r_2 = 7''$, $r_3 = ??$ $L = 12''$

$T_1 = 250C$ $T_3 = 45C$

$T_F = 29C$

$q_r = -kA\frac{dT}{dr} = -k(2\pi r L)\frac{dT}{dr}$

$R_{t,cond} = \frac{\ln(r_2/r_1)}{2\pi L k}$



Start @ end

$q'' = h(T_3 - T_\infty)$

$q'' = 2\frac{W}{m^2K}(T_3 - T_F) = \frac{2W}{mK}(45C - 29C)$

$q'' = 32\ W/m^2$

ASSUME q'' IS SAME THROUGHOUT.

$q''_r = -k\frac{dT}{dr}$ FROM INTERIOR OF CONCRETE TO START OF INSULATION

$32\frac{W}{m} = -\frac{0.8W}{mK}\frac{(T_2 - T_1)}{(r_2 - r_1)}$

PUT r INTO m

$r_1 = .1016\ m$

$r_2 = .1778\ m$

$\frac{q''r\,dr}{-k} + T_1 = T_2$

$T_1 = 250\ C$

$T_1 = 523K$

$T_3 = 318K$

$T_1 - \frac{q''r\,dr}{k} = T_2$

Why aren't my units working??

$523K - \frac{32\frac{W}{m^2}(.1778m - .1016m)}{0.8\ W/mK} = T_2$

$q'' = -k\frac{dT}{dr}$

$\frac{q''r\,dr}{-k} = dT$

$T_2 = 520\ K$

Do again to find necessary thickness of insulation.

$q''_r = -k\frac{dT}{dr}$

$q''\,dr = -k\,dT$

$dr = \frac{-k\,dT}{q''}$

$r_3 - r_2 = \frac{-k(T_3 - T_2)}{q''}$

$r_3 = \frac{-k(T_3 - T_2)}{q''} + r_2$

$r_3 = \frac{-(0.06)(318K - 520K)}{32\frac{W}{m^2}} + 0.1778m$

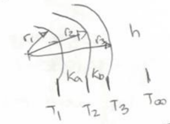
$r_3 = 0.5566m$

$r_3 = 21.9$ inches

THOUGHTS AFTER FIRST PASS AT ANALYSIS

- SEMI REASONABLE.
- ADD MORE CONCRETE → NEED LESS INSULATION?
- 32 W/m² A REASONABLE #?

QUICK 2nd PASS



$T_1 = 250C;\ 523K$ $r_1 = 4'' = .1016m$ $k_a = 0.8\ W/mK$ [concrete]

$T_2 = ???$ $r_2 = 8'' = .2032m$ $k_b = 0.06\ W/mK$ [rice hull]

$T_3 = 45C;\ 318K$ $r_3 = ???$

$T_\infty = 29C;\ 302K$ $h = 2\ W/m^2K$

AT END

ASSUME SAME q'' THROUGHOUT.

$q'' = -h(T_\infty - T_3)$

$q'' = -\frac{2W}{m^2K}(302K - 318K)$

$q'' = 32W/m^2$

AT BEGINNING

$q'' = -k\frac{dT}{dr}$

$\frac{q''(r_2 - r_1)}{-k} = T_2 - T_1$

$T_2 = T_1 - \frac{q''(r_2 - r_1)}{k} = 523K - \frac{32\frac{W}{m^2K}(.2032m - .1016m)}{0.8\ W/mK}$

$T_2 = 519K$

TO END

$q'' = -k\frac{dT}{dr}$

$q''(r_3 - r_2) = -k(T_3 - T_2)$

$(r_3 - r_2) = \frac{-k(T_3 - T_2)}{q''}$

$r_3 = r_2 - \frac{k(T_3 - T_2)}{q''}$

$r_3 = .2032m - \frac{0.06\ W/mK\,(318 - 519K)}{32\ W/m^2}$

$r_3 = 0.58\ m$

$r_3 = 22.84\,in$

MORE CONCRETE MEANT LESS TEMP DROP / in MEANT MORE TOTAL VOLUME OF MAT'L CONSTANT. ANOTHER COMPARISON TO CONSIDER WOULD BE ENERGY NECESSARY TO RAISE EACH AMT OF CONCRETE TO 250C

TOTAL VOLUME OF CONCRETE

ASSUME $r_I = 4''$

Model as cylinder + circle "cap" of same wall thickness

$V = \pi(r^2 - r_I^2)h + \pi r^2(r - r_I)$ $r = L - t$

for 3" wall thickness 12" height (top to bottom not including thickness)

$V_3 = \pi(7in^2 - 4in^2)9in + \pi 7in^2(7in - 4in)$

$V_3 = 1394.87\ in^3$

$V_4 = 2010.62\ in^3$

$\rho = 2320\ kg/m^3$

www.engineeringtoolbox.com/specific-heat-solids-d_154.html

concrete, stone — 0.75 kJ/kg K

concrete, light — 0.96 kJ/kg K

$Q = mc\Delta T$

$c = 0.75\ kJ/kg\,K$ (stone)
$= 0.96\ kJ/kg\,K$ (light)

$V_3 = 1394.87\ in^3 \times \left[\frac{(.0254\ m)}{(1\ in)}\right]^3$

$V_3 = 0.0229\ m^3$

$V_4 = 0.0329\ m^3$

Holy cow! These are HEAVY!

$m = \rho V$ $\quad m_3 = 2320\ kg/m^3 \cdot 0.0229\ m^3 = 53.128\ kg$

$m_4 = 2320\ kg/m^3 \cdot 0.0329\ m^3 = 76.328\ kg$

ΔT

ASSUMING BLOCK STARTS @ $T_1 = 25C$

STONE CONCRETE

$Q_3 = m_3\, 0.75\ kJ/kgK\,(T_2 - T_1)$

$Q_4 = m_4\, 0.75\ kJ/kgK\,(T_2 - T_1)$

$Q_3 = 53.128\ kg\,(0.75\ kJ/kgK)(225K)$ $\quad Q_3 = 8965\ kJ$

$Q_4 = 76.328\ kg\,(0.75\ kJ/kgK)(225K)$ $\quad Q_4 = 12880\ kJ$

LIGHT CONCRETE

$Q_3 = 53.128\ kg\,(0.96\ kJ/kgK)(225K)$ $\quad Q_3 = 11476\ kJ$

$Q_4 = 76.328\ kg\,(0.96\ kJ/kgK)(225K)$ $\quad Q_4 = 16487\ kJ$

Uh oh... that seems like a lot of energy. Do a quick check on potential coming from solar.

ASSUME we can get 8 hrs of 100 W output from solar panel.

$E = 100\ W \cdot 8\ hr \cdot \frac{3600\ sec}{hr} \cdot \frac{J}{W\ sec}$

$E = 2880\ kJ/day$

Well.... we won't be using quite as much mass in our thermal reservoir!!

Okay, new thought. Work backwards from the Energy from the panels (aka the FIRST number)

$Q = mc\Delta T$ $\quad$ WANT m

I think we have light concrete, I'm going to solve operating under that assumption

$m = \frac{Q}{c\Delta T} = \frac{2880\ kJ}{(0.96\ kJ/kgK)(225K)}$

$m = 13.33\ kg$

$V = \frac{m}{\rho} = \frac{13.33\ kg}{2320\ kg/m^3}$ $\quad V = 0.005747\ m^3$

$V = 350.71\ in^3$

Okay Assume inner cook zone is smaller. Perhaps

and assume there is an even wall thickness about the shell.

$V = \pi(r^2 - 4^2_{in})\cdot(8 + (r - 4in)) + \pi r^2(r-4)$

$V = (\pi r^2 - \pi 4^2)(r+4) + \pi r^3 - 4\pi r^2$

$V = \pi r^3 - 16\pi r + \cancel{4\pi r^2} - 64\pi + \pi r^3 - \cancel{4\pi r^2}$

$V = 2\pi r^3 - 16\pi r - 64\pi$

$V = 2\pi r^3 - 16\pi r - 64\pi$ $\quad V = 350.71\ in^3$

$0 = 2\pi r^3 - 16\pi r - 64\pi - V$

$0 = r^3 - 8r - 32 - \frac{V}{2\pi}$

SOLVE FOR r

$r = 8.67\ in$

I must have messed up either in my earlier calcs, or here. Let me think this through/test it.

$V = 2\pi(8.67in)^3 - 16\pi(8.67in) - 64\pi$

$350.71\ in^3 \overset{?}{=} 3457.9\ in^3$

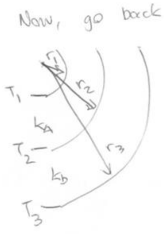
Yeah, I messed up finding my zero

Yep! I had the wrong root!

Correct root

$r = 5.042\ in$

Now, go back to the heat transfer models



T_∞

$q'' = 32\ W/m^2$ $\quad r_1 = 4" = .1016\ m$ $\quad k_A = 0.8\ W/mK$

$T_1 = 250C$ $\quad r_2 = 5.042\ in = .1281\ m$ $\quad k_B = 0.06\ W/mK$

$T_2 = ??$ $\quad r_3 = ??$

$T_3 = 45C$

$T_\infty = 29C$

FIND T_2 THEN r_3

$q'' = -k_A \frac{dT}{dr}$

$\frac{q''\,dr}{-k_A} = dT$

$T_1 - \frac{q''(r_2 - r_1)}{+k_A} = T_2$

$T_2 = 523K - \frac{32\frac{W}{m^2}(.1281m - .1016m)}{0.8\ W/mK}$

$T_2 = 521.9\ K$

$q'' = -k_B\frac{(T_3 - T_2)}{(r_3 - r_2)}$

$r_3 - r_2 = \frac{-k_B(T_3 - T_2)}{q''}$

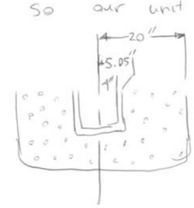
$r_3 = r_2 - \frac{k_B(T_3 - T_2)}{q''}$

$r_3 = 0.1281\ m - \frac{0.06(318K - 521.9K)}{32\ W/m^2}$

$r_3 = 0.5104\ m$

$r_3 = 20.09\ in$

So our unit will look like

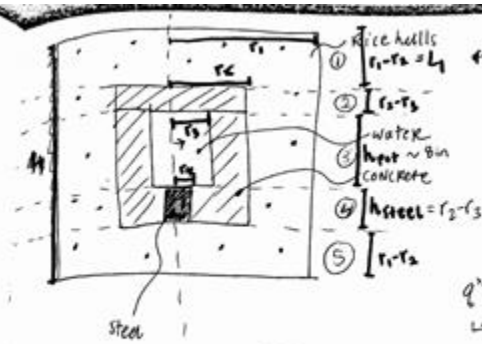


Wow, that's a lot of insulation.

I want to build and test a prototype.

I need to understand how to pour concrete first though.

thermal model



$q'' = 32\ W/m^2$

↳ what Spencer used

sections 1,2,3,4,5 in parallel
each different material in series

① all Rice hulls, estimated as solid disk

$$R_1 = \frac{r_1 - r_2}{K_{Rice}\,\pi r_1^2} \quad \sim \text{cylindrical wall thickness } (L_1)$$

② Rice hull + concrete, estimated as cylinder for rice hull, disk for concrete

$$R_2 = \underbrace{\frac{\ln(r_1/r_2)}{2\pi K_{Rice} \cdot L_1}}_{\text{cylinder of rice hulls}} + \underbrace{\frac{r_2 - r_3}{K_{concrete}\,\pi r_2^2}}_{\text{disk of concrete}} \quad r_2 - r_3 \sim \text{cement wall thickness}$$

③ Rice hull, concrete, water; estimated as cylinder

$$R_3 = \underbrace{\frac{\ln(r_1/r_2)}{2\pi K_{Rice} \cdot h_{pot}}}_{\text{cylinder rice hulls}} + \underbrace{\frac{\ln(r_2/r_3)}{2\pi K_{concrete}(h_{pot})}}_{\text{cylinder concrete}} + \underbrace{\frac{h_{pot}}{K_{water}\,\pi r_3^2}}_{\text{disk water}}$$

④ Rice hull, cement, steel rods

$$R_4 = \frac{\ln(r_1/r_2)}{2\pi \cdot K_{rice} \cdot h_{steel}} + \frac{\ln(r_2/r_3) \cdot 4}{2\pi \cdot K_{concrete} \cdot h_{steel}} + \underbrace{\frac{h_{steel}}{K_{steel} \cdot \pi \cdot r_4^2}}_{\text{steel disk}}$$

Contents


```
%Heat Transfer Analysis - Solar Cooking Senior Project
%Amanda Gyokery, Spencer Davis, Kyle Smit
```

Clear

```
clear;
close all;
clc;
```

Material Properties

```
rho_concrete=1840;  %kg/m^3, density of lightweight concrete from mrmca.org
rho_steel=7854;     %kg/m^3, density of plain carbon steel (HT textbook)
```

Dimensions

```
%radius,english units
r1_in=10;      %in, rice hull
r2_in=6;       %in, concrete
r3_in=4;       %in, water
r4_in=2;       %in, steel

%convert to metric
r1=r1_in*.0254;    %m
r2=r2_in*.0254;    %m
r3=r3_in*.0254;    %m
r4=r4_in*.0254;    %m

%heights
L1=r1-r2;       %m
L2=r2-r3;       %m
h_pot=8*.0254;  %m
h_steel=r2-r3;  %m
```

```
%volumes/masses
V_steel=pi*r4^2*h_steel;              %m^3
m_steel=rho_steel*V_steel;            %kg

V_water=pi*r3^2*h_pot;                                        %m^3
V_concrete=pi*r2^2*(h_steel+h_pot+L2)-V_water-V_steel;        %m^3

m_conc=rho_concrete*V_concrete;       %kg
```

Thermal Constants

```
k_c=0.8;                %W/m*K, thermal conductivity of concrete
k_rice=0.05;            %W/m*K, thermal conductivity of rice hulls
k_steel=49.2;           %W/m*K, thermal conductivity of steel from HT book at 523K (250C)
k_water=679.1*10^-3;    %W/m*K, thermal conductivity of water at 100C

c_steel=434;            %J/kg*K, specific heat of steel
c_conc=960;             %J/kg*K, specific heat of light concrete
```

Thermal Resistances

```
R1=L1/(k_rice*pi*r1^2);
       %K/W, rice hulls estimated as solid disks
R2=log(r1/r2)/(2*pi*k_rice*L1) + ((r2-r3)/(k_c*pi*r2^2));
       %K/W, rice hull as cylinder and solid disk for concrete
R3=log(r1/r2)/(2*pi*k_rice*h_pot) + log(r2/r3)/(2*pi*k_c*h_pot) + h_pot/(k_water*pi*r3^2);
       %K/W, rice hull as cylinder, concrete as cylinder, water as disk
R4=log(r1/r2)/(2*pi*k_rice*h_steel) + log(r2/r4)/(2*pi*k_c*h_steel) + h_steel/(k_steel*pi*r4^
2);    %K/W, rice hull as cylinder, concrete as cylinder, steel as disk
R5=L1/(k_rice*pi*r1^2);
       %K/W, rice hulls estimated as solid disks

R_tot=((1/R1) + (1/R2) + (1/R3) + (1/R4) + (1/R5))^-1
       %K/W, total resistance of system
```

```
R_tot =

    2.9160
```

Heat Loss

```
T_max=297;              %C, temperature we want the thermal storage to be at
T_min=45;               %C, temperature of the outside of the insulation

delta_T=T_max-T_min;    %Change in temperature from hot steel rods to outside of insulation

q=delta_T/R_tot         %W, Heat loss

%This code allows us to change dimensions, materials, and temperatures for
%the rebar stove design to find the total heat loss of the system.
```

Power output from solar panel

```
P_rated=100;            %W, output power from solar panel
t=8;                    %Hrs, time of sun exposure

E_in=P_rated*t*3600;    %J, energy output of solar panel (into thermal resevior) in one day
```

Available energy

```
E_loss=q*t*3600;            %J, energy lost to heat in one day
E_avail=(E_in-E_loss);      %J, energy to heat resevior
```

Stored energy

```
T_init=20;                                      %C, intial temp of steel
T_steel=E_avail/(m_steel*c_steel)+T_init        %C, T of steel if all energy goes into steel
T_s_c=E_avail/(m_steel*c_steel+m_conc*c_conc);  %C, change in T if energy goes to steel and
concrete
```

```
T_steel =

  298.6172
```

Heat Loss when all energy goes into rebar

```
q_flux=32;  %W/m^2*K, from Concrete Sleeve Analysis

T_steel_outer=T_steel-((q*r4)/k_steel)      %C, T of outside of steel using 1-D conduction of
 a plane wall

T_conc=T_steel_outer-(q*r2*log(r2/r4))/k_c  %C, T of concrete using 1-D conduction of a cylin
der

%The temperature of the concrete seems high (280C). This model assumes a steel cylinder is at
 298C in the center of a concrete cylinder.
%The model doesn't account for heat stored in the concrete. The heat flux assumed may be inco
rrect.
%More analysis may be needed to find the temperature that the concrete could get to when
%all the energy from the solar panels goes into heating the steel rods.
```

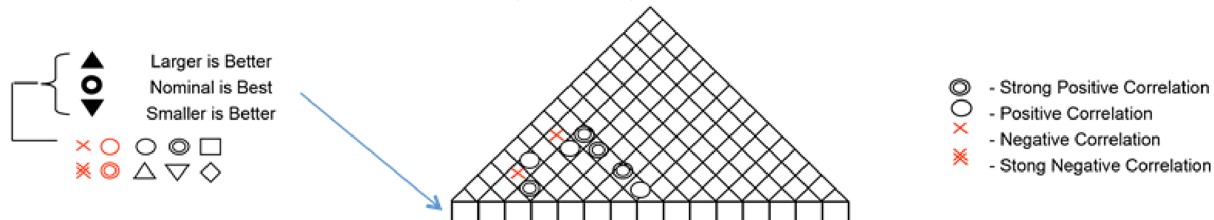
```
T_steel_outer

  298.5280
T_conc =

  280.4418
```

Published with MATLAB® R2016a

Appendix B: QFD charts developed during this project



Customer Desciption:
1 = Poor in Africa
2 = Dr. Schwartz
3 =

Customer Requirements (Whats)	Importance	A: Description of spec	B: Unit cost <$200	C: Slow temp. loss	D: Bring 1L H2O to boil	E: Local materials	F: Low emissions	G: Optimized year round	H: Thermally efficient	I	J	K	L	M	N	O	Customer Ratings 1 (Bad)	2	3	4	5 (Good)
Customer's Needs and Reqs																					
Low cost	5		9			3															X
Able to cook into the night	3			9	9			1	9												X
Able to cook	4			3	9			1	9												X
Can build with local materials	2		3			9															X
Safe for breathing	6						9		1								X				
Work consistently	1							9	9											X	
Targets		Numbers & Tolerances	<$200	5C/hr	3 hours AM1.5G	<50mile radius	CO<9(g/MJ) ; PM<168(mg/MJ)	Maxize energy collection over 365 days	>35%												
Weighted Importance																					
% Importance																					

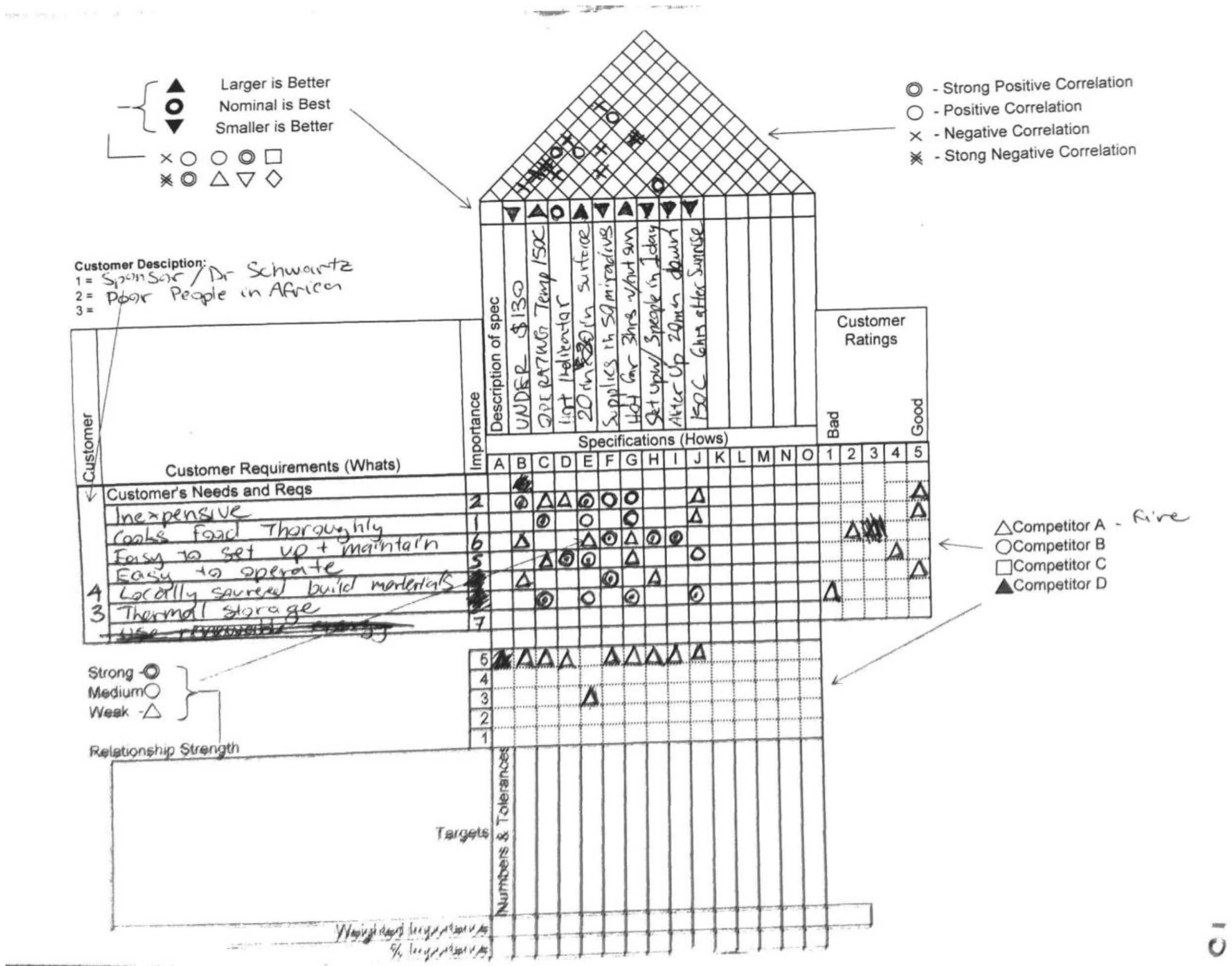
Specifications (Hows)

X - Fire

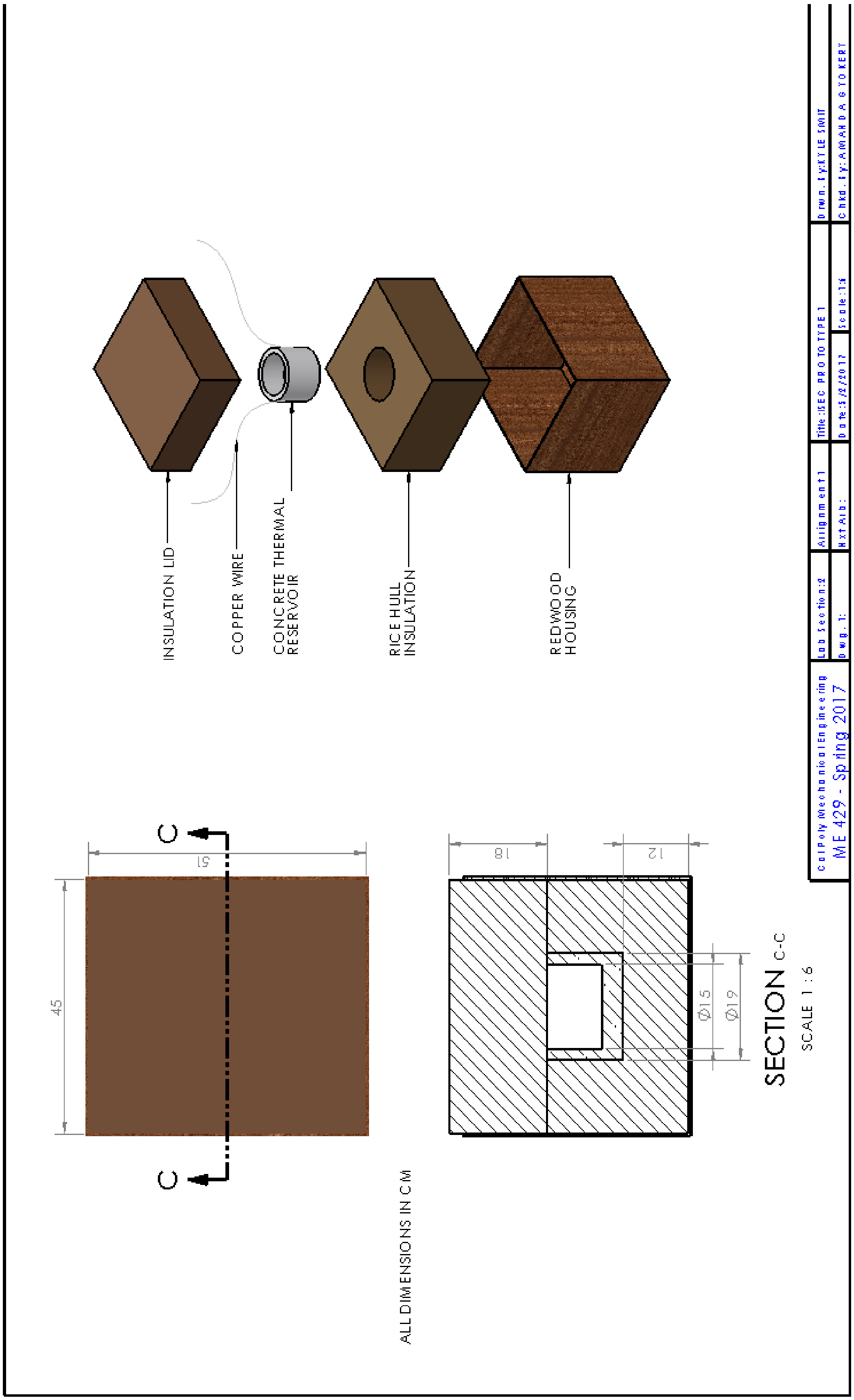
Strong - 9
Medium-3
Weak - 1

Relationship Strength

.


Larger is Better
Nominal is Best
Smaller is Better
- Strong Positive Correlation
- Positive Correlation
- Negative Correlation
- Stong Negative Correlation
Customer Desciption:
1 = Sponsor / Dr Schwartz
2 = Poor People in Africa
3 =
Customer
Customer Requirements (Whats)
Importance
Description of spec
UNDER $130
Specifications (Hows)
Customer Ratings
Bad
Good
Customer's Needs and Reqs
Inexpensive
Cooks food Thoroughly
Easy to set up + maintain
Easy to operate
Locally sourced build materials
Thermal storage
Competitor A - fire
Competitor B
Competitor C
Competitor D
Strong
Medium
Weak
Relationship Strength
Targets
Numbers & Tolerances

Appendix C. Solidworks model and drawings.

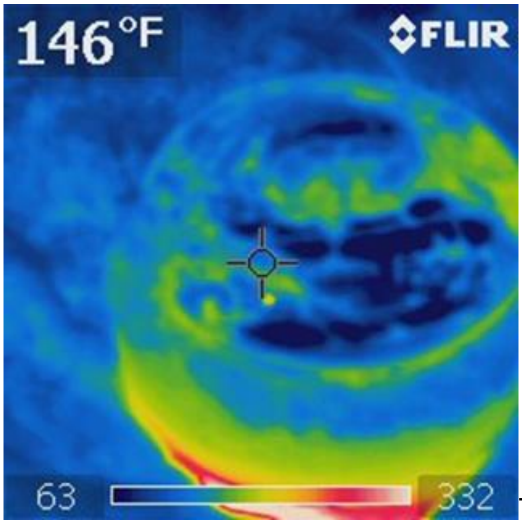


Appendix D. Safe use instructions

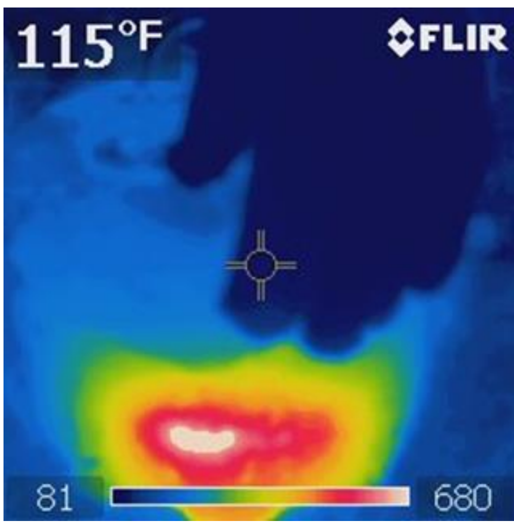
When assembling and operating the ISEC follow these instructions to remain safe:

- Never touch the concrete reservoir when it running or hot.
- If smoke appears, disconnect from power and douse with water immediately and frequently.
- Make sure all wires insulated or embedded in concrete.
- Do not put any part of your body directly above the ISEC when cooking. Steam burns may occur.
- Keep flammable material away from ISEC.
- Store in a cool dry place.
- Never touch bare wire.

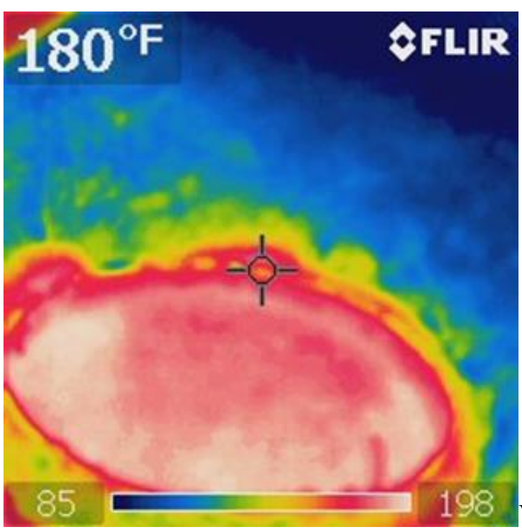
Appendix E. Infrared pictures of test 2



Top of pot. Red hotspot is on the side.



Hot spot on side of concrete reservoir.



Water inside pot.

Appendix F: Design Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: ANYANWU COOKWARE Advisor: DR. DAVOL

Y	N	
☐	☒	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☒	2. Can any part of the design undergo high accelerations/decelerations?
☐	☒	3. Will the system have any large moving masses or large forces?
☐	☒	4. Will the system produce a projectile?
☐	☒	5. Would it be possible for the system to fall under gravity creating injury?
☐	☒	6. Will a user be exposed to overhanging weights as part of the design?
☐	☒	7. Will the system have any sharp edges?
☐	☒	8. Will any part of the electrical systems not be grounded?
☐	☒	9. Will there be any large batteries or electrical voltage in the system above 40 V?
☒	☐	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☒	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	☒	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☒	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☒	14. Can the system generate high levels of noise?
☒	☐	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☒	☐	16. Is it possible for the system to be used in an unsafe manner?
☐	☒	17. 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.

Design Hazard Checklist, Page 1

Appendix G: Design Verification Plan

TEST PLAN									
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsility	Test Stage	SAMPLES		TIMING	
						Quantity	Type	Start date	Finish date
1	Specification 2	1L of water in cooking unit. Initial temperature of 20°C. Subject unit to the power rating of the chosen solar panel at AM1.5G insolation conditions for 3 hours.	Water reaches 100°C	Amanda	PV	3	C	4/13/17	4/20/17
2	Specfication 3	ISEC has been subjected to the equivalent of 8 hours of AM1.5G insolation conditions, then is allowed to cool, closed, for 6 hours.	Magnitude of the average rate of temperature change at the cooking surface of the unit remains at or below 6.67°C/hr	Amanda	PV	3	C	4/13/17	4/20/17
3	Specification 4: Thermal efficiency	1L of water in cooking unit. Initial temperature of 20°C. Subject unit to the power rating of the chosen solar panel at AM1.5G insolation conditions for 3 hours.	Energy absorbed by water (measure temperature and mass of water at end of the experiment, then do thermodynamic analysis) exceeds 45% of the energy provided to the unit from the power delivery system.	Kyle	PV	3	A	4/13/17	4/20/17
4	Specification 5: Emissions	1L of water in cooking unit. Initial temperature of 20°C. Subject unit to the power rating of the chosen solar panel at AM1.5G insolation conditions for 3 hours. CO monitors placed at top and bottom of unit	CO monitors never measure more CO than allowed by Tier 4 Clean Cooking Standard CO Limits	Spencer	CV	3	A	4/13/17	4/20/17
5	Specification 7	1L of water in cooking unit. Initial temperature of 20°C. Subject unit to the power rating of the chosen solar panel at AM1.5G insolation conditions for 8 hours.	Temperature at exterior of unit remains below 45°C for the duration of the test.	Kyle	PV	3	C	4/13/17	4/20/17

For Test Stage:
CV=Concept Verification
PV=Product Verification

For Samples:
A=Concept Verification
C=Product Verification

Appendix H: Sample calculations

5/3 - Excel Sample Calcs

31

Find thermal Resistance...

$$R_{top} = \frac{h_{top}}{K_{rice} \cdot \pi \cdot r_{out}^2} = \frac{0.23m}{(0.06\frac{W}{m\cdot K})(\pi)(0.23m)^2} = 20.57\ K/W$$

$h_{top} = 0.20m$

$K_{Rice} = 0.06\ W/m\cdot K$

$r_{out} = 0.23m$

$$R_{mid} = \frac{\log(r_{out}/r_{conc})}{2 \cdot \pi \cdot K_{Rice}\, h_{conc}} = \frac{\log\left(\frac{0.23m}{0.095m}\right)}{2 \cdot \pi \cdot (0.06\frac{W}{m\cdot K})(0.14m)} = 7.27\ K/W$$

$r_{conc} = 0.095m$

$h_{conc} = 0.14m$

$$R_{bot} = \frac{h_{bot}}{K_{rice} \cdot \pi \cdot r_{out}^2} = \frac{0.12m}{(0.06\frac{W}{m\cdot K})(\pi)(0.23m)^2} = 12.03\ K/W$$

$h_{bot} = 0.12m$

$$R_{TOT} = \left(\frac{1}{R_{top}} + \frac{1}{R_{mid}} + \frac{1}{R_{bot}}\right)^{-1} = \left(\frac{1}{20.57K/W} + \frac{1}{7.27K/W} + \frac{1}{12.03K/W}\right)^{-1}$$

$R_{TOT} = 3.69\ K/W$

32

Calculate heat loss...

$$q = \frac{\Delta T}{R_{TOT}} = \frac{2.5°C \cdot (\frac{1K}{1°C})}{3.69K/W} = 0.67\ W$$

ΔT = change in temp from exterior concrete (interior insulation) to exterior insulation

$\Delta T = 27.5°C - 25°C = 2.5°C$

use data — assume exterior always @ 25°C

Find Energy in system...

$$E = E_{prev} + (P_{in} - q) \cdot t = 0^{W} + (150W - 0.67W) \cdot 1200s = 179{,}188J$$

E_{prev} = energy from previous time = 0W

P_{in} = Power provided = 150W

t = time step = $20min\left(\frac{60s}{1min}\right) = 1200s$

Find temperature Rise of system...

$E = mc\Delta T$

$$\Delta T = \frac{E}{(mc)_{water} + (mc)_{conc}} = \frac{179{,}188J}{\left(1kg \cdot 4180\frac{J}{kg\cdot K}\right) + \left(4.5kg \cdot 960\frac{J}{kg\cdot K}\right)} = \boxed{21K \text{ or } 21°C}$$

$m_{water} = 1kg$

$c_{water} = 4180\ J/kg\cdot K$

$m_{conc} = 4.5kg$

$c_{conc} = 960\ J/kg\cdot K$

Table from Excel Calculations of Heat Loss, Energy, and Temperature

Delta T (C)	Heat Loss (W)	Time step (s)	Energy	Temp (C)	Time (min)
0	0	0	0		0
2.5	0.68	1200	179188.8	21.1	20
15.7	4.25	1200	354094.6	41.7	40
27.2	7.35	1200	525268.9	61.8	60
37.9	10.25	1200	692971.3	81.5	80
48.4	13.09	1200	857266.7	100.9	100
59.7	16.14	1200	1017895.6	119.8	120
64.8	17.52	1200	1176869.6	138.5	140
67.9	18.36	1200	1334837.8	157.0	160
70.3	19.01	1200	1492027.3	175.5	180

Appendix I: Tabulated Data From Tests 1, 2, 3, and 4

Test 1: First Prototype Test

Time	Water Temp	Reservoir side temp
0	20.6	19.8
20	20.9	21.9
40	25.3	34.4
60	33.7	52.2
80	45.7	60.6
100	59.4	68
120	71.4	75.4
140	82.4	83.9
160	92.6	88.5
180	97.7	93.3

Test 2: Second Test of First Prototype

		Under thermal reservoir	On copper wire near thermal reservoir	Side of reservoir near copper wires	Side of reservoir opposite copper wires	In the water	In the insulation
Time (actual)	Time (min)	T1 (C)	T2 (C)	T1 (C)	T2 (C)	T1 (C)	T2 (C)
10:25 AM	0	25.1	25.7	20.3	22.1	21.7	23.2
10:45 AM	20	68.9	29.4	27.5	24.1	20.5	25.6
11:05 AM	40	91.8	32.9	40.7	32.9	24.2	34.7
11:25 AM	60	102.8	39.5	52.2	43.3	31.1	46.7
11:45 AM	80	107.7	47.1	62.9	56	33.9	59.2
12:05 PM	100	110.7	59.2	73.4	68	35	72.1
12:25 PM	120	116.3	72.6	84.7	80.1	37.5	85.2
12:45 PM	140	130.3	83.6	89.8	85.2	39.6	90.5
1:05 PM	160	145	86	92.9	90.2	41.5	94.6
1:25 PM	180	165.6	88.4	95.3	91.8	48.6	96.1
Power off at 1:35							
1:45 PM		145.9	54	86.7	83.2	52.4	85.2
2:00 PM		132.2	77.3	87.4	86.3	53.6	87.8

Test 3: Final Prototype Three Hour Heating Test

Time	In insulation	Bottom of reservoir	Cook surface	In water
0	15.9	15.4	16.8	18.7
20	16.5	30.6	32.7	19.9
40	20.8	55.3	37.8	23.4
60	30.9	76.6	48.3	30.5
80	42.9	86.6	57.3	41.3
100	49.6	91.6	65.5	52.5
120	53.1	100.3	72.8	61.9
140	55.1	109.8	78.4	68.6
160	56.4	119.1	82.5	73.6
180	56.8	128.4	86.2	77.7
200	56.8	137	90.2	81.1
220	56.6	145.6	94.7	81.3
240	56.7	154.1	98.8	80.4
260	56.6	161	102.6	81.6
280	56	172.6	108.6	83.6
300	57.5	179.9	111.7	85

Test 4: Final Prototype Three Hour Heating and Cooling Test

Time	Time	In insulation	Bottom of reservoir	Cook surface	In water
12:55	0	18.2	18.8	17.5	17.7
1:25	30	20.7	51.3	31.6	22.3
1:55	60	27.6	80.5	47.7	32.4
2:25	90	36.8	108.4	65.9	47.1
2:55	120	44.9	129.5	82.3	60.9
3:25	150	53.3	146	97	74.2
3:55	180	62.7	165.8	111.1	86.6
4:25	210	70.6	173.9	117.5	94
4:55	240	74.5	158.8	111.9	94
turn off					
5:25	270	74.9	145.5	106.8	92.5
5:55	300	72.8	127.9	99.6	89
6:25	330	68.9	113.8	93.3	84.9
6:55	360	66.3	105.4	88.8	82.3
7:25	390	63.7	96.9	84.5	78.9
7:55	420	60.8	90.3	80.4	75.7