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Forge: Thermoelectric Cookstove

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SANTA CLARA UNIVERSITY

Department of Mechanical Engineering and
Electrical Engineering

I HEREBY RECOMMENDED THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

Austin Jacobs, John Maffeo, Matt Nelson,
Jared Sheehy, Isaac Stratfold, and Brad Ydens

ENTITLED

FORGE: THERMOELECTRIC COOKSTOVE

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FORGE:
THERMOELECTRIC COOKSTOVE

By

Austin Jacobs, John Maffeo, Matt Nelson,
Jared Sheehy, Isaac Stratfold, Brad Ydens

SENIOR DESIGN PROJECT REPORT

Submitted to
The Department of Mechanical Engineering and
Electrical Engineering

of

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for the degree of
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and
Bachelor of Science in Electrical Engineering

Santa Clara, California

June 9, 2016

ABSTRACT

Our interdisciplinary team, known as Forge, has built a cookstove that not only can be a portable cookstove, but also includes a port to charge devices such as a phone using thermoelectrics. The product has been designed for developing areas in Nicaragua where power is inaccessible and a multi-purpose cookstove/phone charger could be of use. The cookstove features a cylindrical combustion chamber that can be used for gasification. Gasification is a burning process where smoke from the fire is also burned, creating higher temperatures and a cleaner burn. The combustion chamber is insulated using refractory cement, which will drop the temperature from about 700 Celsius inside the chamber to 200 Celsius outside the chamber. The cookstove outputs heat at a rate of 4.6-6.6 kW. The cookstove has thermoelectric modules attached to the outside, which, by utilizing the Seebeck effect, convert excess heat into electrical energy. Ideally, the energy would be transferred into the phone at 5 volts and 0.5-0.6 amps and some of the electrical energy would be used to power a cooling fan to help the stove function properly. The final temperatures that were recorded ranged from around 400ºC to 700ºC in the combustion chamber and around 500ºC for the cooking surface. Gasification was successfully occurring during this stage, and the smoke was being visibly burned off. The electrical output was less successful, resulting with only around 0.08 V coming out of the thermoelectric generators due to the lack of air flow within the electrical housing and poor electrical connection. The stove does achieve its primary functionality of being more than capable of boiling water, something that presently available cookstoves in Nicaragua cannot do consistently.

Acknowledgements

Team Forge would like to thank many individuals who spent countless hours helping us complete this project to the best of our ability. We would like to thank Dr. Robert Marks and Dr. Sally Wood, our advisors, for helping us work on the project through both insight on the subject and recommendations on how to work successfully as a group. We can't thank them enough for the hours they spent meeting with us, making sure we produced the best possible project.

We would also like to thank the School of Engineering for funding us $2500 to create our project. Without their funding we would not have had the chance to create the prototype we have been working towards throughout the senior design process.

Several organizations gave us great insight on how we could improve our design, and we are grateful for each of them. Susan Kinne of Grupo Fenix was very helpful in giving us information on the market in Nicaragua. Judith Walker of African Clean Energy gave us very helpful tips on how we can build alternate designs based on what we needed. Lucas Wolf of Prolena gave us an idea on what the market was for cookstoves in Nicaragua. Each of these companies were very generous for giving us some of their time and insight and we can't thank them enough for doing so.

We would like to thank Opeta Henderson for helping keep track of our budget as we bought all the parts we need. We would like to thank PWP Manufacturing for helping us machine the main housing for our project. Finally, we would like to thank Dr. Timothy Hight, our academic advisor, for helping us stay on track for our project and helping us throughout the process. We would like to thank everyone who helped us in completing this project.

-Team Forge

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Chapter 1 - Introduction

1.1 Background

Modernized countries, and citizens within them, have the luxury of fairly simplistic and uniform methods of providing power to their population. In third-world or developing countries, the power delivered is restricted to those living in urban environments; this leaves many rural residents without power. Both Africa and South America have countries in which less than thirty percent of their citizens have power. The Forge design team seeks an affordable solution to provide off-grid power for people in developing countries. To do this, Team Forge designed a cookstove that will both cook food and charge devices. The latter is accomplished by using thermoelectric modules that convert excess heat into electrical energy.

1.2 Related Work

Central and South America was the choice market for our stove, and we specifically chose Nicaragua because of its low per capita income and high average retail electricity tariff relative to neighboring countries. Their relative poverty and lack of access to electricity makes them a perfect target for a product such as ours to create the most impact with our current specifications and limitations in mind. Furthermore, we were already aware of similar ventures being conducted in the area, and the design project preceding our own venture targeted Nicaragua as well, so we knew we would have a plethora of existing resources and information to work with.

In researching cookstoves currently used in Nicaragua, many were found to come with various downsides. According to *"Who Adopts Improved Fuels and Cookstoves? A Systematic Review",* by Jessica Lewis and Subhrendu Pattanayak[1], most developing countries use fuel sources such as wood and coal to cook, and about 2 million people die each year from pollutants

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[1] Lewis and Pattanayak

released by inefficient stoves that use these fuels[2]. This paper stresses two of the biggest problems we'll face when building the cookstove: efficiency and safety.

Coal is the biggest producer of airborne pollutants, emitting carbon dioxide, sulfur dioxide, mercury, and other additional poisons.[3] Although this data has been gathered by coal power plants which produce far more pollution than individual cookstoves, it does show that there are better options to explore. Dry wood, as a single example, is a better combustible fuel and is used in many stoves where the dryness of the wood allows for a more thorough burn and keeps the fuels from jamming and blocking any form of implemented filtration system[4].

A previous SCU Senior Design Team attempted to build a thermoelectric cookstove and faced similar issues with regards to filtering the air pollution. One way our predecessors tried to limit the pollution was to add a simplistic filtration system, which created a cleaner output as well as also improving the efficiency[5]. A filtration system, in order to be considered effective, needs to filter out combustion particles that are created from burning fuels. A study done by Stanford engineers[6] (the study implemented conditions within the various levels of smog in China as an extreme point of interest) found a material called polyacrylonitrile to be effective against smaller smog particles (smaller particles can be more dangerous to the human respiratory system, due to being able to move outside of the areolae and past natural counter-measures), Polyacrylonitrile is a rigid thermoplastic that is resistant to most solvents and chemicals, and has low permeability to gas[7].

This may not be the ideal material to use in a filtration system due to its cost, but the Stanford study does show that there are a variety of materials that can reduce air pollution. These are noted as well in the study and have been a great help in our research. The previous cookstove team also found a multipurpose use for the filtration system, which was quite accidental in development. Along the ventilation shafts, air holes were added to reuse the filtered air to

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[2] Lewis and Pattanayak

[3] Coal Power: Air Pollution

[4] Wood Heating and Air Pollution

[5] Horman, 25

[6] Carey

[7] Polyacrylonitrile (PAN) | Chemical Compound

oxygenate the combustion chamber, making for a more efficient burning process.[8] We have built upon and improved this design to increase the device's efficiency.

Similar to the previous process, allowing air to reenter the combustion chamber can create gasification. This is accomplished if the burn is at a high enough temperature (typically over 700º Celsius) and if oxygen is forced into the fire. If our cookstove uses this method, the burn would be more efficient and would not require a filtration system. Due to limited knowledge about gasification and limited equations, the best way to optimize gasification is through trial and error. Given our limited knowledge, gasification is the best option since it is the cleanest burn for the lowest cost.

In order for our project to be successful, the basics of thermodynamics and heat transfer must also be thoroughly understood in order to achieve an appropriate temperature difference that could be useful for converting heat into electrical energy. The first thermodynamic law states that the cyclic integral of the heat transfer is equal to the cyclic integral of the work[9]. While this definition may be as simple as work equals heat, it does show that energy in a substance can be extracted as heat. The heat we generate must also be transferred in our system. Heat can be transferred by conduction, convection, and/or radiation[10]. For the sake of simplicity for our project, conduction and convection will be the two types of heat transfer primarily utilized, because energy lost as radiation would essentially be reabsorbed by the system and converted to conduction and/or convection. Both conduction and convection will apply when heat is escaping our device and reaching the outer surface of the cookstove. In order to have a reduced temperature on the outer edges of the stove to mitigate burns, a thermally insulating material can be placed in between the heat source and the outer edges.

Excess heat produced by the stove will also be converted to electricity via thermoelectric modules that operate under the Seebeck Effect, a corollary to the Peltier effect (which is used in cooling appliances such as refrigerators). The Seebeck Effect occurs when a temperature difference between two materials creates a flow of electrons[11], thus creating a source of current which can be harvested and used to power and charge devices. The thermoelectric portion of our

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[8] Horman 30
[9] Borgnakke 342
[10] Berman 96
[11] Civie

stove will not reduce the heat used for the cooking process, but instead uses the conservation of energy on excess heat to create a large enough voltage and current to charge a mobile phone.

Aside from the technical research on how to make the cookstove function, research was conducted on Nicaragua, where we are planning to distribute the device. Team Forge so far has held conference calls with representatives from two companies that are well rooted in the markets in Nicaragua as well as one company in the cookstove business. The first company we talked with was Grupo Fenix, a company based in Nicaragua that's been operating for around 20 years, distributing cookstoves that are essentially boxes with mirrors in them to focus the sun, and, while providing a large cooking surface, their stoves occasionally fail to reach the boiling point of water and are quite expensive. We discussed the pros and cons with them regarding their design, and they agreed that having a cook stove like ours that can reach significantly higher temperatures than theirs would be ideal. The next company was African Clean Energy, and although it is based in Africa, it has a very similar product to our own that uses gasification to burn their fuel. They gave us a few ideas including using refractory ceramics as the heat shielding within the burn chamber, and the idea of having a licensee for the product to make the product more affordable in our target market. Our final contact was with Proleña, a company in Nicaragua that sells basic ceramic stoves for rural villages. They gave us information regarding the fuel sources used as well as information including the types of food cooked, how it is prepared, and how it's stored. This information will be discussed later on.

1.3 Project Objective

The Forge team wants to build a functional thermoelectric cookstove that can be marketed in a third-world country, specifically Nicaragua. It is worth noting that this is the third time this project has been worked on. Team Matador completed the most recent design three years ago. They improved upon the first design by making their design more robust combustion chamber and a more efficient, cleaner burn. Our design will build off Team Matador's design and attempt to make it smaller (optimally having a cooking surface being a foot in diameter), cheaper, and aesthetically pleasing. The design will be built efficiently, ethically, and frugally; all components needed for a successful third-world country project. As mentioned, our hope is that our cookstove can be marketed in Nicaragua. If we can not accomplish a fully functional prototype, we hope that the project will be built efficiently enough where a future senior design group can finish it and market it. As a team, we hope we can learn how to use the design process to build a functional cookstove that can help the greater good.

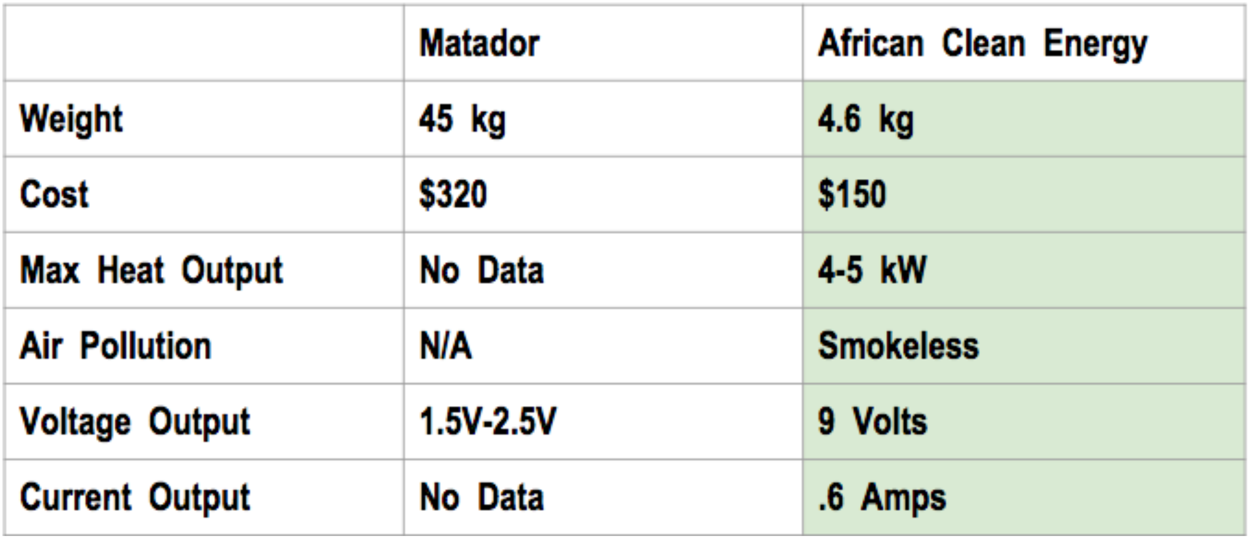
Chapter 2 - Systems

2.1 Functional Analysis

The primary function of our project will be to cook something, or the ability to boil water by having the cooking surface reach at least 100º Celsius. The secondary function of our device will be the ability to generate electricity during the cooking process. Our stove will require fuel and oxygen as basic inputs to function, while cookware and raw food will be required to meet its primary function. The stove will output heat from the cooking surface and electricity generated by the thermoelectric system. Our product will be constrained by the availability of the inputs required for it to function, as well as the necessity of a safe operating environment.

2.2 Benchmarked Results

Table 2.1: Benchmarking Results for Similar Products



	Matador	African Clean Energy
Weight	45 kg	4.6 kg
Cost	$320	$150
Max Heat Output	No Data	4-5 kW
Air Pollution	N/A	Smokeless
Voltage Output	1.5V-2.5V	9 Volts
Current Output	No Data	.6 Amps

Team Forge’s cookstove has numerous competitors that have also created similar products. One of these products is from African Clean Energy, named the ACE 1 Cookstove, a cookstove that can generates energy using an optional solar power as an accessory. The product is the biggest competitor in terms of design, as they produce gasification. The solar energy is also used to charge cellular devices. The product is marketable in areas where solar energy is easy to access.

Team Matador, the previous senior design project, constructed a cookstove that also targeted Nicaragua for marketing. The cookstove has a large cooking surface to service an entire village. It has an efficient burn and has a relatively large heat output. The cookstove has thermoelectric modules attached to it, but does not create enough voltage to charge a phone. The product costs $300. The cookstove is also heavy, weighing approximately 45 kg.

BioLite makes a cookstoves that also harvests energy using a thermoelectric generator. The excess energy can be used for lights, charging devices, and powering internal fans. The cook stoves are primarily designed for campers who will be away from electricity. The basic cookstove that BioLite sells costs a realistic $130, marketed to campers.

Table 2.2: Key features, prices, locations, and shortcomings of similar products currently available in the market.

Company	Product	Price	Distribution	Key Features	Areas for Improvement
African Clean Energy	ACE 1	$150	Africa	Gasification, Solar panel, USB charging	Decrease cost
Team Matador	Matador	$300	Nicaragua	TEG's, large cooking surface	Efficiency in circuits
BioLite	BioLite Campstove	$130	Worldwide	Small, USB charging, open fire	Increase efficiency of fire, include cooking surface

After consulting multiple companies in similar areas of the business, we have created a benchmark from which to build off of. Starting with the pricing, the price range for similar devices is around $150 - $200. Team Matador designed a product that cost $300. Taking all of these prices into account, we are attempting to design a product that will cost $150 or less to purchase. When we talked with Grupo Fenix, they said that anything more than $200 would be too expensive for the average person to buy in these communities, so we have a few solutions to this problem. One would be to sell the device to a group of people in the community to use as a collective, that way they can split the cost of the device amongst a few families. The other solution would be one similar to African Clean Energy's original solution, which is to sell the product with a contract, where the customers can buy it over time, allowing them to spend less every month and still have money for other living expenses, in essence, creating a micro-loan agreement that would bring easy-access electricity to areas where electricity is not readily available.

2.3 Customer Needs

Our target audience resides in Nicaragua. The customers in the greatest need of our product are also the most remote; thus, they are the most difficult to contact. The simplest method of understanding these users is to interview those who have been to Nicaragua and have experience designing products like ours. One such group that we were in contact with was Grupo Fenix, a non-governmental organization with the goal of researching, developing, and applying appropriate and renewable energy technologies in Nicaragua. We contacted Susan Kinne, their Head Coordinator, and during our conference call with her, we were able to ask several questions about the needs of our potential customers.

We learned from her that, as we expected, access to power in remote areas is limited. On the other hand, when we inquired about the prevalence of cell phones in the region, she told us that there is a major market for mobile devices. She said that with regards to priorities, these impoverished people care about water, air, cell phones, then food in a hierarchical order. Residents of our target areas are virtually guaranteed to own and regularly use a cell phone and often prioritize owning one over other necessities as explained. The usage of firewood is widespread, however there are no products similar to ours that attempt to use stoves to generate electricity. If we can keep our costs down, there will be a market for our product; however, our customer base recycles and reuses just about everything, making it difficult if not impossible to source scrap metal and other materials since they will likely be used for other purposes. We also considered that our product could be used for a micro-business (cooking with the stove and supplying power to others for a fee), but we learned that there was a similar attempt with limited success.

The last major aspect that we learned from our interviews was to pay specific attention to the types of foods the locals eat, as well as the way they prepare the food. Our contact with African Clean Energy told us that they were originally thinking about spreading to Peru, but decided to cancel the entire operation simply because one of the local Peruvian food staples could not be prepared using their stove. With this information, we decided to incorporate a modular cooking surface for our stove, which would allow the preparation of a variety of foods they eat, including the preparation of rice, beans, and tortillas. With this new design, we can have a flat cooking surface, an open flame, or a stand that would allow consumers to use their own pots and pans.

2.4 Design Safety

During the design process, many aspects were evaluated in order to make the best possible product we can make. The most important thing our group focused on was the safety of our design. The cook stove's customers will not have a technical background and may easily make mistakes while using our product. Team Forge designed the cookstove with the goal of keeping customers safe while simultaneously serving their needs. Reliability is deeply valued in our product for the same reason safety is valued in our cookstove. The cook stove must be easy to use and work every time in order for our customers to truly utilize its features. If not, the product will not be used, even if they have a need for its use. The third aspect of great importance is the cost of our product. Our team is working on improving Team Matador's design, and making the cookstove cheaper will allow us to compete with other products. Team Forge aims for a product to cost about $150, similar to that of African Clean Energy's cookstove.

There are other attributes that are not as important as the ones already listed, but which are still desirable for Team Forge's optimal design. For instance, the cookstove must achieve a certain heat and power output for it to be utilized to its fullest potential. Similarly, the aesthetic, ergonomics, and usability of the cookstove needs to be taken into account. The cook stove designed by Team Matador was rather large for its general purpose, so Team Forge has designed our cookstove to be smaller and more portable. This change is also due to the product being marketed at a significantly lower price than Team Matador's product. While the criteria listed are important, the criteria that will greatly benefit the cookstove are safety, reliability, and cost.

2.5 System Level Requirements

Certain requirements need to be met when designing our product, but more importantly, we need to decide which requirements should be the main focus for our design and functionality. Regarding these issues, we created a criterion matrix which looks at each aspect of the device and compares it to the others to rank them in order of what we believe to be the most important function, and what could be ignored while in production. After compiling the matrix, it was determined that safety is of the utmost priority, with reliability coming second, since reliability is closely intertwined with safety as we don't want the stove to fail when the customer is using it. Cost follows this, since we wouldn't be able to distribute this device if no one could buy it. Next comes the functions of the device: heat output, power output, and the usability. And finally comes size and then weight. We deemed weight to be the least important factor, since although it could be portable, all other criteria were of higher value than the weight, including the size, which is controlled by the type of cooking needed.

2.6 System Sketch with User Scenario

The system level sketch shows the basic operation and function of the cookstove. The system level sketch above outlines the three major processes at work when using our cookstove design. The first step requires the procurement and insertion of biomass into the cookstove's burn chamber. For its use in Nicaragua, the majority of biomass collected will be scrap/forest wood. After the biomass has been properly inserted into the burn chamber, the user can proceed to step two: ignition. In the ignition step, the system is powered on, and the biomass has been ignited within the burn chamber using a match, lighter, or other product. The system then burns until gasification occurs. Once the gasification of the system is considered self-sustaining (the released synthetic gas is reignited at the top by the fire), the user moves to step three: cooking and charging. Finally, the user places his or her cookware atop the cookstove. Additionally, the user may plug in a cell phone or other portable device to the USB port to be charged.

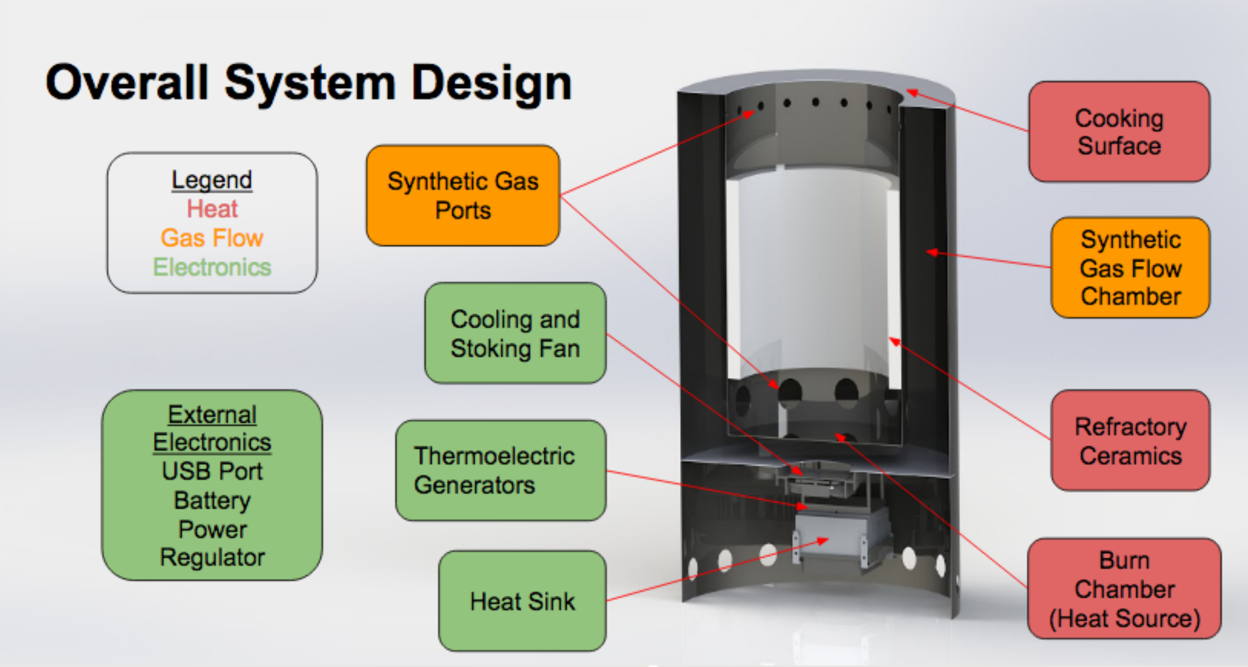


Figure 2.1: Overall System Design

2.7 Team and Project Management

In designing this product, many safety hazards can occur for both Team Forge and possible customers Exposure to the higher temperatures within the cook stove, up to 700º C, is one of the most significant risks. Safety guidelines will be provided with the product to ensure no customer comes in contact with the combustion chamber while in use. Finally, the wiring will be contained internally, so customers will only be exposed to an external USB charging port. The safety guidelines will also include cautions with regards to the voltage and current produced by the thermoelectric modules.

Chapter 3 - Subsystems: Combustion Chamber

Figure 3.1: Overview of Combustion Chamber

3.1 System and Subsystem Layout Design Overview

The combustion subsystem of our device is divided into four main sections, which are the refractory insulation, the combustion chamber itself, the gas flow chamber, and the outer casing. The refractory insulation is the first thing the heat from the burning biomass comes in contact with, and it serves to insulate the metal walls of the chamber by reflecting heat back into it. The combustion chamber itself contains the burning fuel and the refractory cement cylinder and has inlet and outlet ports at the bottom and top, respectively, to allow synthetic gas to enter and exit the flow chamber. The flow chamber itself is an air gap between the combustion chamber and the outer wall of the device. This gap reduces the heat transfer from the combustion chamber to the casing, adding further insulation between the burning fuel and the user, and provides a cylindrical channel for the synthetic gas to flow to the top of the stove for reignition. The final section of the combustion subsystem is the outer casing, the top of which provides a hot surface at the top to cook. This section also encompasses the electronics and other components while providing a structurally sound and aesthetically pleasing form factor.

3.2 Options and Tradeoffs

Many different design options exist for this project, and there are tradeoffs associated with each design decision. Aspects such as material choice, housing design, cooling subsystem design, and electronic component design all factor into the design's ergonomics, size, portability, functionality, cost, and other criteria. It is important then, to acknowledge and analyze the tradeoffs associated with different design choices. The cylindrical housing design was chosen to maximize airflow and enable gasification. Other housing designs were considered, such as the use of a rectangular casing that would allow for better packing efficiency and easier manufacturing, however this design did not allow for adequate internal flow. Additionally, the use of a cylindrical design versus a rectangular one minimizes the amount of material used, which reduces the overall weight of the device.

The flow subsystems required a great deal of consideration. In order to maintain a high temperature difference between the sides of the thermoelectric generator, our primary design uses a fan to force air over a heat sink in contact with the cold side of the thermoelectric generator. This provides a cheaper solution, in terms of required materials and input power, than other active cooling solutions like liquid cooling. This method is likely not as efficient as liquid cooling, however, in the interest of keeping the cost low, we decided to use a heat sink. To drive the flow inside the housing for gasification, a simple axial computer fan was chosen. Off the shelf computer fans have high market availability, low cost, and ability to drive our system with low-power requirements for high efficiency models. Alternative radial fan designs are available that would be more efficient, but would likely require more design work to create shrouding. In addition, the added costs to procure and develop a radial fan would make it impractical for use in our project.

3.3 Detailed Design Description

Achieving gasification is consistent with the primary system level criteria of maintaining safety and reliability. Exposure to toxic combustion products is a safety concern, and a stove that does not consistently achieve gasification would be deemed unreliable. Therefore, enabling synthetic gases to be released by the burning fuel had to be able to freely flow through the outer shell and reignite at the top of the stove, even without the effects of the fan. Large holes were added at the bottom of the combustion chamber, their size chosen so that synthetic gas could flow out while air could flow in, allowing the fire to be stoked while enabling gasification. Hot synthetic gas is able to travel up the flow chamber and exit via smaller ports at the top of the combustion chamber, where it can be reignited for an efficient burn. The diameter of the combustion chamber was chosen to accommodate a half-inch thick refractory cement cylinder while still allowing adequate space for wood logs or any other fuel the user could have difficulty breaking down. The gap between the actual base of the stove and the base of the combustion chamber was created so that synthetic gas and air could travel freely, and to insulate the electronics from direct thermal contact with the burning fuel.

3.4 Finite Element Analysis

With no way to directly model combustion in SolidWorks, we chose to model it as dual volumetric radiative heating and volumetric conductive heating. Although this is not the ideal way for modeling combustion dynamics, we did not have the knowledge to program or the access to a program that computed a FEA of combustion. An area of significance for all FEAs is the accuracy of the data calculated through the FEA versus actual results. We had some issues initially with strange output from our FEA, so we opted to increase the number of elements in our mesh and to include narrow channel refinement as well as ray tracing refinement to improve our results. This came at a great computational cost, where our earlier and more inaccurate FEA could be calculated in less than twenty minutes, the refined approach took more than four hours to complete.

Our results of the temperature distribution showed a maximum temperature of 432º Celsius at the outer surface of the A1008 steel for the 5 millimeter thick refractory alumina cylinder simulation. The ambient temperature was assumed to be 25 Celsius and the pressure was assumed to be 1 atm. We were hoping for lower values at the outer wall, for touching metal at a temperature this high even for a short period of time would cause serious injury to the user. These high temperatures are likely due to the fact that we considered the flame to be uniformly at 1000º Celsius. Realistically our flame will only reach this temperature at the core of the burning fuel and will become much cooler towards the top. As seen in Figure D.4, the temperature gradient varies with distance along the y-axis (towards the top of the model). This was expected, since the alumina layer on the inside only covers some of the combustion chamber. Figure D.5 details the flow within our cookstove. The dark red cylinder in the center represents the combustion, and the colored lines are flow trajectories moving through the model. The boundary conditions were set so that flow could enter the model at the base and leave at the top. The flow simulation matches our understanding of gasified flow behavior.

3.5 Manufacturing Process

The combustion chamber and outer casing are two different sections of the same physical part. The entire metal structure is made of cold formed 1008 sheet steel that has been rolled and cut into the correct shapes. Holes were drilled into the combustion chamber before assembly, and then the combustion chamber tube, top casing ring, combustion chamber bottom, outer casing bottom, and outer casing tube were all welded together. The refractory cylinder was cast in a cylindrical mold using a mix of 4 parts powdered cement to 1 part water. This was cured for approximately 24 hours, and then removed and placed into the stove. The first firing of the cylinder had to be done slowly due to residual water inside the cylinder that could potentially cause it to crack. After firing, the prototype combustion subsystem of the cookstove was considered complete.

Chapter 4 - Subsystems: Thermoelectric Modules

4.1 Subsystem Requirements

There are a few questions that must be addressed and answered before moving on with the project as it stands; namely, “Why do we need or want electrical power for this device at all? Wouldn’t a solar array, or any other form of alternate energy, be easier to maintain and utilize?” We can start with the first question. The first functionality of the device is a design for a cookstove that reduces toxic/dangerous emissions from current cooking processes used in rural areas (namely, Nicaragua, where we based most of our research and resources). The newest venture of the project was to also use the ideas present from previous implementations of the project[12] as well as a devoted electrical engineer to troubleshoot and devise a way to more efficiently transfer heat into useable electricity. The second question on the choice of alternate energy sources is also a phenomenal question that we pored over in an effort to get the most ‘Bang for our Buck’. We found that other forms of power production were unsuitable for our project for multiple reasons: Solar panels were very negatively impacted by large amounts of heat that would be generated by the device… and the distance between the stove and the solar panels would make the design into two separate projects (making our attempt at power generation in our device redundant); where charging a device with USB at times that the cookstove was not in operation would be a waste of effort as well as a source of issues that could arise from having sensitive solar components close to a heat source that they were not designed for. Any form of thermal wind made by the stove would not be enough to power a turbine of enough size to be worthwhile at the scale we designed, and thinner blades for a small thermal gust fan run the risk of melting and/or halting the gasification process. Other concepts like solar devices would not be capable of charging phones at night, which led to thermoelectric converters, and more specifically, to an implementation of Peltier/Seebeck devices, which has an advantage over ACE’s product.

Our design’s power production comes from the electrical effect documented as the Peltier/Seebeck effect, which states that an electrical difference in materials is correlated with a gradient in temperature.

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[12] Horman 31

$E_{emf} = -S \cdot (\nabla T)$ Equation (4.1)

This equation states that a voltage (E) is generated by a difference in temperatures multiplied by a constant (S) based on the materials being used.

The Peltier effect is very commonly used throughout the world as a cooling system, with a supplied current and voltage creating a temperature difference that is used to maintain temperatures for many applications ranging from use in technical labs to mini-fridges in college dorms. One of the problematic issues that we found as we progressed with the project is that almost all documented information regarding these thermoelectric phenomena are described in terms of the Peltier effect, but the inverse Seebeck effect is peculiarly under-researched. Though this was an initial setback, we did find that the data used for the Peltier effect was similar to the data we needed for the Seebeck effect if the power is corrected by reducing it fifteen to twenty percent.

TEC1-12706, a generic module which costs about \$2.00 per unit, uses the Peltier effect. We used these devices for their low cost and lengthy lifetime (tested at 200,000 hours of usage). They show, through an albeit confusing way, that the power used at specific voltages and currents generates specific output temperature differences. In the same way, we used the differences in temperature to generate power that we used within the project.

With the power generated with these TEGs, we chose to implement a design (based on previous discussions with potential users in Nicaragua) with an output power in accordance with USB 2.0 standards (5V, .5 amps). We will also discuss the option of replacing the USB output with a larger battery system, in case of alternate needs.

4.2 Options and Tradeoffs

With cost being one of our primary design criteria, a viable electrical source option for our system was to use a simple Peltier unit (earlier referenced as a TEC1-12706) in an inverted format in order to have a cheap Seebeck unit, meaning that instead of powering up the unit with current and voltage to create a temperature difference we used a temperature difference to generate voltage and current. This allowed us to cheaply and easily procure an electrical source that also gave us a multitude of testing and implementation variations such as connecting several devices serially to generate high voltage, multiple in parallel for high current, and combinations of the two for desired output current and power levels. One of the limits we worked under with the TEG's was the internal temperature maximum, since some of the components would melt at 138º C. We found that the best temperature difference for safety of the TEGs and continuous use of the stove would be in a range of 35 centigrade to 60 centigrade. With further testing, we found that these temperatures gave us a voltage of 1.2 - 1.9 volts and .46 - .6 amps. We will expand upon the importance of this within the detailed description.

A circuit known as a Buck-Boost converter was also used in order to maintain a voltage of 5V for our USB charging output. The Buck-Boost converter was acquired from Linear. We looked at multiple different implementations that we could use with no outside help, but decided to go with the advice of experts in the field. Our attempts at a scaled down version, aimed at multiple different end results, are added below.

4.3 Detailed Design Description

The intricacies of our design can be partitioned into three major components: the TEG's, the circuitry necessary to regulate the power generated by the TEGs, and the USB standard that we are delivering the power to.

The TEGs are fairly simplistic in design, with two alumina ceramic plates sandwiching the semiconductors soldered together with bismuth-tin. This makes the TEG's very stable and durable, unless they are exposed to temperatures higher than 138 centigrade.

The second portion pertains to the circuitry, which is comprised of soldered connections to the TEGs and the Buck-Boost converter we acquired from Linear Tech (LTM8045, PDF is in the appendix and hyper linked here: http://cds.linear.com/docs/en/datasheet/8032fg.pdf). The Buck-Boost converter allows us to make sure variations in voltage and current from the TEGs are changed into a constant output that we desire in order to meet specifications of USB 2.0. This circuit has the ability to increase or decrease the voltage using a conversion of the current if the input ever falls short or exceeds the 5 Volts, respectively, keeping the USB device safe from overcharging or any other charging-related issue.

The LTM8032 itself is embedded within a demo board supplied by Linear tech in the configuration shown above as a low-noise DC/DC regulator. As was iterated above, we are using this implementation to safely ensure the right voltage and current are supplied to our USB charger.

The final piece of this system is the USB charger itself, which is connected to the outputs of the LTM8032 circuit-board at the power ports as shown below. The USB port connects with a soldered connection to Ports one and four.

4.4 Design Drawings

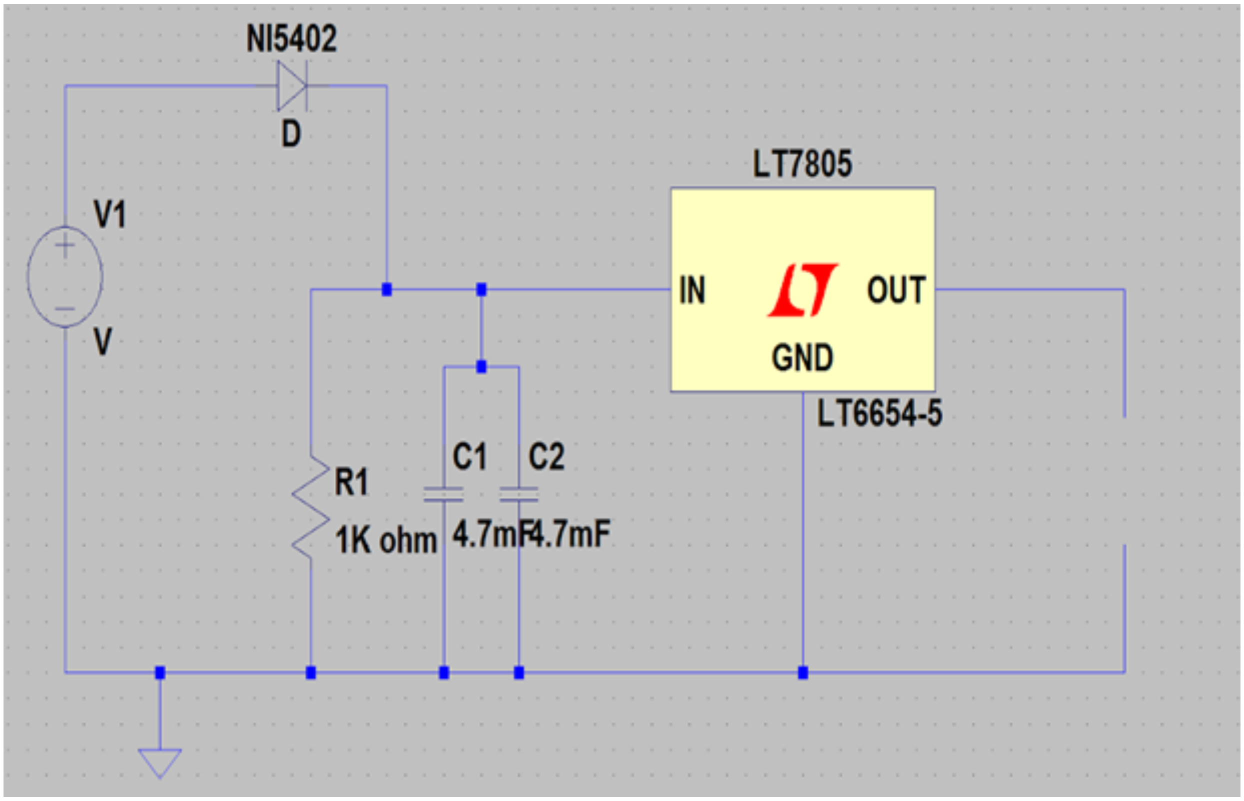

Figure 4.1: Prototype On-Demand Charging System

The above design (Figure 4.1) takes inspiration from the previous team's designs, as well as the basics of solar charging circuits used commonly as camping circuits. The circuit takes power from the power source (a simple array of TEGs in this case), and contains the power with the group of linear loads in the circuit before it goes through a grounded regulator. The 'trickle' of current will grow as the temperature differential increases across the TEGs.

Future iterations of this include placing a killswitch between the diode and the power source in case of an emergency as well as an LED at the output to indicate the device was ready to charge a USB device safely.

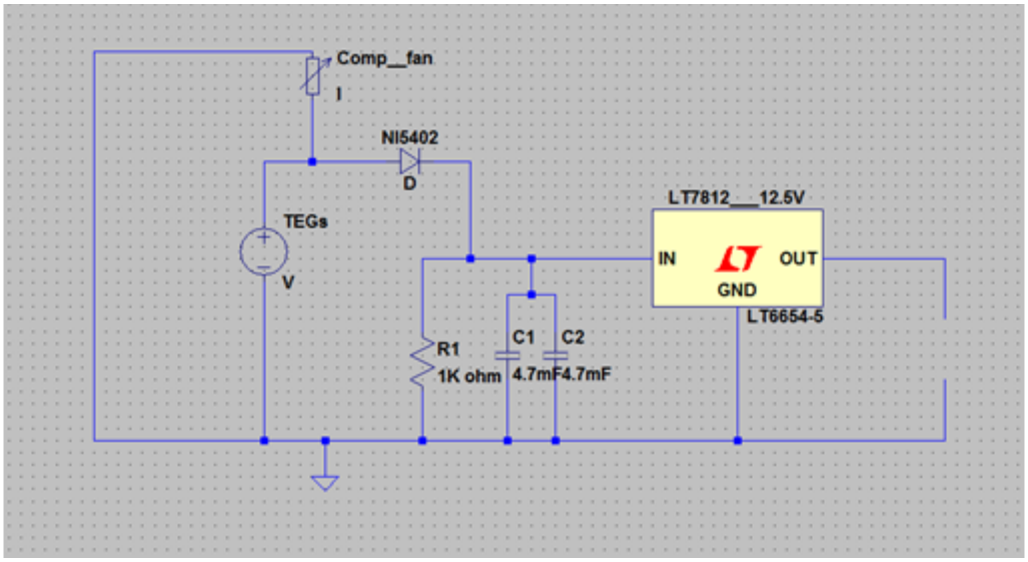

Figure 4.2: Charging Design Prototype 2

One of the simple fixes to the power problem in the rural portions of developing nations came as a shock to our initial assessment, mostly in the case of using car batteries as a common charging method for cellular devices. One of the ways we discussed helping, in case the community preferred to stick with their own way of charging phones was to configure the stove to charge a car battery to be used in a similar fashion as how it is already being used in the area.

This design follows the general 'trickle' power charger system, and would require more than one Peltier unit as described in previous problems. One of the other problems present in this design has to do with charge time. Although the customer could charge a car battery in parts while they use the device, in order to fully charge a car battery, the stove would have to be running for far longer than it would take to cook dinner which is waste of fuel and detrimental to the original purpose of the stove.

4.5 Final Project Design and Implementation:

Part 1

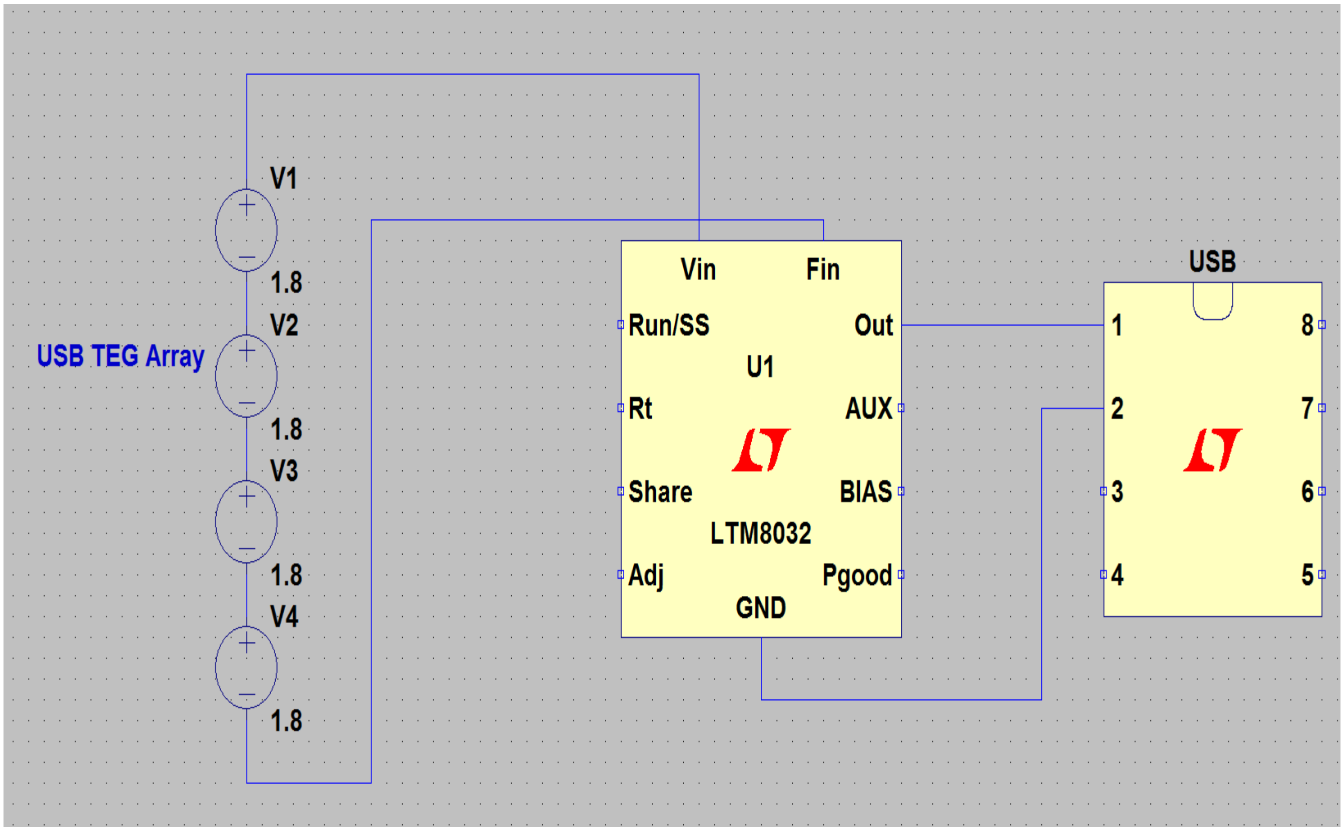

Figure 4.3: Finalized Charging Circuitry

Figure 4.8 attends to the needs of the USB device, and focuses exclusively upon this function. It was decided upon review and testing that the multi-faceted approach we first attempted in an effort to maintain one circuit was too convoluted and prone to issues on a mass production scale. The first circuit deals with the USB power, and ignores the inputs for data as there is no data being transmitted from an electrical power source. The 1.8V DC sources symbolize individual TEG's, which are added in series to gain the desired voltage for the Buck-Boost converter to deliver to the USB (F) port.

Part 2

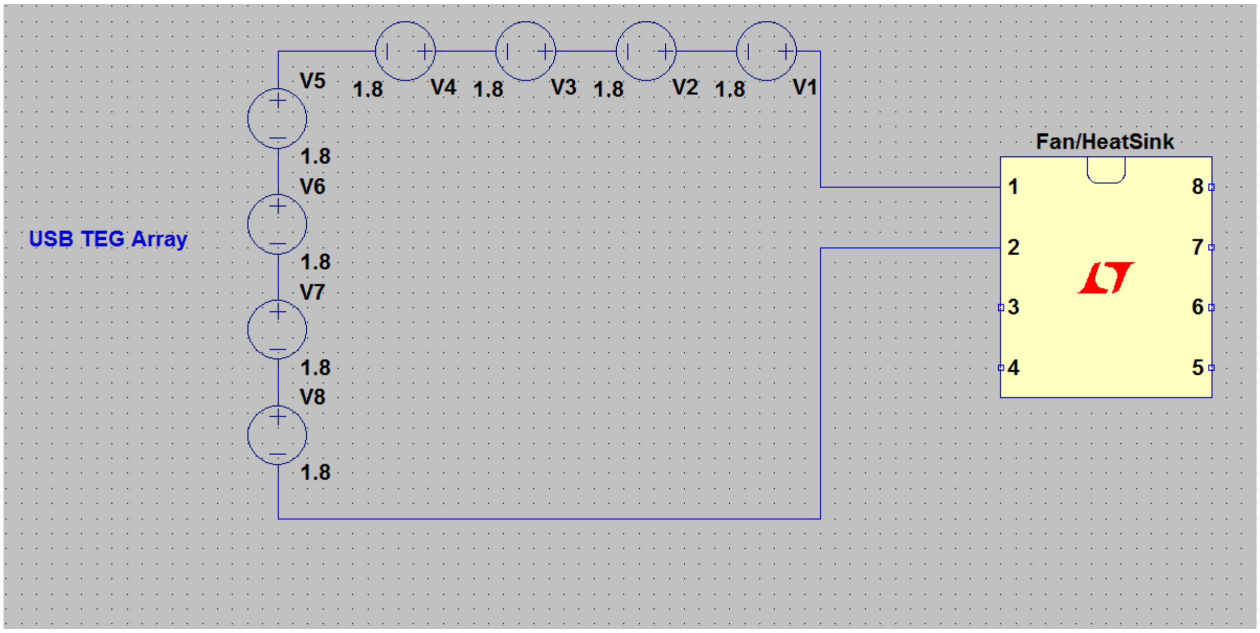

Figure 4.4: Finalized Fan Circuitry

The second circuit (as shown above) takes its full attention as the fan which simultaneously cools the internal portion of the cookstove, but also stokes the gasification process expanded upon in previous sections of the report. Whereas in the first circuit the electrical power is regulated at five volts, we decided to let the voltage have a bit more free reign. This was decided with the idea that the hotter the gasification process became, the greater the difference in temperature would become, inducing a higher voltage which would allow the system to cool down and drop voltage.

This cycle would continue to regulate the internal temperature in a way that would require no outside interference, making a negative feedback loop which would keep the system from reaching such a high temperature that the system would be too warm in all parts to function as a charger (due to the lack of temperature differences which would halt the Seebeck effect from occurring).

Chapter 5: Results

Figure 5.1: Prototype Cookstove Test

5.1 Results from Combustion Chamber Test

Results for the combustion chamber were found through detailed testing of the product. Thermocouples as well as an IR temperature probe were used to find temperatures of stove surfaces over time. Stove temperatures were measured over time, and not just at steady state in order to understand the time required for the stove to reach a stable temperature (steady state). This time is needed, for it allowed calculation of time where a user can safely touch the outside surface of the stove.

The temperature distribution for the outer surface of the combustion chamber was created from data taken *via* both thermocouple and IR probe. The temperature distributions recorded, as shown in Figure 5.2, showed some consistency with the expected values with the surface temperature finite elements analysis calculation, however, these values were much lower than the analysis showed, and was likely the result of improper initial conditions within the analysis. This error is likely due to an incorrect assumption of combustion temperature in the FEA or incorrect material emissivity data for the refractory cement in the FEA.

Tests were conducted both with and without a cement element inside the combustion chamber in order to gauge various effects of its presence. The temperatures recorded showed that the addition of a cement element in the prototype both decreased outer surface temperature and increased overall temperature output at the top of the stove. These results show the beneficial nature of the cement material's inclusion. The refractory cement both increases the temperature within the combustion chamber and serves to resist radiative heat transfer to the outer wall surface.

The tests to confirm whether gasification was present were done visually. Ideally, testing for molecules from the fire's output and confirming whether products of synthetic gas combustion are present can test for successful gasification.

The equipment necessary for this testing was not available to Team Forge, so an alternative testing methodology was used. Since gasification results in a smokeless burn, the main visual testing criteria would come from whether smoke could be seen during testing. Another method for testing successful gasification involves visually inspecting the synthetic gas output ports on our design to see if secondary combustion is occurring. Using both of these testing methodologies it was confirmed that gasification was occurring during the testing process. After an initial burn period the smoke in the fire dissipated and secondary combustion was visible in the synthetic output ports; gasification was present.

In order to gauge the heat output from our stove in operation versus competition the heat output during our test was measured by heating a fixed volume of water on our stove and recording the time it took to boil. Knowing the specific heat of water, the latent heat of vaporization of water, the amount of water used, and the time it took for the water to boil allowed for the calculation of the heat transferred to the water. It was found through thermodynamic calculations (Appendix D.) that the heat output of our stove under non-ideal conditions (high winds limited the heat transfer from the flames to the cookware) was 4.91kW. This heat output was consistent with our expectations and similar to competing products.

Table 5.1: Temperatures Recorded on Cookstove with/without Refractory Cement Insulator

(Red is without ceramics, Green is with. All Temps in Celsius)

No Fan (13 mph wind)	0 minutes	5-7 minutes	8-12 minutes	17-18 minutes	25-27 minutes	31-34 minutes	41-43 minutes
Combustion Chamber Base	24	NA	NA	NA	NA	NA	NA
Combustion Chamber Top (Inner diameter of top ring)	24	230	250	200	280	400 (115 outer)	380
Thermoelectrics/Fan	24	130	135	**50**	150	220	290
Exterior Wall	24	60	200	150	150	200	240
Cooking Surface (1 inch above top)	24	430	430	150	600	NA	650 (620 3 inches above)
No Fan (12 mph wind) (constantly adding more wood)	0 minutes	5-7 minutes	11-12 minutes	17-18 minutes	24-25 minutes	30-31 minutes	36-38 minutes
Combustion Chamber Base	30	380	590	550	N/A	500	720
Combustion Chamber Top (Inner diameter of top ring)	30	290	345	460	500	440	570
Thermoelectrics/Fan	26	60	245	275	350	310	280
Exterior Wall	30	46	76	110	110	110	120
Cooking Surface (2 inches above top)	30	N/A	N/A	N/A	180 (60 in pot)	300 (boiling water)	N/A

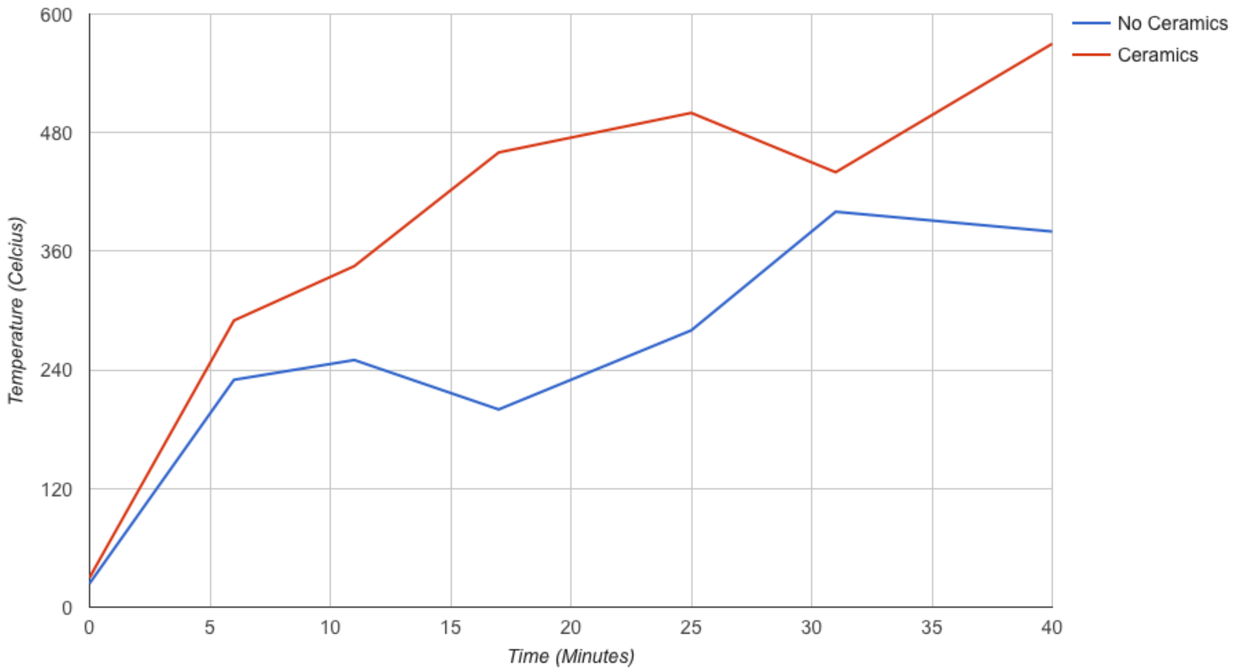

Figure 5.2: Cookstove Surface Temperature vs Time

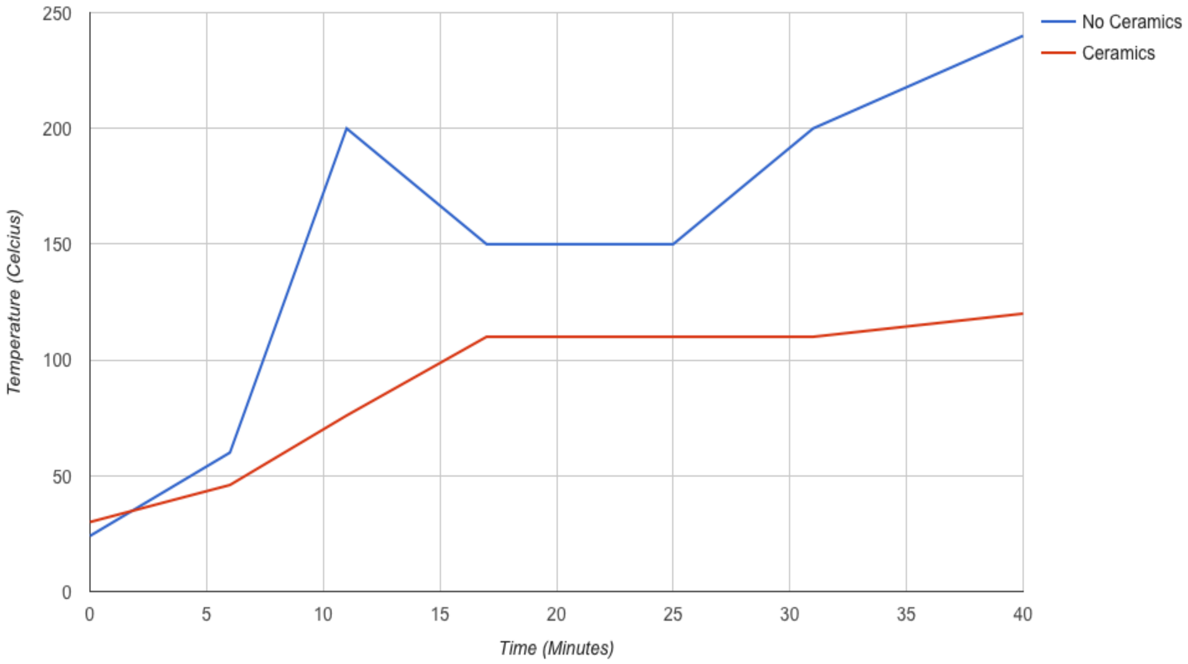

Figure 5.3: Exterior Wall Temperature vs Time

5.2 Thermoelectric Test Results

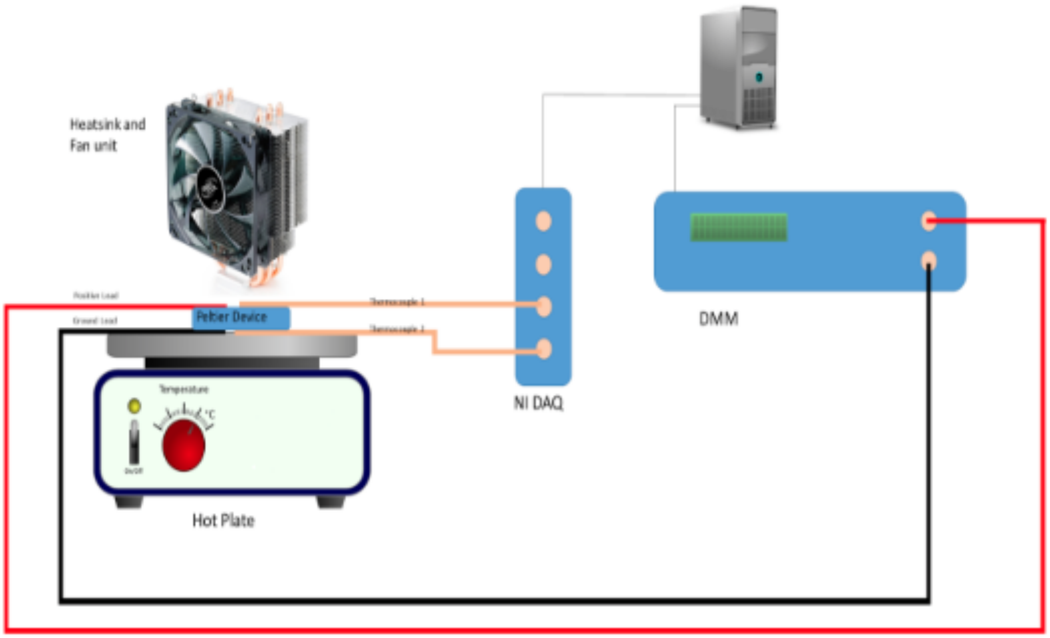

Figure 5.4: Thermal Testing Setup

The thermoelectric testing process (as seen above in a basic diagram), consisted of placing thermocouples on each side of the thermoelectric generators. This allowed us to obtain reliable and consistent data which would record the current and/or voltage we would be receiving as a result of the temperature differences.

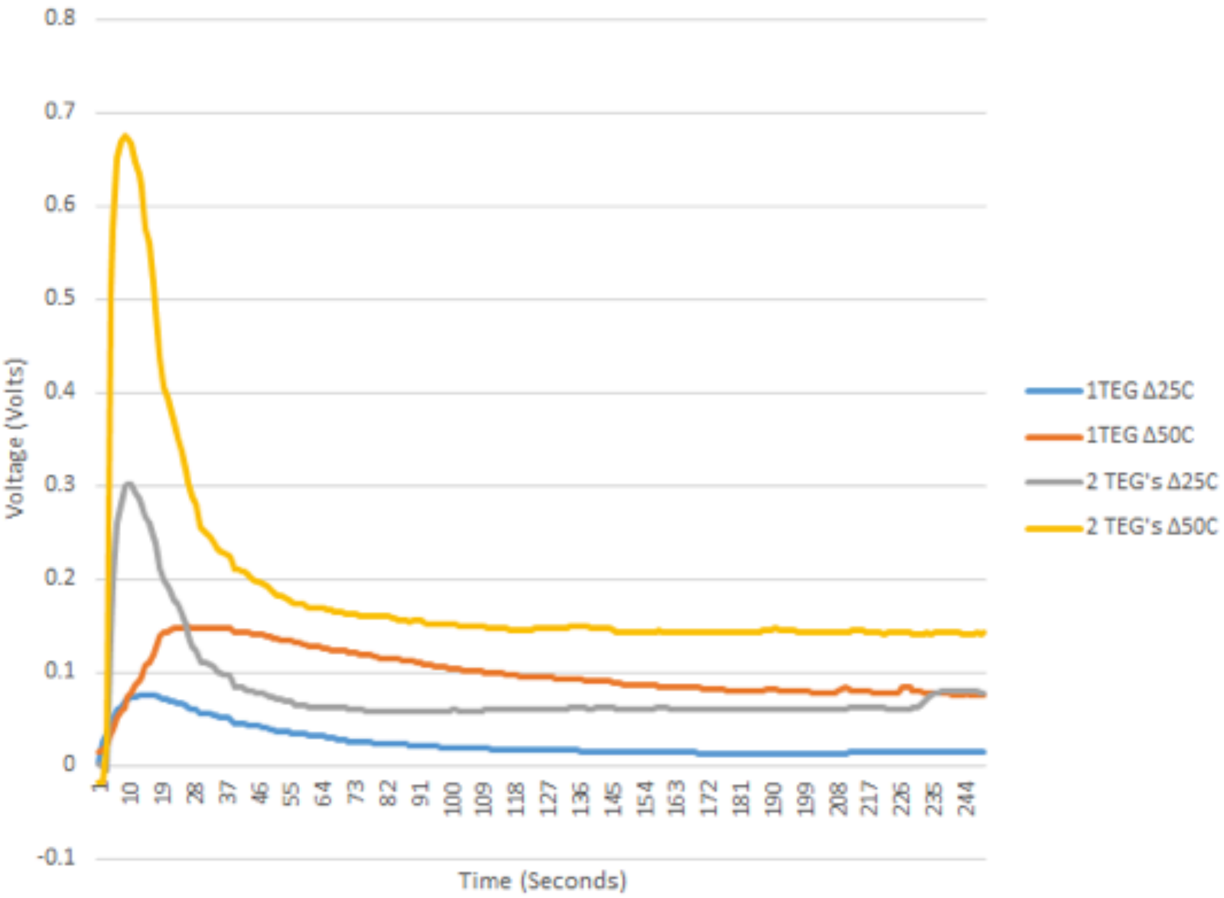

Figure 5.5: Thermal Testing Voltages from TEGs in Series Without Fan or Heat Sink on Hotplate

The graph above (Figure 5.5) shows the voltage as a function of time without any form of thermal dampening, where we are able to see that the TEGs follow a seemingly linear progression in values as they are added in series after the first initial voltage spike. This means that connecting two TEG's in series creates a voltage greater than or equal to the voltage made by two unconnected TEG's under the same conditions.

Table 5.2: Temperatures and Voltage Recorded using Thermoelectric Generators

Thermoelectric Test	0 minutes	4-6 minutes	13-14 minutes	17-18 minutes	25-26 minutes
Combustion Temperature (Celsius)	27	550	664	410	640
Thermoelectrics/Fan Temperature (Celsius)	27	36	53	75	77
Voltage Output (Volts)	0	N/A	0.08	0.06	0.07

Unfortunately, our final tests that we conducted with the electrical systems and thermoelectrics in place were unsuccessful. The cookstove again succeeded in gasifying the material being burned and resulted with a clean burn, but the output of our thermoelectric generators yielded near-negligible results. Due to the limited clearance within the electronic housing section of the cookstove, the TEGs and fan apparatus were within close proximity of the air intake at the bottom of the chamber, and thus most likely congested the cooling area. The fan was not able to start due to the almost even temperatures within the TEG area, which resulted in minimal voltage output and could not start the charging process. The predicted power output (over an hour of cooking, with a steady 15 volt and .6 amp current power supply) was 9 Watt/hours, and we unfortunately did not reach this predicted output. For the future iteration of the cookstove, the base volume will need to be increased to better incorporate the heat sink, fan, and cooling plate for the thermoelectrics to better result in a wider temperature difference. Contrary to the individual tests of the TEGs, they lacked proper airflow from the fan and were not capable of cooling efficiently. Adding a battery to the circuit will allow the fan to immediately begin cooling the TEGs, and would hopefully result with the predicted tests' outcomes.

Chapter 6: Cost Analysis

Table 6.1: Overall Prototype Cost

Part or Service	Unit Price	Quantity	Total Expenditure
TEGs	\$1.93	12	\$23.18
Circuit Board	\$8.25	2	\$16.50
EE Wires/etc.	\$41.64	1	\$41.64
CRS 1008	\$102.09[1]	0.5	\$51.05
Computer Fan	\$15.00	1	\$15.00
Manufacturing	\$700	1	\$700
TOTAL	—	—	\$847.37

[1] Unit cost is based on price for 30 sq. ft. Sheet

As shown in Table 6.1 above, the prototype cost for the initial design was \$105 based on the parts alone, and a total of \$805 including the manufacturing of the design from our manufacturing company, PWP. For our project, it was determined that the manufacturing for our design would drop significantly from \$700 for a single prototype to \$250 for a mass production price. The value of \$700 was significantly higher than originally thought due to the fact that the parts given to the company were not keyed to location for the welding process, and required most of a day to complete instead of around 40 minutes on average. This is a significant driver on the price for our design since welding is a manual process and thus increases the cost of the design by a large margin. Other similar designs in the region, like from Proleña, are priced around \$500, and are very limited in their function. When compared to the mass production cost of our design, around \$350, ours is much more affordable than similar devices. Unfortunately, the cost that was desired, around \$150, is still out of reach for our current design. Hopefully with future iterations and optimizations, the cost of this device will drop enough to reach this threshold.

Chapter 7: Business Plan

7.1 Executive Summary

The Forge stove harnesses the heat of gasification to generate electricity, and it is designed to serve the impoverished population of rural Nicaragua. By providing both electricity and a source of clean cooking, the stove justifies its target price of $130. The business plan begins with a trial phase, in which stoves will be shipped from the United States to Nicaragua and sold in partnership with NGOs, such as Grupo Fenix. At the conclusion of this phase, stove production will be scaled up or will give way to the use of frugal thermoelectric kits in their place.

7.2 Introduction

"Impoverished, alone in the dark." This sentiment has likely been felt throughout areas of rural Nicaragua, where, as of 2005, only 35% of the population has power[13]. Contrasted with the 90% of the population that has energy access in urban areas, this figure suggests the need for a call to action: in one of the world's poorest nations, a gap in resources and opportunity is still perpetuated. With our product, The Forge, we can close this gap, empowering citizens of rural villages with both the literal and proverbial power necessary for economic freedom. Our product is a modular cooking surface that uses gasification in its heating process, which yields a clean burn and high temperatures, which are then harnessed to also generate electricity. This electricity can be used to power the unit itself, a cell phone, or even a car battery. It can also, however, be used to start a microbusiness, and Forge users can gain economic empowerment by selling the electricity to other members of their community. In addition, our product serves a dual purpose, and by providing a cooking surface with clean emissions we meet an environmental imperative as well. According to the United Nations Development Programme, Nicaragua has set targets for 90% of its citizens to have access to electricity and cut use of fossil fuels by 90%[14] by 2020. Thus, our product will fill a unique niche by providing an additional good to the Nicaraguan government in addition to driving progress toward its electrification goal. By filling multiple

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[13] Grogan 253

[14] UNDP

needs with a portable, affordable unit, Forge more than meets the demands of its potential users, and, with success in Nicaragua, can be scaled to impact lives throughout the developing world.

7.3 Goals and Objectives

Unlike a traditional business, Forge is not strictly motivated by profits and the traditional bottom line. Instead, we choose to focus on a double bottom line, which incorporates a social return on investment as well as a financial one. This does not make Forge a charity; while a focus will be placed on achieving social good, the business will stand to be self-sufficient. In other words, we intend to operate Forge at modest profit with massive potential for social gain. With this in mind, a double-bottom line venture still must be held accountable to metrics and process, and we choose to use a modified version of Robert Kaplan's Balanced Scorecard to measure our impact and effectiveness. Clark, et al.[15] highlight the focus on outcomes of the business process, and this strategy will serve Forge well. Integration of Forge technology into the market is crucial, and tracking growth and customer feedback is integral to our success. In other words, Forge will challenge itself to meet the needs of its customers and partners in addition to investors.

To have success and deliver social impact, Forge will need to coordinate with partners to help distribute the product, meet customer needs, and achieve long-term market penetration. Working with the Nicaraguan government and non-government organizations (NGOs) will be essential to both maintaining a low cost and reaching customers at the end of the supply chain. Proleña and Grupo Fenix, two NGOs active in northern Nicaragua, both had conversations with the Forge team, and their knowledge of the market and customer base already has contributed to the Forge design. They also work to distribute, and in some cases, build the cookstove technology employed in northern Nicaragua, and their help would be key to ensuring that the Forge stove reaches customers and makes the desired social impact.

Last, our team hopes to execute a three-phase business plan, to introduce our product to the market, to refine its tracking, and, eventually, translate to scaling. The first phase of the plan will involve an initial trial, in which we leverage partnerships with Grupo Fenix, Proleña, or another organization to deliver prototypes or the information on how to build the prototypes to

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[15] Clark, Long, Rosenzweig, and Olsen

customers in centralized villages. The second phase will constitute an evaluation of our strategy, in which we decide whether to begin manufacturing units in Nicaragua, continue with the onsite application of the technology, or exit. In our final phase, as Nicaragua adds infrastructure, we will scale the technology to provide greater generation, while the cookstove can be used to reach the extremes of our market base and serve last-mile customers.

7.4 Description of Product

The Forge cookstove harnesses the gasification and Peltier/Seebeck effects to enable efficient fuel combustion and reuse the excess heat generated from this burn to create electricity. The generation of electricity from excess heat is achieved via TEGs, or thermoelectric generators. These devices use the temperature differential between the stove casing and the ambient air to produce electricity. The casing of the stove is composed of Cold Rolled Steel (CRS) 1008, fourteen thermoelectric generators, a computer fan, and the circuitry necessary for power output. The user inserts biomass into the top of stove and ignites it. The burning fuel is then stoked by the fan, which causes gasification to occur. Simultaneously, the computer fan cools the cold side of the TEGs, creating a large enough temperature difference for the TEGs to generate electricity. Some of this electricity will be returned to the system to help power the computer fan, while the remainder will be outputted to a USB device or car battery.

Ultimately, the value of this product lies in its versatility for its price. In Section 7.6, the Forge stove is compared to units already used in the Nicaraguan marketplace. Neither the Grupo Fenix solar cooker nor the Proleña Mega Ecofon generate electricity, and both are currently priced higher than our target price [16]. Our prototype, which is comparably priced when produced at scale using current manufacturing methods, still maintains the advantage of electricity generation. Paul and Uhomoibhi[17] note that electricity generation also provides an economic benefit, and microbusinesses such as mobile charging stations can flourish with access to reliable electricity[18]. This further justifies the price of the cookstove, and for a low-income market base, every dollar they spend must add value. The Forge stove also boasts a clean burn, reducing the exposure of users to particulates that results from other methods of cooking. In essence, the

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[16] Thermelectric Generators Fan or Heat Sink on Hotplate. .32 Horman 12

[17] Paul and Uhomoibhi

[18] ICL 1104

Forge stove excels because it meets a wide assortment of its market's needs in one, has a moderate price tag, and the solutions currently employed in rural Nicaragua cannot do the same for the same dollar amount.

7.5 Potential Markets

As noted in the introduction, the target market for Forge is the rural, mountainous northern part of Nicaragua. First and foremost, the market's dire need for electrification made it a clear choice for our product. As of 2012, only 77.9% of Nicaragua's population has access to electricity, placing the country in the bottom five in the Americas for total electrification[19]. This percentage, however, is not representative of the rural, undeveloped North, where only 42.7% of the population has access to electricity. Especially when compared to the same statistic in 2010 of 43.2%, this figure is alarming; not only is the problem severe, but change has stagnated, and significant improvement has yet to be documented.

Forge's lightweight, modular design makes it ideal for rural Nicaragua, allowing it to mitigate one of the market's major challenges: developing a supply chain. Both Proleña and Grupo Fenix said the solution was to build their stoves on location. Grupo Fenix took a low-tech approach, using reflective panels to create a cookstove that utilized sunlight, while Proleña trained locals to build more advanced cookstoves alongside technicians. In both cases, their products tended to be large and immobile, creating limitations on their use and where they could be used. Research also supports their claims, and, in his paper *Rural Nonfarm Incomes in Nicaragua,* Leonardo Corral states that only 43% of houses have access to a dirt road, and only 22% of these households can access electricity[20]. Thus, we believe that as a mobile solution, Forge can alleviate the supply chain woes of Proleña and Grupo Fenix, and can provide an alternative to large unit construction on site.

Finally, the Nicaraguan government's commitment to electrification, particularly in the renewable energy sector, is another market factor that falls in Forge's favor. The government has stated that it wants to reach full electrification by 2017, an ambitious effort that will require significant investment in renewable energy sources[21]. In addition, the country has a soft

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[19] World Bank
[20] Corral 429
[21] BNEF

commitment to reach 74% renewable energy by 2018 and 91% renewable energy by 2027[22]. These goals suggest that the government is open to bringing in renewable energy, and this may serve to be beneficial as Forge advances into later stages of its business model. The government has already instituted subsidies for energy distributors at a rate of $.05-$.06 per kilowatt hour. This service is provided to distributors using various renewable energy sources, including biomass, and the subsidy goes to either providers who intend to install infrastructure or support current generators. Currently, Forge falls in the later group, and if the thermoelectric generation technology proves to be scalable as infrastructure improves, we can transition into generating renewable energy large scale, while maintaining the current cookstove model for fringe customers.

With all of this in mind, the market serves as an ideal environment to test the scalability and use of the thermoelectric technology in the field. Grupo Fenix and Proleña each serve a base of potential customers in our target market, and Proleña already employs a strategy that may serve as a viable contingency plan for Forge. If circumstances make our target price of $130 unattainable, then we will begin by employing an onsite manufacturing plan similar to Proleña's strategy. Unlike the Mega Ecofon stove that they produce, however, the Forge technology is less expensive, more mobile, and has the added benefit of electricity generation. Electrical components would still need to be shipped to site, but their weight is insignificant relative to that of a full cookstove. Were this implementation to succeed, then larger-scale local manufacturing could take place, and the proof of concept could still lead into the eventual phase of scaled-generation with the rise of infrastructure.

7.6 Competition

Currently, Forge does not face direct competition in the northern Nicaraguan market. The market is sparse, and this is not without reason. According to the World Bank, the adjusted net income per capita per Nicaragua was about $1700 USD in 2014[23]. This number, however, does not reflect the vast divide between the wealthy and the poor within the nation. The World Food Programme states that, as of 2010, 76% of the population survives on less than $2 USD per day, a staggering level of poverty that does not support large, single-payment purchases. Thus,

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[22] Thermelectric Generators Fan or Heat Sink on Hotplate. .32Climatescope
[23] World Bank

affordability is an issue, and any product brought to market must justify its price against alternatives, including, in the case of a cookstove, electing to cook over an open fire. Another difficulty is expanding a supply chain to Nicaragua's mountainous North. Based on our conversations with Grupo Fenix and Proleña, we discovered that a supply chain is difficult to maintain. The lack of infrastructure outlined in the previous section is the reason behind this, and shipping large cookstoves or quantities of materials is both expensive and a logistical challenge. Non-modular solutions are often constructed in rural villages themselves, as manufacturing and distributing a finished product is difficult and costly[24].

While they may not necessarily produce energy, other cookstoves can compete with Forge in price and in the primary function, green cooking. In Table 2.1, we see one of the cookstoves Grupo Fenix uses to serve people in the region. Already the price of the stove stands out; $300 is a high price for a cookstove, and this price sits well above our target price of $130. In addition, this stove uses reflective panels to generate heat, and it reaches a cooking temperature of 150° C[25]. This temperature is not sufficient for many cooking needs, and, along with the price and large size of the unit, we feel that the stove discussed can be improved upon, and our solution and those of others can outperform this model.

Proleña, on the other hand, has a stove that better serves their audience. The Mega Ecofon is priced at $203, making it a more affordable option than Grupo Fenix's solar stove[26] Similarly, however, it is not mobile; the stove is large, with a design, according to Horman, "recommended for small businesses"[27]. This limitation gives the Forge stove an upper hand, and its lightweight design allows it to be moved, perhaps allowing it to reach last mile customers who lack the materials to construct a Mega Ecofon stove. The Mega Ecofon also does not generate electricity, and, like the Grupo Fenix stove before it, it has a difficult time justifying its price.

Although they do not serve the Nicaraguan market, African Clean Energy produces the ACE 1, a cookstove that competes very well with the Forge Stove. With a price of $150, the stove is affordable, and it uses a similar gasification process[28]. It also generates electricity;

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[24] Proleña
[25] Grupo Fenix
[26] Proleña
[27] Horman 13
[28] African Clean Energy

unlike the Forge stove, however, it uses solar energy instead of thermoelectric components to generate its power. The stove also is lighter than the Forge model, and, at 4.6 kg, it is less than half the weight of our team's product. Currently, the ACE 1 is superior to our prototype in nearly all facets, and it is the benchmark for our team's design process. While we are confident that we can price our stove below $150 in the future, we currently cannot, and we hope to emulate the success that African Clean Energy has enjoyed.

7.7 Sales/Marketing Strategies

To market the Forge stove effectively, we will need to prove to our customers that the stove is both affordable and worth the substantial price. To do so, we will utilize a variety of tactics already in use; in particular, we will use methods already in use by Proleña and Grupo Fenix to take our product to market. Proleña allows customers to pay for stoves in installments, as a collective, or by using their labor to build models onsite[29]. We will continue this method, and in our first phase we will test the installation of the thermoelectric components on site as a method to reduce the sticker price of our stove. In addition, Nicaragua currently has a thriving microfinance market, with over $568 million in outstanding loans[30]. We hope to tap into this network, and help our customers take small loans to pay for our product over time instead of as a lump sump. Finally, we will recruit Proleña and Grupo Fenix volunteers to help to market our product; they will advocate for the potential benefits of clean cooking and the possible implications electricity can have on individual micro business, generating trust among our customer base and further justifying to them the price of the cookstove.

In addition to serving rural villages, Forge also seeks to reach last mile customers. These customers are outside the reach of traditional supply chains, and whether it be for logistical or economic reasons, this problem is a challenge that Forge is willing to accept. As Corral stated previously, a significant portion of households do not have access to dirt or paved roads, and this could stymie any effort to ship a 10 kg stove to their location. Therefore, we will serve these customers by delivering a kit of thermoelectric components instead, and providing a more frugal, albeit less effective, solution to them. For payment, Forge intends to utilize a scheme similar to the Grupo Fenix nano loan. This microfinancial tool allows families to take a small loan, which

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[29] Proleña
[30] MixMarket

they can pay back by hosting technicians who assemble their stoves and educate customers about the product[31]. Our team plans to use a system in this fashion to ensure that these customers can afford our stove, regardless of their income level. The costs of this are built into our overhead, and we feel that our service to these customers will contribute meaningfully to our social impact.

7.8 Manufacturing

To manufacture Forge's prototype cookstove, our team contacted PWP Manufacturing to produce our initial model. The costs of this single stove were estimated to be $706.11, with labor constituting the majority of the expenditure (PWP). The material used, Cold Rolled Steel (CRS) 1008, required intensive manual labor to be formed to fit our stove. Much of this cost, however, can be distributed over multiple stoves. In our first phase of the model we will be prepared to manufacture a 20 stove starting inventory, at the projected cost of $309.90 per stove. This will not be sufficient as we scale, however, and upon the start of phase two, we will produce a cast of our combustion chamber to reduce labor cost for use with injection molding. This will cost thousands of dollars and is not economical for the team's trial period, but, as Forge continues to grow, we will have the capacity to scale our operation and invest in efficient production.

Last, our location of manufacturing will change over the course of our Forge's lifetime. For phase one of our business plan, we will begin by manufacturing our prototypes in the United States and shipping them to Nicaragua. For this phase, we estimate our shipping costs for 20 units to total $1811.50, and we can accept this price for our trial phase. With scale, however, we cannot maintain our target price along with these shipping cost, and moving manufacturing to Nicaragua is our best solution for phase two and beyond. To start with manufacturing at this phase, we believe $20,000 will be sufficient to begin our search, and, along with developing a cast for our chamber, this should give us reasonable accommodations to begin our work. Our inventory will increase on a yearly basis, and, from Table 7.3 and Table 7.4, you can see that our overhead costs have risen to represent this increase.

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[31] Grupo Fenix

7.9 Product Cost and Price

The production cost of our prototype is outlined in the table below:

Table 7.1: Prototype Cost by Part

Part	Vendor	Unit Price	Quantity	Total Expenditure
TEGs	Vktech	$1.93	12	$23.18
Circuitboard	Mouser	$8.25	2	$16.50
CRS 1008	MkMetal	$102.09[1]	0.5	$51.05
Computer Fan	Fry's Electronics	$15.00	1	$15.00
TOTAL	—	—	—	$105.73

[1] Unit cost is based on price for 30 sq. ft. Sheet

These costs are representative of producing an individual unit, and do not include a bulk discount. While hard numbers are not available for purchasing each component in bulk, we have received estimates from vendors and industry experts on prices when our project achieves scale. By purchasing steel by the ton in bulk quantities as opposed to in single sheets, we can purchase steel at a rate of approximately $18 per unit, cutting costs by nearly 70%[32]. In addition, we can purchase TEGs for about $1 each in bulk quantities, further lowering costs of our units. The team believes that materials costs can be reduced by approximately 50% in bulk, giving us a target materials price of $58 for the second phase of our plan.

Notably, labor costs are absent from the above table. PWP Manufacturing, the company that manufactured our prototype, estimated a labor cost of over $500 for a single unit. They did, however, state that a great deal of the costs stemmed from high fixed costs, and that, were manufacturing scaled to 500 units, our contact estimated that costs would total $309 per unit, with a considerable decrease if a more effective method of manufacturing were used instead of manual fabrication and welding. Thus, the solution to our costing problem lies in reducing labor costs. To do so, our team will turn to a less labor-intensive manufacturing process. The two alternatives recommended by our manufacturer were powder metallurgy and casting the combustion chamber into a mold. Both processes are similar in that they have large fixed costs

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[32] Alibaba

upfront that will translate to savings in the long run. Our teams believe that casting is the most viable method at the moment, and we will begin with this approach in phase two of our business plan. Our target price for labor at this point is $40/unit, and with casting, this is an attainable goal.

In total, our projected materials and labor costs total to $98 for a single unit. Although $130 is our target price for the product, this is not realistic to deliver to the end consumer. Whether the stoves are produced in Nicaragua or in the United States, shipping costs will be considerable, particularly in the case of last mile distribution. Until Forge can ascertain the expense of shipping our stoves at the conclusion of phase one, our team intends to charge a price closer to $150. This price is consistent with the standard set by African Clean Energy as seen in section 7.7, and we believe that this price is both affordable to our customers and reasonable for us to gauge shipping prices early on in our business's development. As phase two comes about and our costs become fully apparent, we can transition to a price closer to our $130 target, reaching a broader user base and increasing Forge's social impact. Finally, we will price the thermoelectric kits at $50 in our phase one trial, and move to a price of $30 in phase two as Forge scales.

7.10 Service or Warranties

In determining an appropriate warranty for the Forge cookstove, we found that separating the electrical system and the combustion chamber into two separate categories best allows us to serve our customer base and maintain low costs. Vktech estimates their thermoelectric devices have a lifetime of 200,000 operating hours, which is a time well beyond the expected lifetime of our units[33]. This estimate does not, however, necessarily account for outdoor usage in a rural environment, and we will provide a warranty lasting for the duration of each phase of our business plan, at each phase electing to continue the warranty ourselves or to train Proleña technicians to install the system and continue to distribute parts to them. Our team elected to take this approach in order to ensure and maintain the trust of our customers as well as to guarantee the ongoing use of our cookstove after a potential exit from the market.

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[33] Vktech

The combustion chamber, on the other hand, is difficult to effectively warranty. Due to the high materials cost, high labor cost in the first phase of our plan, and our inability to repair the metal frugally, Forge will not provide a warranty for stoves that become defective after use. While the team intends to ensure that all stoves are in working order upon shipment, we cannot affordably offer a warranty that extends beyond manufacturing defects. Thus, in order to uphold customer trust, we can offer a discount on the thermoelectric kit in the event that the cookstove is no longer operable.

7.11 Financial Plan and Funding

To finance Forge, our team would employ a hybrid monetization model as a part of three phase plan for our product. Our team has produced a phase one plan, and, depending on the outcome of phase one, two phase two plans that will detail our progression. For phase 3, the team believes that further investigation into the technology and cost projection is necessary, and this area of the plan is certainly an area in which a future design team could expand upon the project. That being said, our projection for Forge is that the project is viable through phase two, and that investors will receive full return at the completion of the second phase.

In both plans that we have produced, phase one is identical; Forge will produce 20 stoves and prepare 20 electrical kits to distribute to partner technicians. The stoves and kits will be shipped to Nicaragua, and a Forge team member would accompany them to oversee their sales and distribution. In each table below, you can see that we have projected a cost of about $10,000 for this phase. This includes the costs of manufacturing the stoves, the cost of assembling the electrical kits, and the overhead of flying a team member to Nicaragua, paying for his lodging, and overseeing the development of the project. Based on the price of our goods in this phase one period, we expect revenue of $4000. This will leave us with $4000 of cash on hand, enough to account for any potential setbacks that may result. We intend to fund this with a $10,000 grant or angel investment; at this stage in our business plan, we do not intend to create profits, and this proof of concept of our technology could be applied to other ventures as well. From here, we can process feedback from our partners and customer segment, and move forward with the phase two plan that best suits the situation. Version A involves moving stove manufacturing to Nicaragua and moving forward with production there, while Version B involves moving forward with the modular kits to continue the spread of technology through the country.

Table 7.2: Business Plan A

	Phase 1	Phase 2				
Forge - Business Plan A	FY1	FY2	FY3	FY4	FY5	FY6
Stoves Sold	20	40	100	200	500	1000
On-site Setups	20	15	40	60	100	150
Cost per Stove	$309.90	$108.00	$108.00	$108.00	$108.00	$108.00
Cost per Setup	39.68	$20	$20	$20	$20	$20
Overhead	$3,000	$20,000	$5,000	$5,000	$5,000	$5,000
Total Cost	$9,991.60	$24,620.00	$16,600.00	$27,800.00	$61,000.00	$116,000.00
Price per Stove	$150	$130	$130	$130	$130	$130
Price per Setup	$50	$30	$30	$30	$30	$30
Revenue	$4,000	$5,650	$14,200	$27,800	$68,000	$134,500
Grant Money	$10,000	$0	$0	$0	$0	$0
Investment	$0	$20,000	$0	$0	$0	$0
Annual Profit	($5,991.60)	($18,970.00)	($2,400.00)	$0.00	$7,000.00	$18,500.00
Total Net Cash	$4,008.40	$5,038.40	$2,638.40	$2,638.40	$9,638.40	$28,138.40
In-Field Stoves/Setups	40	95	235	495	1095	2245

On the previous page, the first financial plan for Forge is detailed, outlining projected costs and revenue through FY6 of our venture which we project to be 2023. Version A of the plan accounts for the scenario in which our stove technology performs well, and is a success in phase one. Here, we move into Nicaragua to begin production while preparing to bring manufacturing to scale. We also will continue to support the kit for customers who cannot receive a full stove due to logistical issues. This action is accounted for in overhead; the $20,000 is spent to acquire manufacturing space, produce a casting mold for our combustion chamber, and to maintain any lodging costs for technicians in the field. To pay for this upfront, we will seek a venture capital investment of $20,000 for a 40% stake in Forge. Unlike in the previous round, we will apply for venture capital because we can expect a rapid return on investment. In the first 5 years, we project a 125% return on investment, with growth vastly increasing in the coming fiscal years. The table above stops in FY6, the first possible exit for investors at which their investments can be recouped with a modest profit. They can, however, remain invested to capture significant gains in coming years. At the conclusion of phase two of this plan, Forge will have brought over 2000 stoves and setups into the field, creating both the social impact and modest line that it originally sought out.

Table 7.3: Business Plan B

	Phase 1	**Phase 2**				
Forge - Business Plan B	**FY1**	**FY2**	**FY3**	**FY4**	**FY5**	**FY6**
Stoves Sold	20	0	0	0	0	0
On-site Setups	20	80	150	300	500	750
Cost per Stove	$309.90	$309.90	$309.90	$309.90	$309.90	$309.90
Cost per Setup	39.68	$20	$20	$20	$20	$20
Overhead	$3,000	$3,000	$3,000	$3,000	$3,000	$3,000
Total Cost	$9,991.60	$4,600.00	$6,000.00	$9,000.00	$13,000.00	$18,000.00
Price per Stove	$150	$0	$0	$0	$0	$0
Price per Setup	$50	$30	$30	$30	$30	$30
Revenue	$4,000	$2,400	$4,500	$9,000	$15,000	$22,500
Income						
Grant Money	$10,000	$0	$2000	$0	$0	$0
Annual Profit	($5,991.60)	($2,200.00)	($1,500.00)	$0.00	$2,000.00	$4,500.00
Total Net Cash	$4,008.40	$1,808.40	$2,308.40	$2,308.40	$4,308.40	$8,808.40
In-Field Stoves/Setups	40	120	270	570	1070	1820

Version B of the plan portrays a scenario in which the stove technology is non viable relative to the kits. Here, we will continue to support the kits, selling additional quantities of them and working through our partners, providing technicians to educate and assist in the construction of frugal stoves onsite. Noticeably, our costs are much lower; with no overhead going toward a cast or a base of manufacturing each year, our costs are markedly lower. In addition, our materials costs are significantly decreased in this model, ultimately meaning that Forge would not have to turn to venture capital and sell shares of ownership. While Forge's profits are dramatically more modest in this scenario, the team would only need to seek a small grant in FY3 to maintain a reasonable share of net cash on hand. This would ensure that Forge could remain solvent if unexpected expenditures occurred, and allow the team to continue to make a reasonable impact, selling 1820 units as opposed to 2245. This approach, however, is notably less conducive to growth, and it may render the third phase ultimately unviable.

Phase 3 is the final stage of Forge's mission, and, as implied above, this project is best suited to occur after Version A of the business plan. Here, Forge will reinvest remaining profits to move into large scale generation, using the thermoelectric technology to move to large scale generation. We imagine our technology providing something of a "microgrid," bringing centralized power to region. While our engineers believe this scale is achievable and a reasonable endgame for Forge, they have not produced a design to implement it in Nicaragua. Thus, with additional time, our team hopes that future research can produce an actionable design and plan for phase three, in which Forge can maximize impact, reap the aforementioned subsidies described by Jacobs, et al.[34], and continue into the future.

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[34] Jacobs

Chapter 8: Engineering Standards

8.1 Economic

To generate the social impact that our team desires, the Forge stove needed to be designed with the economic concerns of our customers in mind. The market we intend to serve is one of the world's poorest, and the product that we provide must justify every cent spent on it. To make sure that Forge met this goal, we sought to use the most inexpensive materials suited for rural Nicaragua, and our goal is to be able to provide a target price of $130. In addition to a low price, we also added to the economic appeal of the stove by increasing its value through additional functions. While the price of a stove is high compared to that of a solar panel, the price of including circuitry in the stove is more comparable, and the stove itself can produce a clean burn and generates electricity independent of conditions. Thus, by using inexpensive materials and filling multiple niches in the market, our team has developed a solution that meets the economic needs of the Nicaraguan people.

8.2 Environmental

The largest positive environmental impact of Forge is its ability to produce a cleaner burn of conventional fuels. A study was conducted in Florida aimed at determining the amount of air pollution emitted from a proposed Gainesville Renewable Energy Center biomass plant. Similarly, a power plant called ELCOGAS in Spain uses the gasification process to have a more efficient burn as well as to minimize the pollutants emitted. Although both power plants use a type of biomass as fuel, the amount of air pollution measured between the two showed that ELCOGAS had lower emissions in all categories. The following chart shows the data recorded in the two studies, as well as the percent increase of Gainesville Renewable Energy relative to ELCOGAS.

Table 8.1: Gainesville Renewable Energy Center vs ELCOGAS

Types of Air Pollutants Emitted	Gainesville Renewable Energy Center[35] (lb/MWh)	ELCOGAS[36] (lb/MWh)	Percent Increase
Nitrogen oxides	.95	.88	8.0%
Sulfur Dioxide	.56	.15	273%
Particulates	.57	.044	1195%

While not all of the possible air pollutants were listed on both charts, the percentages listed on both reports show the gasification process produces less air pollution than a regular biomass burn. Although the pollutant recovery method ELCOGAS employs will not be used in the Forge cookstove, the potential for significant pollutant recovery in gasification versus typical combustion is notable.

8.3 Social & Sustainability

Forge's impact on society is intended to be positive. However, there are certain foreseeable ethical ramifications to be considered. First, people could use this device primarily to charge their mobile devices (instead of this being a secondary feature), and thus be constantly burning fuel and emitting carbon instead of cooking. Secondly, people may find our product too confusing or inviable for their needs, and thus they would be out the money they spent on our device, and the device itself would be sitting unused, taking up space and decomposing into the environment. Both scenarios involve environmental damage, but there is little we can do to change how people use our device. They either like it and use it, or they do not.

8.4 Ethical

Forge is designed for a wide audience (an entire country, in theory), and children, the

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[35] PFPI

[36] Ratafia-Brown, 2-6

sick, and the elderly all fall into it. A stove is an intrinsically understandable device, and Forge is designed so that the only apparent difference between it and a regular cookstove is Forge's ability to generate electricity. Children who don't yet understand the dangers of an open flame should be supervised, as well as those who cannot completely control their motor movements. These decisions ultimately rest upon the users to protect others around them and prevent unwanted use. We will protect ourselves legally from unwanted and unreasonable liability, but our design should be easily understood and safe enough to prevent most foreseeable issues.

8.5 Health & Safety

Traditional cookstoves do not have any method of filtering or cleaning their emissions, and thus the fumes emitted by a contained biomass-burning fire are innately hazardous to the respiratory systems of those using them. Forge's gasification effect attempts to remedy this by reigniting gases that are normally released as pollutants for what is referred to as a "cleaner" burn. There are still pollutants released by Forge, including carbon monoxide and dioxide, and so it should only be used in a well ventilated environment. Furthermore, the physical weight of Forge makes it so that it is heavy enough to not topple when loaded with fuel and cooking, but light enough to move when unloaded and cool. This makes the cookstove safer than existing portable cookstoves, but still convenient for the user.

8.6 Arts

Table 8.2: SCU Core Arts & Humanities

Team Member	Description	Locations
Matt Nelson	Passive Cooling System	Figure E-1
Matt Nelson	Fan Cooling System	Figure E-2
Matt Nelson	Closed Loop Cooling System	Figure E-3
Isaac Stratfold	Stove Base	Figure E-4
Austin Jacobs	Casing Design #1	Figure E-5
Austin Jacobs	Casing Design #2	Figure E-6
Austin Jacobs	Thermoelectrics #1	Figure E-7
Austin Jacobs	Thermoelectrics #2	Figure E-8
Jared Sheehy	Split view of cook stove	Figure E-9
Jared Sheehy	Cooking Prongs	Figure E-10
Jared Sheehy	Handle	Figure E-11

Chapter 9: Conclusion

Team Forge designed and had a functional thermoelectric cookstove built and tested within the timeframe that was previously established so as to complete it within the senior school year. Our goals were to design, build, test, and analyze our cookstove such that it met the requirements of our original ideas, and looking back on the accomplishments of our team, we believe that we have created a successful product. Our baseline goals were to have a cookstove reach boiling temperatures for water around the cooking surface and to have thermoelectric generators convert the excess heat from the core chamber into electricity to charge a device using a USB outlet. The voltage and current we needed to supply through the USB are 0.5 amps with 5 volts, and 9-12 volts for our fan which worked in conjunction with our heat sink.

Our secondary goal was to be able to have gasification occur in the device to be able to supply a constant, clean burn while running the cookstove. This process essentially burns off all tars and carcinogens produced through a standard burn process, and leaves the cookstove with a smokeless burn. In order to produce the efficiency and heat transfer containment that we desired, we looked into refractory ceramic plating for the inside of the combustion chamber. Through our finite element analysis results, we found that the cookstove's outer surface wall temperatures would be around 400 ºC, which would be too hot for consumers to effectively go near when cooking or else risk serious burns. When we conducted our first test with the device, without any electronics or refractory elements to get a baseline of our temperature gradients, we found that the highest output temperatures were only around 240 ºC and were thus significantly lower than our computer analysis results predicted. We ran a second test with refractory cement instead of ceramics to see what our profile would look like, and found that although the results were better for the outer temperatures, and the benefit of having the cement permanently attached was almost even with the drawback of its high weight and internal design.

Since we managed to get our design completely manufactured from PWP, our physical product is perfectly designed to how we CAD modeled it. Regarding our electronics and circuitry, we were given a buck-boost converter from Linear Technologies to be able to control the output of the combustion chamber such that the electricity generated never exceeds the maximum values needed for the USB device. One place that could see improvement with the design is our outer aspects of the cookstove. We originally planned to have handles attached to the side of the device to allow for easier transport, but since our device was manufactured without handles, it proved exceedingly difficult if not impossible for us to assemble a set of handles and attach them to the device without compromising the integrity of the device's ability to gasify. Some aspects in the next design that can be improved upon are its portability, which, in its current state, is possible to carry since it is around 10 Kg, but having the availability of handles would be much more successful. Finding an affordable solution for ceramic internal tiling would also be a significant improvement to the design, since although the temperatures generated were well under our estimates, they were still higher than we would have liked. Our removable refractory cement was one option, but its weight was far too high to justify its use, and we did not trust its integrity under the conditions we wanted it to function with, with the way we developed it.

Something that we learned throughout the process of this design project was that we can never truly trust simulated results for our project since although they give a good estimate of what we are to expect, one incorrect input variable will lead to completely different results. Setting up timelines and charts to keep us on track over the course of a few months was much better for our team to work with than having a general idea of how we should proceed even if some points seemed excessive. Aside from that, we discovered that it was very important to not only get to know each other in the team, but how important it is to properly work with other people over such an extended period of time. A final technical aspect that we learned was how to manage and balance all the costs of the project, from purchasing the materials to getting our designed manufactured, to buying devices for testing.

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APPENDIX A: Team Management

Challenges, both blocking and non-critical, must be dealt with swiftly as they arise during the design and construction of our device. When they become apparent, obstacles to the completion of the project must be dealt with by priority, which will be determined by how detrimental they are to the whole process. We will often have to decide as a group what to do when certain challenges arise, even if they affect only one aspect of our final product (an issue with an electrical component, for example). Everyone on the team will be tasked with overcoming the challenge, unless the challenge requires a specific specialty that certain members do not have. Ultimately, it's the responsibility of the entire team to overcome challenges.

The process of completing our project falls into three distinct phases, ideally one for each quarter. The first is the design phase, in which we completed a full outline of what our device does, how it works, how it looks, and what it is made of. In order to to this, research was completed about the background of the design. This included basics of thermodynamics, seebeck effect, voltage and current needed to charge a phone, fuel emissions (including gasification), and thermal conduction. This phase also included applying for grant money for research and development. Numerous grants were reached out too, and Team Forge graciously got funding from Santa Clara's School of Engineering. This phase included research for a possible market as well. Nicaragua became the ideal choice because they were the target market of the Team Matador and also have numerous developing areas (off the power grid) that could use the cookstove. Finally, the first phase consisted of routine documents in understanding producing this conceptual design report, and finishing any other necessary documents. These documents helped keep Team Forge on the same page. It also helped supervisors be aware of the progress on the project.

The second stage is the fabrication stage. This includes the purchase of any materials and the construction of all the individual parts of our product. Materials needed to be purchased include sheet metal for housing, thermoelectric converters, wires and fans for cooling the wires, thermal insulators, and testing equipment. More details about the materials being purchased are in the budget (Table 4). This stage also includes the creation of prototypes and iterations. The project was constructed in conjunction with PWP Manufacturing. This stage concluded with a solid prototype and flowed into the next stage.

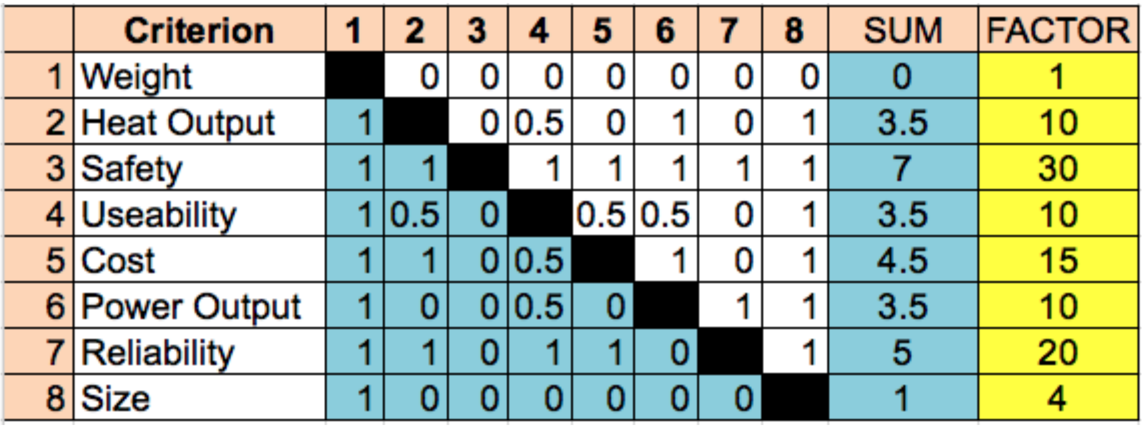
The final stage is the assembly stage, which included the final presentation of our thesis and product. Several tests were conducted in this stage in order to understand problems from the initial prototype. This stage included the completion of the final product after several tests and alterations. The final product was presented as well as our completed thesis paper.

APPENDIX B: PDS

Table B.1: Product Design Specifications

Requirement	**Reason**	**Unit**	**Value/Range**
Performance			
Output Voltage	USB output specification	Volt (V)	5.00 ± .25 V
Output Current	USB charging specification	Amp (A)	1.0-3.0 A
Input Temperature	Material/ Thermoelectric Properties	Celsius (C)	260-595 C
Material Properties			
Scrap Metal/Chimney Pipe	Combustion Chamber	N/A	Sheet metal, .778 m^2
Various Requirements			
Mobile Device Housing Required	LiPo Batteries Can be flammable / explosive in high heat	N/A	Plastic/metal housing set away from heat source
Cost Constraint	Customers will have very limited income	United States Dollars (USD)	<120 USD per unit
Ergonomics	Ease of operation essential for uneducated consumers	N/A	Simple product design- put above a heat source.
Quality / Reliability	Embedded circuitry halts output if outside of specification	Volt, Amp,Celsius	(Performance Specifications)

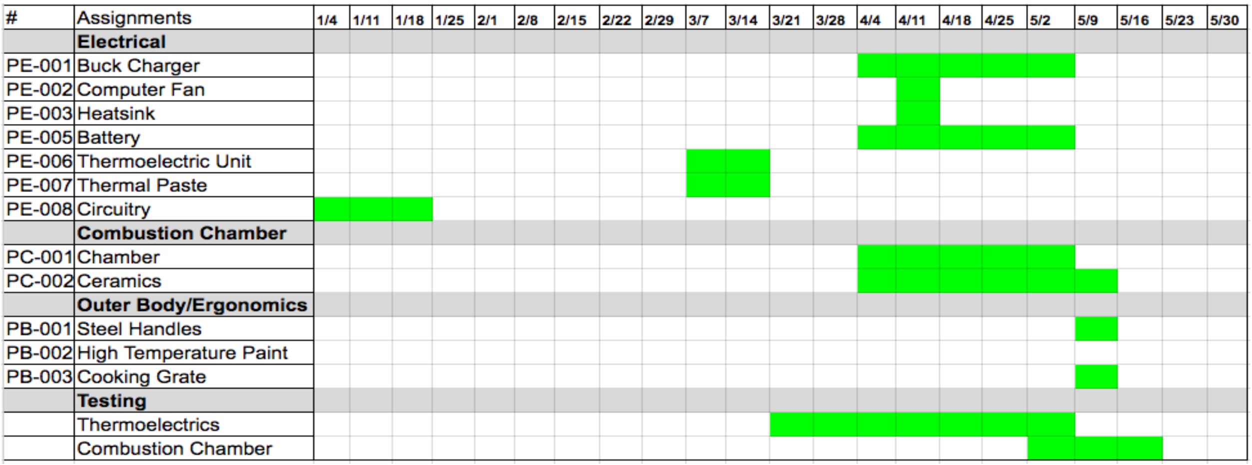
Table B.2: Criteria Matrix for Function Weights



	Criterion	1	2	3	4	5	6	7	8	SUM	FACTOR
1	Weight		0	0	0	0	0	0	0	0	1
2	Heat Output	1		0	0.5	0	1	0	1	3.5	10
3	Safety	1	1		1	1	1	1	1	7	30
4	Useability	1	0.5	0		0.5	0.5	0	1	3.5	10
5	Cost	1	1	0	0.5		1	0	1	4.5	15
6	Power Output	1	0	0	0.5	0		1	1	3.5	10
7	Reliability	1	1	0	1	1	0		1	5	20
8	Size	1	0	0	0	0	0	0		1	4

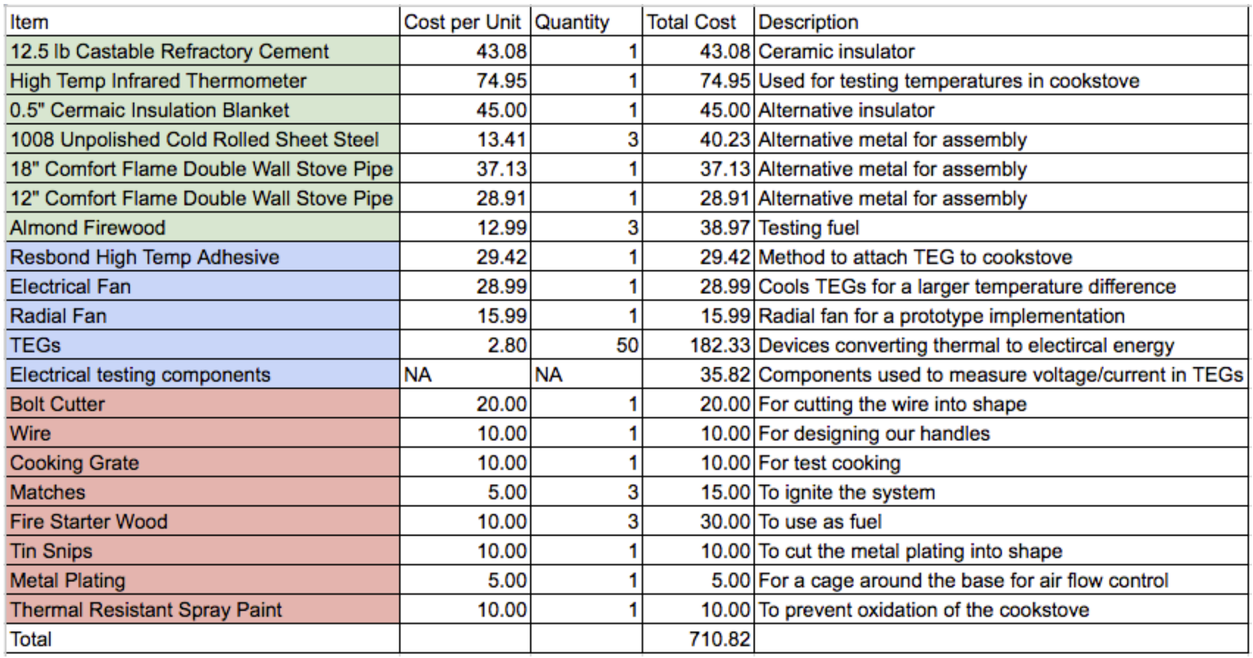
APPENDIX C: Budget and Timeline

Table C.1: Time Table for Prototype Completion



#	Assignments	1/4	1/11	1/18	1/25	2/1	2/8	2/15	2/22	2/29	3/7	3/14	3/21	3/28	4/4	4/11	4/18	4/25	5/2	5/9	5/16	5/23	5/30
	Electrical																						
PE-001	Buck Charger														🟩	🟩	🟩	🟩	🟩				
PE-002	Computer Fan															🟩							
PE-003	Heatsink															🟩							
PE-005	Battery														🟩	🟩	🟩	🟩	🟩				
PE-006	Thermoelectric Unit										🟩	🟩											
PE-007	Thermal Paste										🟩	🟩											
PE-008	Circuitry	🟩	🟩	🟩																			
	Combustion Chamber																						
PC-001	Chamber														🟩	🟩	🟩	🟩	🟩				
PC-002	Ceramics														🟩	🟩	🟩	🟩	🟩	🟩			
	Outer Body/Ergonomics																						
PB-001	Steel Handles																			🟩			
PB-002	High Temperature Paint																						
PB-003	Cooking Grate																			🟩			
	Testing																						
	Thermoelectrics												🟩	🟩	🟩	🟩	🟩	🟩	🟩				
	Combustion Chamber																		🟩	🟩	🟩		

Table C.2: Team Forge Expendatures



Item	Cost per Unit	Quantity	Total Cost	Description
12.5 lb Castable Refractory Cement	43.08	1	43.08	Ceramic insulator
High Temp Infrared Thermometer	74.95	1	74.95	Used for testing temperatures in cookstove
0.5" Cermaic Insulation Blanket	45.00	1	45.00	Alternative insulator
1008 Unpolished Cold Rolled Sheet Steel	13.41	3	40.23	Alternative metal for assembly
18" Comfort Flame Double Wall Stove Pipe	37.13	1	37.13	Alternative metal for assembly
12" Comfort Flame Double Wall Stove Pipe	28.91	1	28.91	Alternative metal for assembly
Almond Firewood	12.99	3	38.97	Testing fuel
Resbond High Temp Adhesive	29.42	1	29.42	Method to attach TEG to cookstove
Electrical Fan	28.99	1	28.99	Cools TEGs for a larger temperature difference
Radial Fan	15.99	1	15.99	Radial fan for a prototype implementation
TEGs	2.80	50	182.33	Devices converting thermal to electircal energy
Electrical testing components	NA	NA	35.82	Components used to measure voltage/current in TEGs
Bolt Cutter	20.00	1	20.00	For cutting the wire into shape
Wire	10.00	1	10.00	For designing our handles
Cooking Grate	10.00	1	10.00	For test cooking
Matches	5.00	3	15.00	To ignite the system
Fire Starter Wood	10.00	3	30.00	To use as fuel
Tin Snips	10.00	1	10.00	To cut the metal plating into shape
Metal Plating	5.00	1	5.00	For a cage around the base for air flow control
Thermal Resistant Spray Paint	10.00	1	10.00	To prevent oxidation of the cookstove
Total			710.82	

APPENDIX D: FEA Diagrams and Calculations

Radiation Temperature Drop Inside Combust Chamber

Assume Diffuse, Gray

(1) $$q_{1,2} = \frac{\sigma A_1 F_{1\to2}\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2}\left(\frac{r_1}{r_2}\right)}$$ "radiation"

$$T_2^4 = T_1^4 - \left[\frac{q_{1,2}\left(\frac{1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2}\right)\left(\frac{r_1}{r_2}\right)}{\sigma A_1 F_{1\to2}}\right]$$

$T_2 = 687°C$

Variables:

$\sigma = 5.67 * 10^{-8}$

$A_1 = \pi r^2 = .018 m^2$

$r_1 = 3in = .076 m$

$F_{1\to2} = .705$

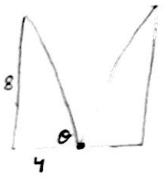
$T_1 = 1000°C$

$r_2 = 4in = .102 m$

$\varepsilon_1 = 1$

(2) $\varepsilon_2 = .06$

(3) $q_{1,2} = 2500 A_1 = 45 W$



$\tan\theta = \frac{8}{4}$

$\theta = 63.4°$

$2\theta = 126.9°$

$F_{1\to2} = \frac{126.9}{180} = .705$

Figure D.1: Detailed Calculations for Heat Dissipation Part 1

Hand Calculation Model

Heat rate in Cylindrical Wall

(1) $q = \frac{2\pi L k \Delta T}{\ln(r_2/r_1)}$ $^{\boxed{a}}$ "Conduction"

Solving for T_f

$$-\left[\frac{q \ln(r_2/r_1)}{2\pi L R}\right] + T_0 = T_f$$

Inside to outside ceramic conduction:

$T_f = 687°C - 10.88 = 676°C$

Through the inner steel layer conduction:

$T_f = 676.1°C - .011°C = 676.09°C$

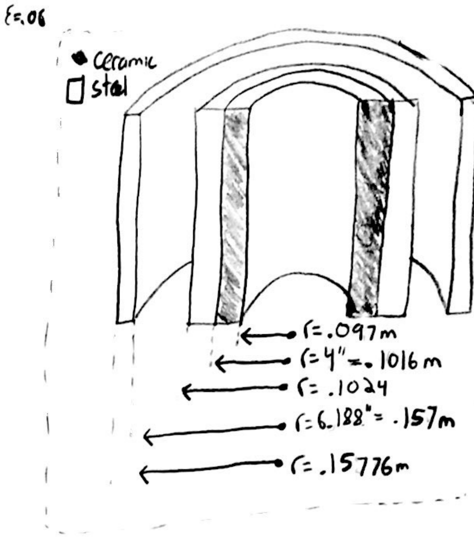
Radiation Through Steel Walls:

$$T_F^4 = T_0^4 - \left[\frac{q\left(\frac{1}{\varepsilon} + \frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{r_1}{r_2}\right)}{\sigma A_0 F_{1\to2}}\right]$$

$T_F = 659°C$

Conduction through outer steel wall:

$T_f = 659 - .007 = 659°C$



Variables Known:

$T_\infty = 23°C$

$t_{steel} = .03in = .000762m$

$t_{ceramic} = 5mm = .005m$

$L = .3048m = 12"$

(4) $k_{steel} = 16.2 \frac{W}{mK}$

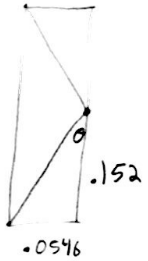
(3) $k_{ceramic} = .1 \frac{W}{mK}$

$T_0 = 687°C$

$q = 45\ W$

(5) $\varepsilon_{steel} = .57$

$A_0 = 2\pi r_{steel} L = .196m^2$



$\tan(\theta) = \frac{.0546}{6} = .359$

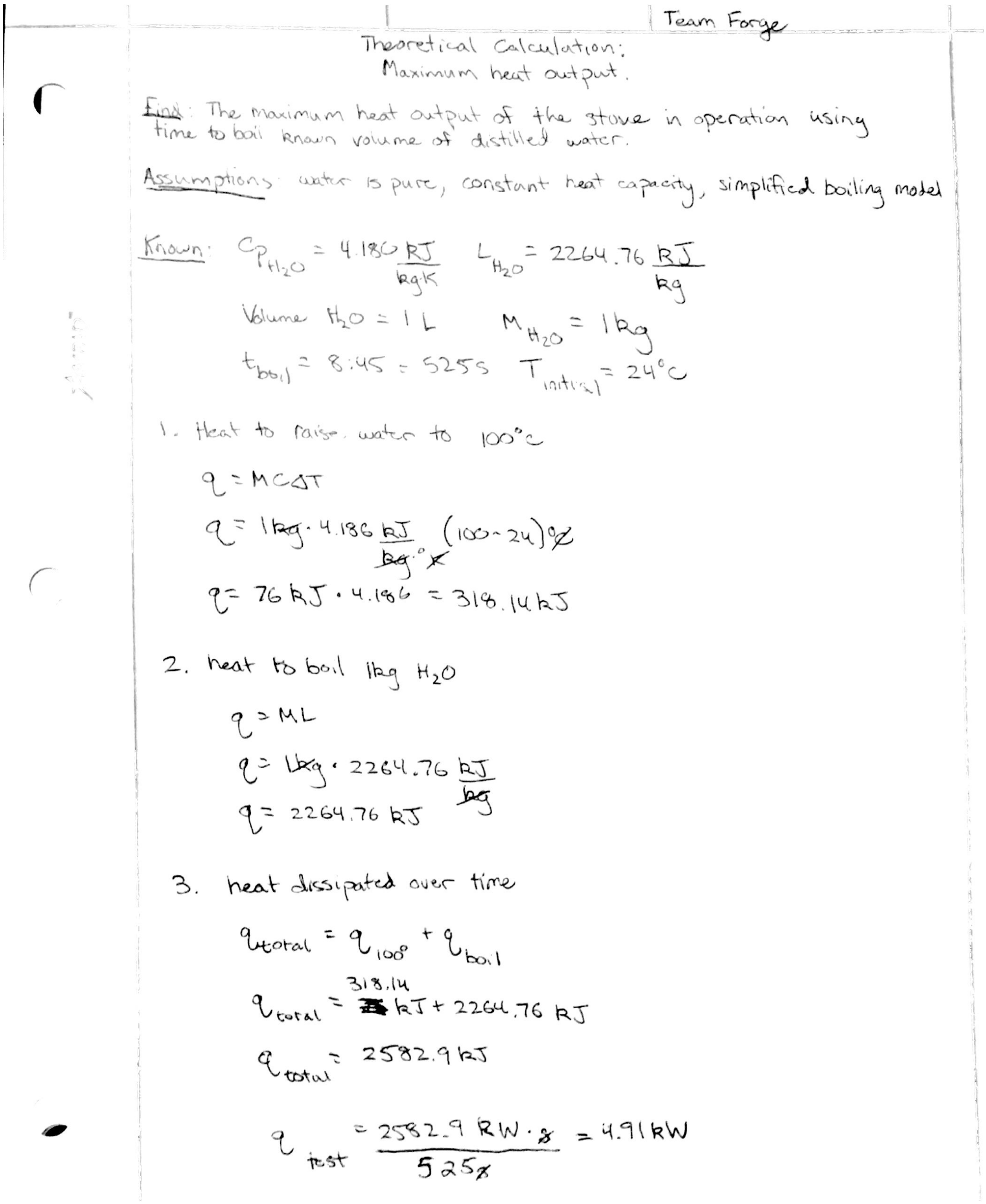
$\theta = 19.75°$

$2\theta = 39.5°$

$1 - f_{o\to f} = \frac{39.5}{180} = .219$

$f_{o\to f} = .781$

Figure D.2: Detailed Calculations for Heat Dissipation Part 2



Team Forge

Theoretical Calculation:
Maximum heat output.

Find: The maximum heat output of the stove in operation using time to boil known volume of distilled water.

Assumptions: water is pure, constant heat capacity, simplified boiling model

Known: $Cp_{H_2O} = 4.186 \frac{kJ}{kg \cdot K}$ $L_{H_2O} = 2264.76 \frac{kJ}{kg}$

Volume $H_2O = 1\ L$ $M_{H_2O} = 1\ kg$

$t_{boil} = 8{:}45 = 525\ s$ $T_{initial} = 24°C$

1. Heat to raise water to 100°c

$q = MC\Delta T$

$q = 1\ \cancel{kg} \cdot 4.186 \frac{kJ}{\cancel{kg} \cdot \cancel{°K}} (100-24)\cancel{°K}$

$q = 76\ kJ \cdot 4.186 = 318.14\ kJ$

2. heat to boil 1 kg H_2O

$q = ML$

$q = 1\ \cancel{kg} \cdot 2264.76 \frac{kJ}{\cancel{kg}}$

$q = 2264.76\ kJ$

3. heat dissipated over time

$q_{total} = q_{100°} + q_{boil}$

$q_{total} = \overset{318.14}{} kJ + 2264.76\ kJ$

$q_{total} = 2582.9\ kJ$

$q_{test} = \frac{2582.9\ kW \cdot \cancel{s}}{525\ \cancel{s}} = 4.91\ kW$

Figure D.3: Heat Output for Combustion Chamber

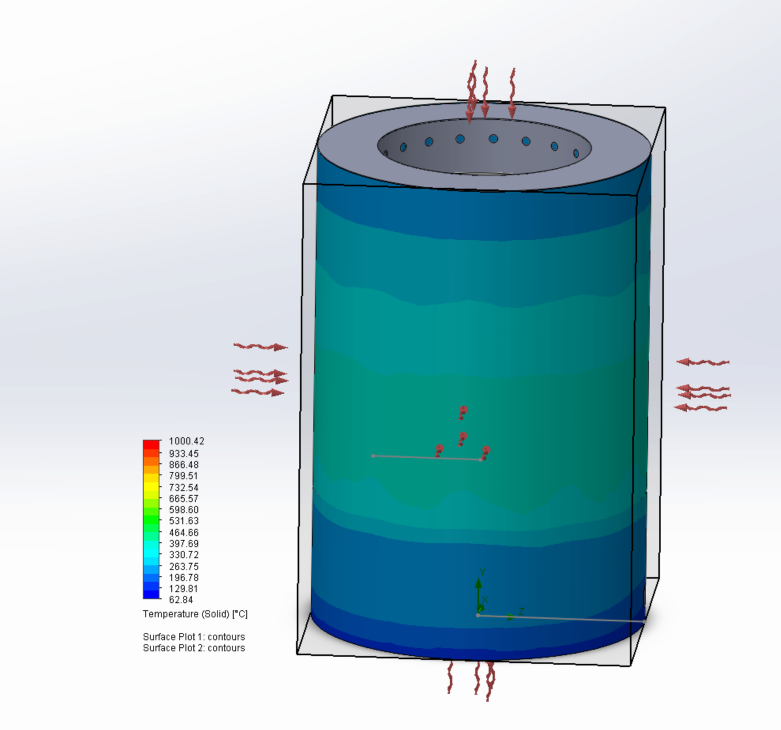


Figure D.4: Temperature distribution on outer wall of gasification chamber at 1000º Celsius

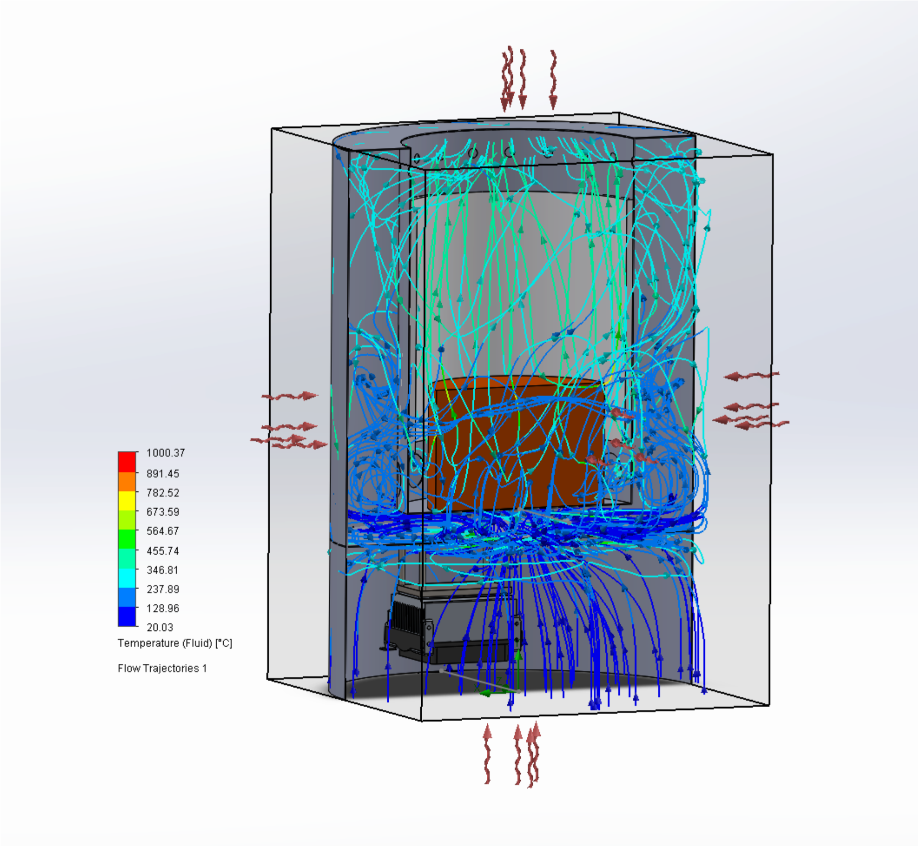


Figure D.5: Temperature and flow trajectory of gas inside our chamber at 1000º Celsius

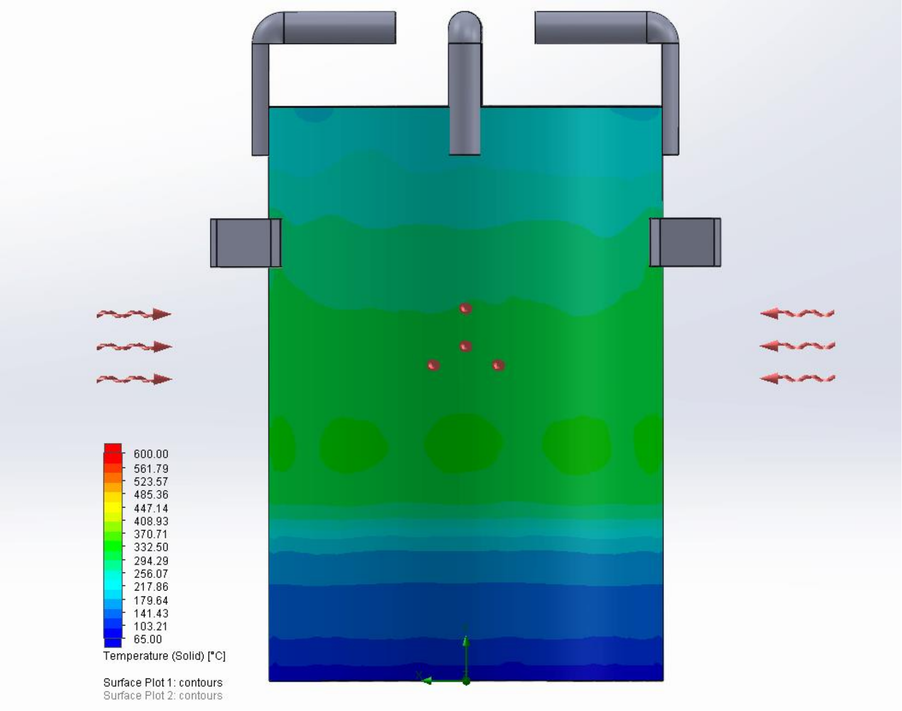


Figure D.6: Temperature distribution on outer wall of gasification chamber at 800º Celsius

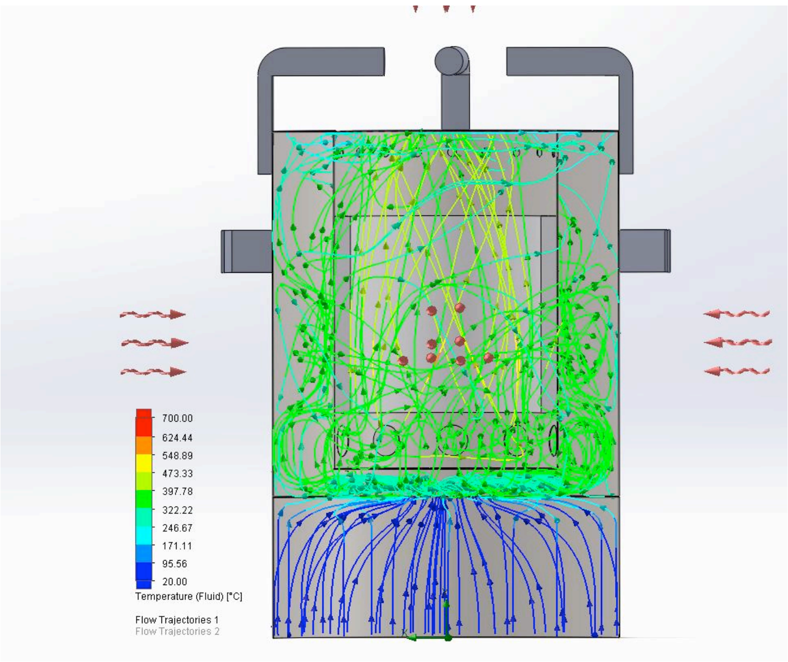


Figure D.7: Temperature and flow trajectory of gas inside our chamber at 800º Celsius

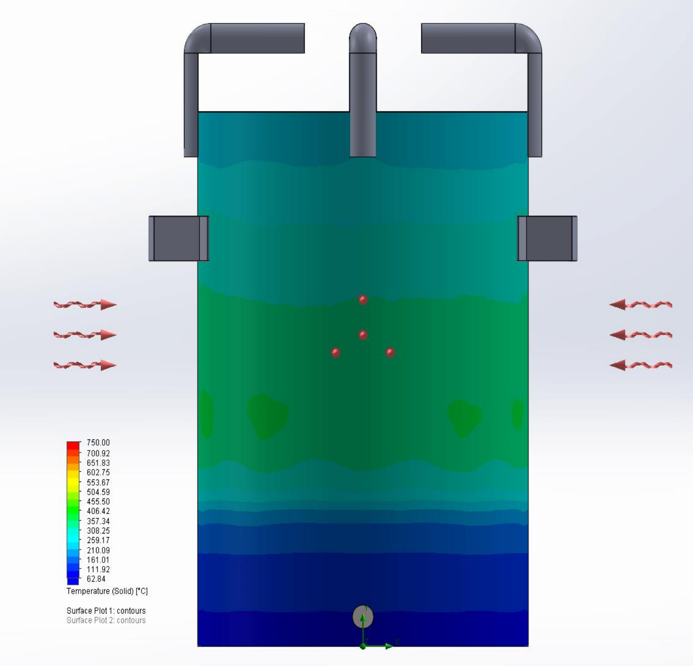


Figure D.8: Temperature distribution on outer wall of gasification chamber at 750º Celsius

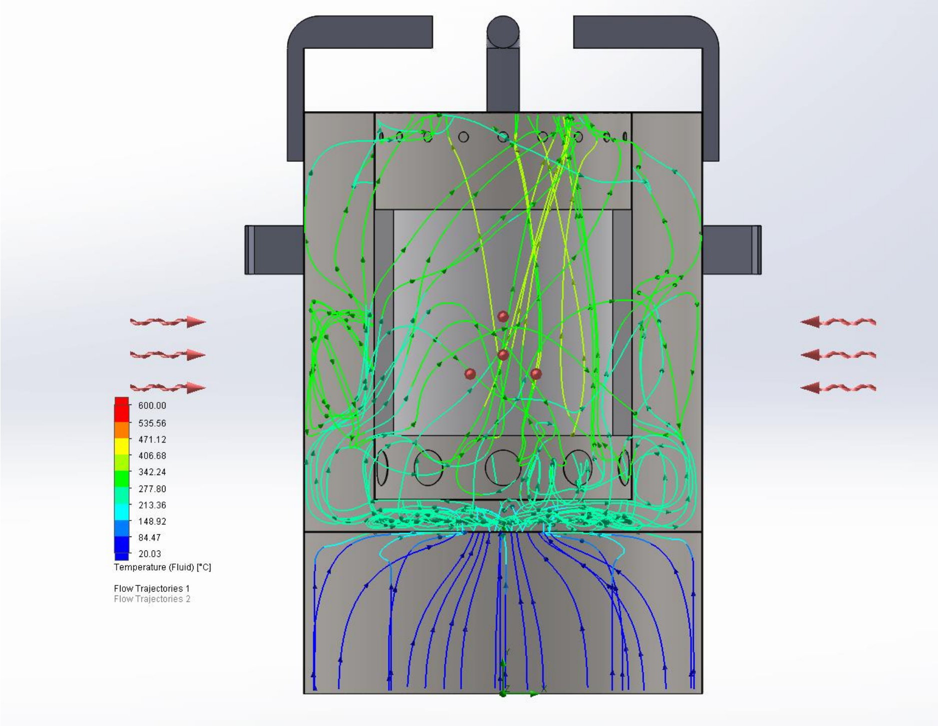


Figure D.9: Temperature and flow trajectory of gas inside our chamber at 750º Celsius

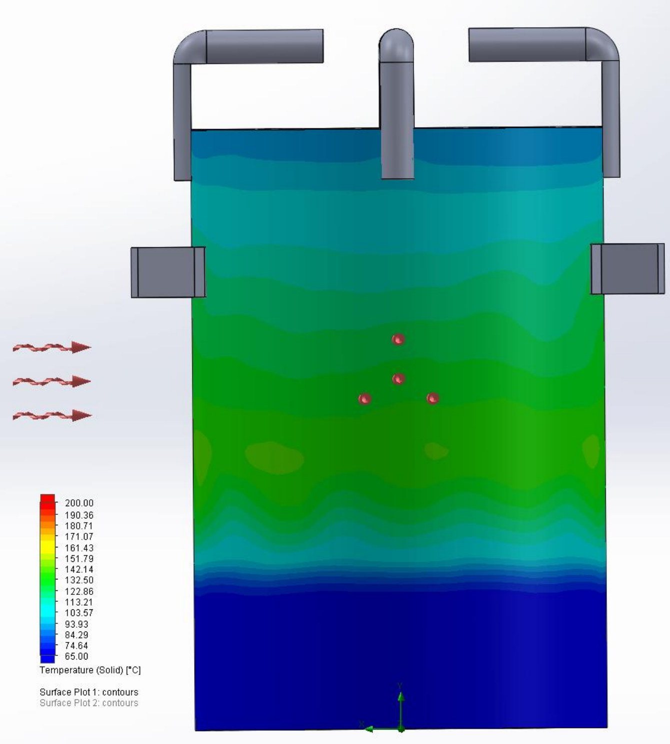


Figure D.10: Temperature distribution on outer wall of gasification chamber at 600º Celsius

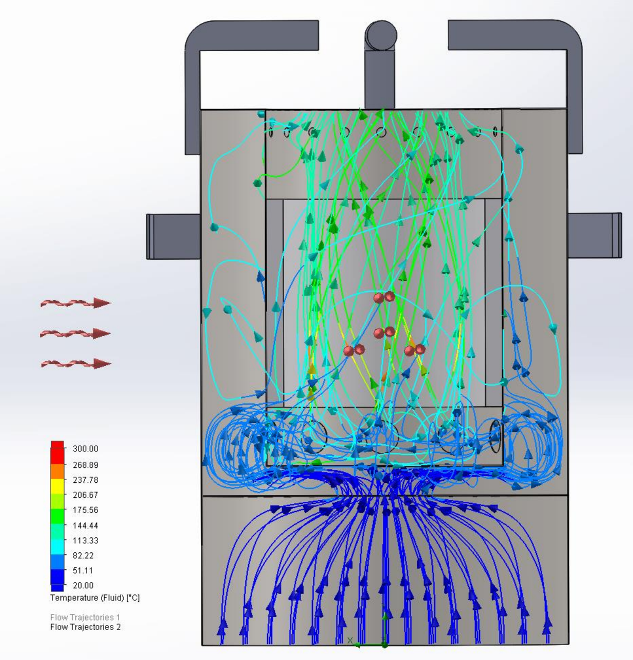
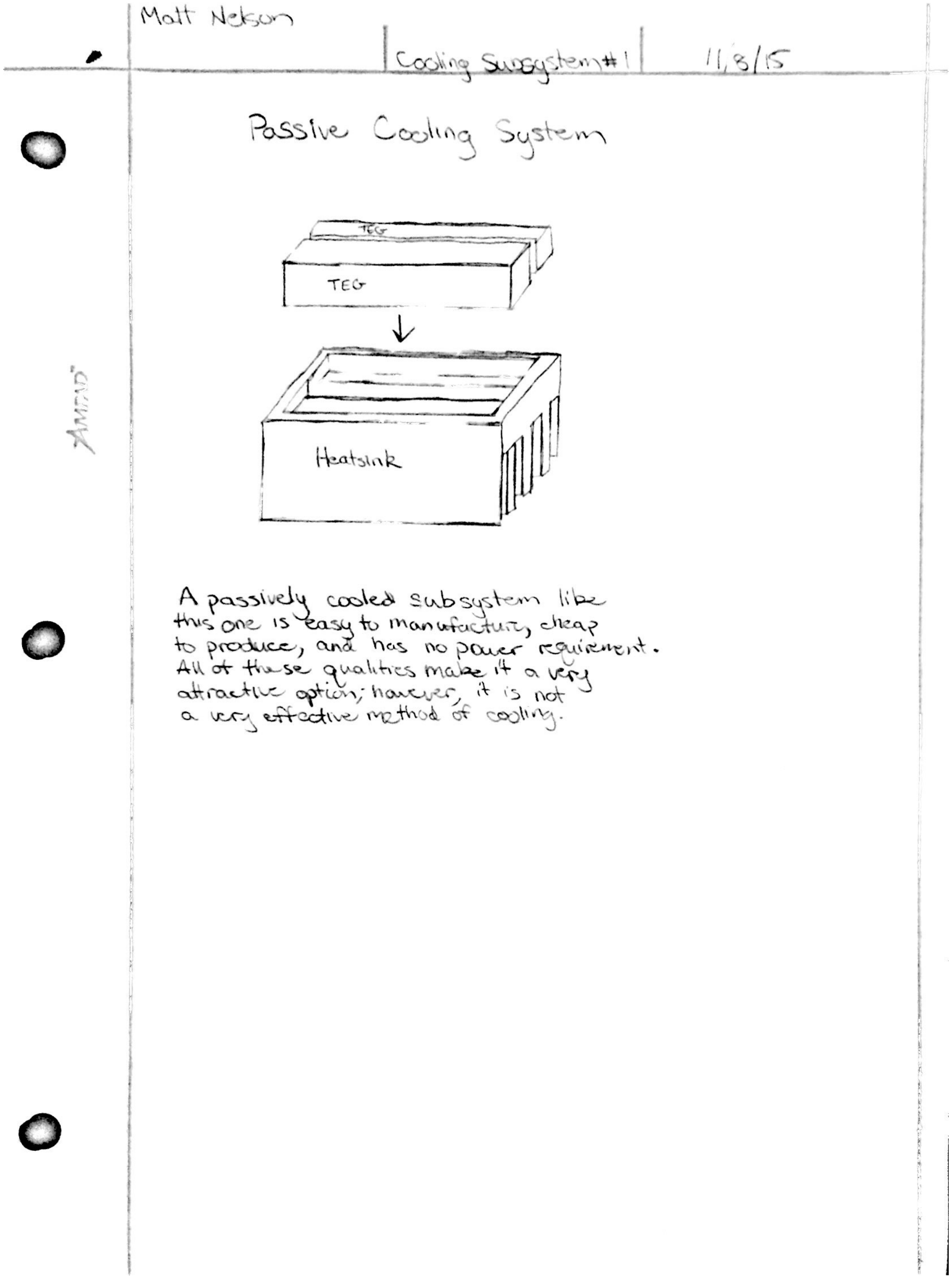


Figure D.11: Temperature and flow trajectory of gas inside our chamber at 600º Celsius

APPENDIX E: Detailed Diagrams



Matt Nelson

Cooling Subsystem#1

11/8/15

Passive Cooling System

A passively cooled subsystem like this one is easy to manufacture, cheap to produce, and has no power requirement. All of these qualities make it a very attractive option; however, it is not a very effective method of cooling.

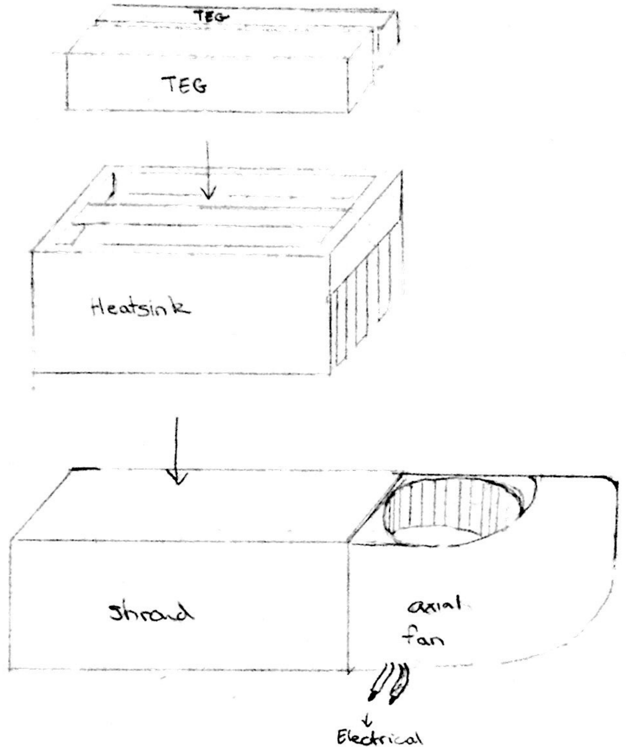
Figure E.1: Nelson Attributed Drawing 1

Matt Nelson

11/8/15

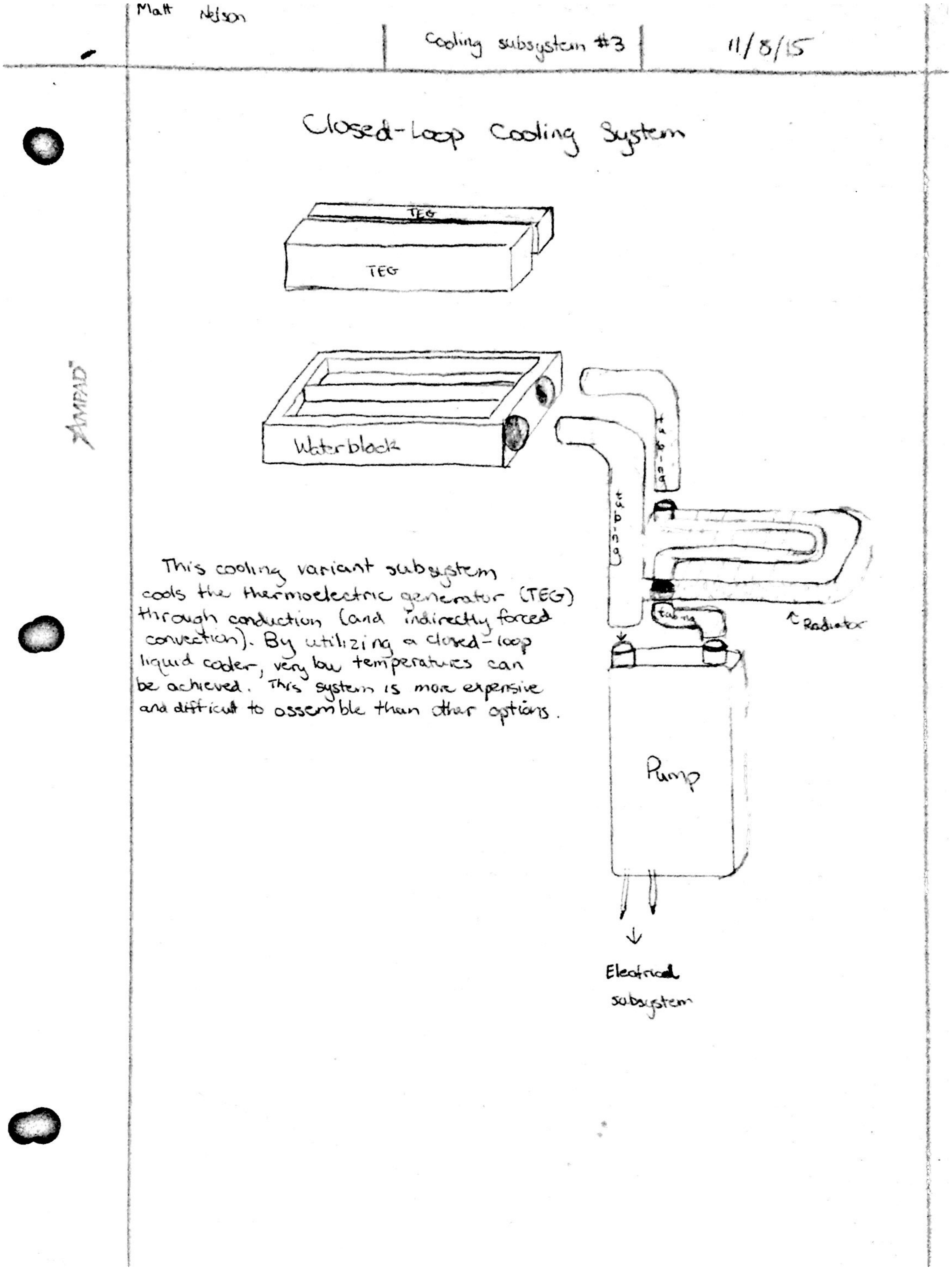
Cooling subsystem #2

Fan Cooling System



This cooling variant subsystem uses forced convection and conduction to help cool the thermoelectric generators. The axial fan draws ambient air through the shroud and by the side of the heatsink. The heatsink is heated through conduction of the hot side of the TEG and cooled by forced convection. This system would be fairly cheap to manufacture and easy to assemble.

Figure E.2: Nelson Attributed Drawing 2



Matt Nelson | Cooling subsystem #3 | 11/8/15

Closed-Loop Cooling System

This cooling variant subsystem cools the thermoelectric generator (TEG) through conduction (and indirectly forced convection). By utilizing a closed-loop liquid cooler, very low temperatures can be achieved. This system is more expensive and difficult to assemble than other options.

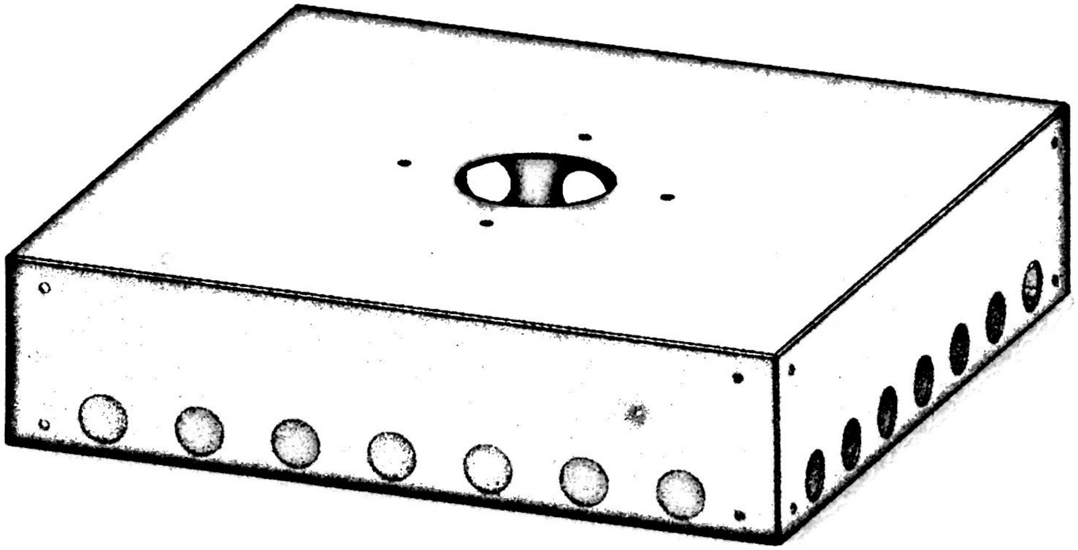
Figure E.3: Nelson Attributed Drawing 3

Isaac Stratfold

FORGE

Stove Base

4/4/16



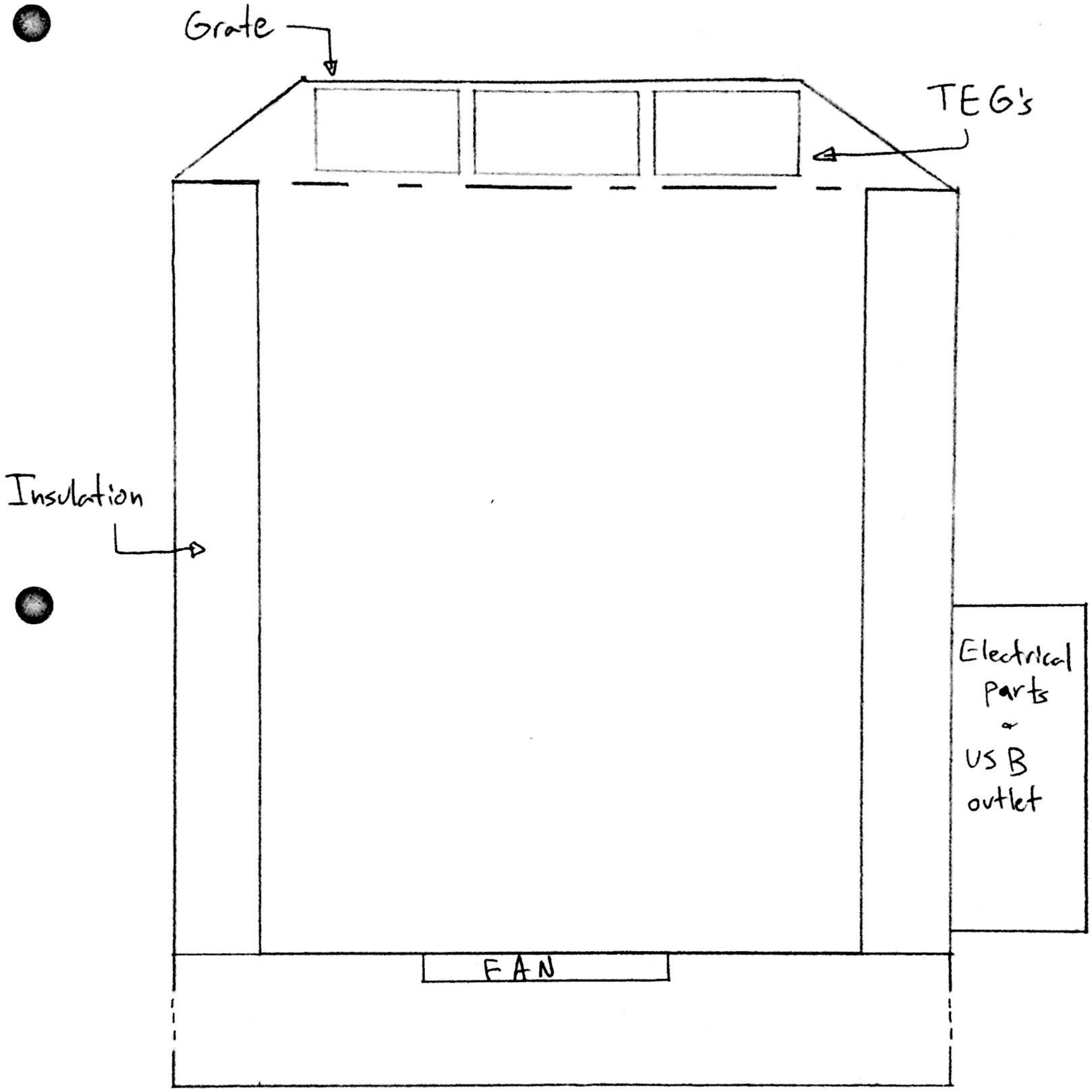
Material: 1080 Sheet Steel (weldable)

Thickness: 0.0762 cm

Description: A square base for the stove which provides adequate ventilation for the components & combustion process and suitable space for the TEG element and fans.

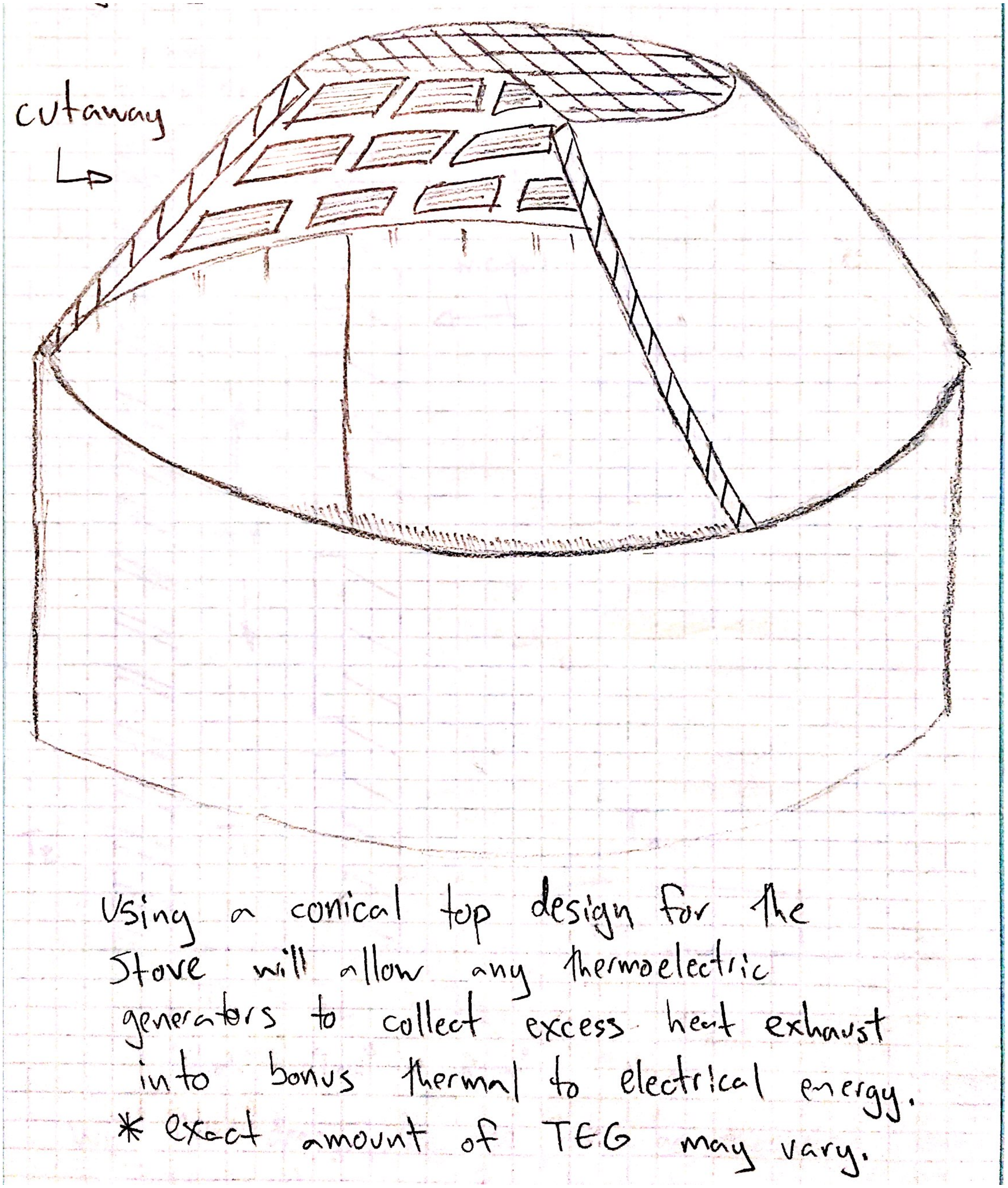
Figure E.4: Stratfold Attributed Drawing

Casing Design #1



Austin Jacobs
4/3/16

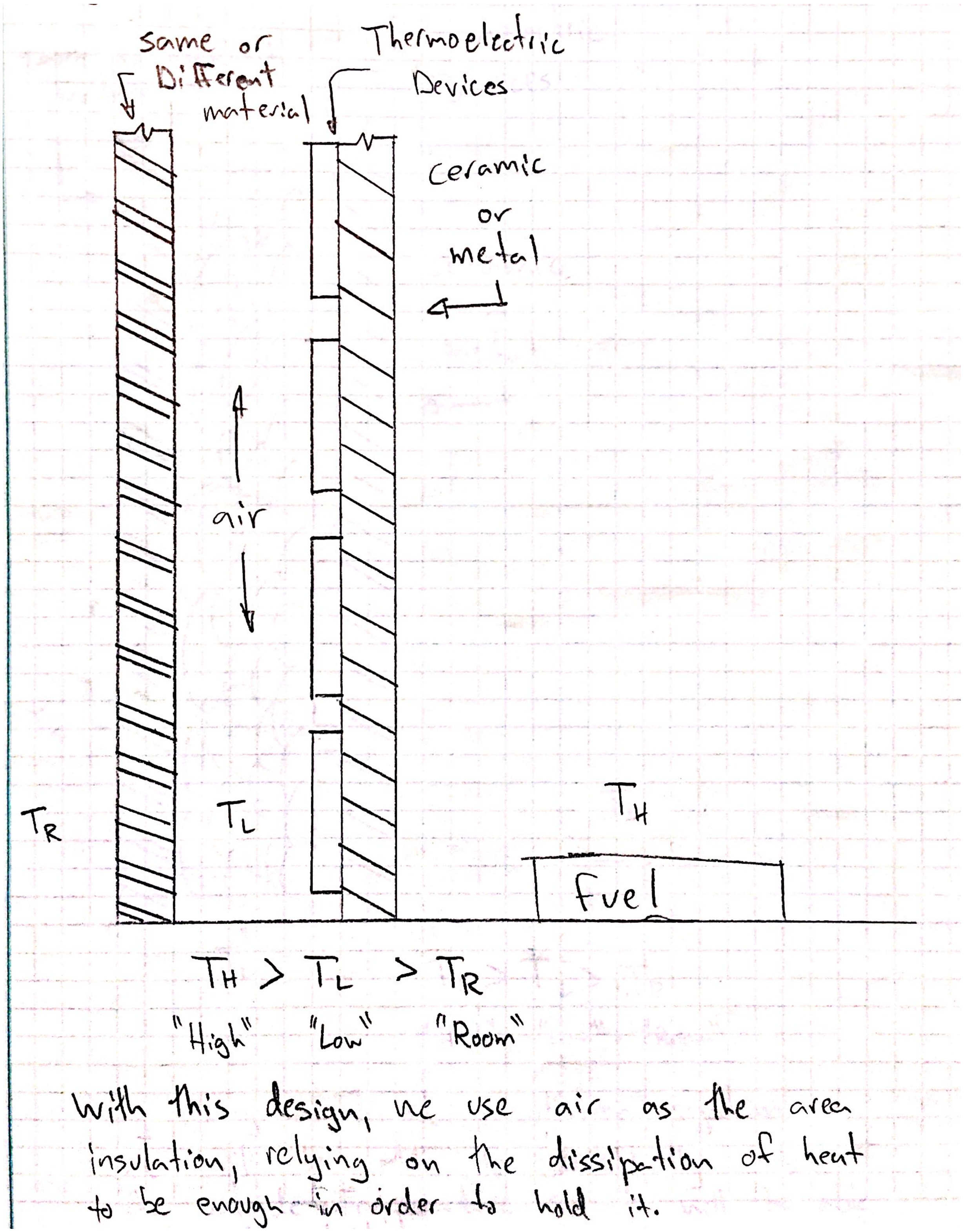
Figure E.5: Jacobs Attributed Drawing 1



Using a conical top design for the Stove will allow any thermoelectric generators to collect excess heat exhaust into bonus thermal to electrical energy.

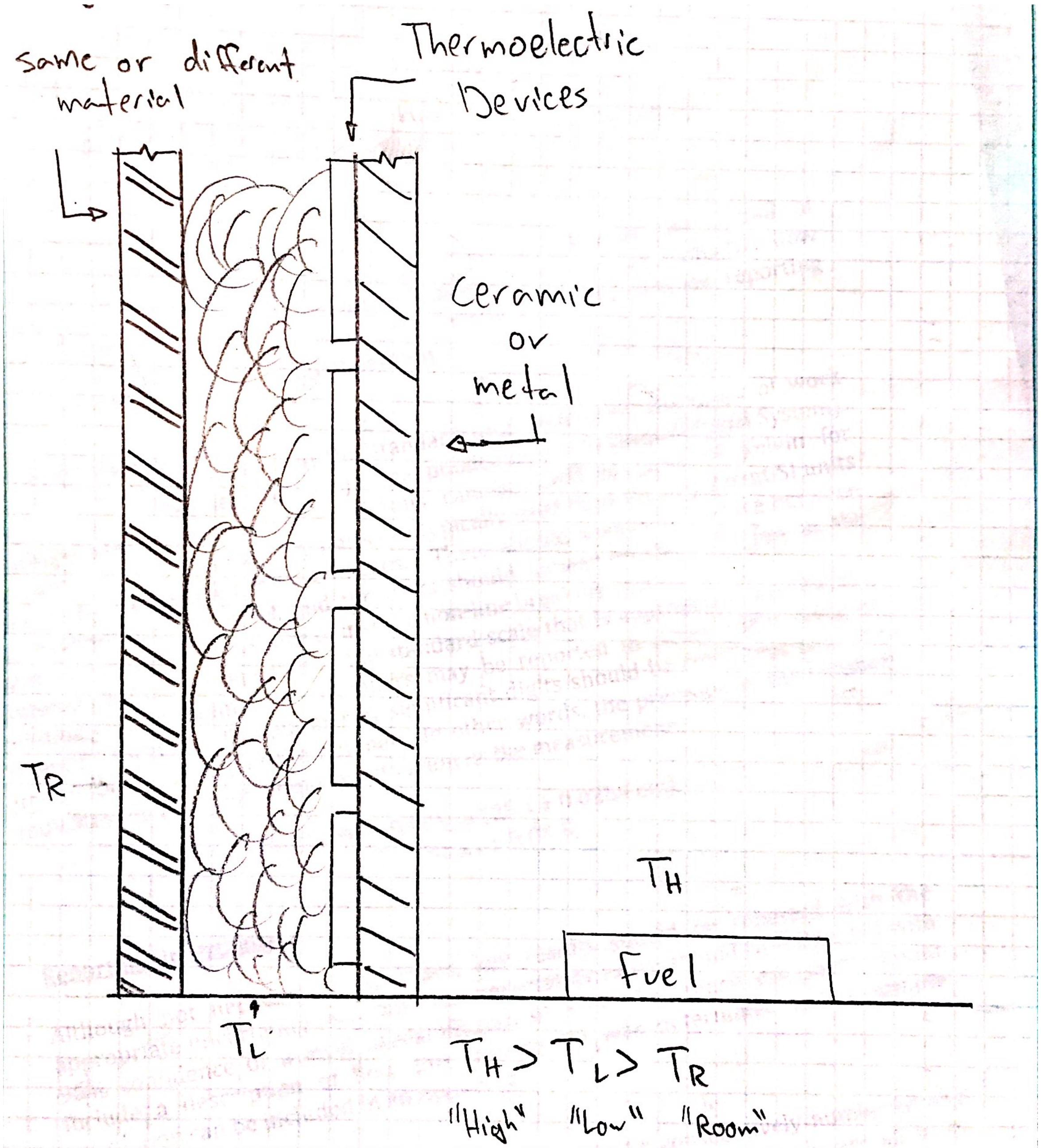
* exact amount of TEG may vary.

Figure E.6: Jacobs Attributed Drawing 2



With this design, we use air as the area insulation, relying on the dissipation of heat to be enough in order to hold it.

Figure E.7: Jacobs Attributed Drawing 3



By using a tiered insulation system, we will be able to drastically reduce the outside temperature so it will be able to be held.

Figure E.8: Jacobs Attributed Drawing 4

Split View of Cookstove

Jared Sheehy
4/4/16
Scale 1:3

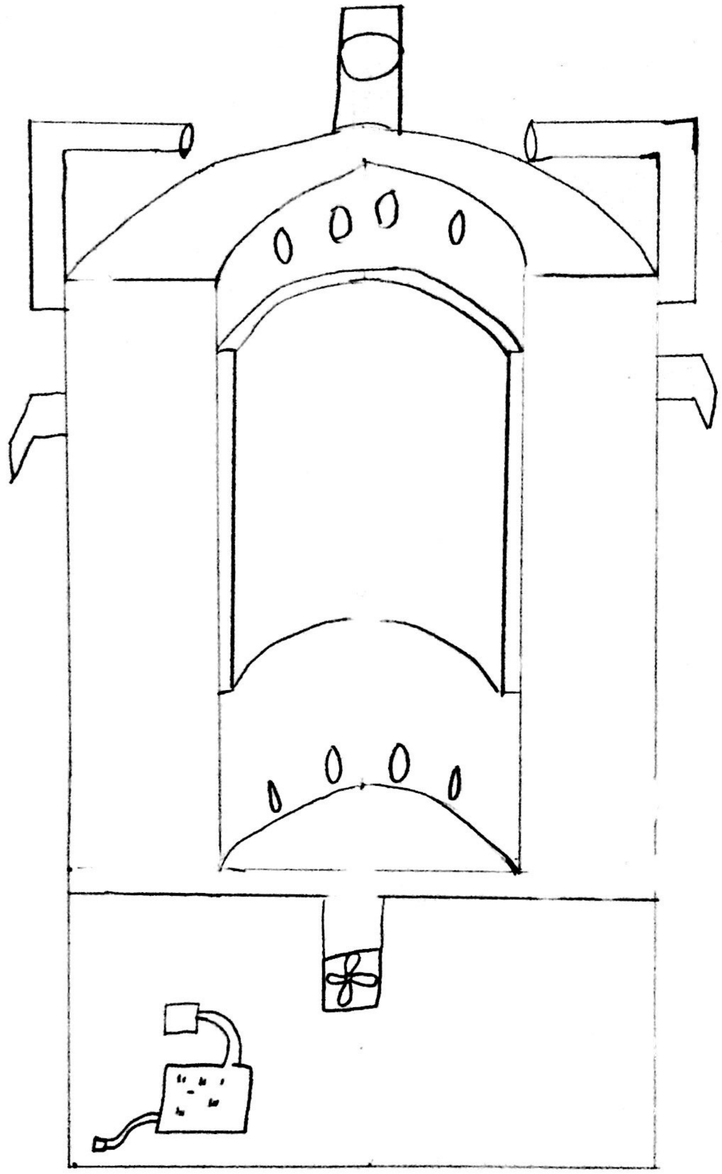
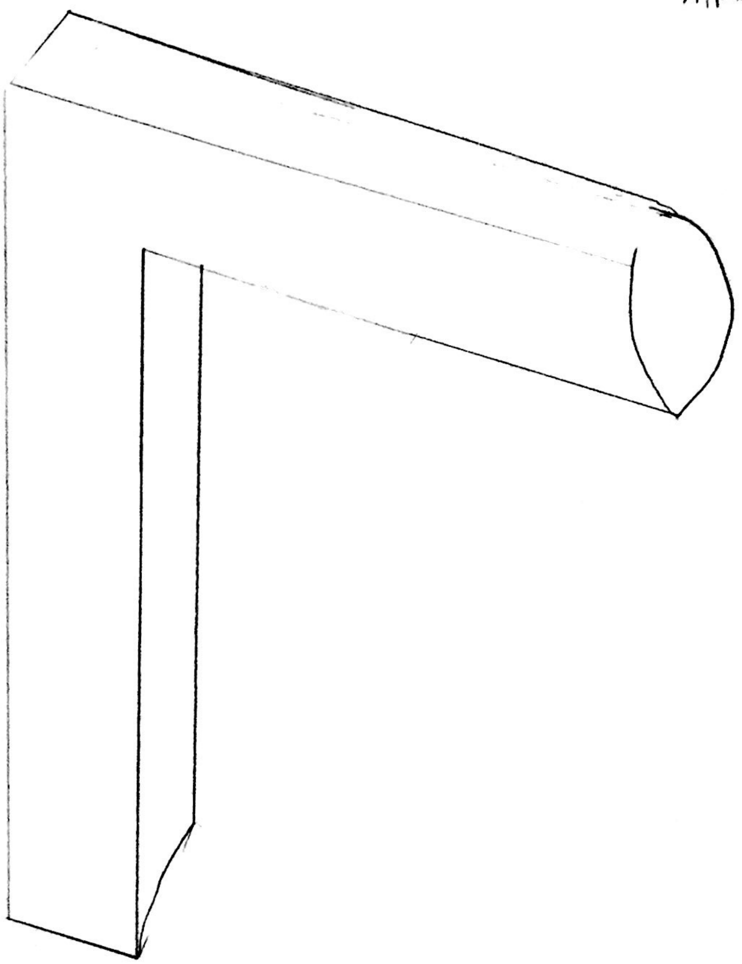


Figure E.9: Sheehy Attributed Drawing 1



Cooking Prongs

Jared Sheehy
4/4/16
Approx to Scale

Figure E.10: Sheehy Attributed Drawing 2

Handle

Jared Sheehy
4/4/16
Appx to Scale

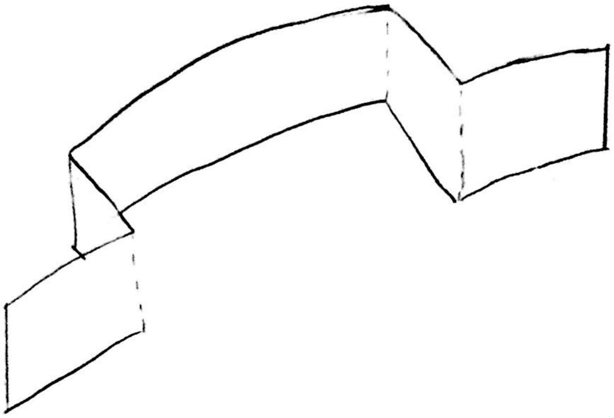


Figure E.11: Sheehy Attributed Drawing 3

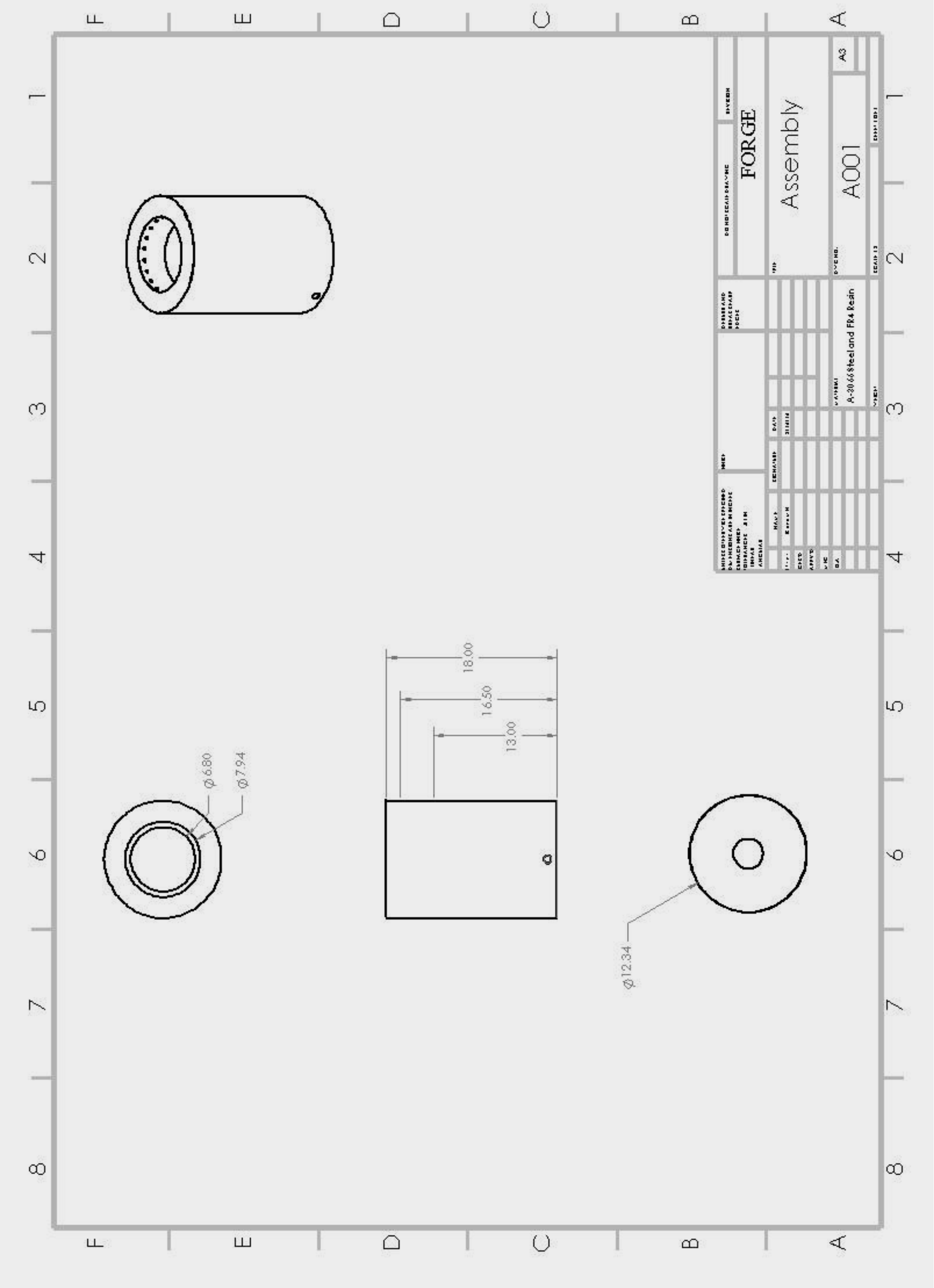


Figure E.12: Assembly Drawing

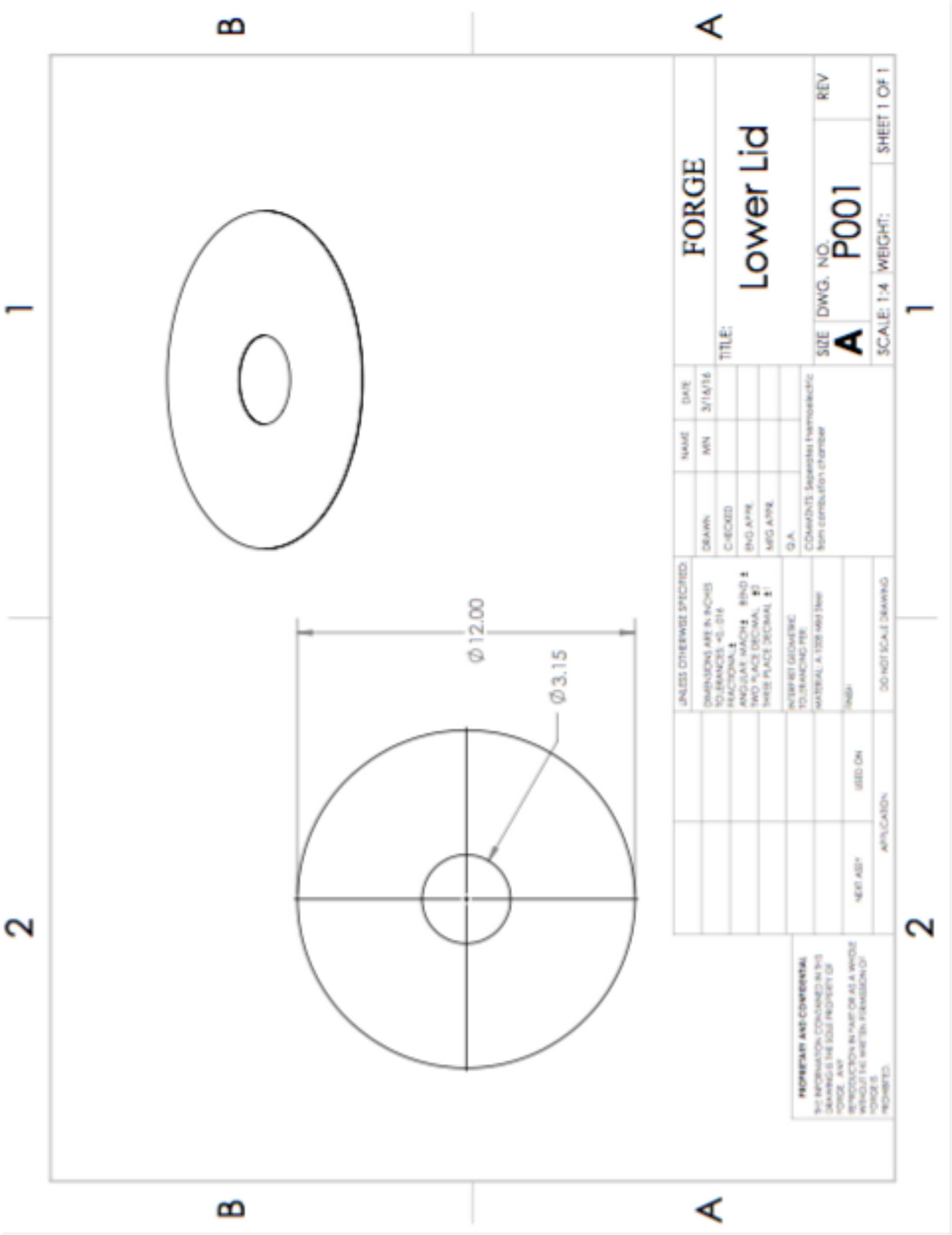


Figure E.13: Lower Lid

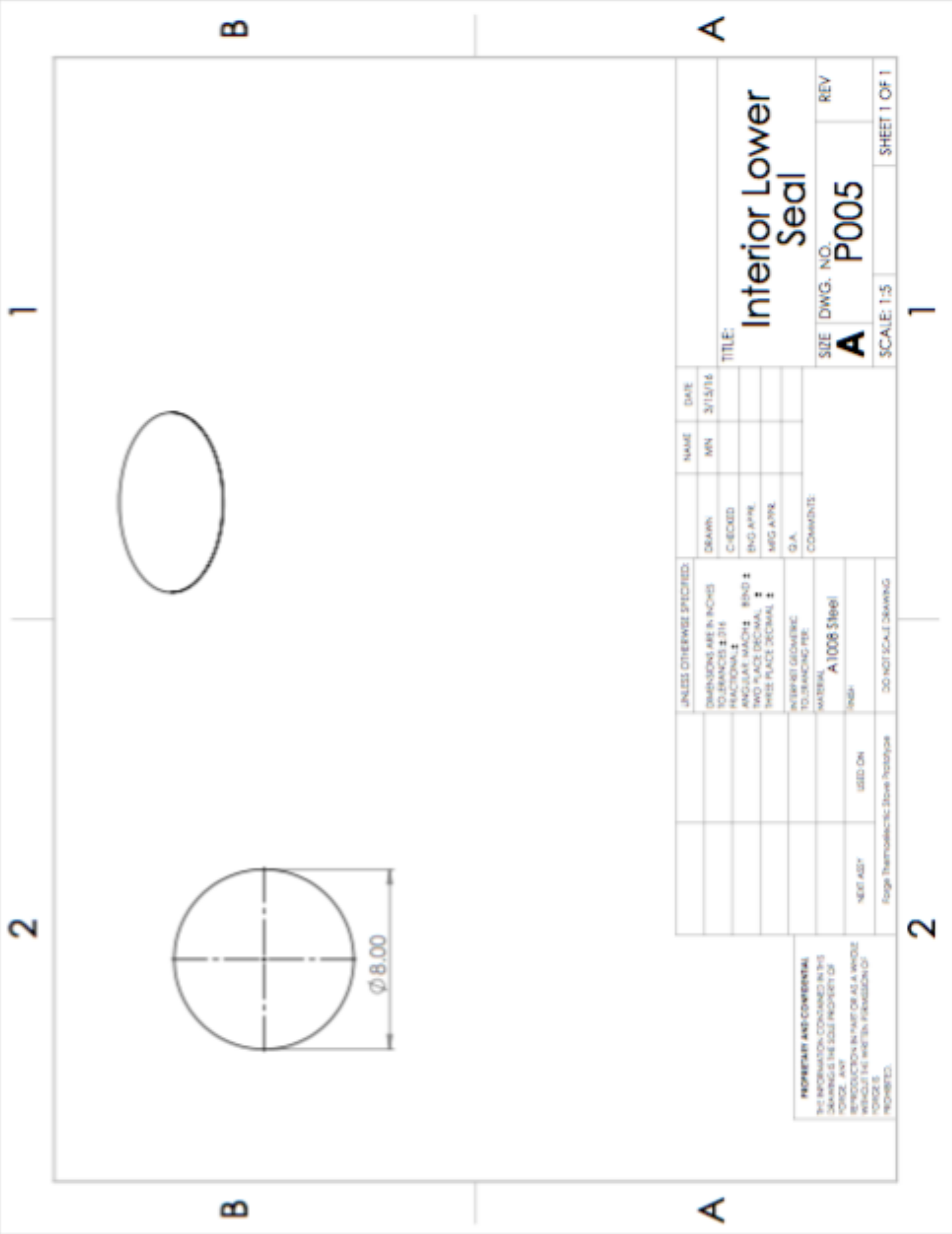


Figure E.14: Base of the Combustion Chamber

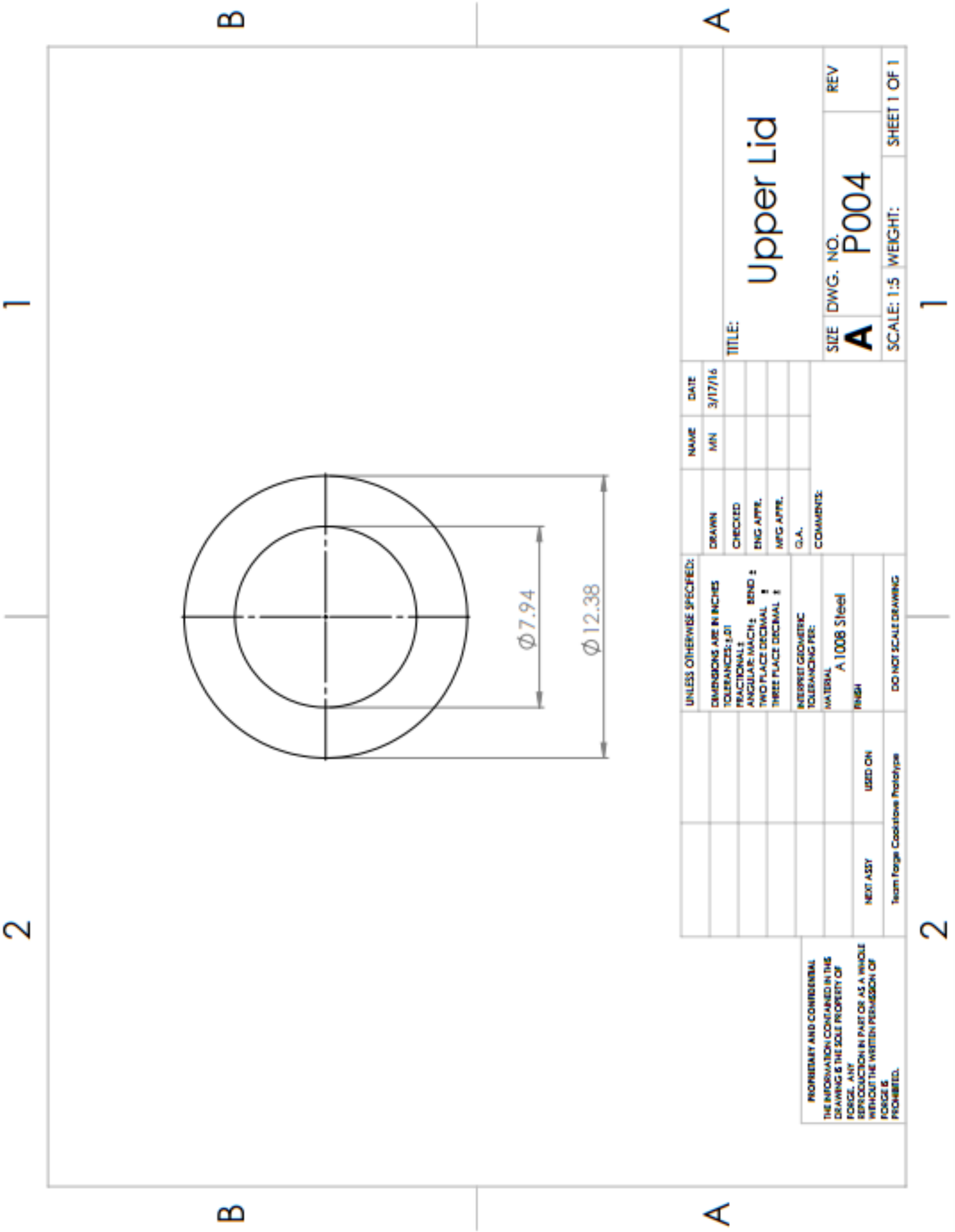


Figure E.15: Upper Lid

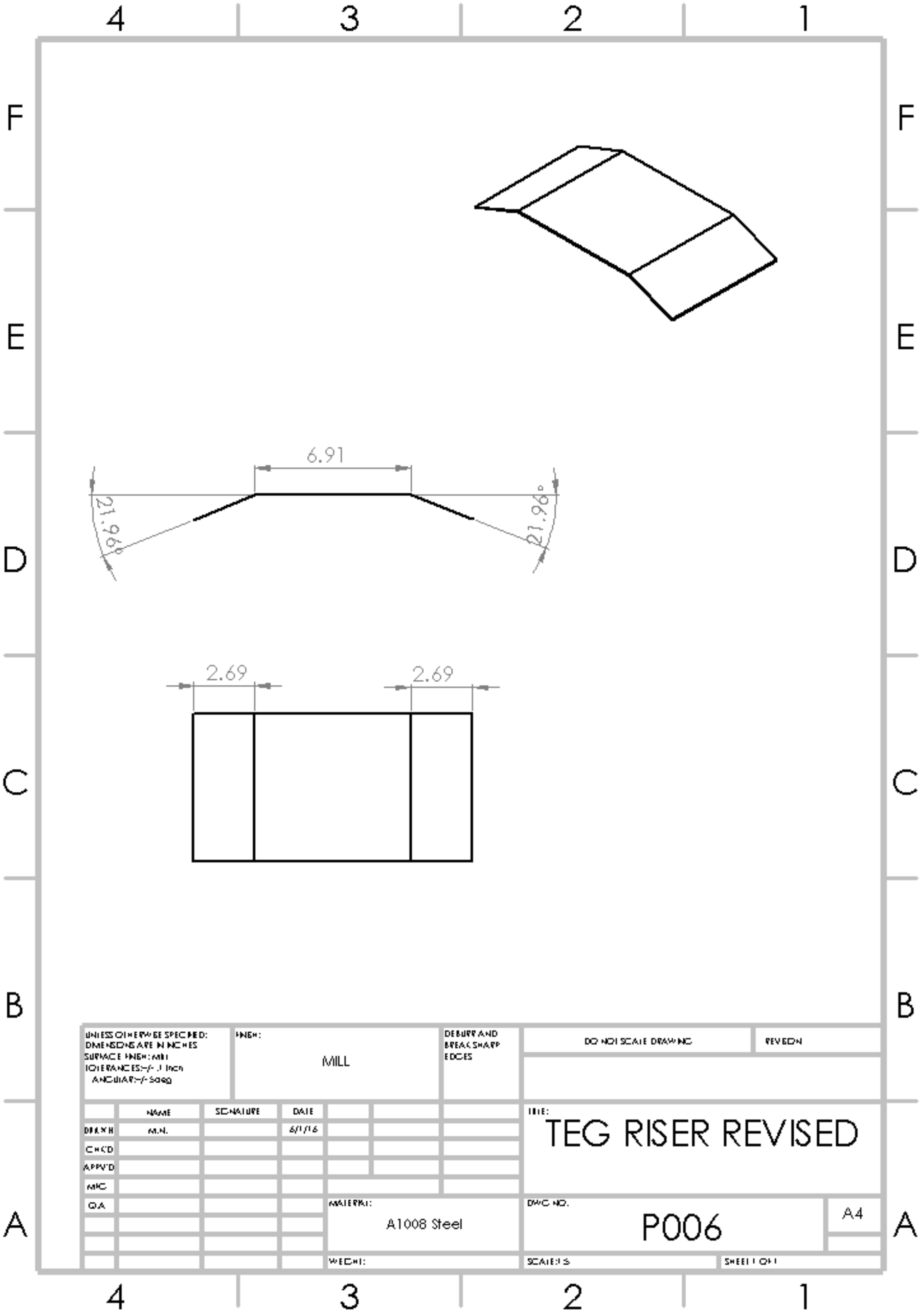
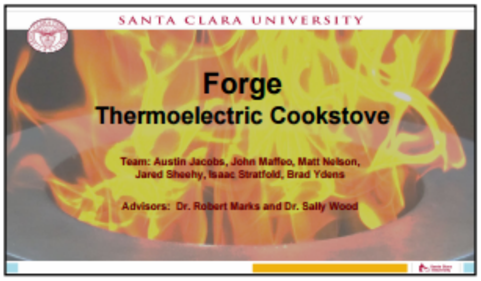


Figure E.16: TEG Holding Apparatus

APPENDIX F: Conference Presentation



SANTA CLARA UNIVERSITY

Forge
Thermoelectric Cookstove

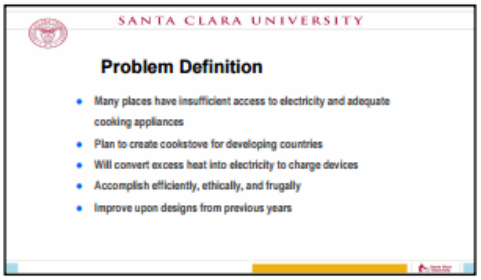
Team: Austin Jacobs, John Maffeo, Matt Nelson,
Jared Sheehy, Isaac Stratfold, Brad Ydens

Advisors: Dr. Robert Marks and Dr. Sally Wood

SANTA CLARA UNIVERSITY

Overview

1. Problem Definition, Theories, Initial Criteria, and Benchmarking
2. Market Information and Business Plan
3. Technical Overview
    a. Physical Design and Manufacturing
    b. Combustion Chamber Subsystem
    c. Thermoelectric Subsystem
4. Testing Results and Comparisons
5. Operation, Future Improvements, and Conclusion



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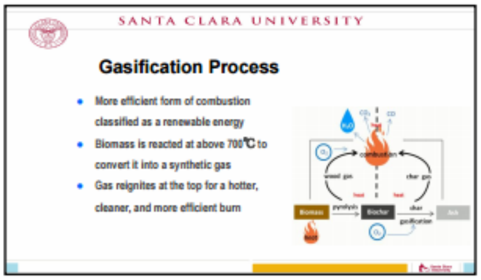
Problem Definition

- Many places have insufficient access to electricity and adequate cooking appliances
- Plan to create cookstove for developing countries
- Will convert excess heat into electricity to charge devices
- Accomplish efficiently, ethically, and frugally
- Improve upon designs from previous years



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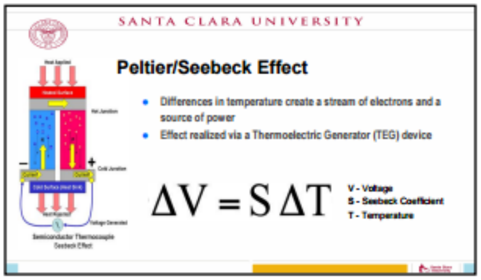
Gasification Process

- More efficient form of combustion classified as a renewable energy
- Biomass is reacted at above 700℃ to convert it into a synthetic gas
- Gas reignites at the top for a hotter, cleaner, and more efficient burn



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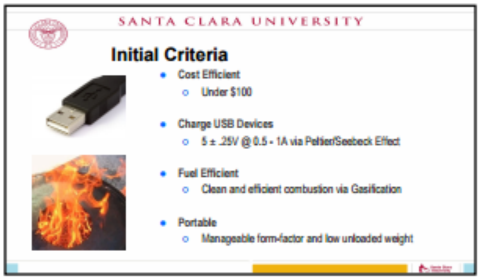
Peltier/Seebeck Effect

- Differences in temperature create a stream of electrons and a source of power
- Effect realized via a Thermoelectric Generator (TEG) device

$$\Delta V = S\,\Delta T$$

V - Voltage
S - Seebeck Coefficient
T - Temperature



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Initial Criteria

- Cost Efficient
    - Under $100
- Charge USB Devices
    - 5 ± .25V @ 0.5 - 1A via Peltier/Seebeck Effect
- Fuel Efficient
    - Clean and efficient combustion via Gasification
- Portable
    - Manageable form-factor and low unloaded weight

Figure F.1: Senior Design Presentation Slides

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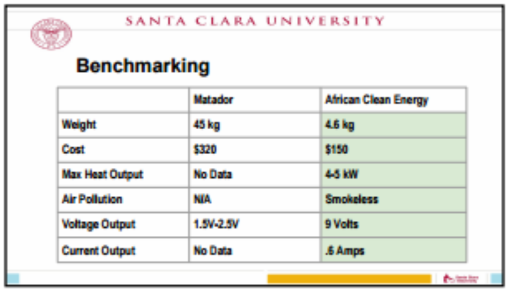
Similar Products

Matador

BioLite

African Clean Energy



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Benchmarking

	Matador	African Clean Energy
Weight	45 kg	4.6 kg
Cost	$320	$150
Max Heat Output	No Data	4-5 kW
Air Pollution	N/A	Smokeless
Voltage Output	1.5V-2.5V	9 Volts
Current Output	No Data	.6 Amps

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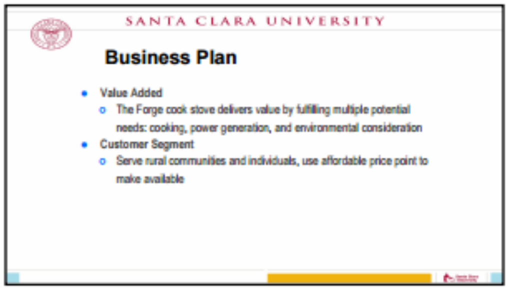
Market

Percent of Population with access to Power in IDB Member Countries

- Impoverished with limited access to power
- South/Central America
- Nicaragua
  - High need, low electrification in northern region
  - Majority of people have cellphones
  - Subsidies lead to favorable business environment
- Multiple possible business models: sell units or go to course-based model



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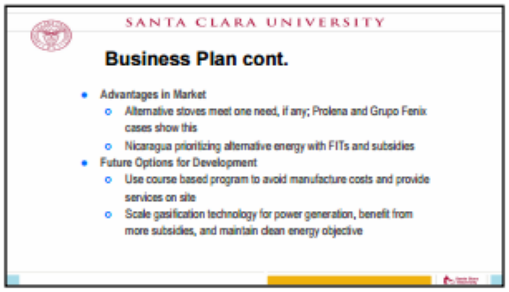
Business Plan

- Value Added
  - The Forge cook stove delivers value by fulfilling multiple potential needs: cooking, power generation, and environmental consideration
- Customer Segment
  - Serve rural communities and individuals, use affordable price point to make available



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Business Plan cont.

- Advantages in Market
  - Alternative stoves meet one need, if any; Prolena and Grupo Fenix cases show this
  - Nicaragua prioritizing alternative energy with FITs and subsidies
- Future Options for Development
  - Use course based program to avoid manufacture costs and provide services on site
  - Scale gasification technology for power generation, benefit from more subsidies, and maintain clean energy objective

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Physical Design

- Intended to Satisfy Criteria
  - Frugality
  - Weight
  - Manufacturability
- Cylindrical Design
  - Simplistic and elegant
  - Unifies elements
  - Promotes gasification

Figure F.1 cont.: Senior Design Presentation Slides

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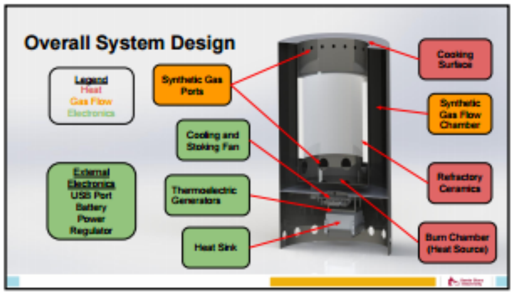
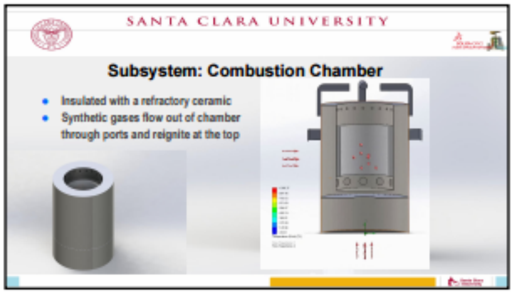
Manufacturing

- Metalwork
  - Rolling - done by hand
  - Welding - done by hand
  - Laser cutting - computer aided



Overall System Design



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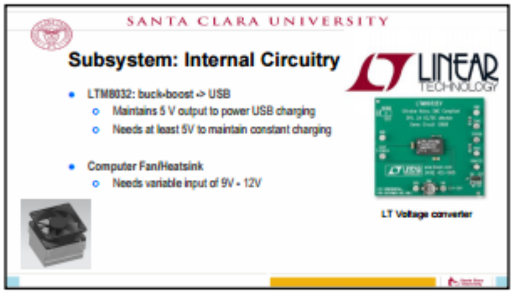
Subsystem: Combustion Chamber

- Insulated with a refractory ceramic
- Synthetic gases flow out of chamber through ports and reignite at the top



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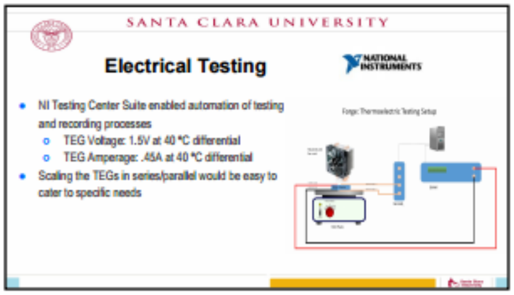
Subsystem: Internal Circuitry

- LTM8032: buck-boost -> USB
  - Maintains 5 V output to power USB charging
  - Needs at least 5V to maintain constant charging
- Computer Fan/Heatsink
  - Needs variable input of 9V - 12V

LT Voltage converter



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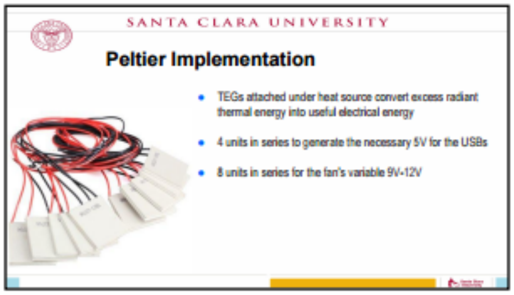
Electrical Testing

- NI Testing Center Suite enabled automation of testing and recording processes
  - TEG Voltage: 1.5V at 40 °C differential
  - TEG Amperage: .45A at 40 °C differential
- Scaling the TEGs in series/parallel would be easy to cater to specific needs



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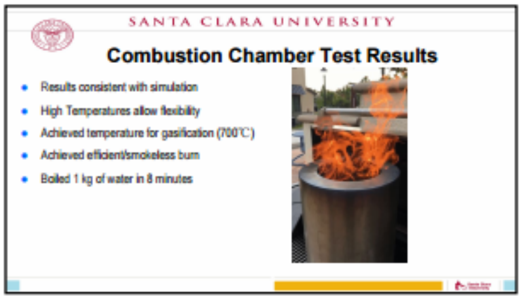
Peltier Implementation

- TEGs attached under heat source convert excess radiant thermal energy into useful electrical energy
- 4 units in series to generate the necessary 5V for the USBs
- 8 units in series for the fan's variable 9V-12V

Figure F.1 cont.: Senior Design Presentation Slides



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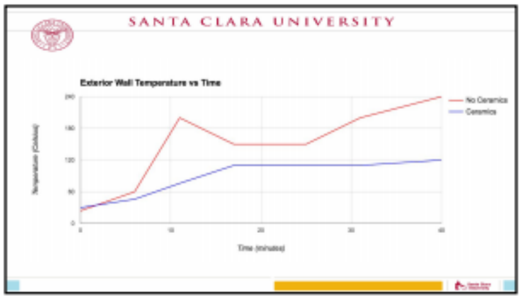
Combustion Chamber Test Results

- Results consistent with simulation
- High Temperatures allow flexibility
- Achieved temperature for gasification (700℃)
- Achieved efficient/smokeless burn
- Boiled 1 kg of water in 8 minutes



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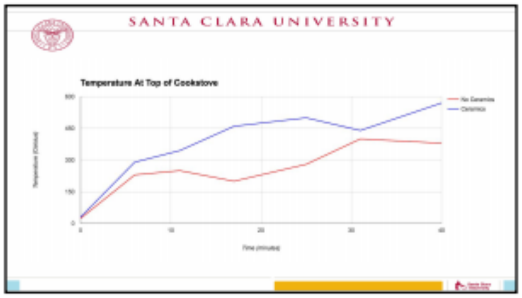

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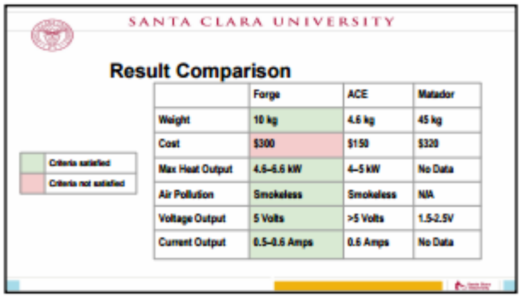

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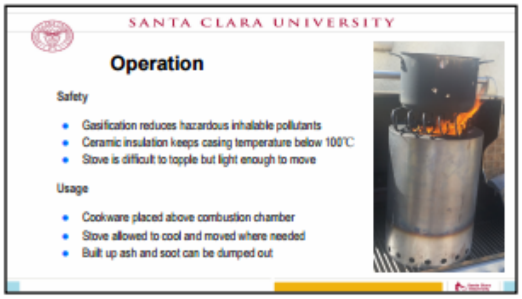
Result Comparison

🟩	Criteria satisfied
🟥	Criteria not satisfied

	Forge	ACE	Matador
Weight	10 kg	4.6 kg	45 kg
Cost	$300	$150	$320
Max Heat Output	4.6–6.6 kW	4–5 kW	No Data
Air Pollution	Smokeless	Smokeless	N/A
Voltage Output	5 Volts	>5 Volts	1.5-2.5V
Current Output	0.5–0.6 Amps	0.6 Amps	No Data



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Operation

Safety

- Gasification reduces hazardous inhalable pollutants
- Ceramic insulation keeps casing temperature below 100℃
- Stove is difficult to topple but light enough to move

Usage

- Cookware placed above combustion chamber
- Stove allowed to cool and moved where needed
- Built up ash and soot can be dumped out

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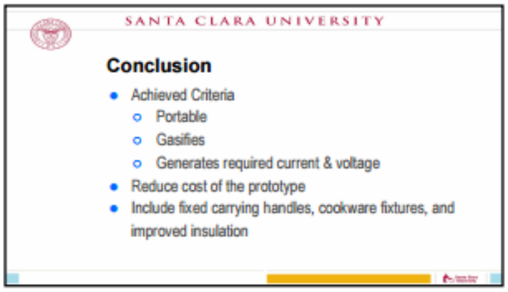
Possible Future Improvements

- Implementation of TEGs in other industries
- Exploration of robust heat-resistant TEGs and different TEG arrangements
- Alternate manufacturing methods
  - Automated welding
  - Powdered steel molding

Figure F.1 cont.: Senior Design Presentation Slides



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Conclusion

- Achieved Criteria
  - Portable
  - Gasifies
  - Generates required current & voltage
- Reduce cost of the prototype
- Include fixed carrying handles, cookware fixtures, and improved insulation

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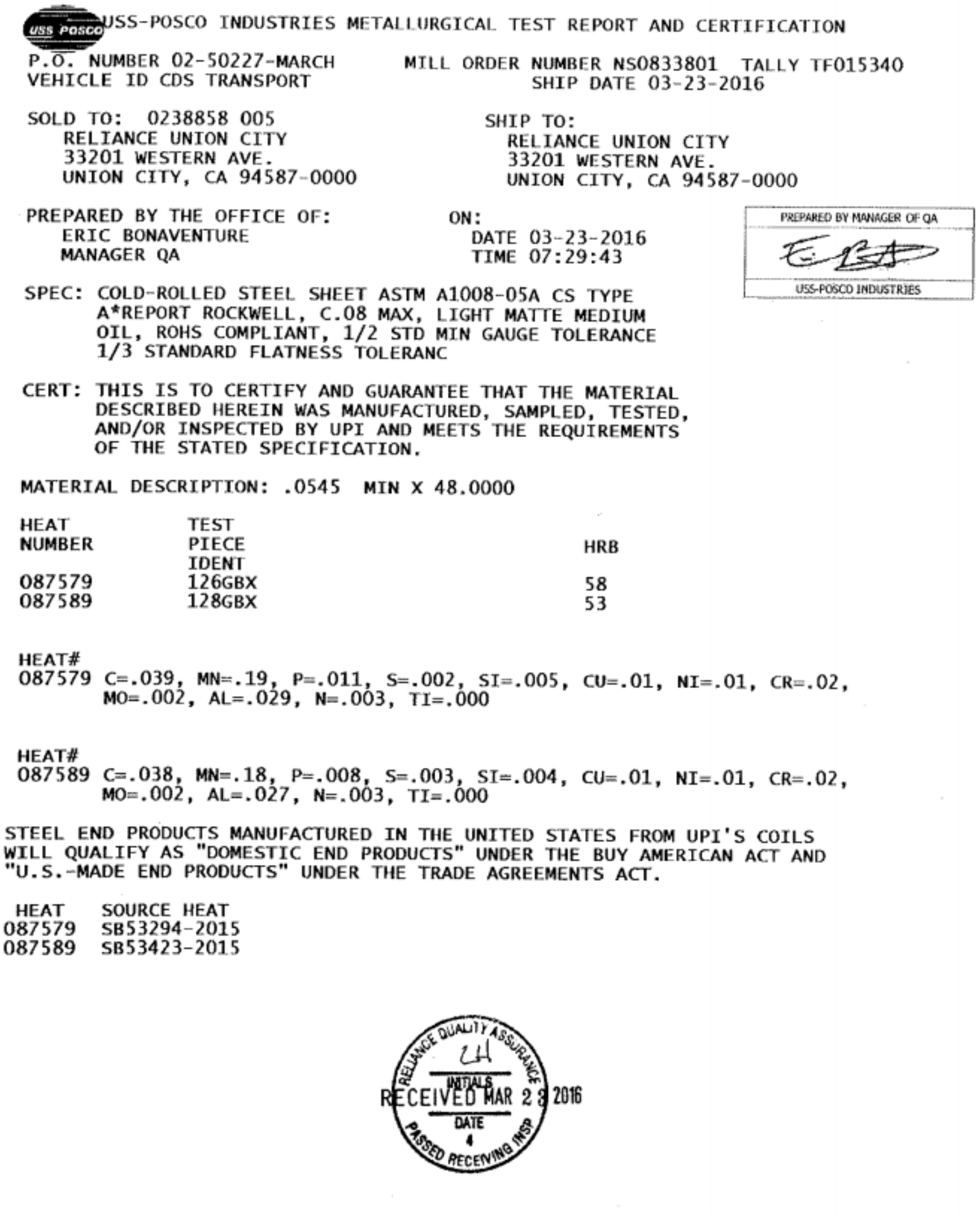
English Advisors: Loring Pfeiffer & Robin Everest

Course Advisor: Timothy Hight

Figure F.1 cont.: Senior Design Presentation Slides

APPENDIX G: PWP Test Report



USS-POSCO INDUSTRIES METALLURGICAL TEST REPORT AND CERTIFICATION

P.O. NUMBER 02-50227-MARCH
VEHICLE ID CDS TRANSPORT

MILL ORDER NUMBER NS0833801 TALLY TF015340
SHIP DATE 03-23-2016

SOLD TO: 0238858 005
RELIANCE UNION CITY
33201 WESTERN AVE.
UNION CITY, CA 94587-0000

SHIP TO:
RELIANCE UNION CITY
33201 WESTERN AVE.
UNION CITY, CA 94587-0000

PREPARED BY THE OFFICE OF:
ERIC BONAVENTURE
MANAGER QA

ON:
DATE 03-23-2016
TIME 07:29:43

PREPARED BY MANAGER OF QA
USS-POSCO INDUSTRIES

SPEC: COLD-ROLLED STEEL SHEET ASTM A1008-05A CS TYPE A*REPORT ROCKWELL, C.08 MAX, LIGHT MATTE MEDIUM OIL, ROHS COMPLIANT, 1/2 STD MIN GAUGE TOLERANCE 1/3 STANDARD FLATNESS TOLERANC

CERT: THIS IS TO CERTIFY AND GUARANTEE THAT THE MATERIAL DESCRIBED HEREIN WAS MANUFACTURED, SAMPLED, TESTED, AND/OR INSPECTED BY UPI AND MEETS THE REQUIREMENTS OF THE STATED SPECIFICATION.

MATERIAL DESCRIPTION: .0545 MIN X 48.0000

HEAT NUMBER	TEST PIECE IDENT	HRB
087579	126GBX	58
087589	128GBX	53

HEAT#
087579 C=.039, MN=.19, P=.011, S=.002, SI=.005, CU=.01, NI=.01, CR=.02, MO=.002, AL=.029, N=.003, TI=.000

HEAT#
087589 C=.038, MN=.18, P=.008, S=.003, SI=.004, CU=.01, NI=.01, CR=.02, MO=.002, AL=.027, N=.003, TI=.000

STEEL END PRODUCTS MANUFACTURED IN THE UNITED STATES FROM UPI'S COILS WILL QUALIFY AS "DOMESTIC END PRODUCTS" UNDER THE BUY AMERICAN ACT AND "U.S.-MADE END PRODUCTS" UNDER THE TRADE AGREEMENTS ACT.

HEAT	SOURCE HEAT
087579	SB53294-2015
087589	SB53423-2015

RELIANCE QUALITY ASSURANCE
LH
INITIALS
RECEIVED MAR 2 3 2016
DATE
4
PASSED RECEIVING INSP

Figure G.1: 1008 Cold Rolled Steel Test Report