Modular Plancha Cookstove Design for Capacity Building in Santa Catarina, Guatemala

by

Sylas Horowitz

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

February 2023

Signature of Author: ____
Department of Mechanical Engineering
December 16, 2022

Certified by: ____
Daniel Sweeney
Research Scientist, Lecturer
Thesis Supervisor

Accepted by: ____
Kenneth Kamrin
Associate Professor of Mechanical Engineering
Undergraduate Officer

Modular Plancha Cookstove Design for Capacity Building in Santa Catarina, Guatemala

by

Sylas Horowitz

Submitted to the
Department of Mechanical Engineering on December 16, 2022
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

ABSTRACT

Indoor air pollution from cooking on inefficient firewood cookstoves and open fires leads to 3.2 million premature deaths every year (World Health Organization, 2022). In Santa Catarina Palopó, Guatemala, women spend much of their time cooking and primarily use wood fuel, which disproportionately exposes them to air pollutants. An efficient, modular, user-friendly cookstove would improve the health, safety, independence, and cooking experience of women in the community while helping families save wood fuel. Through the Guatemala-based non-profit, Link4, women and builders in Santa Catarina co-designed, prototyped, and user-tested a cookstove that could be manufactured locally for community capacity building. A prototype was also produced in D-Lab to evaluate emissions and efficiency through burn testing. The resulting prototype was a horizontal-feed fiber-reinforced concrete rocket stove with perlite insulation and a plancha (flat stovetop), similar to but smaller than traditional Guatemalan stoves. The size and geometry was designed for modularity and portability, allowing multiple stoves to be used in various configurations, and to maximize thermal efficiency. A burn test D-Lab demonstrated a thermal efficiency of 13-14%. A user test in Guatemala found that the stove heated up quickly and reduced fuel consumption but required more tending and was difficult to transport.

Thesis Supervisor: Daniel Sweeney
Title: Research Scientist, Lecturer

Acknowledgements

I would like to thank Omar Crespo Cardona from Link4 for his dedication to the Santa Catarina community, for facilitating the co-design process, and for his amazing mentorship and design insights. Thank you to the Santa Catarina designers, cooks, and builders, and user testers Rosa Nimacachí, Alma Cumes, Teresa Nimacachí, Rudy Mata, Pedro Nimacachí, and Nicolasa López for their incredible work, knowledge, and time. Thank you to my thesis advisor, Dan Sweeney from D-Lab, for his mentorship, especially for guidance in cookstove design and burn testing. Thank you to D-Lab shop manager Jack Whipple for providing materials, a workspace, and generously supporting me throughout the prototyping process. Thank you to the MIT Department of Mechanical Engineering for their financial support for the V2 and V3 prototypes at MIT and in Guatemala, and for supporting Link4 in conducting user testing in Guatemala.

I would like to acknowledge the work of my fellow students on my team from the D-Lab: Design course during the Fall 2020 semester, Isabel Barnet and Hye Yeon Oh, for their collaboration on the assessment of user needs and initial co-design session. I would also like to acknowledge UROP researcher Karina Lara for her collaboration on building the V3 prototype and on conducting the burn test during the Fall 2022 semester.

Table of Contents

List of Figures

Introduction

1.1 Project Background

In Santa Caterina Palopó, Guatemala, inefficient firewood stoves or open fire cooking are the cause of many problems for the women usually in charge of preparing meals. Poor firewood combustion and indoor smoke emissions lead to health problems. The relatively low thermal efficiency of the current designs result in longer times spent on preparing food. Through collaboration with local women via the non-profit Link4, and feedback from a previous prototype (the Chaparra Redonda [Appendix A], IDDS Hogares Sostenibles 2017), this thesis presents an investigation toward a more user-friendly, space-efficient, structurally-sound firewood stove that can be manufactured and adopted by members of the community. The stove will promote safe and fuel-efficient cooking without compromising the local cultural traditions of preparing a meal, thus helping families save time and money in the long term and providing women with more independence.

1.2 Motivation

1.2.1 Indoor Air Pollution from Firewood Cookstoves

Around 70% of households in Guatemala use firewood for cooking (Clean Cooking Alliance, 2021). Exposure to fine particles ($PM_{2.5}$) from cooking in poorly ventilated homes can be up to 100 times greater than recommended by the World Health Organization (WHO). Incomplete combustion of wood fuel leads to Household Air Pollution (HAP) of $PM_{2.5}$, carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), and volatile organic compounds (VOC), as well as hazardous air pollutants such as polycyclic aromatic hydrocarbons (PAH) and formaldehyde. HAP contributed to more than 5000 deaths in Guatemala and were the second cause of disability-adjusted life years (DALYs) in 2010. This is linked to health issues including lower respiratory infection, asthma, lung disease, and cardiovascular disease. Globally, one-third of the population (around 2.4 billion people) cook using solid fuels in open fires or inefficient stoves, leading to 3.2 million premature deaths every year (World Health Organization, 2022).

Many households in Guatemala cook on open fire or traditional "comal" stoves using biomass fuel (wood, crop residues, charcoal), while improved designs feature a plancha (rectangular metal surface useful for warming tortillas), chimney, and closed combustion chamber where fuel can be fed. Liquefied Petroleum Gas (LPG) is also widely available and meets WHO standards. LPG is more common in urban areas. However, many families opt for wood stoves in rural areas because wood fuel is cheaper and can be harvested without purchasing a large LPG tank. The women involved in this project also noted that they prefer the flavors created when cooking on a traditional wood stove, which is generally a cultural preference in Guatemala. Firewood is an inexpensive fuel source that can cook greater volumes of food for long durations, especially for special occasions (Moran-Taylor, 2010).

1.2.2 Impact on Women, Families, and Broader Community

In Santa Catarina Palopó, and many rural communities in Guatemala, women oversee cooking and may spend many hours of their day preparing breakfast, lunch, and dinner. Improving the efficiency and user-experience of the cookstove will provide women independence by reducing the time they must spend tending to the fire while, for instance, beans are left to simmer. Lower indoor emissions of air pollutants from cooking will reduce the disproportionate health impact on women who generally experience higher exposure to pollutants while cooking. Higher efficiency stoves will reduce wood consumption, reducing family's time and financial burden, and consumption of environmental resources.

A user-friendly stove design will improve the cooking experience and quality of food by improving the heat distribution across the plancha and making it easier to clean and maintain. A simple, repeatable, modular design can also contribute to ease of maintenance. Transporting the stove across hilly terrain in Santa Catarina can be addressed by making the stove modular. It can be configured in a way that saves space in the kitchen and integrates with other furniture in the room. Modularity will also allow families to combine stoves and expand the cooking surface based on the size of the family.

Capacity building of the Santa Catarina community will be at the forefront of the design, implementation, and production of the stoves. Link4 employs women who are in charge of cooking as designers, and community members such as concrete workers as builders. The goal of this project is not to fix a problem from the outside, but rather to provide resources and technical assistance while collaborating with community members to locally manufacture and benefit from the use of improved stoves.

1.3 Local Context: Santa Caterina Palopó

Santa Caterina Palopó is a municipality in the Sololá department of Guatemala—a mountainous village on the shores of Lake Atitlán. 86.1% of Santa Catarina's 4,926 residents speak the indigenous language Kaqchikel, and almost all of the population are of Mayan ancestry, according to a 2018 census ("City Population," 2022). Subsistence farming and fishing is common in the community, and weaving is common among women. There is also a growing tourism industry with jobs in providing various goods and services.

Figure 1: Location of Catarina Palopó, Guatemala. Source: https://en.wikipedia.org/wiki/Santa_Catarina_Palop%C3%B3#/media/File:Guatemala_location_map.svg

1.4 Stakeholder Analysis

The stakeholders in this project, their interests, and their level of influence should be understood. MIT D-Lab and Link4 aim to support the needs of women in Santa Catarina by working with them to design technological solutions, and have great influence over the direction, timeline, and resources allocated to this project. The women hope to improve their ability to prepare nutritious, quality food for their families, spend less time tending to the stove, improve their ability to multitask while preparing food, reduce spending on firewood, have a more modular, portable stove, and reduce safety and health risk from indoor air pollution. D-Lab and Link4 use co-design principles to ensure the Santa Catarina community drives the design process and has final say over decisions and how this technology is implemented.

This project is financed by grants from the Guatemalan government and the Clean Cooking Alliance to help them meet their goals to improve clean cookstove access. Banks may be involved in microfinancing to improve affordability. Local materials suppliers, stove manufacturers, and distributors stand to benefit economically from contributing to the production of the stove. Therefore, both profits and benefits will stay within the community.

Identification of User Needs

2.1 Community Engagement Methodology

User needs were initially assessed through virtual discussions with three women in Santa Catarina— Rosa Nimacachí, Alma Cumes, and Teresa Nimacachí—during the course 2.722 (D-Lab: Design) in spring 2021 with fellow students Isabel Barnet and Hye Yeon Oh. To avoid steering the conversation based on preconceptions, open-ended questions were asked such as "how do you spend your time on a typical day?", "what kinds of foods do you prepare?", and "what joys and challenges do you find with cooking?" The team consolidated assessed needs on a spreadsheet and organized them into four categories: design, feasibility, fuel, and functionality (Appendix B).

The team brainstormed concepts for cookstove designs based on the needs assessed. Three core design features were identified: modularity, chimney, and workspace. A virtual co-creation session was organized in which the women were prompted to brainstorm ideas for these three features through sketching activities. The student team then developed these ideas into refined sketches and computer-aided design (CAD) models using Solidworks. The women were continuously consulted for feedback on these sketches throughout the process, and two additional design sessions were held. The design went through a series of iterations.

2.2 Results of Co-Design Sessions

From the co-design sessions, eight key needs were identified. The stove must be

1. An appropriate height and plancha size.
2. Made of local and affordable materials.
3. Modular.
4. Equipped with an effective chimney system.
5. Able to dry excess wood.
6. Easy to integrate with a work surface for cooking preparations.
7. Easy to clean.
8. Structurally sound and durable.

An average woman in Guatemala is 151 cm ("Average height," n.d.). Therefore, a comfortable stove height should be about 85 cm. Based on Rosa's experience, planchas typically contain four burners with concentric circles that can be removed to adjust the size of the burner, allowing for different pot sizes or a flat surface for cooking tortillas. Larger burners should be located toward the front directly above the combustion chamber where the stove is hottest, with smaller burners toward the back. A plancha size of 30 by 50 cm or 40 by 40 cm is suitable for a family of up to four. This is a good baseline for a single module, because larger or growing households can purchase additional modules to satisfy their needs. Households contain an average of six members, but can go through many changes depending on the circumstance. Larger households can reach up to fifteen members.

In order to accommodate this changing size of households, modularity was suggested by Omar Crespo from Link4. In addition to providing larger stovetop surfaces, modularity improves fuel efficiency by enabling the user to only fuel the modules needed based on the size of the meal being prepared, rather than firing up a much larger cooking surface. As suggested by Alma's schedule (Appendix C), women can spend more than four hours per day cooking and tending to the fire, so maximizing fuel efficiency could allow women to spend more time doing other things they enjoy, such as weaving, reading, and spending time with loved ones. Modularity also provides ease of maintenance, repair, and replacement of easily replicable parts. Further, modularity improved mobility by reducing the weight of individual pieces. The women expressed the desire to transport the stove easily into their homes, and to be able to move them around indoors to save space or simply rearrange furniture.

There will be four main "modules" in the stove system: the stove, base, chimney, and preparation tables. The base should also be something easily transportable and very study (the previous "Chaparra Redonda" [Appendix A] design used a wooden base that failed under the weight of the concrete stove body). The chimney system will be vital to preventing indoor air pollution. Along with the rest of the stove, it should be modular to fit various homes and multi-stove configurations, and made from accessible materials, but it should also be as airtight as possible. Many homes in Santa Catarina are multi-family homes with multiple stories, so the chimney may need to go through thick walls on lower levels. Homes with roof access may find it easier to cut through roofing to fit the chimney. The chimney should be flexible to account for these scenarios. The women have stated that they like to cook with a preparation table beside the stove, and an auxiliary table behind them. A work surface will be integrated into the modular configurations of the stoves.

Families typically store wood in "loads," which are about 40 logs. On average, a family consumes 3 loads per week. Usually, one week's worth of firewood (3 loads) is dried at a time. Therefore, the stove should dry between 1 to 1.5 loads (40-60 logs) per module. During the rainy season, the wood requires more than one day to dry. The storage shelf for drying wood should make use of the heat from the stove (i.e. placed beneath the combustion chamber). Each log is cut to roughly 6 cm by 6 cm by 36 cm, so the shelf must be designed to fit 40 to 60 logs in each module. However, wood consumption should decrease with increased efficiency, so these loads may be smaller. Later in the design process, the women decided that drying 15 logs at a time should be sufficient.

The materials that make up the stove should be easy to wipe down, including the stovetop and base. This also includes having a removable ash-tray that can be cleaned out as the wood burns, which is something many of the women ideated during the co-design session. User needs are synthesized in Table 1 below.

*Table 1: User needs and quantifiable design attributes that would satisfy these needs. *logs are 6x6x36 cm each*

User Need	Attribute	Quantity	Unit
Suits family of four	Plancha Dimensions	30 x 50	cm
Comfortable height for average Guatemalan women (151cm)	Stove Height	85	cm
Portable	Weight of each module	<50	lbs
Affordable	Cost of standard stove	<100	USD
Storage for drying wood	Load	15-60	logs*

Cookstove Design

3.1 Design Considerations

3.1.1 Synthesis of User Needs

The co-design sessions resulted in a concept consisting of multiple, small stoves and preparation tables that can be modularly configured in the kitchen, unlike the Chaparra Redonda, which featured one large, round stove with multiple combustion chambers (Appendix A). These modules will be lightweight, compact rectangular pieces so they can be fit together to maximize space in the room, as shown in figure 2.

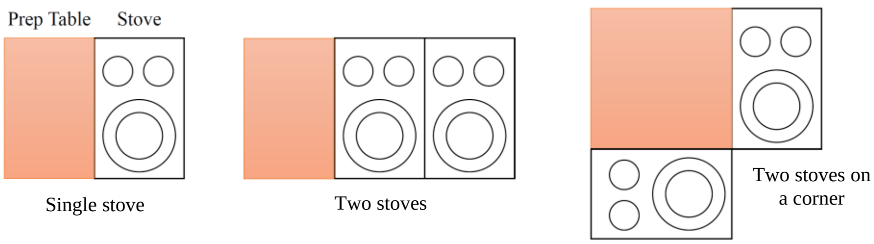

Figure 2: Example of possible stove module configurations.

Figure 3 outlines design options for the stove, base, chimney, and preparation table, which were synthesized based on needs identified throughout the community engagement process. The stove base may be made from cinder blocks or stacked bricks or manufactured to be more complex, such as a welded steel frame. Cinder blocks, bricks, and steel are all locally available. While a welded frame can offer additional features such as a custom shelf for storing wood, it would be more expensive to manufacture than stacking smaller bricks. Two designs for feeding wood fuel into the rocket stove were considered: horizontal and gravity feed. Horizontal feed is common in typical Guatemalan stoves. Gravity feed may be unfamiliar for families to adopt, but it allows wood to slide diagonally into the combustion chamber, reducing time needed to tend to fire. For the chimney system, exhaust gases may escape from the back or top of the stove and exit through the wall or ceiling. Placing the chimney on the top surface would save space behind the stove for ceiling-chimneys.

Other user needs highlighted by the women are shown in figure 4. A wooden preparation table with foldable legs was designed to hook onto the side of the stoves. In the original concepts of the stove, both the gravity and horizontal feed styles could be tested by laying the rack that supports wood fuel on either the diagonal or horizontal slats—a feature that may be revisited in the future. An ashtray made of folded sheet metal is placed below the slats, which makes the stove easier to clean. A storage shelf is situated below the combustion chamber so the warmth can be used for drying up to one "load" of wood. An adjustable vent on a hinged door to the opening of the combustion chamber was also proposed to modulate fire levels, which helps preserve wood, and may be added to future prototypes.

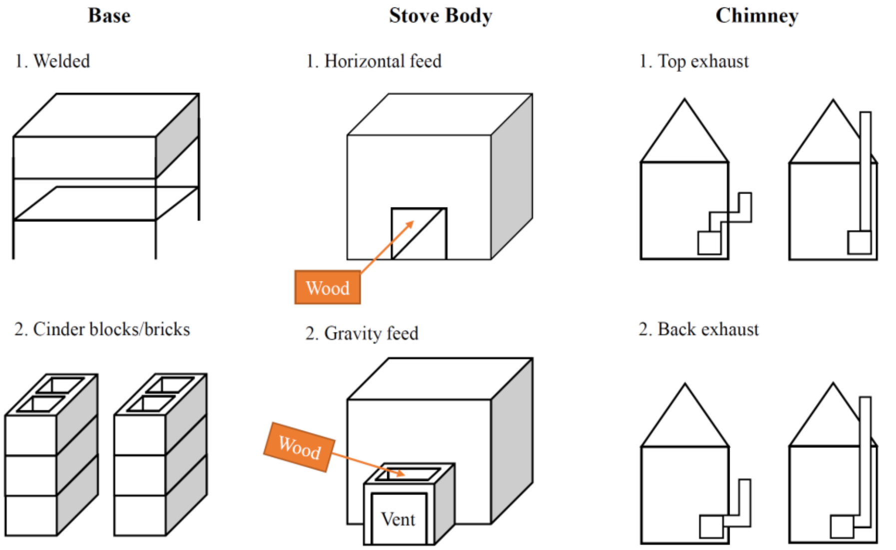

Figure 3: Diagram of options for the base, stove body, and chimney.

3.1.2 Overall Design

The cookstove is a "rocket stove" design consisting of a concrete body with an L-shaped combustion chamber composed of refractory bricks. It is insulated with a layer of perlite between the concrete and refractory layers. The base is a simple stack of cinderblocks, which are available locally in Santa Catarina Palopó. A steel plancha is fastened on top. The plancha consists of burners with concentric rings that can be removed to account for various pot sizes. A slot in the combustion chamber elevates a rack that holds wood, allowing for proper airflow underneath. An ashtray beneath the rack of bent sheet metal makes the stove easy to clean.

There are three versions of the design, as depicted in figure 5. The first version (V1) was designed as a

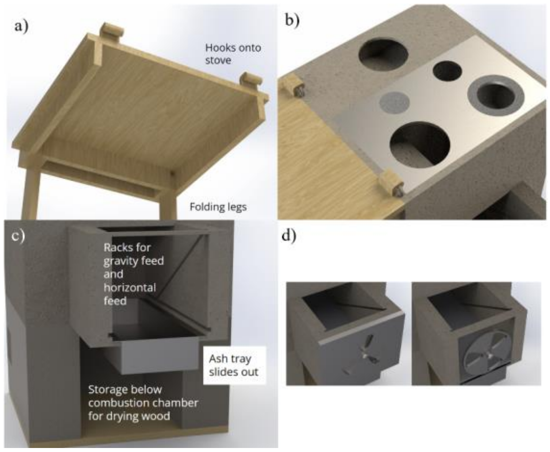

Figure 4: CAD renderings of design features considered; (a) Wooden side table for food preparations with foldable legs that can be hooked onto the side of the stove; (b) Removeable burners on plancha, allowing cooks to use various pot sizes and provides additional surface area for cooking tortillas; (c) racks to hold wood in slots for gravity or horizontal feed, ash tray, and wood storage; (d) Swinging door and adjustable vent controls airflow, managing fire.

result of initial co-design sessions. The second version (V2) was generated after further discussion among community members over a three-month period. With a focus on reducing the size of the module, the stove is narrower, with only two concentric burners and a rectangular opening in the back for a chimney, rather than on the top surface. The gravity feed design and vent were no longer of interest and would require behavior change for uptake, so these features were removed for simplicity. V2 is composed of 12 molded, rectangular components. The third version (V3) was a result of feedback from the builders in Guatemala adjusting the design to simplify mold making and overcome challenges with fitting the chimney, and contains 9 components, 5 of which can be constructed from cutting refractory bricks. V3 features one large burner with smaller burners in the back rather than two larger burners. The chimney opening is round and situated on the top surface again for easier integration. Space is saved in the V3 design by shortening the length of the combustion chamber, so wood may stick out, which is common in Guatemalan cookstoves. See Appendix D for detailed CAD renderings and stove dimensions.

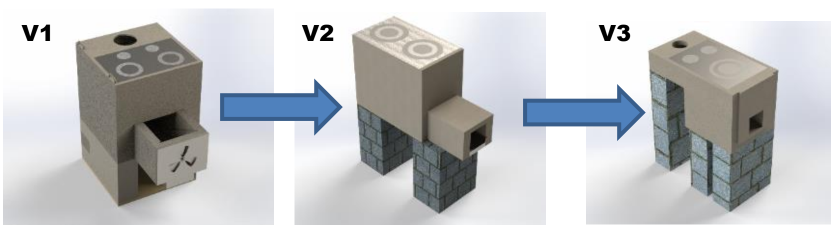

Figure 5: CAD renderings of the three versions of the cookstove.

3.1.3 Design for Manufacturing

A foam model of V2 was constructed in the D-Lab workshop. This model was used as a tool in deciding how the geometries of the stove could be divided into separate moldable components, with the goal of minimizing mold complexity and the number of molds. Three main components were identified; (1) the main body, (2) the horizontal section of the combustion chamber, and (3) the vertical section—as shown in figure 6. To reduce mold complexity, the three components were split into 9 distinct concrete parts (11 total) and one refractory part. The molds and their dimensions are shown in figures 7 and 8. When V3 was designed in consultation with concrete workers in Santa Catarina, the molds were simplified into 4 concrete parts and 5 simple refractory parts, which could be cut from refractory bricks. The concrete parts are fastened with concrete anchors and clamps in the prototype, though they may be mortared in future iterations.

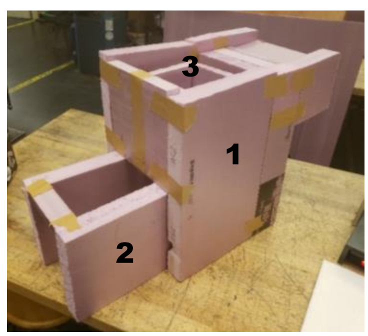

Figure 6: Foam model of stove.

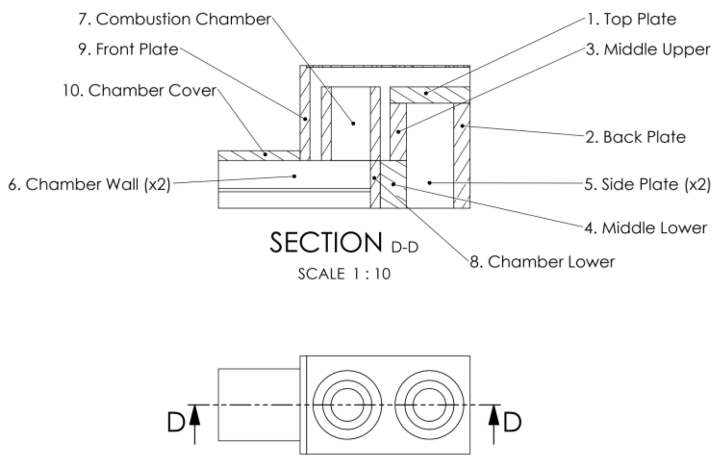

Figure 7: Cross section of stove numbered by mold for V2 (see Appendix D for an exploded view).

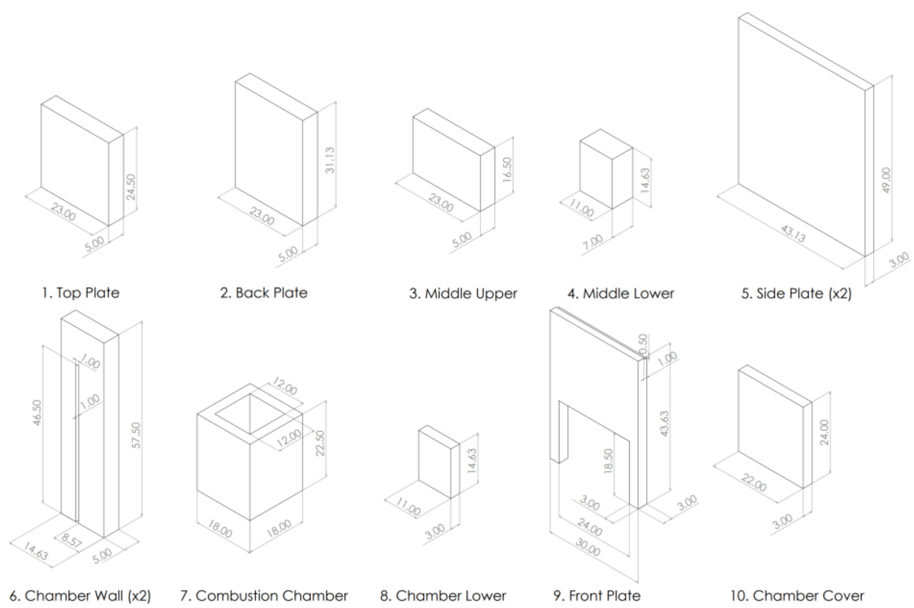

Figure 8: Dimensions of molds for V2.

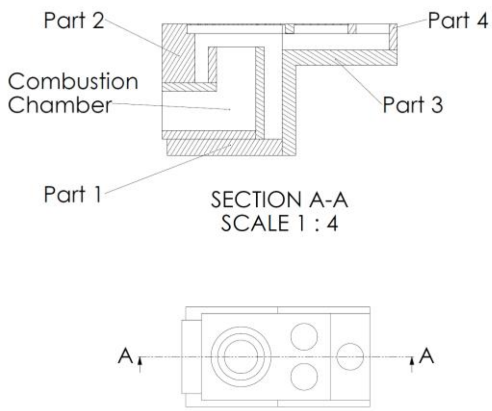

Figure 9: Cross section of stove numbered by mold for V3.

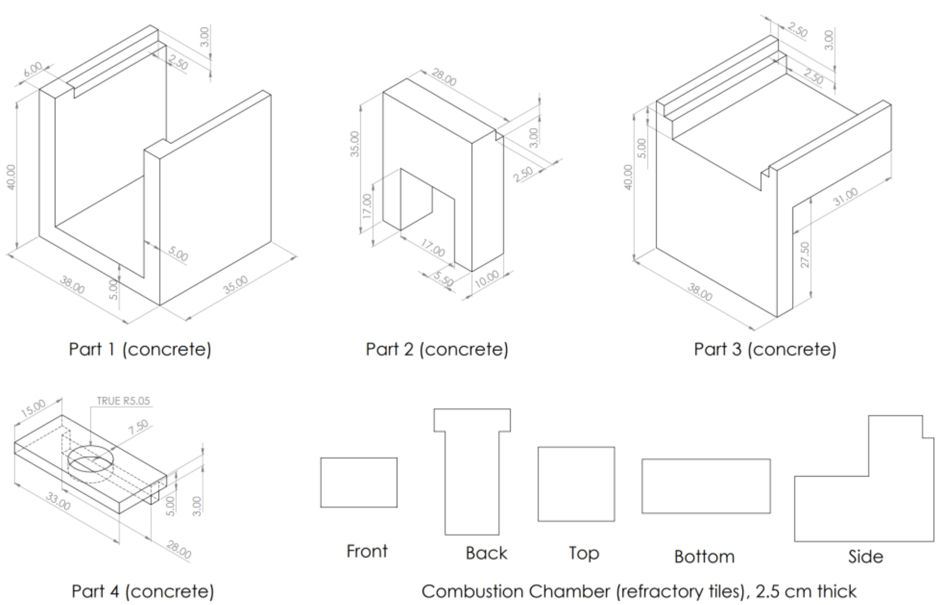

Figure 10: Mold dimensions for V3.

3.2 Combustion Efficiency

The rocket stove design allows for a thermal efficiency of ~30%, compared to efficiencies of ~10% on open fires (Hudelson et al.). Thermal efficiency is defined as the ratio of energy input from wood to energy transferred to heat a pot of water, while combustion efficiency is defined as the ratio of wood fuel to useable heat (not necessarily the heat transferred to the pot). Combustion efficiency is important because the incomplete combustion of wood results in smoke, which is a mixture of carbon monoxide, particulate matter, and many other hazardous air pollutants, while complete combustion results in just carbon dioxide and water vapor emissions.

Combustion efficiency is improved by increased turbulence of airflow, which promotes the interaction of oxygen with the fuel. Turbulence is determined by a Reynolds number

$$Re = \frac{\rho v D}{\mu} \qquad (1)$$

where ρ is the density of air $[kg/m^3]$, v is the fluid velocity $[m/s]$, D is the characteristic length of the combustion chamber $[m]$, and μ is the dynamic viscosity of air $[\frac{kg}{m-s}]$. The Reynolds number must be greater than 4000 to achieve turbulent flow, which can be achieved by increasing the cross-sectional area of the combustion chamber or forcing a draft (i.e. using a fan) to increase the velocity of air. Fuel efficiency is improved by increasing the time air spends inside the combustion chamber, which can be done by choking airflow with a ring or circulating airflow with a vane. Combustion can be improved simply by elevating the wood to allow air to flow beneath it (Bryden et al., 2005). This design uses a grate to lift the wood above the floor of the combustion chamber. The turbulence and time air spends in the chamber should be optimized such that temperature is also maximized. While too little draft creates more smoke, too much draft will cool down the fire.

Commented [S1]: This also has the effect of reducing the velocity. Sometimes we add a feature in the combustion zone to "trip" turbulence e.g. a choke ring.

According to the conservation of energy

$$\Delta E = E_{in} - E_{out} \qquad (2)$$

$\Delta E = E_{in} - E_{out}$The energy input can be determined by the energetic capacity of wood

$\Delta E = E_{in} - E_{out}$The energy input can be determined by the energetic capacity of wood fuel

fuel

$$E_{in} = m_f L_f - m_c H_c \qquad (3)$$

$E_{in} = m_f L_f - m_c H_c$where

The energy output, or the energy transferred to boil the pot of water, can be determined by

$$E_{out} = m_w c_p \Delta T + m_e L \qquad (4)$$

$E_{out} = m_w c_p \Delta T + m_e L$where

Thermal efficiency is then determined by

$$\eta = E_{in}/E_{out} \quad (5)$$

Hudelson et al. finds that greater thermal efficiency can be achieved with a higher inlet diameter, shorter chimney, medium insulation (i.e. perlite), and lower stove-to-pan gap. Brayden et al. recommends using a short chimney in the combustion chamber that is about three times taller than its diameter. A shorter chimney will bring hotter gas to the pot while producing more smoke. In V2, the chimney was about three times the diameter, while in V3, the chimney is slightly more than twice the diameter. Draft is improved by maintaining a constant cross-sectional area where air moves through the stove, and Brayden et al. references a 12 cm by 12 cm square combustion chamber, which was selected for this stove. The chimney opening was also sized at 144 cm^2. A smaller size will both reduce wood use and smoke. However, there must be a balance between preventing heat loss and designing a stove that is acceptable to users. Guatemalan cookstoves usually have larger combustion chambers, which are seen as producing a stronger fire, so small combustion chambers will require some behavioral change for uptake. Since the stoves are meant to be modular and used in tandem, cooks can prepare larger meals with two separate, more efficient stoves in place of one larger, less efficient stove.

Materials should be selected such that the layer in contact with the fire is refractory (heat resistant) which blocks radiation and convection, followed by insulation (pumice, perlite, etc.) to minimize conduction, and an outer cladding layer (usually metal, but concrete in this case). Perlite insulation filled the opposing side of refractory parts in the body of the stove.

Prototyping

4.1 Parallel Prototyping Methodology

Two of the same cookstoves were prototyped: one at MIT D-Lab and one in Santa Catarina. The D-Lab prototype served to investigate mold fabrication and conduct a burn test. The burn test intends to measure mass, temperature, $PM_{2.5}$, CO, and CO_2 data to determine emissions and thermal efficiency. The goal of the Santa Catarina prototype was to build and incorporate local knowledge through the design and building of the cookstove and gain user feedback by testing in homes. The prototyping phase was coordinated through remote communication with the Santa Catarina team. The prototyping process started with the V2 design, but shifted to the V3 design before the V2 prototype could be completed. Both teams worked experimentally to empirically determine the most simple-yet-effective manufacturing process for the stove, which is outlined in the following sections.

4.2 Mold Manufacturing

Figure 11: Photo of a V2 mold.

The initial V2 molds were constructed from plywood, fastened using wood screws, and lined with wax paper, as shown in figure 11. They were fastened such that the mold could be easily deconstructed when releasing the brick from it, without damaging either the brick or the mold. Due to difficulties in working with concrete, the D-Lab team did not complete the V2 prototype and awaited feedback from the builders in Guatemala.

The builders in Guatemala began constructing molds based on local knowledge of working with concrete. The designers and builders worked to design V3 to minimize the number of molds without introducing too much complexity. Initially, the Guatemala-based team used foam board to construct the molds, which they scored and fastened with tape. These molds failed under the weight of the concrete, so they shifted to medium-density fiberboard (MDF) fastened by clamps. The MDF was successful in the creation of the V3 prototype, but they reported some bowing of the material.

Figure 12: Photo of the mold for Part 2 of V3.

Following feedback from the Guatemala team's successful prototype, MDF and plywood was selected for the D-Lab V3 prototype, as shown in figure 12. The D-Lab team opted to solely use plywood with wax paper lining for Parts 1, 3, and 4 of V3.

4.3 Concrete Mixing and Materials

Figure 13: 1:2:2 volumetric ratio of cement, sand, gravel (left) and 1:2:4 volumetric ratio cement, sand, gravel (right).

Concrete typically consists of cement, sand, and gravel mixed with water. At D-Lab, two mixtures were tested: 20% cement, 40% sand, and 40% gravel (a 1:2:2 ratio) and 14.29% cement, 28.57% sand, and 57.14% gravel (a 1:2:4 ratio), by volume. As shown in figure 13, the 1:2:2 ratio maintained better conformity and was less brittle due to the higher concentration of cement and smaller particles.

The 1:2:2 mixtures were prepared for the V2 molds. It was found that the mixture was best when there is enough water for the mixture to maintain its shape when packed by the trowel. A crumbly mixture was a sign of too little water, and a runny mixture was a sign of too much water. Increasing the amount of water decreases the strength, but enough water must be added to activate the cement. While enough curing occurred in 24 to 48 hours to take the bricks out of their molds, it takes concrete around 28 days to cure to its full strength. The V2 molds were easy to release

without much damage to either the bricks or the mold. However, the mixture still resulted in a brittle brick (figure 14).

With feedback from the D-Lab team's experimentation, the Guatemala-based team tested mixtures that would provide more strength. Chicken wire was initially considered to be used as reinforcement. The builders recommended adding fibers and an acrylic fortifier to the mixture. They also decided to just use sand and not gravel to promote more uniformity in the particle size. The ideal ratio was determined to be a 1:1:1/8:1/2 volumetric ratio of cement, sand, fiber, and acrylic fortifier (38.1% cement, 38.1% sand, 4.76% fiber, and 19.05% acrylic fortifier).

Figure 14: Photos of V2 molds after pouring (upper) and after curing (lower). The front plate part broke during removal.

Replicating the process determined by the Guatemala team, the prototype was successfully built in D-Lab. Figure 15 shows both prototypes.

(a) **(b)**

Figure 15: V3 prototypes in (a) Guatemala (courtesy of Omar Crespo) and (b) in D-Lab's Burn Lab

Burn Testing

5.1 Burn Test Methodology

A water boil test (WBT) was conducted in D-Lab's Burn Lab to gain a preliminary sense of the thermal efficiency of the stove by heating a pot of 3L of water to 90°C. The WBT consisted of a "cold start," in which water was heated when the stove was first ignited, and a "hot start," in which water was heated when the stove was already hot, following the cold start. Thermal efficiency was calculated based on Equation 5. To determine the energy input (Equation 3), the initial and remaining mass of fuel was measured and the difference was taken to determine m_f (fuel consumed). The mass of remaining char, m_c, was also measured. Natural hardwood fuel with an L_f of 18,414 kJ/kg and char with an H_f of 29,500 kJ/kg was used. To determine the energy output (Equation 4), the initial and final mass and temperature of water was taken to determine m_w, m_e, and ΔT. Water temperature data was recorded in Celsius at a resolution of a second using digital temperature probes (Vktech DSl 8b20) read into an Arduino Mega. D-Lab's Burn Lab setup also contained an exhaust fan connected to a pneumatic system that monitors $PM_{2.5}$, CO, and CO_2 data. These analyzers were not used for this WBT but will be for future tests. This WBT was also conducted once. Future tests will be needed to validate the statistical significance of the data.

5.2 Burn Test Results & Discussion

Based on the single test, a thermal efficiency of 13% was found for the hot start, and 14% was found for the cold start. This performance is slightly better than an open fire (~10% efficiency) but worse than other rocket stoves (~%30 efficiency). The cold start took 0.485 kg of fuel, and the hot start took 0.433 kg of fuel. It took 26 minutes for 2.673 kg of water to reach 92.3°C with a starting temperature of 27.7°C from a cold start, and 19 minutes for 2.573 kg of water to reach 89.9°C from a 29.3°C starting temperature from a hot start. The results are shown in Table 2.

Table 2: Results of single water boil test.

Value	Cold Start	Hot Start
Efficiency	**13%**	**14%**
Fuel consumed	0.485 kg	0.433 kg
Water volume	2.673 kg	2.573 kg
Initial water temperature	27.7°C	29.3°C
Final water temperature	92.3°C	89.9°C
Time to reach final temperature	26 minutes	19 minutes

Inefficiencies in the stove are theorized to be a result of imperfect craftsmanship and dimensions of the constructed combustion chamber that were inconsistent with the design plan. The lower part of the combustion chamber should be 12 cm by 12 cm, but the actual dimensions were 9 cm by 11 cm on the lower part, and 11.5 cm by 7 cm on the upper part. The parts were fastened by simple clamps rather than mortar, causing smoke to be visually observed escaping through gaps between the parts, especially at the edges of the plancha.

The Guatemala team measured surface temperatures of their stove (Figure 16).

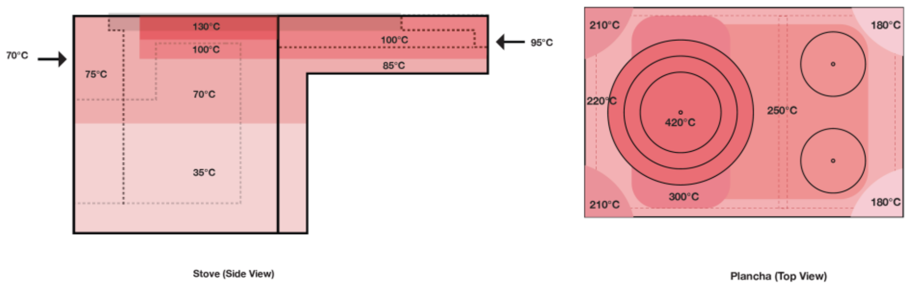

Figure 16: Diagram of stove temperatures in various regions. Measurements taken using an infrared thermometer from the Guatemala V3 prototype (Courtesy of Omar Crespo, Link4).

User Testing Results & Discussion

To expand on the V2 design plans, the builders—Rosa Nimacachí, Rudy Mata, and Omar Crespo—held a co-creation session that resulted in V3 of the stove. The stove was constructed by Rosa Nimacachí, Pedro Nimacachí, and Omar Crespo. They reported that the many parts in V2 were too heavy to carry in Santa Catarina's hilly terrain, so they redesigned the parts to the 4 concrete parts, maintaining around 5 cm of thickness. According to Omar, while most of the pieces were "fine," the largest piece (Part 1, Figure 10) was too heavy. One person was hired to install the stove, which took 4 hours (Figure 17).

Figure 17: Photo of a builder having trouble moving Part 1

After casting, the parts were sanded, which caused some of the sharp edges to be lost. This may have jeopardized some of the air-tightness in the design. All of the pieces were placed together with no fasteners, except for Part 1 and 3, which were screwed together with concrete anchors.

The design team was initially under the assumption that pumice, which would be used as insulation, was abundant because of its natural presence in Lake Atitlán. However, the build team has trouble finding pumice stones in stores locally, and they had to outsource.

The stove was tested for two week by Nicolasa López, who is a part of a family of three (Figure 18). Rosa checked in with López after day four, eight, and after the final day. A paraphrased report from Rosa follows:

López reported that she loved the stove and that it is ideal for a small family of three to five people. While it was intended that bigger families could get a separate module, she ***said she would rather get a scaled-up stove than to buy an additional module.*** *It would demand too much attention to tend to multiple combustion chambers.* ***This stove requires more tending*** *because she had to put wood in more frequently, compared to a typical big stove where they put a lot of wood in at once. At first, she doubted the stove because of its small size. As time went on, she voiced content with the small size because it takes up less space, and found that once she put up the fire,* ***the plancha would heat up super fast****.*

The firewood she bought was dry. She had to split the firewood into three pieces to get it to the ideal size for burning so the air can flow [about 3 cm by 3 cm from a typically 6 cm by 6 cm log]. She often managed to split it in half and still fit it, because ***there was no understanding of why someone should take the extra work to split it to smaller sizes that would burn more efficiently.*** *However****, she perceived that she is consuming less firewood compared to the normal-sized stove that she has.*** *The* ***firewood would break and fall to the ground****. Traditional stoves are much longer to accommodate longer wood. She also observed a lot of smoke coming from the front [which was corrected in the design of D-Lab's V3 prototype], as well as from the cracks by the entrance to the combustion chamber.*

She commented that the hot temperatures on the side did not feel unsafe [though they reached temperatures of 70℃, according to Figure 16]. ***Temperature variation was useful for cooking in different areas.*** *When cooking, she used the big burner in the front and then moves it to the back. Then, she uses the front to cook tortillas, and keeps it warm in the back. The family liked that the stove releases heat to the surrounding room, especially in November because it keeps them warm.*

Figure 18: Photos of designer and builder Rosa Nimacachí testing the first tortilla (left) and user tester Nicolasa López with the prototype during a two-week test (left)

Omar reported that López "loved the size," which is surprising because many people prefer a bigger stove so they could cook more food and faster. This stove was able to illustrate the perception that a smaller stove (which are typically more thermally efficient) can heat food more quickly without taking up space in the house. López often cooked eggs and coffee in the morning, and beans, rice, and corn tortillas for other meals. Preparing maize for tortillas requires boiling maize, which usually takes 3 hours. She reported that she was able to do it faster. She estimated that she is 40-50% less wood, according to her perception.

Omar also reported that people did not see the value in installing the chimney properly in the wall or root. Someone would need to provide an understanding for the sealing chimney, since many chimneys in Santa Catarina are not properly installed. Further, the elbow connector to the chimney was observed to not be pulling well, which can result in more smoke.

Summary and Conclusion

The design, prototyping, and user-testing of the cookstove followed co-design principles with the ultimate goal of capacity building, centering the needs and wellbeing of the Santa Catarina community. Omar Crespo with Link4 and Santa Catarina community members, Rosa Nimacachí, Alma Cumes, and Teresa Nimacachí, provided insight into eight core design requirements: an appropriate height and plancha size, local and affordable materials, modularity, an effective chimney system, the ability to dry excess wood, easy integration with a work surface for cooking preparations, easy of cleaning, and structural soundness and durability. A single stove would suit a family of 5-6, but multiple stoves and preparation tables could be placed together and configured to fulfill larger-scale food preparation (i.e. for bigger families, special events, etc.), while also being compact enough to fit in smaller kitchens.

The stove design went through three evolutions: V1, V2, and V3. The stoves maintained a core concept of a traditional Guatemalan cookstove with a plancha. It followed a "rocket stove" design with a concrete body, refractory combustion chamber, and space between the body and combustion chamber for perlite insulation. The base consisted of cinderblocks. Special, less traditional design features were removed in V2 for simplicity, and it was made to be more compact. V3 followed from a building co-creation session with Rosa Nimacachí, Rudy Mata, and Omar Crespo, who downsized the amount of concrete parts to be casted. V3 was constructed in parallel at D-Lab (to conduct a burn test) and in Guatemala (to conduct a user test). UROP student Karina Lara assisted Sylas Horowitz on the building of V3 and burn testing. In Guatemala, Rosa Nimacachí, Pedro Nimacachí, and Omar Crespo built V3.

The final stove consisted of a 12 cm by 12 cm combustion chamber that maintained constant cross-section area throughout the stove to improve airflow and maximize combustion efficiency. The vertical "chimney" portion of the combustion chamber was slightly more than twice its diameter—a design principle that facilitate draft while heating the plancha faster. A concrete mixing ratio of 38.1% cement, 38.1% sand, 4.76% fiber, and 19.05% acrylic fortifier was determined. Successful molds were constructed of a mix of MDF and plywood fastened by clamps and screws. Concrete parts were stacked, and only Parts 2 and 3 were fastened, using masonry anchors. The burn test found a 13% thermal efficiency for a cold start and 14% for a hot start. It took 26 minutes for 2.673 kg of water to reach 92.3°C with a starting temperature of 27.7°C from a cold start, and 19 minutes for 2.573 kg of water to reach 89.9°C from a 29.3°C starting temperature from a hot start. The plancha reached a temperature gradient ranging from

180°C (on the back corners) to 420°C (directly above the combustion chamber). The front body of the stove reached temperature ranging from 35°C to 70°C.

In the future, the combustion chamber should be lengthened, adding a rack (to elevate the wood), ashtray, and vent (these features were present in V1 but removed for simplicity of the initial prototype) to improve and control airflow for better thermal efficiency, and to prevent wood from falling out of the chamber. Community member Nicolasa López tested V3 for two weeks, and found that the stove required more tending, which she theorized would make it difficult for someone to tend to more than one module. As shown in the V1 design, a gravity feed mechanism could be implemented to minimize the need to tend to the fire so frequently. She found that the smaller stove heated up much faster and that she saved on firewood. However, users may have a negative perception of these design changes. Users are used to larger cookstoves with a horizontal feed that use thicker pieces of wood, so users would have to find value in these new design features first. Users would also need to see value in installing the chimney properly for the stove to be most effective at reducing indoor smoke. Other future design considerations suggested by López are increasing the width to accommodate two normal-sized pots to fit side-by-side and including a side-pocket for storing cutting trays and other cooking supplies. The stove should also be more lightweight (i.e. lighter concrete mix) for ease of transport. While the stove parts were transported and assembled with moderate difficulty, Part 1 was found to be too difficult to carry over the hilly terrain. A more locally available insulation material than pumice may also be considered. The concrete parts also became blackened after a few uses, so the longevity and heat resistance of the material should be tested and adjusted. In both the Guatemala and D-Lab prototype, smoke was observed escaping from cracks between the concrete parts, so fabricating parts with a tighter fit and/or using mortar between parts should address this issue.

The D-Lab team will adapt some of these design changes, re-cast concrete parts that experiences cracking and warping, and fabricate a new V3 for burn testing. Around five burn tests are typically conducted to determine statistically significant values. Future burn tests will also measure PM2.5, CO, and CO2 emissions. The Guatemala team will adapt design changes and conduct user tests with more families in the community. Members of the Santa Catarina community will drive how the stove is implemented.

References

Average height of men and women worldwide. Worlddata.info. (n.d.). Retrieved December 4, 2022, from https://www.worlddata.info/average-bodyheight.php

Bryden, M., Still, D., Scott, P., Hoffa, G., Ogle, D., Bailis, R., & Goyer, K. (2005). *Design Principles for Wood Burning Cook Stoves*. Aprovecho Research Center.

City Population. (2022, September 14). *SANTA CATARINA PALOPÓ*. www.citypopulation.de. Retrieved December 4, 2022, from https://www.citypopulation.de/en/guatemala/admin/solol%C3%A1/0711__santa_catarina_palop%C3%B3/

Clean Cooking Alliance. (2021, June). *Global Alliance for Improved Cookstoves - Guatemala.* . Retrieved from https://cleancooking.org/wp-content/uploads/2021/06/210-1.pdf

Hudelson, N., Bryden, K. M., & Still, D. (n.d.). *Global Modeling and Testing of Rocket Stove Operating Variations*. Retrieved December 4, 2022, from http://bioenergylists.org/stovesdoc/Ogle/nordicarocket.pdf

Moran-Taylor, M. J., & Taylor, M. J. (2010). Land and leña: Linking transnational migration, Natural Resources, and the environment in Guatemala. *Population and Environment*, *32*(2-3), 198–215. https://doi.org/10.1007/s11111-010-0125-x

World Health Organization. (2022, July 27). *Household air pollution*. World Health Organization. Retrieved December 4, 2022, from https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

Appendices

Appendix A: Chaparra Redonda Reference Images



Appendix B: Consolidation of Needs, Ranked by Rosa

Ranking	Need	Category
	The stove keeps extra firewood dry	Design
1	**The design is modular**	**Design**
3	Less supervision is required while stove is on	Design
2	The stove provides a sufficient workspace for preparing food	Design
	The stove provides storage space for extra wood and tinder	Design
	The stove has an enjoyable look and feel	Design
	The stove is your preferred shape and size	Design
2	The stove is affordable	Feasibility
1	**The stove is locally manufactured and distributed**	**Feasibility**
3	The stove is easy to maintain and repair	Feasibility
4	Fire is easy to start	Fuel
2	There is less smoke	Fuel
3	The stove is more efficient (less wood is needed)	Fuel
1	**The stove runs on a fuel source other than wood (i.e. gas, biomass, charcoal, solar)**	**Fuel**
3	You save time tending to the fire	Functionality
1	**The stove is durable**	**Functionality**
2	You can easily move the stove	Functionality

Appendix C: Schedule of a Typical Day in Alma's Life

Time	Duration	Task
5:30	30 mins	Wakes up, grooming
6 am	5 mins	Starting fire for breakfast
	30-45 mins	Preparing breakfast (typically eggs, beans, coffee, tortillas)
7:30	?	Cleaning house, children help
11 am	30 mins	Preparing fire for lunch
	1-1.5	Preparing lunch (usually tortillas)
2 pm	3 hours	Time for self; weaving; reading
5 pm	1 hour	Preparing dinner
6 pm	?	Reading, studying
?	?	Prepares tortillas for next day
11 pm		Goes to bed

Appendix D: CAD Renderings and Dimensions of Cookstove V2 and V3

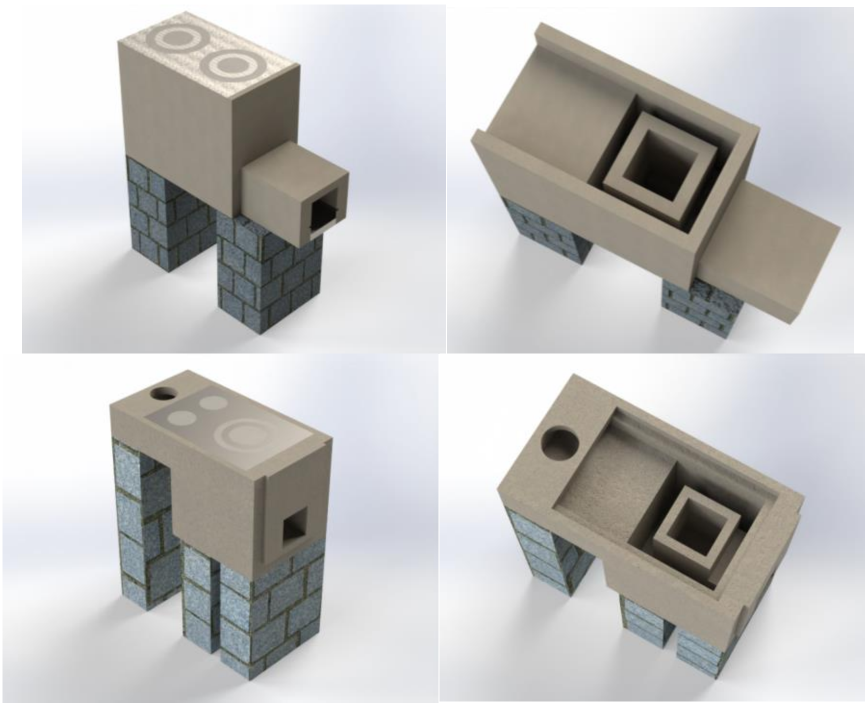

Figure 19: Renderings of full cookstove module with plancha (left) and without plancha (left).

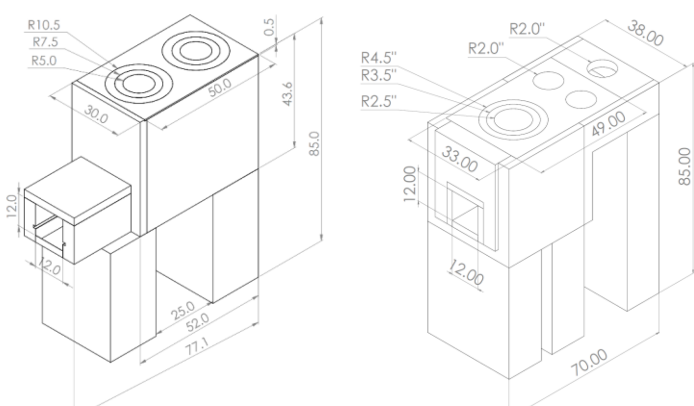

Figure 20: Diagram of cookstove with dimensions for V1 (left) and V2 (right).

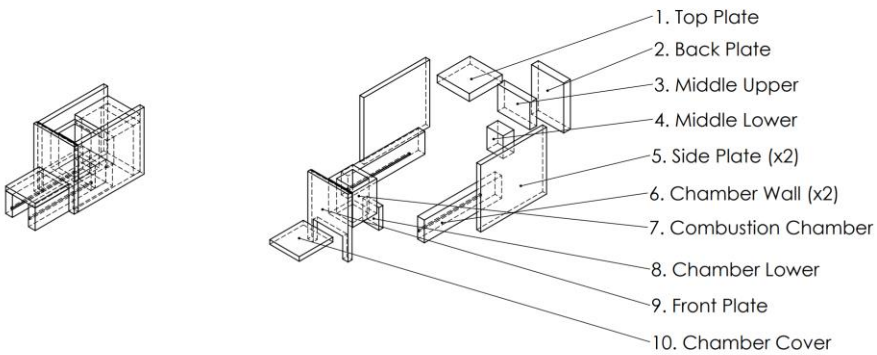

Figure 21: Exploded view of stove with components numbered by mold for V1.