Participatory Methods in Technical Design: Household Biomass Stoves

by

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Abstract

Participatory Design represents an important methodology focused on involving people who experience problems in the process of defining and solving them. This is especially important in global development, where diverse stakeholders attempt to tackle poverty challenges. In this thesis, I analyze a case study of improving biomass stoves in the Himalaya through the lens of participatory design to inform design practice and research. Biomass cooking and heating cause high levels of indoor air pollution especially in the Himalaya where households need accessible and affordable wood fuel for cooking and heating during extreme winters. Prior to fieldwork, I facilitated ideation sessions to generate solutions to these challenges, and we pursued prototyping and testing of a chimney retrofit to a traditional stove. This incremental innovation had increased chances of long-term adoption and impact because it would not require users to change cooking practices or discontinue using their traditional stove. Lab testing resulted in several design guidelines, rather than optimized parameters, to enable fieldwork. In the field, the team co-designed a chimney clay stove with a lead user, trained under a local stove master in constructing improved clay stoves, and designed a one-pot clay chimney stove and modifications to metal chimney stoves using principles of participatory design. The chimney modification reduced indoor PM 2.5 and CO mass concentrations by 32.3% and 78.5%, respectively, while maintaining usability characteristics. Design experiences allowed the team to recognize the technical skills in materials and construction necessary for successful clay stove design and document cultural value placed on this expertise. The team also documented user innovations on stoves, which are sparse in literature, but further demonstrate the feasibility and value of increased user participation in designing improved stoves. Inspired by field work, I present a short review of literature on gender in biomass stove technology and recommendations to involve women and gender specialists in designing improvements to traditional stoves. In addition, I propose a new model for calculating thermal efficiency and a method for estimating space heating in biomass stoves used for cooking and heating. With the new model, clay multi-functional stoves can achieve up to 35% efficiency, which raises the standard for new stoves entering the market and better reflects actual usage and fundamentals of thermal efficiency.

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MIT is located on the traditional, unceded territory of the Wampanoag Nation.
I acknowledge the painful history of genocide and forced removal from this territory,
and honor and respect the diverse indigenous people who continue to call this area home.

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Chapter 1: Introduction

Participatory Design (PD) methods offer concrete activities for creating a more democratic process, in which those impacted by technology have the opportunity to influence decisions surrounding the design and implementation of that technology in context. To foster participation, designers must recognize the practical understanding, or tacit knowledge, possessed by users, who are experts in their own experiences. Lead User Theory (LUT) applied in PD methods also allows designers to recognize technical expertise possessed by lead users and create positive design outcomes [1], [2]. PD originated in the Scandinavian workplace in response to challenges with producing technology that fit the context and needs of users. Similar challenges arise in developing technology fit for base of the pyramid (BoP) markets when designers fail to consider contextual factors and/or assume the needs of those living in poverty. PD methods enable user engagement in the development process, such that solutions reflect the socio-cultural context of use and better meet user needs. The complex challenges associated with biomass cooking and heating, particularly in the Himalayan Region present a useful opportunity to assess PD processes in BoP contexts through exploring an incremental innovation concept for reduced household air pollution (HAP). Literature on engineering design for development and biomass technologies offers important principles to guide designers looking to impact this field. Specifically, biomass combustion, heat transfer, and fluid flow represent the key operating principles of stove technology. In addition, designing for customization and multi-functionality and recognizing the importance of cultural values in technology adoption offer strategies to increase the long-term adoption and sustainability of innovations.

To address high levels of HAP, MIT D-Lab explored clay chimney stove designs and modifications to traditional biomass stoves using participatory design methods during Spring and Summer 2022. First, researchers engaged in user-centered design to generate a variety of concepts to address complex challenges with cooking and heating in the Himalaya, to select a concept based on feasibility and impact, and to prototype and test in the lab. We chose to explore adding a chimney to a traditional stove as a type of incremental innovation to address HAP and aimed to prioritize prototyping this concept in the field to get feedback in context and provide a vehicle for continued learning about and discussion of home energy challenges. Rather than optimizing physical parameters of the prototype for best performance, laboratory tests prior to travel allowed the team to generate design guidelines for successful chimney stove design in the field. This flexibility in the design parameters allowed the team to co-design in Pata, India with a lead user with technical expertise in stove materials and construction and influence in her community's social network. In Salambu, Nepal, the team trained under a Stove Master from Matribhumi Urja, a Nepali clean cookstove company, to learn more about improved chimney stoves and earthen materials while installing Matribhumi Urja improved cookstoves in Salambu households. The team also prototyped a one-pot stove and stove modifications for elderly residents in Kyanjin Gompa, Nepal. Field research consisted of qualitative interviews and performance testing of biomass stoves in addition to prototyping stoves and modifications.

In this thesis, I present the results from laboratory preparation and field research, descriptions of prototyping processes, and reflections on these experiences from a participatory design perspective. I also analyze additional facets of biomass cooking, including gender and performance metrics, with a participatory design lens to inform future research and practice in biomass stove design and innovation.

Chapter 2: Background

2.1 Participatory Design

MIT D-Lab defines participatory design (PD) as “a family of approaches that actively involve the people who are affected by the challenges to help ensure that the designed product or service is sustainable and beneficial for users and other stakeholders” [3, p. 126]. There are a variety of terms related to and associated with PD, including co-design, frugal innovation, appropriate technology, user-centered design, etc. In this work, we use PD as the umbrella term and outline a framework which specifies the meaning of participation in the design process and the relationship among these related terms.

2.1.1 Historical Origins

PD emerged formally in Scandinavia in the 1970s, describing the process by which union workers participated in designing computer systems and implementation plans in the workplace along with developers and management to improve production [4], [5], [6]. Companies began practicing PD methods in recognition of the need for technology to better fit the skills and practice of users and the contextual environment in which it is used [7]. Several aspects of the workplace landscape in Scandinavia enabled the emergence of PD, including the high unionization, large social democratic parties, and homogenous population, all of which contributed to a more democratic workplace favorable for PD methods [6]. Scandinavian approaches to PD recognize that design occurs in social context, and design processes and products reflect the values of those involved in decision-making [4]. Because of their democratic workplace values, Scandinavian approaches to PD emphasize democracy in the design process [8]. In this approach, participation entails influence and power in decision-making, not just the opportunity to share perspectives [9].

The participatory design process entails negotiation among stakeholders with diverse interests and perspectives [4], [6]. According to Gregory [4], conflicting interests, perspectives, and values are resources for design that reveal opportunities for innovation through the process of mutual learning. The process of mutual learning and negotiation of interests needs to happen on a level playing field, however, for it to be truly democratic. In the context of the Scandinavian workplace, this means that management must cede some power and control in order to enable democratic participation in decision-making from unions and workers [7]. Designers also need to shift to the role of facilitators in order to create an environment where users are free to express their ideas and actively participate in design among diverse stakeholders [6], [7].

Part of this facilitation involves enabling communication between stakeholders. Ehn [6] explains how users and designers utilize design artifacts and tools, such as prototypes and mockups, to draw meaning from discussion so that both parties learn from each other. Users possess practical understanding, or tacit knowledge, of their practice, which cannot be described in language. The knowledge is in the action itself, not the description of the action. Users lack technical knowledge which supplies possibilities for innovation, while designers lack users’ practical skill and knowledge of processes which contextualize the use of a tool. To bridge this gap in knowledge, users and designers share experiences through “design-by-doing” activities, such as interaction with design representations and visits to relevant sites, which allow users to participate in design and designers to participate in practical use [6, p. 70].

An alternative to PD is the expert design model, in which technical specialists share expert opinions which trump other perspectives [8]. This type of interaction does not involve democratic decision-making or mutual learning, but relies on technical, propositional knowledge to indicate the design pathway. In contrast, PD methods assume that those using technology are in the best position to decide how to improve it. In line with acknowledging practical understanding, or tacit knowledge, designers must also recognize that users are the experts on their own experiences. In this way, designers assume the role of consultants supporting users in realizing new possibilities [8]. Despite the application of these concepts in the unique context of Scandinavia, the elements and core vision of PD prove to be useful in global context, especially in diverse stakeholder groups with large gaps in shared experiences and knowledge.

2.1.2 Bottom of the Pyramid Markets

In 2002, C.K. Prahalad [10] proposed a new perspective on global poverty challenges and those living in those realities, at the time defined as living on less than $2 USD per day. Prahalad [10] questioned why, with the innovations and technology emerging in the 20th century, global poverty remains such a pervasive issue. The current approach is to encourage philanthropy from the top of the pyramid to help “the poor,” donating money to provide for basic needs. Prahalad argued that to eradicate poverty, we need a new approach. Rather than viewing those living in poverty, at the Bottom of the Pyramid (BoP), as victims or burdens of the state, we can see them as resilient, creative partners in innovation. Because of the limited resources in BoP contexts, attempts to address poverty require innovation, not just in technology, but in finance and policy as well, for sustainable, holistic solutions. In this way, the BoP offers a source of innovation and a new market ripe for investment [10].

In 2002, 20% of the global population controlled 85% of global wealth [10]. Prahalad [10] explained that collaboration and co-creation among stakeholders enables BoP access to innovative products and services while also creating profitable business for BoP investors. In 2019, C.K. Prahalad’s daughter, Deepa Prahalad, authored an update to her father’s revolutionary approach to reducing global poverty [11]. Over the years after Prahalad’s seminal book, wealth became increasingly concentrated at the top of the pyramid. In 2017, 8.6% of the global population controlled 86.3% of wealth [11]. However, according to Deepa Prahalad [11], a dramatic reduction in extreme poverty has occurred in the years since Prahalad’s original work, and emerging markets are the fastest growing global economies, so BoP markets still offer important opportunities for new enterprises and innovation.

According to Deepa Prahalad [11], several key factors support the growth of C. K. Prahalad’s approach to poverty eradication, including increased access to digital technology, industry acceptance of the approach, and the increased desire for companies to do good (rather than “do no harm”). The increasing access to cell phones and internet supports the involvement of global users in the design process to create new technologies and innovations. For investors, developers, users, and other stakeholders living in different locations around the world, increased access to these technologies enables collaboration across geography, removing barriers to communication and co-creation. Deepa Prahalad claims that society has accepted “innovation as the antidote to poverty” and companies and new enterprises continue to invest in developing solutions to address challenges in BoP contexts [11, p. 1]. In addition, the UN Sustainable Development

Goals have provided organizations with clear and explicit strategies for addressing global challenges, and there is a call from consumers for businesses to use ethical, sustainable models for creating solutions and generating profit. Together, these conditions support the continued growth in BoP market strategies and related innovations [11].

2.1.3 Challenges in Design for Development

While BoP markets present a valuable opportunity for innovation and socially oriented businesses to address global poverty challenges, the approach to developing technology significantly affects the success of products and services for these markets. In a study conducted by Wood & Mattson [12], researchers identified seven pitfalls of engineering projects in BoP markets that impede success. The majority (78.9%) of cases exhibited one or more of the first three pitfalls:

1. Lack of historical and cultural context of the community
2. Insufficient plan for long-term sustainability
3. Assuming the needs of individuals experiencing poverty.

Engineers in unsuccessful global engineering projects lacked knowledge of contextual factors, such as cultural practices and historical influencing events, which affect the development and implementation of new technology. In addition, projects failed to create structures and build relationships with local organizations to sustain and support the implementation of the innovation. The third pitfall describes how failed engineering projects in BoP markets involve designers assuming they understand the needs of those living in poverty, without engaging them in sharing their perspective or influencing design decisions [12].

These pitfalls correlate with the motivations for pioneering PD methods in Scandinavia in the workplace. There was a failure on the part of developers to recognize the social context in which technology is used and developed. Similarly, engineers may omit factors of the community context such as social and cultural practices which influence new technology implementation. Design reflects the values of those making decisions, so designers and technology developers must understand the socio-cultural context in which people interact with technological designs and engage in the innovation development process. Throughout *Participatory Design: Principles & Practices,* authors emphasize how unions and labor organizations in Scandinavia and the US can structure negotiations and bargaining to improve the technology development process for better workplace outcomes [5], [6], [7]. Implied in these outcomes is the necessity for engineers and designers to create structures to sustain long-term success of new technology and innovations. In BoP markets, this means developing relationships with local organizations, such as government bodies, NGOs, and/or informal local leadership and creating necessary infrastructure and/or policy structures to enable continued development and usage of new technologies. One can see how applying the principles of PD in BoP markets may help avoid these pitfalls and result in innovation which suits the local context while effectively addressing poverty challenges and democratically engaging users in the development process.

2.1.4 Engineering Design in Development

PD methods and approaches continue to evolve as practitioners utilize these strategies in BoP markets. PD concepts may be particularly important for scientists and engineers creating technology for developing contexts because of the nature of traditional processes and training in technical analysis in these fields. Conventional engineering and technology development presents design as a linear series of technical analysis progressing under the control of developers [8], [13], [14], in which complex problems are decomposed and these subproblems are isolated and solved independently [15]. Conventional processes also take place in laboratory or controlled settings, disconnected from the context of real use [16]. Training and experience in these processes can cause engineers to expect success in projects based on exceptional laboratory performance, without consideration for actual use in context and the needs of users [16]. Engineers may also expect to move linearly from problem to solution, when design in practice requires iteration and flexibility to adapt to changing conditions and new information [8], [13], [14], [17]. Engineering technical training and traditional processes exclude consideration for socio-cultural context of technology products and the design process, so experience with PD approaches has the potential to improve engineering design outcomes and transform engineering education and training.

Murcott [16] emphasizes that the world needs a new generation of engineers and scientists to address issues of global poverty and security, in terms of resilience to environmental disasters and degradation and access to healthcare and education, among other social and environmental needs. Murcott explains the concept of "co-evolutionary design for development" in which development partners, engineers, designers, scientists, and end-users engage as equals working toward a common goal through shared learning experiences in the socio-cultural context of technology use [16, p. 124]. Specifically, engineering design and iteration takes place in context rather than in a controlled setting–the real world becomes the "laboratory" for experimentation [16]. The notion of co-evolutionary design aligns strongly with early principles of PD, especially the emphasis on democratic participation of users among other stakeholders in the development process and the use of design-by-doing activities to facilitate the mutual learning required in PD and co-evolutionary design. Smith & Adams [3] explain that firsthand experience in developing context is a tenet of the MIT D-Lab approach to engineering education in addressing global poverty issues. Not only does spending time in the community enable deeper understanding of the socio-cultural context [18], but it also incites empathy in students in addition to dialogue with users in developing communities [3]. Empathy and personal connections help break down cultural barriers and challenge preconceived assumptions among diverse groups [1], [3], which left unaddressed can lead to unsuccessful projects in BoP markets [12]. According to Grudin [19], engineers may lack empathy for non-technical users. Scientists and engineers may believe technical knowledge can be separated from and elevated above other forms of knowledge in design projects [4], resulting in lack of respect for tacit knowledge and practical experience of users [19]. Thus, PD methods and co-evolutionary design for development are vital for use in practice with engineers, scientists, and other technical fields to facilitate a collaborative learning process and sustainable impact.

2.1.5 Participatory Design Frameworks

PD in literature centers on collaborative engagement and participation among diverse stakeholders in the socio-cultural context of usage through mutual respect and learning. Many frameworks exist for mapping the facets of the PD concept in research and practice. Jagtap et al. [20] outline a useful typology for participatory design in resource-constrained contexts, categorizing frameworks based on the usage and meaning of participation (Figure 1). Frameworks are classified as one of the following types:

1. Frameworks defined by **levels of participation** in the design process.
2. Frameworks focused on the participatory design **process**.
3. Frameworks which incorporate participation in design as **part of other models**.
4. Frameworks defining different **types of stakeholders** participating in the process of designing with resource-limited communities.

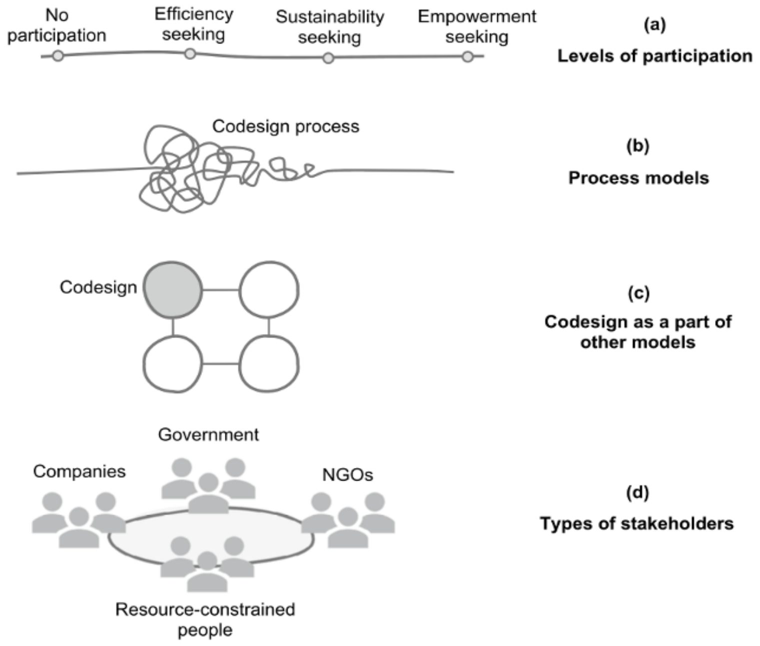


Figure 1: Typology of models of participatory design in low-resource communities. Source: [20]

We will focus on the first type, frameworks defined by the levels of participation of resource-constrained communities in the design process. Leith et al. [21] describe participatory design as existing on a spectrum based on the level of involvement of users and who holds decision-making power, as shown in Figure 2.

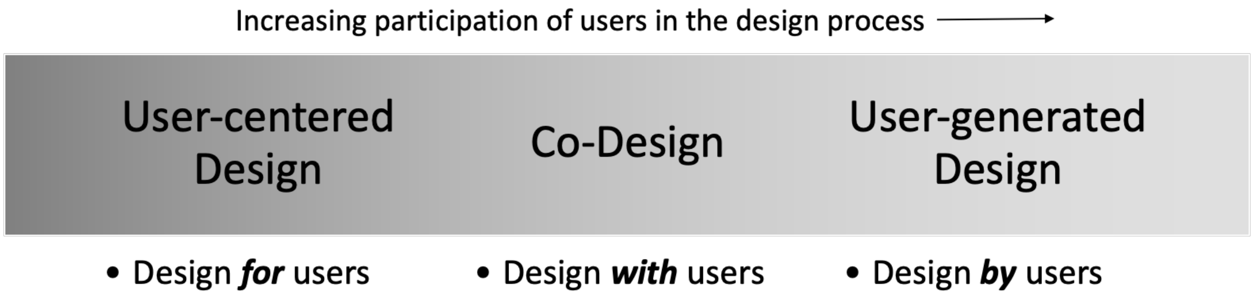


Figure 2: Participatory Design Spectrum

In user-centered design, or design “for” users, designers consult users in the design process, but ultimately make decisions about the design. In contrast, in co-design (design “with” users), designers, users, and other stakeholders participate as peers in the design process, and collectively make design decisions. At the other end of the spectrum, in user-generated design or design “by” users, users are the designers and utilize the design process to tackle challenges they themselves experience [21].

Robinson et al. [22] describe a similar framework; however, they also include a “level 0” in which communities are not involved in the design process or in design-related decisions. This is an important level to include because it is used in practice, sometimes out of necessity such as for emergency response. Robinson et al. [22] explain that “level 0” may be appropriate for short-term humanitarian response, but these responses will not be informed by contextual understanding of community challenges. For some design practitioners, “something is better than nothing” when faced with providing for the basic needs of communities or forcibly displaced people.

Stakeholders may practice different types of participatory design at different stages in the design process, depending on the desired outcomes of the project [21]. Figure 3 displays the extent to which different levels of participation enable particular project goals based on [21].

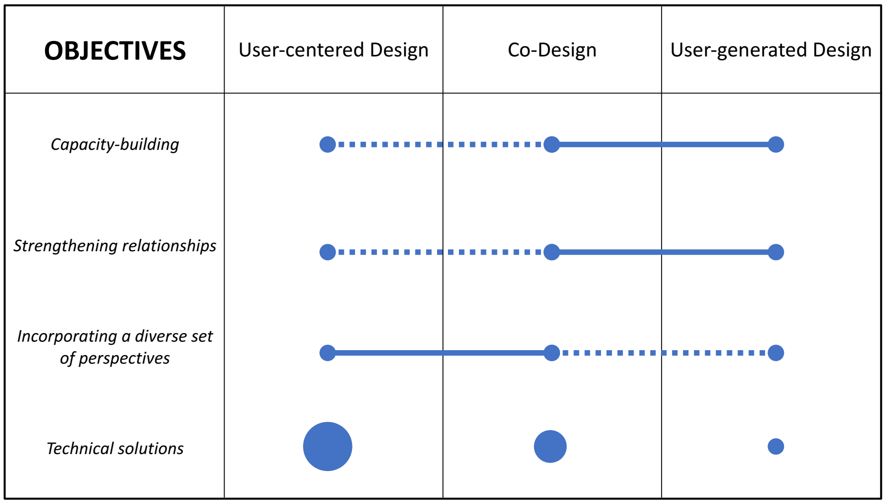


Figure 3: Project Objectives and Level of Participation

For example, if an explicit goal of the project is to build some capacity, users need a higher level of participation in the process than afforded by user-centered design, so the team may choose to engage in co-design or facilitate user-generated design in this case [21]. Projects typically have multiple objectives, so the design team must balance these goals and weigh the costs and challenges associated with different approaches to choose the level of participation in their design process.

2.1.6 Principles of Design in BoP Markets

Scholars provide several key principles for design in development, creating multi-functional and customizable products adapted to local context. Viswanathan & Sridharan [1] analyzed student teams designing products for BoP markets and identified key aspects of successful products and strategies for product development in BoP markets. Successful products are designed for multiple purposes, customization, low literate users, and local sustainability. Products in BoP may be used for purposes beyond what the designers intended originally, creatively adapting to resource limitations. As a result, BoP markets demonstrate a need for multifunctional products, since products made for particular purposes may be less successful than those with more flexible use cases [1]. In addition, Viswanathan & Sridharan [1] found that the ability to customize products was an important feature of successful designs in BoP markets, allowing local stakeholders and distributers the flexibility to fine-tune products to fit their specific needs. Also, student groups utilized existing social networks to disseminate product information orally rather than through written communication to overcome literacy barriers. Viswanathan & Sridharan [1] also mention how their results, especially the need for customization, suggest using a more participatory approach to product development for more accurate incorporation of user needs into product designs.

Mattson & Wood [18] also present principles for design in development from engineering literature to ensure technology fits the intended context. Importantly, Mattson & Wood [18] claim testing in context is essential to product development and should not be saved for the end. Simulation cannot account for the complexity in political, social, cultural contexts nor the complex physics needed for comprehensive testing in the lab. Field testing is needed throughout the development process. In addition, Mattson & Wood find, “importing technology without adapting it to the specific developing world context is ineffective and unsustainable” [18, pp. 121403–2]. Burleson et al. [23], [24] also stress the importance of considering a wide range of contextual factors in engineering design for development and presents a tool to aid practitioners in considering technical and nontechnical factors, such as social, cultural, and political context, in the design process.

2.1.7 Lead User Theory & Innovation Capacity in Co-design

Lead User Theory (LUT) and Innovation Capacity (IC) frameworks present additional tools for analysis in the context of co-design and engineering design in development. Eric Von Hippel at MIT Sloan developed LUT in the 1980s, pioneering a new perspective on user contributions to product development [25]. At the time, analysts started realizing that existing market research methods of understanding user needs for product development were inadequate for rapidly changing technologies. Typically, users selected for market research already use existing products in the category of interest, and this experience with current products and their embeddedness in usage patterns prevents users from envisioning novel concepts [25]. Specifically, Von Hippel [25] explains how individual products are part of larger usage patterns involving multiple products, creating a complex system of usage and preference. This complexity makes it difficult for users to evaluate how a new solution might compete with existing ones in terms of usage choices or how a new product might affect usage patterns [25].

In slower-moving product categories such as vehicles, Von Hippel [25] suggests that typical users with prior experience with these products can still contribute to innovation in this category. However, the experience of typical users with products in rapidly evolving technology sectors may not be relevant to product development processes seeking novel and innovative concepts [25]. To mitigate this, Von Hippel [25] proposes that a “lead user” possesses the following characteristics which give them valuable insights for market researchers beyond that of typical users:

1. Lead users face needs before the general population.
2. Lead users can benefit significantly from a solution addressing those needs.

The first characteristic refers to lead users being at the "front of the trend" in reference to the S-curve model of technology diffusion seen in Figure 4. In the second characteristic, Von Hippel [25] refers to the benefits of investing resources in new, unproven concepts that may address needs. The level of benefit may be demonstrated in part by lead users attempting to create their own solutions. In a study on PC-CAD system users, the most important indicator of a user being a lead user is having created their own system [26]. Urban & Von Hippel [26] also suggest that lead users can be "created" if developers can increase the benefit for users who innovate to stimulate user innovation.

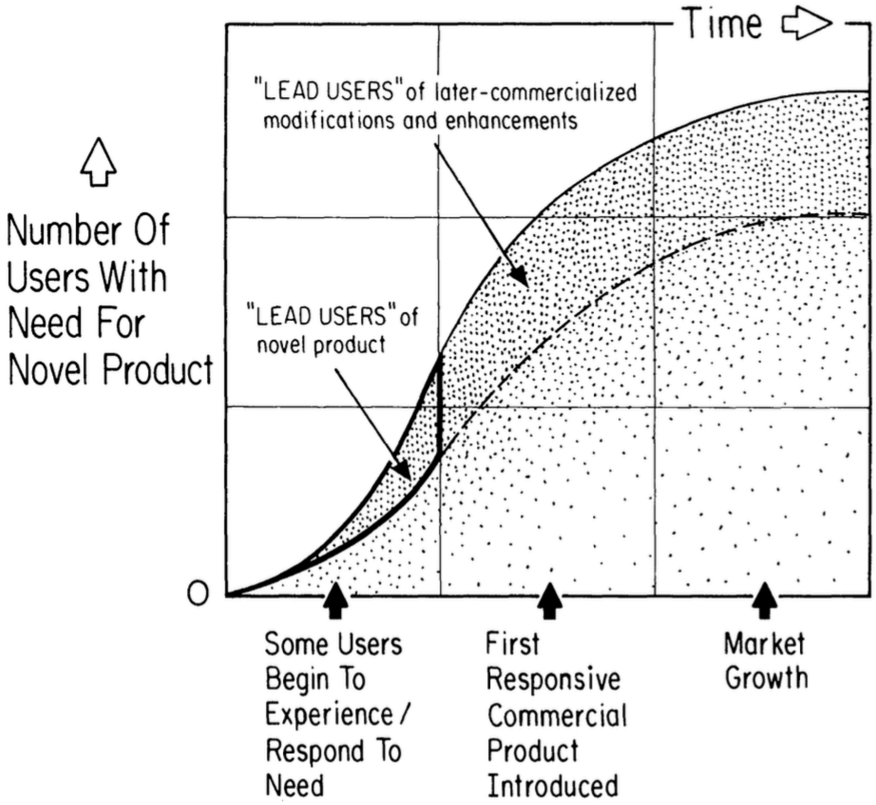


Figure 4: Position of Lead Users in the life cycle of new products. Source:[25]

An important concept enabling user innovation is the capacity to innovate (C2I), which Allebone-Webb et al. generally define as "the ability of actors to continuously identify constraints and opportunities, and to mobilize capabilities and resources in response" [27, p. 1]. In a paper exploring C2I in adaptable farming systems, Allebone-Webb et al. [27] describe a framework of capacities encompassing C2I dimensions in the context of understanding and strengthening local innovation systems, identifying four capacities encompassing C2I:

1. Creation of novel methods and strategies
2. Access to social network for expanded resources
3. Experimental, iterative approach to enable adaptative response
4. Collaboration for action and transformation

The first capacity for innovation is the ability to envision and create new methods and strategies, the ability to use creativity to adapt to identified problems and to have an open mindset. The second capacity relates to the ability to access resources and information relevant for innovation through other people, which is related to social networking and communicating and comprehending information. The third capacity is to have a flexible, iterative approach, a willingness to experiment, take risks and adapt based on the result. The fourth capacity entails co-creation and collaboration to incite change, being motivated to participate in innovation and being able to facilitate and motivate others to achieve action. These capacities are inherently connected, and each dimension can be broken down further into sub-capacities [27].

Allebone-Webb et al. [27] generated a list of indicators of C2I based on the four key capacities identified in their literature review to track impact on programs intended to strengthen local innovation systems and C2I. These are presented for evaluation at three levels: individual, community, and local system. At the individual level, C2I skills and abilities and one's confidence in one's skills and abilities indicate level of C2I along with quantity and quality of experimentation. At the community level, indicators include quality of stakeholder engagement and collaboration for collective action, strength or numbers of innovation-related organizations, strengthened network, and innovation outputs. At the local system level, institutional changes and shifts in social norms and attitudes to enable innovation indicate C2I [27].

These indicators assess the *products* of innovation and the *processes* of innovation to support strengthening of local innovation systems. This departs from more traditional metrics which focus solely on outputs or products of innovation. As C2I increases, so should the quality of products of innovation, the effectiveness of innovation processes, and overall occurrence of innovation activity [27]. Based on Von Hippel's LUT, understanding and increasing C2I may have important implications for accessing lead users in product development.

Scholars have initiated research in LUT and innovation in developing contexts and in relation to design processes. Among several identified factors affecting the effectiveness of the product development process for BoP contexts, Viswanathan & Sridharan [1] explain that lead users, more than typical users, have the ability to draw insights through aspiration and creativity, and therefore offer valuable input into the design process. Students in Viswanathan & Sridharan's case study identified innovative users who created their own solutions because of the lack of commercially available products. In contrast to consumers in developed markets, consumers in BoP markets are limited by financial, social and time constraints, among other barriers, which prevent significant investment in exploring new concepts. The authors discuss how these innovative users share characteristics with Von Hippel's Lead Users, but more research is needed to identify characteristics unique to BoP contexts [1].

Ross et al. [2] analyzes LUT in the context of co-design and BoP context to identify characteristics of lead users that produce positive co-design outcomes in BoP markets using a case study of co-design of an improved cookstove with a lead user. Extended research on Von Hippel's LUT identifies the importance of users' technical expertise and access to prototyping resources for increasing the propensity to innovation [28]. Ross et al. [2] use Von Hippel's original two characteristics of Lead Users as well as these two indicators of C2I in their analysis. Their results indicate that being ahead of trend or encountering needs before other users did not correlate with co-design outcomes. In addition, in engaging lead users in co-design, users innovate because of high expected benefits, both from the product and process of co-design, including social benefits of increased self-esteem and standing in the community, and capacity-building in developing technical skills associated with constructing the innovation product.

Technical expertise and knowledge of construction and materials for creating stoves proved significant for the lead user in participating in co-design with the design team. More importantly than access to prototyping materials was the lead user's strong social network which allowed her to elicit feedback from other users [2].

Ross et al. [2] also identified a missing element in the framework, which is design communication, or the ability of the lead user to turn user needs into technical design features in communication with the design team. Scandinavian pioneers of PD also explain the importance of communication among stakeholders in the design process. According to Grudin [19], the different types of knowledge possessed by users and technical specialists can present communication barriers, so engineers with technical knowledge and users with practical understanding must learn to communicate with each other to facilitate deep mutual understanding of context. The ability of the lead user to communicate with the design team and the lead user's comprehensive understanding of community needs and ability to turn those into design features was seen as more important than the lead user being ahead of the trend or having unique needs [2]. Based on these results, Ross et al. [2] present a new framework for characteristics of lead users linked to positive co-design outcomes:

- May benefit socially, financially, and in skill-building
- Has technical expertise
- Has good design communication skills
- Has access to user preferences through a social network

Scholars agree that innovation capacity represents an important characteristic of lead users. In particular, Ross et al. [2] and Allebone-Webb et al. [27] both emphasize the importance of social networks and communication for collaboration for enabling innovation in BoP contexts. To contribute to positive PD outcomes, lead users may also need technical expertise, beyond the tacit knowledge of typical users, related to the particular product to allow them to effectively turn user needs into design features in communicating with the design team. While being ahead of the trend proved to be an important characteristic in lead users in developed markets, this may not apply to users in BoP contexts, possibly because some of the technologies which need innovation and improvement in these markets are not rapidly evolving as in Von Hippel's original framework. However, modified frameworks of LUT present useful tools for assisting in selection of users for participation in co-design and may also be helpful in analyzing local innovation systems.

2.2 Case Study: Biomass Cooking and Heating

Around the world, 2.4 billion people use biomass fuels, coal, and kerosene for cooking using open fires and traditional stoves with thermal efficiencies as low as 5% [29]. Over half, and in some cases up to 100%, of rural residents in developing countries use these traditional methods of cooking, which results in extremely high levels of indoor air pollution, up to 20 times higher than what is recommended as safe by the World Health Organization [30]. In 2020, 3.2 million deaths worldwide from respiratory infection, lung cancer, heart disease, and stroke were directly linked to household air pollution (HAP) [29]. Biomass stoves and open fires prevail in communities around the world as a primary method of cooking and heating, due in part to the easy access and affordability of this fuel and technology, but these practices cause deadly health complications, especially in women.

While traditional biomass technology causes serious health issues in users, these stoves present several significant benefits which perpetuate their usage in communities around the world and make it difficult for improved stove programs to achieve widespread adoption. Traditional stoves possess a number of benefits for users, including the ability to cook traditional dishes with preferred utensils–benefits that go unrecognized in large-scale program efforts [31], [32], [33], [34], [35], [36]. Even households with access to liquified petroleum gas (LPG) stoves persist using their biomass cookstove because they prefer the taste of food cooked on traditional stoves [37], [38]. Furthermore, where improved cooking and heating stoves are adopted, they are used in tandem with traditional stoves in a process called "stove stacking," where households use different stoves for particular cooking tasks [32], [35], [38], [39], [40]. In cold regions, space heating from biomass stoves is of particular importance, especially in high altitudes where temperatures drop below freezing in winter [32], [33], [35], [36], [37], [41], [42], [43]. The many benefits of traditional stoves create challenges for improved stove programs looking to promote new designs and change cooking practices in order to reduce emissions and HAP. These challenges are further exacerbated when programs fail to recognize these and other user needs related to cooking and heating in context.

Many cookstove projects have been implemented around the world in under-served communities, and many have been unsuccessful because organizations failed to understand and meet the needs and values of the community. This is a common reason for failed global development projects in BoP markets [2], [12], [44], so there is a need for engineers and designers to better understand community context throughout the design process when developing technology. According to the World Bank [30], failed past cookstoves programs paid little attention to stove design, market development, and consumer research which are essential to long-term, sustainable business growth. Some early programs distributed improved stoves demonstrating high efficiencies in lab testing; however, these stoves often performed poorly in the context of real use, and often failed due to poor quality [30], [43], [45].

Even for stove programs that focused on design, manufacturing and marketing of stoves that met thermal efficiency and emissions requirements set by the scientific community, there was a lack of emphasis on investigating stove adoption and the social process of technology diffusion, and an assumption that superior technical performance of improved stoves was the only necessary motivation for widespread adoption [33], [42]. For example, some improved stove programs required adopters to change cooking practices and traditional recipes or limited the type and size of the utensils used for cooking. Neglecting to account for local context such as cooking practices and available pots and pans may explain the lack of widespread adoption of improved cookstoves [43]. In addition, past programs intended the improved stove to replace the traditional stove, but this rarely occurred in practice. This conflict between intended and actual usage demonstrates the historical lack of connection among users and the cookstove design and engineering community, and the resulting inability of stove designs to meet user needs and achieve desired impact. The historical neglect of local context, user needs, and cooking practices in stove programs demonstrates the need for increased user involvement in the design and development of improved cooking technologies for sustainable impact.

While there are many historical examples of unsuccessful programs and stove designs, there are also several examples of successful stove programs and designs that effectively incorporate user needs and local context. For example, the Kenya ceramic Jiko (KCJ) stove has achieved widespread adoption across Africa. First developed in 1982, the KCJ charcoal stove is used in over 50% of urban Kenyan households today, owing its success in part to the incorporation of design features from the traditional Jiko stove and the compatibility with local cooking practices [46], [47]. A more recent example is the Matribhumi Urja improved stove (M-ICS) in Nepal. The M-ICS design has been thoroughly tested and iterated over the past decade to be easy to use and maintain as well as improve HAP and thermal efficiency [48]. In addition, Matribhumi Urja's distribution model leverages existing community networks in remote villages in Nepal. Matribhumi Urja stove masters travel to communities and host training workshops in which they teach local women how to build the M-ICS using locally available clay and the Matribhumi Urja construction kit. Once women are trained in the construction process, they earn income by building M-ICS in homes in their community. KCJ and M-ICS represent two of several operations that successfully created and implemented programs to design and disseminate stoves that reduce HAP while meeting user needs in local context.

2.3 Biomass Stove Design

2.3.1 Technology Overview

Biomass stoves vary greatly across communities worldwide. Stove designs can be classified as "traditional" or "improved." Traditional cookstoves (TCS) refer to indigenous designs familiar to users with long-standing utility in communities, whereas improved cookstoves (ICS) typically refer to stoves designed with the intention of improving thermal and fuel efficiency using engineering principles [30], [45], [49]. TCS designs range from three-stone open fires to large, semi-permanent clay fixtures in household kitchens [45], [49]. ICS designs include portable manufactured metal stoves (such as the one in Figure 5) and heavy fixed stoves made from clay, cement, mud, and/or ceramics with improved efficiency and emissions to reduce air pollution and fuel usage [49], [50]. Stove performance is characterized in terms of both efficiency and emissions [50], [51]. The different metrics used for these characteristics are discussed in detail in Chapter 3.

Figure 5: Greenway Smart Stove. Source: [52]

Literature discusses biomass cookstoves and biomass heating stoves separately, but in practice households in colder regions often use TCS for space-heating benefits as well [30], [32], [33], [35], [36], [37], [41], [42], [43], [53]. In the academic community, the few improved stoves designed for both heating and cooking are denoted dual-purpose or multi-function [49]. In this section, I describe biomass stoves generally in terms of operating principles and relevant design features used to improve combustion, heat transfer, and fluid flow, then I offer insights specific to both cooking and heating stoves because of the importance of both functions to the region described in the following case study.

2.3.2 Engineering Design Principles of Biomass Stoves

Biomass stoves operate with governing principles of combustion, fluid flow, and heat transfer. These processes create complex phenomena and interactions in stoves, making designs challenging to model and improve [50], [54]. However, literature identifies both best practices and design features for improving complex processes in biomass stoves. This section presents an overview of these principles and practices for improving stove performance.

Combustion

The first process of interest in biomass stove design is combustion, which is the chemical reaction between fuel and oxygen that supplies heat for the stove. Combustion of solid fuels, such as wood, agricultural waste, charcoal, etc., starts with heating the fuel, which causes the breakdown of chemical bonds and the release of volatile gasses. These gasses react with oxygen in the air and ignite to release heat [55]. Figure 6 illustrates this process on a matchstick. Complete combustion of the fuel produces water vapor and carbon dioxide [56], but incomplete combustion produces pollutants such as particulate matter, carbon monoxide, NOx and SOx [57], known as products of incomplete combustion (PICs), which are detrimental to health and the environment [29], [53], [55]. Cleaner and more complete combustion means that the chemical energy stored in the fuel is more fully converted to heat, resulting in a higher combustion efficiency [57]. Maintaining high temperatures allows for more complete combustion and cleaner emissions from the stove [57], [58]. Some stoves use gasification, or indirect combustion, which separates the combustion process into two steps—the release of volatile gasses from the solid fuel to form char (pyrolysis), and the burning of the volatile gasses—to improve emissions and efficiency [54].

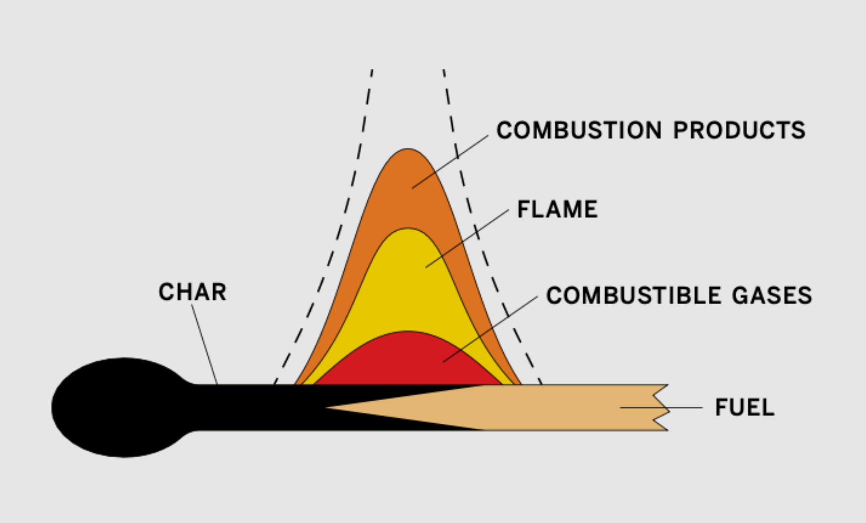


Figure 6: Combustion of solid fuels illustrated on a matchstick. Source: [55]

Combustion of volatile gasses occurs around 550°C and can reach up to 1100°C, so the materials used in the combustion chamber (the part of the stove where the combustion process occurs) must be able to maintain and withstand these high temperatures [54]. Common metals, though highly conductive and useful for maintaining high temperatures, are not durable enough to withstand fire temperatures long-term. While heavy materials, such as clay and ceramics, are much more durable, these have high thermal mass, so they absorb heat initially, cooling the combustion process [50], [54], [58]. To mitigate this, designers can use small masses of these durable materials, such as ceramic tiles, around the combustion chamber to withstand fire temperatures, and then insulate around them to maintain high combustion temperatures [58]. This allows the outer body of the stove to be made from metal while maintaining material integrity and high temperatures in the stove, seen in Figure 7.

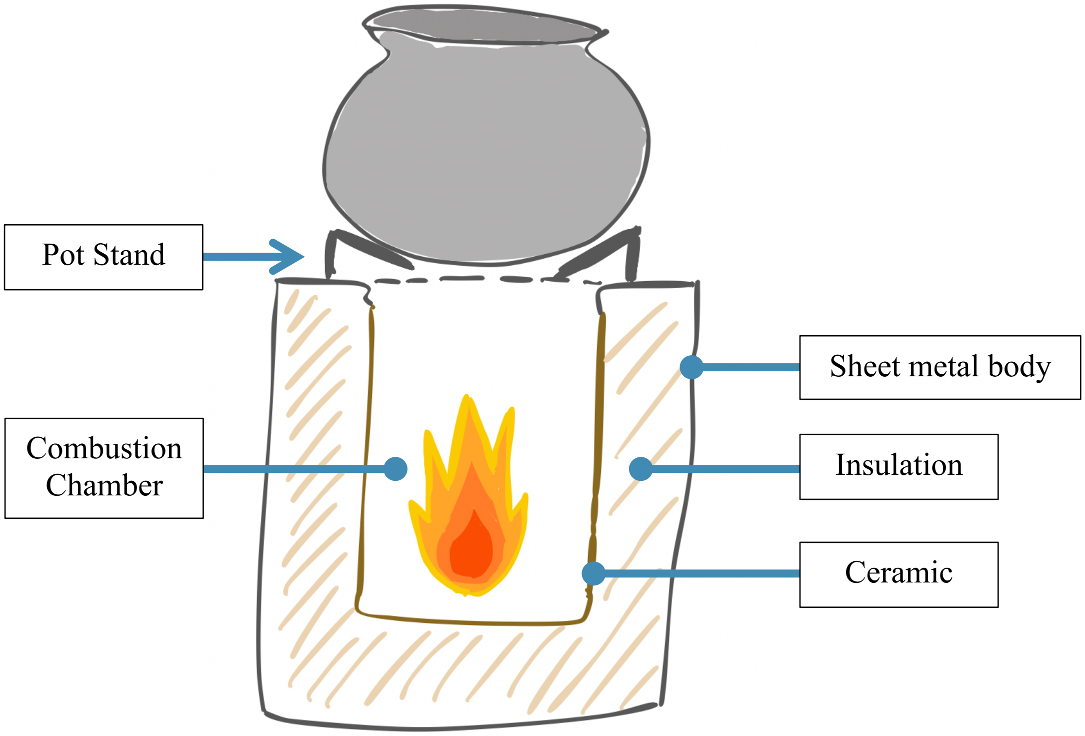
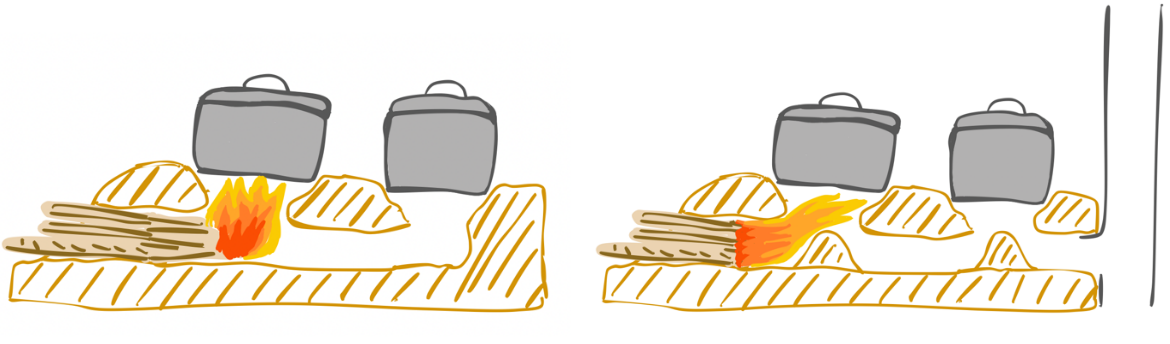


Figure 7: Cross-section of improved stove

Fluid Flow

To allow for complete combustion, stoves need air supply to provide oxygen to react with the fuel, and sufficient mixing of volatile gasses with the air. Many stove designs use natural convection to drive air flow since this is less expensive than forced draft stoves [50]. In natural draft stoves, like the ones in Figure 8, the density of hot flue gasses from combustion is lower than the density of ambient air because of the increased combustion temperatures, resulting in a natural, buoyant flow of ambient air into the stove [55]. However, utilizing this natural flow means stove performance is very sensitive to geometric design parameters and increased difficulty in modeling since natural convection is more closely coupled with heat transfer and combustion processes [50]. Some improved stoves contain fans to provide forced draft for more control over the air supply and draft speed [55], including most gasifier stoves which have much cleaner combustion [50]. Stoves need excess air (more than stoichiometric) and proper mixing of the air with volatile gasses from the fuel for more complete combustion [50], [55]. Too much air cools the fire, so designers have to engineer stoves to achieve high temperatures with sufficient oxygen for optimal combustion.



(a) (b)

Figure 8: Cross-section of two-pot (a) traditional stove (b) improved chimney stove

Grates are one design feature used to assist primary air flow in stoves. These are typically made of metal and elevate the fuel while allowing air to pass through them. They are placed in combustion chambers to allow air to flow through them and over the fuel [50], [54], [57], [58]. Chimneys are also seen as aiding in combustion by creating draft that pulls air through the stove and out the chimney [54]. Chimneys are also seen as important features for removing pollutants from the kitchen to reduce exposure and associated health risks [58]. Because chimneys increase draft in stoves, they can draw too much air into the stove and cool combustion. Reducing the chimney diameter can reduce the draft and allow more complete combustion, but a chimney that is too small can choke the fluid flow and cause combustion products to flow out of the fuel inlet of the stove (fugitive emissions) [55]. Scholars also recommend small firebox openings to limit the amount of air and prevent cooling in the combustion chamber [58]. However, small firebox openings require users to reduce the size of the fuel into smaller pieces, increasing the burden of fuel processing [59]. Dampers are also used to control air flow and stove power, but this limits the air flow and can cause incomplete combustion [50]. Slowing draft also reduces convective heat transfer, so dampers typically worsen stove performance [54], [58]. Some stoves provide secondary air downstream from the combustion chamber to burn remaining products of incomplete combustion by adding air inlet holes near the exit of the stove [55]. Other stove designs incorporate internal geometric features, such as vanes or a choke ring, to disrupt fluid flow and promote mixing of flue gasses for more complete combustion [55].

Heat Transfer

Heat transfer processes are necessary for transferring energy from burning fuel to the desired end and executing the desired stove function. Heat transfer in stoves occurs through conduction, convection, and radiation (Figure 9). Heat is conducted through the combustion chamber walls and stove body. The flow of air and hot flue gasses causes convective heat transfer to the stove and other contact surfaces [57]. Radiation from the fire heats the stove and other surfaces in view [55], [57].

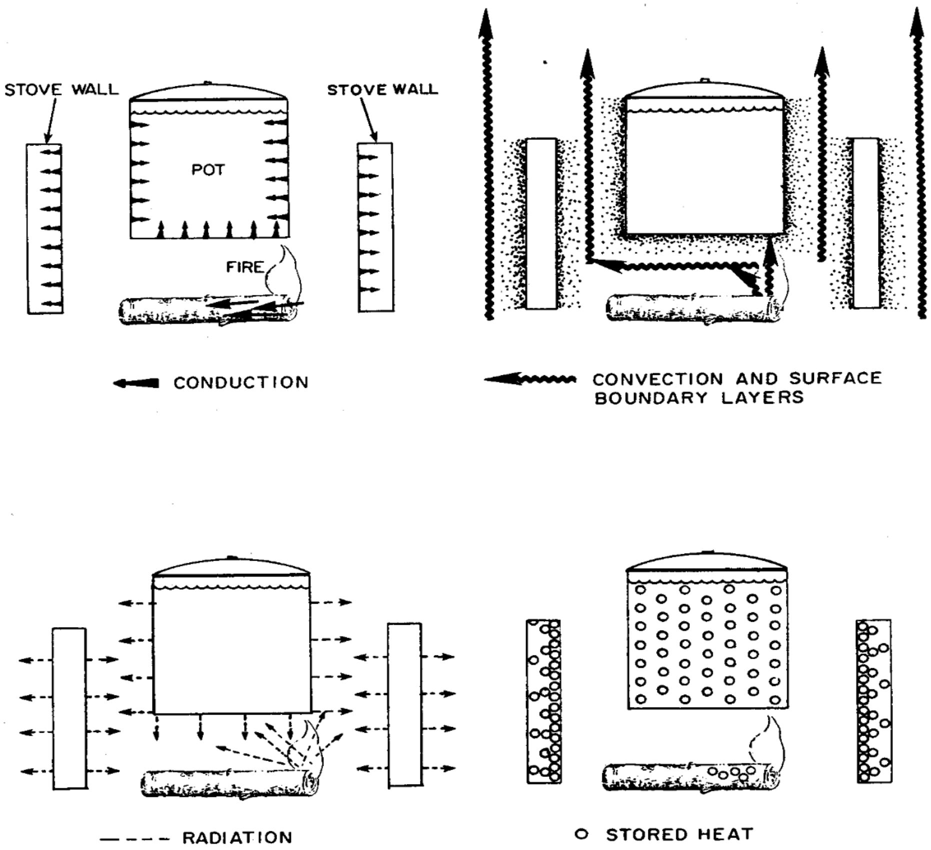


Figure 9: Heat transfer modes in cookstoves. Source: [57]

Heat can also be stored in the stove itself. For stoves with high thermal mass (heavy clay stoves), large amounts of heat from the fire and hot flue gasses are absorbed by the body of the stove, to be released slowly as radiative heat [57], [58]. Table 1 compares the heat transfer pathways in two chimney cookstoves. In open fires, only 15% of energy from the fire is absorbed by the pot, with 85% being transferred to the environment [60]. In Baldwin's study [57], a stove made of heavy thermal mass absorbed 29.2% of energy from the fire, whereas the uninsulated metal stoves lost 40.4% of heat through the stove body. In both stoves, the chimney routed 22 to 39% of the heat from the fire out of the kitchen. Small losses occur from incomplete combustion of the fuel [57].

Table 1: Heat transfer pathways in two chimney stoves, in percent of total heat

Heat Transfer Pathway	Absorbed by pots	Absorbed by stove body	Convection & radiation through stove body	Chimney exhaust	Lost due to incomplete combustion	Other
Heavy stove with chimney (2 pot)	15.4	29.2	1.9	39.0	2.7	11.8
Uninsulated metal stove with chimney (2 pot)	27.9	2.0	40.4	22.2	7.8	-

*All data from [57]

Increased velocities reduce the boundary layer on surfaces in contact with flowing hot gasses, allowing more convective heat transfer [57]. In metal stoves with high conductivity, designers add insulation to prevent heating losses through conduction to the environment [50], [57], [58]. Optimizing the combustion process improves emissions, but losses in thermal efficiency primarily occur in transferring heat from the fire to the pot for cooking or the room for heating [54], [57]. The following sections assess function-specific design considerations for improving stove performance and reducing fuel usage.

Cooking Specific Considerations

ICS are designed to optimize heat transfer from the fire to the pot(s) for improved performance. Baffles are one feature used to direct the flow of hot gasses toward the pot for improved heat transfer [50]. Scholars remark on the significance of the cooking utensils on stove performance, and recommend using metal pots with large, flat bases to maximize conduction and surface area for heat transfer to the pot contents [54], [58]. However, literature on cookstove adoption recommends designing stoves to accommodate user choice of utensils and other contextual factors for sustainable impact [43]. Other considerations include the gap between the stove and the pot, sometimes referred to as channel gap, which can be designed to promote high speed flue gasses contacting the pot for enhanced convection [57]. Designers also have to consider the distance between the fire and the pot. Too large distance reduces view factor for radiation heat transfer from the fire to the pot; too small and the pot will cool the fire temperature and cause incomplete combustion, so designers have to carefully choose this distance and validate with testing for best performance [54], [57].

Performance aspects relevant to the user include turn down ratio and pot power ratio (PPR) in multi-pot stoves. The turn down ratio describes how well the user can adjust the power output of the stove [54] and is defined as the ratio of maximum to minimum firepower for a stove [55]. Cooking tasks may require high power (such as bringing water to boil), medium power, or low power (such as simmering), so it is important for the cook to be able to control the output power of a stove [57]. In addition, multi-pot stoves involve transferring heat to more than one pot. These stoves have increased surface area just by having more than one pot to transfer heat to [57]. Tang developed PPR as a performance metric for biomass stoves in the Himalaya. PPR is the ratio of power of the primary pot to the secondary pot in 2-pot stoves [41]. The distribution of heat among multiple pots is an important usability characteristic for cooks who expect to execute multiple cooking tasks at the same time on their multi-pot stove.

Heating Specific Considerations

In designing heating stoves, it is important to consider the method of heat transfer from the fire to the room. Bryden et al. [56] provide a useful guide for types of heat exchangers used in biomass heating stoves, and how to choose between them. These types include hot flue gasses heating either thermal mass or air in the room.

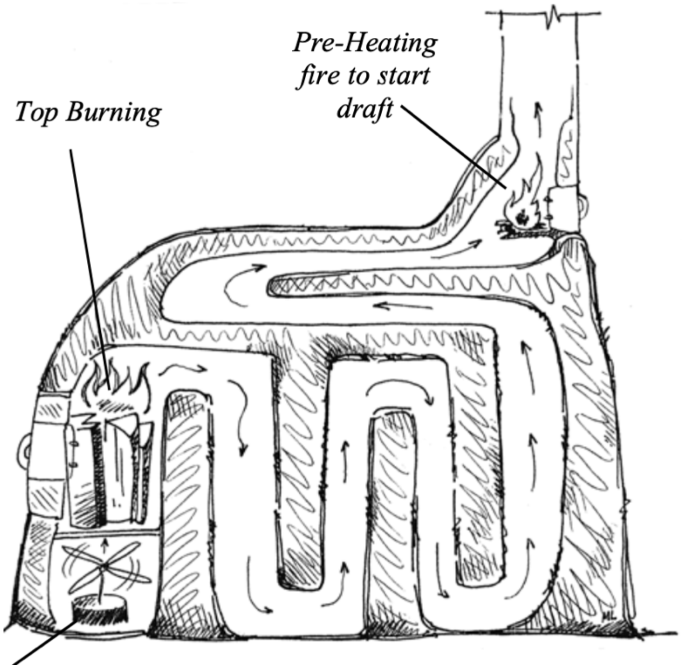


Figure 10: High mass heat exchanger with forced convection. Source: [56]

One of the primary considerations for choosing between these types is the air exchange rate in the room. Large thermal masses, like the one in Figure 10, are useful in homes where room air is replaced regularly, through open windows or doors or through leaks and cracks in the home, since the stove stores large amounts of heat that is slowly transferred to the room through radiation. In contrast, air heat exchangers heat the room air only to have it flow outside in more drafty homes with high air exchange rates [56]. Kitchens which use unvented stoves indoors are designed to be drafty, allowing some air infiltration to remove pollutants from biomass combustion [41]. Air heat exchangers, such as in Figure 11, can be used in homes with insulation and sealed cracks since it will be retained in the room. Thermal mass heat exchangers allow heat to be released slowly, providing gentle radiative heat for relatively stable room temperatures, but these masses also take long periods to heat up, and the rate of heating cannot be adjusted once the energy is stored [56].

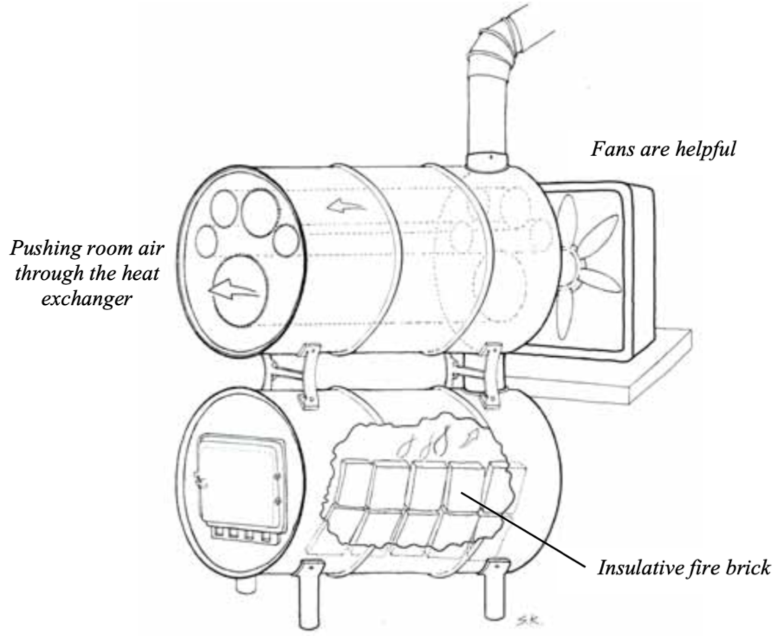


Figure 11: Air heat exchanger made from two 55-gallon drums. Source: [56]

On the other hand, air heat exchangers (typically made from metal) heat up quickly and can be more easily adjusted by the user if the weather changes suddenly [56]. Low thermal inertia also facilitates hotter combustion temperatures since the stove quickly heats up. Thermal mass stoves also take up more space and are much heavier than air heat exchangers. However, large thermal inertia also means that thermal mass stoves can be fired at high power in large burns without overheating, which allows for improved efficiency. To match efficiency, air heat exchangers have to accommodate smaller, hot fires to improve emissions. To increase heat transfer in chimneys, non-circular conduits maximize the surface area to cross-sectional area ratio in the chimney and allow for more contact between the chimney and hot gasses. A shallow, rectangular chimney is better in this case than a circular chimney pipe [56].

2.4 Applying Theory to the Case Study

2.4.1 Participatory Design in Biomass Stoves

The benefits of using participatory design approaches are now being appreciated in development of improved cookstoves. Studies of cookstove programs promote user participation to meet objectives and achieve long-term impacts on health and the environment by allowing a deeper understanding of local context and user needs [35], [45], [61]. Literature outlines several examples of designers consulting users in different parts of the design process, especially in problem-framing and opportunity identification [31], [34], [35], [36], [37], [38], [39], [41], [62]. Honkalaskar et al. [42] describe one example of co-design in cookstove product development, in which they worked with women and villagers to inform and identify the highest priority need, devise testing methods, and provide feedback on the designs, and engaged local blacksmiths in manufacturing and distribution of the resulting product. However, few cookstove projects engage users as peers in the design process for increased participation. The complex phenomena involved in biomass stoves make successful design of these technologies highly technical and challenging. Leith et al. [21] explain how user-centered design may be better for more technical solutions, unless end-users also possess the necessary technical expertise. For technically complex biomass stove projects using participatory design methods, user-centered design is a common level of engagement because users may not have technical knowledge of combustion, fluids, or heat transfer needed to inform design decision-making for this type of technology. However, users in some regions possess technical skills in constructing, maintaining, and tending traditional cookstoves [41]. There is an opportunity for stove designers to collaborate with users in co-design to leverage engineering expertise in stove processes and practices and indigenous knowledge of construction and materials for stove innovation. Increased participation in the design process increases users' feeling of ownership over the solution [21], which may lead to increased adoption and sustainable impact of the design.

2.4.2 Innovation Models & Biomass Stoves

Design and innovation are closely linked in practice and in literature. According to Edwards-Schachter [63], innovation must be implemented in some way to move from being an invention to an innovation. Innovations are often classified based on the nature of their impact, as seen in Table 2.

Table 2: Innovation Typology

Type of Innovation	*Impact*
Incremental	Technology Improvements in existing systems
Radical/breakthrough	New Technology Competencies
Disruptive	Full replacement of the mainstream product in the market
Transformative	Transformation of socio-political systems involving technology and the market

Incremental innovation focuses on technology improvements in existing systems [64], optimizing or refining existing products to better meet current user or market needs [65]. Alternatively, disruptive innovation focuses on market impact [66], [67], [68], while radical or breakthrough innovation centers around the creation of new technical competencies [63], [64], [65]. Transformative innovation is defined as impacting socio-technical systems as well as the market, resulting in system-level change and innovation [63].

For design in development, Viswanathan & Sridharan recommend the bricolage approach rather than the breakthrough approach to innovative products [1]. Breakthrough or radical innovation, while adopted slowly, has the potential to create dramatic changes in technology frames [65]. In contrast, the bricolage approach can be considered a type of incremental innovation that involves designing a low-tech solution and iteratively developing it through engaging with local stakeholders [1].

Some literature suggests that incremental innovations that improve existing cooking and heating systems may be more successful than disruptive innovations intending to replace traditional biomass stoves. This type of incremental innovation is also referred to as an “intermediate”, or “additive” solution [43, p. 23], and scholars believe these may have more success than disruptive or mass-manufactured improved stove designs because solutions that improve rather than replace traditional technologies allow for “gradual transitions, design experimentation, and greater latitude for participation by stakeholders” [61, p. 4] and do not require users to change cooking practices to adopt them [43].

Other cookstove projects pursued these types of solutions with positive reception, preserving the usability of traditional stoves while reducing emissions or improving heat transfer [43], [69]. For example, Khandelwal et al. [43] experimented with a metal insert for traditional stoves that introduced secondary airflow to effectively reduce emissions and fuel usage. Udaykumar et al. [36] also describe designing and testing a metal fuel grate in Rajasthan, India, the dimensions of which were easily modified to accommodate different stoves and contexts. Because of the diverse cooking practices and utensils across India, Udaykumar et al. [36] argue that solutions must be customizable to fit local context in order to achieve desired impact on biomass fuel usage. This aligns with general principles of design in development to design for local customization and adapt designs according to local contextual factors [1], [18], [24]. Incremental innovations in biomass stoves seem to align with design principles for development and allow for increased participation by users in the design process to achieve sustainable impact.

2.5 Value and Contribution of this Work

The work described in this publication is part of a larger, long-term effort by MIT D-Lab on biomass cooking and heating, home energy and thermal comfort. In the Himalayan region of India and Nepal, the issues of indoor air pollution and energy poverty are especially exacerbated. During the winters, many residents in these rural areas rely on traditional clay cookstoves for both cooking and heating, but homes still remain around the same temperature as the ambient freezing outdoors. In addition, these communities have very limited access to resources—some are only accessible by two-day hike or helicopter because of poor infrastructure—so households lack easy, affordable access to alternative methods of cooking and heating. Himalayan communities have also been overlooked in large-scale development programs due in part to their remote locations and small populations. Improved stove companies instead opt to target urban areas with established infrastructure and reliable income rather than remote villages or households with low socioeconomic status [32]. In the Himalaya, many homes lack chimneys for their wood-burning stoves. Past research by MIT D-Lab in the Himalaya shows that levels of indoor air pollution are orders of magnitude above what is considered safe by the World Health Organization, putting these communities at high risk for illness and early death [41], [70].

The MIT D-Lab Himalayan Home Energy (HHE) Project addresses issues of indoor air pollution and home energy in the Himalayan region by engaging users in the design process using PD methods to ensure solutions meet their needs and match local context. Over the past decade, researchers at D-Lab have cultivated relationships with various partners in India and Nepal and rely heavily on these partners to coordinate field research and testing in remote communities to help achieve D-Lab goals for research, education, and practice. Over the past several years, students, researchers and local partners gained a holistic understanding of cooking and heating needs and practices in the Himalaya through conducting user-centered research investigating traditional stove construction and efficiency as well as user needs related to cooking and heating technology, among other contextual factors to inform new stove designs.

When I started working on the HHE project for my thesis, there was interest from partners, communities, and researchers in exploring solutions to many of the problems identified during previous field work. As a result, my work centered on prototyping solutions to address home energy needs in the Himalaya through PD methods. I describe the pre-travel work and field work in-depth and provide reflections on the processes and products of PD to contribute to design methodology research and inform engineering design practice for development. Specifically, the approach we took to experimentation and design to increase participation of users in design of technical artifacts with cultural significance and the use of prototyping to facilitate mutual learning among stakeholders provides important insights for future work in design research.

Chapter 3: Methodology

To effectively contribute to research in the fields of design methodology and biomass stoves, I employed a variety of methods in design strategy and data collection and analysis to assess the described work. This section explains the participatory design methods used and how I define different levels of participation and reports challenges and limitations of the approaches as well as the experimental and field research methods of assessing user needs and technical performance as they relate to household energy and biomass stove technologies.

3.1 Participatory Design Framework

The participatory design spectrum outlined by Leith et al. [21] is defined by the level of participation of resources-constrained communities. I use this framework, with the addition of a "level 0" from Robinson et al. [22] to discuss the level of participation employed during different parts of the project based on the roles and contributions of stakeholders involved. In line with Burleson et al. [23], I also explain the context and logic behind design decisions and the chosen level of participation for different parts of the project to provide as much detail as possible on our design process. Challenges and limitations are also discussed for each portion of the project. The following sections of this chapter explain the quantitative and qualitative methods of data collection and analysis employed for investigation.

3.2 Stove Performance Method

Experiments were conducted using a modified version of the standard Water Boil Test (WBT) described in the IWA 11 standard to measure emissions and performance of the stove under different design conditions [71]. The standard WBT was modified by the International Standards Organization in 2018 to create the current standard ISO 19867 - Clean Cookstoves and Clean Cooking solutions [51]. The tests conducted previously by Tang followed the modified IWA 11 testing protocol, so this method was preserved in this experimentation such that the results were directly comparable to results from Tang's field and lab experiments, rather than adopting the updated ISO 2018 method. Since the update, researchers have published findings comparing these standards, so future investigations can adopt the new protocol and use these findings to compare results with prior work using IWA 11 [72].

The operating principle of the WBT is that the amount of energy necessary to raise the temperature of a mass of water is known (specific heat) and for wood fuel of a known calorific value, the thermal efficiency can be calculated for a known temperature change. Thermal efficiency is defined as the ratio of the net energy output to the energy input, which in this case is the ratio of the heat transferred to the water to the chemical energy stored in the wood fuel. By measuring the temperature change in 2 Liters of water, the heat transferred to the water can be calculated. Measuring the amount of fuel used in this process allows calculation of the total energy stored in the wood based on the lower heating value (LHV). I use $LHV = 16.2\ MJ/kg$ for mixed hardwood to analyze lab tests. $LHV = 17.8\ MJ/kg$ is used for Chir pine for field tests.

$$\eta_{cooking} = \frac{Q_{pots}}{E_{wood}} = \frac{m_{water}\, c_{water} \Delta T}{m_{wood} LHV} \tag{3.1}$$

$$\eta_{cooking} = \frac{m_{water,total}\, c_{water}(\Delta T_{pot1}+\Delta T_{pot2})}{m_{wood} LHV} \tag{3.2}$$

For stoves with more than one pot, the temperature of both pots is monitored, and the efficiency includes the useful heat transferred to both pots. The modified WBT consists of two high power phases: a cold-start phase and a hot-start phase. In these high-power phases, the fire is tended to maintain maximum heat transfer to the pot, so the tester consistently adds wood pieces to fill the firebox to replace the ones that are consumed and turned to charcoal. The cold phase starts with the stove at room temperature. The cold phase ends when the water reaches 90°C to prevent evaporation and mass loss from occurring. The hot phase starts right after the cold phase concludes and the water is replaced, when the stove has absorbed some heat from the fire. The pots are covered with tight-fitting lids throughout the test to reduce evaporative losses. The overall thermal efficiency for the cooking vessel is calculated from the combined heat transferred in both phases.

$$\eta_{cooking} = \frac{Q_{cold} + Q_{hot}}{E_{wood}} = \frac{\dot{Q}_{cold}\, t_{cold} + \dot{Q}_{hot} t_{hot}}{E_{wood}/(t_{cold}+t_{hot})} \tag{3.3}$$

Aggregated emissions are measured and reported for testing. Average emissions, emission rates and emission factors are reported for each pollutant. Carbon dioxide (CO_2), carbon monoxide (CO), and fine particulate matter (PM 2.5) are reported. Lab tests additionally measured oxygen (O_2), nitrogen dioxide (NO_2), nitrogen monoxide (NO), and sulfur dioxide (SO_2) concentration levels during the test. Lab testing in this project measured total emissions from the stove (including the chimney) whereas field testing measured fugitive (indoor) emissions only. The specifics of the lab and field experimental setups are described in more detail in later chapters. See [41] for information on the instrumentation and sensors used for testing.

I calculated emissions statistics using the carbon conservation method described in ISO 19867 [51], [73], which assumes that the carbon in the fuel (which is assumed to be $C_6H_{10}O_5$) combusts to form CO_2, CO, and PM 2.5. The mass of carbon is conserved, so using the mass of fuel burned and the measured concentrations of pollutants, the mass emissions for each pollutant can be calculated. PM 2.5 is assumed to be 80% carbon by mass, and the concentration is measured in grams per cubic meter. CO_2 and CO are measured in parts per million (ppm), so these are converted to mass concentrations to allow calculation of emissions. I use Equations 3.4 – 3.9 for this analysis.

$$C_i\ [g/m^3] = C_i[ppm]\frac{M_i P}{RT} \tag{3.4}$$

$$C_{carbon,i} = C_i \frac{M_{carbon}}{M_i} \tag{3.5}$$

$$C_{carbon,total} = \sum C_{carbon,i} \tag{3.6}$$

$$m_{carbon,total} = m_{fuel}\frac{M_{C_6}}{M_{C_6H_{10}O_5}} = m_{carbon,PM} + m_{carbon,CO} + m_{carbon,CO_2} \tag{3.7}$$

$$m_{carbon,i} = m_{carbon,total}\frac{C_{carbon,i}}{C_{carbon,total}} \tag{3.8}$$

$$m_i = m_{carbon,i}\frac{M_i}{M_{carbon}} \tag{3.9}$$

Emission factors (EF) and emission rates (ER) are then calculated based on the total mass of each pollutant for each test using Equations 3.10 – 3.11.

$$EF_i\left[\frac{g}{MJ}\right] = \frac{m_i}{Q_{water}} = \frac{m_i}{\dot{Q}_{water}t_{test}} \tag{3.10}$$

$$ER_i\ \left[\frac{g}{min}\right] = \frac{m_i}{t_{test}} \tag{3.11}$$

Together, efficiency and emissions metrics characterize the performance of biomass stoves.

3.3 Qualitative Research Methods

In addition to quantitative testing on stove efficiency and emissions, the team conducted qualitative research to continue developing an understanding of the challenges related to cooking and heating in the Himalaya. Qualitative methods are used extensively in marketing and design research, especially to increase depth of understanding and explain and explore user motivations, attitudes, and behaviors [74], [75]. Ethnography, a qualitative research method, emphasizes immersion in subject activities in natural settings and understanding behaviors from the subject's point-of-view [76]. Ethnographic methods, such as observation and interviews, aim to understand human behavior, while designers aim to design artifacts that support this behavior. Thus, ethnographic methods present useful tools for designers and researchers to interact with users and gain understanding of complex behaviors to contextualize design [76]. In particular, in-depth interviews are useful for exploring complex attitudes, beliefs, and feelings, and are commonly used in new product development [74]. When conducted in the setting where a new product will be used, interviews and observations provide important context for users and designers to communicate about needs and allows focus on user activities as opposed to technology [76]. The in-depth interviews and observations employed in this field work were structured to gain insights specifically about complex usage patterns, perceptions and attitudes toward cooking and heating technologies to inform future design projects.

3.3.1 Interview Protocols

The research design, instruments and consent method used in this study underwent ethical review by the MIT Committee on the Use of Humans as Experimental Subjects (COUHES). Overall, the research team and I created the interview protocol to allow data collection that built on previous findings while also gathering data specific to solutions and more complex associations related to stove technology. Prior fieldwork constructed foundational understanding of user considerations and home energy needs. For this field work, we specifically wanted to understand how users prioritize various needs and gain in-depth information on usage and nuanced insights into preferences from users in influential positions in their communities. The interview protocol was adapted from the one used in the January 2022 field visit to the Himalayan region by D-Lab [41]. That protocol was originally built from a Makaa stove adoption study conducted in Uganda. The interview results were recorded using KoboToolbox[1] and Google docs. Interviews were designed to be structured to allow for easy data input into KoboToolbox and later analysis, and to allow rigorous data collection even by less-experienced interviewers. At the start of fieldwork, it became evident that the primary interviewer, Sucheta Baliga, had extensive experience

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[1] Kobotoolbox.org

conducting interviews on cookstoves. As a result, Baliga was able to develop rapport with interviewees quickly during the research and gather additional insights outside of the structured interview questions. These insights were recorded as field notes via Google docs. These insights and the results of the interview questions are discussed in Chapter 5: Design With and For Users: Prototyping In-Context. The full interview protocol is included in Appendix C: Field Work Interview Protocols.

The interview protocol was split into six sections:

1. Identification and Demographics
2. Stove Types and Respondent Role
3. Biomass Stove Usage Details
4. Stove Lifecycle and Construction
5. Perceptions and Needs
6. Wrap-up

The first and last sections gathered personal information from the respondent about the location and contact preferences after the project. Section 2 aimed to identify the number and type of stoves possessed by the user and the functions of these stoves as well as the role of the respondent in the household (whether they were responsible for most of the cooking and/or firewood collection and preparation). Questions in this section also differentiated between which stove the user *primarily* used and which stove the user *preferred* to use to understand complex usage patterns and decision-making. Section 3 contained questions regarding the fuel collection methods and burden to users, and the amount of time spent cooking and heating the home on a daily basis to inform daily usage. For section 4 interviewers asked users about the frequency and materials used to rebuild clay stoves, as well as failure modes that would require maintenance and reconstruction.

Section 5 questions attempted to demystify some of the challenges with adoption for improved biomass stoves by gathering insights related to user perceptions and preferences related to their stove(s). Interviewers asked users directly what features and attributes of their stove they felt were important using visuals of attributes, including smoke, space-heating capacity, cooking time, and amount of fuel. Interviewers also presented users with neutral images, drawn by Lai Wa Chu, of a woman cooking on a traditional stove and on an improved chimney stove and asked them to describe what was happening in the picture and how the woman was feeling (see Appendix C: Field Work Interview Protocols). This is known as a projective technique, since interviewees project their own feelings about a subject (in this case, biomass stoves) onto the neutral character in the image. Their feelings are revealed in their description of the neutral character [77]. This technique is useful when respondents may have difficulty responding to direct questions about their feelings on a subject or if they may feel the question is an invasion of privacy [74]. Perceptions and attitudes drive consumer decision-making, so it is important to gather these insights for product design [78]. The interview protocols were piloted first in a village outside Dehradun, then again in Uttarkashi after adjustments.

3.3.2 Observations

Observations of cooking utensils, stove features, and innovations were also recorded to enable future designs to fit cooking practices and tools. The team observed the users igniting and preparing the stove for the water boil test and conducting their day-to-day activities. These observations were recorded in field notes on paper and daily team debrief notes in Google docs. Daily debrief meetings also allowed the team to document relevant stakeholders, locations, tests conducted, and construction completed for each day of field research and discuss and record observations and insights from the team. The debrief meeting notes template is included in Appendix D: Field Debrief Notes Template. Photos of each stove tested and constructed were taken. After the field work concluded, these photos were sorted into folders and labelled to allow matching of stove photos with interview respondents across the different locations. In general, observations played a smaller part in the research and data collection in order to prioritize time for prototyping.

3.3.3 Sampling and Selection

For this field research, we aimed for a small sample size to allow time for multiple data collection methods and for prototyping stove solutions with users. This allowed us to focus on depth in gathering insights rather than aiming for statistically significant results. Ideal candidates for interviews were leaders in the community, either unofficial or official (e.g. leader of a local women's group), because their role would allow them to influence others in the community and increase the extent of impact of the project. If not leaders, we selected interviewees with high foot traffic in their home and excitement about the opportunity to improve their biomass stoves. We also ensured that those users whose stove we modified had an alternative stove to cook on or, if not, we provided meals for them during the project. We relied heavily on local partners to assist in selection of participating households.

3.3.4 Analysis and Reporting

Interview results are reported using numbers rather than percentiles due to the small sample size. In addition to quantitative metrics and qualitative insights from original protocols, I coded additional notes (including quotes) from interviews by topic area and report these in results to add depth and meaning to the data collected.

Chapter 4: User-centered Concept Development & Prototyping

Prior to field work in the Himalaya, I led the MIT-based design team in a series of ideation sessions to generate solutions to challenges with home energy. Subsequent selection of the solution to implement in the field research was based on the impact to users and feasibility of prototyping and successful implementation. Laboratory experiments conducted prior to travel helped answer key questions on performance and proved crucial to informing field design work with users.

4.1 Theme & Approach

Research by MIT D-Lab and partner organizations in collaboration with the HHE Project conducted prior to field research in August 2022 allowed identification of important user needs related to cooking and heating technologies in the Himalaya. Community members expressed interest in participating in prototyping and developing solutions to the needs they had communicated, and in some cases, also indicated fatigue from data collection from multiple organizations. Because of this, the field research in August 2022 was scoped to prioritize exploration of solutions with users in the field while continuing to understand challenges related to home energy and thermal comfort in the region.

In general, prototypes are defined as “an approximation of the product along one or more dimensions of interest” [75, p. 297]. Traditional prototyping in marketing is done by developers to get feedback from users on their designs [75], [79]. In product development, prototypes are also used for communicating ideas to partners, ensuring successful integration of subsystems, demonstrating functionality milestones, and answering key questions about feasibility and the ability of the design to meet user needs [75]. While this type of prototyping comes from the perspective of the designers, *cooperative prototyping* occurs in collaboration between designers and users to facilitate mutual learning. According to Bodker et al., “The cooperative prototyping approach establishes a design process where both users and designers are participating actively and creatively with their different qualifications” [79, p. 170]. In this approach, prototypes are seen primarily as learning vehicles to support imagination and discussion of challenges and solutions by making abstract concepts more concrete. Cooperative prototyping requires the designers to give control to the users and shift their role from managers to facilitators, which allows users to participate and cooperate more fully in the design process. The cooperative prototyping method from PD aligned well with the current state of the HHE project, which aimed to explore solutions while continuing to understand problems experienced by users. I planned and scoped the project work to fit this overarching theme. With the broader context of HHE and the scope of the project work in mind, I prepared materials for facilitation of ideation sessions to generate solutions for prototyping in the field.

4.2 Concept Generation

I familiarized myself with literature, findings from past D-Lab trips to the region, and interactions with previous trip leaders to understand stove technology and current research in the field. In late spring 2022, I organized three ideation sessions to generate concepts to prototype in the field during August 2022. Using past field data and photos, I prepared two design briefs, one for each location of interest for concept generation and selection. These briefs took the form of

PowerPoint presentations, which I shared with a group of MIT students and HHE PI Dr. Dan Sweeney who participated in the ideation sessions.

The participants included Lisa Tang, the master's student who previously traveled and conducted field research, along with the project PI, two students traveling with me for the next field visit Meghana Vemupalli and Lai Wa Chu, and another MIT student Janice Moya. These participants were chosen because all had prior experience with engineering design for development, primarily in the context of D-Lab's participatory design approach, to ensure alignment in the mindset toward poverty challenges and those living in poverty as agents of change. The ideation team also consisted of a mix of participants with prior trip experience and those new to the project, including me, in order to bring a balance of tacit knowledge gained in the field as well as fresh perspectives and ideas on the challenges at hand.

The HHE project at D-Lab engages with many different partners in India and Nepal in both practice and academia to conduct research and development projects in the region relating to home energy. In early spring 2022, I began participating in biweekly conference calls with these partners to understand current research and technology development various stakeholders held interest in, and to learn more about the context of the challenges with biomass cooking and heating. Based on these interactions, I expected to need capacity-building sessions prior to ideating virtually in order to develop the participatory mindset, practice interacting virtually through the Miro tool, and align on best practices for ideation to facilitate fruitful and effective sessions resulting in creative ideas tied to user needs. It was necessary to choose a concept quickly to allow time for lab testing to address identified risks, so the PI and I decided to engage solely with MIT affiliates for ideation and engage with in-country project partners on the phone for feedback on generated solutions and in the field during research.

Prior to the brainstorming sessions, I shared documentation of previous trip research findings in the Himalaya as well as publications on designing cooking and heating technologies with participants new to the project so that all participants came to the ideation sessions with similar background knowledge of challenges with biomass stoves and basic design principles of these technologies. One session was conducted in-person in Building N51 and the second was conducted virtually to accommodate traveling participants. The first session focused on ideating for households in the village of Uttarkashi, India while the second focused on different user groups in Kyanjin Gompa, Nepal. The following sections describe the ideation activities and concepts generated during the sessions.

4.2.1 In-Person Ideation: Uttarkashi, India

First, I gave a general overview of challenges and user needs related to household energy in the Himalaya. Table 3 summarizes the general goals of the HHE project based on previously conducted Energy Needs Assessments in several communities in the Himalaya. The project aims to improve home comfort and reduce burdens while maintaining the benefits of biomass technology.

Table 3: Himalaya User Needs for Biomass Technology

Desired Improvements	Preserved Features
Reduce indoor air pollution and smoke exposure Increase indoor temperature in winter Reduce fuel consumption Reduce the burden of stove maintenance	Cooking time Preferred fuel type (i.e. wood) Compatibility with pots and utensils Ease of use Low cost Locally sourced materials Ease of manufacturing/construction

Prior research revealed several benefits of traditional biomass stoves, outlined in the "Preserved Features" column of Table 3. These benefits partially explain the persistent usage of this technology despite the major health drawbacks and must be considered in new design efforts aiming for sustainable impact.

In addition to general project goals and user needs during the design brief at the start of the ideation session, I presented information unique to Uttarkashi, India, including geography and climate, cooking and heating technology and expenses, and key biomass technology practices.

- Uttarkashi is located in the Uttarakhand province of India near the Himalaya Mountain region at an elevation of 1200 meters.
- The average temperature of Uttarkashi is around 5°C in winter and 20°C in summer.
- Households in Uttarkashi rarely use LPG, primarily relying on biomass stoves with no chimney for cooking.
- Households carry hot coals and char from a biomass stove in the separate kitchen to the main house for heating.
- Households spend 4-5 hours every few days collecting firewood nearby for free.

The above information contextualizes user needs for idea generation specific to the Uttarkashi community. For example, the information on collection time and cost of firewood contextualizes the level of burden this presents to users and allows designers to consider different design trade-offs based on perceived priorities.

After reviewing information about the community and engaging the group in informal discussion about related challenges and user needs, I facilitated a modified 6-3-5 brainwriting activity [80] with the ideation team using paper and colored markers and pens. Before beginning, I reminded the team of best practices for brainstorming activities: suspending judgment (offering suggestions rather than criticism), limiting distractions (no phones or computers during the activity), and welcoming ideas that seem infeasible [75]. I chose the brainwriting activity for the first session since it explicitly requires adding to others' ideas, encouraging a generative mindset. As engineers and scientists, we consistently use evaluative mindsets and make judgments regarding technology [14], so in practice it can be helpful to start ideation sessions with either a warm-up activity or an activity such as brainwriting which explicitly asks for additive suggestions rather than evaluative. This iteration of the activity relied on sketches since literature shows that sketches are helpful for communicating design concepts and ideas [75].

In this activity, each of the five participants (including the facilitator) spent 5 minutes sketching 1-3 concepts addressing the needs of community members in Uttarkashi. (In the traditional 6-3-5 method, there are 6 participants, generating 3 ideas, in 5 minutes [80]). After 5 minutes, each person passed their sketch to the right. Then, each participant spent 5 minutes adding to their neighbor's sketch. After these 5 minutes, everyone passed their current paper to the right, repeating the process until all participants added to all sketches, and the sketches were returned to the original owner. Participants then studied their sketches to see the additions made by other members of the team. Figure 12 shows the 12-sketch output of the session.

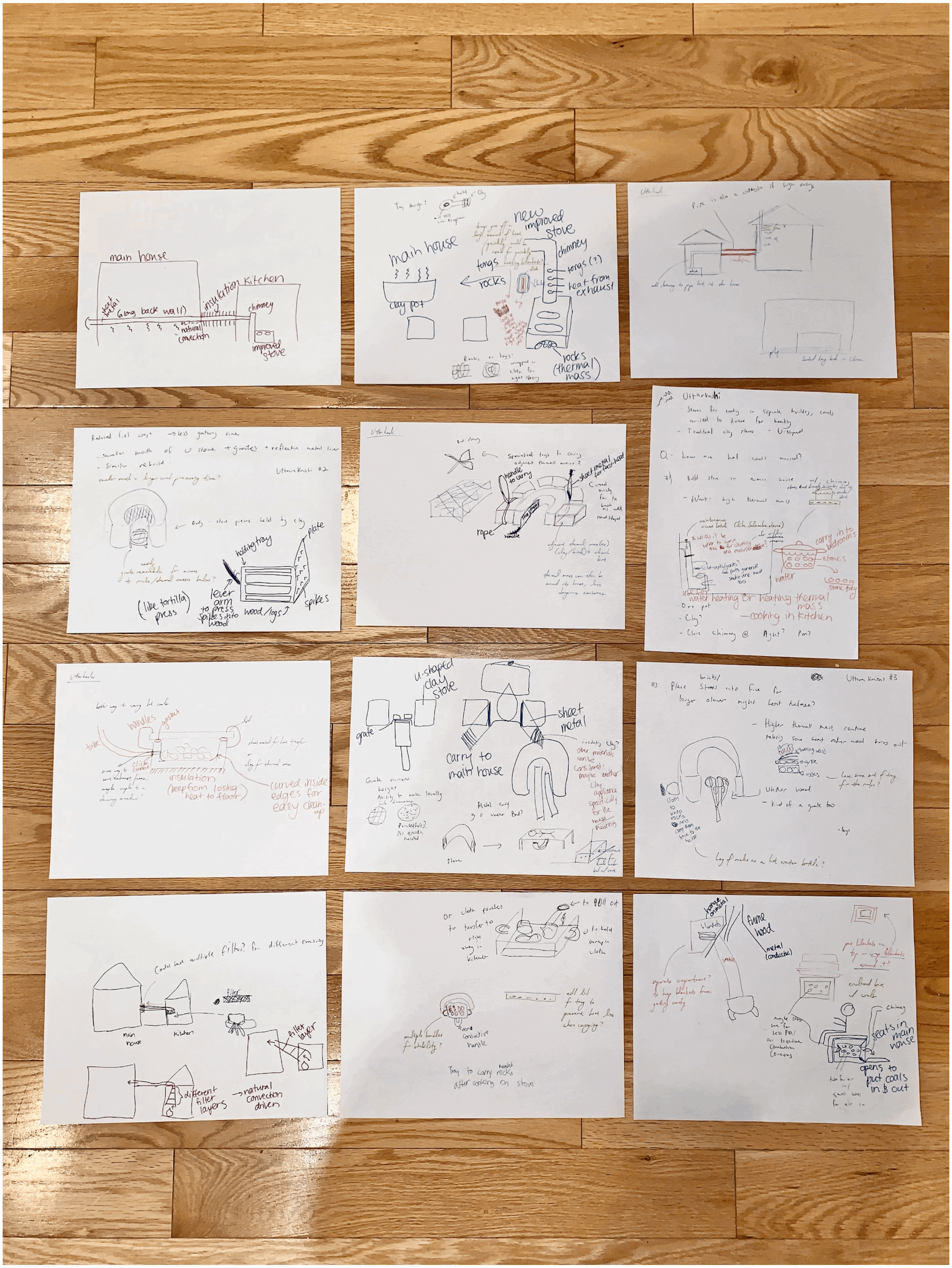
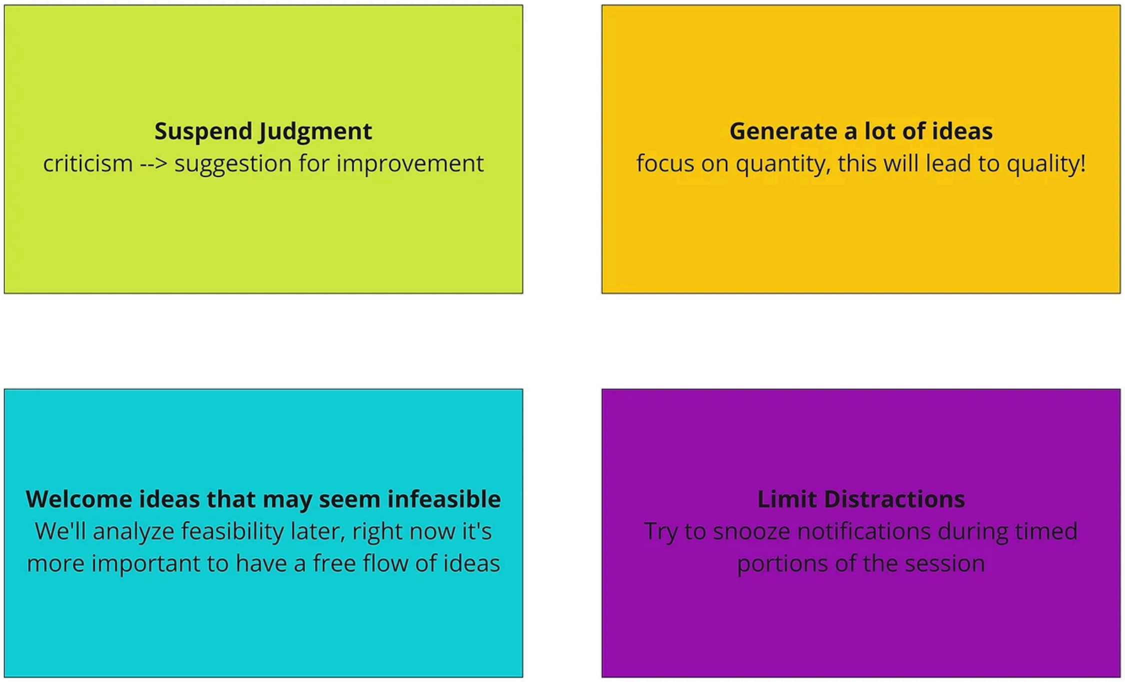


Figure 12: Concepts from Ideation Session for Uttarkashi, India

I then facilitated discussion of the results with the ideation team, noting observations and any repeated ideas. Concepts primarily addressed the need to reduce household air pollution and displayed modifications to the current practice of utilizing coals for home heating. One example is heating thermal mass in the stove during cooking and then collecting it safely for heating the home. Another example uses waste heat from a chimney to heat the home while also reducing indoor air pollution in the kitchen.

4.2.2 Virtual Ideation Session: Kyanjin Gompa, Nepal

The second session was conducted over Zoom using the Miro online whiteboard[2] as a collaboration tool for ideation. At the start of the session, I reviewed the user needs associated with household energy presented in the initial session. Two of the three previous participants attended the second session, with the addition of the HHE PI. I reviewed guidelines for group ideation, seen in Figure 13.



Suspend Judgment
criticism --> suggestion for improvement

Generate a lot of ideas
focus on quantity, this will lead to quality!

Welcome ideas that may seem infeasible
We'll analyze feasibility later, right now it's more important to have a free flow of ideas

Limit Distractions
Try to snooze notifications during timed portions of the session

Figure 13: Brainstorming Guidelines

Similar to the first session, the group reviewed information unique to Kyanjin Gompa and related user needs. I prepared a mind map prior to the session to display information about needs general to the region and needs for three different user groups: inhabitants of the elderly housing block, single elderly men, and guest house owners and operators. The mind map included photos from prior field visits to further contextualize the presented user needs.

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[2] Miro.com

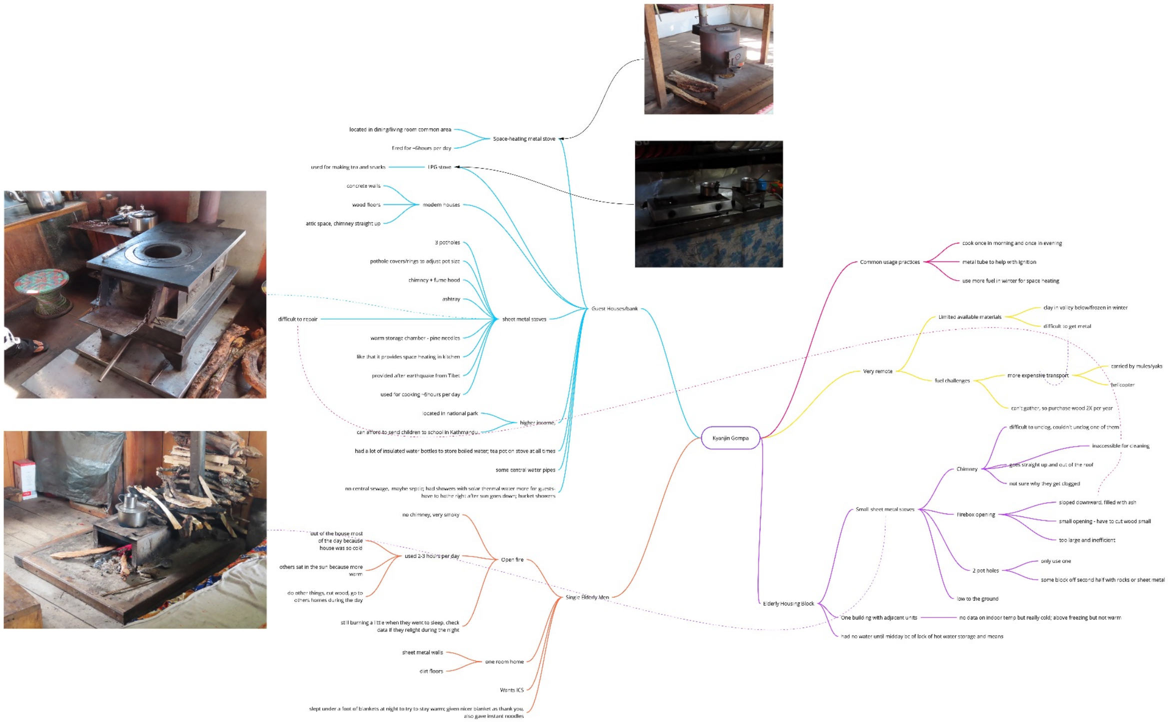


Figure 14: Mind map displaying information about three user segments in Kyanjin Gompa

I prepared three activities in different sections of the board. Again, the team began with a brainwriting activity to activate a generative mindset for ideation. In the virtual environment, participants captured concepts and ideas in words on sticky notes. Each participant used a different color sticky note to record their ideas. After everyone added to each idea, the group discussed the resulting concepts. The results of this exercise are illustrated in Figure 15.

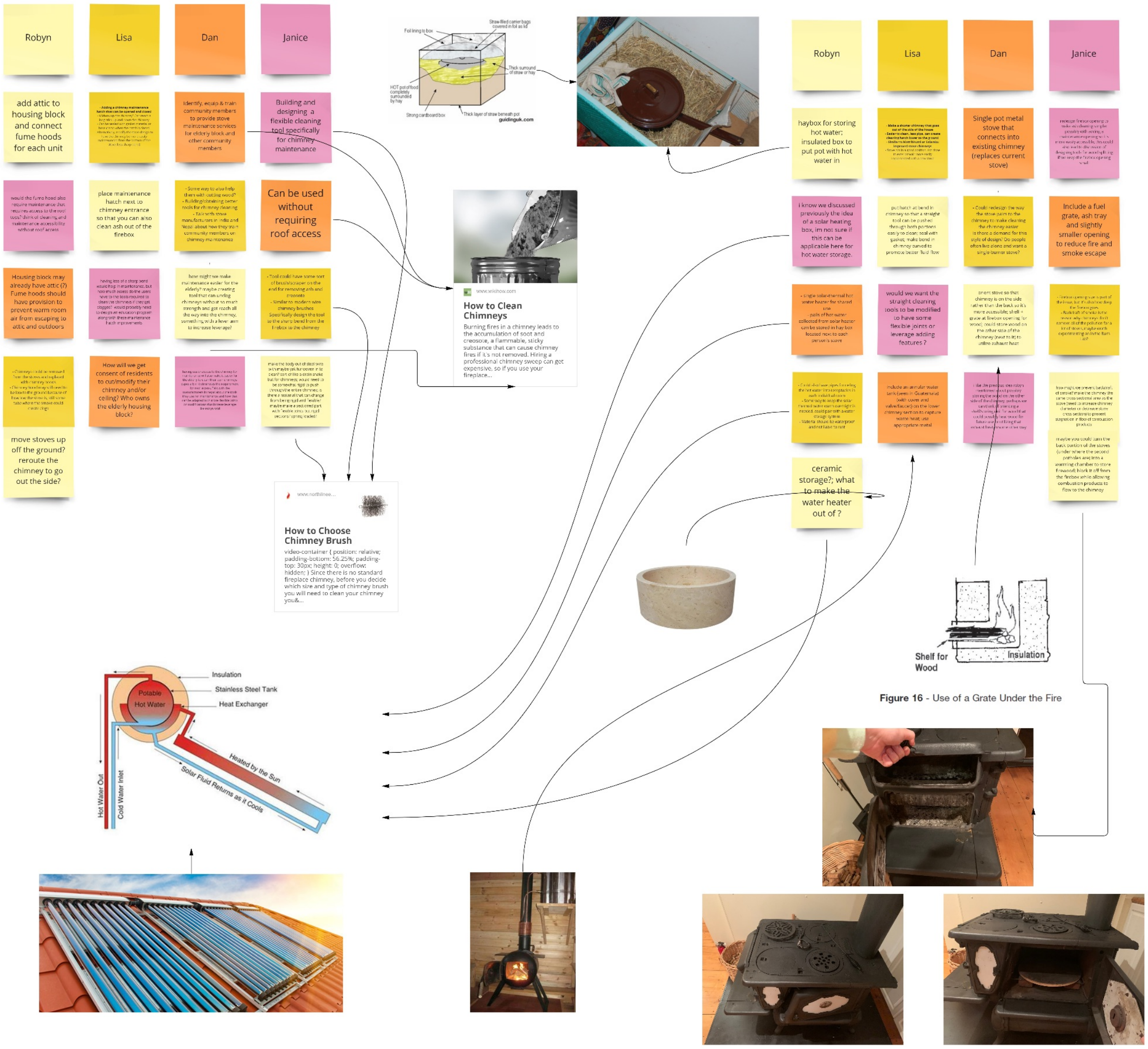


Figure 15: Brainwriting activity for elderly housing block

A total of 17 ideas and 11 questions emerged from this activity. Some of the ideas included sustainability considerations, including maintenance tools for cleaning chimneys and training programs for community members to inform them of proper maintenance and basic operating principles of chimney stoves. After the session, I reviewed the generated concepts and added visuals and links to technologies and concepts described to enhance the information in the whiteboard.

In the second activity, the ideation team considered the elderly men living in single room homes in Kyanjin Gompa. Participants had five minutes of open-ended brainstorming to add as many ideas as they could to sticky notes. At the end of the allotted time, I facilitated group categorization of the different ideas generated, resulting in the following list of themes:

1. Solar energy utilization
2. Home improvement, ventilation solutions
3. Replacement stoves
4. Water heating solutions
5. Personal heating solutions
6. Community-scale solutions
7. Remaining questions

These categories were not mutually exclusive, but rather represented common themes among ideas generated during open-ended brainstorming. Following categorization and labeling of the categories, the group continued brainstorming within each category for several minutes at a time and then discussed the resulting concepts together. One idea for improving home energy in the home improvement category was to insulate the single-person homes, then add ventilation from chimneys or fume hoods to remove indoor air pollution. Examples of community-scale solutions are the introduction of a meal delivery service for the single elderly men or a public bath for hot water. This produced 34 ideas and 4 remaining questions.

The final activity utilized the SCAMPER method [75]: Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, Reverse. Participants generated concepts for guest houses by considering existing and possible technology and the associated action word to stimulate ideas. The method is used to encourage designers to view technology or products from different perspectives and think about new ways to complete tasks. I chose this method for considering guesthouses in Kyanjin Gompa because these community members tend to earn higher income from tourism and have more access to technologies addressing air quality and thermal comfort needs, such as stoves with fume hoods or chimneys, stoves specialized for heating, and LPG stoves. With the variety of technologies and resources available, I hypothesized that the SCAMPER method would enable novel improvements to emerge from the activity by considering guesthouse energy from new perspectives. Because of the simplicity of the technologies used in home heating and cooking, the different prompts were difficult to distinguish, and participants became concerned over which category or prompt their idea might fit in. This activity allowed participants to produce specific technical modifications to relevant technologies, such as adding removable fins to chimneys to increase heat transfer to the room and the creation of a warm storage chamber for preheating firewood and removing moisture from fuel. The team generated 44 ideas, 5 strategies (addressing the needs of guesthouses and elderly men together, creating a student project to work with the Kyanjin Gompa yak cheese factory on energy challenges, etc.), and 2 additional questions from this exercise.

At the conclusion of the session, the group discussed the ideation experience and the various activities. Collectively, participants agreed that they felt constrained by the SCAMPER method, which dictated particular kinds of modifications at different times in the activity. In contrast, the brainwriting and brainstorming activities allowed more freedom in idea generation. While both the SCAMPER and brainstorming activities contained categories of ideas, brainstorming allowed the categories to emerge and the participants to agree on the categorization while the SCAMPER method preselected categories which the team felt limited their ideation. Despite the feelings of limitation imposed by the SCAMPER method, it allowed the team to explore specific technical modifications, whereas the open-ended brainstorming allowed for non-technical solutions, such as the meal service, to emerge. The open-ended brainstorming and brainwriting methods seemed to enable more holistic consideration of challenges and opportunities during ideation, whereas the SCAMPER method seemed to focus participants on creating technical improvements to current technology challenges. More questions emerged from the brainwriting activity. Fewer questions were produced with each subsequent activity, so this may suggest that the team ran out of questions, became more comfortable with uncertainties, and/or adopted a more generative mindset over the course of the session.

4.2.3 Statistical Analysis of Ideation Activities

To evaluate the outputs of the different activities, I conducted statistical analysis of the ideas from each activity in the virtual session. These ideas were rated in terms of feasibility, novelty, uniqueness, and variety by considering the questions in Table 4.

Table 4: Variables and Questions for Scoring Ideas

Variable	**Defining Questions**
Feasibility	How feasible is it to prototype and test the idea? How feasible is it to implement the idea in the remote field work locations?
Novelty	How different is the idea from prior work in the field? Has it or a variation of it been tested or implemented before to address home energy challenges?
Uniqueness	How different is the idea from other ideas generated in the session?
Variety	What is the span of the solution space? Is the idea most relevant to one particular dimension (technical, social, economic, etc.) or does it span several dimensions?

I rated ideas for feasibility and novelty on a scale of 1 to 5 and then averaged to give a feasibility and novelty score for each idea. Uniqueness of an idea was determined by counting the number of occurrences of similar ideas, then rating the uniqueness on a scale of 1 to 5. A variety score on a scale of 1 to 5 was given by identifying dimensions of an idea (technical, social, economic, etc.) and then assigning values to these dimensions based on their occurrence in the generated ideas. The scores of ideas from each activity were averaged to give a score for each variable for each of the three activities. A complete list of idea descriptions and scores from each activity are included in Appendix A: Ideation Activity Results.

Table 5: Mean Scores for Each Dimension and Activity

	Feasibility	**Novelty**	**Uniqueness**	**Variety**
Brainwriting	2.9412	4.2941	2.0588	1.4706
Brainstorming	3.1471	2.8529	3.5588	1.4118
SCAMPER	3.3636	2.9091	2.9318	1.3182

Table 5 shows the mean scores for ideas from each activity in the session in terms of the variables. The SCAMPER method produced ideas with slightly higher feasibility, while Brainwriting outputs were rated higher on novelty and variety. Brainstorming allowed an increased number of unique ideas. To understand the significance of the differences in these scores, I conducted randomization tests on each combination of activities [81]. This test does not require assumptions about the distribution or population and allows testing of a null hypothesis from two independent samples [81]. Each test was replicated 100,000 times to generate a distribution of mean differences of the random permutations of the data. The actual mean difference between activities was then compared to this distribution to calculate the two-tailed p-value, or the probability that the difference resulted from random chance rather than a relationship between the two activities.

Table 6: P-values from Randomizations Tests on Activities

	Feasibility	**Novelty**	**Uniqueness**	**Variety**
Brainwriting vs. Brainstorming	0.5835	0.0003	0.00001	0.7626
Brainwriting vs. SCAMPER	0.1896	0.00002	0.0327	0.5486
Brainstorming vs. SCAMPER	0.4163	0.7807	0.0218	0.6251

Table 6 shows the p-values for each activity and variable. For novelty, we reject the null hypothesis for the Brainwriting activity tests; This activity resulted in increased novelty in generated ideas over the Brainstorming and SCAMPER methods for a significance level of 0.05. For uniqueness, we also reject the null hypothesis for all tests based on a significance level of 0.05. Brainstorming resulted in the most unique ideas, then SCAMPER, then Brainwriting. Brainwriting may result in less unique ideas because participants add to others' ideas in this structured activity. This requires participants to contribute ideas around the same original idea, resulting in less unique ideas. Brainstorming, on the other hand, allowed each participant to freely generate ideas to address the needs described, so this unstructured method resulted in many more unique ideas to emerge from the activity. It is possible that the structure of the SCAMPER activity caused the lower uniqueness score compared to brainstorming. This method does not require participants to add to other ideas, however, so this may explain the increased uniqueness compared to Brainwriting.

Based on the tests, we accept the null hypothesis for feasibility and variety variables for all activities, so any variations in feasibility and variety scores are likely to have occurred at random. Our original hypothesis based on team discussion was that Brainstorming and Brainwriting allowed increased variety in ideas over the SCAMPER activity, but the data does not support this. Additional data should be taken to better assess feasibility and variety variables between different ideation activities. In addition, the variables used in this analysis are not necessarily independent. For example, an idea that has been demonstrated many times before (low novelty) may be more feasible to test and implement (high feasibility). Also, an idea more relevant to a social rather than technical dimension may receive both a higher uniqueness score and variety score if most of the other ideas are technical solutions. Future work should analyze the relationship between these variables in addition to the relationship between different activities.

The ideation sessions enabled the consideration of various concepts to implement in the field the following August. In addition to providing specific designs to consider testing and implementing, reflecting on the ideation activities allowed me and field work team to consider how to prioritize different user needs, the requirements of different approaches and concepts in terms of resources and long-term support for sustainable impact, as well as potential risks to users associated with different ideas.

4.2.4 Limitations

The sample size here was low (only 95 total ideas), so this may limit the confidence in the conclusions suggested by the results. In addition, I participated in the ideation activities and scored the generated ideas, so this introduces potential bias in the scores used in this analysis. The activities analyzed were facilitated in sequence with the same group. While this reduces variation from individual differences in participants by preserving the composition of the team, it also may be the cause of some variation in the results of the different activities. For example, the number of questions generated in each activity went down as the session progressed. This could be a result of the activity itself but also could be because participants "warmed-up" over the course of the session and were more generative by the end. The virtual nature of the session may also have contributed to results, so additional research should investigate these effects on ideation results in design.

4.3 Concept Selection

Following the ideation sessions, the design team had two months to prepare for the field research in India and Nepal. I analyzed ideas from the ideation sessions and identified several technical solutions among the results to consider for implementation in the field. Table 7 shows the Pugh chart used to select among these technical solutions based on user needs, feasibility and interest of the team.

Table 7: Pugh Chart for Concept Selection

Solution *Criteria*	**Haybox**	**Chimney modification**	**Adjustable thermal mass**	**Combustion chamber insulation**
Impact on HAP	0	++	-	0
Space heating function	0	-	+	-
Time and fuel amount required	0	?	?	+
Change in cooking practices	0	+	+	+
Ability to test in lab before travel	0	0	0	-
Feasible to prototype in the field	0	++	++	+
Stakeholder interest & expertise	0	+	-	+
Sum	**0**	**5**	**2**	**2**

A haybox was chosen as the datum since this is a common method for reducing emissions from biomass cooking. It is an insulated box in which the cook places a pot once it reaches cooking temperature on the stove. The pot continues cooking the food inside the "haybox," since it is insulated, and the cook can put the fire out to reduce both fuel usage and emissions per cooking task [58]. The other ideas chosen for consideration are adding insulation to the combustion chamber, chimney, and adjustable thermal mass (adjustable in terms of level of heat supplied to the room). While the adjustable thermal mass addresses space heating needs, it would not improve HAP levels in the kitchen. Insulating the combustion chamber has the potential to reduce HAP and relates to our stakeholders' interest and expertise, but this requires materials analysis and selection. With limited time for laboratory testing before fieldwork, and limited knowledge of material availability in specific locations, it seemed less feasible to prototype combustion chamber insulation in the lab and in the field compared to the other solutions. Ultimately, the chimney modification is feasible to prototype from commonly available materials and has the most potential for impact on HAP for the user, so we chose to pursue this solution.

The field visit team chose a solution to maintain the benefits of traditional stoves, such as space heating and compatibility with cooking practices and utensils, while improving HAP levels to maximize impact to the user. Modifying a traditional stove to add a chimney can remove almost all HAP from the kitchen [58]. It also seemed feasible to implement a variant of this concept in all travel locations to address user needs. In choosing this concept, we decided not to attempt to increase efficiency or improve total emissions. Instead, the modification is intended to *maintain* cooking time and amount of fuel required in addition to efficiency and total emissions. This choice reflects the approach to prioritize user needs and preserve the benefits of traditional stoves, even at the expense of technical performance, and can be classified as an incremental solution. The team aimed to use the prototyping experience as a vehicle to continue learning about challenges with HAP and thermal comfort in context with users.

Climate change presents a real and urgent need to address emissions and motivates many innovations in biomass stoves among other industries and technologies around the world. While researchers, practitioners, and policymakers have come together to address the UN Sustainable Development Goals with innovation [29], it is important to be mindful of how these topics are approached when engaging with communities experiencing poverty challenges. Baliga, the lead interviewer, explained that in discussing climate change during previous focus groups and interviews, community members are told to change their cooking practices to mitigate climate change, but do not have access to the tools, technology, or clean fuels to enable these changes. Community members also communicated that it felt hypocritical for researchers and those living in privilege to tell them how to live their daily lives. Concepts related to sustainability and health carry cultural and social meaning depending on the local context, and products incompatible with local culture are ultimately unsustainable [1]. Rather than the global understanding of sustainability—profits, people and planet—Viswanathan & Sridharan [1] encourage a more local understanding of sustainability: individual, family, and community welfare. The local meaning of sustainability may be socially constructed by stakeholders involved in a particular project, suggesting the need for collaborative, participatory methods in designing such solutions [1]. While addressing total emissions of biomass stoves was outside the scope of this work, we designed the interview protocol to include questions related to sustainability, but focused on the effects felt by users, such as how fuel usage has changed over the past decade, and whether they perceived changes in climate events and weather patterns that affected their agricultural practices. These questions were unsuccessful (interviewees did not report long-term changes related to climate change), so we did not include these in the final version of the protocol. Additional work is needed to facilitate constructive conversations around climate and sustainability in BoP contexts.

To test the feasibility of the chosen concept, the team prototyped and tested a chimney stove in the lab prior to traveling. Previous literature associates chimney stoves with lower efficiency [33], [58], so laboratory testing allowed us to assess whether adding a chimney would worsen the already relatively low efficiency of traditional clay stoves. Experiences prototyping and laboratory testing also allowed the team to establish design guidelines to use during the field work.

4.4 Chimney Prototype Construction

Previously, Lisa Tang [41] constructed a prototype traditional stove for conducting tests to measure efficiency and emissions in the lab. In order to generate test results comparable to Tang’s results, the design team modified this prototype and constructed a chimney to use in testing. For stove dimensions and MIT Burn Lab set-up details, refer to Tang’s thesis [41].

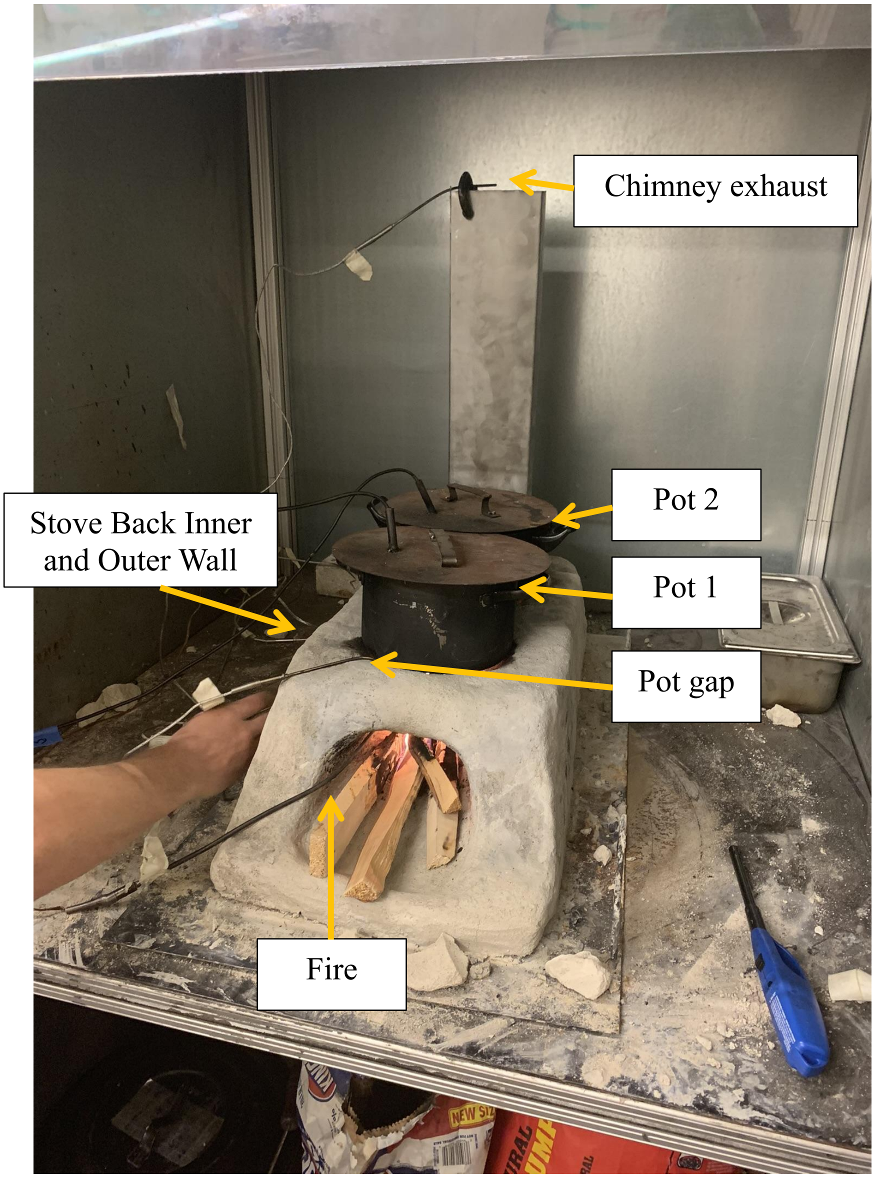


Figure 16: Prototype stove with chimney in MIT Burn Lab, temperature measurement locations

Sheet metal was used for the chimney to increase the immediate heating benefits of the stove when it is first ignited, and the large clay thermal mass is still cold. Stove exhaust gasses retain heat, which become losses when leaving the kitchen in a chimney, so we expected an uninsulated metal chimney to transfer more of this heat to the kitchen due to its high thermal conductivity as opposed to a clay chimney with high thermal mass. The chimney was constructed out of sheet metal using sheet metal shears and sheet metal bending. The seam was fabricated by inserting a piece of lumber into the chimney and hammering along the seam.

Figure 17: Sheet metal chimney with hammered seam

To modify the traditional stove, the team used chisels to remove material from the back of the stove (behind the second pothole) to create a hole for the chimney. The chimney was placed at the back of the stove and a sand-clay mixture (see [41]) was used to secure it in place. In total, three chimneys were prototyped with this construction method for laboratory testing. The next section explains the different testing conditions with these different chimneys.

4.5 Laboratory Testing Experimental Design

Rather than aiming to optimize design parameters to maximize technical performance of the chimney stove, laboratory testing was designed to generate key learnings related to risks to the user for the design and inform a set of design guidelines for the team to use in the field. Smith et al. [3] suggest co-design may require additional planning and facilitation to engage users as part of the design process, so creating design guidelines from lab experimental results also enabled the team to more effectively practice co-design with users in the field.

One of the key risks associated with chimney stoves is their tendency to decrease the overall thermal efficiency, thereby increasing the fuel required and the time taken for cooking [33], [58]. As such, one of the primary objectives of the laboratory experiments was to identify design features that allow the cooking time and fuel required to stay the same after the addition of a chimney. Key findings from literature review on design features included the importance of the fuel inlet area and chimney cross-sectional area, as well as features like baffles to direct hot gasses toward the pot [58], [82]. Lab experiments tested these features, which were sized relative to the existing dimensions of the stove and within the constraints of the burn lab setup. Table 8 summarizes measurements of the design features and the condition name. The time and fuel for the test as well as overall efficiency were then compared with the results from testing on the traditional stove to assess the effectiveness of the design feature.

Bryden et al. [58] recommend maintaining constant cross-sectional area throughout the stove, so the chimney cross-sectional area was designed to match the existing firebox opening in the two-pot *chulha* prototype. Tang [41] reports this to be 15 cm by 10 cm, but the measured value of the firebox opening at the time of the experiments was documented at 9.5 cm by 6.5 cm. The firebox experiences high temperatures from close contact with the combustion process, so cracks form in this area and the stove must be repaired, which may explain the change in measurement. To size the chimney, I used the measured value of the cross section, which results in a cross-sectional area $A_c = 61.75\ cm^2$. After removing material from the back of the stove to make the hole for the chimney, we measured the dimensions of the opening at the back of the stove to be 10 cm by 6.5 cm, giving a cross-sectional area $A_c = 55.00\ cm^2$. We chose to initially size the chimney at 12 cm by 5 cm, which gives $A_c = 60.00\ cm^2$, approximately equal to the cross-sectional area of the rest of the stove. The second chimney was sized to be half of the cross-sectional area, in line with MIT D-Lab handbook recommendations to reduce the area in case the chimney pulls too much draft [55].

Table 8: Lab Test Variables and Condition Name

Chimney Height	Chimney Area	Baffle Height
"Full" 60 cm	"Full" 12 x 5 = 60 cm^2	"Tall" 2 in
"Half" 30 cm	"Half" 12 x 2.5 = 30 cm^2	"Medium" 1.5 in
		"Short" 1 in

The burn lab fume hood contains a mesh net, which is 85 cm above the platform where the *chulha* sits during testing. To ensure the chimney fit under the fume hood and mesh net, I chose the initial height of the chimney to be 60 cm. To reduce draft, we constructed another chimney with half this height to understand to what extent chimney height affects the user parameters.

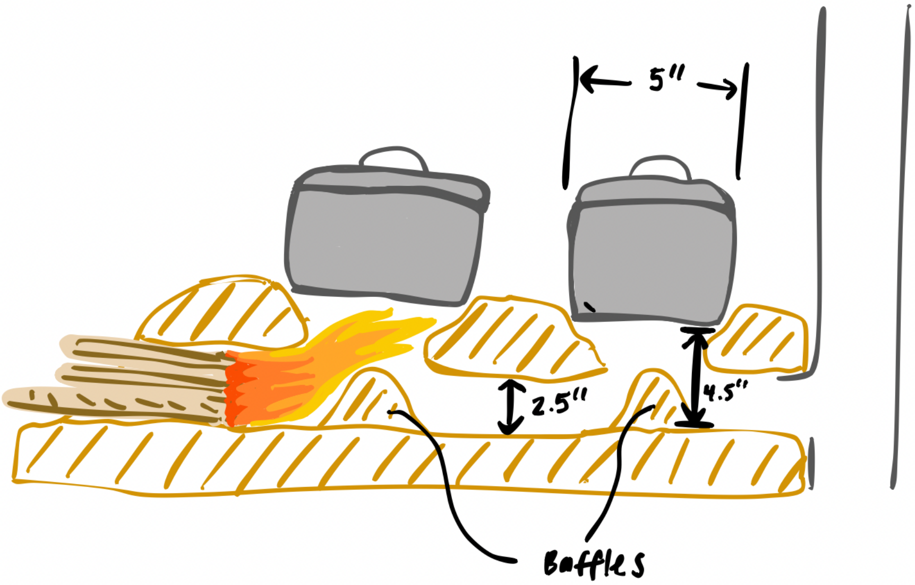


Figure 18: Internal Geometry of Modified Two-Pot Prototype

We also made baffles from the same sand-clay mixture used for the stove [41] to direct the flow of hot flue gasses. Initially, we sized the baffles to maintain the cross-sectional area from the firebox to the back of the stove. At the pothole, the opening creates a larger cross-sectional for the flow, so the baffle reduces the size of the enlargement. Baffles were constructed for 2”, 1” and 1.5” heights.

4.6 Prototype Test Results

Table 9 displays average fuel used and average test duration for each combination of design features. Values better than the baseline traditional stove are highlighted green, values that are comparable are in yellow, and values that do not meet the established baseline are in red. The full height chimney with half the cross-sectional area and short baffles resulted in the combination with the test time and fuel amount closest to or better than the baseline for comparison. This chimney/baffles design iteration was better than the traditional stove with no additional design features, but the traditional stove with pot stands performed better in terms of test time and fuel use.

Table 9: Summary of Affected User Parameters from Lab Tests

TEST CONDITIONS			USER PARAMETERS			
Chimney Height	*Chimney Area*	*Baffles*	*Cold phase time (min)*	*Hot phase time (min)*	*Total Test Time (min)*	*Fuel use (kg)*
Full	Half (Taped)	None	44.3	25.7	70.0	0.762
	Half	Short	30.7	22.7	53.3	0.703
		None	38.5	28.5	67.0	0.925
Half	Full	None	73.8	35.2	109.0	0.652
		Medium	36.5	35.0	71.5	0.764
No Chimney with grate*			37.7	23.0	60.7	0.721
No Chimney with pot stands*			27.6	19.8	47.4	0.560
Baseline (no features)*			**32.0**	**18.17**	**50.17**	**0.834**

*Data from [41]

The tall baffles built initially to maintain the cross-sectional area of the stove proved to block the flow too much, so this test was unsuccessful (the test was concluded before the water started boiling because it was taking much too long). It is possible that these baffles may have worked if the stove had more room for a firebox. In traditional stoves, the fire is kept directly beneath the primary pothole since the hot gasses flow upward from natural buoyancy. In chimney stoves, the draft pulls the flames and hot gasses back toward the chimney. The prototype was originally built to replicate traditional stoves, so this meant that there was no room in front of the first pothole for a firebox. The tall baffles were placed underneath the first pothole, and at this height the chimney never started pulling draft since they blocked the flow of hot gasses to the rest of the stove.

In all tests, the chimney started pulling draft several minutes after the fire started. Figure 19 shows temperature data during a test with full chimney height, taped half chimney area, and no baffles conditions.

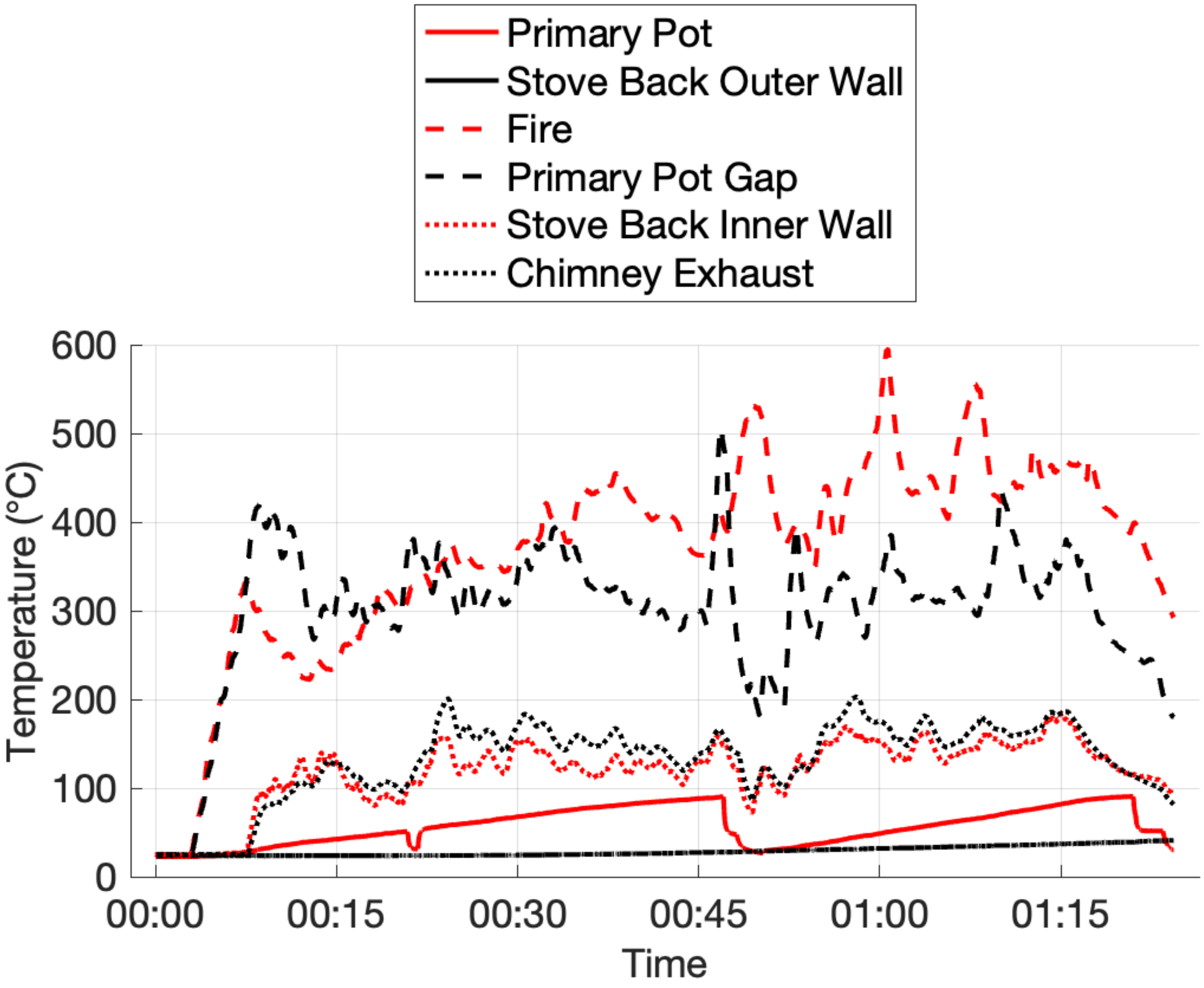
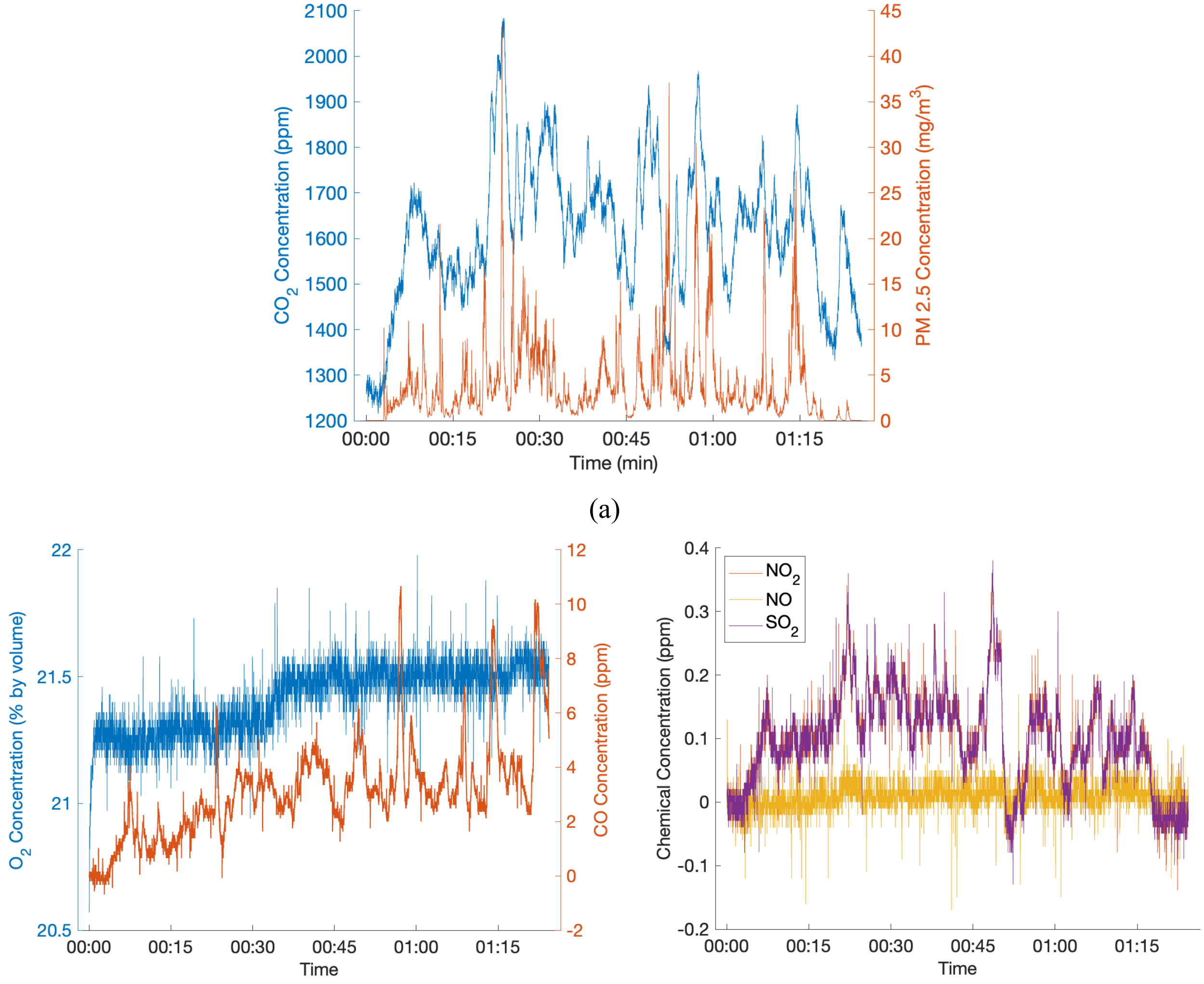


Figure 19: Temperature Plot for Test Date 6-27

The start of the test (00:00) indicates the lighting of the firestarter. Approximately three minutes into the test, the burning fuel created a sustainable fire, indicated by the sudden increase in temperatures of the fire and primary pot gap. Once a bed of coals accumulated, around eight minutes into the test, the chimney started pulling draft, indicated in the figure by the sudden increase in the back inner wall and chimney exhaust temperatures. The stove back inner wall and the chimney exhaust temperatures are closely matched over the course of this test, indicating that the hot flue gasses do not lose much heat from the back of the stove to the chimney exit under these testing conditions. Figure 19 also shows the two peaks of the primary pothole from the cold and hot phases of the test. The outer wall of the stove slowly heated via conduction through the stove body.

The burn lab sensors also measured CO_2, CO, NO_2, NO, SO_2, O_2, and PM 2.5 concentrations during the test. The concentration of CO_2 indicates the level and consistency of the firepower over the course of the test. Figure 20a shows a relatively consistent concentration of CO_2, meaning the researcher was able to maintain constant high power throughout the WBT. The average PM 2.5 concentration in this test was 4.1658 mg/m^3, but as you can see in Figure 20a the concentration reached values much higher than that, with a maximum of 43.5 mg/m^3.



(a)

(b)

(c)

Figure 20: Concentration vs. Time for 6-27 WBT (a) CO_2 and PM 2.5 (b) O_2 and CO (c) NO_x and SO_x

As shown in Figure 20b, oxygen levels remained around 21.3 - 21.5% by volume throughout the WBT as expected. The average CO concentration was 3.0418 ppm with a maximum of 10.6700 ppm. Figure 20b shows this stayed somewhat constant throughout the test with a slight gradual increase over time. The NO level remained close to zero, while the levels of NO_2 and SO_2 rose a little during the test (Figure 20c) but stayed well below the safe limit of 5 ppm for 8-hour exposure [83], [84].

Though our research objectives focused on assessing the changes in user parameters related to efficiency, I also present data collected on emissions to inform further research into design modifications of traditional stoves. Table 10 summarizes the emission rates (ER) for PM 2.5 and carbon monoxide CO. ER meeting WHO Air Quality Guidelines (AQG) are highlighted in green. Interestingly, the combination which afforded the longest testing time (undesirable to users) also resulted in the least fuel consumption and lowest emission rates of both PM 2.5 and CO. It is important to note that tests measured total emissions for both traditional and improved (chimney) stove iterations. In actual usage, some emissions from the improved stove would leave the kitchen through the chimney, resulting in reduced HAP.

Table 10: Summary of Total Emission Rates from Lab Tests and WHO Air Quality Guidelines

TEST CONDITION			EMISSION RATES	
CHIMNEY		**Baffles**	**PM 2.5 (mg/min)**	**CO (g/min)**
Height	**Area**			
Full	Half (Taped)	-	18.97	0.07
	Half	-	41.32	0.33
		short	67.15	0.29
Half	Full	-	29.47	0.11
		medium	87.03	0.25
*vented WHO Air Quality Guideline^*			*0.8*	*0.59*
No chimney*		Grate	59.32	0.25
No chimney*		Pot Stands	14.86	0.11
No chimney*		-	133.22	0.39
*unvented WHO Air Quality Guideline^*			*0.23*	*0.16*

*Data from [41]

^WHO targets for biomass combustion to meet published Air Quality Guidelines [53]

The traditional stove (no chimney) with pot stands also performed better in terms of emissions than most of the chimney stove iterations. However, as mentioned, the chimney stove would remove most pollutants from the kitchen and reduce respiratory exposure, so this design would still improve HAP over the unvented traditional stove with pot stands. All of the improved stove design iterations meet the WHO biomass combustion AQG for CO ER but had PM 2.5 ER three orders of magnitude larger than the emission target.

Table 11 displays stove emission factors and performance tiers from the ISO standard [51]. The different performance tiers are color-coded, with the worst-performing Tier 0 in red and best-performing Tier 5 in green. Most prototype iterations, both with and without chimney, met Tier 1 performance based on CO EF. However, none of the iterations achieved greater than Tier 0 for PM 2.5 EF, which is the lowest performing tier rating. None of the prototype iterations achieved greater than Tier 1 efficiency levels.

Table 11: Summary of Lab Emission Factors, Efficiency, and ISO Voluntary Performance Targets

TEST CONDITION			EMISSION FACTORS		COOKING EFFICIENCY (%)
Chimney Height	**Chimney Area**	**Baffles**	**PM 2.5 (g/MJ)**	**CO (g/MJ)**	
Full	Half (Taped)	-	34.67	19.37	-
	Half	-	13.51	17.12	9.24
		short	19.82	14.09	11.49
Half	Full	-	18.24	11.54	8.89
		medium	36.55	17.09	9.39
No chimney, with grate*			16.37	11.67	16.09
No chimney, with pot stands*			2.45	2.96	15.91
No chimney (baseline) *			28.39	13.89	12.25
Tier 5			≤ 0.005	≤ 3.0	≥ 50
Tier 4			≤ 0.062	≤ 4.4	≥ 40
Tier 3			≤ 0.218	≤ 7.2	≥ 30
Tier 2			≤ 0.481	≤ 11.5	≥ 20
Tier 1			≤ 1.03	≤ 18.3	≥ 10
Tier 0			>1.03	>18.3	< 10

*Data from [41]
^Voluntary Performance Targets [51]

Surprisingly, the traditional stove prototype (no chimney) with pot stands performed best out of all iterations in terms of emissions, even achieving Tier 5 performance for CO ER. However, even this iteration does not achieve a factor beyond the baseline performance tier for PM 2.5 EF. It is likely the large thermal mass of the stove contributes greatly to cooling the combustion process, leading to the high presence of fine particulate matter and other PICs in stove emissions. In terms of efficiency, none of the iterations produced thermal efficiency better than Tier 1 performance.

Based on these results, we created design guidelines to use in the field work. We noticed that the height of the chimney was less impactful to the performance than the chimney area, so our guideline was to create a chimney with half the area of the cross-section of the stove. We planned to match the height of the chimney to the window in the user's kitchen to avoid creating another hole in the wall. In addition, we planned to add a firebox in front of the first pothole to prevent fugitive emissions from the fuel inlet and use short baffles to direct the flue gasses toward the pot. Our testing experiences also showed us that the chimney starts pulling draft several minutes after the start of the fire, so we should also expect this in field tests.

In addition to the insights informing stove design, I gained additional insights for tending and maintaining the fire. In early tests, we used wood with higher moisture levels. We learned it is very difficult to keep moist wood lit, even if we chop it into smaller pieces to increase the surface area. In addition, I learned not to move the wood pieces around often, I need to let the fuel heat up in particular spots and burn to maintain the fire rather than rotating the wood piece to get even heating across the surface area. Bryden et al. [58] stress the importance of users' skill in tending the fire to stove performance, and that even an open fire tended by an expert can achieve better performance than an ill-designed and ill-tended improved stove. In addition, the testing standard requires maintaining constant power during phases of the test [71], so how the researcher tends the stove fire can affect testing results. Therefore, the experience gained with tending and maintaining the stove allowed me to gain tacit knowledge important for repeatable field testing and comparable performance results from stove research in the field.

4.7 Challenges & Limitations

The research team completed at least two successful tests for each testing condition result reported. The ISO recommends five repeat tests as best practice [51], so it is not possible to make statistically sound conclusions based on the results of this lab testing. For several tests, the thermocouple on the second pot failed to record temperature data. As a result, it was not possible to assess the efficiency or PPR for these tests.

Chapter 5: Design With and For Users: Prototyping In-Context

The field work prioritized prototyping in-context, collaborating with users and local partners when feasible, to explore solutions and gain insights to biomass cooking and heating technologies. This chapter details the prototyping process in terms of PD and construction methods to contribute to biomass stove research and design research methodology based on the insights in this case study.

5.1 Overview of Field Work

5.1.1 Locations Overview

Field research was conducted in late July through August 2022 in the Himalayan regions of India and Nepal. Multi-day visits were made to the village of Pata in the state of Uttarakhand, India and the villages of Salambu and Kyanjin Gompa in Nepal. Shorter day visits were made to households in Uttarkashi, India and Dalchoki, Nepal. Table 12 summarizes the conditions and climate of these locations.

Table 12: Geographic Data for Field Research Locations

Location	*Elevation* (m)*	*Travel time during rainy season^*	*July temperature (night/day)*	*January temperature (night/day)*	*Weather Reference Location*
Uttarkashi	1158	4-6 hours from Dehradun	20°C / 31°C	5°C / 15°C	Uttarkashi [85]
Pata	~1200-1500	1-2 hours from Uttarkashi			
Dalchoki	2123	3 hours from Kathmandu	20°C / 25°C	6°C / 16°C	Dalchoki [86]
Salambu	1525 - 1657	5-8 hours from Kathmandu	14°C / 25°C	4°C / 14°C	Dhulikhel [87]
Kyanjin Gompa	3890	2.5 days on foot from Syrapubesi	7°C / 16°C	-7°C / 3°C	Langtang Valley [88]

*Elevation was measured using a satellite GPS; Pata elevation is estimated based on Uttarkashi.
^Travel time is based on this field work and is for motor vehicle travel unless otherwise noted.

Increasing elevation decreases atmospheric pressure, decreasing the boiling point of water. The elevation factors into calculations of equivalent dry fuel and efficiency of the stoves. Ambient temperature affects stove performance and gives some indication of the space-heating needs of particular locations. The travel time is also included here to indicate relative remoteness of the different locations visited, which relates to the level of access to improved technologies for cooking and heating.

The research team conducted interviews in all field visit locations. Multi-day visits involved performance testing and prototyping solutions in addition to qualitative data collection. Table 13 shows the specific inputs and outputs for the three multi-day visit locations.

Table 13: Field Work Summary for Multi-Day Locations

Location	*Inputs*	*Expected Outputs*
Pata	Cooperative prototyping: Collaborate with users to modify traditional clay stove design to include a sheet metal chimney	Learn from users about local materials and construction methods Test the feasibility of the concept in-context and evaluate the extent to which it meets user needs
Salambu	Install improved stoves using local materials	Learn from stove master about construction methods, local materials, and features of improved stove design
Kyanjin Gompa	Modify and perform maintenance on metal stoves in elderly housing block	Reduce fugitive emissions and fuel consumption of stoves to better meet needs of elderly
	Design and install one-pot improved clay cookstove design in single room home	Evaluate prototype performance and ability of single pot stove design to meet user needs in-context

In Pata, the team aimed to engage a lead user in co-design for prototyping a clay stove with a chimney in order to leverage user knowledge and expertise in traditional construction methods and use of local materials and to ensure the resulting prototype fit their needs. In Salambu, the goal was to learn from a Nepal-based Stove Master and gain more experience with local materials and clay construction by installing ICS in homes. While the M-ICS design was developed by Matribhumi Urja using PD methods, our experience installing M-ICS in Salambu focused on following the process of the lead manufacturer, so the construction did not require much design on the part of the research team. However, the interviews and testing conducted in Salambu consulted users and investigated local context to inform future design work, so the fieldwork in Salambu entailed user-centered design. The construction training in Salambu informed user-centered design work in the next location Kyanjin Gompa, where we consulted users and prototyped modifications to reduce HAP levels for elderly residents. The following sections describe processes and results of the field work in detail, then summarize findings from all locations for a comprehensive description of the work completed for this research.

5.1.2 Stove Performance Testing in the Field

Field tests on biomass stoves were conducted using a modified WBT as described in 3.2 Stove Performance Method. The team used Type K thermocouples and microDAQ data loggers to record temperature data and Sensen HAP monitors [89] to measure ambient humidity, temperature, and emissions concentrations. Sensen data loggers were placed in multiple locations throughout the kitchen during each test. Wood moisture measurement on household biomass fuel was taken at three locations on 1-4 pieces of wood. The energy needed to evaporate the mass of water in the wood is accounted for in stove efficiency calculations based on the local boiling point of water for the location elevation. For firepower and efficiency calculations, I used 17.8 MJ/kg for LHV of Chir pine from the Himalaya [41]. I calibrated Sensen CO measurements using equation 5.1 [89]:

$$C_{CO}\ [ppm] = \frac{1}{10^{-4}SG}(V - V_0) \tag{5.1}$$

V is the measured voltage from the sensor in Volts, V_0 is the zero-point value, S is the sensitivity of CO module, and G is the gain for the system. In this Sensen, $S = 2.43$ and $G = 1.2257$ [89]. PM 2.5 measurements are calibrated by multiplying the measured value by 1.79 [89].

To estimate 24-hour exposure, I assumed that the concentrations during the WBT occurred three times per day (once for each meal), averaged over 24 hours.

$$C_{24h} = C_{WBT}\frac{t_{test}}{24\ h} \tag{5.2}$$

While it is more accurate to measure concentrations over 24 hours or more for exposure, this calculation provides a useful estimate of personal exposure to compare with WHO Air Quality Guidelines (AQG). This estimate is only calculated from tests with sensors placed in front of the stove, where the cook might sit, since this would be most representative of personal exposure.

5.1.3 Interview Respondents

The team conducted 9 structured interviews throughout the field work with cookstove users. The average age of respondents in Kyanjin Gompa was 65; elsewhere the average age was 43. Seven women and two men were interviewed. All of these respondents do the primary cooking and fuel collection for their household, and 7 of the 9 cut and chop the firewood for cooking and heating. Four of the 9 had only one cookstove in a single-room home; three of these were single-person households in Kyanjin Gompa; the remaining household was a very low-income household in Uttarkashi. The other five respondents had multiple cookstoves, consisting of LPG and one or more biomass stoves. We also conducted one open-ended interview with a local health volunteer in Dalchoki, Nepal to explore potential health benefits and understand perceptions of improved cookstoves.

5.2 Co-Design of Improved Stove with Lead User in Uttarakhand, India

5.2.1 Location Background & Field Work Objectives

The design team from MIT, local partners and researchers traveled to Uttarkashi, Uttarakhand, India, where we stayed in a simple hotel for the duration of the research in this area. Uttarkashi (elevation 1158 m above sea level) is located 4.5 hours by bus from Dehradun, the capital of the Uttarakhand state in Northern India. The Himalaya Mountain range runs along the Northern border of the province.

Figure 21: Map of Uttarkashi, Uttarakhand, India[3]

The town of Uttarkashi is located on the Ganges River (see Figure 22), making it a popular religious destination for Hindus [90]. The town has a local market and is accessible by motor vehicles on paved roads. Our partner Emmanuel Kamathan, a principal at Emmy's School in Uttarkashi, accompanied us in visiting a low-income community in Uttarkashi located on the riverbank. We also acquired prototyping materials at the Uttarkashi town market, including cardboard for rapid prototyping and sheet metal (galvanized steel) for building a chimney. We purchased the sheet metal from a local metalworker.

Figure 22: Uttarkashi and Pata, India with the Ganges River[4]

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[3] Made using maps.google.com

[4] Made using maps.google.com

The team, accompanied by a colleague of Kamathan, visited the village of Pata, embarking on a winding mountain road in a van for 1.5-2 hours to reach the mountain community from Uttarkashi. Here, the team spent three days conducting research and prototyping with community members. The fieldwork completed in this location is described in part in [91].

5.2.2 Background on Selected Household and Lead User

Ross et al.'s framework provides key characteristics of lead users for positive co-design outcomes as described in 2.1.7 Lead User Theory & Innovation Capacity in Co-design. Of the four characteristics, three are useful for initial selection of the lead user for the co-design process:

- May benefit socially, financially, and in skill-building
- Has technical expertise
- Has access to user preferences through a social network

The fourth, possessing good design communication skills, is not as easily assessed prior to designing with the user. In collaboration with the local leaders, known as the *gram panchayat* of Pata*,* the team identified Samira (pseudonym to preserve anonymity) to interview and engage in co-design. Her position as one of the leaders of the local women's association, interest in improved stoves, and previous experience designing and experimenting with her own stove afforded her the social network access and technical expertise we were looking for in a lead user. The team explained that we intended to prototype a chimney stove, which would allow her to gain experience with a new stove feature and provided appropriate compensation for her participation to increase the benefits to Samira for participating in the co-design process. After we met Samira and described our project and purpose, she agreed to help us conduct a WBT on her traditional stove and participate in an interview.

Baliga conducted an interview with Samira in Hindi, learning key information about her experience with cookstoves and perceptions of improved fuels: the importance of time, taste, safety and convenience in choosing between an Liquified Petroleum Gas (LPG) stove and a traditional one. Samira is a 40-year-old wife and mother of two living in a two-story home made from wood and clay, and under a small window in her kitchen are a traditional, two-pot clay *chulha* (Hindi for stove, Figure 23) and LPG stove, a common clean fuel cookstove.

Figure 23: Samira's traditional stove during initial WBT

We learned that even though Samira primarily uses her LPG stove to cook food and make tea, she prefers to use her traditional stove because of the taste of food, other uses in addition to cooking, and health and safety concerns with LPG. She remarked, “The taste of food is better on the *chulha*. Gas tastes like a dead person,” specifically noting that *roti*, an Indian flatbread, tastes better cooked on a traditional *chulha*. Regarding health, she shared her perception that “more people are falling sick because more food is getting cooked on gas. *Chulha* food makes you feel better when you are sick.” She also fears the effects of the gas stove on her and her family’s safety, saying “[the gas stove] can burn up the house, all my people, my whole life. *Chulha* is far safer.” However, the speed afforded by the gas stove makes it an appealing choice when Samira is pressed for time. She explains, “If you don't have enough time, you use gas, and when you have more time, you use *chulha*.” In addition to cooking, Samira values the traditional stove’s capacity for space heating in the winter, water heating during power cuts in the rainy season, and keeping snakes and mosquitos away.

Samira also shared her observations about stove performance, and how she has improved her own stove as a result. She previously noticed that her mother-in-law’s stove was much bigger than hers, but that cooking can be done more efficiently on a smaller stove. She noted that in taller stoves, the “fire goes everywhere, it gets wasted,” so she prefers shorter stoves. Her observations align with established cookstove design guidelines and engineering principles that convey the importance of heat transfer from the fire to the pot in overall efficiency [54], [57].

In addition to the survey, the team conducted a WBT to establish the baseline performance of the traditional stove for comparison after the modification. This baseline test allowed us to keep constant parameters such as wood moisture level, kitchen dimensions, and other variables that affect the calculated efficiency and usually make field testing difficult to analyze and compare universally. The team rotated tending the stove for the WBT one at a time; the smoke from the fire caused eye irritation and light-headedness after a few minutes of sitting in the kitchen. We were also able to observe how Samira ignited and tended the stove during the WBT, and which utensils she used with it, which helped the team better understand stove usage in context and improve our own fire-tending skills for future testing.

5.2.3 Co-Design Process Prototyping & Testing

Together, Samira and the team designed the improved clay stove, combining Samira's skills and knowledge of local materials and the team's engineering experience to modify the traditional design to include a chimney. First, Samira indicated the desired dimensions of the stove body and placement by putting bricks on the ground in the kitchen, which we measured with a measuring tape we brought. This ensured that the stove could accommodate the size of wood pieces and size and type of cooking utensils she desired (a stove's inability to accommodate preferred fuel and utensils is seen as a barrier to adoption and use [31], [32], [33], [35], [36]). Using the guidelines and learnings from previous lab testing, I estimated the chimney dimensions. The height of the chimney was determined by the height of the window in the kitchen. We decided to route the chimney exhaust through the existing window (open to the outside air with a mesh cover) rather than cutting a new hole in the wall. This would allow Samira to more easily uninstall the chimney prototype in case the design did not work well for her in the long term.

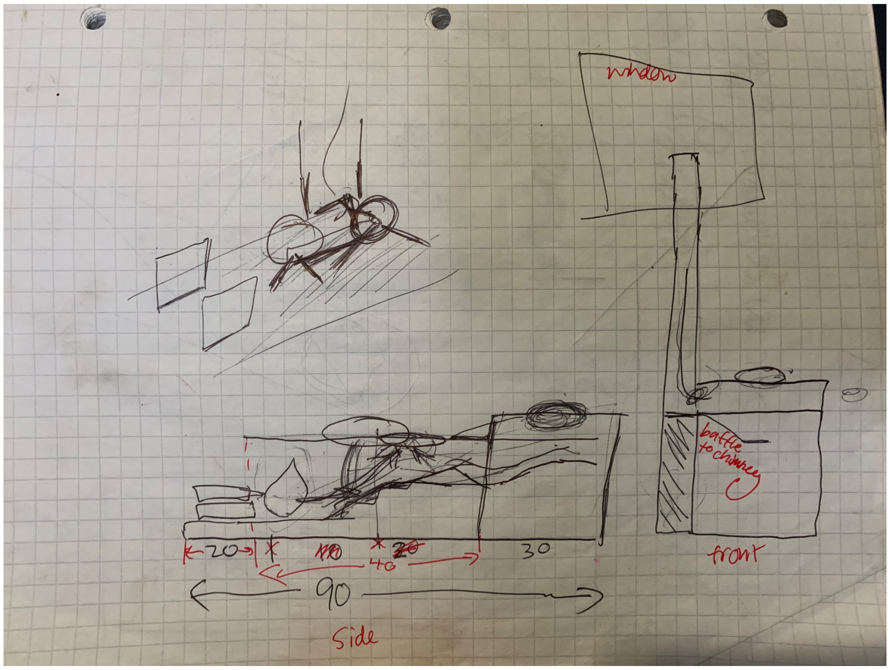

Figure 24: Original design sketch from my field notes, dimensions in cm

The team worked together to incorporate additional features to the design to increase the heat transfer to the pot and the natural convective air flow of the hot flue gasses, seen in Figure 24. These included baffles under each pothole to direct the gasses toward the pot, as well as a slight increase in elevation from the front of the stove (fuel inlet) to the back (chimney) to aid in natural convection. These features were made of rock, bricks, and clay along with the rest of the stove body. Sheet metal was chosen for the chimney to increase the space heating benefits of the stove when it is first ignited, and the clay body is still cool. Stove exhaust gasses retain heat, which become losses when leaving the kitchen in a chimney, so we expected an uninsulated metal chimney to transfer this heat to the kitchen via conduction and convection due to its high thermal conductivity as opposed to a clay chimney with high thermal mass which would first absorb, then radiate this heat slowly. With added features and Samira's dimensions, we were ready to start building the stove.

Figure 25: From left to right, Robyn Richmond, Dan Sweeney, Sucheta Baliga, and Samira mixing clay for the improved stove

Samira and the team shared construction methods for building the stove from clay and the chimney from sheet metal, learning from each other to complete the stove. To build the body of the stove, we first had to gather the right materials. Samira taught us the local recipe for clay mixture: soil, fresh cow dung, rice husks (agricultural waste from rice farming), and water. She showed us how to mix them together with our hands to achieve the right consistency, seen in Figure 25. The resulting mixture was easy to work with and sticky enough to apply to the bricks. Together, we laid the bricks and applied the clay to make the stove body. Samira demonstrated how to throw a handful of clay on the brick so that it would stick. The stove was not sized to match the brick dimensions, so we had to break some bricks and rocks to follow the design. Samira, unsurprisingly, was incredibly skilled at breaking the rocks to the desired shape. She had metal stove grates and a few pieces of steel rebar, which we placed on the potholes to support the top of the stove. After laying the bricks, rocks, and metal for the stove, Samira showed us how to use water and clay to add a thin layer to the outside, creating a smooth finish. We left a hole on the side of the stove near the wall for the chimney.

After learning from Samira how to build the stove, we taught her how to make a chimney from sheet metal using the sheet metal purchased in Uttarkashi, as well as shears, hammer, power drill, and rivets we brought with us (available in Uttarkashi). First, we measured the sheet metal and cut it to match the chosen dimensions. Then, we used a square post on a nearby building as the form to bend the metal into a rectangular shape. One person held the metal against the post, while the other hammered the metal against the edge of the post to make a 90-degree angle. After bending the metal into a rectangular prism, we showed Samira how to drill holes in the metal with the power drill and fasten the edges together with rivets (Figure 26).

Figure 26: Left to right, Robyn Richmond, Samira, Sucheta Baliga fastening the chimney with rivets

We attached the chimney to the stove body, using clay to seal around the chimney-to-stove seam and drilling brackets into the wall for support. We made several segments of the chimney and fastened them together at right angles to make the exhaust path with corners. We cut a small hole in the mesh covering the window for the chimney path. We routed the chimney through the window rather than through a new hole in the wall for risk mitigation, so that she could more easily remove the attached chimney if it stopped working for her, as this stove was designed as a prototype rather than a permanent final product. The chimney outlet pointed up, so the smoke exhausted up rather than out into a walkway next to her house. To finish off the stove, we filed the corners on the sheet metal and layered a thin film of clay on the outside of the chimney to reduce the surface temperature, and therefore risk of burns.

5.2.4 Results & Discussion

To evaluate the stove, both Samira and the team tested the new design and concluded that the stove functioned as desired. The night we finished building, Samira fired the stove to speed up the drying clay, which allowed us to conduct a WBT and her to cook breakfast for her family on the stove the following day. When we arrived to conduct the test, Samira reported on the stove performance based on her cooking experience. The back pothole was not heating up, meaning either the pot power ratio was imbalanced (only the front pot heats up) or the hot flue gasses were not effectively transferring heat to the back pot. We inserted a baffle under the second pot to route the hot gasses under the pothole and then out through the chimney and increase the heat transfer to the second pot. During the WBT test, Samira indicated that, with the design adjustments, this stove would work for her (Figure 27). The second test also revealed that the stove no longer caused noticeable irritation from indoor smoke emissions; several members of the team and the community (including a small child) were present in the kitchen at any given time during this test, rather than the cook being the only person in the kitchen.

Figure 27: Left to right, Sucheta Baliga, Samira, Robyn Richmond conducting WBT on improved stove

The results from the testing and analysis are summarized in Table 14. The emissions data shown are average concentrations taken over the course of each test for the Sensen located above the primary pot of the stove (you can see the gray Sensen box suspended by a stick in Figure 27). The thermal efficiency is the combined thermal efficiency of the cold and hot phases of the test. The cooking time is represented by the time to boil water in both hot and cold phases of the test. Cooking time, fuel used, and thermal efficiency of the improved chimney stove are all within 10% of the original traditional stove, while the emissions of fine particulate matter and carbon monoxide decreased by 32.3% and 78.5% respectively. The clay on the improved stove was still wet during the WBT, causing it to absorb more energy from the fire, so we expect the boiling time to decrease and the efficiency to increase during regular use, a potential improvement over the traditional stove. The Pot Power Ratio (PPR) is also preserved from the traditional stove after we add a baffle under the back pothole, so the distribution of heat between the pots is maintained for cooking tasks on the new stove.

Table 14: Performance Comparison of Traditional and Improved stoves in Pata

	Test time (min)	**Fuel Used (g)**	**Thermal Efficiency**	**PM 2.5^ (mg/m^3)**	**CO^ (mg/m^3)**	**PPR**
Traditional stove	61	1516	8.62%	4.57	421.27*	1.63
Improved stove	66	1460	8.45%	3.09	90.72	1.81
Change	*+8.1%*	*–3.7%*	*–2.0%*	*–32.3%*	*–78.5%*	*+11.0%*

*This CO level is outside the calibrated range of the sensor, so it may have additional error.
^Emissions concentrations are fugitive emissions averaged over the test.

The decrease in pollutants is lower than expected since the chimney would theoretically remove almost all combustion products from the kitchen. This could be explained by a few different factors. In unvented, traditional stove designs, it is advantageous to leave a narrow gap between the stove and the pot to increase the convective heat transfer from the hot flue gasses to the contents of the pot. Chimney stoves typically eliminate this gap to prevent pollutants from entering the room. Our improved stove design maintained the gap between the pot and the stove, allowing pollutants to leak out of the stove into the kitchen. In both tests, the Sensen pollution monitor was placed above the first pot on the stove (see Figure 27), meaning the pollution readings would reflect this leakage and may explain why the decrease in pollutants is less than expected. The team noticed smoke emitting from the pot gap during the WBT, and in discussion with Samira she indicated that in her next rebuild of the stove, she would seal the pot gap to reduce these emissions levels in the kitchen. Another potential source of pollutants in the improved stove could be backflow through the window. The window and door of the kitchen were not sealed, so some smoke from the chimney could have blown back into the kitchen through these entry points during the test. Even so, the CO levels decreased significantly, potentially because of the draft supplying more air for more complete combustion.

To assist with maintenance in case of issues with the sheet metal chimney, the team shared the contact information of the metalworker in Uttarkashi with Samira. On returning to the market, the team also mentioned to the metalworker that there may be an additional source of work in Pata and other villages based on the community's interest in our project. More work and facilitation are needed for long-term sustainability if this solution is to be scaled, but these initial steps plant the seed for future work on improved stoves in this location.

Samira's lead user characteristics contributed positively to the co-design process. Her technical expertise in stove construction enabled her to contribute meaningfully to the design, beyond that of a typical user who also could have assisted in choosing dimensions to fit their kitchen and utensils. In addition, we were able to teach her how to work with sheet metal, and she gained experience in constructing a chimney stove and related features, allowing her to benefit from the process through capacity-building. For the final WBT, Samira invited people from her community network to see the new stove design, increasing awareness of this concept and gaining feedback from more potential users. Samira also demonstrated design communication skills in her ability to assess and modify the design to ensure it fit her needs. For example, in the new design, the back pothole is slightly elevated to assist with buoyant heat transfer to the back pot. During prototyping, Samira showed us that this elevation would interfere with the first, lower pothole, and prevent her from using her preferred pot. We adjusted the position of the first pothole together to make sure the pot fit. This presents an additional case study applying Ross et al.'s framework [2], further demonstrating its usefulness in biomass stove co-design.

From our preliminary user feedback and results, we successfully modified a traditional stove design to remove smoke from the kitchen while maintaining usability and performance expectations of users. As mentioned, the objective of the improved stove design was to reduce indoor air pollution, as an initial step to move the project into the solution space as we continue to define the problem space. The process of designing and prototyping with Samira in co-design as well as the mixed methods data collection revealed valuable insights into user priorities for cookstoves and usage practices.

In addition, the design guidelines developed during laboratory testing proved useful for enabling co-design with Samira. Because these guidelines allowed flexibility in the dimensions of the stove, Samira was able to choose stove dimensions that fit her preferences. While the stove performance was not optimal, it still allowed for significant impact on HAP and enabled increased user participation in the process of designing a stove. Future work should explore how to build flexibility in technical design principles to enable increased participation of users in the design process and to allow solutions to be more easily customized for particular users.

5.2.5 Follow-up Results

Dr. Pranava, one of our partners in India who collaborated with us in Pata, returned to Samira's home October 2022 to get feedback on the design. Pictures show the chimney is still in place, but she had rebuilt the stove to further improve the performance in the two months since we had installed the chimney. First, she had reduced the size of the firebox at the front of the stove so the fire was closer to the front pothole. She had also replaced the metal baffle under the second pothole with a brick/clay baffle. Rather than fixing its position, she kept it moveable so she could adjust how much heat was directed at the second pot. She used brick/clay rather than metal to prevent risk of cuts from moving the baffle. Samira's continued experimentation and improvement of the design demonstrates the additional capacity she gained from the co-design experience, and suggests long-term sustainability of this solution concept.

5.2.6 Challenges & Limitations

While the team deployed four Sensens at various locations to measure pollutant concentrations during each test, we were only able to recover data from one of these sensors. As a result, we were not able to assess the distribution of pollutants in the kitchen and can only compare emissions taken at one location. The concentration distribution likely changed between tests because of the drastic change in fluid flow between the two stoves, so our calculated reductions in HAP are not a comprehensive reflection of the change in emissions concentrations in the kitchen. In addition, best practice according to the ISO standard is to complete at least five replicate WBTs and report the mean for each metric [51]. Due to travel limitations, the team only conducted one test for each condition (traditional and improved), so this limits the validity of the results.

Overall, the team was able to engage Samira and provide space for her to contribute meaningfully during the design process, but at different times during prototyping there were challenges with maintaining the egalitarian partnership required for co-design among Samira and the team. Anytime diverse stakeholders collaborate to address complex problems, each brings their own interests, values, and goals to the table [92], [93]. In this project, the team would have greatly benefited from an alignment meeting prior to the fieldwork, in which the group discussed the various goals of each member, assessed the feasibility and level of priority of these goals, and aligned on the common approach the group would take to achieving these. My goal for the research was to learn from users and use prototyping as a vehicle for hands-on engagement and mutual learning, which requires co-design methods to achieve. Some team members prioritized construction and testing, which can be more efficient when technical experts take the lead and utilize a more user-centered approach [21]. An alignment meeting to agree on the level of participation of users may have allowed more effective engagement of Samira in the prototyping process. In addition, not all partners had familiarity with PD methods, so additional capacity-building with our partners may have also enabled more effective collaboration. This may have allowed for everyone to adopt a learning mindset, and approach working with Samira as an opportunity to learn from her expertise. In addition, the inclusion of Samira in the design process was limited to the prototyping stage. Ideally, Samira also would have been directly involved in concept generation and selection as well, but this was not possible within the constraints of this work.

5.3 Training under Stove Expert in Salambu, Nepal

5.3.1 Location Background & Field Work Objectives

The second multi-day location the team visited was Salambu, Nepal. MIT and Kathmandu University (KU) partners have previously collaborated with the workers at the Dhulikhel Hospital Community Outreach Center in Salambu on projects related to improving home energy, HAP, and thermal comfort, especially to improve health outcomes for community members in this village. Salambu is located at 1657 meters above sea level. In addition, another Nepal-based partner organization Matribhumi Urja has expertise in improved stoves and has iteratively refined their Matribhumi-Improved Cookstove (M-ICS) design over the past decade. Because of Matribhumi Urja's expertise in chimney stoves, the team planned to train under a Matribhumi Stove Master by building M-ICS in Salambu households to gain insights into constructing clay improved stoves with local materials. The team also collaborated with KU students to construct M-ICS and collect data in this location.

Figure 28: Map of Nepal fieldwork locations[5]

The team traveled eight hours to Salambu by bus from Dhulikel. The initial trip took longer because the road was extremely muddy from the monsoon season rains. The bus had to travel slowly, so an assistant to the driver could jump out and throw large rocks on the road to increase traction for the bus. At one point, the bus got stuck in the mud, so the team had to get out to reduce the weight and help dig the wheels out. Stepping in the mud allowed leeches to attach to our feet. The return trip was much faster because the driver learned of a different route with better road conditions.

The research team and KU students stayed at the Salambu Health Center during the field research. Each day, the research team walked 20 minutes down the steep mountain incline to the lower part of the village to collect data and construct stoves.

5.3.2 Background on Nepal-based Partner: Matribhumi Urja

Matribhumi Urja is a Nepal-based stove organization that has spent more than a decade refining their improved stove design M-ICS. The M-ICS design is a two-pot stove made primarily from local clay, and features a chimney made from sun-dried clay blocks to remove smoke from the kitchen. The M-ICS also has a specialized metal grate to support airflow to the fuel and a baffle under the second pothole to direct hot gasses.

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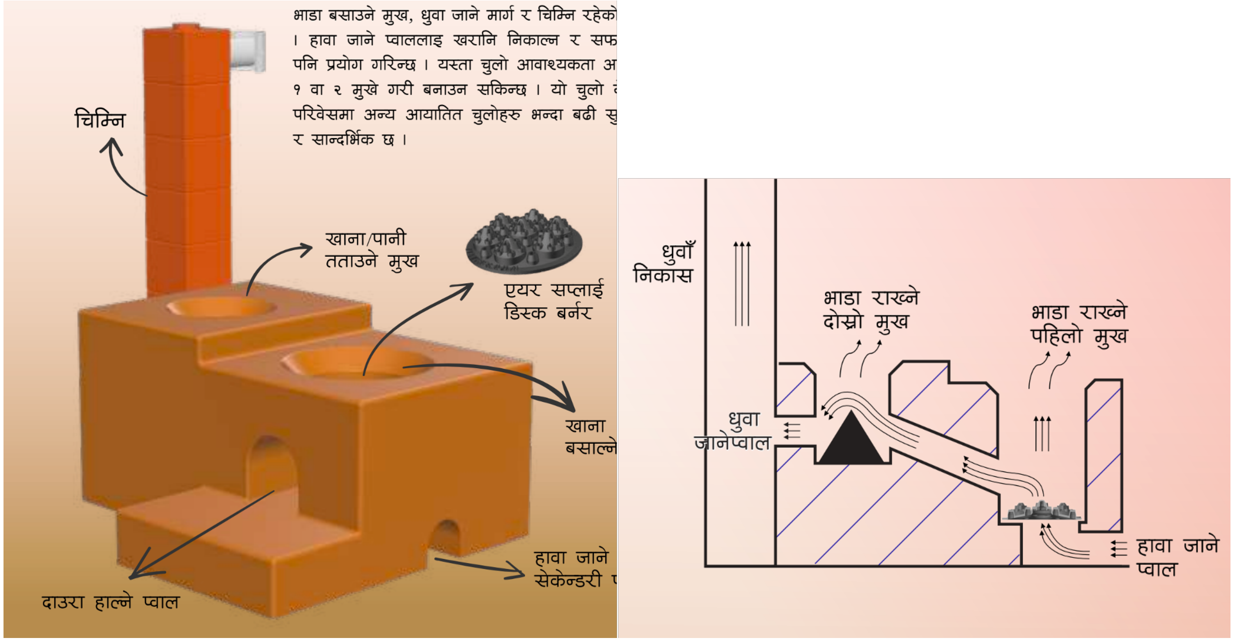
[5] Made using maps.google.com



(a) (b)

Figure 29: (a) Rendering and (b) cross-section of M-ICS. Source: [48]

Matribhumi Urja operates by sending Stove Masters to train women in communities around Nepal to build the M-ICS using a construction kit. The trained women then use the construction kit to build M-ICS in households in their community to earn income.

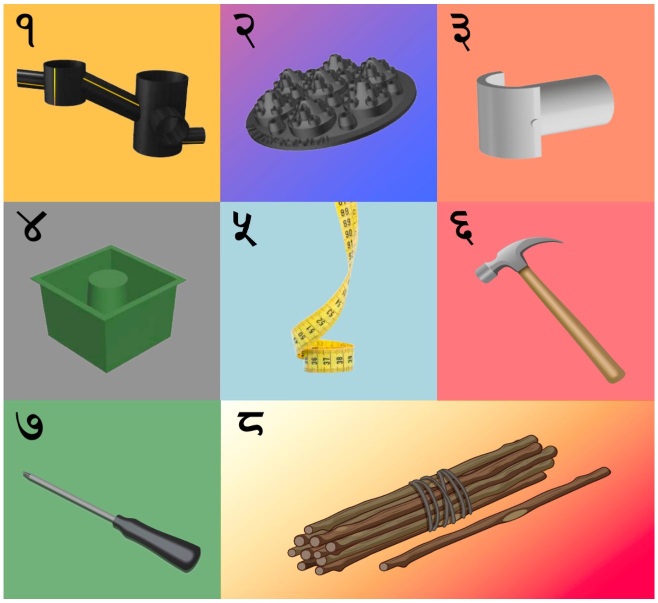


Figure 30: Components of the Matribhumi Construction Kit. Source: [48]

The construction kit includes tape measure, PVC pipes, plastic injection-molded chimney block mold, steel supports, chimney rain guard, fuel grate, and plastic angle guide. The PVC pipes are used as molds to create the internal flow geometry in the stove. Steel supports add structural integrity around the firebox, which is more susceptible to cracking due to the high combustion temperatures. The sheet metal rain guard is fixed to the outlet of the chimney to prevent rain from entering the chimney. The plastic angle guide is used to chamfer the potholes for a tight seal between the pot and the stove. The team trained under a Stove Master named Dilli Dai (*Dai* means brother in Nepali) using the Matribhumi construction kit during fieldwork in Salambu.

5.3.3 Background on Selected Households for Installation

As apprentices of the Matribhumi Stove Master, Dilli Dai, the research team completed construction of three M-ICS in Salambu, conducting interviews and WBTs in these households as well. The three women respondents who did the primary cooking in these homes were between ages 47 – 57 with 2-4 people in each household. All three had 3-4 stoves (*chulho* in Nepali) in use, including an indoor and/or outdoor traditional stove, an improved biomass stove, and an LPG stove.

Figure 31: One-pot TCS in separate kitchen

Two households use their LPG most often, but neither of these prefers their LPG stove above the others. One prefers her traditional biomass *chulho*, while the other prefers her improved biomass stove. The third household reported using LPG for convenience, when she needed to cook or heat something quickly or to prepare meals for guests. This woman also had a clay ICS that she prefers to use because she suffers from chronic migraines that are exacerbated by smoke from traditional biomass stoves. One cook also reported that her improved stove prevents pots from getting black from soot. In Salambu, residents purchase wood from a community forest nearby to use for fuel in their stoves.

Figure 32: HotPoint stove, broken plastic handles pictured bottom left

Two households in Salambu possessed improved cookstoves manufactured and distributed by HotPoint[6]; however, neither of these stoves was in use. In one case, the HotPoint stove was being used as a dustbin, and the family mistakenly thought it was to be used with hot charcoal rather than with wood fuel. In the other, the cook reported that it was "too small and too slow" when asked why she did not like it. The handles on this stove had also broken off, so the cook was not able to touch the metal stove during use because it became too hot. The team improvised some wooden handles (Figure 32) to make the stove usable again.

5.3.4 Construction of M-ICS

The construction process starts similar to how we started with Samira in Pata. The team gathered clay nearby and then mixed this with water.

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[6] https://csrbox.org/India_CSR_products_Hotpoint-Chulha_47

Figure 33: Left – Stove Master and Salambu Health Center worker gathering clay; Right - Dan Sweeney and Meghana Vemulapalli mixing clay and water

Next, the team used the clay mixture to create chimney bricks. These were made before starting installation in households to allow time for drying in the sun. The clay was packed into a plastic mold, then released onto the ground or a platform for drying, seen in Figure 34.

Figure 34: Chimney mold and drying chimney bricks

At each household, Dilli Dai asked the cook to boil equal parts salt and sugar in water, and then mixed this with some of the clay. This clay mixture was used to create more sun-dried bricks for the stove seen in Figure 35. These would be used internally at the hottest points (combustion chamber and flow path of hot gasses) since this mixture has more durability and resistance to high temperatures according to Dilli Dai. We formed the mixture into log shapes to fit around the PVC pipe molds used to create the stove internal geometry.

Figure 35: Sugar-salt-water-clay bricks for high temperature regions of the stove drying in the sun

After removing the old stove with pickaxes and a wheelbarrow, Dilli Dai measured the base of the stove and laid out rocks to approximate the location of the potholes. He also measured the location of the chimney based on this layout to ensure there were no obstructions on the inside or outside walls at this location to interfere with the chimney hole.

After confirming with the cook of each household that the layout would work for them, we started building the stove. We laid firebricks and rocks and covered them with clay, similar to how we did with Samira in Pata. We placed the first and largest PVC pipe to create the combustion chamber and another smaller diameter PVC pipe next to it for the primary airflow to enter underneath the chamber.

Figure 36: Combustion chamber and fuel inlet PVC pipe molds and brick-clay foundation of the stove

After making the base of the stove, we added another PVC pipe mold to the front of the combustion chamber for the fuel inlet. On top of this mold, we placed bent steel rebar and a steel support from the Matribhumi kit to add structural support to the fuel inlet and combustion chamber connection, since the clay is most susceptible to cracking from high temperatures in this area of the stove. One of the sugar-salt clay bricks was placed around the combustion chamber mold at this point in the construction process.

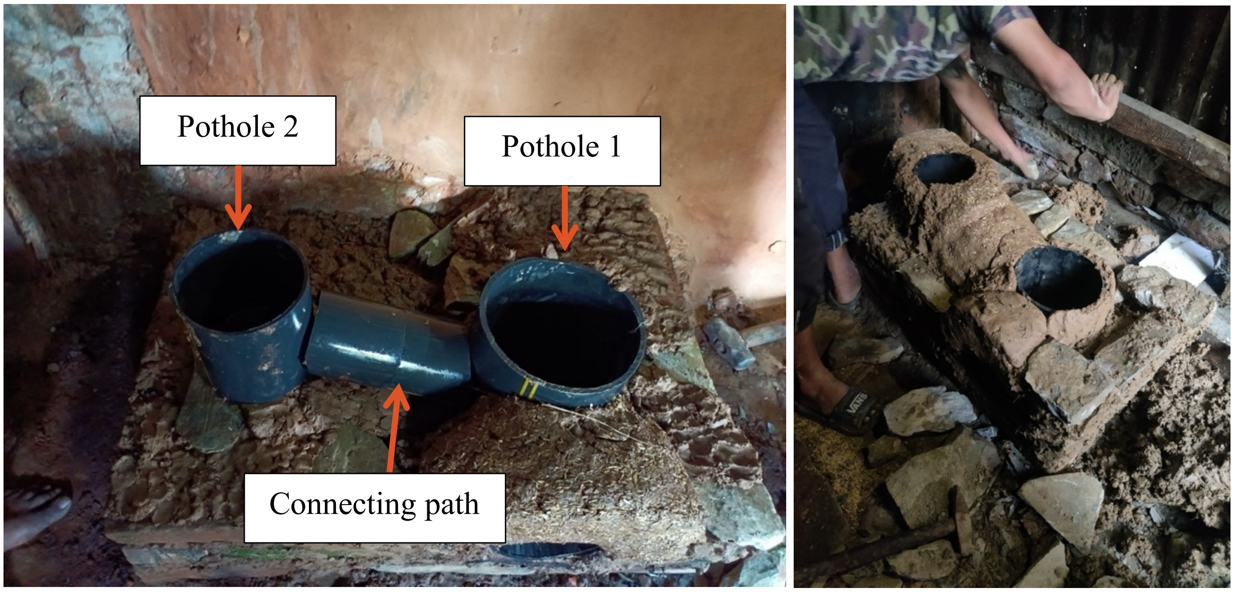

Figure 37: Progress Photo from M-ICS Construction

We continued adding rock and clay to the stove, then added the remaining PVC molds for the second pothole and the flow path connecting potholes one and two (Figure 37). We added the remaining high temperature bricks to the potholes and finished making the body of the stove.

We left the stove with the PVC molds overnight in each household to dry. We returned the next day to remove the molds and continue constructing the stove. The next step in construction was to build a shelf underneath the fuel inlet on which to place the wood. We used rocks, bricks, and clay to build this as well. Using clay and water, Dilli Dai smoothed the surfaces and created sharp corners on all edges for a clean and precise look for the stove. Then, Dilli Dai used a plastic guide to chamfer the potholes. After removing material with the plastic guide, he used one of the household’s pots to smooth the chamfer, seen in Figure 38. He put water on both the chamfer and the pot bottom, placed the pot on the hole chamfer, and moved the pot in circles to smooth the chamfer surface and ensure the pot fit on the hole with a tight seal. This was repeated for the second pothole.

Figure 38: Dilli Dai adding chamfer to potholes for tight seal

On the last day, our team carried the chimney bricks to each home to construct the chimney for each stove. We cut or dug a hole for the chimney in the wall at the measured height (some kitchens had walls of corrugated metal, others were thick and made from rock and clay). We stacked the chimney bricks from the ground to the hole. At the exit of the secondary pothole, we cut a hole in this brick to allow flow into the chimney. We cut a hole on the side of the top brick to match the hole in the wall, and we cut a small hole on the front of the bottom brick to allow cooks to remove ash from the bottom of the chimney. We connected the chimney bricks together with clay to seal them together and prevent smoke from leaking out the sides. The top brick was sealed with a rock and clay—this could be easily removed and resealed to allow chimney cleaning and maintenance for removing creosote. On the outside of the house, we attached the metal pipe and rain guard to the wall to prevent backflow from the wind and water from entering the chimney.

Figure 39: Completed M-ICS in Salambu

For more detail on this construction process, please consult the Matribhumi Manual [48] and/or contact Matribhumi Urja to connect with a Stove Master.[7]

5.3.5 Results & Discussion

The research team conducted two WBTs on one-pot traditional stoves and one on an improved biomass stove (not M-ICS). The results of these tests are summarized in Table 15.

Table 15: Salambu WBT Results

	TCS - A	**TCS - B**	**ICS**
No. of pots	1	1	2
Cooking time (min)	28.5	42.3	41.3
Fuel used (g)	760	570	888
Cooking Efficiency	11.21 %	12.00 %	9.81 %
Indoor PM 2.5 (mg/m^3)	3.45	0.63	0.98
Indoor CO (ppm)	64.27	9.07	6.71
Sensen Location	Doorway	Above Pot	In front of fuel inlet

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[7] https://www.mchulo.com

Interestingly, TCS B and the ICS showed similar emissions characteristics even though the ICS had a chimney. This may be due to the variation in position. There may have been backflow of flue gasses out the fuel inlet in the ICS contributing to the emissions levels. In addition, even though the ICS had two pots, providing more surface area for better heat transfer, it had the lowest efficiency and most fuel usage out of the three. This may be because the stove was larger and absorbed more of the energy from the fire than the smaller TCS one-pot stoves.

The Sensen used to test the ICS was placed in front of the fuel inlet, which is where someone might sit to tend the fire in the stove. As a result, I used the data from this WBT to estimate the 24-hour average exposure for CO and PM 2.5, which can have significant health effects. For this ICS, CO 24-hour exposure is estimated to be on average 0.66 mg/m^3, which meets the WHO AQG of 4 mg/m^3 [53]. Sitting in front of the ICS, a person may be exposed to an average 84.5 $\mu g/m^3$ of PM 2.5 over 24 hours. The WHO AQG is 15 $\mu g/m^3$ PM 2.5 for 24-hour exposure, and the first interim target is 75 $\mu g/m^3$ [53], so this does not even meet intermediate air quality goals for improving health. In the households we observed, the cook does not sit in front of the stove all the time while cooking, they leave the kitchen to do other tasks while they wait for food to cook. Thus, this estimate may not be representative of actual personal exposure, though it does provide insight for personal exposure levels in cases where the cook sits at the stove during cooking.

Regarding the construction experience, the team gained valuable tacit knowledge on local materials and insights to improved clay stove design. In particular, the sugar-salt clay mixture for increased durability to high temperatures was new information to the team. This insight is particularly useful because it utilizes readily available household items to increase durability rather than requiring expensive or specialized materials that may be difficult to acquire in remote locations. Also, the method of smoothing the outside of the stove and creating sharper corners using the plastic tool increased the aesthetic appeal of the stove, which users value [94]. Using the cook's pot as a tool for finishing the chamfer on the potholes allowed us to expand our view of what the tools available to us as designers are in these remote locations. The M-ICS design and implementation utilizes primarily locally accessible and affordable materials to deliver an innovative design that reduces HAP in household kitchens.

The interviews and observations allowed the team to see the results of the HotPoint stove distribution in this area, and the limited impact of this design on the community. The user perceptions and lack of usage demonstrate the importance of testing in-context with users and creating sustainable designs for lasting impact.

5.3.6 Follow-up Results

A team of students returned to Salambu the following year (2023) and reported anecdotally that the households where we installed M-ICS the previous year generally liked the Matribhumi stoves, and all were still in use. In one woman's home, the M-ICS was in nearly perfect condition because she maintained it so well. She and other women in the community had built more M-ICS in homes nearby using the construction kit because they liked the design so much.

5.3.7 Challenges & Limitations

Several members of the research team became ill during fieldwork in this location. I was sick and bedridden for three of the five days we spent there, so I missed most of the construction of the first two M-ICS and the interviews conducted with two of the women in these households.

Three additional members of the core research team (out of six total) were ill at some time during field research in Nepal, so the construction and research took more time than expected. As a result, we were unable to conduct WBTs on the finished M-ICS stoves. Lab testing results show the M-ICS can reach up to 26% efficiency according to the International Network for Sustainable Energy [95], which would be an improvement over all baseline stove tests. However, it is unclear what the performance of M-ICS is in the field or over time after wear and tear on the stove, so I cannot draw any conclusions on the actual impact of the new designs.

While we gained valuable insights into construction of ICS and the M-ICS design, at times it was difficult to learn and gain experience during the construction process. We had assumed that the Stove Master would conduct the installation process similar to the trainings Matribhumi provides for local women, which would allow us to learn the process and apply it ourselves. However, the Stove Master focused on building stoves in as many households as possible, which would increase awareness of Matribhumi in this community and help assess the impact of a future training. Again, we may have benefited from an alignment meeting where we discussed various goals of the fieldwork and agreed on the priorities and approach to construction in Salambu.

5.4 Stove design and modifications for users in Langtang Valley, Nepal

5.4.1 Location Background & Field Work Objectives

The final and most remote location of the field research took place in Langtang National Park, a popular tourist destination in Nepal for trekking and sightseeing. The trek to Kyanjin Gompa begins at Syabrubesi at 2380 meters altitude [96]. After reaching Syabrubesi by van, the remainder of the trip continues on foot. The only way to reach Kyanjin Gompa (3890 meters) from Syabrubesi is by foot, by mule, or by helicopter. In the rainy season (June to August), the Langtang trek is muddy, with leeches present on the plants along the trail. Along the trek are guesthouses with water and freshly cooked meals, as well as beds for nightly stays. The trek to Kyanjin Gompa during the rainy season in 2022 took 2.5 days on foot. Our trekking guide took us on a slightly more difficult route to avoid potential landslides. Mule trains carrying goods passed us on our way along the trail. On April 25, 2015 the Gorkha earthquake hit Nepal, devastating villages in the Langtang River Valley and triggering over 4000 landslides in the region in the weeks following the initial event [97]. Over 9,000 people died across Nepal, India, China and Bangladesh, and over 600,000 structures in Nepal were damaged or destroyed as a result of the 7.8 moment magnitude earthquake [98]. During our trek in Langtang, we passed a shrine memorializing the lives lost on the trek as a result of the event.

One of the primary reasons for field research in this location is the remoteness. These communities have even more limited access to improved technologies because of the limited modes of transport, and the winters are more extreme due to the high altitude, making space heating an important function of stoves for community members. There are two groups of interest that we planned to engage with during the research—elderly living in a government housing block and single elderly men living in basic single room homes. Pre-travel ideation activities included generating ideas for the guesthouses along the trek to Kyanjin Gompa in addition to the elderly residents in this location; however, because of guesthouses' higher income from tourism and their use of improved technologies to meet their needs, the team decided not to pursue interventions with this user group and focus on the more pressing needs of the elderly. The team aimed to apply the knowledge gained from experiences in the previous locations to improve HAP for the elderly groups in Kyanjin Gompa and engage them in discussion about their challenges for user-centered design.

5.4.2 Background on Elderly Housing Block

In Kyanjin Gompa, the elderly housing block was provided as relief from the 2015 earthquake, which killed the families of several elderly men and women. An NGO quickly built the housing block with individual quarters for each inhabitant, each outfitted with a large, two-pot uninsulated metal stove with a chimney which was transported via helicopter to the remote village. This humanitarian aid was provided in response to immediate needs for shelter and cooking technology in the aftermath of the earthquake for this population. In the time since the provision, flaws in the design have revealed themselves to researchers visiting the community in Kyanjin Gompa. The stoves are much too large for a single elderly user, and result in high fuel consumption [37], [41]. In addition, some of the chimneys are completely blocked with creosote, rendering them ineffective in removing emissions from the kitchen [37], [41].

One man, age 70, and one woman, age 64, from this housing block were interviewed during this field research. Both reported that they liked that their stove produced only a little smoke, but that they would prefer a smaller stove that used less fuel. They do maintenance to remove ash and soot from their stove every 1-2 weeks. The elderly man stores his firewood in large quantities inside his home to protect it from the rain and elements. The woman explained that collecting fuel is very difficult for her, and she is not able to purchase it locally. She has a gas stove but cannot afford the fuel so she cannot use it. All the elderly users we interviewed use juniper branches to ignite the fire in their stoves.

5.4.3 Stove Modifications on Imported Stoves in Elderly Housing Block

In response to challenges with the imported cookstoves, the research team modified these stoves for improved performance and ability to meet the needs of the elderly users. The team improvised a tool to remove creosote buildup from the chimney of one elderly woman to allow emissions to exit her one-room home.

Figure 40: Hired porter and Dan Sweeney cleaning chimney from the roof of the elderly housing block

In addition, team members blocked off part of the large stove to reduce energy losses and therefore the fuel needed to fire the stove. One user had already attempted to reduce the size of her stove but had blocked the path to the chimney as well. The team adjusted this modification to both reduce the stove internal size and allow flue gasses to travel to the chimney exit.

5.4.4 Background on Selected Single Elderly Men

Also in this community, there are several elderly men who live in single room homes. Local members of the community look after them to make sure they are taken care of. These men live in modest homes made of corrugated metal on a wooden frame, with an opening for a door. They cook on an *odhan*, which is a pot stand over an open fire.

Figure 41: Pawan-ji's odhan and collected fuelwood

We specifically worked with one of these men, Pawan-*ji* (pseudonym used to preserve anonymity; the suffix *ji* is used in Nepali to show respect) to install a one-pot chimney stove in his home. Pawan-*ji*'s *odhan* sits right next to his bed so that the coals from the fire provide warmth while he sleeps. He places juniper branches on the corrugated roof to dry to use as kindling for the fire in the evening.

5.4.5 Design of One-pot ICS for Pawan-*ji*

The team designed, prototyped, and constructed a single-pot improved stove for Pawan-*ji* using the skills and knowledge gained from experience in the previous locations and in lab testing prior to fieldwork. First, I sketched the prototype dimensions using the M-ICS construction kit molds for reference, seen in Figure 42.

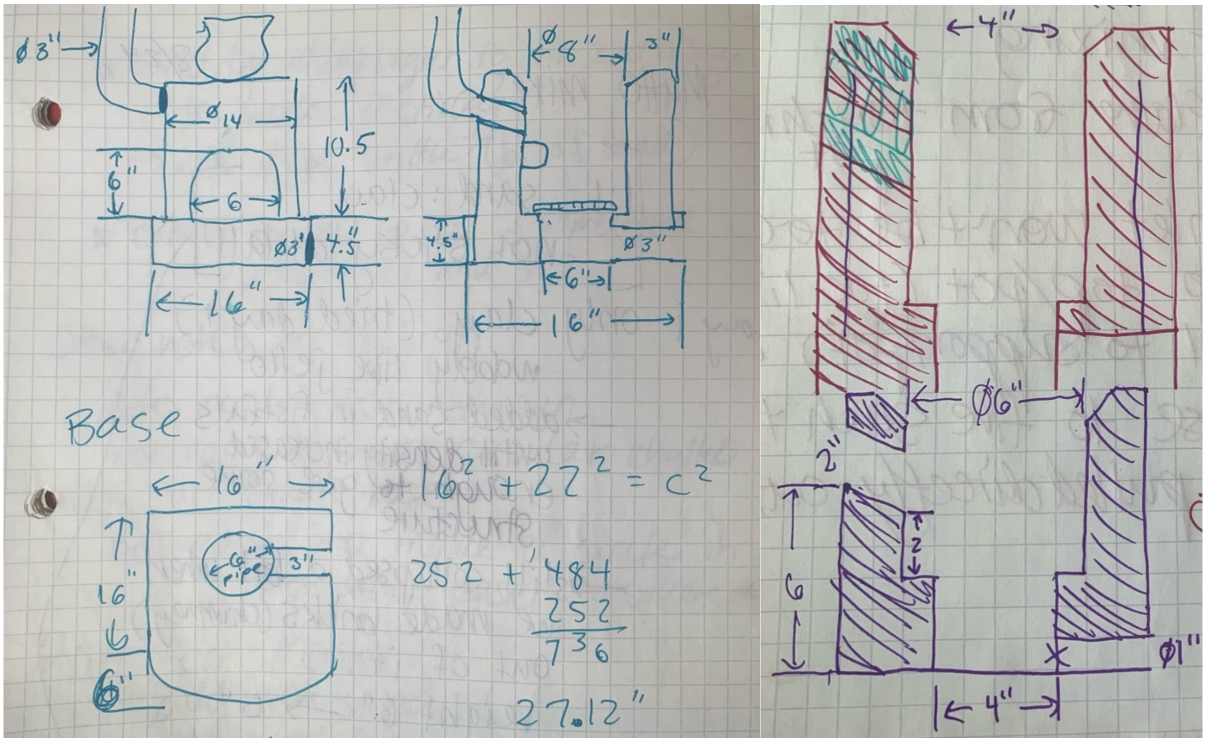


Figure 42: Original sketches of the prototype stove from my field notebook

Then, the team constructed a prototype stove in a courtyard in the community to test the design before installing it in Pawan-*ji*'s home. The resulting prototype had poor structural integrity. The locally sourced clay was much finer than we experienced in other locations and had an almost gelatin-like consistency when mixed with water. The stove did not fully dry and seemed to sag to the side from its own weight. Figure 43 shows the prototype stove construction using the Matribhumi kit.

Figure 43: Left to right - Robyn Richmond and Rahul Paramane constructing the prototype one-pot stove

In response to this performance, the team tested several different combinations of the fine clay mixed with coarse sand and large sawdust particles to see which mixture might be a stronger option for constructing the single pot design in Pawan-*ji*'s home. In addition, I made modifications to the design dimensions, including increasing the height of the pot above the fire to allow more mixing of the hot gasses before exiting the stove through the chimney.

After choosing a mixture of sand and clay and finalizing the stove dimensions, the team was ready to construct the stove in Pawan-*ji*'s home. As we learned from the Matribhumi Stove Master, we asked Pawan-*ji* to boil water with salt and sugar to mix with clay and sand for the firebox of the stove. Pawan-*ji* also helped us gather rocks and clay nearby to use in the stove. We constructed the chimney from scrap sheet metal found in the courtyard we used for the prototype. We did not have a Matribhumi specialized grate, so we cut steel rebar in pieces to form the grate for the stove. We did our best to smooth the stove surfaces and sharpen the corners and edges, but as you can see in Figure 44 we were not able to match Dilli Dai's skills in this aspect.

Figure 44: Robyn Richmond sitting on Pawan-ji's bed next to the finished one-pot stove with chimney

On our final morning in Kyanjin Gompa, the team removed the PVC pipe molds and fired the one-pot stove to help with drying. We showed Pawan-*ji* how to use a screwdriver to open a joint in the chimney for maintenance and cleaning. We made sure he knew that we were unsure how this new design would perform with the local clay and sand mixture, and that he should adjust or remove it if it did not meet his needs. With difficulty, we said goodbye to Pawan-*ji* and our local partners and began our challenging trek down Langtang River Valley.

5.4.6 Follow-up

The team of students and researchers also returned to Kyanjin Gompa the following year to test a water-heating attachment for the chimney stoves in the elderly housing block. They used cardboard sketch models to communicate their ideas and plans for installing the water-heater to the imported stoves to overcome hearing and sight impairments in elderly users.

Unfortunately, Pawan-*ji*’s one-pot stove had crumbled because the clay was too sandy and cracked from the heat of the fire, so he had returned to using his *odhan.* The team installed a new metal chimney stove design in Pawan-*ji*’s home. Also, it seems that tourism is increasing to this village, so the residents we worked with may get electricity access and induction stoves as a result of the increased income.

5.4.7 Results & Discussion

The team prototyped a one-pot clay stove for use by the single elderly men in Kyanjin Gompa but faced challenges with the new design. The primary difficulty came with the clay mixtures used to construct the stove. The team was unable to identify a lead user with technical expertise of stove construction and local knowledge of clay with whom to co-design, so we had to improvise and rely on our limited experience from the past few weeks to bridge this gap. The follow-up results indicate that this was not sufficient to create a successful design. Having a lead user like Samira could have greatly improved the quality of the one-pot design. Despite the poor quality of the prototype, the concept of a one-pot stove may still be worth exploring for this user segment to meet their specific needs.

The challenges with the stoves in the elderly housing block demonstrate the importance of building long-term relationships and following up with users to ensure the designs meet their needs for sustainable impact. While the housing block and stoves provided immediate relief for those affected by the earthquake, the flaws in the stove design in particular cause increased burdens from HAP and fuel collection on the elderly residents. Our team prototyped modifications to address these challenges, but the original NGO should also play a role in modifying the designs or replacing them. As designers, we have a responsibility to users of our designs, especially in the context of global development, to ensure our designs help in the long-term.

5.4.8 Challenges & Limitations

Due to the long trek to and from this location, the team had to adjust how we recorded data and notes on tests. Although two tests were conducted measuring the performance of a stove in the elderly housing block, the notes on these tests were lost during fieldwork, so I am unable to report the impact of the modifications made on the stove.

In addition, the elderly people living in the housing block spoke only Tibetan. To conduct interviews, our local contact asked interview questions in Tibetan, translated the answers into Nepali to our trekking guide, who then translated them into Hindi for Baliga to document in English in KoboToolbox and Google docs. It is likely that some insights were lost in the translation process. Also, not all interviewers possessed the same level of experience, which may have affected both the inquiries and reporting of responses during the research. These elderly people also had very poor hearing. Our local contact had to shout questions directly in their ears during the interview so that they could hear. It is possible that they misunderstood some questions, which may have affected the interview results.

While it may have been beneficial to engage the users in this location in the design process to ensure the products fit their needs, the advanced age of these users meant they had limited physical abilities. The elderly men and women we interacted with in the elderly housing block had arthritic hands and very poor eyesight. They were not able to see the images used during the interviews, something we had not anticipated, and we were unable to get results from this part of the protocol. Their mobility and sensory limitations made it infeasible for them to work on the modifications and maintenance with us, so their participation was limited to some consultation for user-centered design. Future projects should consider creating innovative methods for consulting users with sensory limitations and language barriers to increase their ability to influence the design process.

5.5 Overall Results & Discussion

5.5.1 Comparison of Performance Results

Table 16 shows the performance results from field testing in Pata and Salambu. The best value for each parameter is highlighted green, and the worst is highlighted in red.

Table 16: Summary of Field Test Results

Location	**Pata**	**Salambu**	**Pata**	**Salambu**	**Salambu**
Type	Improved (chimney)	Improved (chimney)	Traditional	Traditional A	Traditional B
No. of Pots	2	2	2	1	1
Test Time (min)	65.72	41.25	60.78	28.50	42.33
Avg Pot Power (W)	426.77	504.01	502.73	646.10	403.77
PPR	1.81	5.90	1.63	-	-
Fuel Consumed (g)	1440	788	1476	691	386
Firepower (W)	5,053	5,137	5,834	5,764	3,364
Cooking efficiency	8.45%	9.81%	8.62%	11.21%	12.00%
Emissions Sensor Location	Above Primary Pot	In front of fuel inlet	Above primary pot	Doorway	Above primary pot
Average CO (ppm)	79.20	6.71	367.75*	64.27	9.07
Average CO_2 (ppm)	1670	424	2865	1299	362
Average PM 2.5 (mg/m^3)	3.09	0.98	4.57	3.45	0.63

*CO readings were only calibrated up to 100 ppm, so this is outside of the calibration range

Traditional stove B in Salambu performed better than most other stoves, using the least amount of fuel, with highest cooking efficiency, and lowest CO_2 and PM 2.5 emissions (and relatively low CO emissions) in comparison to the Pata stoves with the same sensor location. Because we measured fugitive emissions, we are unable to report emission factors, but the low pot power of TCS B suggests that the emission factor may not be lowest among the tested stoves. The other Salambu traditional stove, TCS B, had the highest pot power and shortest cooking time. As Bryden et al. [58] explains, some traditional stoves and open fires can very effectively deliver high heat to pots for cooking. The Salambu improved stove had much lower emissions than the Pata improved stove; however, the emissions sensor in Pata was placed directly above the unsealed primary pothole, so this would have much higher emissions concentrations from the fire than a sensor placed in front of the fuel inlet, upstream from combustion.

The pot power ratio of the ICS in Salambu is much higher than that of the two-pot stoves in Pata. This means more of the heat goes into the primary pot than the secondary pot. Because the WBT phases end when the primary pot reaches 90℃, this means the test is faster for a stove with more heat directed at the first pot. PPR is an important usability characteristic [41], and some cooks may prefer the heat to be more distributed between the two pots on their stove while others may want to maximize the heat to the first pot. Thus, minimizing test time may not maximize user preferences for cooking because of its close coupling with PPR. More research should investigate the coupling between test time and PPR and user preferences for these performance metrics to inform future design work.

5.5.2 Interview Insights

Cooking Systems and Stoves

Of the 9 people interviewed, 5 had more than one stove. All of these respondents had one LPG stove and at least one biomass stove. Four of the five reported using LPG for most cooking indoors, but only one of these *prefer* their LPG stove above the others. Most of these respondents prefer their biomass cookstove(s) because of the taste of food cooked with biomass (all 4), the cost savings and easy access to fuel from cooking with firewood rather than LPG, and the perception of safety of biomass in comparison to LPG. As Samira explained, she believes LPG poses a threat to her family. Similarly, the leader of the women's group in Dalchoki described how she "can leave *chulho* unattended, but not LPG because it will blow up." These safety perceptions are important to note for programs aiming to improve HAP through increasing access to LPG, and more research and design work should be done to address these safety concerns with design, transparency, and training.

The unused manufactured improved stoves left in Salambu, though anecdotal accounts, illustrate what is documented in literature; the lack of sustained use of manufactured improved cookstoves, the failure of programs to create long-lasting impact, and the need to go beyond providing access to improved cookstoves to achieve impact on health outcomes (Ruiz-Mercado + probably Khadelwal). It is important to note that user perceptions play an important role in influencing stove usage. Though smokeless *chulho* designs similar to the HotPoint one observed in this location may offer improved efficiency, if users perceive them as too small or slow, then they will not use them. Norman [99] introduced the importance of signifiers in design, which signal to users the possibilities of a design. New designs must incorporate signals that allow users to perceive what is possible with the new design based on their previous experiences. Improved stoves must also demonstrate clearly observable benefits over traditional methods to gain acceptance from users.

Seasonal Usage and Other Functions

All interviewees reported using their biomass cooking stove for heating purposes, either directly to heat the surrounding kitchen, or indirectly (three participants) with hot char from the biomass stove. Four of the nine participants live in a single room home with one stove, using this for both heating and cooking. Of the participants with multi-room homes, two heat their separated kitchen, two heat an attached kitchen, and one participant heats both an attached and separated kitchen. Additional uses of the biomass cookstove include the smoke keeping pests away and the fire for lighting, which a lower-income household reported using instead of a flashlight with expensive batteries.

All interviewees reported using their cookstove more in the winter due to the heating benefits. For respondents with multiple stoves, this means choosing biomass over LPG more frequently in winter than in other seasons. Only two respondents indicated variation in usage in the rainy season, but their reports conflicted in increasing or decreasing usage. These conflicting reports may be due to the varying storage methods for firewood; some households had the capacity to keep firewood dry from the daily rains, whereas others did not, and spent more time lighting wet wood when it rained.

Four of the nine participants light their stoves once in winter and keep it lit all day for warmth. The remaining participants light their stoves the same number of times in all seasons. Two of these participants were members of the elderly housing block in Kyanjin Gompa and reported that they would like to keep their stove lit longer in winter for additional heat, but due to their limited ability to collect and store fuel they cannot keep the fire going and use blankets for warmth instead. Only one other participant (in Dalchoki) mentioned the burden of fuel collection, and their response conveyed that for them, collecting firewood from the nearby forest for 1.5 hours each day was part of daily life, but that improved cookstove programs might have more impact on those who have to travel further for wood fuel.

Five participants reported needing the most heating in 3-4 months of the year, November through February; all of these participants reside in the lower elevation (sub 2500 m) Himalayas. The remaining participants (elevation 2500 - 4000 m) noted needing additional heating in only 1-2 months, January and February. This is surprising; due to the colder temperatures in the higher elevation regions of the Himalayas, one would expect increased heating needs in more months of the year. The surprising heating needs may be explained by higher elevation residents' higher tolerance to moderately cold temperatures, by lower standards of home heating comfort of the lower-income participants in Kyanjin Gompa, or by the need for heating in only one room, where all indoor activities occur. More research should be done to investigate heating needs, including temperatures different users find comfortable.

Impact of 2015 Earthquake in Nepal

Several users in Nepal described how their cooking and heating systems changed after the devastating earthquake in 2015. The survey did not explicitly gather information related to this event; rather it came up naturally during some interviews. For the elderly men interviewed in Kyanjin Gompa, their technology changed after this event; the man in the elderly housing block reported having a wood-fuel heating system before the earthquake, and wishing he could have that back. Pawan-*ji* changed from a three-stone fire to an *odhan* (a pot stand to go over an open fire) after the earthquake, which he likes better because he can move it easily and use different size pots. For other users, their homes were rebuilt differently. One user reported having a large dining area, where the *chulho* would heat up the entire space. Now, she only has a separate kitchen heated with the *chulho*. Another user said her home before the earthquake was large with a small courtyard in the center where the family would gather around a traditional stove or three-stone fire for warmth. Now, homes are smaller with no courtyard, so she thinks improved cookstoves have more potential impact on households. These courtyards likely allowed the release of smoke while also warming the inside of the home, but now homes can only heat a separate kitchen with more limited ventilation. The changes in homes and cooking and heating systems as a result of this event will likely affect any future cookstove programs, and we think documenting these initial user observations of the long-term effects of this event will be useful for identifying trends moving forward.

5.5.3 User Innovations

Some users made modifications and observations to improve their stoves on their own. Users like Samira have experience experimenting and innovating on their own stoves, which has allowed them to observe and improve their stoves over time. In Samira's case, she noticed that decreasing the height of the stove allowed her to cook more efficiently. This aligns with cookstove design principles; literature similarly tells us that decreasing the height of the combustion chamber increases the efficiency of the stove [54]. One user uses an old oil can as the firebox because “it makes the fire hotter”; from a technical perspective this is likely true–the oil can heats up more quickly than the surrounding clay because of higher thermal conductivity, allowing for more complete combustion from higher flame temperature. This was a very low-income household (Uttarkashi), but they were willing to spend 20-25 Indian rupees (INR) to purchase an (empty) oil can each time they rebuilt the stove because of the benefits they had experienced when using it (For reference, the income level at the poverty line is 2.15 USD or 179.40 INR per person per day [100], so this would be up to 14% of their daily income). Not only does this demonstrate the importance of innovation and improvement to biomass stoves, but also the need for these improvements to be observable by users to justify changes in cooking practices or economic investment. Furthermore, the health volunteer’s mother-in-law in Dalchoki modified her M-ICS so that coals from the fire could be pulled out from the firebox on a shelf in the front of the stove to provide heating, because she felt this was easier than the tray most others use to store coals for heat. These users improved their own stoves, both for performance and usability, but always to modify the cookstove to better fit their needs and priorities.

The team also observed user innovations that were detrimental to stove performance in Kyanjin Gompa. A few users blocked off part of their large metal stoves to decrease size of the firebox and therefore the required fuel; however, these barriers also blocked the flow to the chimney, resulting in increased HAP levels. Even though not all were successful, these innovations demonstrate that users are willing to adapt and change their cookstoves to meet their needs.

Previous literature cites traditional stoves as easy to construct, requiring little to no technical skill [31], [43], and indicates that traditional stoves are locally uniform in certain villages [31]. However, the field research revealed multiple cases of user innovation and how the tacit knowledge and experience of users, specifically women in our field research, can match the technical knowledge of trained engineers. Future research needs to investigate user innovations since these are not well-documented in literature. In addition, research studies should investigate innovation capacity in remote communities. There may be an opportunity to implement innovation capacity-building workshops in this context to enable user-generated designs of improved cookstoves that effectively meet user needs.

5.5.4 Construction Methods & Local Expertise

There is some recognition of the value placed on the skill of building traditional stoves in literature. In a case study in Northern India, Lambe [31] notes that the stove construction method is passed down in households through women and girls, with value placed on the ability to make a “good” and visually appealing *chulha*. In the team’s own field research in Dehradun, a local milkman remarked that he chose his wife because she knew how to build a good *chulha*. Women take pride in possessing the skills to effectively manage their kitchen and in the quality of their cooking. The health volunteer we interviewed in Dalchoki mentioned that her new Matribhumi improved cookstove deposits soot only on the bottom surface of cooking utensils rather than the entire pot surface, making them easier to clean and look prettier. She said they clean their stove every morning and take pride in maintaining the stove. We observed another user in Salambu who kept her improved stove incredibly well-maintained and showed pride in her improved cookstove in her home. In the projective exercise in the interview, some users associated the traditional cookstove with an “unmanaged kitchen.” The leader of the women’s coop in Dalchoki explained, “women’s empowerment starts when you give them an improved cookstove. Life revolves around the *chulho*; improve cooking, you improve the woman’s life.” Literature also suggests that women’s responsibilities for building and maintaining the stove contribute to female empowerment. Khandelwal notes that the traditional cookstove is an “egalitarian technology” [43, p. 20] due to local construction by women and local craftspeople and is associated with “female competence” in the household [43, p. 14].

Engaging in participatory design allowed the research team to understand the importance and value of this skill firsthand; technical expertise from local construction experience directly contributed to the quality of stove designs, and this value became easily apparent to all those participating in prototyping. The failed one-pot stove installed in Kyanjin Gompa demonstrates the negative effects on the design when the team lacks a lead user or manufacturer with this construction expertise. In Salambu, the team successfully installed three identical M-ICS stoves under the guidance of the Stove Master. In co-design in Pata, combining user expertise of local materials and construction methods with the engineering technical knowledge of the visiting design team lead to mutual learning and shared understanding of indoor air pollution and cooking and heating needs in the Himalayan region. The prototyping experiences provided context for continued learning about challenges with home energy in the Himalayan Region. In addition, the manufacturing methods and improved stove features reported here inform future product development efforts targeting this region for long-term impact and scalability.

5.5.5 Challenges with Participatory Design Methods

Challenges with PD in Pata and Salambu can be attributed primarily to misalignment of stakeholders. While the core research team aimed to learn more about the construction process from those with technical expertise, other stakeholders focused more on efficiently constructing stoves, the product of the design process. We aligned with all stakeholders prior to fieldwork on what we planned to do, which was construct improved stoves and modify traditional stoves for improved HAP. However, we did not explicitly discuss our process focus, so I recommend that alignment meetings with stakeholders bring this to the forefront rather than keeping it implicit.

Other challenges with PD occurred in Kyanjin Gompa, where users lacked motor and sensory skills that limited their participation in the design process. This is difficult to resolve; the many issues with the imported stoves in the housing block demonstrates the long-term consequences of excluding users from the design process. However, the users’ hearing impairment made conducting interviews and communicating our intended modifications difficult. The use of sketch models and mock-ups in stove design should be explored further for work with users with limited physical abilities, particularly for designing stove modifications with users.

5.5.6 Limitations

This research contains findings based on nine respondents, so the small sample size limits the generalizability of the results. In addition, data from 2 tests, 3 Sensens, and 2 interviews were lost, which further limited the data available for analysis. The data we were able to recover needed calibration because the clocks on the data loggers stopped working, so there may be additional error incurred in the emissions results. Finally, the process findings and PD outcomes are the result of reflection from myself and other researchers involved in the project rather than rigorous qualitative assessment, so personal bias may have affected the presented findings.

Chapter 6: Gender in Biomass Technologies in the Literature

The field research described in the previous chapter of this thesis shed light on the significance of gender in biomass technologies, especially in the lack of recognition in literature on women's construction expertise and innovations. This inspired me to conduct a literature review on gender and biomass cooking in South Asia to understand how to approach participatory design of these technologies in the future.

6.1 Background on Gender in Biomass Stoves

Traditional biomass cooking and associated technologies are deeply gendered. The negative health effects of biomass fuel usage affect women and children more adversely because they spend more time in the kitchen [101]. In addition, Beck et al. [101] suggest that primarily women collect firewood for cooking and heating purposes, and, when carried in large quantities (20-30 kg) on top of the head, this practice can lead to skeletal and muscular damage, spinal injury and neurological damage, and even damage to reproductive organs. On average, women who live near dense forests walk 1-4 km and take up to four hours to collect wood [101].

The management of energy resources and associated technology are also gendered. Women are the primary cooks for their family, responsible for providing meals for the entire, often multi-generational, household [102]. The matriarch of the household often custom-builds a biomass stove for the kitchen to fit their cooking utensils [101]. Thus, usage and construction of biomass cooking and heating technology is entrenched in gender and cultural norms, adding to the complex and diverse context of these challenges but also to the potential for well-implemented and designed solutions to positively affect women.

6.2 Criticism of Stove Programs

Many cookstove programs have attempted to address challenges presented by biomass cooking and heating, but few have achieved widespread adoption, especially in India. There are many organizations and interventions that aim to address challenges experienced by women, but several present the needs of women and claim to solve women's problems in problematic ways.

Listo's analysis [103] of the energy poverty literature shows how some energy programs construct the image of women as homogenous, vulnerable, suffering, helpless victims of poverty and erase the diversity and complexity of experiences of women [103]. These programs present women as passive recipients of technology, where the improved cookstove with increased efficiency is the technology that saves them from violence and drudgery. This is known as "techno-saviorism," where women are the objects receiving technology that solves all their problems [103, p. 12].

Fuel collection for biomass stoves illustrates the false expectation of homogeneity in women's needs. Some interventions justify the need for improved biomass technology by citing women's heavy burden of collecting firewood and other biomass fuels for cooking and heating in order to evoke pity [104]. While this need is real and significant for some women, it is not felt equally by all. As mentioned in Chapter 5: Design With and For Users: Prototyping In-Context, some women in the case study viewed collecting firewood as a normal daily chore they have done their entire lives rather than a burden of suffering, while other women—more elderly with more limited physical abilities—explained that they experienced significant difficulties in collecting and cutting wood to use for cooking and heating, and used less firewood as a result of this physical burden. Presenting the physical burdens and imagery of women carrying headloads of firewood fails to capture women's own perceptions of the burden of fuel collection [104].

Some past programs even suggest that improved cookstoves, by reducing the burden of fuel collection, linearly lead to reduced rape and sexual violence, since women would travel less frequently to collect firewood with a more efficient stove and therefore be less exposed to gender-based sexual violence [103]. Viewing women as passive objects of suffering leads to program strategies centered around a particular cookstove design or clean fuel distribution expected to reach widespread adoption by solving the homogenous needs of women [103].

Technology is limited in its ability to address complex social problems and can even exacerbate oppression of women. Vyas et al. explain how the usage of LPG, a cleaner fuel option compared to biomass, is used in rural North India to promote seclusion of women [105]. Khandelwal et al. [104] also describe how adoption of mass-manufactured improved stove designs causes women to lose some autonomy. While women build and repair traditional *chulhas* themselves, improved stove designs are purchased in a capitalist economy. Some women even go into debt purchasing improved stoves [104].

In cooking, another traditionally feminine practice, women derive power and pleasure from their ability to make choices to cook from scratch or with convenience foods, using these choices to either challenge or reinforce gender norms [102]. Similarly, women may derive power and pleasure from the choices they make in using certain cooking technology. As the designers and builders of the traditional cooking hearth, women have the agency to adjust the design and/or location of biomass stove technology in part because of the accessibility of construction materials [101].

When programs inappropriately promise women's empowerment from cookstove distribution, this can result in allocating funds to these programs and away from social programs better suited to addressing complex gender issues [103]. By recognizing the diversity and complexity in lived experiences of women with biomass cooking and heating, programs can develop a variety of technologies implemented in a multitude of approaches in collaboration with women to more successfully address challenges and achieve widespread impact.

6.3 Recommendations

These insights on gender in biomass stove technology further support the need for participatory approaches in stove design programs. To effectively manage the complexities of gender in this field, projects and interventions need to engage women in the process of defining challenges with biomass technology and creating solutions to address these challenges. According to Mattson & Wood [18], one of the key principles of design in developing contexts is involving women in co-design and intentionally investigating unique challenges experienced by women and children. This affords women power to influence how the problems they face are understood and addressed, a necessary element for ensuring that interventions are sustainable and successful in achieving positive impact.

There are challenges to including women in the design process. Gender dynamics and norms influence PD outcomes, and power relations may not enable women's voices to be heard [21]. Jagtap et al. [20] report that PD activities led by a female facilitator increase the likelihood of women sharing their opinions. In the field research described in the previous chapter, the core field research team was made up of three women and three men, and a woman was present, if not leading, interviews with all respondents. As described in the methods chapter, the primary interviewer (a woman) was able to gain additional insights through developing rapport with household respondents, who were primarily women. This may not have occurred if the research team was majority men, or if the interviewer was a man. For future stove projects and especially for large-scale interventions, I recommend involving a gender specialist in the design process in addition to involving women from communities who will be affected by the problem. A gender specialist can add rigor to research on the effects of cookstove programs on women and gender roles in households and allow for more accurate reporting on the social impacts of technical designs. This aligns with Mattson & Wood [18], who recommend that interdisciplinary teams tackle poverty challenges to ensure projects consider non-technical factors affecting successful products because of the typically technical focus of engineers during design projects.

Chapter 7: Thermal Efficiency Model for Dual-Purpose Stoves

7.1 Motivation & Background

Although biomass stove designers and researchers worldwide recognize the multi-functionality of traditional stoves and the reliance on biomass for both cooking and heating, the important space-heating function of many cookstoves is omitted in calculating thermal efficiencies of such dual-purpose stoves. There is a need to account for space-heating in HAP assessments to accurately evaluate risks for populations with this need [106]. Space-heating is considered in health assessments and recognized in usage, so metrics for performance evaluation should also account for this useful energy. In the results of a search of scholarly articles evaluating thermal efficiency of stoves used for cooking and heating, only one article defined an efficiency metric for combined cooking and heating stoves [107]. The established WBT defines thermal efficiency for the cooking task, counting only heat transferred to the pot as useful energy [51], [71]. The community of practice for biomass stoves needs to account for useful heat transferred to the room and the stove in calculating thermal efficiency to report metrics in line with actual usage and function of stoves in households.

7.2 Proposed Efficiency Model Calculation

To reflect stove function more accurately in efficiency metrics, the overall thermal efficiency of the stove should include useful heat transferred to the cooking vessel and to the room for heating, similar to [107].

$$\eta_{thermal} = \frac{Q_{useful}}{E_{fuel}} = \frac{Q_{pots}+Q_{room}+E_{stored}}{m_{fuel}LHV} \tag{7.1}$$

Clay stoves provide space-heating from their large thermal mass, which heats up during cooking and serves to warm the room for the cook and their family. Scholars consider energy stored in large stoves to be losses since it is not hot enough to continue cooking food after the fire is put out [57]. However, this stored heat becomes useful when it is radiated to the room for heating, even after the end of the test. Equation 7.1 accounts for all forms of useful heat sourced from clay biomass stoves, reported in total energies rather than power to include stored energy useful after the test.

When starting from ambient temperature, the clay stove penalizes the combustion processes by cooling the reaction and causing more incomplete combustion of wood fuel. When the stove reaches higher temperatures (above ambient) later in the cooking process, it begins providing useful space heating and keeps combustion processes at higher temperatures. This penalty is reflected in the emissions of CO and PM 2.5, so the proposed model does not inaccurately reflect the performance of the stove. The proposed model better reflects the fundamental definition of thermal efficiency for calculating the performance of dual-purpose cooking and heating stoves.

7.3 Estimations for Space-Heating Radiation and Storage

One of the challenges with including space-heating in efficiency metrics is defining the procedure for measuring and calculating the heat transferred to the room and stored in the stove consistently across different stoves and in both laboratory and field experimental settings. This section presents a method for estimating space-heating power from the stove.

In designing wood burning heating stoves for use in drafty, uninsulated, and unsealed homes, researchers at Aprovecho Research Center [56] recommend using materials with large thermal masses which provide gentle radiative heat for long periods of time. WHO guidelines for biomass combustion modeling use an average air exchange rate of 15 air changes per hour [53]. This means every four minutes, outside air replaces air inside the kitchen, so any air heated via convection and conduction from the stove would soon be replaced by colder outside air in a kitchen with this exchange rate. Because of this, in estimating heat transferred to the room, I assume that primary heat transfer is via radiation and neglect convection and conduction.

The heat flux for radiation in Watts per square meter is given by Equation 7.2. The temperature of the stove is measured with a Type K thermocouple placed on the surface of the stove in lab and field research settings. The heat flux is calculated for each temperature measurement collected during the test.

$$\dot{q}'' = \varepsilon\sigma({T_{stove}}^4 - {T_0}^4) \tag{7.2}$$

The integral of the heat flux over the duration of the test is calculated numerically and multiplied by the approximate surface area of the stove to estimate the radiation heat transfer to the room in Joules (Equation 7.3).

$$Q_{room} = A_{surface} \int_{t=0}^{t=test\ end} \dot{q}''dt \tag{7.3}$$

The surface area was estimated using the dimensions of the stove and assuming a rectangular prism shape. Only the sides and the top of the stove (minus the area of the potholes) was included since the front is primarily made up of the fuel inlet and the back is not seen by the room (radiation heat transfer depends on the view factor of the surface).

The energy stored in the stove was calculated based on the mass, specific heat capacity, and change in temperature of the stove seen in Equation 7.4 [57].

$$E_{stored} = m * c * \Delta T_{stove} \tag{7.4}$$

The mass of the stove was estimated based on volume times density. Volume is calculated assuming the stove is the shape of a rectangular prism. I subtracted the volume of the fuel inlet assuming it extends the length of the stove. The value for c was taken from Engineering Toolbox for Sandy Clay [108]. The density corresponds to the calculation by Tang for the lab prototype used in this research [41].

7.4 Results & Discussion

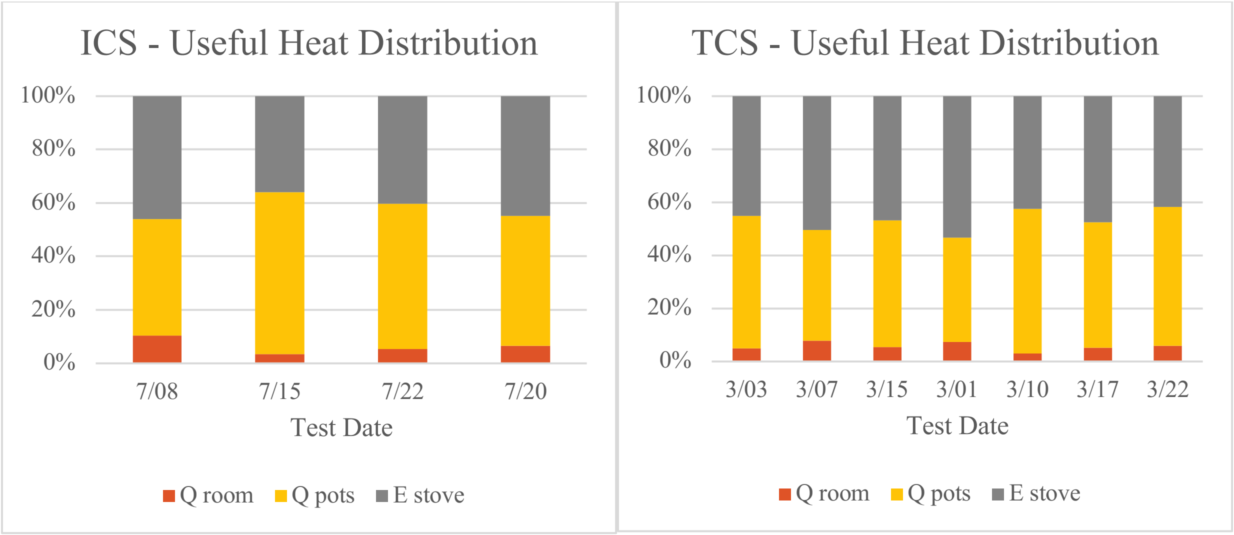
With data from the lab test results described in Chapter 4: User-centered Concept Development & Prototyping, I used the proposed model to estimate the multi-function (cooking and heating) efficiency of the prototype stove. Table 17 shows the change in thermal efficiency from the cooking-only model to the dual-purpose model.

Table 17: Comparison of thermal efficiencies for different models

Test Condition		**Test Date**	$\eta_{cooking}$	$\eta_{multi-function}$
Improved chimney stove	Half Height, Full Area, No Baffles	July 8	10.71%	22.64%
	Full Height, Half Area, Short Baffles	July 15	13.93%	18.99%
		July 22	8.99%	13.92%
	Full Height, Half Area, No Baffles	July 20	8.46%	15.91%
Traditional Stove*	Pot Stand	March 3	10.93%	20.24%
		March 7	15.49%	35.59%
		March 15	16.61%	33.96%
	Grate	March 1	16.04%	35.02%
		March 10	16.20%	27.02%
		March 17	14.20%	26.83%
		March 22	19.42%	34.30%

*Data from [41] re-analyzed by the author

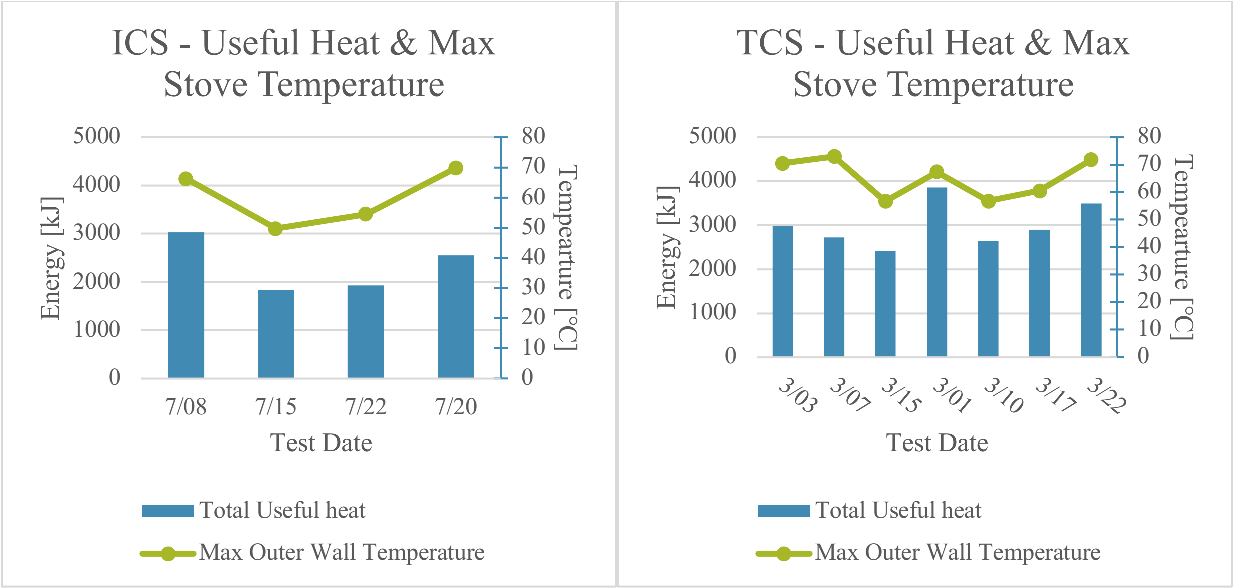
For the full area chimney test (July 8), the efficiency of the stove more than doubled. Efficiency of the half area chimney tests increased by ~5 - 7.5 percentage points when accounting for space-heating. The efficiency also increased significantly for the traditional stove, reaching 35% efficiency with the multi-function model. This has important implications for improved stove designers and manufacturers. With the cooking efficiency model, efficiencies of dual-purpose traditional stoves are much lower, so it is easier for stove manufacturers to market improved stove designs as having much higher efficiency. Using the multi-function model for thermal efficiency described here would raise the efficiency baseline for manufacturers and designers of improved stoves if they want new designs to be competitive with homemade traditional stoves. This may result in innovative new stoves with increased benefits to users, and therefore increased chances of adoption of new stove designs. Figure 45 shows the normalized distribution of energy across the three uses of heat for tests with the improved stove and traditional stove prototype with reliable surface temperature measurements.



(a) (b)

Figure 45: Useful Heat Distribution in (a) Improved Stove (b) Traditional Stove

In the improved stove, the energy transferred to the stove accounts for 35-50% of useful heat, while the heat radiated to the room makes up 10% or less of this useful energy. As you can see, the energy for space-heating is not negligible in comparison to cooking energy. The full area chimney test (7/08) resulted in more stored energy in the stove relative to the pots and radiation. From the lab testing, we learned that the area of the chimney had more influence on the draft than the height, and that baffles for directing hot gasses to the pot were integral to the design. This may explain why the two tests using baffles (July 15 & 22) have a higher percentage of heat transferred to the pots rather than the stove or room. In addition, the full area chimney tests (no baffles) resulted in more heat transferred to the stove. This may be due to the higher velocities inside the stove due to higher draft from the larger chimney area, which would reduce the boundary layer thickness and increase convective heat transfer from hot flue gasses to the stove. These variations may not be statistically significant though, so additional testing should investigate heat distributions in clay stoves. In the traditional stove (data from [41] re-analyzed by the author), the energy transferred to the room accounts for 45-55% of useful heat, and the heat radiated to the room makes up 10% or less. So, the heat distribution between the improved and traditional stoves is similar. Figure 46 shows the total useful heat and maximum wall temperature for each test.



(a) (b)

Figure 46: Total Useful Heat & Maximum Stove Temperature for (a) Improved stove (b) Traditional stove

Max outer wall temperatures correlate well with total useful energy in the stove, as expected since this is used to calculate energy stored and radiated. Maximum wall temperatures ranged from 49.75°C to 69.75°C in the improved stove and 56.69°C to 73.00°C in the traditional stove (data from [41] re-analyzed by the author). The proposed model depends heavily on the accurate temperature measurement of the stove surface for estimating the radiation heat transfer and energy stored in the stove.

7.5 Limitations & Future Work

One of the challenges with the proposed method is measuring a consistent surface temperature from the stove. It was difficult to maintain the position of the thermocouple throughout the duration of the lab tests amidst the water replacement and continuous fuel loading, which sometimes resulted in shifting the probe position. The team attempted to measure surface temperature during field testing but were only able to get reliable data for one WBT. I do not present it here because there are no other field tests for comparison. The team tried using aluminum tape to fix thermocouples to the stove surface, avoiding contacting the probe end with the tape so as not to affect the measured temperature. This only worked if the tape adhered to the clay surface, and if the end of the probe remained in contact with the surface amidst temperature changes in the stove surface. During data analysis, I estimated radiation heat transfer using the average stove temperature and compared it to the value calculated by integrating the heat flux over the test time (see equations 7.2 and 7.3). The estimates using the average stove temperature were comparable to the exact radiation heat transfer, likely because the wall temperature gradually, and somewhat linearly, increases in temperature. Calculating the heat stored in the stove only requires the initial and final temperatures, so for simpler data collection, researchers could measure the initial and final temperatures of the stove and use the average to calculate radiation heat transfer to the room. Additional measurement sensors and methods should be explored in future research to better estimate space-heating from dual-purpose stoves.

In addition to the surface temperature, stove volume, surface area, density, and specific heat were necessary for calculating energy stored in the stove and radiated from the surface. For a prototype created in a laboratory setting, the material composition and stove geometry is known, so researchers can more easily derive these values for the model calculations. However, this may be an additional challenge in field work, especially for material properties. There is an opportunity to create a test that estimates density and specific heat of a clay stove to enable analysis of field data using the proposed model.

Chapter 8: Conclusions & Future Work

8.1 Summary of Case Study Findings

PD methods offer useful tools for design practice in engineering for development to involve stakeholders and users affected by challenges in the process of solving them. Improved biomass stoves have had limited success in addressing global HAP and household energy challenges, due in part to the lack of involvement of users in the design process. PD methods in designing improved biomass stoves has the potential to increase the success of innovations for long-term, sustainable impact. This thesis describes using PD methods for data collection and prototyping biomass stove improvements in the Himalaya.

To prepare for in-country fieldwork, I facilitated user-centered design for ideation, selection, prototyping, and testing. I conducted two ideation sessions, one virtual and one in-person. The different activities helped the team generate a total of 95 ideas to preserve the benefits of traditional stoves and address needs specific to the Himalaya. The team chose to prototype and test a traditional stove modified with a chimney because it was feasible to prototype in the lab and in the field and it had the most potential to impact HAP, a key user need. Pursuing a modification to a traditional stove also increased the chances of long-term adoption since this is an incremental innovation rather than an entirely new stove designed to replace a traditional stove. Lab testing allowed the team to create design guidelines for flexibility in the geometry of the design. This included making the chimney half the cross-sectional area of the fuel inlet, adding short baffles to direct airflow, and shifting the firebox from under the primary pothole to in front of the first pot. Lab testing also demonstrated that we could implement the modification while maintaining fuel usage and cooking time. While the chimney did not significantly reduce total emissions, this concept still had the potential to remove most indoor air pollution from the kitchen, so we traveled to communities in the Himalaya to prototype this in context with users.

In Pata, the team worked with local leaders to identify a lead user with technical expertise in stove construction and social influence in the community with whom to co-design a clay stove with a chimney. Without the expertise of Samira on materials, clay mixtures, and construction methods, the stove quality in Pata would have suffered. Similarly, our team possessed the technical knowledge to modify the stove to add a chimney, without compromising thermal efficiency. Because of co-design, we were able to operate on equal footing, learn from each other, and create a stove with improved kitchen air quality that also met user needs. Testing showed a 32.3% decrease in indoor PM 2.5 and an 81.2% decrease in CO concentrations while maintaining fuel usage and cooking time within 10%. The flexible design guidelines allowed Samira to choose dimensions that fit her kitchen and cooking utensils; creating guidelines rather than optimized parameters for the stove geometry allowed increased user participation in the design process while still generating meaningful impact on HAP. In Salambu, constructing three M-ICS with the Matribhumi Stove Master allowed the team to gain more insights into improved stove features and clay stove manufacturing processes and materials to use in future design work. Matribhumi uses locally available materials, including salt, sugar, and clay, and simple tools, including a cook's own pot, to create aesthetically pleasing, durable improved stoves. We also observed the lack of usage of improved manufactured stoves in two Salambu households due to disrepair and user perceptions of their lack of utility, which can inform future stove programs. Elderly residents in Kyanjin Gompa participated in interviews for user-centered design of modifications and a one-pot improved stove. PD presented additional challenges in this location because of the limited abilities of the elderly residents. Lost data and time limitations prevented analysis of the impact of the modifications and one-pot stove, but another research team confirmed that the one-pot design for Pawan-*ji* was not durable enough to withstand daily use and combustion temperatures. The team had limited experience with clay, and the clay in this region differed greatly from that in Salambu and Pata. We were unable to identify a lead user with whom to co-design the one-pot stove, and the resulting design quality suffered.

The research and field work revealed important nuances of biomass stove usage. Many interviewees had multiple stoves that they use for different purposes. While several use their LPG stoves most often out of convenience, they prefer to use their biomass traditional or improved stove because of the taste of food, easily accessible fuel, and perceived safety. Surprisingly, residents who experience more extreme winters reported needing heating in fewer months of the year than others at lower altitudes, potentially because of their higher tolerance to cold weather. All interviewees use their biomass stoves for both heating and cooking. Several users modified their own stoves to better meet their needs for fuel consumption, space-heating, and/or cooking efficiency, and although not all were successful, these innovations demonstrate the willingness of some users to adapt stoves. The 2015 earthquake in Nepal affected housing structures in the Himalayan Region, which also caused changes in biomass technologies and indoor air pollution. The expertise of users, especially women, in constructing stoves was valued by communities and represented in some scholarly research. The field work allowed the team to recognize the value of this construction expertise firsthand, and inspired me to investigate gender, women, and cookstoves further in South Asia.

Literature explains that some stove programs promote images of women as homogenous and suffering, leading to one-size-fits-all technology solutions that claim to solve women's problems. Without including women in conversations and development efforts, design practitioners and researchers have no way of knowing whether their approach is effectively balancing the urgent need to address women's challenges related to biomass technology while also recognizing their agency and power in kitchen management, or the extent to which particular burdens are a reality for the women being targeted by an intervention. PD and principles of design for development tell us to engage women in the design process to better recognize diversity of experiences and address complexities related to biomass technologies.

PD research also revealed a gap in performance metrics and communities of practice for biomass stoves. While cooking and heating are seen as closely coupled in assessing health and environmental impacts of biomass, the design communities for cooking stoves and heating stoves are largely separate. In addition, designers extend the metrics used to evaluate stoves optimized for cooking to traditional stoves, which meet both heating and cooking needs. The metrics used to evaluate performance should reflect actual usage and functionality of the stove by accounting for useful heat transferred to the pots, stove, and room. The model proposed in this thesis uses stove geometry and surface temperature measured during a standard WBT to estimate heat stored in the stove body and radiated to the room. Using the new model to analyze lab prototype tests caused thermal efficiency to increase, and in some cases to double. Energy stored in the stove accounts for 35-50% of useful heat using the new model, while heat radiated to the room during the test only accounts for up to 10%.

8.2 Contributions to the Field

The detailed account of PD methods applied to biomass stove design provides a useful case study for evaluating participation of users in technical design. In particular, we engaged with a lead user in co-design, leveraging her technical expertise, social network, and design communication skills for mutual learning by providing benefit to the lead user, which enabled increased design quality. This was demonstrated by a similar process conducted without a lead user, where the stove design quality suffered. The process of using laboratory testing to create flexible design guidelines effectively enabled co-design in the field, allowing the user to contribute to choosing design parameters to fit the particular context. This process should be replicable for other technical products to enable increased participation from users and increased chances of adoption and sustainable impact.

Researching biomass stove technology with a participatory lens also revealed key insights to inform future work. This thesis describes technical expertise in construction and materials and instances of user innovation that are not well documented in literature. The process of engaging users with PD methods to improve biomass technology should be replicable to implement in other locations with complex usage patterns and needs to ensure resulting designs reflect the values and practices of users. The proposed efficiency model more accurately represents the thermal efficiency performance of dual-purpose cooking and heating stoves in alignment with fundamental principles of thermodynamics by accounting for heat stored in the stove for later space-heating, heat radiated to the room, and heat transferred to the pots for cooking. This raises the baseline for new designs entering the market, which may result in increased user benefits from innovative new stoves.

8.3 Future Work

MIT D-Lab continues to explore challenges with home energy and thermal comfort in the Himalaya through research and course projects using PD methods. The communities of practice in biomass cooking and heating should collaborate to align on performance metrics that reflect actual usage patterns and usability preferences of users. Future work in biomass technologies should also involve interdisciplinary teams, specifically including gender specialists, to better address complex socio-cultural dynamics of this technology in households across South Asia. In particular, women who do the primary cooking should be included in designing interventions aimed at addressing their needs and challenges. Additional research should investigate the innovation adoption patterns of improved biomass stoves and modifications to better understand how to create sustainable designs with long-term impact. Also, designers should engage stakeholders in PD to consider how to ethically and appropriately recognize the technical expertise and tacit knowledge of users in stove construction, and how to share and distribute the rewards of successful collaborative designs.

Design research should investigate how lead users impact co-design in case studies beyond biomass technology to understand these dynamics in designing other technical products. More case studies should also apply and evaluate the process of creating flexible design guidelines and the extent to which it enables co-design and desired impact. Additional work should explore the use of tactile models to communicate design ideas for users with limited sensory abilities.

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Appendices

Appendix A: Ideation Activity Results

Table 18: Idea Descriptions and Scores from each Activity

Activity	Idea description	Feasibility	Novelty	Uniqueness	Variety
Brainwriting	Attic + fume hood	1	4	4	1
	chimney maintenance hatch midway up with gasket seal	4	4	3	1
	maintenance hatch on stove for cleaning fierbox	5	4	3	1
	education program for users on stove maintenance	2	5	2	3
	tools for maintenance	4	3	1	1
	training program for community members on stove maintenance	2	5	2	3
	tools for cleaning chimney	4	3	1	1
	tool with lever arm for chimney cleaning	2	5	1	1
	tool with flexible joints for chimney cleaning (rigid to remove material, flexible to go around sharp corners)	2	5	1	1
	flexible cleaning tool for chimneys without roof access	2	5	1	1
	cleaning tool with brush/scraper for removing ash and creosote	4	3	1	1
	cleaning tool like a drain snake; rigid and flexible sections, spring-loaded	3	5	1	1
	move stoves off the group and reroute chimney out the side	1	5	5	1
	collaborate with manufacturers in Nepal to adapt maintenance tools to have more flexible joints or modifications that increase leverage	4	4	2	3
	tool for chimney cleaning made of steel wire and woven yak fur	4	5	1	1
	consult stove manufacturers in India & Nepal about training users for maintenance	4	4	2	3
	fumehood heat extraciton before exhaust	2	4	4	1
Brainstorming	district water heating and distribution	1	4	4	3
	District water heating via solar?	1	5	4	3
	little brother/sister model	2	4	5	3
	meal prep and delivery service	1	5	5	5
	make food outside earlier in the day before the sun sets, store in haybox to keep warm for eating later	4	1	3	3
	public bath / sauna	1	4	4	3
	solar thermal heating thermal mass; bring inside at night for warmth	4	4	3	1

	Solar thermal water heaters, like the ones guest houses have - kind of expensive though	3	1	4	1
	on sunny days if they typically spend it outside their home maybe we can introduce solar thermal heaters to them and they can use those for heating up firewood or rocks	3	4	3	1
	Pair hot water heater to the new stove	4	3	5	1
	insulated containers like we discussed before, for storing hot water	5	2	3	1
	Providing them with hot water bottles, store hot water and to put under blankets at night	4	1	4	1
	store heated water underground? is the ground cold too?	3	5	3	1
	heat water with stones in it before letting fire got out after dinner; put stones under blankets for warmth	3	3	3	1
	water bed heated with solar thermal??	1	5	5	1
	hot water bottle personal heater	5	1	4	1
	more blankets	5	1	4	1
	heating up stones or other materials for people to put in their blankets at nice	5	3	3	1
	install fume hood or window for ventilation	3	4	4	1
	attic space and ventilation passage/ hood	1	4	4	1
	Better house insulation and sealing of cracks - pair with added chimney	3	2	3	1
	insulate attic space; rodents okay if they get in here they'll stay out of main home	2	2	3	1
	create new housing block	1	3	3	1
	insulation panels	5	1	3	1
	look at house insulation design, seal up cracks and possibly design for a chimney addition	3	2	3	1
	weatherization	4	1	3	1
	yak dung or human waste to make biogas (in a factory/plant)	2	5	5	1
	Adding a chimney to remove pollutants from house	4	4	3	1
	Better one-pot cookstove instead of open fire, could also place a piece of metal over the pot hole to change it to a heating stove	3	3	3	1
	single pot sheet metal stove with chimney; include pot covers so cold air can't get in during the night when stove isn't being used	4	2	3	1
	wall mounted 20L bucket stove	5	2	3	1
	Single pot metal stove with chimney	4	2	3	1
	build ICS in home; smaller with one pot hole and limited thermal mass to ensure short cooking time	4	2	3	1

	single pot metal stove redesign would be better for this	4	2	3	1
SCAMPER	sbstitute space heating stov for solar thermal	3	2	1	1
	cookstove move to outdoor area for more ventilation, put space heating stove or solar thermal in kitchen	4	2	1	1
	use solar thermal water heating for heating rooms (like radiator)	3	2	1	1
	basic cooking on chulo with a dish solar cooker	4	1	1	1
	space heating stove with solar-thermal hot water system	3	2	1	1
	solar thermal water heating and cooking; concentrated solar for cooking (hotter temps)	2	2	1	1
	solar heating thermal mass for nighttime heating	3	2	1	1
	storage for solar thermal heated water so bathing can be done anytime of day	5	2	1	1
	sunlight and biomass to heat and cook	3	4	1	1
	replace chimney with heat exchanger for better kitchen heating and exhaust gas absorption	4	2	2	1
	water heating and chimney to recover waste heat	3	2	2	1
	cooking and water heating, make chimney into heat exchanger with water	3	2	2	1
	Combine cooking and water heating, attach water heater to the chimney	3	2	2	1
	heat transfer to minimize chimney exhaust temperature	3	3	2	1
	Extruded rods from chimney to heat up blankets before bed or dry laundry	4	4	2	1
	add removeable fins to chimneys to increase heat transfer from exhaust	4	4	2	1
	Make the space heating stove more efficient - added surface area on the stove/chimney to radiate more heat	5	3	2	1
	heat sink on pot hole in kitchen stove to increase space heating if secondary pot hole not used	4	5	2	1
	space heating and water heating = radiator water heater	3	2	2	1
	Funnel heat from the kitchen to the bedrooms or guest rooms somehow, or use thermal masses like water bottle or stones	3	2	2	1

	space heating in living room with boiling water for tea/personal heating at night	2	3	2	1
	gray waste water (warm) use in radiator?	2	4	3	3
	Change current firebox to be smaller, maybe have less space under the secondary pot hole	4	4	3	1
	Reduce opening size of firebox, or make it variable, in order to reduce backdraft of smoke into the kitchen	5	3	3	1
	insulate firebox of space heating stove with removeable panels to control amount of heat	5	3	3	1
	the stove combustion volume to improve fuel burning	5	3	3	1
	single room heating to multi room heating	2	3	3	1
	DIY firewood chopping with a local service provider (mechanized)	2	4	4	5
	make chimney easily replaceable/interchangeable	2	5	4	3
	Change chimney tube size? Clogging isn't an issue yet for these stoves, but larger chimney may be less likely to clog	3	5	4	3
	warm storage chamber use for preheating wood	5	3	4	1
	Substitute the existing grate with a grate with smaller slots, so hot char does not fall through	5	2	4	1
	the fuel grate to prevent unburned fuel from falling into the ash bin	5	2	4	1
	Wood drying rack in the living room, where wood gets radiative heating from the stove	5	3	4	1
	preheat pots on space heating stove before cooking?	2	1	5	3
	cookstove UI to allow selection of cooking or heating mode	2	4	5	3
	some firewood with waste briquettes	4	2	5	1
	run a cycle of some kind - cogeneration	1	3	5	1
	the chimney to allow the user to control draft	4	2	5	1
	storage for hot tea and hot water; highly insulated thermos	3	2	5	1
	LPG lighter to make ignition easier	2	4	5	1
	pulley system for wood transport to kitchen	5	4	5	1
	Conductive patch on top of the heating stove for better water heating?	2	4	5	1
	modify wood stoves to take LPG since guest houses have more income	2	5	5	1

Appendix B: Lab Tests Full Results

Table 19: Lab Tests Full Results - Temperature

TEST CONDITIONS				TEMPERATURES									
Date	Chimney		Baffles	Fire		Gap		Inner Wall		Outer Wall		Chimney Exhaust	
	Height	Area		Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg
6_15	Full	Full	none	585.5	141.7115	461.25	222.0266	85.5	39.2372	40.75	29.8557	459.25	167.3497
6_27	Full	Taped Half	none	594.75	382.1915	507.25	315.62	184.75	123.1551	41	28.236	202.75	136.8711
6_28	Full	Taped Half	none	448	251.7383	175.75	106.869	-	-	37.75	26.8672	199.25	103.6076
6_30	Full	Taped Half	none	-	-	471.25	269.3922	420.25	-	48.75	30.8589	340	159.8328
7_1	Half	Full	none	-	-	392.5	208.9508	85	42.9881	67.25	42.4334	205.5	106.3651
7_5	Half	Full	none	-	-	-	-	-	-	53.5	33.667	226	89.5984
7_6	Half	Full	none	-	-	346	186.231	-	-	68.75	40.8014	211	106.4854
7_8	Half	Full	none	-	-	457.25	270.6887	98	56.864	66.25	40.6187	250.25	111.5177
7_11	Half	Full	none	-	-	434.75	268.3588	87.75	48.9969	61	39.296	205	98.3997
7_12	Half	Full	medium	-	-	444.5	333.9554	57	42.1383	66.25	38.6097	126.5	65.0601
7_13	Half	Full	medium	-	-	381.5	270.1281	-	-	51	33.4495	-	-
7_15	Full	Half	short	657.25	-	502.25	375.4573	346.5	91.9792	49.75	29.7108	156.5	63.276
7_18	Full	Half	short	409.25	-	532.75	340.3363	359	165.3527	-	-	183.25	92.6743
7_22	Full	Half	short	593.25	229.6575	529.5	415.4177	-	-	54.5	34.3051	-	-
7_19	Full	Half	None	-	-	303	186.5356	655	336.752	-	-	239.5	153.3386
7_20	Full	Half	None	-	-	510.25	350.2046	546.5	253.9668	69.75	36.5184	325.25	138.40679

Table 20: Lab Tests Full Results – Pollutant Concentrations

TEST CONDITIONS				POLLUTANT CONCENTRATIONS					
Date	Chimney		Baffles	PM 2.5 (mg/m3)		CO (ppm)		CO_2 (ppm)	
	Height	Area		Max	Average	Max	Average	Max	Average
6_15	Full	Full	none	400	15.9511	25.5263	3.9454	2364.8	1547.5
6_27	Full	Taped Half	none	43.5	4.1658	10.67	3.0418	2083.1	1641.1
6_28	Full	Taped Half	none	67.6	3.6084	7.9712	1.8812	2082.2	1561.2
6_30	Full	Taped Half	none	-	-	19.63	6.1941	-	1522.3
7_1	Half	Full	none	41	4.7139	9.8377	3.2738	1711	1363.5
7_5	Half	Full	none	86.5	4.4962	11.3562	3.3809	2036	1458.5
7_6	Half	Full	none	43.4	5.7648	10.32	3.6291	1859.4	1401
7_8	Half	Full	none	142	10.65	29.6872	5.6532	2025.6	1474.2
7_11	Half	Full	none	153	12.3783	28.4037	5.5035	1982.7	1489.1
7_12	Half	Full	medium	168	29.3394	34.4137	11.012	1981	1582.4
7_13	Half	Full	medium	322	24.047	42.9422	11.0595	2174.8	1659.8
7_15	Full	Half	short	190	16.4959	42.1928	7.2142	1927.9	1556.9
7_18	Full	Half	short	57.5	9.5372	36.3978	12.0123	2427	1797.8
7_22	Full	Half	short	299	38.1273	47.0978	21.6473	2292.1	1870.9
7_19	Full	Half	None	47.2	8.1308	29.148	12.6791	2263.5	1754.3
7_20	Full	Half	None	233	14.0369	43.6852	12.1912	2763.2	1729.9

Table 21: Lab Tests Full Results - Emission Factors and Rates

Test Conditions				Pollutant Emissions					
Date	Chimney		Baffles	PM 2.5		CO		CO_2	
	Height	Area		EF (g/MJ)	ER (g/min)	EF (g/MJ)	ER (g/min)	EF (g/MJ)	ER (g/min)
6_15	Full	Full	none	33.9350	0.5698	9.6151	0.1615	933.5033	15.6748
6_27	Full	Taped Half	none	6.8506	0.1010	5.7300	0.0845	1089.6015	16.0629
6_28	Full	Taped Half	none	6.6613	0.0814	3.9781	0.0486	957.6512	11.7057
6_30	Full	Taped Half	none	90.4905	0.1590	48.4165	0.0851	11252.1886	19.7703
7_1	Half	Full	none	5.5899	0.1097	4.4472	0.0873	375.2320	7.3633
7_5	Half	Full	none	11.3032	0.0877	9.7361	0.0756	866.0271	6.7226
7_6	Half	Full	none	16.5303	0.1246	11.9205	0.0898	911.8796	6.8710
7_8	Half	Full	none	21.8434	0.2627	13.2733	0.1596	854.4086	10.2763
7_11	Half	Full	none	35.9624	0.2994	18.3158	0.1525	1288.6096	10.7296
7_12	Half	Full	medium	-	-	-	-	-	-
7_13	Half	Full	medium	28.4963	0.4342	15.0129	0.2288	915.8139	13.9546
7_15	Full	Half	short	20.8300	0.4438	10.4352	0.2223	644.8565	13.7397
7_18	Full	Half	short	8.4470	0.1755	12.1874	0.2533	826.6713	17.1788
7_22	Full	Half	short	30.1933	0.5893	19.6372	0.3832	1000.0122	19.5165
7_19	Full	Half	None	9.2901	0.2022	16.5951	0.3611	951.8540	20.7123
7_20	Full	Half	None	17.7428	0.2937	17.6521	0.2922	1108.6909	18.3540

Table 22: Lab Tests Full Results – Limited Performance Metrics Test Dates 6-27 through 7-6

Test Conditions				Performance Metrics				
Date	Chimney		Baffles	Fuel Use (kg)	Duration (min)			Average Firepower (W)
	Height	Area			Cold Phase	Hot Phase	Total	
6_27	Full	Taped Half	none	0.759	43	30	73	2732.4
6_28	Full	Taped Half	none	0.627	50	27	77	1991.6
6_30	Full	Taped Half	none	0.9	40	20	60	3375
7_1	Half	Full	none	0.6	60	52	112	1296
7_5	Half	Full	none	0.575	95	22	117	1176.1
7_6	Half	Full	none	0.584	72	45	117	1222.3

*Thermocouple for second pot failed on these experiments, so pot power, PPR, and efficiency are not possible to calculate or report

Table 23: Lab Tests Full Results - Performance Metrics

TEST CONDITIONS	Date		6_15	7_8	7_11	7_12	7_13	7_15	7_18	7_22	7_19	7_20
	Chimney	Height	Full	Half	Half	Half	Half	Full	Full	Full	Full	Full
		Area	Full	Full	Full	Full	Full	Half	Half	Half	Half	Half
	Baffles		none	none	none	medium	medium	short	short	short	None	None
PERFORMANCE METRICS	Fuel Use (kg)		1.026	0.825	0.676	0.868	0.66	0.595	0.655	0.858	0.859	0.99
	Duration (min)	Cold Phase	66	86	56	47	26	33	32	27	29	48
		Hot Phase	22	24	33	38	32	19	22	27	30	27
		Total	87	110	89	85	58	52	54	54	59	75
	Pot Power (W)	Cold Phase	179.4421	137.9015	-	215.5069	277.2664	273.3657	296.7056	335.6023	369.3256	216.2944
		Hot Phase	583.6418	427.9322	334.2705	243.0234	235.017	497.445	418.5456	315.2534	356.2265	381.8957
		Average	279.8568	200.4572	138.7748	227.9996	253.9563	355.1098	346.3442	325.2709	362.665	275.9109
	Pot Power Ratio	Cold Phase	0.3475	2.7688	-	5.3682	62.1951	23.7186	9.1111	11.501	4.2661	3.7932
		Hot Phase	0.5824	2.88	2.4699	4.9714	7.2409	5.7468	3.3748	10.5483	2.1432	3.598
		Average	0.4058	2.7928	-	5.188	31.8755	17.1625	6.7741	11.0173	3.1867	3.7229
	Average Firepower (W)		2916	1871.8	1962.9	2547.4	2582.6	2550	2997.5	3619.7	3623.9	3259.8
	Efficiency (%)	Cold Phase	6.15%	7.37%	-	8.46%	10.74%	10.72%	9.90%	9.27%	10.19%	6.64%
		Hot Phase	20.02%	22.86%	17.03%	9.54%	9.10%	19.51%	13.96%	8.71%	9.83%	11.72%
		Average	9.60%	10.71%	-	8.95%	9.83%	13.93%	11.55%	8.99%	10.01%	8.46%

Appendix C: Field Work Interview Protocols

I. Identification and Basic Demographics
  A. Interview date and time:
  B. Interviewer name:
  C. State/Province:
  D. Local Government Area:
  E. Community/village/ward:
  F. Other location information:
  G. Respondent name:
  H. Respondent gender:
  I. Respondent age:
  J. Number of people in household:

II. Stove Types and Respondent Role
  A. Cooking Methods and Appliances
    1. What type(s) of cookstoves does your family use? (choose all that apply)
      a. Three-stone/open fire
      b. Traditional chulha (indoor)
      c. Traditional chulha (outdoor)
      d. Improved cookstove
      e. Imported/manufactured sheet metal stove
      f. LPG gas
      g. Electric stove
      h. Other
    2. If the family has more than one cookstove, which is used for cooking INDOORS most of the time? (choose one)
      a. Three-stone/open fire
      b. Traditional chulha (indoor)
      c. Traditional chulha (outdoor)
      d. Improved cookstove
      e. Imported/manufactured sheet metal stove
      f. LPG gas
      g. Electric stove
      h. Other
    3. If there are multiple stoves, what foods/drinks do you prepare using the PRIMARY stove discussed previously? (Select all that apply)
      a. Boil water
      b. Boil milk
      c. Make tea/snacks
      d. Cook vegetables
      e. Cook rice
      f. Cook chapatti/roti
      g. Cook meat/fish
      h. Heat water for bathing
      i. Cook food for animals

4. If there are multiple stoves, what foods/drinks do you prepare using the remaining stove(s)? (Select all that apply)
   - a. Boil water
   - b. Boil milk
   - c. Make tea/snacks
   - d. Cook vegetables
   - e. Cook rice
   - f. Cook chapatti/roti
   - g. Cook meat/fish
   - h. Heat water for bathing
   - i. Cook food for animals

5. If multiple stoves are used, which do you prefer? (Choose one) Why?
   - a. Three-stone or open fire
   - b. Traditional cookstove (Select all that apply)
     1. Free fuel
     2. Easily available fuel
     3. Food cooked tastes better
     4. Traditional cooking practices used for a long time
     5. Good quality of cooking
     6. Saving money by using less LPG
     7. Everyone at home prefers food cooked on chulha
     8. other
   - c. Improved cookstove (Select all that apply)
     1. Free fuel
     2. Easily available fuel
     3. Food cooked tastes better
     4. Saving money by using less LPG
     5. other
   - d. Imported sheet metal
   - e. LPG/gas (Select all that apply)
     1. Biomass stove too smoky
     2. Poor wood fuel availability
     3. Difficulty procuring wood fuel
     4. Cooking on wood stove is unsafe
     5. Cooking using wood requires a lot of preparation
     6. Takes too long to start wood fire
     7. other
   - f. Electric stove
   - g. Other

B. Heating Methods and Appliances

1. What method(s) does your household use for space heating inside the home? (Select all that apply)
    a. Hot char from cookstove
    b. Firewood heating stove (used only for heating)
    c. (indoor) Firewood cookstove (used for cooking and heats the room)
    d. Electric heater
    e. Hot water (radiator)
    f. Three-stone or open fire
    g. Other

2. Which rooms do you heat? (Select all that apply)
    a. Separated Kitchen
    b. Attached kitchen
    c. Bedrooms
    d. living/common room
    e. Entire home
    f. Single-room home

C. Respondent Info

1. What is your role in the household? (select all that apply)
    a. Cooks most of the meals for the rest of the household
    b. Collects wood fuel for cooking most often of anyone in the household
    c. Cuts/chops wood for cooking and/or heating most often for the household

III. Stove Usage Details (firewood stove)

A. Fuel collection and processing

1. How do you collect wood?
    a. Delivery
    b. Pick-up
2. What is the cost per kg?
3. How much wood in kg is used per day?
4. Has your daily wood use increased, decreased, or stayed the same over the past decade?

B. Cooking Practices (primary cookstove or most-used firewood cookstove)

1. How many hours per day is the stove used for cooking?
2. How is the fire ignited? (Select all that apply)
    a. Wood
    b. Plastic
    c. Lighter
    d. Paper
    e. Leaves
    f. Crop residue/herbs
    g. Matches

3. How long does it take to start the fire and prepare the stoves for cooking?
4. How many times per day do you start a fire in the stove? (not how many times it is used, how many times do they actually start the fire in the stove)

C. Home Heating Practices (include here if cookstove is used for heating)
  1. (If applicable to the location) How many hours per day (this month) is the cookstove used for heating?
  2. How many hours per day (this month) is the cookstove used to boil water?
  3. During which months of the year does your home require the most heating?
  4. As a result of this method/appliance, is your home warm and comfortable throughout the year? (open-ended question)

D. Regular Maintenance (ask in Kyanjin Gompa only)
  1. What kind of maintenance do you perform on your current stove? (Select all that apply)
    a. Fixing cracks
    b. Cleaning creosote from chimney
    c. Removing ash
    d. Other
  2. How often do you need to perform maintenance on your stove?
  3. Is there anything you would improve about maintenance practices on your stove?

IV. Stove Lifecycle and Construction
  A. Did you or someone in your household build the stove?
    1. If yes:
      a. How often do you build a new stove (replace the stove with a different one)? (No. of years)
      b. What are common reasons that you would need to build a new stove? (Select all that apply)
        1. N/A
        2. Chimney blockage
        3. Out of function
        4. Overuse
        5. Breakage/Cracks
        6. New home
        7. Thinning walls
        8. Convenience
        9. Aspiration
        10. Moved locations
        11. Social pressure
        12. Other
      c. What materials is it made from? (Select all that apply)
        1. unsure
        2. Dung

3. Clay
4. Mud
5. Brick
6. Stone
7. Mild steel rod
8. Galvanized iron sheet
9. Corrugated sheet metal (tin)
10. Other

(d-f) Only ask in Nepal:

d. Have you ever received training on cookstoves before? (Y/N)
e. How much money does it take to build a new stove?
f. Do you receive subsidies to build ICS? (Y/N)

2. If no:
    a. Have you made any modifications to your cookstove?
        1. Yes
            i. What was the purpose of the modification?
            ii. Are you satisfied with the result of the modification? Why?
        2. No

(b-c) only ask in Nepal:

b. How much did it cost?
c. If ICS, was it subsidized?

V. Perceptions
    A. Stove features
        1. What features or attributes do you think are important on your stove? Why? (use to gauge awareness of different features and relative importance so do not prompt respondent with any particular feature or attribute)

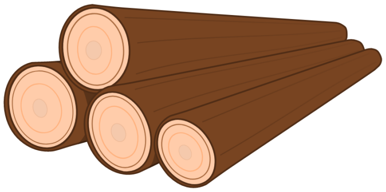
            a. Features (Select all that apply)
                1. Multiple potholes
                2. Pot stand (s)
                3. Chimney
                4. Grate
                5. Holes for chimney maintenance
                6. Pothole covers
                7. Pothole rings for size adjustment
                8. Chimney damper
                9. Warming chamber
                10. Other

            b. Attributes (Select all that apply)
                1. Smoke level
                2. Space heating capacity

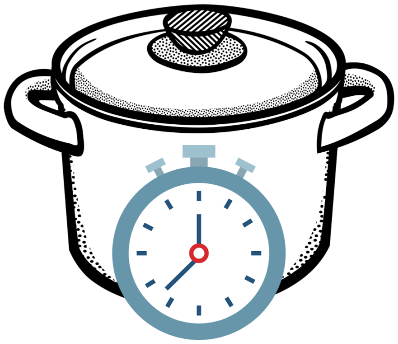
        3. Amount of fuel used
        4. Food taste
        5. price/cost
        6. Maintenance
        7. Firebox size
        8. Time to cook
        9. Versatile nature of stove
        10. Turndown ratio
        11. Other
2. What do you like about your current stove? (Select all that apply)
    a. Space heating
    b. Keeps food hot
    c. Taste
    d. Fast
    e. Large
    f. Cheap
    g. Safe
    h. Other
3. What would you improve about your current cookstove? (Select all that apply)
    a. Smoke reduction
    b. Reduce blackening of utensils
    c. Increase size of inlet to burn larger wood pieces
    d. Nothing
    e. Other

B. User Needs Hierarchy
Rank these design attributes from most important to least important.

Smoke Level



Fuel Used

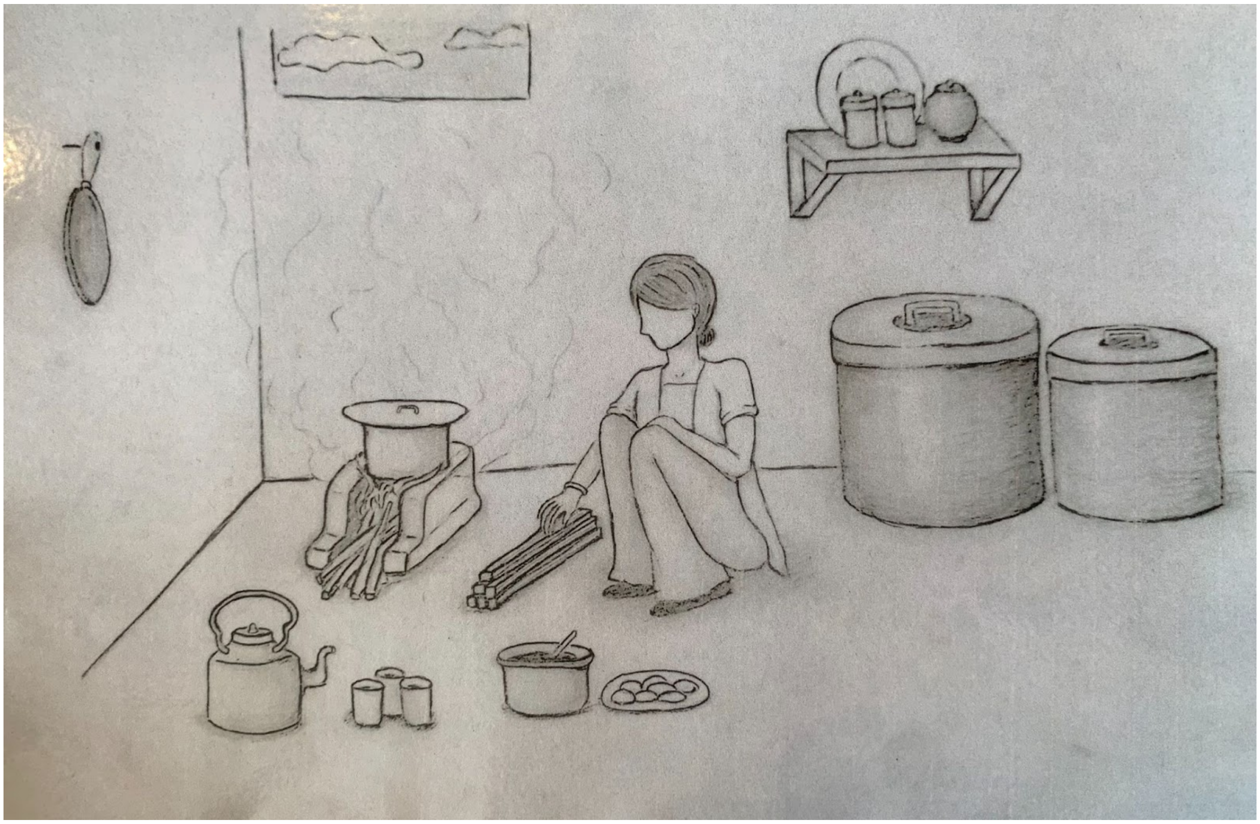


Cooking Time

गर्माहट
garmahat

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________

C. Projective Storytelling
Please describe what is happening in the picture. How do you think this person feels using the stove in the picture? What challenges do you think she may encounter?



VI. Wrap-Up

A. Is there anything else you would like to tell us about cooking and heating in your household or in your community?

B. Are you interested in receiving updates and more information about this project and future activities?

1. If yes, what type of communication would be best?
    - a. Whatsapp message
    - b. Email
    - c. Phone call

2. Contact information
    - a. Name
    - b. Location
    - c. Preferred method of communication

C. Any additional observations that may be relevant for understanding household energy?

Appendix D: Field Debrief Notes Template

Date:
City/Town, Country:
Person Facilitating:
Everyone Present:

<u>Meeting Agenda</u>

Stand-up (5 min):

- 30 seconds per item
    - Locations Visited:
    - No. People Surveyed:
    - No. + type WBT run:
    - Chimney installation progress:
- 1-minute Summary of day's progress, if not covered by above:

Group discussion (10 min)

- Issues that came up during day's work:
- General observations + stories of note:

Goals for Tomorrow (2 minutes):

Appendix E: Field Tests Full Results

Table 24: Field Tests Full Results

Location		**Pata**	**Salambu**	**Pata**	**Salambu**	**Salambu**
Elevation (m)		1200*	1657	1200*	1525	1600*
Ambient Temperature (°C)		25.5	28.0	27.5	26.0	26.0
Type		Improved	Improved	Traditional	Traditional	Traditional
No. of Pots		2	2	2	1	1
Duration (min)	*Cold Phase*	40.22	25.83	19.78	25.00	15.00
	Hot Phase	25.50	15.42	41.00	17.33	13.50
	Total	65.72	41.25	60.78	42.33	28.50
Pot Power (W)	*Cold Phase*	359.10	399.70	610.09	354.41	609.30
	Hot Phase	533.51	678.81	450.93	474.95	686.99
	Average	426.77	504.01	502.73	403.77	646.10
PPR	*Cold Phase*	1.72	7.22	3.12	-	-
	Hot Phase	1.95	3.69	0.91	-	-
	Average	1.81	5.90	1.63	-	-
Fuel Consumed (g)		1440	788	1476	386	691
Fuel Moisture (measured)		16%	14%	14%	11%	17%
Firepower (W)		5,053	5,137	5,834	3,364	5,764
Cooking Efficiency	*Cold Phase*	7.11%	7.78%	10.46%	10.54%	10.57%
	Hot Phase	10.56%	13.22%	7.73%	14.12%	11.92%
	Average	8.45%	9.81%	8.62%	12.00%	11.21%
Emissions & Humidity Sensor Location		Above Primary Pot	In front of fuel inlet	Above primary pot	Above primary pot	Doorway
Avg Relative Humidity		93.229%	77.309%	66.472%	62.334%	91.287%
CO (ppm)	*Max*	188.02^	13.43	859.51^	10.07	117.51^
	Average	79.20	6.71	367.75^	9.07	64.27
CO_2 (ppm)	*Max*	4101	503	7231	383	2125
	Average	1670	424	2865	362	1299
PM 2.5 (mg/m^3)	*Max*	9.47	2.94	9.34	1.23	6.79
	Average	3.09	0.98	4.57	0.63	3.45

*Estimate based on other locations that was used for calculating local boiling temperature

^CO readings were only calibrated up to 100 ppm, so these are outside of the calibration range.