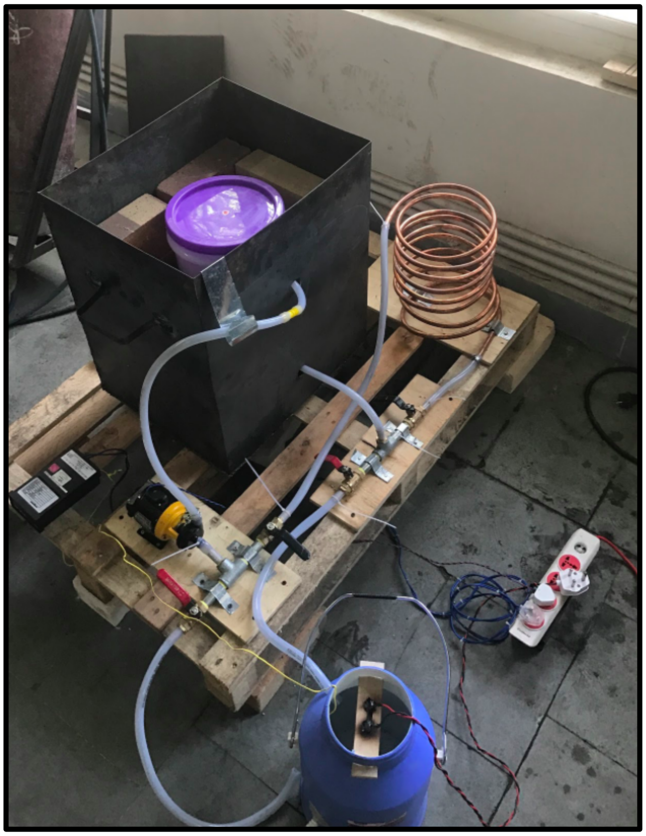
A New Perspective on Domestic Heating in Mandi

Investigating the use of Packed Bed Technology in the Mandi District



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A New Perspective on Domestic Heating in Mandi

Investigating the use of Packed Bed Technology in the Mandi District

submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfilment of the requirements for the
degree of Bachelor of Science

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Report Submitted to:

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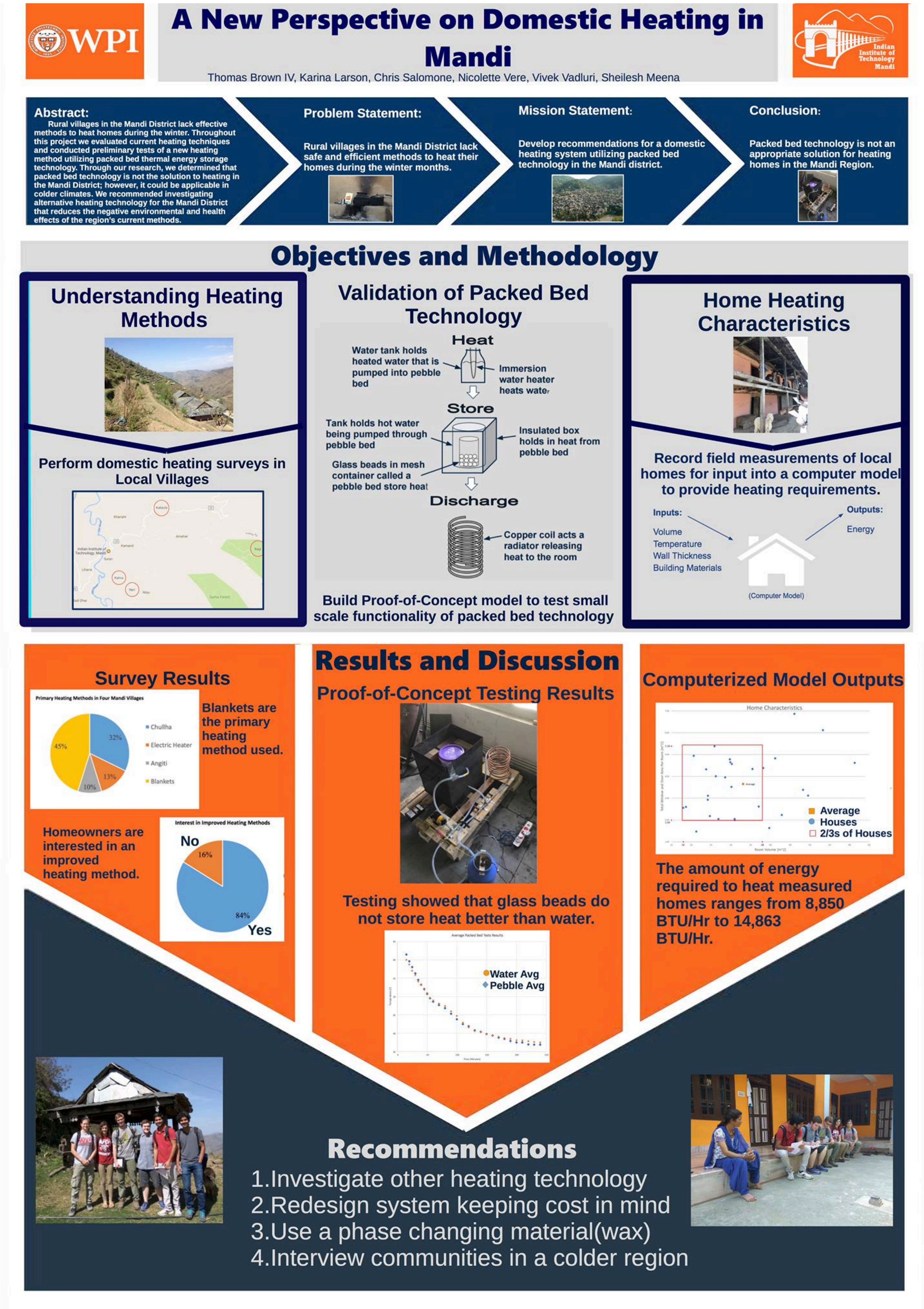
Abstract

Rural villages in the Mandi District lack effective methods to heat homes during the winter. Throughout this project, we evaluated current heating techniques and conducted preliminary tests of a new heating method utilizing packed bed thermal energy storage technology. Through our research, we determined that packed bed technology is not the solution to heating in the Mandi District; however, it could be applicable in colder climates. We recommended investigating alternative heating technology for the Mandi District.

Executive Summary (Poster)



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- All of the local residents that took the time to participate in interviews and allowed us to visit their homes.

- The staff in the mechanical and thermofluid labs that provided us with assistance in creating our Proof-of-Concept.

Authorship

Thomas Brown contributed to the writing and editing of each section of the report; the analysis of the interviews; the design and development of the proof-of-concept; and the design of the poster.

Karina Larson contributed to the writing and editing of each section of the report; the analysis of the interviews; the design and development of the proof-of-concept; and the design of the poster.

Shailesh Meena contributed to the facilitation interviews; the translation and analysis of interviews; and the poster design.

Christopher Salomone contributed to the writing and editing of each section of the report; the analysis of the interviews; the design and development of the proof-of-concept; and the design of the poster.

Vivek Vadluri contributed to the facilitation of interviews; the translation and analysis of interviews; and the poster design.

Nicolette Vere contributed to the writing and editing of each section of the report; the analysis of the interviews; the design and development of the proof-of-concept; and the design of the poster.

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A Case for Improved Heating Methods in the Mandi District

Determining efficient ways to heat rural homes is a problem for many developing countries due to limited access to modern resources. This leaves minimal options to produce reliable clean heat within rural homes. Worldwide, wood is the main resource used to heat rural homes despite its negative long-term environmental and health impacts (Naeher et al., 2007). Therefore, villages worldwide lack safe and effective methods to heat their homes during the winter months.

The Himachal Pradesh region of Northern India is experiencing these same challenges which are exacerbated by its mountainous environment and wide-ranging seasonal temperatures. The Mandi community could benefit from an efficient and environmentally friendly means of heating rural homes. Any future heating method will have to overcome the same challenges, such as a lack of energy sources and minimal finances, in order to be a viable option for the people in the region. Throughout this project, we explored whether packed bed technology could be a viable option for a future heating method that would benefit the region's health and environment.

Rural villages in the Mandi District lack safe and efficient methods to heat their homes during the winter months. Our team worked with professors at the Indian Institute of Technology (IIT) to research and test the efficacy of packed bed technology as a means for heating homes efficiently and effectively. Our project's mission was to develop recommendations for a domestic heating system utilizing packed bed technology in the Mandi District. The objectives developed to achieve this mission were as follows:

1. Understand current practices and attitudes toward domestic heating in the Mandi area.
2. Determine the energy required to heat an average Mandi home.
3. Validate small scale packed bed technology using a physical model.

Challenges of Rural Heating in the Mandi District

Access to modern heating methods is often limited or nonexistent in communities around the world. About 2.5 billion people worldwide depend on traditional biomass fuels for heating and cooking (Ekouev, 2012). Many rural communities in Himachal Pradesh, including villages in the Mandi District, heat their homes with wood, burning fires, or stoves (Jeuland, 2015). These fires are inefficient and harmful to humans and the environment. Burning wood in enclosed spaces can cause negative long-term health effects such as decreased lung function (Naeher et al., 2007). The kind of packed bed technology that is currently used in industrial applications has the potential to play a major role as an alternative source of sustainable residential heat.

Climate in Mandi

The state of Himachal Pradesh has varying climate conditions across the region due to altitude variations caused by the Himalayan Mountains ("Climate"). These conditions make it difficult for a single method of home heating to be effective in the all locations of the region, thus an adaptable method of heating is needed. There are two distinct seasons in the Mandi District of Himachal Pradesh: winter and summer. These seasons are known for their drastically different weather patterns. Table 1 displays average low temperatures in Mandi for each season (Weather).

Table 1 – Average Low Temperatures in Mandi

Season	Month	Average Low Temperature (Fahrenheit)	Average Low Temperature (Celsius)
Winter	October	67.8°F	20.0°C
	November	56.7°F	14.0°C
	December	48.4°F	9.0°C
	January	46.4°F	8.0°C
	February	50.7°F	10.0°C
Summer	March	60.6°F	16.0°C
	April	72.1°F	22.0°C
	May	79.5°F	26.0°C
	June	83.3°F	29.0°C

Typical Building Materials

There is a total of 406 villages in the Mandi District with 99.5% of them defined as rural villages (Census of India, 2011). In these remote villages, construction materials for residential dwellings are typically limited to the resources provided by the region, including timber, cement, slate, brick, wood, and mud. These structures are very simple with a majority containing only one or two rooms. Wood and cement are the two main resources utilized for constructing dwellings in the area. Their abundance makes them the fundamental materials for dwelling construction in Northern India.

The villagers take advantage of the materials that surround them in the mountains and local communities. The foundations of their homes are typically cement. The walls are then constructed using stones, as well as cement, and finally the roofs are created using slate rock as shingles. An example of a typical rural home can be seen in Figure 1. These homes allow for the interior to remain cool during the summer months, however, they are not very warm during the winter. Typically, construction of these homes requires only simple tools and techniques (Dave, 2016). Understanding the composition of a typical Mandi home is key for determining the amount of heat these structures require for use in the design of a heating system.

Current Heating Methods

Figure 1 – A home in Baggi, India

The simplistic nature of the homes, along with a lack of available resources, presents many challenges regarding heat for the winter. The locals most often turn to firewood and blankets to keep warm. Predominantly, fires are used for cooking in Chulha stoves throughout the day and the radiant heat is used for warmth at night. This cooking and heating technique is a traditional practice among local people and therefore they may resist change (Baker, 2016).

Wood fired stoves as they are used in Himachal Pradesh are an inefficient heating method that consumes a large amount of resources. In addition, the locals spend approximately 2.7 hours per person per trip in rural areas to collect firewood (Aggarwal & Chandel, 2010). One major concern is that this current heating method could lead to deforestation. The federal government acknowledged this problem with a timber ban in the 1900's (Ministry, 2017) but it was ineffective. It has since been made less stringent because the community disregarded the law and continued to collect firewood as it was their only source of fuel. As this practice continues, the Mandi community will have difficulty collecting firewood as it becomes less available. The end goal of developing a packed bed technology heating system is to reduce the overall consumption of wood in this region through using the cooking stoves that are already in place as an energy source for the system.

Application of Packed Bed Technology for Heating

A packed bed thermal energy storage system stores heat by pushing a working fluid through a container filled with packed units, such as pebbles, wax, ceramic fragments or metal shards. A packed bed system is comprised of three components: an energy source, a packed bed, and a distribution method. The heat source warms a working fluid (water or other liquid) which in turn warms the packed units in the bed. The packed units are made of materials that can retain heat for an extended period of time so it can be dispersed by the distribution method, which could be a radiant pipe, a fan the like. A simple diagram of a packed bed system can be seen in Figure 2.

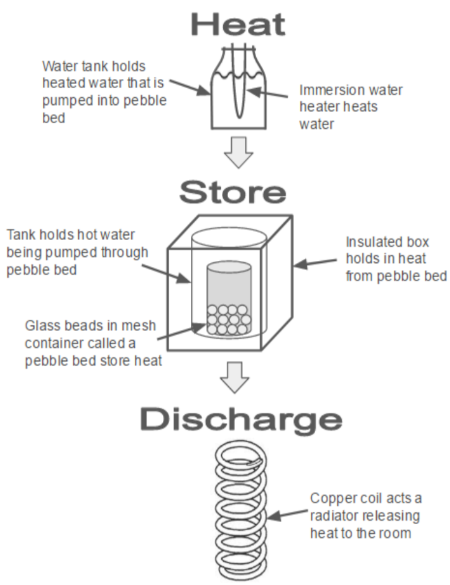

Figure 2 – A schematic showing how the system works

Packed Bed Thermal Energy Storage Technology

The energy source component in a packed bed system is defined as the method by which the working fluid is heated for the packed bed system. The working fluid in this system can be air, gas or liquid. Once power is provided to the energy source, the working fluid is heated and pushed through the system to the packed bed component via the distribution method. The distribution method is dependent on the physical state of the working fluid. If the working fluid is in a gaseous state, the distribution method could be a fan. Furthermore, if the working fluid is in a liquid state, the distribution method could be a pump or siphon. Either version of the distribution system would be powered by the same heat source.

The packed bed portion of the system is charged with the energy produced by the heat source. The packed bed component is a collection of equal-sized packed units of the same material in box or cylindrical container. A packed unit is a container that holds a substance chosen for its heat retention ability, such as wax, alumina, or other high heat retaining materials. The heated working fluid is pushed through the packed bed by a distribution system which heats the packed units. The packed units store this thermal energy and releases it gradually.

The size of the packed units plays a large role in the effectiveness and heat conductivity of the system. If the packed units are larger, then there will be more surface area for heat exchange with the working fluid. Conversely, larger packed units reduce the total pressure of the entire system due to the low number of units. A lower pressure could make movement of the working fluid throughout the system more difficult. A balance between adequate pressure and heat exchange is required for an efficient system ("Segmented" 5).

Latent Heat Thermal Storage System Using Paraffin Waxes

In 1981, undergraduate students at the University of Delaware investigated the feasibility of paraffin waxes as the phase change material within the packed units of a packed bed thermal storage system. The students developed a system that consisted of thousands of 16 oz. beverage cans containing paraffin and a septic tank that held the cans. In this study, water was used as the working fluid to transfer the heat. The results of the study showed that over an 8-hour time period, the paraffin was an efficient material for storing the thermal energy of water.

The system developed at the University of Delaware is an example of a small-scale application of packed bed thermal energy storage technology. Although this technology is used in industry on a much larger scale, this study confirms that it can be scaled down significantly. This study also verifies that these systems can be made out of resources and materials common to the Mandi region (soda cans, cement, and water). We learned of this study through an interview with Professor Guceri of Worcester Polytechnic Institute's mechanical engineering department who was the faculty advisor of this project. A summary of this interview can be seen in Appendix C. This study informed our team of the use of phase change materials in small scale packed bed systems. Ideally, our system would function in a similar manner with comparable results.

Methodology

In order to understand the current methods and opinions of Mandi homeowners regarding domestic heating, we conducted interviews in four villages in the District. In this region, the most abundant source of energy for a packed bed heater is the wood fires that are already being used for cooking and heating. Due to this fact, we targeted villages that would most likely use wood as their primary source of fuel. After research and a discussion with our Indian teammates we decided to survey the following four villages: Baggi, Kataula, Kahra, and Neri.

A total of **30 interviews across the four villages** seen in Figure 3, were completed. We began our interviews with an explanation including that we were students from IIT and that we were performing interviews in surrounding villages regarding heating methods. Then we asked each household a set of standard questions (included in Appendix D) in order to understand the resident's heating methods and opinions.

Figure 3 – A map showing the villages we surveyed

The first three interview questions were designed to explore homeowner's **current heating method** and **electricity availability**. We asked these questions to determine the most common heating methods used and later inform our team's recommendations for using packed bed technology as a heating source in this region.

The second half of the interview consisted of open ended questions that focused on the homeowners' opinions. We obtained information on the **number of people living in the home** and whether or not the family lived in their home year-round. This would help us determine if the residents lived in their house during the winter months and if they had an obvious need for a new heating technology. The next question concerned the common **cooking and heating fuel** that the residents used. This question was intended to determine if firewood is commonly used and if there was a need for the technology from an environmental perspective.

The last three questions determined if there was a need for a new technology from the **homeowner's perspective**. These questions also helped us determine potential characteristics for an improved heating system using packed bed technology. The overall results of these interviews were used to provide recommendations for a heating system design that fulfilled the needs of Mandi homeowners.

In addition to our interviews, we also **measured several physical characteristics** of the resident's homes to later calculate the heating requirements of each structure. With the permission of the homeowners, we ascertained the **volume** of the room, the **wall thickness**, the wall **material**, the number of **windows**, and other thermal characteristics.

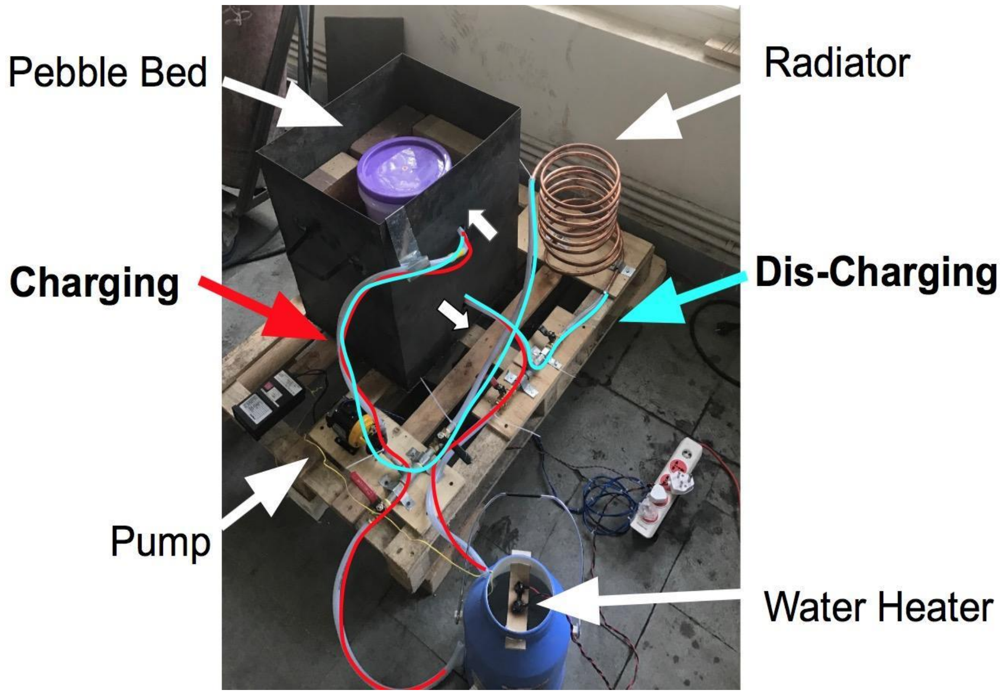

Figure 4 – A photograph of the proof of concept model with labels

These factors were all inputs to the computerized model that helped our team calculate the energy needed for a heating system.

In order to determine the energy required to heat an average Mandi home, we created a **computerized model** of a Mandi home. The computerized model required a variety of home characteristics as inputs and output the **energy required** to heat that home. The purpose of the model was to determine a range of building sizes and features for the development of a heating system using packed bed technology. Based on the resultant energy values, we used this range to provide recommendations for a future heating system design for these homes.

The model itself was programmed using the *Engineering Equation Solver* software which was introduce to our team by Professor Robert Daniello of Worcester Polytechnic. A summary of this interview can be seen in Appendix E. The model consisted of variables that represent the thermal characteristics of a home such as wall thickness and window count. These values are then used in heat transfer equations to produce the total heat loss due to convection and conduction. This resultant heat loss represents the energy required by a packed bed heating system to keep the room at a specified temperature. In our instance, we used a **room temperature of 13°C** and an **external temperature of 8°C** based on average low temperatures in December in the Mandi district ("Weather" 1). To produce a target range of building sizes and characteristics, we inserted each individual home into the model and analyzed the results. The code for the computerized model can be seen in Appendix F

In order to validate small scale packed bed technology using a physical model, we designed, built, and tested a **proof-of-concept packed bed system**. Packed bed technology is currently not being used for residential applications so we designed a smaller example in order to ascertain whether or not this technology functions on such a small scale. The complete building and testing methodologies can be seen in Appendix G and Appendix H.

We divided the system into **two cycles**, a **charging** and **discharging** cycle as shown in Figure 4. The charging cycle pumps water using a one eighth horsepower pump. We chose **water** as our working fluid because it transfers heat easily into the packed bed system. The water is pumped into a plastic container holding the **soda lime glass beads** which store heat. We chose Glass Beads because they were available in the Thermofluid lab at IIT and materials with a higher specific heat capacity would have taken over 4 weeks to deliver to IIT. An example of a material with a higher specific heat capacity would be paraffin wax which hold heat at 2.9 [J/gK], water holds heat at 1.47[J/gK], air holds heat at 1.01[J/gK] and standard glass is 0.84[J/gK] (Solids).

The discharging cycle also used water that was pumped into a coiled **copper** tube acting as a **radiator** for the heat. We chose copper because it has a high coefficient of heat transfer and was readily available in the lab. The entire system was insulated with fire clay bricks to store heat.

The system was not designed with cost as a consideration because we intended to use the the proof-of-concept purely for experimental purposes. The system was simply being used to test if the technology could be scaled down and store heat effectively. The cost to build the proof-of-concept includes a number of parts that we purchased in Mandi and many other materials that IIT provided us. In total, we purchased approximately 4,000Rs worth of equipment in Mandi. This included all of the tubing, fittings, valves, buckets, and the pump required for the system to operate. The Institute provided us with the steel box, copper tubing, bricks, and immersion water heater. We estimate that these components have a value of 3,500Rs. The approximate Bill of Materials Cost of our proof-of-concept was approximately 7,500 Rs and a detailed Bill of Materials can be found in Appendix I.

Next, we ran a variety of tests using the packed bed system, these are outlined below:

Water-Only Test

First, we tested the discharging cycle without any of the glass beads. The packed bed contained no packed units in this test. This was our control to observe how long water would store heat in the absence of the glass beads. The system was designed to be heated using the charging cycle over a long period but to reduce the amount of time required to prepare each test, we preheated the water to 80°C and then circulated it into the system. We recorded the temperature every 5 minutes for the first hour and every 10 minutes for each consecutive hour until the water in the packed bed reached room temperature.

Glass Beads Test

For the second test, we ran the discharging cycle with 5mm glass beads acting as our packed units. The system was preheated the same way as in the first test and then the charging cycle ran until the beads reached 80°C. Then we turned each valve to disable the charging cycle and enable the discharging cycle. We recorded the temperature every 5 minutes for the first hour and every 10 minutes for each consecutive hour until the water in the packed bed reached room temperature. We compared system cooling time without beads and with beads to see if the packed bed could effectively store heat for a longer period of time. We conducted two sets of tests using the same procedure.

Results and Discussion

The following section includes a discussion of the results we obtained by applying the methods outlined above.

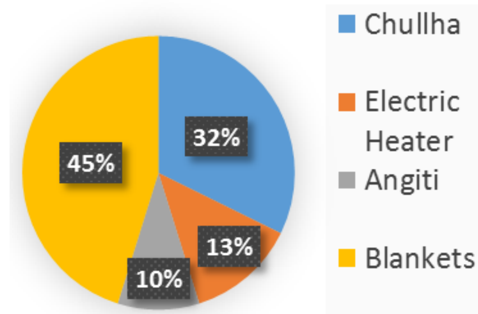

Figure 5 – A pie chart showing primary heating methods

Blankets as the Primary Warming Device

Completing interviews in **thirty** different homes in the Mandi District helped our team determine the current state of domestic heating in the region. Specifically, we gained insight into residents' heating methods, electric availability, fuel usage, and personal perceptions of their own heating methods.

From the homeowners' responses, we found that approximately **45%** used **blankets** as their primary way to stay warm during the winter months. Another **32%** used **chulhas** as their primary heating method, meaning they used their chulhas to cook inside during the day so the chulha's radiated heat would temporarily warm their bodies. Other methods such as electric heaters and *Angiitis*[1] were less common among those interviewed as seen in Figure 5. A complete report of our survey results can be found in Appendix J and Appendix K.

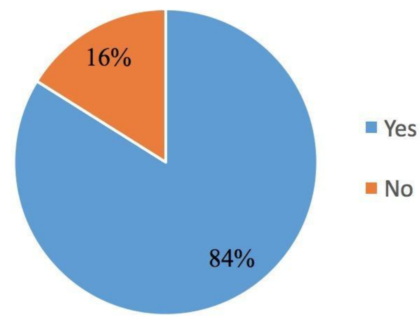

Figure 6 – A pie chart showing percent of villagers who want improvement

There is Interest for Affordable New Heating Systems

Discussions with the homeowners revealed that approximately **84% of them were interested in using improved heating methods** in some capacity as shown in Figure 6**.** Most villagers initially appeared satisfied with their current methods because they had not been exposed to any alternative ways to heat their homes. After further discussing our project, the majority of interviewees expressed interest and seemed open to the idea of an alternative heating system that stores thermal energy. However, among those who expressed interest, nearly all respondents claimed that for them to adopt it, the system would have to be **incredibly low cost** and function more effectively than their current methods.

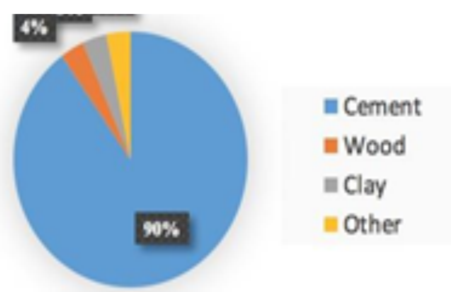

Figure 7 – A pie chart showing primary building materials of homes

Mandi Homes are Small and Mostly Made of Cement

Upon reviewing our field measurements, we were able to draw several conclusions from the collected data. The first conclusion was that the majority of rural houses in the

[1] A small metal container used in India that holds coals for people to bring inside and heat their homes.

Mandi District used cement as their primary building material. As seen in Figure 7, 90% of the homes we measured used cement as the primary material for their structures. This is due to its low cost, availability, and its ease of use.

The next conclusion that we observed from our measurements was that the median volume of the rooms requiring heat ranged from approximately $27m^3$ to $38m^3$ as seen in Figure 8. This $11m^3$ gap provided us with vital information regarding how adaptable new heating methods will have to be in this region.

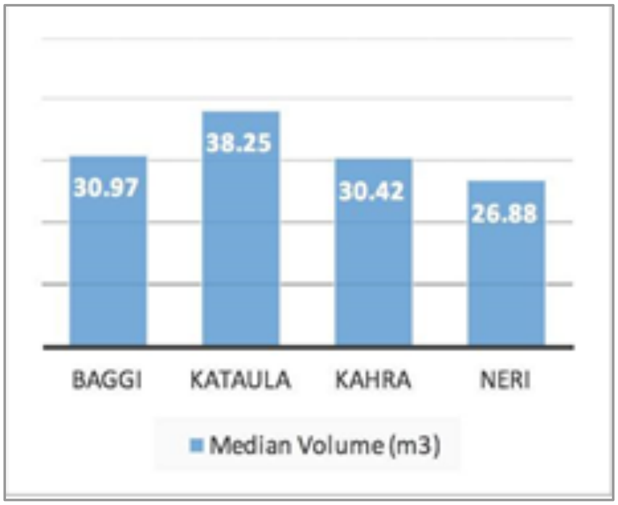

Figure 8 – A bar graph showing median volume of homes for four villages

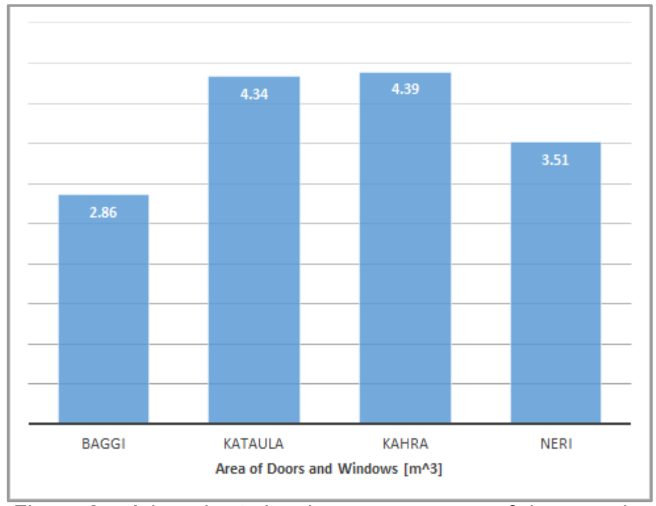

Figure 9 – A bar chart showing average area of doors and windows in four villages

Windows and Doors Are Major Sources of Heat Loss

Another major heat loss factor for these homes was the size of doors and windows in the room. When combining the areas of all of the windows and doors, we observed that the median open areas ranged from $2.86m^2$ to $4.39m^2$ between communities as can be seen in Figure 9. Overall, the home characteristics across the four villages provided us with information regarding the material and size of a room that a packed bed system would have to heat.

In order to determine the amount of energy required to heat a Mandi home, we created the below chart, Figure 10. The X axis represents a home's total room volume and the Y axis represents the total area of a home's doors and windows. These are two factors that greatly impact heat loss. We then used our home measurements and our computerized model to calculate the amount of heat that a heating system would have to produce for each of the houses we surveyed.

To determine a range of energies for the Mandi District, we focused on room volumes and total window areas that encompassed two thirds of the houses we surveyed as illustrated by the red box. This area represents houses with a total room volume from 18m^3 to 38 m^{3}and a total window area from 1.99 m^2 to 5.38 m^2.

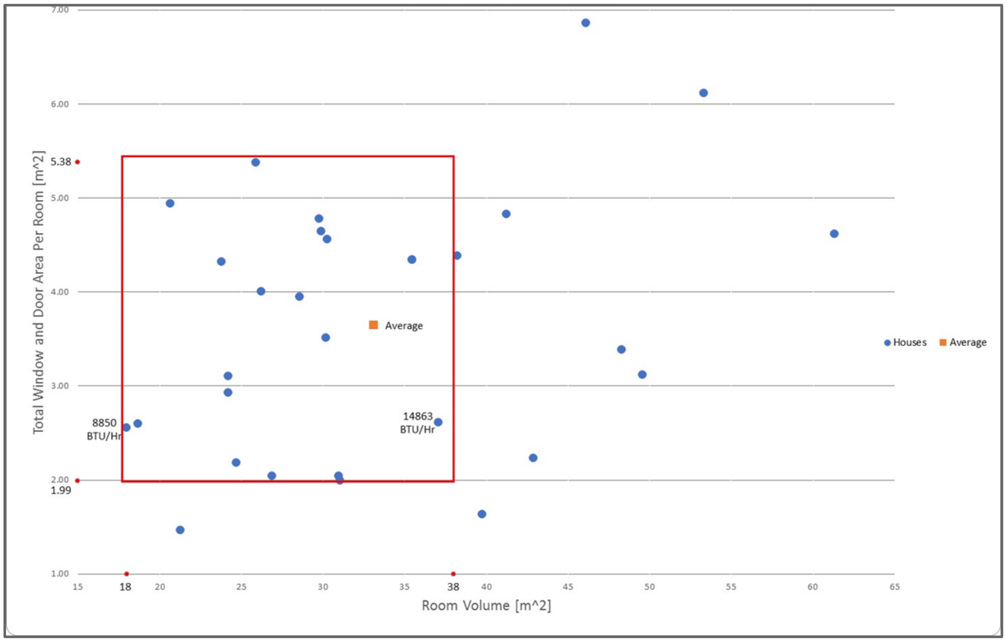

Figure 10 – A scatter plot describing the heating characteristics of the measured homes

Most Mandi Homes could be Heated by just Two Electric Space Heaters

Within the four villages, the amount of energy required to heat two thirds of the homes we surveyed ranges from **8,850 BTU/Hr to 14,863 BTU/Hr** as can be seen in Figure 10**.** We believe that a heater for this region should be able to operate within this energy target. For perspective, an efficient 2500 Watt electric **space heater** can produce around **8,800 BTU/Hr.**

The Proof-of-Concept Showed Glass Beads are Not Better than Plain Water

The results of the four tests carried out using the packed bed system can be seen in Figure 11. The blue represents the average values from the two tests that included the discharge cycle without glass beads. the water temperature in the packed bed took approximately 240 minutes to discharge and return to room temperature. The second set of tests (in orange) included the 5 mm soda lime beads, and also took approximately 240 minutes to discharge the heat. Obviously, the soda lime glass beads could not retain heat more effectively than our control tests. There are several possible reasons for this that are discussed in depth below.

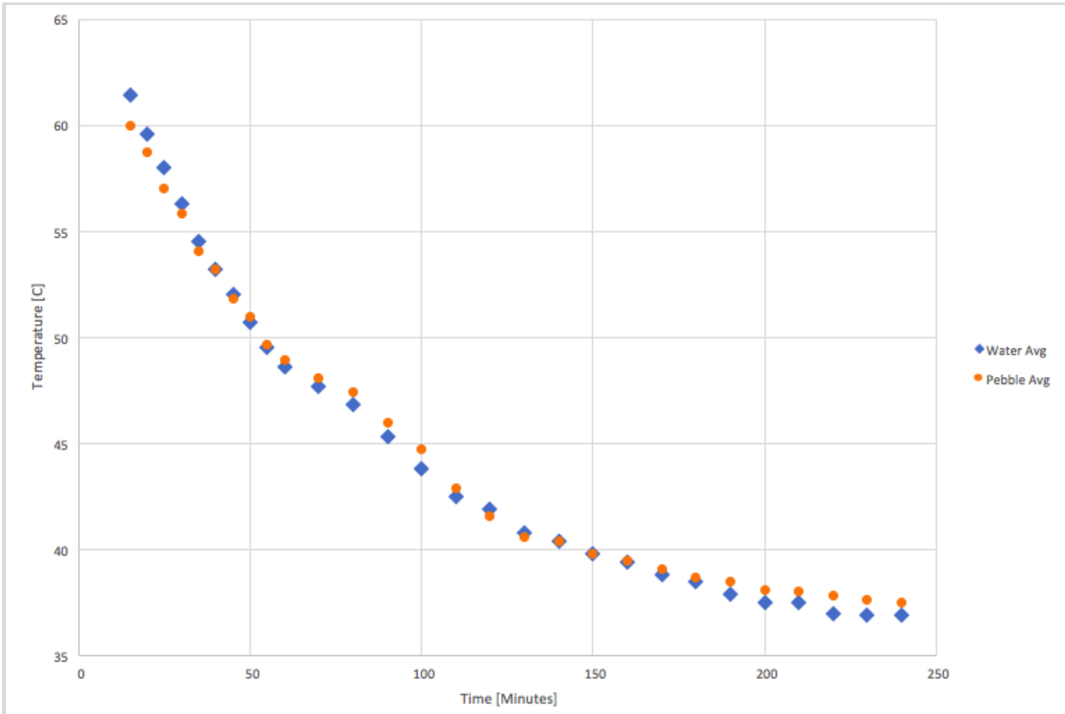

Figure 11 – A chart displaying the results of the proof of concept tests

Due to time restrictions, ordering any materials from outside the Mandi area was not an option. Ordering alternate materials would have taken several weeks for delivery. This would have pushed system development and testing beyond a reasonable completion date. Therefore, we were limited to the soda lime glass beads available at IIT. Of those, we chose 5mm glass beads because they were the largest option and had the most surface area. If better heat transfer materials were available for testing, the system may have performed differently in terms of heat retention. As previously mentioned in the Methodology, the specific heat capacity of paraffin wax and water would have outperformed the glass beads.

The **pump** powering our system was also a limiting factor in our design. We had very few options in terms of horsepower. The speed and torque of the pump controlled the flow rate of water through the system. Due to the constraints of our charging and discharging cycles, the system could only operate within a **small range of flow rates**. For example, if the flow rate was too high, fluid would enter our pebble bed faster than it could drain. The pump available for testing was one **eighth horsepower**. We determined that this power rating was **too high** after initial testing. Our solution was to restrict the flow rate using ball joints in the system. This restriction was overheating our pump which required us to design additional equipment to maintain a safe operating temperature for the duration of each test. A **smaller pump** was not available at IIT or in Mandi. If a smaller pump was available, the cost of the system would decrease and its efficiency would increase due to less restriction.

Recommendations

The completion of building our proof-of-concept packed bed and social interviews revealed a variety of recommendations that are vital for the future of this project. If the development of a packed bed heater continues, the following information must be kept in mind.

Target New Heating Technologies to Colder Regions in India

Upon review of the survey results, we discovered an interesting fact regarding the people who live in the rural villages near the IIT Kamand campus. The majority of families do not use a space heater in their homes during the winter. In fact, the most common method used for warmth was simply putting more clothes on and wrapping themselves in blankets. These responses told us that the people living in this part of Himachal Pradesh do **not experience enough cold weather** to require space heating in the form of a packed bed heater. Our recommendation for further development is to **venture farther north** to a region where people require space heating in order to survive the winters.

Lower the Cost of the Packed Bed System and Explore Subsidies

The survey of villagers near IIT Kamand revealed that space heating is not required to survive the winter in this climate. Despite not necessarily needing this technology, a majority of families did specifically mention that they would be accepting of an improved form of heating in addition to their current use of blankets. The only stipulation being that the improved technology **must cost less** than what they currently use. While this might be extreme, in order for a heating technology to be feasible in this region, the total operating cost should be as cheap as a blanket. The current cost of packed bed technology, as we designed it, is far too high for homeowners in the Mandi district. The expense for the materials alone was approximately **7,500Rs**. This does not include any of the costs associated with bringing it to market. The blankets that they currently use cost less than **100Rs per year**. Even if our concept was adjusted for realistic use, for example, by using a chullah instead of a water heater and a water syphon instead of a pump, the cost of the overall system would decrease but still remain too high for the target homes. Our recommendation for the high cost of the packed bed technology is to adjust the system and to use more **common materials** while also working to **subsidize** the cost of the heater by perhaps partnering with the Indian government to help this technology reach locations in need.

Couple Packed Bed with Chulhas to Reduce Cost

The ideal packed bed heating system would run using a chulha and a thermosiphon, eliminating the need for electricity. In our proof-of-concept experiment, we used a hot water heater and a pump to control the water, temperature, and flow. These adaptations were requirements to complete a proof-of-concept of the scaled down packed bed system. However, these additions would make our system too costly for use in small village homes in Himachal Pradesh. The hot water heater and the pump add significant costs to the system that would be too great for our stakeholders. Despite this, we believe our system could be adapted to **use a chulha and a thermal siphon** to reduce costs of the technology. This recommendation would be valuable to consider in further development of the packed bed technology for use in this region

Experiment with Phase-Changing Material like Paraffin Wax

The goal of a thermal energy storage device is to hold heat for an extended period of time. Due to lack of availability, our team did not have access to the correct materials which would have been ideal to create the packed units in our system. The 5mm glass beads that we were provided on site, did not have optimal thermal storage capacity for our needs. However, past research has shown that phase-change materials are often best for this application. This material is known to have a significantly higher heat capacity than any other materials. Often waxes and paraffin are used in this form. Based on our team's research, we recommend that any future development of our proof-of-concept should use a phase-changing material.

New System Should Output 9,000 to 15,000 BTUs/hr

Based on our home measurements and our computerized model results, we recommend that any future heating system for this region is designed keeping an energy output range of around 9,000-15,000 BTUs/Hour in mind. Based on the homes that we measured, to maintain a temperature differential of 5°C between the outside of the home and the inside of the home, this amount of energy is required

Conclusion

In conclusion, we determined that **packed bed technology is not an appropriate solution** for heating homes in the Mandi Region. The results from our local surveys showed that there is a **desire for an alternative, low cost, system** but our analysis shows that packed bed technology is not the solution due to its technical complexity and high cost. There is still an acute problem in Mandi that could be addressed in order to **increase the comfort** of those living in rural villages. In addition, while packed bed technology may not be appropriate for these homes, we believe there is still a potential use for this system in the northernmost colder parts of India that experience severe winters.

Although our proof-of-concept is not designed for home use, we believe that our device can be used in future experiments with other materials inside the packed bed. As a result of this project, we believe there is a future for small scale packed bed heating systems given the right climate and consumers. We also believe that the Mandi District could benefit from an alternative heating system as long as it complies with the specific needs of its residents.

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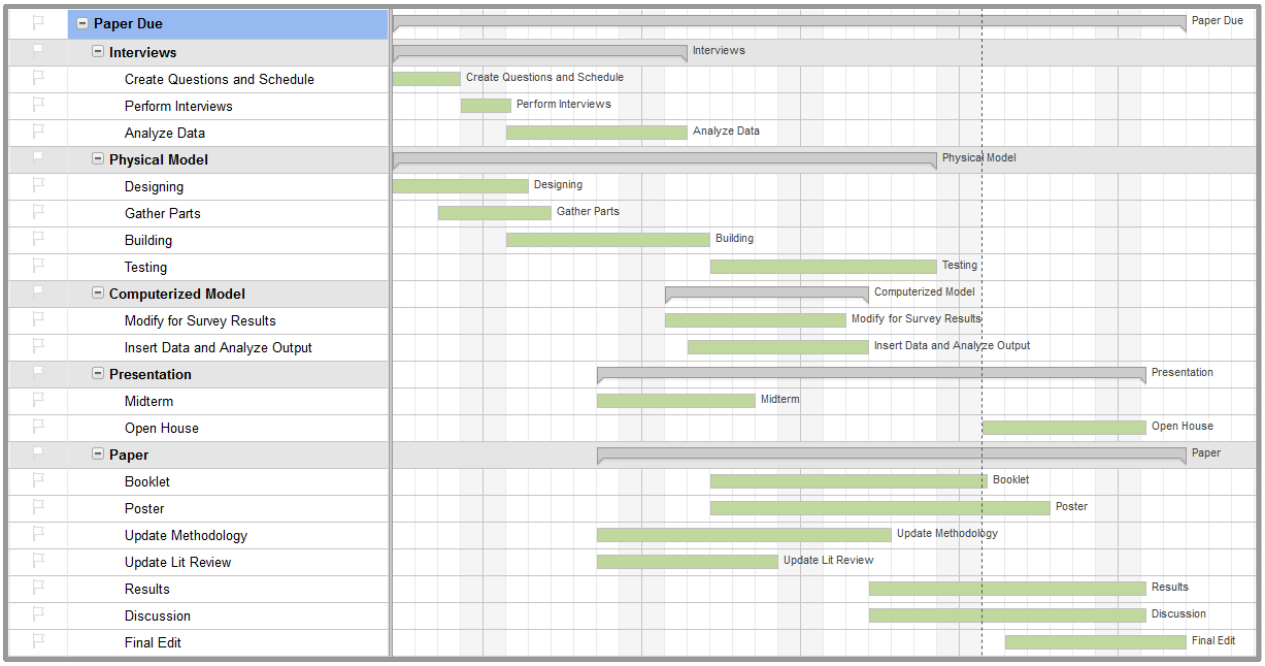
APPENDIX A: Project Gantt Chart



APPENDIX B: Selcuk Guceri Ph.D. Interview

Professor of Mechanical Engineering at Worcester Polytechnic Institute

Interviewed on February 16, 2017 at Worcester Polytechnic Institute

Interview Summary:

The goal of this interview was to learn about Professor Guceri's work that he completed at the University of Delaware in 1981 on a packed bed thermal storage system prototype. He shared a variety of original documents containing drawings and data collected from the project. Professor Guceri explained the goal of their project was the using Paraffin Waxes and locally found materials to develop their own version of a packed bed thermal storage system. This system used 10,000 cans full of Paraffin as in the Figure A placed in a septic tank. The tank, as shown in Figure B, would then be filled with hot water that heats the paraffin. Professor Guceri's explained that this storage system was very efficient considering the materials being used. Further analysis of this Project can be found in Chapter 2 Section 2.6 of the paper.

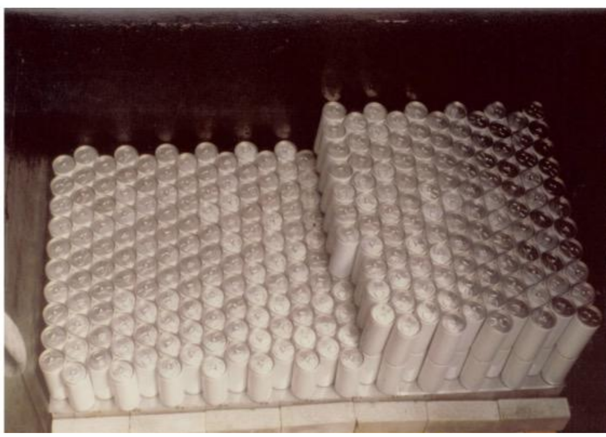


Figure A

Figure B

APPENDIX C: Survey Questions

Short Questions

1. How do you heat your home? (choose one)
    a. *Chulah*
    b. *Electric heater*
    c. *Do not Heat*
    d. *Other:(eg. firewood outside the house)*

2. Does your home have electricity? If yes…
    a. Do you experience power outages often?
        i. *Once a day*
        ii. *Twice a day*
        iii. *Multiple times a week*
        iv. *Other:*
    b. Do you have a hot water heater in your home?

Measured Survey Permissions:

Can we have your permission to measure your home?
Can we have your permission to photograph your home?

Open Ended Questions

1. How many people live in your home?
    a. *Adults:*
    b. *Children (under 18):*
    c.

2. How many months a year do you live in this home?

3. Fuel:
    a. *What fuel type do you use?*
    b. *How do you get this fuel?*
    c. *If the fuel is bought, how much does it cost?*
    d. *How long does it take to get this fuel?*
    e.

4. Generally, how long does it take to heat your home to a comfortable temperature?
5.How comfortable do you feel with the current temperature?
6. Using your current methods, how comfortable are you in the winter months regarding temperature?
7. How satisfied are you with your current heating methods?
8. Is there anything that you want to improve about how you heat your home?

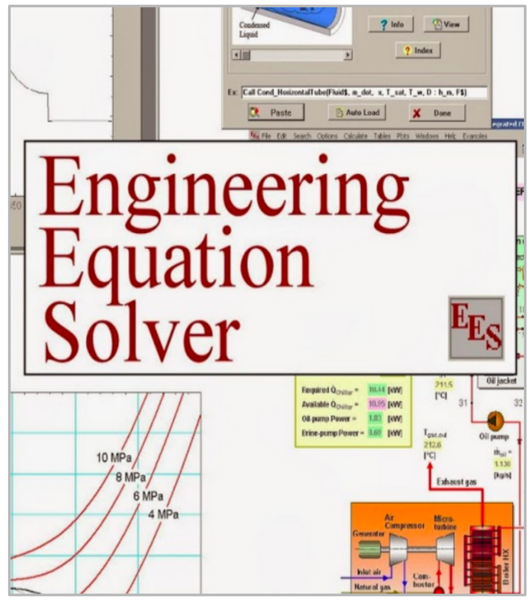
APPENDIX D: Robert Daniello Ph.D. Interview

Professor of Mechanical Engineering at Worcester Polytechnic Institute

Interviewed on February 14, 2017 at Worcester Polytechnic Institute Campus

Interview Summary:

The goal of this interview was to discuss the use of various computer programs for building our model as described in Chapter 3. After introducing Professor Daniello to the goal and objectives of our project, he strongly recommended the Engineering Equation Solver(EES) software. EES has thermal properties and unit conversion pre-built into the 'solve' portion of the program. We discussed how this would save our team many hours of programing. After discussing the use of this program, we questioned Professor Daniello about various example packed bed thermal storage heat transfer problems that he brought to the interview. The results of the interview included the decision to use the EES program as well as an initial understanding of the two major components of our model, our house related model and our thermal system related modeling.



APPENDIX E: Computer Model Code

```
"Model of the House"

"INPUTS"

height_H= 2.71  [m]"home height "
length_H= 3.69  [m]"home length"
width_H=  3.02  [m]"home width"
th_H=     0.61  [m]"Thickness of home walls"
area_W1=  2.27  [m^2]"window areas"
area_W2=  0     [m^2]
area_W3=  0     [m^2]
area_D1=  1.24  [m^2]"door areas"
area_D2=  0     [m^2]

"HOME PROPERTIES"

"area of home walls"
area_H=(height_H * length_H * 2) + (height_H * width_H * 2) + (length_H * width_h)

"conduction heat transfer coefficient"
k_H=conductivity('Concrete_ stone mix', T=T_C)

"Temperature Material"
T_C= 299[K]

"convective heat transfer coefficient"
h_H= 14.32

"Temperature In"
Tin=285[K]

"Temperature Out"
Tout=280[K]

"Atmospheric Pressure"
P=80[kpa]

"time"
seconds=3600[s]

"WINDOW PROPERTIES"

"thickness"
th_W=0.025[m]

"total area"
area_W=area_W1 + area_W2 + area_W3

"conduction heat transfer coefficient"
k_W=conductivity('Wood_pine', T=T_G) "Glass_soda _lime"

"Temperature Material"
T_G= 299[K]

"DOOR PROPERTIES"

"Thickness"
th_D=0.05[m]

"total area"
area_D= area_D1 + area_D2

"conduction heat transfer coefficient"
k_D=conductivity(Wood_pine, T=T_wood)

"Temperature Material"
```

```
T_wood= 299[K]

"EQUATIONS"

q_cond_H = (k_H*(area_H - (area_W + area_D))/th_H)*(Tin-Tout) "conduction of home walls minus area of windows/doors"

q_conv_H = (h_H*(areaa_H - (area_W + area_D)))*(Tin-Tout) "Convection of home walls minus area of windows/doors"

q_cond_W = ((k_W*area_W/th_W)*(Tin-Tout))"conduction of windows"

q_cond_D = (k_D*area_D/th_D)*(Tin-Tout)"conduction of doors"

q_total= q_cond_H + q_conv_H + q_cond_W + q_cond_D "total q"

q_time= q_total*(seconds)

q_btu= q_time*convert(J, btu) "convert to BTU/Hr"
```

k	1.4	W/mK			q=h*A*dTemp	
A	9	m^2				
dTemp	14	degreesC		Pr	Cp*u/k	98.8928571
density	2400	Kg/m^3				
g	9.81	m/s^2		Ra	(g*beta*dTemp*L^3)/alpha*v	18.4043146
beta	0.00041667	m^3/kg	"1/density"			
L	0.58	m		Nu	text book equation 9.20	5.93400932
alpha	0.00077778		"k/density*cp"			
cp	0.75	kJ/Kg		h	Nu*k/L	14.3234708
v	0.78					
u	184.6					

APPENDIX F: Building Process

Steps to Build the Proof of Concept:

Step 1: Bought and Collected Materials.

Step 2: Put holes in Plastic Container for Plastic barb fittings. Sealed with putty.

Step 3: Cut and shaped mesh for inside of plastic container to hold pebbles:

-Dimensions of mesh insert here

Step 4: Assembled control valves for charging and discharging cycles:

-added teflon between valve and pipe connections

Step 5: Decided placement of bricks:

-had to allow for tubing to enter and exit pebble bed and outer box

Step 6: Cut holes in outer box:

- need to not be blocked by bricks and align with the upper/lower portions of the pebble bed plastic container

Step 7: Configure and Mount Pump on Pallet Foundation.

Step 8: Build Radiator.

Step 9: Fixture Radiator.

Step 10: Cut and assemble tubing.

Step 11: Fill with Water and check for leaks.

Step 12: Functionality

APPENDIX G: Experimental Procedure

Testing:

Test 1: System without Pebbles

- Fill system with 80C water and run distribution cycle until the bed is room temperature. Record time.

Test 2: System with Pebble 5mm

- Fill system with 80C water and run charging cycle for 1 hour
- Run distribution cycle until the bed is room temperature and record time.

Methods for Testing:

1. Fill and seal the system. Check for leaks.
2. Check pump function.
3. Charge for X-time.
    a. Record: Temperature @ inlet/outlet of Bed in 5min intervals
    b. Record: Temperature of Bed in 5min intervals

4. Discharge cycle:
    a. Record: Temperature of the Pebble Bed.
    b. Record: Inlet/outlet Temperatures going into the radiator.
        1. Hour 1: Record Temperature in 5 min intervals
        2. Hour 2+: Increase interval length accordingly (TBD)

APPENDIX H: List of Materials

Acquired on Campus:

- Steel box (dimensions)
- Soda lime beads: 4mm, 5mm
- 1HP and 0.5HP pumps
- Copper pipes 10mm OD 8mm ID 20ft
- Insulatory Bricks
- Glass wool
- Nuts/Bolts for Mesh box (x20)

Purchased in Mandi:

- PVC Ball Valve (x4)
- T joint (x2)
- ½ inch piping(15m)
- Mesh (28in x 28in proximately)
- Hose clamps (x8)
- Hose Connections (x8)
- Electrical Tape (x1)
- Bond Set Sealant (6 boxes)
- Plastic containers (x3 of varying slides)

APPENDIX I: Complete Survey Results

Questions:	Repsonse:	Baggi(11)	Kataula(7)	Kahra(4)	Neri(9)	Number Total	Precent Total
Primary Heating Method	Chullha (Heating)	2	5	0	3	10	32.26
	Electric Heater	0	2	1	1	4	12.90
	Angiti	0	0	0	3	3	9.68
	Blankets	9	0	3	2	14	45.16
Cooking Method:	Chullha(cooking)	11	5	3	9	28	90.32
	LPG	0	1	0	0	1	3.23
	Chullha(cooking) +LPG	0	1	1	0	2	6.45
Electricity:	Yes	11	7	4	9	31	100.00
	No	0	0	0	0	0	0.00
Power Outages:	Daily	1	0	2	0	3	9.68
	1-2 Days/Month	3	1	2	3	9	29.03
	2-3 Days/Month	0	0	0	3	3	9.68
	3-5 Days/Month	0	0	0	3	3	9.68
	5-6 Days/Month	2	0	0	0	2	6.45
	Rarely	5	6	0	0	11	35.48
Adults:	1	0	0	0	0	0	0.00
	2	0	2	1	4	7	22.58
	3	2	3	0	1	6	19.35
	4	0	0	0	2	2	6.45
	5	2	1	0	0	3	9.68
	6	3	1	1	2	7	22.58
	7	0	0	2	0	2	6.45
	8	2	0	0	0	2	6.45
	9	1	0	0	0	1	3.23
	11	1	0	0	0	1	3.23
Children	0	1	0	0	0	1	3.23
	1	0	1	1	2	4	12.90
	2	5	5	0	2	12	38.71
	3	2	1	2	2	7	22.58
	4	1	0	0	3	4	12.90
	5	1	0	1	0	2	6.45
	6	1	0	0	0	1	3.23
Fuel Type	Wood	11	4	2	9	26	83.87
	Gas	0	0	0	0	0	0.00
	Wood and Gas	0	2	1	0	3	9.68
	Electricity and Wood	0	1	0	0	1	3.23
	Electricity	0	0	1	0	1	3.23
Collection Method	Collect from Forest on Back	11	5	4	9	29	93.55
	Other	0	2	0	0	2	6.45
How Comfortable are you?	Comfortable	0	1	2	2	5	16.13
(In Winter Months)	"Comfortable" no reference	7	5	1	3	16	51.61
Question 6	Un-Comfortable	4	1	1	4	10	32.26
	No Response	0	0	0		0	0.00

How Satisfied are you?	Satisfied	0	3	1	1	5	16.13
Question 7	"Satisfied" no reference	4	2	0	1	7	22.58
(With current heating methods	Not Satisfied	7	1	1	5	14	45.16
	Mostly satisfied	0	1	1	2	4	12.90
	No Response	0	0	1	0	1	3.23
Would Like Improvement?	Yes in some form	10	5	4	7	26	83.87
	No in some form	1	2	0	2	5	16.13

APPENDIX J: Complete Measurement Results

Village:	BAGGI										
House Number:	1	2	3	4	5	6	7	8	9	10	11
Ceiling height (m):	1.93		2.04	1.92	2.10	2.03	2.12	2.01	1.95	1.92	2.06
Central Room Length (m):	3.15		3.44	3.89	3.63	6.02	4.39	3.23	3.41	3.23	2.96
Central Room Width (m):	3.08		2.94	4.96	4.06	4.05	5.18	4.60	3.71	3.44	7.56
Volume (m^3):	18.69		20.67	37.09	30.97	49.59	48.32	29.91	24.72	21.31	46.12
Wall Thickness (m):	0.48		0.64	0.55	0.58	0.61	0.51	0.48	0.48	0.51	0.56
Wall Material Type Primary:	Cement	Homeowner didn't allow us to take measurements	Cement	Cement	Cement	Cement	Cement	Wood	Clay	Cement	Cement
Wall Material Type Secondary:	Wood		Wood					Clay			
Roofing Material Primary:	Slate		Wood	Wood	Wood	Wood	Wood	Wood	Wood	Wood	Wood
Roofing Material Secondary:	Wood										
Floor Material:	Wood		Cement	Wood	Wood	Wood & Mud	Wood	Wood	Clay	Cement	Cement
Number of Windows:	2		2	2	1	1	2	2	1	0	3
Area of Window 1 (m^2):	0.39		1.71	0.75	0.69	0.63	0.98	2.31	0.70		1.59
Area of Window 2 (m^2):	1.11		1.54	0.70			0.78	0.90			1.32
Area of Window 3 (m^2):											2.63
Material of Window:	Wood		Wood	Open	Open	Open	1 Wood-1 Open	Glass	Open		2 Glass-1 Open
Number of Doors:	1		1	1	1	2	1	1	1	1	1
Area of Door 1 (m^2):	1.08		1.68	1.16	1.35	1.37	1.62	1.43	1.48	1.46	1.32
Area of Door 2 (m^2):						1.11					
Material of Door	Wood		Wood	Wood	Wood	Wood	Wood	Wood	Wood	Wood	Wood
Number of Stoves/heating methods and type/model:	Blankets used		Chulah	Fire pit in room			Fire pit in room		Fire pit in room		
General Location of building (on a hill/in a valley etc):	Hill		Hill	Hill	Hill	Hill	Hill	Hill	Hill	Hill	Hill
OTHER:	2 Floors		2 Floors		2 Floors	2 Floors	2 Floors	2 Floors	2 Floors	2 Floors	2 Floors

Village:	KATAULA						
House Number:	1	2	3	4	5	6	7
Ceiling height (m):	2.23	2.71	2.68	2.90	1.95	2.04	2.04
Central Room Length (m):	3.90	4.51	3.66	4.42	6.49	3.93	3.93
Central Room Width (m):	2.74	4.36	3.90	3.35	3.14	4.42	4.42
Volume	23.81	53.34	38.25	42.91	39.76	35.49	35.49
Wall Thickness (m):	0.56	0.34	0.56	0.15	0.53	0.61	0.61
Wall Material Type Primary:	Cement	Cement	Cement	Cement	Cement	Cement	Cement
Roofing Material Primary:	Wood	Cement	Cement	Cement	Wood	Wood	Wood
Floor Material:	Cement	Marble	Cement	Cement	Cement	Cement	Cement
Number of Windows:	2	1	1	1	0	1	1
Area of Window 1 (m^2:)	1.91	4.56	2.81	0.56		1.37	1.37
Area of Window 2 (m^2):	1.19						
Material of Window	2 Glass	Glass	Open (Cloth)	Glass		Glass	Glass
Number of Doors:	1	1	1	1	1	2	2
Area of Door 1 (m^2):	1.22	1.55	1.57	1.67	1.63	1.78	1.78
Area of Door 2 (m^2):						1.18	1.18
Material of Door:	Wood	Wood	Open	Wood	Wood	Wood	Wood
General Location of building (on a hill/in a valley etc):	Near Road	Modern		Modern	Chulah in room		
OTHER:							

Village:	KAHARA			
House Number:	1	2	3	4
Ceiling height (m):	2.04	2.71	2.75	2.56
Central Room Length (m):	3.42	5.16	3.63	3.39
Central Room Width (m):	4.45	2.95	2.99	3.03
Volume (m^3):	31.05	41.23	29.79	26.24
Wall Thickness (m):	0.53	0.28	0.28	0.25
Wall Material Type Primary:	Concrete, Stones/Mortar	Cement	Cement	Cement
Roofing Material Primary:	Wood	Cement	Cement	Cement
Floor Material:	Wood	Cement	Cement	Cement
Number of Windows:	1	1	1	2
Area of Window (m^2):	0.89	2.91	3.34	2.72
Material of Window:	Wood	Glass	Glass	Glass
Number of Doors:	1	1	1	1
Area of Door (m^2):	1.10	1.91	1.43	1.28
Material of Door:	Wood	Wood	Wood	Wood
Number of Stoves/heating methods and type/model:	LPG			
General Location of building (on a hill/in a valley etc):	Top of Hill	Top of Hill	Hill	
OTHER:				

Village:	NERI								
House Number:	1	2	3	4	5	6	7	8	9
Ceiling height (m):	1.93	2.38	2.58	2.77	2.47	2.44	2.74	2.04	2.71
Central Room Length (m):	3.60	3.26	3.54	4.05	3.63	3.89	4.02	4.54	3.69
Central Room Width (m):	2.59	3.12	2.65	5.46	2.90	3.02	2.74	2.90	3.02
Volume (m^3):	18.01	24.23	24.21	61.35	25.93	28.59	30.28	26.88	30.19
Wall Thickness (m):	0.61	0.53	0.67	0.51	0.64	0.61	0.38	0.61	0.61
Wall Material Type Primary:	Cement	Cement	Cement	Cement	Cement	Cement	Cement	Cement	Cement
Wall Material Type Secondary:	Clay								
Roofing Material Primary:	Cement	Cement	Cement	Cement	Wood	Cement	Cement	Cement	Cement
Floor Material:	Cement	Cement	Cement	Cement	Cement	Cement	Cement	Cement	Cement
Number of Windows:	1	1	1	1	2	1	1	1	1
Area of Window 1 (m^2):	1.36	1.54	1.21	3.29	1.64	2.50	3.05	0.58	2.27
Area of Window 2 (m^2):					2.13				
Material of Window:	Glass	Open	Glass	Glass/Wood	Glass	Glass	Glass	Glass	Glass
Number of Doors:	1	1	1	1	1	1	1	1	1
Area of Door (m^2):	1.20	1.56	1.72	1.33	1.61	1.45	1.51	1.46	1.24
Material of Door:	Wood	Wood	Wood	Wood	Wood	Wood	Wood	Wood	Wood
General Location of building (on a hill/in a valley etc):	On Road	In Valley	In Valley	Valley	Valley	Valley	Valley	Valley	Valley
OTHER:									