Research Plan to Evaluate Efficiency and Emissions in Cookstoves for Lesoit, Tanzania

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Executive Summary

This report outlines the research paper plan for next semester. The research paper will compare mathematical predictions for the efficiency and emissions of solar cookers and improved biomass cookstoves with efficiency and emissions values obtained through testing. The team's findings will help future capstone teams develop and test improved cook stoves and solar stoves which will reduce harmful cooking emissions, reduce wood collection time, and provide economic opportunity for the women of Lesoit, Tanzania.

The team has also created a survey which will provide information on health issues, fuel use, and experience with alternative cooking methods. This survey will be taken to Lesoit for the summer 2016 trip. It is important that any cooking alternatives be made from inexpensive locally available materials to provide an economic opportunity in their manufacture and sale. For this reason, a materials list was included for each of the cooking alternatives.

For emissions testing, the improved cookstoves will be tested for Carbon Monoxide (CO) and Particulate Matter (PM), as they are primary contributors to emissions related health problems. The testing procedure and analysis which will be used is that in the Water Boiling Testing version 4.2.3. Predictions will be made using the three heat transfer mode equations and the finite difference method in Matlab.

The design and reasoning for each cooking alternative which will be tested and analyzed is also provided, as well as a project plan which outlines the specific tasks which will be completed next semester.

1. Background and Clients

The village of Lesoit is located in the Manyara region of north-eastern Tanzania in Southeast Africa. The population of the village is two thousand people and twenty thousand cows [1]. To obtain water for drinking and other household uses, the women of Lesoit usually walk 2-3 miles to the community well and benefit from the use of rainwater during the rainy season. The women also spend a large amount of time collecting wood from the forest for cooking. Daily sunlight averages 12 hours per day throughout most the year, but in April the sunlight drops to around 6 hours per day due to the rainy season [2]. Figure 1 shows the village location [3]. There are three sub-villages within Lesoit, and they are all located around the center sub village of Changombe. The women of Lesoit typically use the three-stone cooking stove, and some use the jiko charcoal stove. The smoke from these stoves helps to prevent pests and treat ceilings.

Figure 1: The village of Lesoit location [3]

2. Problem Statements and Goal

The majority of cooking in Lesoit is done by women using three stone stoves. These stoves consist of a fire surrounded by three stones upon which a cooking pot is placed. The fuel for these stoves is wood from the forest which surrounds the village. As a result of these cooking practices, indoor air quality is very poor and the time required to collect the wood fuel is significant. Studies show that indoor air pollution can cause serious health problems such as reduced birth weight, increased risk of chronic respiratory conditions, acute respiratory infections, and eye irritation and blindness [4] [5] [6]. Additionally, the time investment required for wood collection reduces the amount of time which these women could spend on educational, entrepreneurial, or other beneficial pursuits. By studying the emissions and performance of different cooking alternatives, a number of suitable designs can be introduced which will reduce health issues stemming from emissions exposure and reduce wood collection time either through improved cooker performance or increased use of alternative fuel sources such as manure or solar power.

3. Survey

This survey will provide information about current cooking practices, health, and other background information relevant to this project.

<u>Health</u>

These questions are intended to gather background information on the current health of those exposed to cooking emissions.

1. Do you wear any form of smoke protection such as a bandana?
2. Would you be willing to wear smoke protection?
3. Have you ever suffered eye or lung issues from smoke exposure?

<u>Fuel</u>

These questions are intended to gather information on current fuel use.

4. Do you dry firewood before using it? If so, for how long?
5. How much time per week do you spend collecting wood?

6. Have you ever made charcoal out of manure?
7. How much wood do you use per week for cooking?

Emissions and Exposure

These questions are intended to gather information on kitchen ventilation and the degree to which the women of Lesoit are exposed to cooking emissions.

8. How long do you spend cooking?
9. Are you continuously in front of the stove when cooking or do you walk away periodically?
10. Does your kitchen become visibly smoky when you cook?
11. Does the rest of the home become smoky when cooking?
12. Do you light fires for heat? If so how much wood do you go through per week for heating?
13. How many openings does your kitchen have?
14. Would you be open to the increased kitchen ventilation such as more openings or a cooking chimney/smoke hood?
15. How often do you cook indoors vs outdoors?

Experience

These questions are intended to help our group understand the previous experiences of the women of Lesoit with methods to reduce emissions exposure and improve health.

16. What time of day do you cook? Would you be open to cooking more during midday? (solar cookers)
17. How long does each meal take to cook on average?
18. Have you ever used an improved cookstove such as a jiko? If so what did you think of it?
19. What features would you like in a stove? Portability, ease of maintenance, ease of use, etc.
20. Have you ever used a solar cooker? If so, what did you think?

4. Materials

The cook stoves that will be tested will be made out of local materials available in the village of Lesoit. Local materials are ideal to the women, as they can buy them and build the stoves themselves. Durability is also considered when choosing the materials to ensure that they will last a long time. The Bill of Materials was created to be sure that every part needed for the stoves is accounted for. This helps the team to have a specific capital cost of each cook stove. The cost of some parts are not available in the United States but are to be obtained on the Tanzanian summer 2016 trip. Carbon Monoxide emissions testing tubes prices are also listed, and added to the Bill of Material to give the team a clear idea of how much the testing will cost.

Table 2: The bill of the materials used by the team

Alternatives and Testing material	Parts and devices needed	Quantity	Price ($)
Air quality testing	Gastec (Gas Sampling Pump)	1	N/A
	Glass tubes (Drager tubes) to test Carbon monoxide (CO)	20 testing Drager tubes	140,[7]
	Met One Model 212	1	N/A
Three stones stove	Wood	5 lb	(Tanzania)
	Base material	Three average to big size stones	N/A
Jiko stove	Jiko (The stove itself)	1	(Tanzania)
	Wood and manure	5 lb each	(Tanzania)
Gasification stove	Aluminum or steel or stainless steel	# ft^2 area and # ft thickness	(Tanzania)
	Wood and Manure	5 lb each	(Tanzania)
Rocket Stove	Aluminum or Steel	1 ft^2 area and 0.1in thickness	(Tanzania)
Solar stove	Reflector	1 Mylar Roll	30, [8]
	Absorber	One Copper pipe (Black Matte Paint)	15, [8]
	Design with Insulation	Wood	30, [8]
	Tracking system	2 of 5 watts solar panels	40, [8]

Air Quality Testing Materials

For the emissions testing, the group is going to test for particulate matter (PM), and carbon monoxide (CO). In order to conduct these tests successfully a particle counter is needed as well as the dragger pump and a dragger emissions testing tube. The particle counter that the group planning to use in Met One Model 212, which is available at Northern Arizona University (NAU) environmental engineering lab. The particles sizes that Met One can observe and count are between 0.5um to 10um [9]. Met One works using a laser-diode based optical sensor in order to observe the particular matter based on the ranges of sizes needed. The particle counter must be installed on a top of the tripod indoor or outdoor to collect the data needed. The Gastec GV-100/110 Gas Sampling Pump is the device that will be used to drag air into the dragger tube in order to test for specific emission like Carbon Monoxide [10]. It is available in the environmental engineering labs at NAU. The Drager tubes needed to test for CO are Dräger Tube Carbon Monoxide 2/A 2-300 ppm Draeger 6733051 to test for CO between the ranges of 2-300 ppm in concentrations and Dräger Tube Carbon Monoxide 5/C 5-700 ppm Draeger CH256016733051 to test for carbon monoxide between the ranges of 5-700 ppm in concentrations [11]. The tubes work by breaking the top and bottom glass ends then connecting the top end to the pump. After pulling air through the tube a change in color will occur indicating the concentration of carbon monoxide.

Figure 2: Gas Sampling Pump available at NAU environmental lab [10].

Figure 3: Drager glass tubes to test the concentrations of carbon monoxide [11].

Figure 4: Met One Model 212 [9].

5. Testing and Predictions

To understand which factors make a particular stove design effective, the team will use heat transfer equations to predict the performance of several improved cook stoves and compare the results to those obtained through testing and analysis. The team's findings will help future capstone teams develop and test improved cook stoves specifically suited for use in Lesoit, Tanzania.

5.1 Testing Protocol

Improved Cookstoves

The testing which will be used is “The Water Boiling Test version 4.2.3, Cookstove Emissions and Efficiency in a Controlled Laboratory Setting” [12]. Originally developed in 1982 by Volunteers in Technical Assistance, this protocol for testing stove performance has been updated several times by groups from UC Berkley, the Aprovecho Research Center, Engineers in Technical and Humanitarian Opportunities of Service, and the Global Alliance for Clean Cookstoves. This test has been used in a number of studies [13] [14] [15].

This test consists of three phases designed to obtain data which will allow for comparison between stoves and insight into stove performance in different circumstances. These phases are the cold start, hot start, and simmer. The cold start phase examines how well the stove performs in bringing room temperature water to boil when both pot and water begin at room temperature, while the hot start begins with room temperature water and a pre heated pot. The simmer tests how well the stoves perform in a function similar to real world cooking, by simmering water at $T_{simmer} = (T_{boil} – 3° C)$ for 45 minutes. For full instructions see pages 13-19 of the Water Boiling Test version 4.2.3 in appendix A, [12].

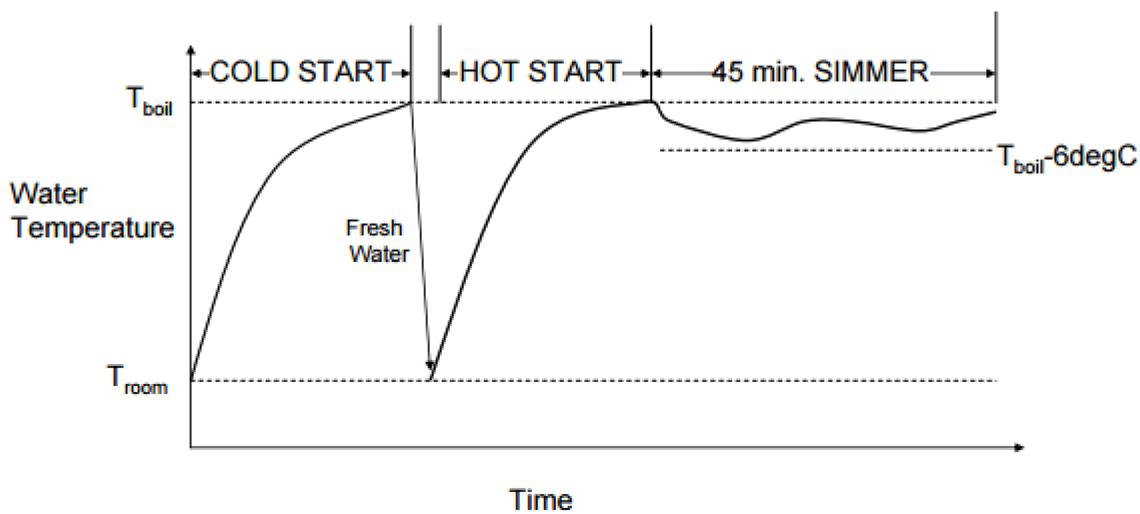
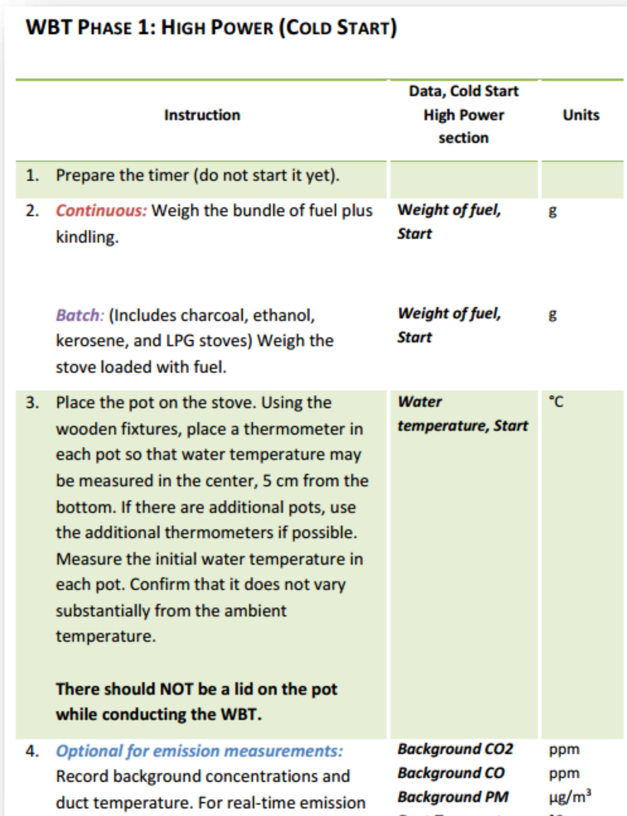


Figure 5: Water Boiling Test phases [12]

Items needed for this testing include stop watch, chemical hood, particle counter, carbon monoxide Drager tube, scale, fuel, oven for drying fuels to constant moisture content, thermometer, and pots of various sizes. Data including time to boil, initial mass of water, final mass of water, initial mass of fuel, final mass of fuel, mass of char/ash, initial water temperature, final water temperature, number of particles released, and carbon monoxide concentration will be collected and used to analyze the performance of each stove.



WBT PHASE 1: HIGH POWER (COLD START)

Instruction	Data, Cold Start High Power section	Units
1. Prepare the timer (do not start it yet).		
2. *Continuous:* Weigh the bundle of fuel plus kindling.	***Weight of fuel, Start***	g
Batch: (Includes charcoal, ethanol, kerosene, and LPG stoves) Weigh the stove loaded with fuel.	***Weight of fuel, Start***	g
3. Place the pot on the stove. Using the wooden fixtures, place a thermometer in each pot so that water temperature may be measured in the center, 5 cm from the bottom. If there are additional pots, use the additional thermometers if possible. Measure the initial water temperature in each pot. Confirm that it does not vary substantially from the ambient temperature. **There should NOT be a lid on the pot while conducting the WBT.**	***Water temperature, Start***	°C
4. *Optional for emission measurements:* Record background concentrations and duct temperature. For real-time emission	***Background CO2*** ***Background CO*** ***Background PM***	ppm ppm μg/m³

Figure 6: Water boiling test instructions [12]

Solar Stoves

The solar testing and performance standard ASAE S580.1 by the American Society of Agricultural and Biological Engineers will be used to evaluate and compare solar cookers [16]. To begin, each cooker will be loaded with an equal share of 7kg of potable water, which will be weighed to determine mass. Wind speed and air temperature will be recorded to ensure relative uniformity in testing conditions. Water temperature will be recorded at ten minute intervals in degrees Celsius for use in the power calculation explained in the following section. Stoves which are capable of sunlight tracking will be continually adjusted to receive maximum sun exposure. Testing will conclude when a minimum of six temperature recordings are made.

5.2 Efficiency and Emissions Analysis

The long term goal of the team is to ensure that the people of Lesoit have access to stoves which are safe and perform well. Toward this end, data from the testing outlined in the previous section will be analyzed by metrics from the Water Boiling Test 4.2.3 [12] which allow for stove comparison.

Improved Cookstoves

Emissions Analysis

Emissions testing will focus on carbon monoxide and particulate matter of 10 microns and smaller as they are primary contributors to cookstove emission related health problems [17]. For data collection in laboratory testing a carbon monoxide dragger tube and a particle counter will be used which will provide carbon monoxide concentration values and number of particles released. Field testing of carbon monoxide concentrations in Lesoit kitchens will also be conducted, and used to approximate particulate count as described in this study [18]. While equipment for field testing particles directly exists, it is outside the budget of this study.

The metrics which will be used to compare the stoves are as follows:

emissions/time – This will show us the rate at which each stove produces emissions. It is calculated by $\text{Concentration}_{CO}$/time for CO and (number of particles)/time for particulate matter.

emissions/$\text{mass}_{\text{fuel}}$ – This metric gives emissions relative to fuel. It is calculated by $\text{Concentration}_{Co}/(\text{mass}_{\text{fuel}})$ and (number of particles)/($\text{mass}_{\text{fuel}}$). Where $\text{mass}_{\text{fuel}} = \text{mass}_{\text{initial}} - \text{mass}_{\text{final}}$

Emissions/energydelivered – This metric gives emissions relative to the amount of energy actually delivered to the water or food. It is calculated by $Concentration_{Co}$/($energy_{delivered}$) and (number of particles)/($energy_{delivered}$). Where $energy_{delivered} = \Delta E_{H20} + \Delta E_{vap}$, ΔE_{H20} is the energy required to raise the temperature of the water and is equal to (specific heat of H_20)*($T_{final} - T_{initial}$)*($mass_{H20}$), and ΔE_{vap} is the energy required to vaporize water and is equal to (specific enthalpy of water at boiling)*($mass_{vap}$).

* For phase 1 and 2, ΔE_{vap} will equal zero as these phases end once the water reaches boiling point.

<u>Efficiency Analysis</u>

thermal efficiency = $energy_{delivered}/energy_{fuel}$ – This metric gives a value for the fraction of energy which goes into heating the water/food compared to the total amount of energy released from the fuel. It is calculated using $energy_{delivered} = \Delta E_{H20} + \Delta E_{vap}$ and $energy_{fuel} = (mass_{fuel})$*(Heating value of fuel). Where ΔE_{H20} is the energy required to raise the temperature of the water and is equal to (specific heat of H_20)*($T_{final} - T_{initial}$)*($mass_{H20}$), and ΔE_{vap} is the energy required to vaporize water and is equal to (specific enthalpy of water at boiling)*($mass_{vap}$).

fuel consumption rate = $mass_{fuel}$/time – This metric gives an understanding of how quickly each stove uses fuel, this is important because it will allow us to approximate how much fuel will be needed for daily cooking. Time is in seconds and $mass_{fuel} = mass_{initial} - mass_{final}$ where mass is in kilograms.

power = $energy_{delivered}$/time – Power will allow us to compare cookstove results to results obtained from solar cooker testing and analysis. Time is in seconds and $energy_{delivered} = \Delta E_{H20} + \Delta E_{vap}$, where ΔE_{H20} is the energy required to raise the temperature of the water and is equal to (specific heat of H_20)*($T_{final} - T_{initial}$)*($mass_{H20}$), and ΔE_{vap} is the energy required to vaporize water and is equal to (specific enthalpy of water at boiling)*($mass_{vap}$).

Solar Cooker

As solar cookers produce no emissions, only a performance analysis needs to be conducted. **Power = energy$_{delivered}$/time –** This is the primary performance parameter used in the ASAE S580.1 testing protocol [16]. It will allow for comparison to any other solar stoves and the tested improved cookstoves. It is calculated by (specific heat of H_20)*(T_{final} – $T_{initial}$)*($mass_{H20}$)/(600). This testing protocol measures temperature in 10 minute intervals, which leads to a time of 600 seconds. Further research will determine whether this power value needs to be standardized to a standard isolation.

5.3 Predictions

Equations to predict stove performance are outlined below, though further research will be conducted in the future to determine *all* of the necessary equations, as the current model may be incomplete. Additionally, factors such as stove dimensions and materials will need to be found once the test stoves are delivered.

Improved Stoves Predictions:

To predict the improved stove’s thermal efficiency, the combustion and heat transfer efficiencies are needed. $\eta_t = \eta_c \times \eta_h$

$$\eta_c = \frac{Mass\ of\ CO\ emmissions\ (g)}{Dry\ wood\ consumed\ (kg)}$$

The three modes of heat transfer -- conduction, convection, and radiation -- and the finite difference method in Matlab [19] will be used to obtain the heat transfer efficiencies for the improved cook stoves.

The three governing heat transfer equations are:

$$Q_{cond.} = \frac{k \cdot A \cdot \Delta T}{L} \rightarrow Conduction$$

$$Q_{conv.} = h \cdot A \cdot \Delta T \rightarrow Convection$$

$$Q_{rad} = A \cdot \sigma \cdot ({T_2}^4 - {T_1}^4) \rightarrow Radiation$$

The conduction heat transfer will be considered for the floor of the stove to the ground. The convection heat transfer will be considered for the inner surface of the stove (losses) and the outer surface of the pot (gains). The radiation heat transfer will be considered between the flames and the stove.

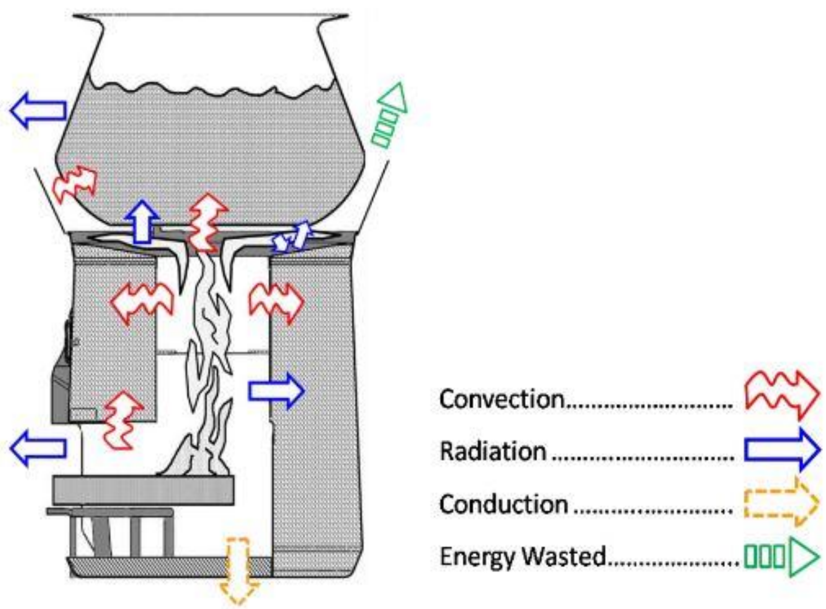


Figure 7: Heat transfer modes schematic on improved cook stoves [19].

To obtain the heat transfer efficiency, heat transfer modes schematics similar to the one above (Figure 7) are needed for all of the improved stoves which will be considered. Additionally, the three heat transfer mode equations will be needed, and they will be implemented with the finite difference method in Matlab [20].

<u>Solar Stoves Predictions:</u>

The solar stove predictions will be used to compare the different solar stove designs. Performance of the solar stoves will be compared based on the time to heat equation from initial and final temperatures. The time to heat equation and components are:

$$t_{heat} = \frac{-1}{K_2} \ln\left(1 - \frac{K_2}{K_1} \Delta T\right)$$

$$K_1 = \frac{I \cdot \eta_o \cdot A}{m \cdot c_p}$$

$$K_2 = \frac{k \cdot A}{m \cdot c_p}$$

For these equations, the I is the radiation from sunlight, the η_o is the optical efficiency, the A is the collector aperture area, the m is the mass in the pot, the c_p is the specific heat capacity at a constant pressure, and the k is the thermal conductivity. Direct Solar radiation will be used for the radiation for a concentrated solar collector and global solar radiation will be used for the flat solar collector [21].

6. Proposed Design Alternatives to the Stoves

Based on biomass stove and solar cooker research, four designs were chosen for testing, analysis, and comparison with analytical predictions. Each of these designs have characteristics which are likely to make them suited for use in Lesoit, Tanzania.

6.1 Jiko stove:

The jiko is an hourglass shaped metal and ceramic charcoal stove. The stove was designed to be similar to the traditional Kenyan stoves it was intended to replace, a fact which may contribute to its popularity [22]. More than 125,000 jiko stoves are in use in Kenya [23]. The jiko consumes 25% - 40% less charcoal than traditional Kenyan stoves. As charcoal stoves typically have a cleaner emissions profile [24] and the people of Lesoit are familiar with both this stove and charcoal production, this efficient design may be beneficial.

Figure 8: Jiko Stoves [25]

6.2 Gasification stove:

A gasifying stove takes advantage of a process called gasification to produce higher combustion temperatures and a more complete combustion of particulate matter. Gasification is a process wherein fuel is heated to temperatures between 600 ° C – 1500 ° C with limited amounts of oxygen to produce a "syngas" with a heating value of 3.5 - 7.8 MJ/Nm^3 (air gasification) which is composed primarily of hydrogen and carbon monoxide [26]. In gasifying stoves, this syngas is combined with oxygen at the top of the combustion chamber, where it is combusted to produce heat. This technology is promising as basic gasifying stove designs are simple to manufacture and operate, and studies have shown decreased emissions and increased fuel efficiency [27].

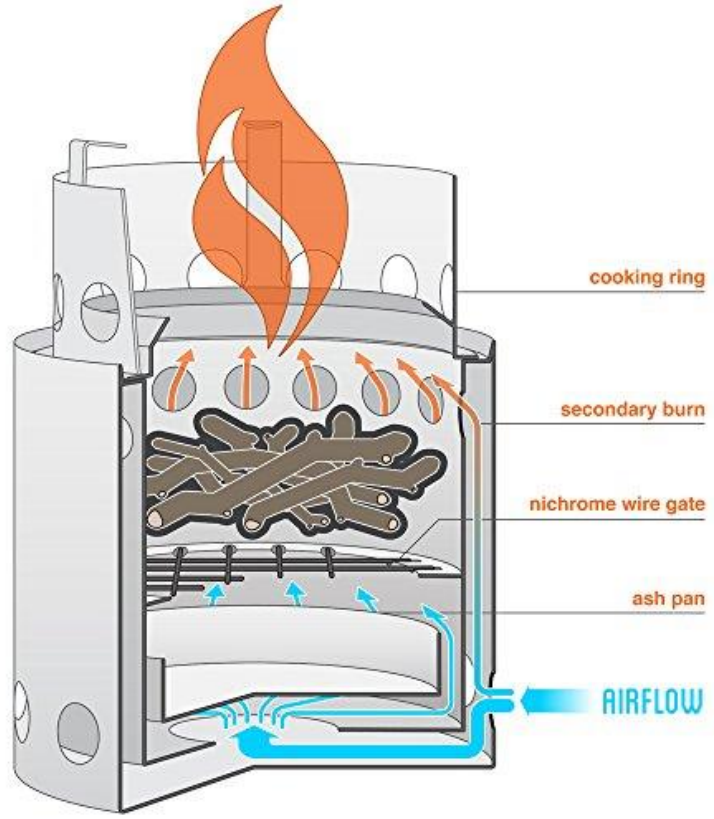


Figure 9: Commercially available gasifying stove, the Solo Stove [28]

6.3 Rocket stove:

Rocket stoves increase fuel efficiency and decrease emissions by using an insulated combustion chamber which is vertically oriented and designed to allow maximum oxygen presence during combustion. If oxygen presence is low, un-combusted particulate matter is emitted. These particles are a primary contributor to health issues caused by prolonged exposure to combustion emissions, and reduce fuel efficiency by consuming fuel without combusting and contributing to the heat needed to cook [29]. The rocket stove is designed to utilize the low pressure zone above the combustion chamber to pull air into and through the combustion chamber, reducing un-combusted particles and increasing efficiency [30].

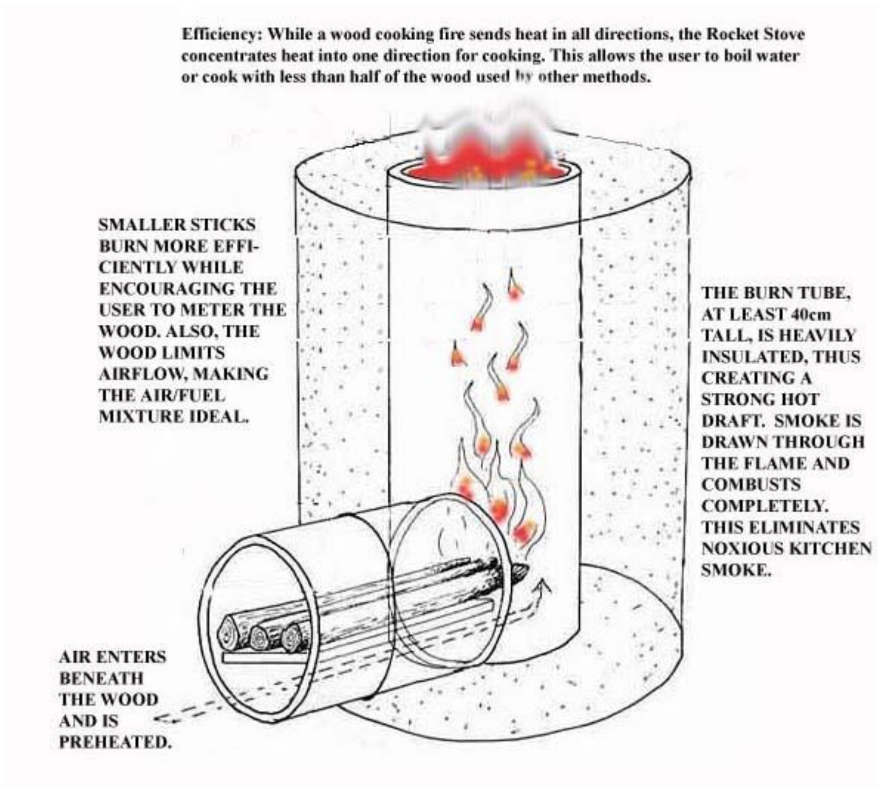


Figure 10: Sketch of a Rocket Stove, Trey Morrison [31].

6.4 Direct Solar Cooker

These cookers reflect and concentrate the heat of the sun onto a cooking apparatus to produce enough heat to cook food. As there is no combustion, emissions are not produced, and the use of the sun’s energy eliminates the need for fuels such as wood or manure [32]. This reduced fuel need helps to satisfy a goal of this project, which is to reduce the time villagers spend collecting firewood so that they may pursue economic or educational opportunities. Direct solar cookers require direct sunlight, and so cannot be used indoors or at night. Despite this, the clear advantages of this technology may prompt a combined solution wherein solar cookers are utilized in conjunction with alternatives which can be used indoors and at night.

Figure 11: Cylindrical solar cooker, the Go Sun Stove [33].

7. Project Management

In order for the team to be organized and ensure that all tasks are completed on schedule, a Gantt chart and a Project Plan were made (see appendix B). The team set up two major goals for the second semester, with one being predicting cooker performance and emissions, and the other being completion of testing and analysis. Due to the lack of emissions with the solar stoves, there will be only efficiency testing to compare it with the improved cook stoves. The improved cook stoves emission tests consist of testing for Carbon Monoxide (CO), and Particulate Matter (PM) to determine the cleanest stove of the four. After completing these goals, the team will focus on making a PowerPoint presentation in preparation for the UGrads symposium. Finally, the team will combine all predictions, testing, and other relevant information regarding the research project into a single document as a final draft. The draft will be checked and revised before being submitted as a final research report. All of the tasks and dates of submissions are listed in the Gantt chart.

8. Conclusion

The goal of this semester was to determine the tasks and plan for next semester which will be necessary to complete a research paper comparing mathematical predictions on cooker performance with results obtained through testing on these parameters. These predictions will be made using the three heat transfer mode equations and the finite difference method in Matlab. The testing protocol and analysis procedure will be that used in the Water Boiling Testing version 4.2.3. The improved cookstoves which will be tested are the Rocket Stove, Gasification Stove, Direct Solar Stove, Jiko stove, and the three-stove stove which is currently in use in Lesoit. The team's findings will help future capstone teams develop and test improved cook stoves and solar cookers which will reduce harmful cooking emissions, reduce wood collection time, and provide economic opportunity for the women of Lesoit, Tanzania.

9. References

[1] National Bureau of Statistics Ministry of Finance, "KEY FINDINGS 2011/12 HOUSEHOLD BUDGET SURVEY," November 2013, [Online], Available: http://www.nbs.go.tz/nbstz/index.php/english/statistics-by-subject/household-budget-survey-hbs/366-2011-12-household-budget-survey-hbs-key-findings-report. [Accessed: 12-May-2016].

[2] British Broadcasting Corporation, “Weather in Dar Es Salam”, 2016. [Online]. Available: http://www.bbc.com/weather/160263 [Accessed: April-04-2016].

[3] College of Engineering, Forestry, and Natural Sciences NAU, “Development for Rural Sustainability”, 2015, [Online], Available: http://www.cefns.nau.edu/capstone/projects/EGR/2015/TanzaniaWaterAssessment/tanzania.png. [Accessed: 12-May-2016].

[4] E. Boy, N. Bruce and H. Delgado, "Birth Weight and Exposure to Kitchen Wood Smoke During Pregnancy in Rural Guatemala", *Environ Health Perspect*, vol. 110, no. 1, pp. 109-114, 2001.

[5] M. Ezzati and D. Kammen, "Indoor air pollution from biomass combustion and acute respiratory infections in Kenya: an exposure-response study", *The Lancet*, vol. 358, no. 9282, pp. 619-624, 2001.

[6] V. Mishra, R. Retherford and K. Smith, "Biomass cooking fuels and prevalence of blindness in India", *Journal of Environmental Medicine*, vol. 1, no. 4, pp. 189-199, 1999.

[7] Drager Safety USA. , “Tubes | Tubes - C to E,”, 2016, [Online]. Available at: http://www.dragersafetyusa.com/c-307-tubes-c-to-e.aspx. [Accessed: 12-May-2016].

[8] The Home Depot. “Home Improvement Made Easy with New Lower Prices | Improve & Repair,”, 2016, [Online], Available at: http://www.homedepot.com/?cm_mmc=sem|g|bt1. [Accessed: 12-May-2016].

[9] Met One Instruments, “Model 212 Eight Channel Particle Counter,” 2016, [Online]. Available at: http://www.metone.com/particulate-aero212.php. [Accessed: 12-May-2016].

[10] EQUIPCO Sales & Service Corp. “GV-100/110 Gas Sampling Pump by Gastec - Gastec Hand Pump - Best Price Guarantee, 2016, [Online], Available at: http://www.equipcoservices.com/sales/gastec/gas_detection_tube_pump.html. [Accessed: 12-May-2016].

[11] Cross Instrumentation, “Draeger Tubes - Carbon Monoxide”, 2016, [Online]. Available at: http://www.buydraegertubes.com/carbonmonoxide5c.aspx. [Accessed: 12-May-2016].

[12] M. Johnson, T. Bond, C. Roden, N. MacCarty, et al, “The Water Boiling Test: Cookstove Emissions and Efficiency in a Controlled Laboratory Setting”, Standards and Testing, Vol 4.3, no. 2, pp 1-89, 2014

[13] J. MCCRACKEN and K. SMITH, "Emissions and efficiency of improved woodburning cookstoves in Highland Gatemala", Environment International, vol. 24, no. 7, pp. 739-747, 1998.

[14] N. MacCarty, D. Still and D. Ogle, "Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance", Energy for Sustainable Development, vol. 14, no. 3, pp. 161-171, 2010.

[15] G. Ballard-Tremeer and H. Jawurek, "Comparison of five rural, wood-burning cooking devices: Efficiencies and emissions", Biomass and Bioenergy, vol. 11, no. 5, pp. 419-430, 1996.

[16] American Society of Agricultural and Biological Engineers, “Testing and Reporting Solar Cooker Performance”, *ASABE Standards,* ASAE S580.1, pp 1-6, 2013

[17] A. Cynthia, R. Edwards, M. Johnson, M. Zuk, L. Rojas, R. Jiménez, H. Riojas-Rodriguez and O. Masera, "Reduction in personal exposures to particulate matter and carbon monoxide as a

result of the installation of a Patsari improved cook stove in Michoacan Mexico", *Indoor Air*, vol. 18, no. 2, pp. 93-105, 2008

[18] L. Naeher, K. Smith, B. Leaderer, L. Neufeld and D. Mage, "Carbon Monoxide As a Tracer for Assessing Exposures to Particulate Matter in Wood and Gas Cookstove Households of Highland Guatemala", *Environmental Science & Technology*, vol. 35, no. 3, pp. 575-581, 2001

[19] E. Yuntenwi, N. MacCarty, D. Still and J. Ertel, "Laboratory study of the effects of moisture content on heat transfer and combustion efficiency of three biomass cook stoves", *Energy for Sustainable Development*, vol. 12, no. 2, pp. 66-77, 2008.

[20] D. Zube, "HEAT TRANSFER EFFICIENCY OF BIOMASS COOKSTOVES", *colostate*, 2010. [Online]. Available: http://dspace.library.colostate.edu/webclient/DeliveryManager/digitool_items/csu01_storage/2011/02/21/file_1/88698. [Accessed: 12-May-2016].

[21] K. Schwarzer and M. da Silva, "Characterisation and design methods of solar cookers", *Solar Energy*, vol. 82, no. 2, pp. 157-163, 2008.

[22] H. Allen, *The Kenya ceramic jiko*. London, UK: Intermediate Technology Publications in association with Appropriate Technology International and CARE, 1991.

[23] E. Hyman, "The strategy of production and distribution of improved charcoal stoves in Kenya", *World Development*, vol. 15, no. 3, pp. 375-386, 1987.

[24] N. Kim Oanh and N. Dung, "Emission of Polycyclic Aromatic Hydrocarbons and Particulate Matter from Domestic Combustion of Selected Fuels", *Environmental Science & Technology*, vol. 33, no. 16, pp. 2703-2709, 1999.

[25] English language, “Kenya Ceramic Jiko,” Kenya Ceramic Jiko. America Pink, 2016, [Online]. Available at: http://america.pink/kenya-ceramic-jiko_2416993.html. [Accessed: 12-May-2016].

[26] S. Sadaka, A. Ghaly and M. Sabbah, "Two phase biomass air-steam gasification model for fluidized bed reactors: Part I—model development", *Biomass and Bioenergy*, vol. 22, no. 6, pp. 439-462, 2002.

[27] G. Kornelius et al., "A wood gasification stove for domestic use: Design, performance and emission factors.", *Clean Air Journal*, vol. 22.2, pp. 16-20, 2012.

[28] Amazon.com, Inc. “Solo Stove & Pot 900 Combo: Ultralight Wood Burning Backpacking Cook System. Lightweight Kitchen Kit for Backpacking, Camping, Survival. Burns Twigs, No Batteries or Liquid Fuel Gas Canister Required,” Amazon: Sports & Outdoors, 2016, [Online]. Available at: http://www.amazon.com/solo-stove-pot-900-combo/dp/b008w0mjju. [Accessed: 12-May-2016].

[29] N. MacCarty, and D. Still, "Assessing Cook Stove Performance: Field and Lab Studies of Three Rocket Stoves Comparing the Open Fire and Traditional Stoves in Tamil Nadu, India on Measures of Time to Cook, Fuel Use, Total Emissions, and Indoor Air Pollution", *Aprovecho Research Center*, Cottage Grove, 2016.

[30] Ashden Trust, “Rocketstove Design Base “, 2016, [Online], Available: http://www.rocketstove.org/. [Accessed: 12-May-2016].

[31] Paul Wheaton permaculture, “Rocket Stove & Oven Design,” permies, homesteading and permaculture, 2016. [Online]. Available at: http://www.permies.com/t/50968/rocket-stoves/rocket-stove-oven-design. [Accessed date: 12-05-2016].

[32] Solar Cookers, “Types and Styles", 2016. [Online]. Available: http://www.solarcooker-at-cantinawest.com/solarcookers-types.html. [Accessed: 12-May-2016].

[33] GoSun Stove, “With Solar Cooking it's all about GREAT FOOD NATURALLY!”, Solar Cooker at Cantina west, 2016. [Online]. Available: http://www.solarcooker-at-cantinawest.com. [Accessed: 12-May-2016].

10. Appendices

10.1: Appendix A

E. Instructions for WBT Phases

Remaining data for the three phases of the test should be recorded on the Test Entry form. The stove should begin at room temperature.

WBT Phase 1: High Power (Cold Start)

Instruction	Data, Cold Start High Power section	Units
1. Prepare the timer (do not start it yet).		
2. *Continuous:* Weigh the bundle of fuel plus kindling.	***Weight of fuel, Start***	g
Batch: (Includes charcoal, ethanol, kerosene, and LPG stoves) Weigh the stove loaded with fuel.	***Weight of fuel, Start***	g
3. Place the pot on the stove. Using the wooden fixtures, place a thermometer in each pot so that water temperature may be measured in the center, 5 cm from the bottom. If there are additional pots, use the additional thermometers if possible. Measure the initial water temperature in each pot. Confirm that it does not vary substantially from the ambient temperature. **There should NOT be a lid on the pot while conducting the WBT.**	***Water temperature, Start***	°C
4. *Optional for emission measurements:* Record background concentrations and duct temperature. For real-time emission measurements, begin recording the particulate matter measurement. For filter-based measurements, turn on flow to the particulate matter filter. Begin recording the emission measurement for CO and CO2.	***Background CO2*** ***Background CO*** ***Background PM*** ***Duct Temperature*** *Real-time emission measurements recorded by emissions equipment*	ppm ppm µg/m^3 °C

Continuous Measurement of Temperature: *The water temperature may be continuously recorded if a device is available to do so.*

Lids: *While a lid helps to retain heat and is often used in actual cooking tasks, it does not affect the transfer of heat from the stove to the pot. Lids may increase the variability of the WBT results, making it harder to compare results from different tests.*

5. Start the fire in a reproducible manner according to local practices. (This procedure should be documented.)		
6. Once the fire has caught, start the timer and record the starting time. Bring the first pot rapidly to a boil without being excessively wasteful of fuel using wood from the pre-weighed bundle. Control the fire with the means commonly used locally. (This procedure should be documented.)	***Time, Start***	hr:min
7. When the water in the first pot reaches the pre-determined local boiling temperature as shown by the digital thermometer, rapidly do steps 7.a – 7.f.		
a. Record the time at which the water in the primary pot (Pot # 1) first reaches the local boiling temperature. Record this temperature also.	***Time, Finish*** ***Water temperature, Finish***	hr:min °C
b. *Optional for emission measurements:* Turn off flow to the particulate matter filter (for filter-based measurements). Remove and properly store filter and then replace filter.		
c. *Continuous:* Remove all wood from the stove and extinguish the flames. Flames can be extinguished by blowing on the ends of the sticks or placing them in a bucket of ash or sand; do not use water – it will affect the weight of the wood. Knock all loose charcoal from the ends of the wood into the container for weighing charcoal. Weigh the unburned wood removed from the stove together with the remaining wood from the pre-weighed bundle. Extract all remaining charcoal from the stove. Weigh this remaining charcoal with the charcoal that was knocked off the sticks.	 ***Weight of fuel, Finish*** ***Weight of charcoal+container, Finish***	 g g g

Emissions During Fuel Measurements: *This procedure is not included in the emission measurement because it is not part of normal operation.*

Alternative Method to Weigh Charcoal: *If your scale can handle the weight of the stove, then you can weigh the whole stove with the charcoal rather than removing the charcoal.*

	Batch: Remove all the remaining from the stove and extinguish the flames. Carefully separate the charcoal and the wood and weigh them separately.	***Weight of fuel, Finish.*** ***Weight of charcoal, Finish***	g
d.	For multi-pot stoves, measure the water temperature from each pot (the primary pot should be at the boiling point).	***Water temperature, Pot #2 – 4, Finish***	°C
e.	Weigh each pot, with its water.	***Weights of Pot with water, Finish***	g
f.	Discard the hot water.		

This completes the high power cold-start phase. Next, begin the high power-hot start phase, immediately while the stove is still hot. *Be careful not to burn yourself!*

Alternative Methods to Charcoal Measurements for Batch-bed Stoves: *In previous versions, the charcoal was not weighed separately. Reflecting the recommendation from several commenters, these instructions have been modified to better account for remaining wood and charcoal. Procedures for batch-fed stoves are being developed including methodology to properly account for energy and carbon remaining. Alternatively, the remaining fuel can be ground to be made more uniform, and then analyzed for heating value and carbon content.*

WBT PHASE 2: HIGH POWER (HOT START)

Instruction	Data, Hot Start High Power section	Units
1. Reset the timer (do not start it yet).		
2. If the pot for the hot start phase has not been prepared in advance, refill the pot with 5 (or 2.5) kg of fresh ambient-temperature water. Weigh the pot (with water) and measure the initial water temperature. For multi-pot stoves, fill the additional pots, weigh them and record their weights.	***Weight of pot(s) with water, Start***	g
3. *Continuous:* Record the weight of the second bundle of fuel plus kindling.	***Weight of fuel, Start***	g
Batch: Weigh the stove loaded with fuel.	***Weight of fuel, Start***	g
4. Place the pot on the stove and replace the thermometer in the pot. Measure the initial water temperature in each pot. Confirm that it does not vary substantially from the ambient temperature.	***Water temperature, Start***	°C
5. *Optional for emission measurements:* For filter-based measurements, turn on flow to the particulate matter filter.	*Real-time emission measurements recorded by emissions equipment*	
6. Start the fire using fuel from the second pre-weighed bundle designated for this phase of the test. Follow the ignition procedure used in Phase 1.		

Continuous Measurement of Temperature: *The water temperature may be continuously recorded if a device is available to do so.*

7. Once the fire has caught, start the timer. Record the starting time. Bring the first pot rapidly to a boil without being excessively wasteful of fuel using wood from the second pre-weighed bundle. Control the fire using the procedure used in Phase 1.	***Time, Start***	hr:min
8. When the water in the first pot reaches the pre-determined local boiling temperature as shown by the digital thermometer, rapidly do steps 8.a – 8.e.		
a. Record the time at which the water in the primary pot (Pot # 1) first reaches the local boiling temperature. Record this temperature also.	***Time, Finish*** ***Water temperature, Finish***	hr:min °C
b. *Optional for emission measurements:* Turn off flow to the particulate matter filter (for filter-based measurements). Remove and properly store filter and then replace filter.		
c. *Continuous:* Remove all wood from the stove and extinguish the flames. Knock all loose charcoal from the ends of the wood into the combustion area (you will not weigh the charcoal at this stage). Weigh the unburned wood removed from the stove together with the remaining wood from the second pre-weighed bundle. *Batch:* Weigh the stove loaded with fuel. Record zero for the weight of charcoal.	 ***Weight of fuel, Finish*** ***Weight of fuel, Finish.*** ***Weight of charcoal = 0, Finish***	 g g g
d. For multi-pot stoves, measure the water temperature from each pot (the primary pot should be at the boiling point).	***Water temperature, Pot #2 – 4, Finish***	°C
e. Weigh each pot, with its water.	***Weights of Pot with water, Finish***	g
9. Return the unburned wood to the stove. Proceed immediately with the low power test.		

Speed and Safety: *Speed and safety are important during Step 8 because the water temperature should stay as close as possible to boiling in order to proceed directly to the simmer phase. The pot of hot water may be temporarily covered with a lid and placed on a hot plate (if available).*

Multi-pot Stoves: *Final temperature and weight of additional pots may be recorded. However, metrics to evaluate energy delivered to additional pots need to be more fully developed. See discussion of multi-pot stove testing in Appendix 2 and the discussion of additional metrics in Appendix 8.*

WBT PHASE 3: LOW POWER (SIMMERING)

This portion of the test is designed to test the ability of the stove to shift into a low power phase following a high-power phase in order to simmer water for 45 minutes using a minimal amount of fuel. For multi-pot stoves, only the primary pot will be assessed for simmering performance.

Instruction	Data, Simmer Test section	Units
1. Reset the timer (do not start it yet).		
2. Record the weight of the pot with water.	***Weight of pot with water, Start***	g
3. *Continuous:* Record the weight of fuel remaining from the hot start high power phase plus the third bundle of fuel plus kindling.	***Weight of fuel, Start***	g
Batch: Record the weight of the stove loaded with fuel remaining from the hot start high power phase	***Weight of fuel, Start***	g
4. Relight the hot wood that was replaced. Follow the ignition procedure used in Phase 1.		
5. *Optional for emission measurements:* For filter-based measurements, turn on flow to the particulate matter filter.	*Real-time emission measurements recorded by emissions equipment*	
6. Once the fire has caught, reset and start the timer. Record the starting time.	***Time, Start***	hr:min
7. Place the pot on the stove and replace the thermometer in the pot.		

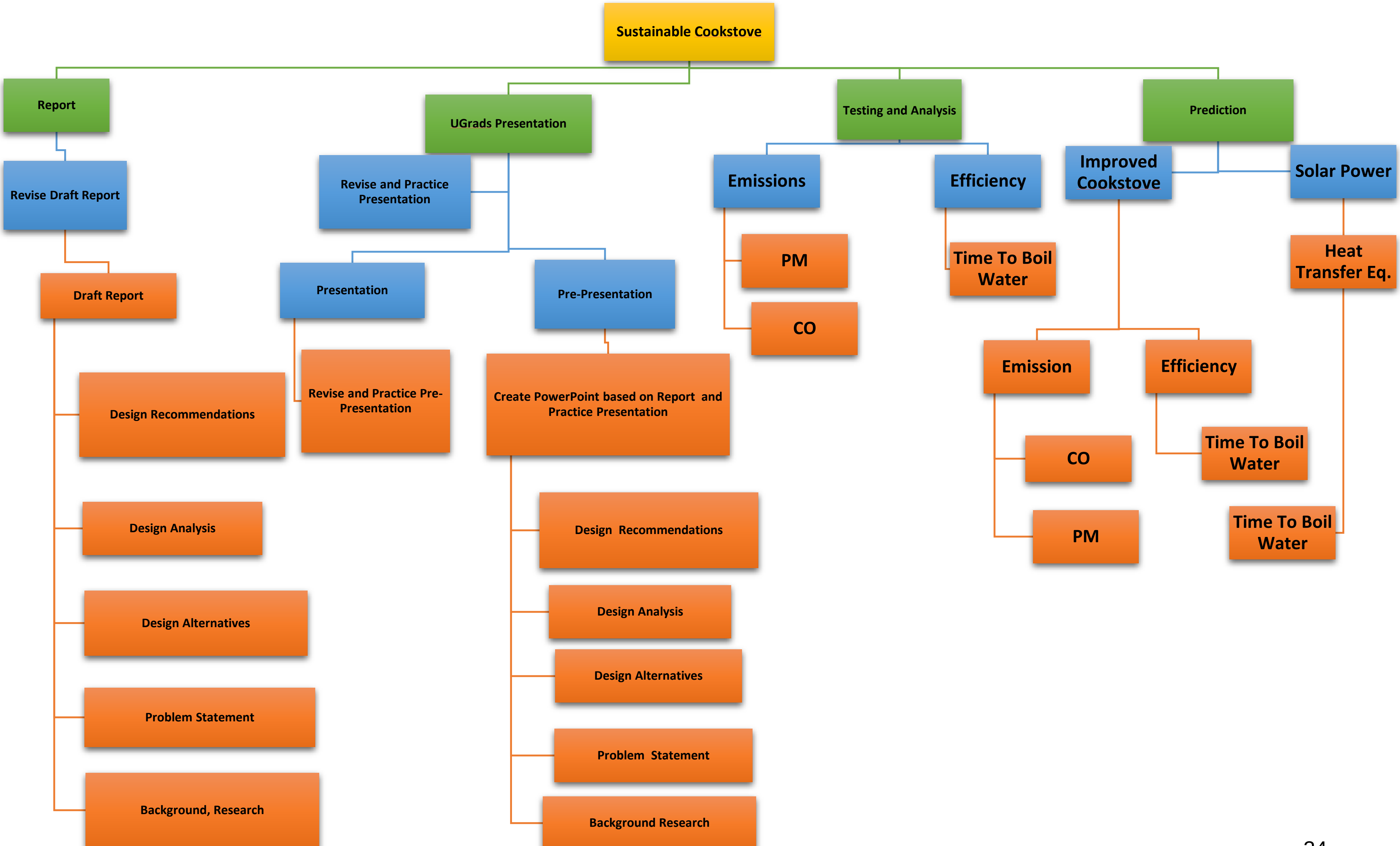
8.	For 45 minutes maintain the fire at a level that keeps the water temperature as close as possible to 3 degrees below the boiling point. The test is invalid if the temperature in the pot drops more than 6°C below the local boiling temperature.		
9.	After 45 minutes rapidly do steps 6.a – 6.d:		
a.	Record the time. Record the final water temperature – it should still be about 3 °C below the established boiling point.	***Time, Finish*** ***Water temperature, Finish***	g °C
b.	*Optional for emission measurements:* Turn off flow to the particulate matter filter (for filter-based measurements). Remove and properly store filter.		
c.	*Continuous:* Remove all wood from the stove and extinguish the flames. Knock all loose charcoal from the ends of the wood into the charcoal container.		
	Weigh the unburned wood removed from the stove together with the remaining wood from the second pre-weighed bundle.	***Weight of fuel, Finish***	g
	Extract all remaining charcoal from the stove. Weigh this remaining charcoal with the charcoal that was knocked off the sticks.	***Weight of charcoal+container, Finish***	g
	Batch: Remove all the remaining from the stove and extinguish the flames. Carefully separate the charcoal and the unburned wood and weigh them separately.	***Weight of wood, Finish*** ***Weight of charcoal+container, Finish***	g g
d.	Weigh the pot with the remaining water.	***Weight of pot with water, Finish***	g

Maintaining Temperature: *Many stoves lack adequate turndown ability, which makes it difficult to maintain the desired temperature without the fire going out (especially after the initial fuel load has been consumed). In this case, use the minimum amount of wood necessary to keep the fire from dying completely. Water temperatures in this case will be higher than 3° below boiling, but the test is still valid. The tester should not attempt to reduce power by splitting the wood into smaller pieces.*

Alternative Methods to Charcoal Measurements for Batch-bed Stoves: *In previous versions, the charcoal was not weighed separately. Reflecting the recommendation from several commenters, these instructions have been modified to better account for remaining wood and charcoal. Procedures for batch-fed stoves are being developed including methodology to properly account for energy and carbon remaining. Alternatively, the remaining fuel can be ground to be made more uniform, and then analyzed for heating value and carbon content.*

10.2: Appendix B

Project Plan



Gantt chart

Task	Name	Assigned Party	Begin date	End date
1	Prediction	Fahad	8/30/16	10/7/16
1.1	Emission Testing	Rawan	8/30/16	9/5/16
1.2	Efficiency Testing	James	9/5/16	9/20/16
1.3	Compile Testing Results	Mohammed	9/20/16	10/7/16
3	Testing	Group	10/10/16	11/11/16
3.1	Emission Testing	Fahad	10/10/16	10/20/16
3.2	Efficiency Testing	James	10/20/16	10/28/16
3.3	Compile Testing and Results	Group	10/31/16	11/11/16
4	UGrads Presentation	Group	11/11/16	12/1/16
4.1	Revise and Practice Presentation	Group	11/11/16	12/1/16
4.1.1	Pre-Presentation	Ibrahim	11/11/16	11/30/16
4.1.2	Create PowerPoint on report	Rawan	11/11/16	11/30/16
4.1.3	Background Research	Ibrahim	11/11/16	11/20/16
4.1.4	Problem Statement	Rawan	11/11/16	11/20/16
4.1.5	Design Recomendations	Ibrahim	11/11/16	11/25/16
4.1.6	Design Analysis	Fahad	11/11/16	11/28/16
4.1.7	Design Alternatives	Ibrahim	11/11/16	11/30/16
4.2	Presentation	Group	11/25/16	12/1/16
4.2.1	Revise/Practice Pre-Present...	Group	11/25/16	12/1/16
5	Report	Group	11/7/16	12/15/16
5.1	Revise Draft Report	James	11/7/16	11/21/16
5.2	Final Report	Fahad	12/1/16	12/15/16
5.2.1	Background, Research	Ibrahim	12/1/16	12/5/16
5.2.2	Problem Statement	Rawan	12/1/16	12/5/16
5.2.3	Design Recommendations	Ibrahim	12/1/16	12/14/16
5.2.4	Design Analysis	James	12/1/16	12/15/16
5.2.5	Design Alternatives	Fahad	12/5/16	12/15/16