Predictions, Testing, and Analysis of Cook Stoves for Women in Rural Africa

EGR 486

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1.0 Executive Summary

Women in rural areas of Africa spend large amounts of time collecting fuel for cooking and heating. They are also exposed to harmful emissions during the many hours spent as the primary cooks. For these reasons, the goals of this project were to understand the principles of heat transfer responsible for improving cook stove performance, to evaluate two common cook stoves using two common fuels, and to create a foundation of understanding and methods for future teams to develop and proliferate improved cook stoves. A total of nine primary tests were conducted to determine the major performance parameters of power, efficiency, and particulate matter emissions. These tests were conducted using the Jiko stove and the Three-stone stove with fuels of wood and team-made charcoal. The results of these tests showed that the Jiko stove was far more efficient, powerful, and clean-burning than the Three-stone stove. They also showed that charcoal in the Jiko produced the fewest emissions, but had slightly lower power than Jiko with wood. Finally, the tests showed that increased air flow rate through the system drastically increased power, but slightly reduced efficiency. The predictive analysis mirrored these power and efficiency findings, but had a moderate margin of error associated with the first order nature of the analysis. It is recommended that future teams explore the production of charcoal from alternative sources such as cow manure, test for Carbon Monoxide and Nitrous Dioxide as well as particulate matter, test additional cook stove designs, utilize remote probe thermometers in testing, and conduct tests in a controlled environment to reduce uncertainty associated with ambient temperature and wind conditions.

2.0 Introduction

The basic background of our project is that our client is the women who live in the rural areas of Africa. This client has been targeted because these women represent the part of society which spend many hours of their time collecting wood and cooking. These women's health is negatively affected by the harmful emissions they’re exposed to during cooking and the hours spent collecting wood preclude them from engaging in financially beneficial endeavors [1] [2] [3]. The team made performance predictions and conducted testing and analysis on two different stoves using two different fuels to determine thermal performance and emissions and better understand the underlying principles affecting these factors.

There are many different cooking techniques and stoves being used in the rural areas of Africa. The 3-stone and the Jiko are two of the most common [4]. They are typical in these areas because they are readily available, inexpensive, easy to maintain, and portable. Woman in rural Africa also tend to cook inside as well as outside so having a portable stove is ideal. The three-stone stove is very simple, it is created by arranging three stones together in a ring with fuel in the middle, giving a place for the pot to rest atop the rocks. The three-stone stove has no cost and provides thermal storage for cooking over long periods. The Jiko is an advanced cook stove which features an hour glass shaped clay body, a metal exterior, and air holes underneath the fuel to encourage strong airflow. It is widely available and thought to be more efficient than the traditional three stone stove.

3.0 Methods

3.1 Primary Testing

The testing protocol was inspired by the Water Boiling Testing version 4.2.3 [5]. The steps of testing protocol are as follows.

1. Fill the pot with approximately 3 liters of water and weigh.
2. Weigh the fuel.
3. Place fuel in stove.
4. Place the particle counter over the stove
5. Weigh lighter fluid (butane)
6. Apply lighter fluid to the base of the fuel
7. Weigh liter fluid to determine mass of fluid used
8. Record initial temperature of water

9. Prepare timer
10. Light fuel
11. Place pot on stove
12. Start timer
13. Start particle counter
14. Record temperature at 3 minute intervals
15. Record particle numbers at 3 minute intervals
16. When temperature changes start decreasing, cease test
17. Stop particle counter
18. Remove and weigh pot
19. Collect and extinguish fuel by depriving of oxygen
20. Weigh fuel

3.2 Rice Testing

An additional test was conducted in Flagstaff and Phoenix to determine the effect of altitude on cooking time. The steps of this test are as follows.

1. Fill the pot with approximately 0.5 liters water and weigh
2. Weigh the fuel
3. Place fuel in stove
4. Weigh the lighter fluid
5. Apply the lighter fluid to the base of the fuel
6. Weigh the lighter fluid to determine mass of fluid used
7. Prepare timer
8. Light Fuel
9. Place pot on stove
10. Start timer

11. Place 1 cup of rice into the water
12. Starting at 10 minutes, remove 1 teaspoon of rice every 1 minute and check for doneness
13. When rice is considered done, cease test

3.3 Charcoal Production

Maple wood was used to make the charcoal because it is considered a hard wood, which is ideal for charcoal production. The steps used to make charcoal are as follows.

1. Acquire metal bin and drill an approximately 0.5 in hole.
2. Weigh a bundle of wood and place into bin
3. Cover Bin with aluminum foil
4. Place bin aluminum side down into fire pit
5. Weigh additional wood
6. Place additional wood densely around metal bin
7. Apply lighter fluid to the base of the wood surrounding bin
8. Light the surrounding wood in multiple places
9. After approximately 1.5 hours, remove surrounding wood
10. Wait for bin to cool
11. Remove charcoal from bin

Note that larger quantities of wood require more time to be turned into charcoal. To record emissions of this process, utilize a particle counter in the same manner described in section 3.1.

4.0 Results

4.1 Thermal Results

Temperature vs Time data was used to create plots for each of the tests. Figures 1 and 2 show these plots for tests 2 and 3 – wood in the Jiko and charcoal in the Jiko, respectively. The temperature vs time plots for the remaining 7 tests can be seen in appendix A.

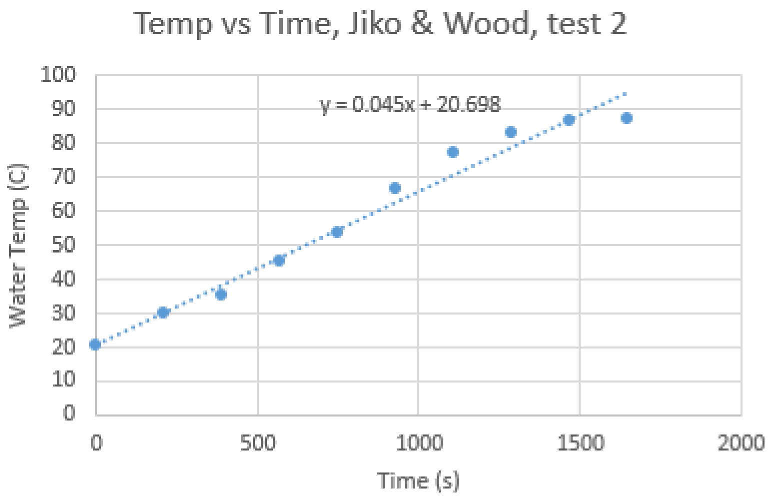


Figure 1: Temperature vs Time, test 2

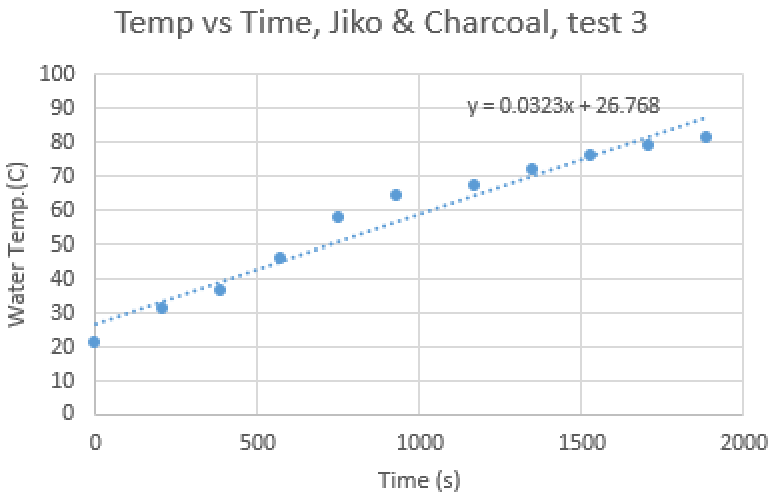
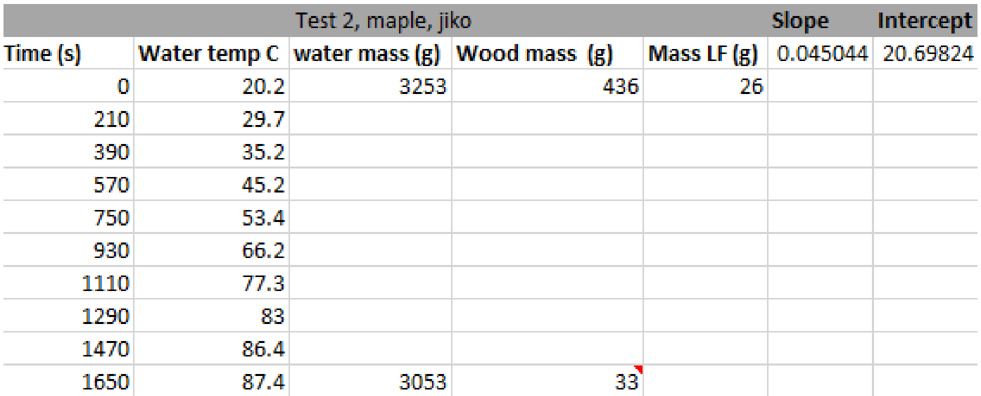


Figure 2: Temperature vs Time, test 3

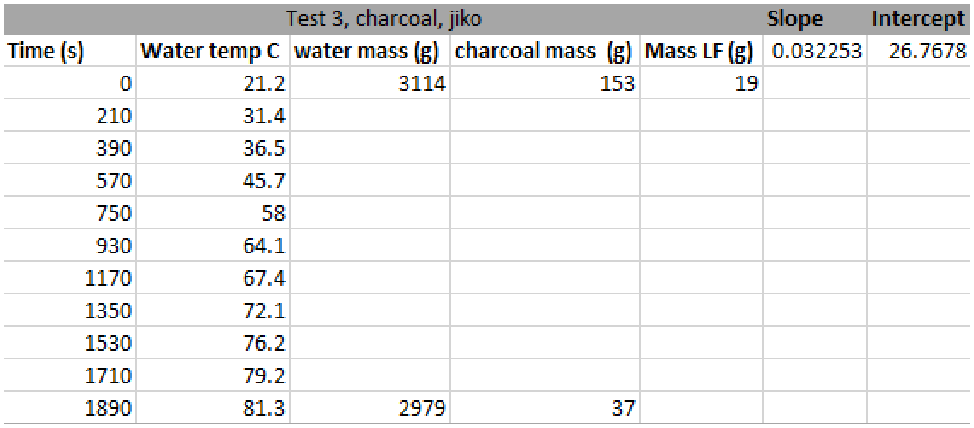
The raw data used to generate figures 1 and 2 can be seen in tables 1 and 2. The raw data for the remaining 7 tests can be seen in appendix B.

Table 1: Temperature vs Time, test 2



Test 2, maple, jiko					Slope	Intercept
Time (s)	Water temp C	water mass (g)	Wood mass (g)	Mass LF (g)	0.045044	20.69824
0	20.2	3253	436	26		
210	29.7					
390	35.2					
570	45.2					
750	53.4					
930	66.2					
1110	77.3					
1290	83					
1470	86.4					
1650	87.4	3053	33			

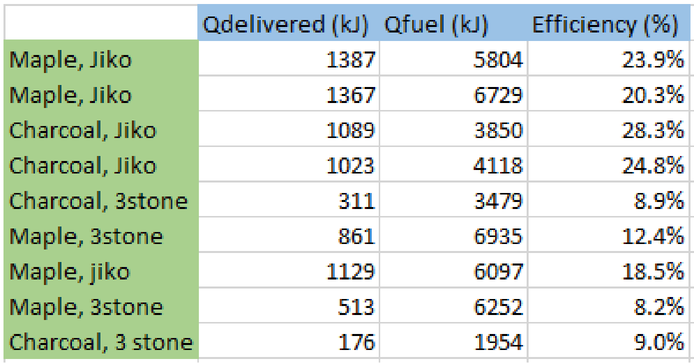
Table 3: Temperature vs Time, test 3



Test 3, charcoal, jiko					Slope	Intercept
Time (s)	Water temp C	water mass (g)	charcoal mass (g)	Mass LF (g)	0.032253	26.7678
0	21.2	3114	153	19		
210	31.4					
390	36.5					
570	45.7					
750	58					
930	64.1					
1170	67.4					
1350	72.1					
1530	76.2					
1710	79.2					
1890	81.3	2979	37			

Energy delivered to the water, potential energy of the fuel, and the thermal efficiency of the stove were found using equations 1-3 in appendix C. The results of this analysis for each test can be seen in table 3.

Table 3: Energy delivered, Fuel Energy, and Efficiency of each test



	Qdelivered (kJ)	Qfuel (kJ)	Efficiency (%)
Maple, Jiko	1387	5804	23.9%
Maple, Jiko	1367	6729	20.3%
Charcoal, Jiko	1089	3850	28.3%
Charcoal, Jiko	1023	4118	24.8%
Charcoal, 3stone	311	3479	8.9%
Maple, 3stone	861	6935	12.4%
Maple, jiko	1129	6097	18.5%
Maple, 3stone	513	6252	8.2%
Charcoal, 3 stone	176	1954	9.0%

A visualization of the efficiency of each stove and fuel type can be seen in figure 3.

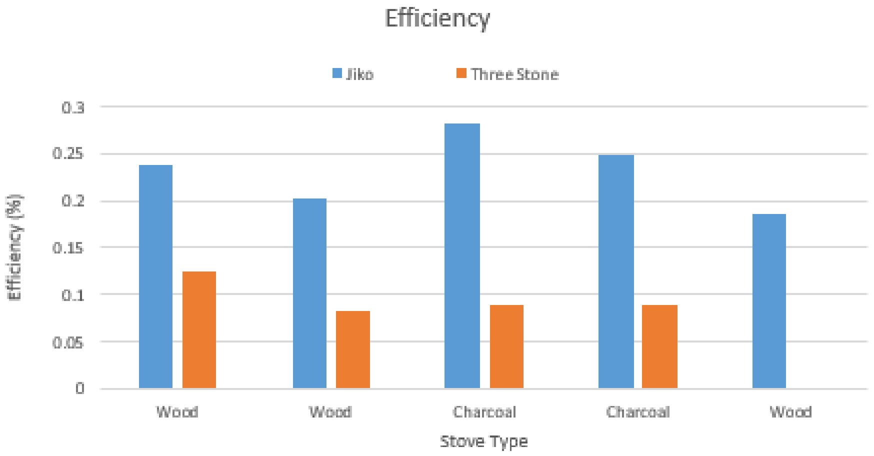
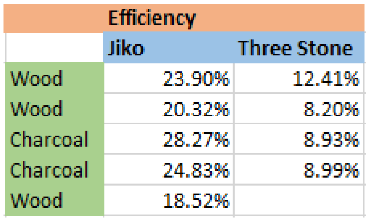


Figure 3: Efficiency for each stove and fuel type

The data used to create figure 3 can be seen in table 4.

Table 4: Efficiency for each stove and fuel type



	Efficiency	
	Jiko	Three Stone
Wood	23.90%	12.41%
Wood	20.32%	8.20%
Charcoal	28.27%	8.93%
Charcoal	24.83%	8.99%
Wood	18.52%	

Power was calculated using equation 4. A visualization of the power of each stove and fuel type can be seen in figure 4.

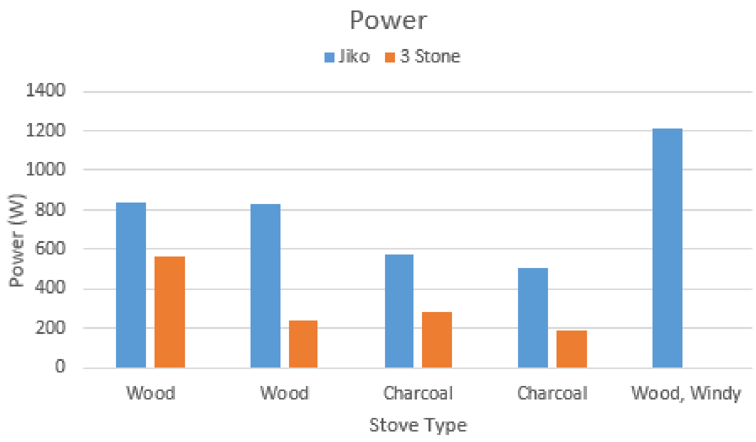
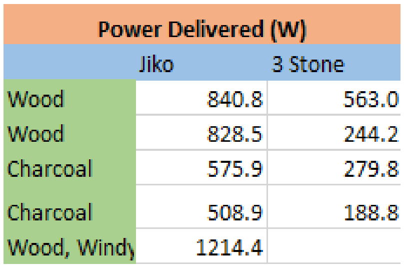


Figure 4: Power for each stove and fuel type

The data used to create figure 4 can be seen in table 5.

Table 5: Power for each stove and fuel type



	Power Delivered (W)	
	Jiko	3 Stone
Wood	840.8	563.0
Wood	828.5	244.2
Charcoal	575.9	279.8
Charcoal	508.9	188.8
Wood, Windy	1214.4	

Burning rate was calculated using equation 5. A visualization of the burning rate for each test can be seen in figure 5.

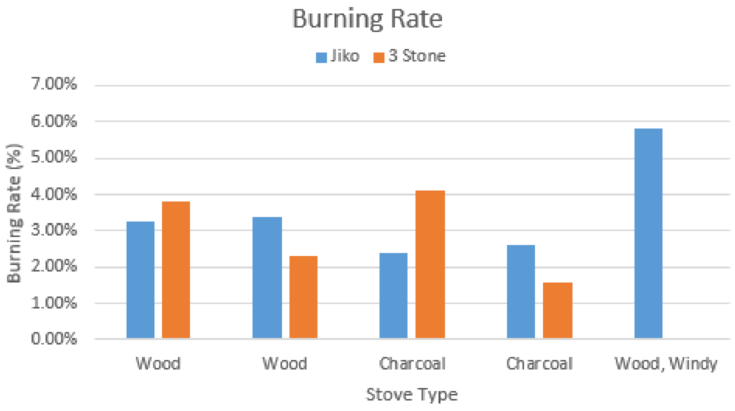
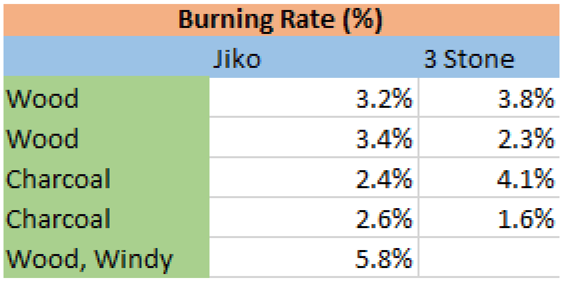


Figure 5: Burning rate for each stove and fuel type

The data used to create figure 5 can be seen in table 6.

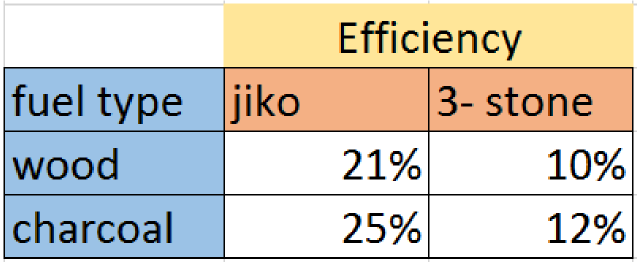
Table 6: Burning rate for each stove and fuel type



Burning Rate (%)		
	Jiko	3 Stone
Wood	3.2%	3.8%
Wood	3.4%	2.3%
Charcoal	2.4%	4.1%
Charcoal	2.6%	1.6%
Wood, Windy	5.8%	

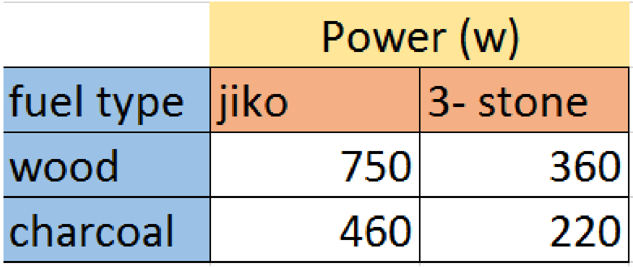
Predictions for the efficiency and power of each stove and fuel type were made using equations 6-24 in appendix C [6]. The results of this analysis can be seen in tables 7 and 8.

Table 7: Predicted Efficiency of each stove and fuel type



	Efficiency	
fuel type	jiko	3- stone
wood	21%	10%
charcoal	25%	12%

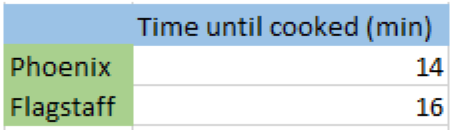
Table 8: Predicted Power of each stove and fuel type



	Power (w)	
fuel type	jiko	3- stone
wood	750	360
charcoal	460	220

The results of the rice testing can be seen in table 9.

Table 9: Rice test at different altitudes



	Time until cooked (min)
Phoenix	14
Flagstaff	16

4.2 Emissions Results

The group tested for emissions in two stoves commonly used in Africa, the Jiko stove and the 3-stones stove. Also, the group tested two different types of fuels which are maple sugar wood and maple sugar charcoal. The charcoal was made from the same wood tested by the team. The Met One Instruments Model 212 particle counter and laptop with the correct software was setup in the testing location [7]. The particulate matter (PM) emitted during the test was counted based on the different particle diameters that the profiler software and particle counter can detect. These diameters are 0.3, 0.5, 0.7, 1, 2.5, 3, 5, and 10 microns. Furthermore, the particle counter device was coordinated with the water boiling test trials to relate the PM emitted to the efficiency and the power produced. The Particles emitted were assumed to be spheres so that the volume of the PM emitted can be obtained, then used with the maple wood density (704.1 Kg/m$^{3)}$ to obtain mass of particles emitted [8]. The results of these tests can be found in figures 6-10.

In Figure 6 it can be seen that the charcoal fuel produces fewer particles counted in terms of PM<=2.5 and PM<=10 when tested in both the Jiko and the 3-stones stove. Also, the Jiko stove produces slightly less PM<=2.5 particles counted than the 3-stones. In Figure 7 it is obvious that the wood as a fuel produces dramatically higher particles counted in terms of PM<=2.5 when tested in both the Jiko and the 3-stones stove. Also, the Jiko stove produces higher PM<=2.5 particles counted than the 3-stones stove. It was noticed that when testing both the charcoal and the wood the PM<=10 produced is not significant because larger size and mass of these particles causes them to quickly settle [9].

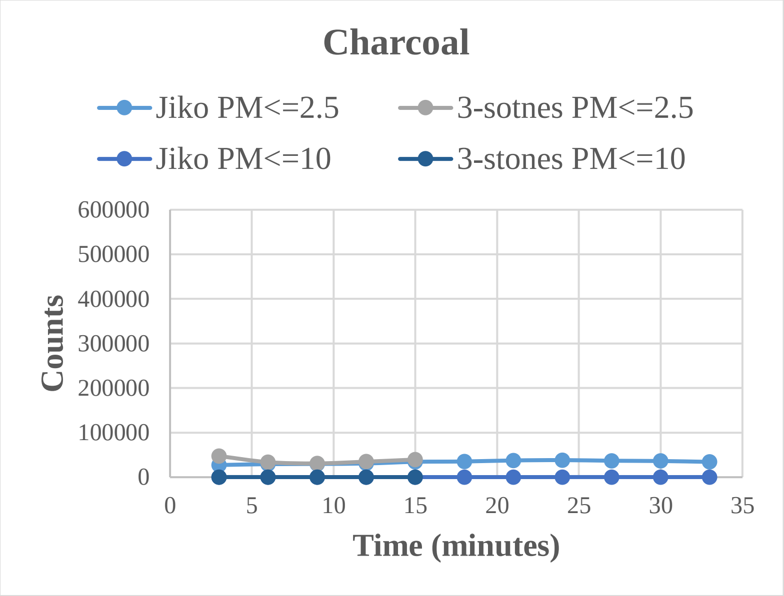


Figure 6: Particles counted using the charcoal in the Jiko and the 3-stones stove.

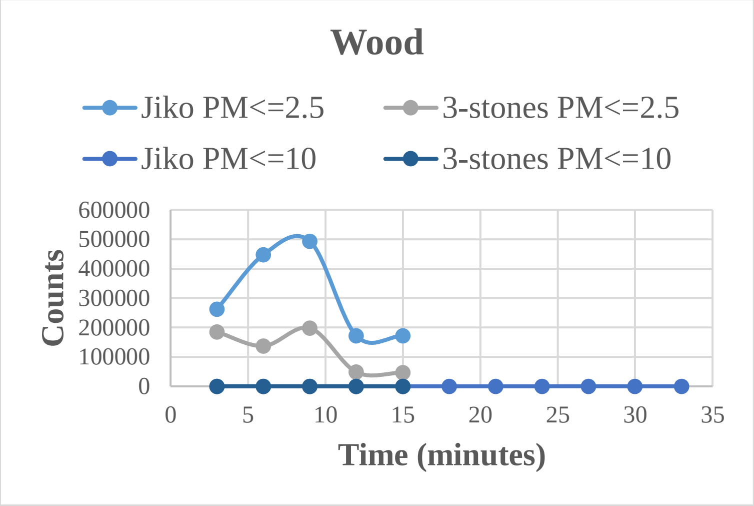


Figure 7: Particles counted using the wood in the Jiko and the 3-stones stove.

In Figure 8 and in Figure 9 it is obvious that the charcoal as a fuel produces fewer emission rate than the wood in terms of PM<=2.5 when tested in Jiko stove. Also, the Jiko stove produces a slightly lower PM<=2.5 emissions rate than the 3-stones. Also, In Figure 8 and in Figure 9 it is obvious that the charcoal as a fuel produces a lower emissions rate than the wood in terms of PM<=2.5 when tested in 3-stones as well stove. Overall, the Jiko stove produces less emissions rate in terms of PM<=2.5.

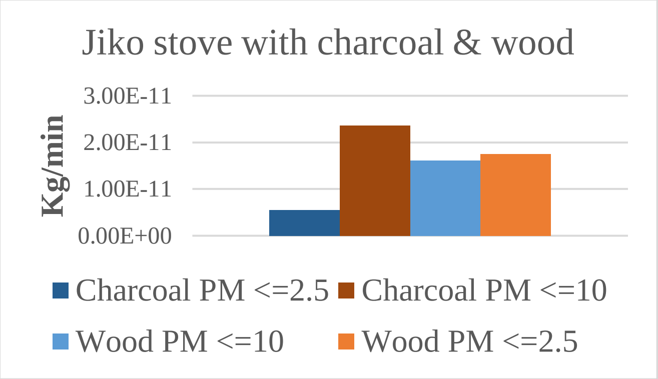


Figure 8: Emissions rate comparison between the charcoal and the wood in the Jiko stove.

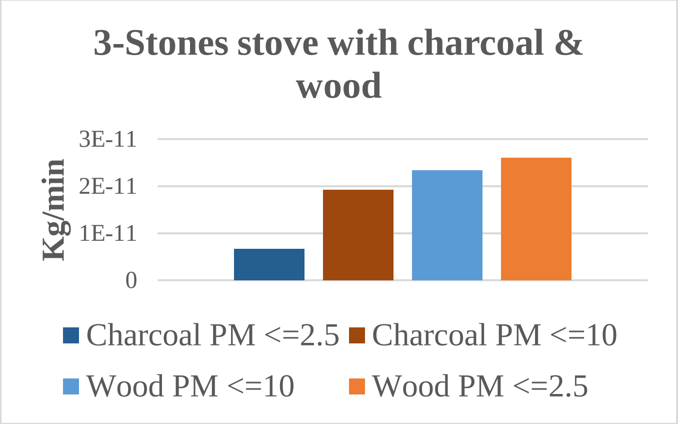


Figure 9: Emissions rate comparison between the charcoal and the wood in the 3-stones stove.

Figure 10 shows the total number of particles less than 2.5 microns emitted when boiling 3 liters of water using the Jiko and 3 stone stove.

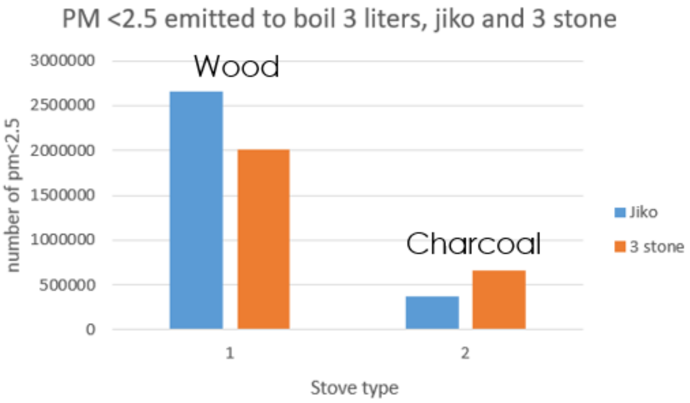


Figure 10: PM<=2.5 Particles counted comparison between the Jiko stove and the 3-stones stove to boil 3 L of water (Column 1 is wood and Column 2 is charcoal).

Table 10 summarizes the particle number data collected for both stove and fuel types.

Table 10: PM data for each stove and fuel type

	Wood		**Charcoal**	
PM Sizes µm	**Jiko**	**3-Stones**	**Jiko**	**3-Stones**
PM<=2.5 (10^3)	1546	1790	151	186
PM<=10 (10^3)	1.02	1.98	1.2	1.12

5.0 Discussion

5.1 Thermal Discussion

The linear regressions in figures 1 and 2 show that the Jiko with wood increased the temperature of the water at a faster rate than the Jiko with the charcoal. This may be due to the increased burning rate of wood seen in figure 5. As the wood consumes a higher percentage of its original mass per time, the power output is subsequently higher, despite the charcoal possessing a higher energy density than the wood [5] [10]. This is reflected in figure 4 and table 5, which show the increased power output of wood compared to charcoal. The association between power output and burning rate is apparent when comparing tables 5 and 6, which show that the windy day test of wood in the Jiko stove increased burning rate by approximately 75%, and power by approximately 45% when compared to the other Jiko with wood tests. This increase in burning rate is also associated with a decrease in efficiency, as shown in figure 3 and table 4. This may be a result of the increased flow rate causing fuel particles to be swept upward and out of the combustion chamber before being fully combusted, leading to decreases in lower overall efficiency. This effect is likely mitigated by the increased oxygen in the combustion chamber increasing flame and air temperature, increasing the effective radiative and convective heat transfer into the water. As the decrease in efficiency is relatively minor -- approximately 2%-3% -- while the increase in power output is practically significant – approximately 45% -- it’s likely that increases in flow through the system would be preferred by users, and should be a point of strong consideration in improved cookstove design. As figures 3 and 4 show, the efficiency and power were greater in the Jiko then in the 3-stone stove. This agrees with predictive analysis, which showed that the shape of the Jiko allowed a larger percentage of radiative heat to be directed into the cooking vessel instead of the ambient air and the improved insulation reduced convective heat losses. Additionally, figure 3 shows that charcoal was more efficient than the wood when used in the Jiko. This may have been due to the slower burn rate increasing the time in which fuel particles lingered in the combustion chamber, leading to higher combustion rates and subsequently efficiency. It may also be due to the increase flame and char temperature of charcoal, which would increase the efficiency of the heat transfer process. Table 7 shows that the thermal analysis predicted increased efficiency for the Jiko compared to the 3 stone, and charcoal compared to wood. The higher predicted efficiency of the Jiko is due to the more favorable view factor -- directing a higher proportion of radiation into the pot – and higher insulation, which provided more resistance to conductive and convective heat losses through the sides of the stove. The charcoal had a higher predicted efficiency due to higher burning temperatures and a slower burn rate, which increased heat transfer between the combustion chamber and the pot bottom. Table 8 shows that the Jiko was predicted to produce more power than the 3 stone, this is due to its improved ability to transfer heat to the water compared to the 3 stone, which loses much of its power in heating the ambient air. Charcoal was predicted to produce less power than wood due to the slower burning rate. Comparing these theoretical values with those obtained through testing shows that the thermal analysis was relatively accurate, but more accurate values could be obtained through a more detailed and extensive analysis. Table 9 shows that rice cooking time increased at the higher elevation of Flagstaff. This is likely due to the reduced boiling temperature associated with the altitude, which reduced heat transfer rate and increased cooking time.

5.2 Emissions Discussion

The tests show that when heating water, the Jiko stove and 3-stones stove produced less PM<=2.5 particles when using the charcoal than when using wood. Furthermore, the Jiko stove produces less PM<=2.5 emissions than the 3-stones when testing it with charcoal, as shown in Figure 10.

Table 10 shows that the wood as a fuel produces more particles PM<=2.5 in both the 3-stones stove and the Jiko stove. The PM<=2.5 is at minimum when using the Jiko stove and the charcoal as a fuel and it is at maximum when using the 3-stones and the wood. In fact, the test in table 10 is several trials that were added together to compare PM production of different sizes between the wood and the charcoal that were used in the Jiko and the 3-stones.

6.0 Recommendations

This project produced useful information and laid a foundation for future capstone teams to develop and test improved cook stoves. That said, there are several steps that could be taken to improve cook stove projects in the future. Nine tests were conducted to determine thermal and emission performance factors, while this provided useful insight, it was too few tests to be significant. Future teams should focus on performing many tests to provide a robust data set. Additionally, future tests should not be limited to two stoves, but should utilize a variety of improved cook stove designs, perhaps collaborating with the ceramics faculty to create new stoves. As tests showed that charcoal is efficient but requires large amounts of wood to produce, future groups could consider alternative methods of making charcoal, such as creating charcoal from animal manure, which is plentiful in rural Africa. Stove performance can vary significantly with wind conditions and ambient temperature. For these reasons, we recommend future tests be conducted in a controlled environment. This project was limited to batch testing to reduce testing error, but future tests may consider controlled continual feed testing in order to examine simmer performance. The emissive data collected was only for particulate matter as this is typically the most damaging emission, but future tests should collect and analyze Carbon Monoxide and Nitrous Oxide emissions, as they are health risks as well [11]. Finally, all future tests should utilize a remote probe thermometer, as thermometers with readouts located on the probe itself become very difficult to read in many testing scenarios.

7.0 Conclusion

The results of this project showed that improved cook stoves such as the Jiko can significantly improve power output, efficiency, and emissions. For these reasons, the increased use of improved cook stoves by rural peoples would likely reduce time spent collecting fuel and improve the health of the women who spend large amounts of time being exposed to cooking and heating emissions. It was also found that the use of charcoal in the Jiko stove was the most efficient combination tested and produced the least amount of harmful particulate matter. This makes charcoal an attractive fuel option from a health perspective but the large amounts of wood required to make the charcoal would negatively impact fuel collection time. For these reasons, it is recommended that future teams seek a method of creating charcoal from more available materials such as cow manure. Research showed that Carbon Monoxide and Nitrous Dioxide can be emitted from cook stoves at harmful levels, so future tests should measure these emissions as well. The predictive analysis and experimental testing showed the significant effects that air flow rate through the system had on efficiency and power. This relationship should be explored further and optimized in future stove designs.

8.0 References

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[2] 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.

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[11]T. Larson, "Wood Smoke: Emissions and Noncancer Respiratory Effects", *Annual Review of Public Health*, vol. 15, no. 1, pp. 133-156, 1994.

9.0 Appendices

9.1 Appendix A

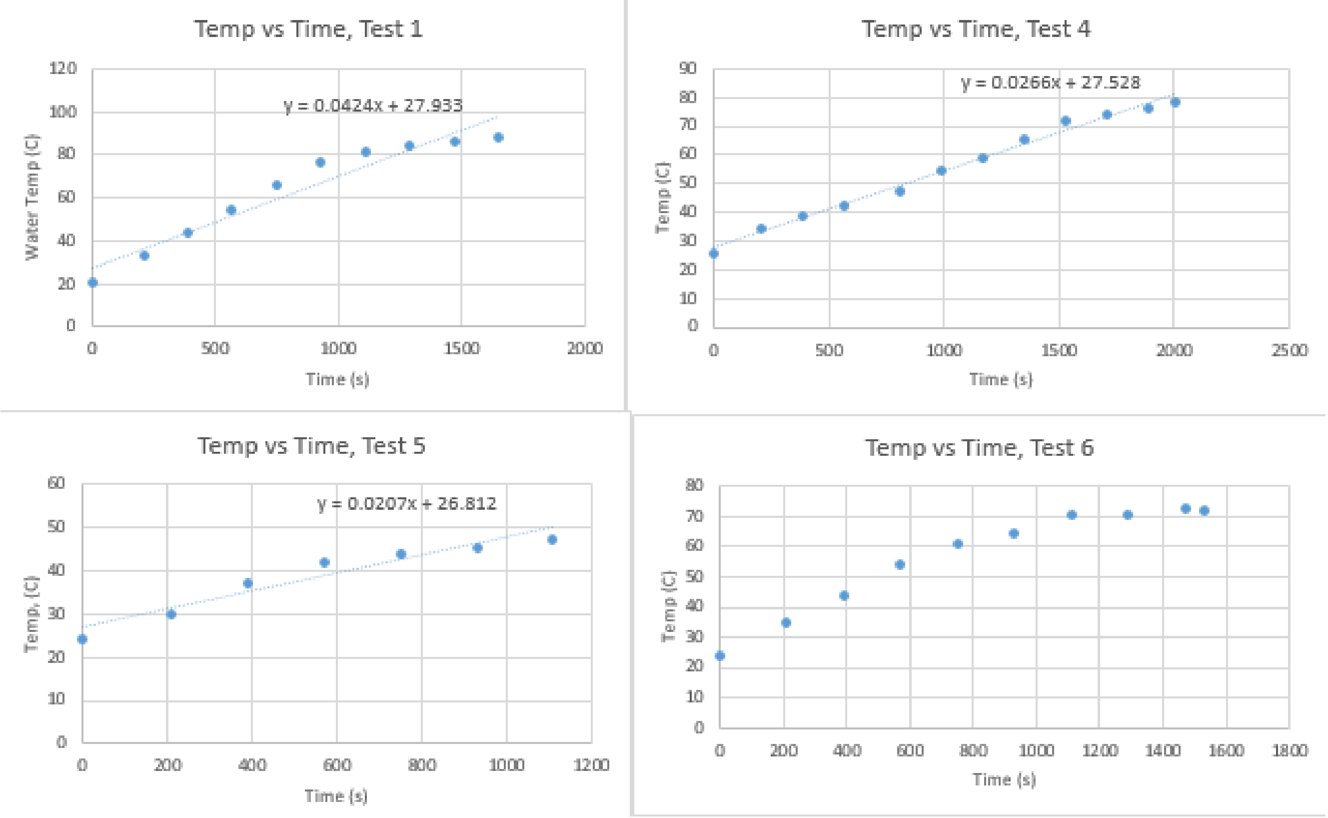


Figure 11: Temp vs Time curves for tests 1, 4, 5, and 6

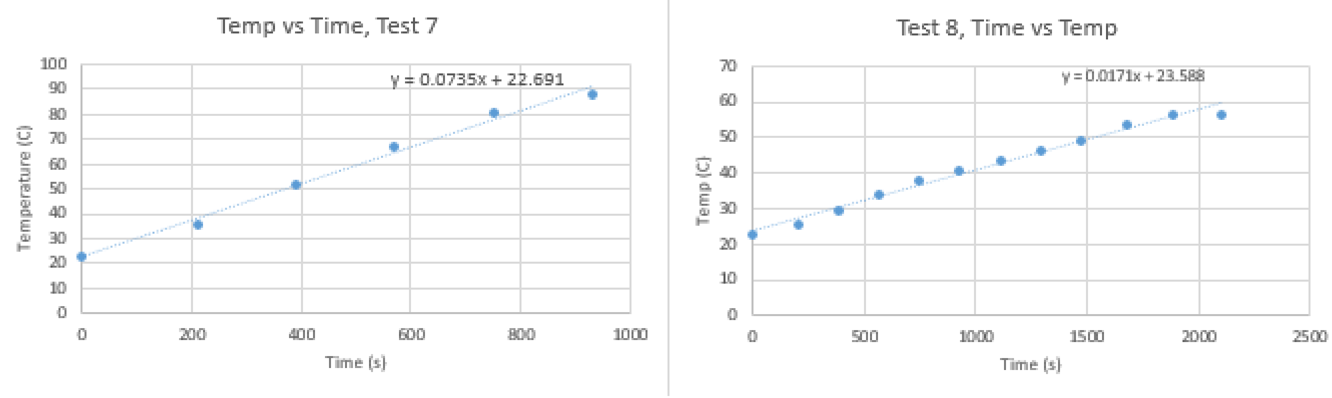


Figure 12: Temp vs Time curves for tests 7 and 8

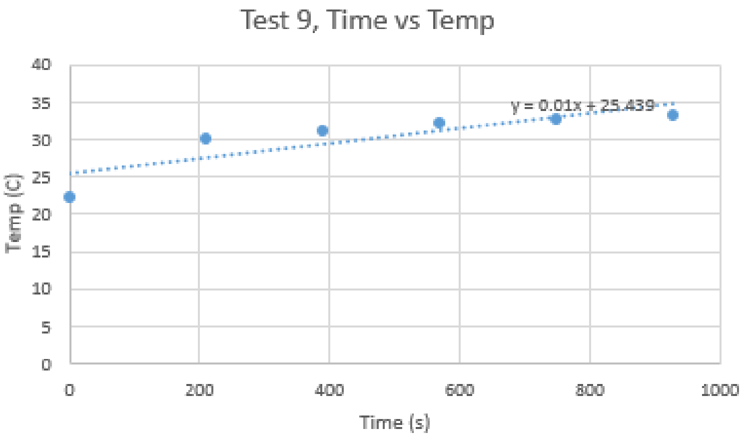
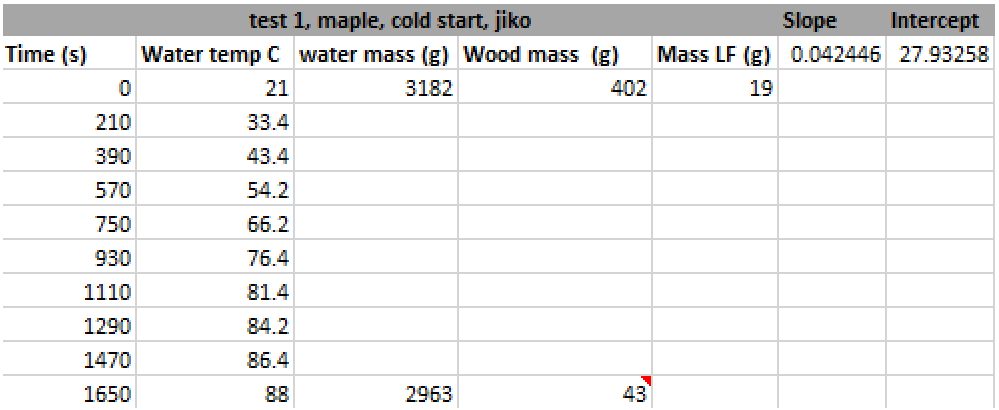


Figure 13: Temp vs Time curve for test 9

9.2 Appendix B

Table 11: Raw data for test 1



test 1, maple, cold start, jiko					Slope	Intercept
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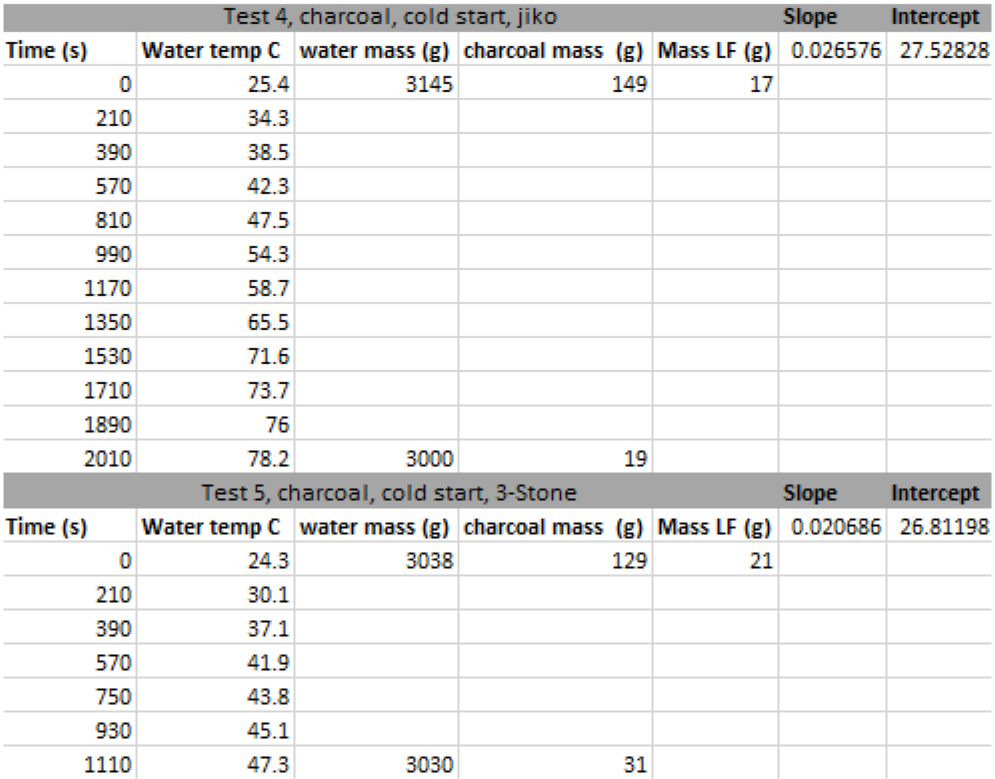
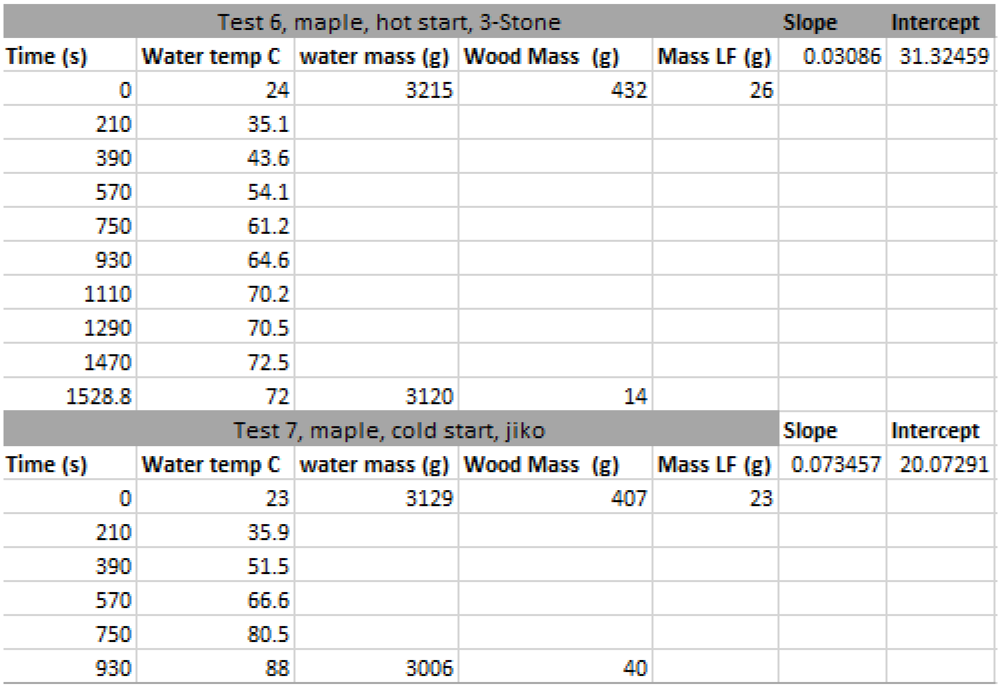
930	76.4					
1110	81.4					
1290	84.2					
1470	86.4					
1650	88	2963	43			

Table 12:: Raw data for tests 4 and 5



Test 4, charcoal, cold start, jiko					Slope	Intercept
Time (s)	Water temp C	water mass (g)	charcoal mass (g)	Mass LF (g)	0.026576	27.52828
0	25.4	3145	149	17		
210	34.3					
390	38.5					
570	42.3					
810	47.5					
990	54.3					
1170	58.7					
1350	65.5					
1530	71.6					
1710	73.7					
1890	76					
2010	78.2	3000	19			
Test 5, charcoal, cold start, 3-Stone					Slope	Intercept
Time (s)	Water temp C	water mass (g)	charcoal mass (g)	Mass LF (g)	0.020686	26.81198
0	24.3	3038	129	21		
210	30.1					
390	37.1					
570	41.9					
750	43.8					
930	45.1					
1110	47.3	3030	31			

Table 13: Raw data for tests 6 and 7



Test 6, maple, hot start, 3-Stone					Slope	Intercept
Time (s)	Water temp C	water mass (g)	Wood Mass (g)	Mass LF (g)	0.03086	31.32459
0	24	3215	432	26		
210	35.1					
390	43.6					
570	54.1					
750	61.2					
930	64.6					
1110	70.2					
1290	70.5					
1470	72.5					
1528.8	72	3120	14			
Test 7, maple, cold start, jiko					Slope	Intercept
Time (s)	Water temp C	water mass (g)	Wood Mass (g)	Mass LF (g)	0.073457	20.07291
0	23	3129	407	23		
210	35.9					
390	51.5					
570	66.6					
750	80.5					
930	88	3006	40			

Table 24: Raw data for tests 8 and 9

Test 8, wood, cold start, 3 stone					Slope	Intercept
Time (s)	Water temp C	water mass (g)	wood mass (g)	Mass LF (g)	0.01713	23.58843
0	22.8	2779	430	33		
210	25.2					
390	29.5					
570	34.1					
750	37.8					
930	40.9					
1110	43.4					
1290	46.4					
1470	49					
1680	53.6					
1890	56.4					
2100	56.2	2724	85			
Test 9, charcoal, hot start, 3 stone					**Slope**	**Intercept**
Time (s)	Water temp C	water mass (g)	charcoal mass (g)	Mass LF (g)	0.010023	25.43922
0	22.3	3155	179	18		
210	30					
390	31					
570	32					
750	32.7					
930	33.2	3141	135			

9.3 Appendix C

Note that terms which are defined in these equations may not be defined again when used in those that follow. Please look to the other equations if a term is not defined.

$$Q_{delivered} = m_{H2O} c_p \Delta \mathrm{T}_{H2O} + h_{vap} \Delta \mathrm{m}_{H2O} \qquad (1)$$

$\mathrm{Q}_{\mathrm{delivered}}$: total energy delivered to the water (j)

$\mathrm{m}_{\mathrm{H20}}$: mass of water (g)

$\Delta\mathrm{T}_{\mathrm{H20}}$: change in temperature of the water (degrees C)

$\mathrm{h}_{\mathrm{vap}}$: specific enthalpy of water at vaporization temperature (j/g)

$$Q_{fuel} = m_{fuel} HeatingValue_{fuel} + m_{LgtFluid} HeatingValue_{LgtFluid} \qquad (2)$$

Q_{fuel}: total potential energy present in the fuel and lighter fluid (j)

m_{fuel}: mass of the fuel (g)

$HeatingValue_{fuel}$: energy density of the fuel (j/g)

$m_{LgtFluid}$: mass of the lighter fluid (g)

$HeatingValue_{LgtFluid}$: energy density of the lighter fluid (j/g)

$$\eta = \frac{Q_{delivered}}{Q_{fuel}} \tag{3}$$

η:Thermal efficiency of the stove (unitless)

$Q_{delivered}$: total energy delivered to the water (j)

Q_{fuel}: total potential energy present in the fuel and lighter fluid (j)

$$power = \frac{Q_{delivered}}{time} \tag{4}$$

power: rate of energy delivered to the water (W)

$Q_{delivered}$: total energy delivered to the water (j)

time: total time of the test

$$BurningRate = \frac{\Delta \mathrm{m}_{fuel}}{time * m_{initial}} * 100 \tag{5}$$

BurningRate: burning rate of the fuel corrected as a percentage of its own weight (%)

$$power = q_{delivered} \tag{6}$$

power: rate of energy delivered to the water (W)

$q_{delivered}$: rate of energy delivered to the water (W)

$$\eta = \frac{q_{delivered}}{q_{fuel}} \tag{7}$$

η:Thermal efficiency of the stove (unitless)

$q_{delivered}$: rate of energy delivered to the water (W)

q_{fuel}: rate of potential energy present in the fuel and lighter fluid (W)

$$q_{delivered} = q_{Conv,potbottom} + q_{Rad.Char} + q_{Rad,Flame} + q_{Rad,innerwalls} - q_{Conv,pot} - q_{Rad,pot} - q_{Rad,Water} \tag{8}$$

$q_{delivered}$: rate of energy delivered to the water (W)

$q_{Conv,potbottom}$: rate of heat transferred from the hot air of the oven to the cool pot bottom (W)

$q_{Rad,Char}$: rate of heat transferred from the radiation of the char to the pot bottom (W)

$q_{rad,flame}$: rate of heat transferred from the radiation of the flame to the pot bottom (W)

$q_{Rad,innerwalls}$: rate of heat transferred from the radiation of the inner walls of the stove to the pot bottom (W)

$q_{Conv,Pot}$: rate of heat transferred through convection from the walls of the pot the ambient air (W)

$q_{Rad, pot}$: rate of heat transferred through radiation from the walls of the pot to ambient air (W)

$q_{Rad,Water}$: rate of heat transferred through radiation from the surface of the water to the surrounding air (W)

$$q_{Rad.Char} = \frac{\varepsilon\,\sigma({T^4}_{char} - {T^4}_{amb})}{R_{total}} \tag{9}$$

$q_{Rad,Char}$: rate of heat transferred from the radiation of the char to the pot bottom (W) ε: emissivity of the char (unitless)

R_{total}: total resistance to thermal radiation from view factors and surface conditions

$$q_{Rad.flame} = \frac{\varepsilon\,\sigma\left(\mathrm{T}^4{}_{flame} - \mathrm{T}^4{}_{amb}\right)}{R_{total}} \tag{10}$$

$$q_{Rad.innerwalls} = \frac{\varepsilon\,\sigma(\mathrm{T}^4{}_{walls} - \mathrm{T}^4{}_{amb})}{R_{total}} \tag{11}$$

$$q_{Rad.pot} = \varepsilon\,\sigma\left(\mathrm{T}^4{}_{flame} - \mathrm{T}^4{}_{amb}\right) \tag{12}$$

$$q_{Rad.water} = \varepsilon\,\sigma\left(\mathrm{T}^4{}_{flame} - \mathrm{T}^4{}_{amb}\right) \tag{13}$$

$$R_{total} = R_{surface} + R_{view} \tag{14}$$

$$R_{surface} = \frac{1 - \varepsilon}{\varepsilon \mathrm{A}} \tag{15}$$

$$R_{view} = \frac{1}{AF} \tag{16}$$

$$q_{Conv,pot} = hA_{pot}\left(T_{pot} - T_{amb}\right) \tag{17}$$

h: convective coefficient of surrounding air (W/m^2K)

$$q_{Conv,potbottom} = hA_{pot}(T_{oven} - T_{amb}) \tag{18}$$

$$T_{oven} = q_{fuel}R_{eq} + T_{amb} \tag{19}$$

Req: equivalent resistance of from all convective and conductive resistances (K/W)

$$R_{eq} = \frac{1}{\left(\frac{1}{R_1} + \frac{1}{R_2}\right)} \tag{20}$$

$$R_1 = R_{conv} + R_{cond}$$

$$R_2 = R_{conv} \tag{21}$$

$$R_{conv} = \frac{1}{hA} \tag{22}$$

$$R_{cond} = \frac{L}{kA} \tag{23}$$

K: conductive coefficient of clay brick (W/mK)

$$q_{fuel} = (BurningRate)(HeatingValue) \tag{24}$$

q_{fuel}: rate of potential energy of the fuel (W)