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Performance of Charcoal Cookstoves for Haiti, Part 2: Results from the Controlled Cooking Test

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DISCLAIMER

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1. Introduction

This report is the second part of an effort to test cookstoves for Haiti at the Lawrence Berkeley National Lab (LBNL) stove testing facility. In January 2010, a massive earthquake rendered hundreds of thousands of Haitians homeless. A large relief and reconstruction effort began almost immediately. Many non-government organizations (NGOs) began considering fuel-efficient stoves as an integral part of the reconstruction effort. In April 2010, LBNL, with support from the Darfur Stoves Project, organized a team of scientists and engineers to undertake a fact-finding mission in Haiti to assess the needs and opportunities for fuel-efficient cookstove intervention. Based on data collected from interviews with Haitians and NGOs, the team (Scott Sadlon, Robert Cheng, and Kayje Booker) identified and recommended stove performance testing and comparison as a high priority need that could be filled by LBNL.

The first part of this report, *Performance of Charcoal Cookstoves for Haiti, Part 1: Results from the Water Boiling Test,* can be found at http://cookstoves.lbl.gov/haiti/lbnl-5021e.pdf. Part 1 presented the results for five charcoal stoves tested using a modified form of version 3 of the Shell Foundation Household Energy Project Water Boiling Test (WBT).[1]

For the second phase of the report, five charcoal cookstoves were tested using a Controlled Cooking Test (CCT) developed from cooking practices in Haiti (see Section 2.4 for the full protocol). While the WBT was developed as a universal laboratory protocol for testing cookstove performance for one standardized task, CCTs more accurately mimic real-world cooking practices, and therefore may be a better indicator of true stove performance in the field.[2] Cookstoves were tested for total burn time, specific fuel consumption, and emissions of carbon monoxide (CO), carbon dioxide (CO_2), and the ratio of carbon monoxide to carbon dioxide (CO/CO_2). These results are presented in this report along with LBNL testers' observations regarding the usability of

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[1] The water boiling test protocol may be found at http://ehs.sph.berkeley.edu/hem/?page_id=38.

[2] For more explanation, see: Smith, K.R., Dutta, K., Chengappa, C., Gusain, P.P.S., Masera, O., Berrueta, V., Edwards, R., Bailis, R., and Naumoff Shields, K., 2007, "Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: conclusions from the Household Energy and Health Project", *Energy for Sustainable Development*, 11(2), pp 5-18.

the stoves. In order to keep this second part of the report largely self-contained, Part 1 and Part 2 have some intentional redundancies.

2. Methods

2.1 Stoves Tested

Four of the stoves tested for the WBTs were included in the CCTs. These stoves are the EcoRecho, the Prakti Rouj, a locally-made replicate of a Mirak stove, and a traditional Haitian stove. The StoveTec model was withdrawn from the CCT tests because its production had been discontinued, and we were unable to obtain the next model in time to include it in the CCT tests. A stove produced by Envirofit (the CH-2200) was included in the CCTs, although it was not received in time to be included in Part 1 of this report. The five stoves used in the CCTs are shown in Fig. 1 and are described in more detail below.

Figure 1: From left to right: EcoRecho, Envirofit CH-2200, Mirak, Prakti Rouj, Traditional

A. <u>EcoRecho</u>: A metal stove with a ceramic liner made in Haiti by D&E Green Enterprises. The pot sits above the charcoal on three triangular metal supports. A door on the front of the stove can be opened or closed to control airflow. This stove costs about 1000 gourdes (US $25) to produce; however, they are being sold at the subsidized price of 450 gourdes as of April 2010 (US $11). The life expectancy for this stove is estimated to be 12-18 months by the manufacturer.

B. <u>Envirofit CH-2200</u>: An all metal stove where the pot rests on a metal grate above the charcoal bed. The air intake door to control airflow is on the bottom of the stove with a level for control on the side. This stove costs US $25. The life of the Envirofit CH-2200 is estimated to be 5 years by the manufacturer.

C. Mirak (copy): A locally-made, scrap metal copy of the Mirak stove designed by CARE and widely available in Port-au-Prince. This stove was purchased for 150 gourdes in April 2010 (US $3.75). The charcoal chamber is hemispherical, and the pot sits directly on the charcoal. The life expectancy for this stove is unknown.

D. Prakti Rouj: An insulated metal stove with a small rectangular charcoal chamber. The pot sits on raised knobs above the charcoal bed and a door on the front of the stove can be adjusted to control airflow. This stove costs US $25. The lifetime of the Prakti Rouj is estimated to be 5 years by the manufacturer.

E. Traditional stove: Made locally in Haiti from scrap metal and widely available. Evenly distributed holes are located all around the sides and the bottom of a rectangular charcoal container. The pot sits directly on the charcoal in the chamber, and ash falls through to a tray underneath. This stove was purchased for 150 gourdes in April 2010 (US $3.75) but it was said they can cost up to 250 gourdes ($6.25). These stoves reportedly last six months to one year.

Stove	Cost (USD)	Expected Lifetime
EcoRecho	$11	12-18 months
Envirofit CH-2200	$25	5 years
Mirak (copy)	$3.75	Unknown
Prakti Rouj	$25	5 years
Traditional stove	$3.75 - $6.25	6-12 months

Table 1: Summary table of five stoves tested, including cost and life expectancy.

We did not receive instructions on using the stoves but performed several practice tests with each stove prior to the official testing. Each stove was operated in order to maximize its efficiency, based on the experience gained during the practice runs, by adjusting airflow if possible.

2.2 Fuels

Ideally for our experiment to be as similar as possible to field conditions, we would have used locally-procured Haitian charcoal for our experiments. Although we did obtain some samples of Haitian charcoal, it was impractical to procure adequate quantities for all testing activities. Instead, the fuel used for all of the CCTs was Grillmark© all-natural lump charcoal. The rectangular lump charcoal was broken into manageable pieces (no larger than approximately 3x2x1 inches). Charcoal samples were analyzed using standard oven-drying procedures and were found to have a moisture content of 5.9%.

2.3 Test System

All testing was performed under controlled conditions at Lawrence Berkeley National Laboratory. The test system consisted of a stove platform under an exhaust hood which drew gases upward through an aluminum duct (15 cm diameter) using two blowers (Fig. 2). Prior to these blowers, the gases were mixed along a long stretch of duct by stationary fan blades and then sampled for emissions data.

Figure 2: The stove testing system at LBNL. The exhaust hood and ductwork is on the right-hand side of the photo, while the instrumentation is on the left.

CO and CO_2 emissions were continuously measured (1-Hz) with a California Analytical Instruments 600-series gas analyzer. In addition to emissions, the weight of the charcoal added to the stove and the temperature of the food were continuously measured and recorded in real time.

2.4 Protocol

The CCT protocol was developed by the LBNL cookstove group based on consultations with Nexant (Peter Scott and Mouhsine Serrar), who had conducted cooking field trials in Haiti, as well as the notes from brief cooking trials conducted by the LBNL observation team. The protocol was designed to create a standardized procedure for laboratory testing, while still closely following the cooking procedure of Haitian women, mimicking the staple Haitian dish of *diri kole ak pwa* (rice with red beans and vegetables). The CCT protocol is divided into three main cooking tasks – beans, vegetables, and rice. The description of the protocol is as follows:

To start the fire, approximately 10-20 grams of fatwood, a sappy pine, was used. The initial amount of charcoal used depended on the cookstove, because some cookstoves were not designed to accommodate the larger initial amounts typically used in the traditional stove. The initial amounts of charcoal used in each cookstove were:

EcoRecho	280g
Envirofit	280g
Mirak	450g
Prakti	200g
Traditional	475g

Additional pieces of charcoal were added as needed to maintain a steady, hot fire, and the total fuel consumed was calculated as the total mass of charcoal added minus the mass of charcoal left over at the end of the test.

2.4.1 Bean Phase

Ingredients:
- 500 g beans
- 71 g oil

- 50 g garlic
- 20 g salt
- 2500 g water

The ingredients were brought to a boil in a covered pot. They were then cooked at a simmer for 20 minutes. At the end of the 20-minute period, the bean dish was mixed well and checked if fully cooked. A bean was considered fully cooked if the skin of the bean came off easily when squeezed. If any of five randomly selected beans was not fully cooked, the bean dish was cooked for an additional three minutes, and the beans were checked again. This process was repeated until the beans were considered fully cooked. At that point, the bean dish was strained in order to separate the beans and the water, both of which were kept in separate dishes for later use.

2.4.2 Vegetable Phase

To represent cooking vegetables, 500 – 1100 g of water was heated for 10 minutes. This portion of the test was intended to maintain a steady fire over a fixed burn time with the water acting as a thermal sink, not a test to see how long it took to boil a specific amount of water. To see the energy needed to boil a fixed amount of water, please refer to the first part of this report.[1]

Simply heating water, instead of heating water with vegetables, is representative of the vegetable phase because vegetables contain a high percentage of water. Boiling vegetables was not considered an endothermic process and therefore water was used as a proxy for vegetables during this phase.

2.4.3 Rice Phase

Ingredients:

- Entirety of the strained cooked beans
- 1400 g strained water from cooked bean dish (if the remaining water from the bean dish was less than 1400 g, tap water was added to reach a total of 1400 g)
- 1100 g tap water
- 1000 g uncooked rice

In a covered pot, the beans and water were brought to a boil. Once the mixture was boiling, the rice was added and again the mixture was covered and brought to a boil. The mixture was then simmered for 20 minutes in the covered pot. At the end of 20 minutes, the rice dish was checked to see if it was fully cooked. The rice was considered fully cooked when no water remained and the rice at the top and bottom of the pan was crisp. If the rice was not fully cooked, it was cooked for an additional 3 minutes, and then checked again. This process was repeated until the rice was fully cooked.

2.5 Analysis

For every metric, we report stove performance for the CCT from the time of the initial lighting of the fire to the time the pot of cooked beans and rice was removed. Therefore, emissions from when the fire was extinguished are not reported. As the CCT protocol is supposed to mimic the making of a Haitian meal, the data is analyzed as one entity, instead of reporting the results of three separate phases.

Because of procedural errors and instrumentation miscalibration during a few experiments, some tests were completed with erroneous emissions data. Although these emissions data could not be used, the specific fuel consumption and total burn time were unaffected by these errors and therefore, that data still was used for this report. This explains the difference in the number of replicate experiments for emissions and fuel consumption.

In three tests, the emission data for CO had clipped readings for values larger than 400 ppm. As CO almost never peaked above 400 ppm, these faults were not found to affect the total CO value for the test so the data was still used in this report with the clipped values replaced with 400 ppm.[3]

When presenting graphs of the results for each stove performance metric, we include error bars equal to the ± 95% confidence intervals calculated using the Student's t-distribution. Due to the small number of tests (ranging from 5-12 tests per stove),

[3] Incorrect data points totaled 2-18 seconds of missing data per 2 hour test. The original values were recorded as null values; however, any values inserted for the skipped seconds between 400 ppm – 1000 ppm did not have any effect on the total CO calculated, so 400 ppm was chosen as an arbitrary value.

confidence intervals are sometimes quite wide. Please see Appendix A for a more in-depth explanation of the statistics background for this report.

3. Results

Results are grouped into three categories:

- **Stove Performance**: total burn time and specific fuel consumption
- **Emissions**: CO, CO_2, and CO/CO_2
- **Usability**: observations of ease of stove use from stove testers at LBNL

3.1 Stove Performance

3.1.1 Total Burn Time

Total burn time is the time from when the charcoal was first lit to when the rice and bean mixture was fully cooked and removed from the stove. Because this CCT protocol was primarily driven by a fixed-duration burn, meaning the major steps were largely dependent on a fixed time period, the difference in time between stoves was fairly small. However, the total burn time can indicate two factors about a stove. The first is ignition time, or how long a charcoal bed takes to fully ignite to the point of being ready to cook. The second is the number of additional three-minute time increments during the beans or rice phase needed for food to be fully cooked. A longer total burn time for this CCT could indicate a stove takes a longer time to light or delivers relatively smaller thermal power into the pot for cooking food.

The average total burn time for each stove can be seen in Fig. 4. The total burn time for each individual test for each stove can be seen in Fig. 5.

Although the Prakti, EcoRecho, and traditional stoves took the least amount of time on average, there were no statistically significant differences between stoves at 95% confidence. As can be seen in the individual tests (Fig. 5), the Prakti, Mirak, and traditional stove tests appear to have clustered in a lower time span with one or two outliers, while the EcoRecho and Envirofit stove tests are more evenly spread over a larger range of times.

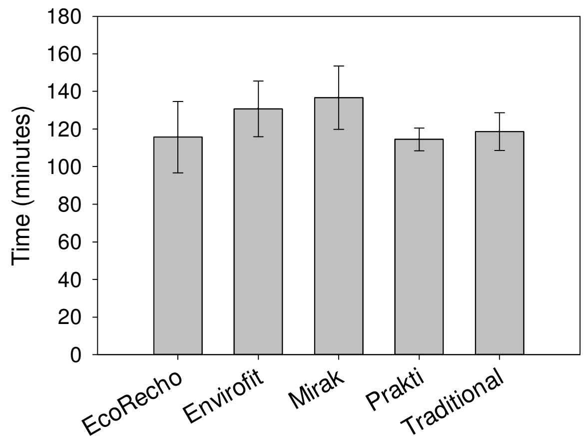

Figure 4: Average Total Burn Time. Error bars are 95% confidence intervals. From left to right, the values are 115.7 ± 18.9, 130.8 ± 14.7, 136.7 ± 16.9, 114.5 ± 6.0, 118.6 ± 10.0.

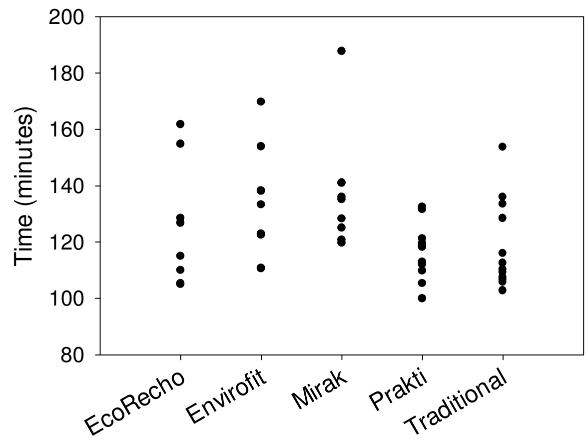

Figure 5: Total Burn Time per test. See Appendix B for specific values.

3.1.2 Specific Fuel Consumption

Specific fuel consumption is defined in the 2007 WBT as "the fuelwood required to produce a unit output" whether the output is boiled water or cooked beans.[4] In the case of the CCT, specific fuel consumption was calculated by:

$$\text{Specific Fuel Consumption} = \frac{\text{equivalent dry fuel consumed (g)}}{\text{total weight of food cooked (kg)}}$$

The equivalent dry fuel consumed was calculated as derived in the first part of this report:[5]

$$F_d = F_m * (1 - 1.08 * m)$$

F_d is the equivalent dry fuel consumed, F_m is the fuel consumed, and m is the moisture content of the fuel (%).

The average specific fuel consumption for each stove can be seen in Fig. 6. The specific fuel consumption for each individual test for each stove can be seen in Fig. 7.

[4] http://ehs.sph.berkeley.edu/hem/content/WBT_Version_3.0_Jan2007a.pdf
[5] http://cookstoves.lbl.gov/haiti/lbnl-5021e.pdf

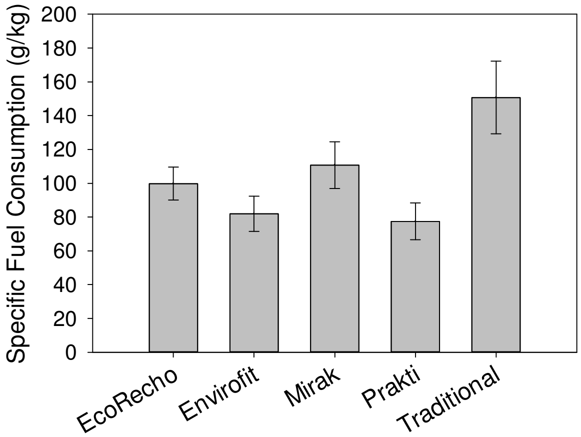

Figure 6: Average Specific Fuel Consumption. Error bars are 95% confidence intervals. From left to right, the values are: 99.8 ± 9.7, 81.9 ± 10.5, 110.7 ± 13.8, 77.4 ± 10.9, 150.7 ± 21.4.

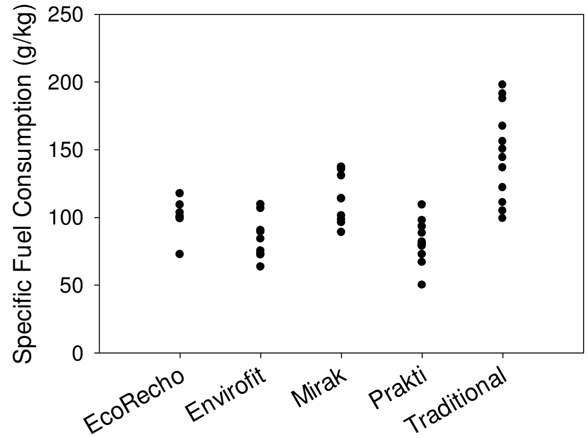

Figure 7: Specific Fuel Consumption per test. See Appendix B for specific values.

All of the improved stoves have a smaller specific fuel consumption than the traditional stove, on a statistically significant basis ($p = 0.05$). The Prakti stove performed the best and was significantly better than not only the traditional stove, but also the Mirak and EcoRecho stoves. The Envirofit stove was also significantly better than the traditional and Mirak stoves.

3.1.3 Stove Performance Conclusions

The correlation between specific fuel consumption and the total burn time can be seen in Fig. 8 below. Data points with a short total burn time and low specific fuel consumption are found in the bottom left hand corner, while long total burn times and high fuel consumptions occur in the upper right hand corner.

It can be seen that the Prakti, EcoRecho, and traditional stoves had generally the shortest burning times. For specific fuel consumption, the traditional stove consumed more fuel than any of the improved stoves, and the Prakti and Envirofit consumed the least amount of fuel on average.

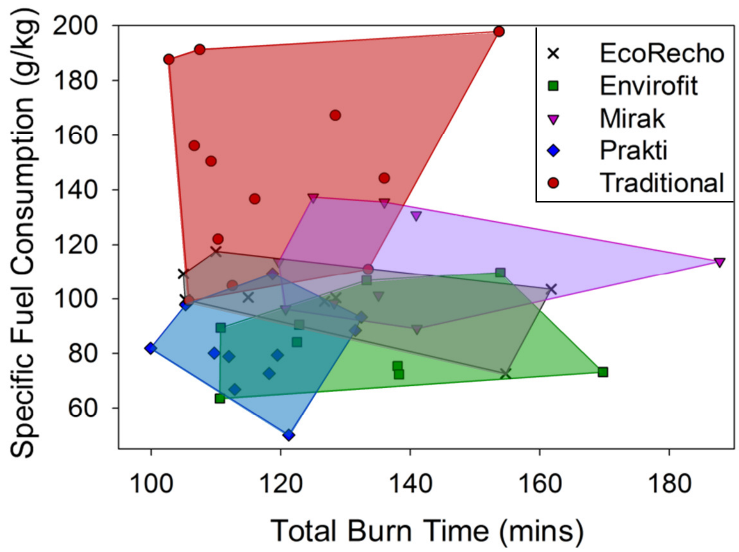

Figure 8: Correlation between Total Burn Time and Specific Fuel Consumption. Shading indicates the convex polygon containing all data points from our tests, not necessarily all potential data points.

3.2 Emissions

3.2.1 Total Carbon Monoxide (CO)

CO emissions were monitored, recorded, and summed for the entirety of each CCT with background CO levels removed. The background CO levels were estimated by averaging the CO levels for several minutes prior to igniting the fire to find a general CO background level. The emissions were originally recorded in ppm and converted to g/m^3. A general equation for the flow rate through our duct system was previously found experimentally and used to convert the emissions from g/m^3 to g.

The average total CO for each stove can be seen in Fig. 8. The total CO for each individual test can be seen in Fig. 9.

The traditional stove emitted significantly more CO than the EcoRecho, Envirofit, and Prakti stoves with 95% confidence. The Envirofit was significantly less emitting than the EcoRecho and Mirak stoves, along with the traditional, emitting the least amount of CO on average. The Prakti emitted the second least on average, but large confidence intervals made it difficult for us to confirm a significant difference with any stove other than the traditional stove. As can be seen in Fig. 9, the results for the Envirofit are tightly clustered, which could indicate either more tests are necessary to determine the broad standard deviation or the stove has a highly predictable CO emission behavior.

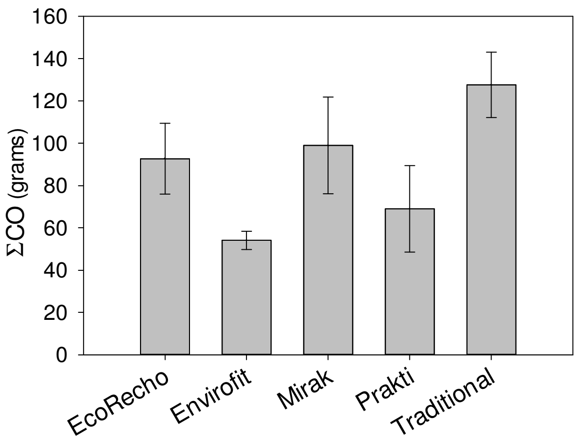

Figure 8: Average Total CO. Error bars are 95% confidence intervals. From left to right, the values are: 92.7 ± 16.7, 54.1 ± 4.3, 99.0 ± 22.9, 69.0 ± 20.4, 127.6 ± 15.5.

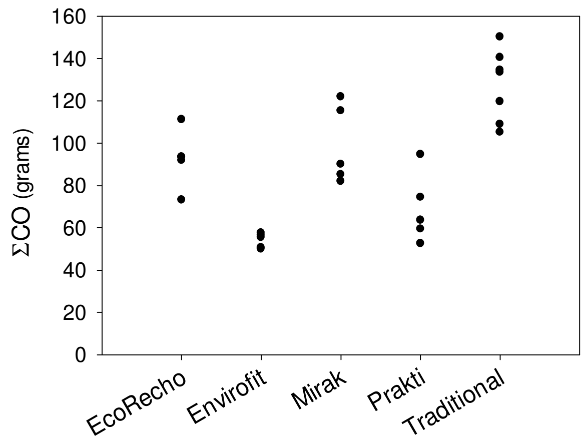

Figure 9: Total CO per test. See Appendix C for specific values.

3.2.2 Total Carbon Dioxide (CO_2)

CO_2 emissions were monitored, recorded, and summed for the entirety of each CCT with background CO_2 levels removed. The emissions were originally recorded in ppm and converted to g/m^3. A general equation for the flow rate through our duct system was previously found experimentally and used to convert the emissions from g/m^3 to g. The average total CO_2 for each stove can be seen in Fig. 10. The total CO_2 for each individual test can be seen in Fig. 11.

As can be seen in Figs. 10 and 11, the Prakti and Envirofit stoves emitted the least amount of CO_2 on average and the traditional stove emitted the most. The traditional stove emitted significantly more CO_2 than the EcoRecho, Envirofit, and Prakti stoves with 95% confidence. The Mirak also emitted significantly more than the Envirofit.

The total CO_2 emission data is included because it is potentially useful for carbon finance projects. It should be noted, however, that CO_2 emission is an unavoidable outcome from the complete combustion of hydrocarbon fuels such as charcoal or fuelwood. Hydrocarbon fuels are largely made of carbon, which is released primarily as CO_2 or CO when combusted. Higher CO_2 emission for a unit mass of fuel means the process of combustion was more complete and released fewer products of incomplete combustion such as toxic gases and particulates that cause health problems. So while it is more desirable to reduce emissions by burning less fuel overall, for a given amount of fuel, it is better to have a higher CO_2 emission than CO emission (a low CO/CO_2 emission ratio). The ratio of CO emission to CO_2 emission is presented in the next section for this reason.

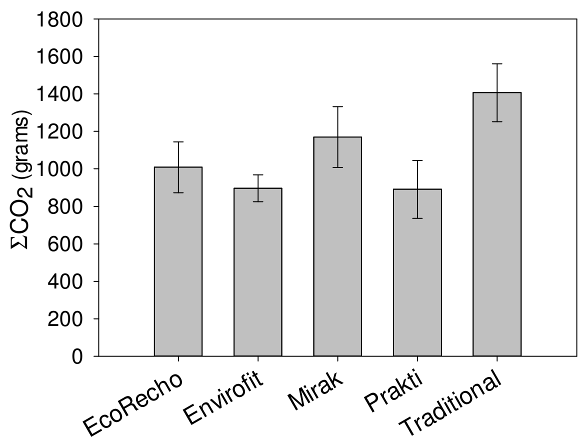

Figure 10: Average Total CO_2. Error bars are 95% confidence intervals. From left to right, the values are: 1008.6 ± 136.5, 896.8 ± 71.6, 1169.9 ± 162.2, 890.8 ± 154.7, 1406.8 ± 154.2.

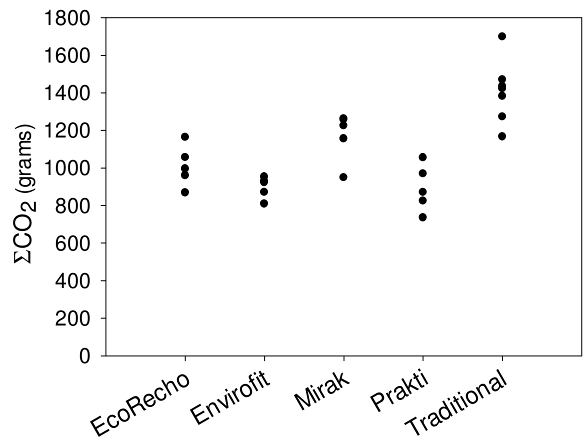

Figure 11: Total CO_2 per test. See Appendix C for specific values.

3.2.3 Ratio of Carbon Monoxide to Carbon Dioxide (CO/CO_2)

The average CO/CO_2 for each stove can be seen in Fig. 12. The CO/CO_2 for each individual test can be seen in Fig. 13.

As can be seen in Fig. 12, the Envirofit had the lowest average CO/CO_2 ratio and had significantly more complete combustion than the EcoRecho and traditional stoves with 95% confidence. The EcoRecho, Mirak, Prakti, and traditional stoves were not significantly different from each other. The EcoRecho and traditional stoves had the highest average CO/CO_2.

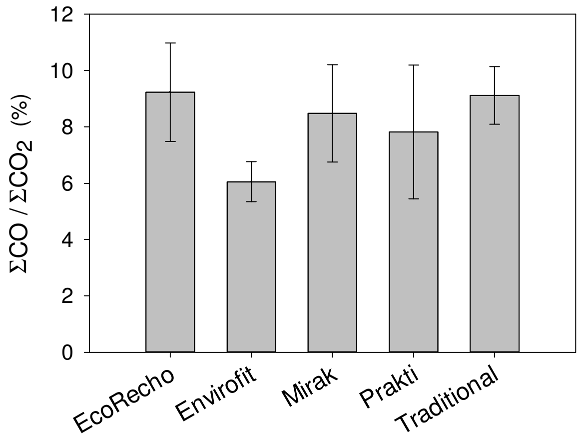

Figure 12: Average Ratio of CO/CO_2 (%). Error bars are 95% confidence intervals. From left to right, the values are: 9.2 ± 1.7, 6.1 ± 0.7, 8.5 ± 1.7, 7.8 ± 2.4, 9.1 ± 1.0.

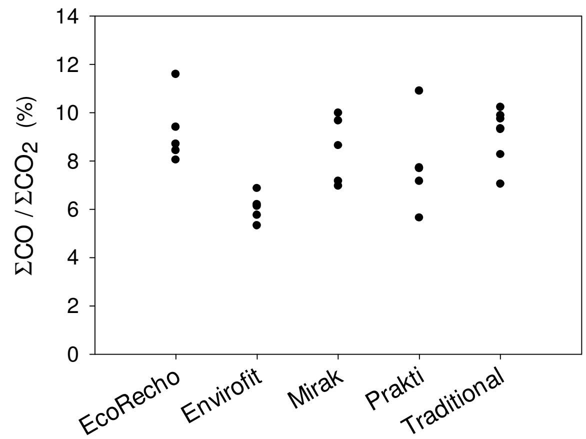

Figure 13: Ratio of CO/CO_2 per test (%). See Appendix C for specific values.

3.2.4 Emissions Conclusions

The traditional stove emitted the most CO and CO_2, indicating it burned the most fuel overall, which is supported by the specific fuel consumption data. In fact, there is fairly good agreement between Fig. 6 and Fig. 10, indicating that the CO_2 emissions are generally proportional to the specific fuel consumption. The Envirofit emitted the least amount of CO and CO_2 on average and had the lowest CO/CO_2. The Prakti emitted the second least amount of CO and CO_2 on average as well as having the second lowest CO/CO_2; however, large error bars prevented us from saying its performance was significantly different from that of other stoves.

3.3 Usability

These comments are from LBNL testers in the laboratory performing the CCTs, so some comments may not be relevant for Haitian cooks. We have previously disseminated our observations and informal user commentary from a single day Haiti cook-off in which most of these stoves were used in cooking *diri kole ak pwa* by Haitian women in the spring of 2010.[6]

[6] Report available online at http://www.fuelnetwork.org/index.php?option=com_docman&task=cat_view&gid=72&Itemid=57&limit=15&limitstart=0&order=date&dir=ASC

- EcoRecho: Testers had trouble with the holes in the charcoal pan, which clogged with ash during cooking. Also, the door regulating airflow only allowed for max air flow or no air flow and became extremely hot during cooking. Although not as cumbersome as the traditional stove, the EcoRecho was heavy due to its ceramic sides. These sides, however, did allow the stove to retain heat well. The EcoRecho had a very stable platform, consisting of movable prongs so the pot could be placed either on the prongs or on the charcoal directly. These prongs kept the pot from smothering the fire, and allowed small pieces of charcoal to be fed while the pot was on. Ash was easy to remove through the door in the front of the stove. The handles were solid and could easily handle dumping ash.

- Envirofit: The latch to control airflow was easy to use, but it became very hot. It would be difficult to regulate airflow for different power settings during cooking, since the air intake door was on the bottom of the stove and could not be seen while testing. Charcoal could be fed with the pot still on only if small pieces were used. This stove was the most portable due to its size and handles. The wooden handles stayed cool enough to move the stove around even while testing. Outer and inner grates had to be removed when dumping ashes or they would fall out into the ash.

- Mirak: The pot rested directly on the charcoal. This led to multiple issues such as reduced airflow leading to a smothered fire, contact with the pot cooling the burning pieces of charcoal, and an unstable pot as the charcoal burned down. The pot had to be removed when adding charcoal. The Mirak was straightforward to use but had no way of regulating airflow. Testers liked the detachable pan for dumping the remaining charcoal without having to move the entire stove.

- Prakti: The four prong platform was a bit unstable (not perfectly even), but overall the stove was found to be sturdy. The handles were small and fell down to rest against the side of the stove, causing them to become extremely hot and hard to maneuver while testing. It was considered the second most portable stove after the Envirofit and the best at regulating air flow. Although the door would get hot during testing, it was easy to move and adjust for any range of airflow. Removal of ashes was straightforward; the ash tray, albeit hot, caught most of the ashes and was easy to handle. This stove was also perceived to be time efficient.

- Traditional stove: The traditional stove is widely adopted in Haiti and was therefore assumed to be highly usable and fit Haitian needs well. The stove was generally stable, had sturdy legs, and had a large pan that could support various pot sizes and shapes. The large pan also allowed for large amounts of charcoal to be added at once. It had no doors which made it easy to use, but left no way to control the airflow for thermal power adjustments. Similar to the Mirak, the pot in the traditional stove sat directly on the charcoal making it potentially unstable and occasionally smothering the coals. The metal handles were sturdy and protruded from the stove, increasing stove usability; however, they would get hot during testing. Removing ash from the stove was difficult as ash would pour out simultaneously from two trays. However, the traditional stove was still a favorite of the testers as it was perceived to cook food quickly.

4. Conclusions

The traditional stove was clearly the least efficient in regard to fuel consumption, but cooked faster on average than two of the improved stoves (Envirofit and Mirak). The Prakti was potentially the fastest stove, although no statistically significant differences ($p = 0.05$) were shown. In terms of specific fuel consumption, the Prakti and the Envirofit used the least amount of charcoal on average.

For CO emission and CO/CO_2, the Envirofit had the lowest emissions on average and released significantly less CO than the EcoRecho and traditional stoves. The traditional stove produced the most CO, and the traditional and EcoRecho stoves had the highest CO/CO_2.

We have included tester comments on usability for stove designers; however it is unknown to what extent these comments are relevant to the user experience of Haitian cooks.

In the future, more emissions data would help decrease the confidence interval error bars, allowing for better comparisons. These tests have shown there are statistically significant differences between the stoves, and most importantly, that there are statistically significant improvements gained with the improved stoves over the traditional stove.

Acknowledgements

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Appendix A: Statistics

To assess the variation in the average value $\bar{x}$ over a number of measurements, the sample standard deviation σ_x is calculated by:

$$\sigma_x = \sqrt{\frac{1}{n-1}\sum(x_i - \bar{x})^2} \tag{1}$$

where n is the number of measurements or sample size and $x_i = 1,2, \ldots n$ are the individual measurements used to calculate the average. A convenient way to calculate the sample standard deviation is using the “STDEV” function in Excel (the “STDEV” function uses $n - 1$ in the denominator).

To assess uncertainty in the average, the standard deviation of the mean $\sigma_{\bar{x}}$, known as the standard error, is calculated as the sample standard deviation divided by the square root of the sample size,

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{n}} \tag{2}$$

For a normal distribution, if a value is reported as the mean plus or minus the standard error ($\bar{x} \pm \sigma_{\bar{x}}$) then there is 68% confidence that measurements will be within these bounds. It is typical to report uncertainty at the 95% confidence level which, for a normal distribution, is approximately two standard deviations from the mean ($\bar{x} \pm 1.96\ \sigma_{\bar{x}}$). When the uncertainty at 95% confidence is used as the error bars for data plotted in bar charts, it can clearly be determined whether differences between two population means are significant; if the error bars overlap, the difference is not statistically significant at the 95% confidence level, and if the error bars do not overlap, then the difference is significant at the 95% confidence level.

When the measurements are assumed to be normally distributed but the sample size is small (n<30) and the population standard deviation is unknown, a Student’s t-distribution is used. When using the Student’s t-test to calculate confidence intervals, and assess statistical significance, the confidence intervals are

$$\bar{x} \pm t_p \sigma_{\bar{x}} \tag{3}$$

where the coefficient t_p is the value of the Student's t-distribution at the chosen level of confidence. A selection of t-values is listed in the table below as an example. It is recommended that sample sizes (the number of tests per stove) be greater than five to reduce the reported uncertainty. For further information, references are listed below.

n (Sample Size)	n – 1 (Degrees of Freedom)	$t_{.975}$ (One sided) or $t_{.95}$ (Two sided)
1	-	-
2	1	12.71
3	2	4.30
4	3	3.18
5	4	2.78
6	5	2.57
7	6	2.45
8	7	2.36
9	8	2.31
10	9	2.26

References

J. R. Taylor, *An Introduction to Error Analysis*, 2nd ed. (University Science Books, 1997).

M. R. Spiegel, S. Lipschutz, and J. Liu, *Mathematical Handbook of Formulas and Tables*, 3rd ed. (McGraw-Hill, 2008).

The following Wikipedia pages are also useful at explaining these concepts: http://en.wikipedia.org/wiki/1.96 and http://en.wikipedia.org/wiki/Student%27s_t-distribution.

Appendix B: Stove Performance Data Tables

Here we present all of the data values for total burn time and specific fuel consumption.

<u>Total Burn Time</u> (minutes)

	Total Burn Time (mins)				
Test #	**EcoRecho**	**Envirofit**	**Mirak**	**Prakti**	**Traditional**
1	110.0	153.9	140.9	132.4	133.5
2	126.8	138.3	120.8	119.5	110.3
3	105.3	110.6	187.8	99.9	107.5
4	115.0	122.5	128.3	109.8	128.4
5	128.5	110.8	119.7	112.0	136.0
6	105.0	122.9	136.0	105.3	109.3
7	161.8	138.0	141.0	131.5	153.7
8	154.8	169.8	125.0	121.3	106.7
9		133.3	135.1	112.9	112.5
10				118.2	102.8
11				118.8	105.8
12					116.0

<u>Specific Fuel Consumption</u> (g/kg)

	Specific Fuel Consumption (g/kg)				
Test #	**EcoRecho**	**Envirofit**	**Mirak**	**Prakti**	**Traditional**
1	117.6	109.7	130.8	93.3	111.0
2	99.1	72.3	96.2	79.4	122.0
3	100	63.6	113.9	82	191.3
4	100.6	84.1	98.4	80	167.4
5	100.4	89.4	113.8	78.9	144.3
6	109	90.5	135.5	97.8	150.4
7	103.5	75.4	89.1	88	197.9
8	72.7	73.2	137.4	50	156.1
9		106.8	101.3	67	104.9
10				72.7	188
11				109.3	99.3
12					137

Appendix C: Emissions Data Tables

Here we present all of the data values for ΣCO, ΣCO_2, and $\Sigma CO/\Sigma CO_2$.

ΣCO (grams)

Test #	1	2	3	4	5	6	7
EcoRecho	93.5	91.9	111.2	93.6	73.3		
Envirofit	50.7	55.5	50.1	56.5	57.6		
Mirak	90.1	115.4	82.0	122.0	85.3		
Prakti	59.5	94.8	74.5	52.6	63.7		
Traditional	133.6	140.6	134.6	150.3	109.0	105.2	119.8

ΣCO_2 (grams)

Test #	1	2	3	4	5	6	7
EcoRecho	1163.4	1056.1	959.8	995.2	868.6		
Envirofit	952.6	808.9	870.1	922.7	930.0		
Mirak	1257.3	1156.1	948.9	1262.7	1224.6		
Prakti	1055.1	869.8	969.1	735.3	824.6		
Traditional	1435.0	1422.7	1382.0	1469.9	1166.6	1272.4	1699.0

$\Sigma CO/\Sigma CO_2$ (%)

Test #	1	2	3	4	5	6	7
EcoRecho	8.04%	8.70%	11.59%	9.40%	8.44%		
Envirofit	5.32%	6.86%	5.76%	6.13%	6.20%		
Mirak	7.16%	9.98%	8.64%	9.67%	6.96%		
Prakti	5.64%	10.90%	7.69%	7.16%	7.72%		
Traditional	9.31%	9.88%	9.74%	10.23%	9.34%	8.27%	7.05%