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Performance of Charcoal Cookstoves for Haiti, Part 1: Results from the Water Boiling Test

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1. Introduction

In April 2010, a team of scientists and engineers from Lawrence Berkeley National Lab (LBNL) and UC Berkeley, with support from the Darfur Stoves Project (DSP), undertook a fact-finding mission to Haiti in order to assess needs and opportunities for cookstove intervention. Based on data collected from informal interviews with Haitians and NGOs, the team, Scott Sadlon, Robert Cheng, and Kayje Booker, identified and recommended stove testing and comparison as a high priority need that could be filled by LBNL.

In response to that recommendation, five charcoal stoves were tested at the LBNL stove testing facility using a modified form of version 3 of the Shell Foundation Household Energy Project Water Boiling Test (WBT). The original protocol is available online at: http://ehs.sph.berkeley.edu/hem/?page_id=38. **Stoves were tested for time to boil, thermal efficiency, specific fuel consumption, and emissions of CO, CO_2, and the ratio of CO/CO_2.** In addition, Haitian user feedback and field observations over a subset of the stoves were combined with the experiences of the laboratory testing technicians to evaluate the usability of the stoves and their appropriateness for Haitian cooking. The laboratory results from emissions and efficiency testing and conclusions regarding usability of the stoves are presented in this report.

2. Methods

2.1 Stoves Tested

For inclusion in testing, we attempted to obtain stoves that were either being considered for distribution by non-governmental organizations (NGOs) operating in Haiti or that were already widely available in Port au Prince.

Based upon these criteria as well as availability of the cookstoves for testing, the following five stoves shown in Fig. 1a were chosen for inclusion in the evaluation.

Fig. 1a: From left to right: Traditional, EcoRecho, Prakti Rouj, StoveTec Two-Door, Mirak

A. 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 typically last only six months to one year.

B. EcoRecho: A metal stove with a ceramic liner made in Haiti. The pot sits above the charcoal on three triangular metal wedges. 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).
C. Prakti Rouj: Insulated metal stove. The rectangular charcoal chamber is the smallest of all stoves. A door on the front of the stove can be adjusted to control airflow. This stove costs US $25.
D. StoveTec Two-Door: Dual-fuel wood and charcoal stove with a metal body and a clay insulated interior. The pot is placed on top of three metal knobs and is not in contact with the charcoal. A door on the front of the stove can be adjusted to control airflow. According to the StoveTec website, this stove can be purchased for a humanitarian project for US $15.
E. Mirak (copy): A locally made, scrap metal copy of the Mirak stove designed by CARE, a humanitarian organization fighting global poverty, and widely available in Port-au-Prince. This stove was purchased for 150 gourdes in April 2010 (US $3.75). The charcoal chamber is half spherical, and the pot sits directly on the charcoal.

We did not receive instructions on using the stoves but did several practice runs with each stove prior to testing. Each stove was operated in order to maximize its efficiency, including varying the power when possible by manipulating airflow.

Although the StoveTec comes with a skirt that can be used for added efficiency, we thought it better to evaluate the stove without the skirt as we were concerned the skirt may not be commonly used. These concerns were based on anecdotal evidence from other countries, in which detachable skirts have generally been discarded, and observation of incompatibility in size between the skirt and the larger rice pots used in Haiti.

2.2 Fuels tested

Grillmark© natural lump charcoal was used for all testing. Charcoal samples were analyzed using standard oven-dry procedures and were found to have 5.9% moisture content. However, results from that experiment were not available in time to incorporate into the efficiency and specific fuel calculations, so reported values are uncorrected for actual moisture content. The expected impact of correcting for moisture content is the efficiency for all stoves will rise somewhere between three and four percentage points (i.e. 31.5% would become 34%). Note, however, that while the oven-dry test confirmed typical rule-of-thumb estimates for charcoal (approximately 5%), the standard WBT procedure includes moisture correction for wood fuels, not for charcoal.

2.3 Test System

All testing was performed under controlled conditions at Lawrence Berkeley National Laboratory. The test system consists of a stove platform and an exhaust hood which draws gasses upward where they are mixed and sampled (Fig. 1b). Both CO and CO_2 emissions were measured with a California Analytical Instruments 600-series gas analyzer and dilution rates were continuously monitored. In addition to emissions, fuel weight and water temperature were measured and recorded in real time.

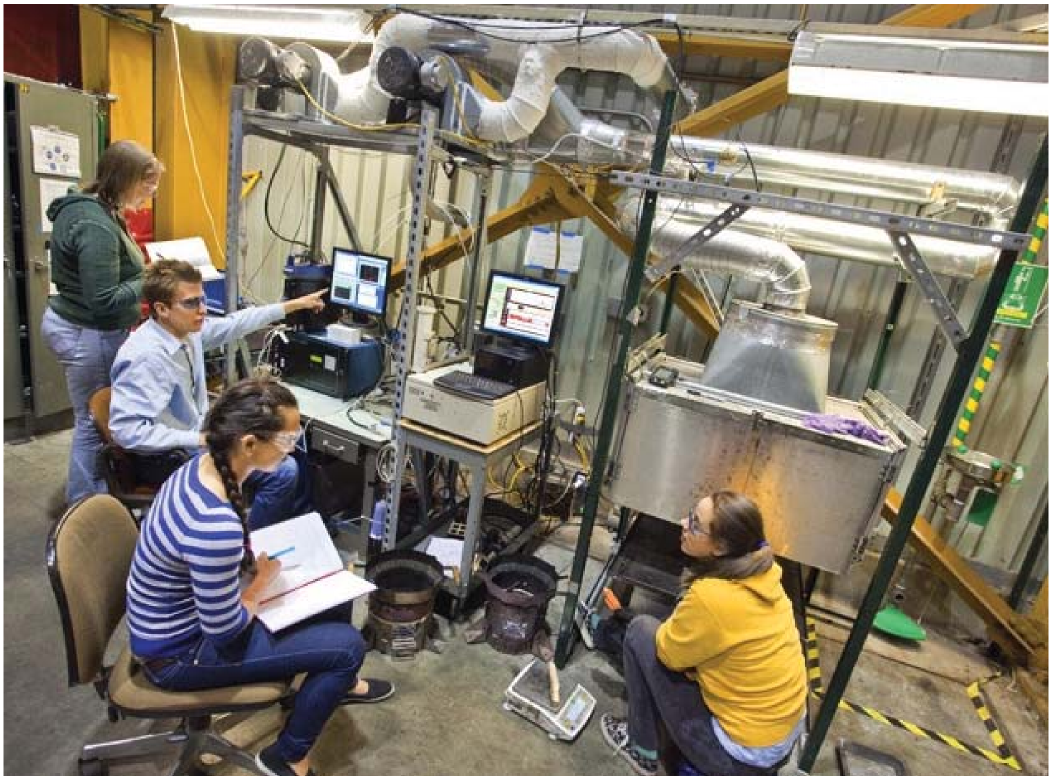

Fig. 1b: Above: The stove testing system at LBNL. Below: A close-up view of a stove (the Mirak) on the testing platform, with the front doors of the exhaust hood open to view the set-up.

2.4 Protocol

A modified form of the Shell Foundation Household Energy Project Water Boiling Test (WBT) version 3.0 was used to evaluate the stoves. The test consists of three phases:

1. Cold Start (high power): Using a cold stove and a cold pot, 2.5L of room temperature water is brought to a boil.
2. Hot start (high power): Immediately following the cold start, the hot water is replaced with a new 2.5L of room temperature water which is brought to a boil.
3. Simmer (low power): Immediately following the hot start, the already boiled water is maintained at a simmer for 45 minutes. In this phase, the stove, pot, and water remain hot from the second phase of the test.

Data for thermal efficiency and emissions were collected for all three test phases. When ventilation doors were available, we kept them open for the high power tests (cold start phase and hot start phase), and 50-60% open during the low power (simmer phase) test.

The same flat-bottom, 15” diameter, aluminum pot purchased in Port-au-Prince was used for all of the tests. We tried to initially load all of the stoves with 250g of charcoal at the beginning of the tests. Note that in some cases the chamber of the Prakti was too small to accommodate the whole 250g, so a slightly smaller amount was used.

The WBT was designed for wood-burning stoves and cannot be exactly applied to charcoal-burning stoves. We made the following modifications to accommodate charcoal stoves. These modifications are consistent with the practices observed in Haiti.

1. To start the fire, a piece of high-resin pine wood was placed on top of the charcoal pile and lit. The testers then blew on the wood to light the charcoal, as was observed in Haiti.
2. When calculating equivalent dry fuel consumed for all phases of the WBT, the wood-burning protocol incorporates the energy required to turn the leftover wood into char. However, we used charcoal instead of wood and because charcoal is essentially char already, we assumed the energy content of the leftover charcoal was the same as the initial charcoal, allowing the change in carbon (ΔC_c) to equal zero. Also, due to differences in the energy content between charcoal and wood, we replaced the coefficient of 1.12 with 1.08. This changed the equation[1] (for example in the cold start phase) from:

$$F_{cd} = F_{cm} * (1 - 1.12 * m) - 1.5 * \Delta C_c$$

to:

[1] F_{cd} is the equivalent dry fuel consumed, F_{cm} is the fuel consumed, m is the moisture content of the fuel, and ΔC_c is the net change in char during the test. For further information see the Shell Foundation Household Energy Project WBT, version 3.0, found at: http://ehs.sph.berkeley.edu/hem/?page_id=38 , and Appendix B for further explanation of the change to the equation.

$$F_{cd} = F_{cm} * (1 - 1.08 * m)$$

2.5 Analysis

For each metric, we report stove performance of the WBT as a whole, averaged or summed over all three phases, as well as the average performance of the simmer phase. Because Haitian cooking often requires long periods of simmering, sometimes for many hours, performance during that phase is particularly important. With that in mind, we have isolated and presented the results of the simmer phase in addition to presentation of results from all phases of the WBT combined. This presentation will enable readers to see how each stove performs specifically during the simmer phase as well as over the entire test.

When presenting graphs of the results for each stove performance metric, we include error bars equal to the ± 95% confidence intervals so comparison between stoves is clearly visible. Due to large variability and the small number of tests, the confidence intervals were sometimes quite large. When confidence intervals are large, often the results aren't statistically significant. Even so, observed differences from the experiments may be practically significant for real-world performance in the field. Additionally, the Water Boiling Tests will be followed up with Controlled Cooking Tests to more similarly represent the cooking practices in Haiti.

To account for the small sample sizes, we calculated the standard deviation and the standard error, and using the Student's t-distribution, we calculated the ± 95% confidence intervals (see Appendix C for details of these calculations). We also conducted hypothesis testing to identify whether differences between stoves were statistically significant at the p=0 .05 level. When significant differences were found at the group level from the 2-factor ANOVA hypothesis test, we followed up with pair-wise analysis using a Tukey HSD test to identify which pairs of stoves were significantly different at the 0.05 level.[2]

3. RESULTS

Results are grouped into three categories:

- **Efficiency:** time to boil, thermal efficiency, and temperature-corrected specific fuel consumption
- **Emissions**: CO, CO_2, and CO/CO_2 ratio
- **Usability**: observations of ease of stove use from stove testers at LBNL

[2] For those not familiar with hypothesis testing, these tests are done by first posing a 'null hypothesis', proposing that stove performance is actually identical and the observed differences are the result of random variation. Statistical analysis is then conducted, and the hypothesis is only disproved, meaning the results are significant if the analysis shows the observed difference in performance could occur from random variation alone less than 5% of the time.

Equations for the various metrics are not presented here but can be found in the Shell Foundation Household Energy Project Water Boiling Test (WBT), version 3.0. The protocol is available online at: http://ehs.sph.berkeley.edu/hem/?page_id=38.

3.1 Efficiency

3.1.1 Time to Boil

Time to boil was measured beginning when the charcoal was considered lit and ending when water started boiling (at local atmospheric pressure). The charcoal was qualitatively determined to be lit when the testers observed there was enough charcoal burning to keep the fire from dying out.

The traditional stove brought water to a boil more quickly than any of the improved stoves. In the cold start test phase, water heated on the traditional stove boiled in only 36.5 minutes, yet the same amount of water took 51.3 minutes to boil in the next fastest stove (the Prakti), a difference of almost 15 minutes. Although all of the improved stoves were much slower than the traditional stove, they performed similarly to each other with averages ranging from 51.3 to 59.8, a difference of 8.5 minutes.

	Average Time to Boil (minutes)	**Rank (Fastest to slowest)**
EcoRecho	55.2	4
Mirak	54.1	3
Prakti	51.3	2
StoveTec	**59.8**	**5**
Traditional	**36.5**	**1**

Table 1: Time to Boil for the Cold Start Phase

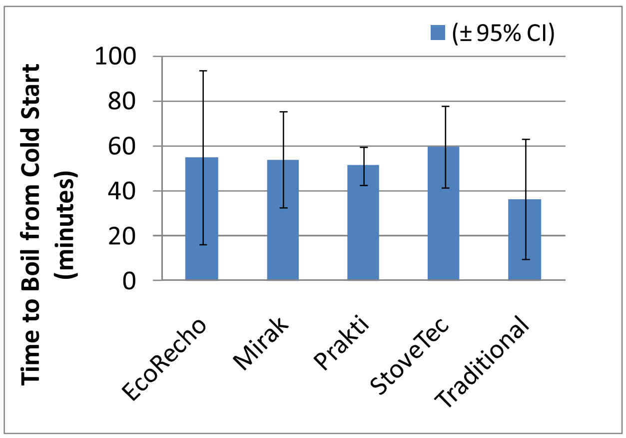

Fig. 2: Time to Boil for the Cold Start Phase. Error bars are ± 95% confidence intervals.

In the hot start test phase, in which room temperature water is placed on already heated coals, the results are similar. Once again, the traditional stove was faster than any improved stove, and the improved stoves performed similarly to one another. One note on the hot start results: the boiling time of the Prakti showed a large amount of variation between tests, with boiling time ranging from 17 to 51 minutes.

	Time to Boil (minutes)	Rank (Fastest to slowest)
EcoRecho	32.1	3
Mirak	**42.1**	**5**
Prakti	33.3	4
StoveTec	29.9	2
Traditional	**24.0**	**1**

Table 2: Time to Boil for the Hot Start Phase

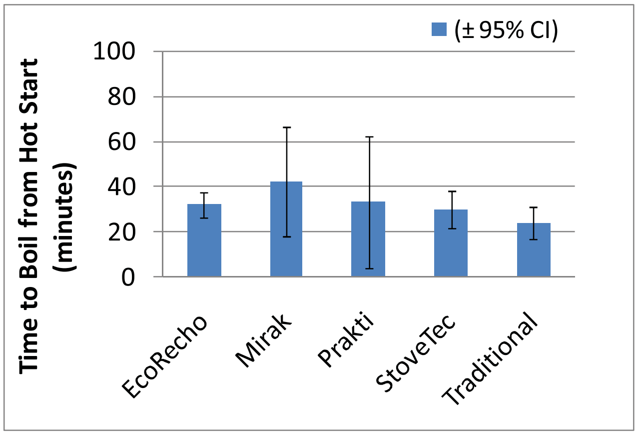

Fig. 3: Time to Boil for the Hot Start Phase. Error bars are ± 95% confidence intervals.

3.1.2 Thermal Efficiency

Thermal efficiency is the ratio of the heat content of increasing the water temperature and evaporating the mass of water released as steam, to the energy consumed by burning wood. Calculations for determining thermal efficiency can be found in the WBT Protocol.

	Efficiency in Simmer Phase (%)	Efficiency Over the Entire WBT (%)
EcoRecho	37.5	31.6
Mirak	34.1	28.6
Prakti	**46.2**	**37.3**
StoveTec	36.6	30.5
Traditional	**28.5**	**22.2**

Table 3: Thermal Efficiency over the simmer phase and the entire WBT

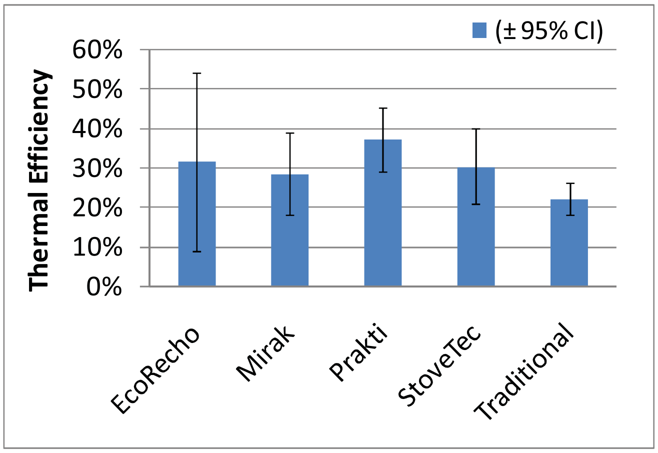

Fig. 4: Thermal Efficiency averaged over the entire WBT. Error bars are ± 95% confidence intervals.

Table 3 above shows the thermal efficiency for the simmer phase as well as the average efficiency over all phases of the WBT. Average thermal efficiency results for the four stoves were better than that of the traditional stove. Results were significant at the 0.05 level for the entire WBT and for the simmer phase. All stoves, including the traditional stove, showed higher efficiency during the simmer phase than the hot or cold start phases.

Fig. 4 shows the average thermal efficiency over all phases. The Prakti and EcoRecho were the most efficient and the traditional and Mirak were the least efficient. In making comparisons between stoves and assessing whether differences between stoves were significant, we found the Prakti and traditional stoves to be significantly different from each other at the 0.05 level.

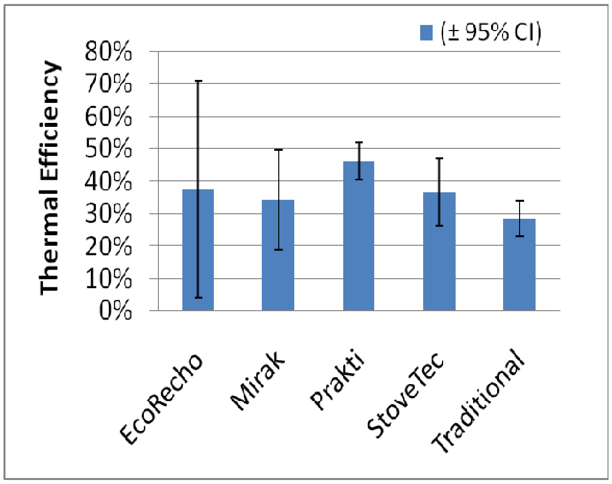

Fig. 5: Thermal Efficiency for the Simmer Phase. Error bars are ± 95% confidence intervals.

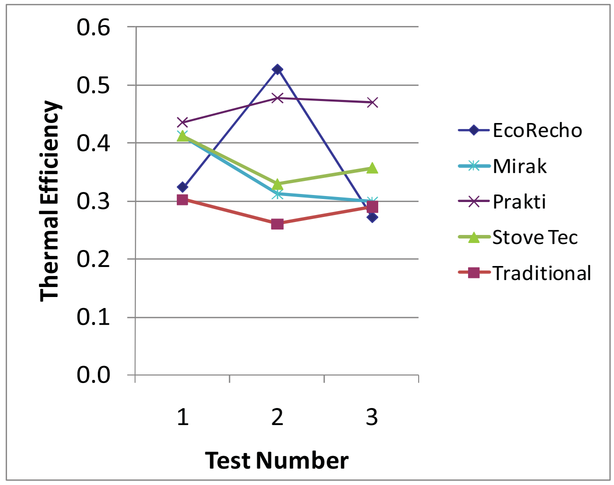

Fig. 6: Thermal Efficiency, Simmer Phase by Test.

When the simmer phase is examined by itself (Fig. 5), the traditional stove fares the worst. The Prakti and traditional stoves were significantly different from each other at the 0.05 level.

The graph illustrating thermal efficiency of the simmer phase over the three simmer phase tests performed for each stove (Fig. 6) is provided to illustrate the variability in results between tests. (The data and standard deviations are also included in Appendix A.) For example, considering the un-averaged individual data points, the EcoRecho had the highest efficiency of any stove as well as one of the lowest. The Prakti consistently performed well, while the traditional consistently performed poorly. Other stoves varied in performance but none so much as the EcoRecho. We note the variation could come from a number of factors, only some of which are related to stove design and actual performance, and that a larger sample size would be useful for future analysis.

3.1.3 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, cooked beans, or loaves of bread. In the case of the cold start phase, high-power WBT, it is a measure of "the amount of wood required to produce one liter (or kilo) of boiling water starting with a cold stove."

Our results show the temperature-corrected specific fuel consumption, which adjusts for differences in initial water temperature.

	Simmer Phase(g)	Total WBT (g)
EcoRecho	324	**479**
Mirak	**289**	507
Prakti	378	539
StoveTec	346	572
Traditional	**808**	**979**

Table 5: Temperature-Corrected Specific Fuel Consumption for Simmer Phase and entire WBT

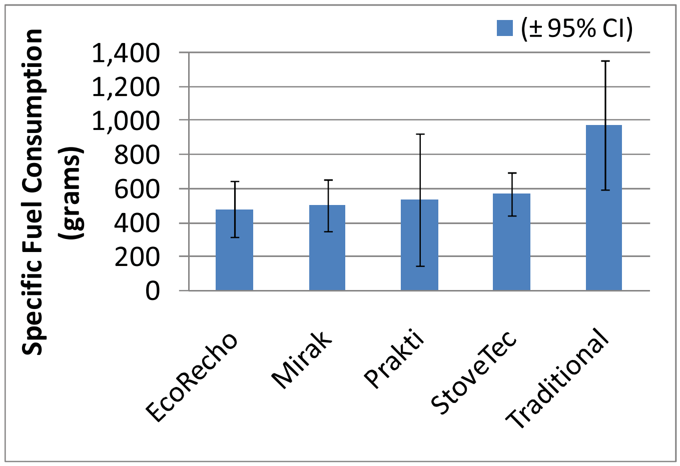

Fig. 7: Temperature-Corrected Specific Fuel Consumption over the entire WBT. Error bars are ± 95% confidence intervals.

As seen in the table of temperature-corrected specific fuel consumption (Table 5), the simmer phase accounted for a large portion of the fuel consumed for each stove. All improved stoves used considerably less fuel than the traditional stove with most using a little more than half that of the traditional stove. However, specific fuel consumption results for the entire WBT (Fig. 7) and simmer phase (Fig. 8) showed so much variation that none of the stoves were significantly different from one another at the 0.05 level for the entire WBT or the simmer phase alone.

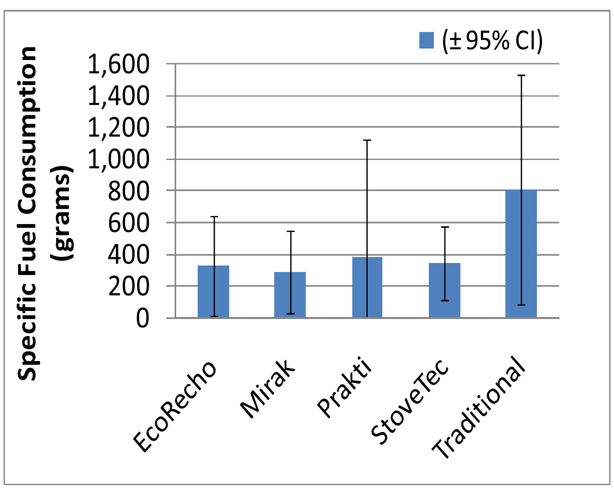

Fig. 8: Specific Fuel Consumption for the Simmer Phase. Error bars are ± 95% confidence intervals.

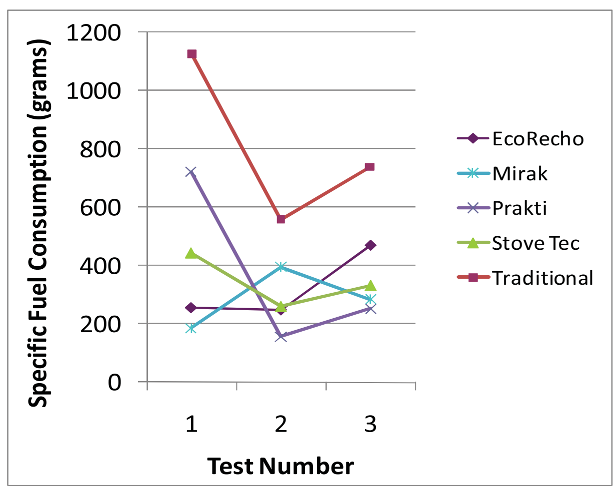

Fig. 9: Specific Fuel Consumption, Simmer Phase by Test.

Fig. 9 shows specific fuel consumption for the simmer phase separated by test number. The traditional stove performed much worse than the improved stoves. Fig. 9 also shows the improved stoves performed similarly to each other with no stove standing out from the others. In fact, the relative stove rankings changed with each test; for example, the Mirak was ranked first, fourth, and second, in tests one through three. In summary, the traditional stove fared worst overall and in every phase individually, the EcoRecho had the lowest average specific fuel consumption in the overall WBT, and the Mirak had lowest average fuel consumption during the simmer phase. However, at the 0.05 level, differences between the stoves were not statistically significant.

The variation in the results for the Prakti stove are particularly large (standard deviation 305g of total fuel consumption 539g), and the results as a whole showed more variation than the other tests with several outliers. We believe some of these results are an artifact of the way specific fuel consumption is calculated in the WBT, specifically the accounting for water boiled off. However, because we do not know exactly what led to these outliers, we did not feel justified in disregarding them. It is worthwhile to note that stoves burning charcoal are much more difficult to regulate for their thermal power output than stoves burning fuelwood. This poor regulation contributes to the high variation in specific fuel consumption.

3.1.4 Efficiency Conclusions

The time necessary to boil water for both hot and cold starts is much higher for all improved stoves than for the traditional stove. This difference is worrisome because stove users often place great importance on cooking time; they are less likely to continue using a stove that heats slowly and lengthens their cooking time. Findings from informal interviews with women in Haiti during the LBNL/DSP trip reflected concerns of lengthy cooking time and was cited as a reason why some had given up on the Mirak. The differences in time to boil between the improved stoves, however, are not large, so it does not yet appear that any of them is a clear leader in terms of time-savings.

For the average performance across all phases of the WBT, thermal efficiency was highest for Prakti and EcoRecho and lowest for Mirak and traditional. Thermal efficiency results were statistically significant at the p=0.05 level for all of the phases of the WBT. At the 0.05 level, the Prakti and traditional stoves were significantly different from each other over all of the phases of the WBT and for the simmer phase alone.

Overall, specific fuel consumption was lowest/best for the EcoRecho and Mirak, and highest/worst for the StoveTec and traditional. The findings for specific fuel consumption had greater uncertainty than those for thermal efficiency. Significant differences in performance were not observed for the full WBT or for the simmer phase.

In conclusion, considering the findings for thermal efficiency and specific fuel consumption in aggregate, the Prakti and the EcoRecho performed the best. However, they were not significantly different from the StoveTec or the Mirak.

3.2 Emissions

3.2.1 Total Carbon Monoxide (CO)

In each WBT conducted, CO emissions were monitored, recorded, and summed for each phase of the WBT. Those sums were then averaged across multiple tests to calculate the total CO released per phase. Total CO emission for the entire WBT, combining all phases, was calculated by summing these averaged phase totals. This summing of averages produces a propagation error, which was taken into account when calculating standard deviations and standard errors.

Results for total CO emission for each stove for the simmer phase alone and over the entire WBT were not significantly different for all of the stoves at the p=0.05 level, meaning true differences between the stoves' emissions performance cannot be detected. Although not significant, total CO emitted over all phases was highest for StoveTec and EcoRecho and lowest for Mirak and Prakti. It should be noted that in terms of CO emissions, not all improved stoves outperformed the traditional stove.

As seen in the error bars of the graphs of CO emissions (Fig. 10 and Fig. 11) both the StoveTec and traditional stove had large variation in their emissions. It was difficult to assess whether the stoves were significantly different in their performance at these sample sizes. It might be easier to distinguish significant differences between the stoves with more tests per stove to obtain larger sample sizes, especially for the simmer phase.

	Total CO – Simmer Phase (g)	**Total CO – All Phases (g)**
EcoRecho	**98.6**	179
Mirak	**59.1**	**134**
Prakti	68.7	136
StoveTec	83.5	**183**
Traditional	91.6	154

Table 6: Total CO Emissions for Simmer Phase and over all Phases

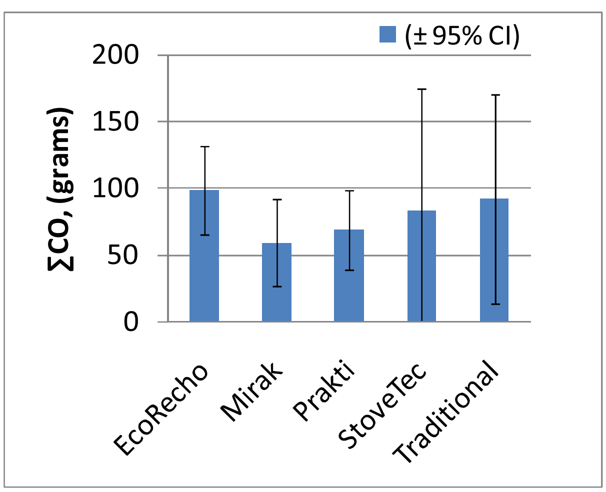

Fig. 10: Total CO Emissions for Simmer Phase. Error bars are ± 95% confidence intervals.

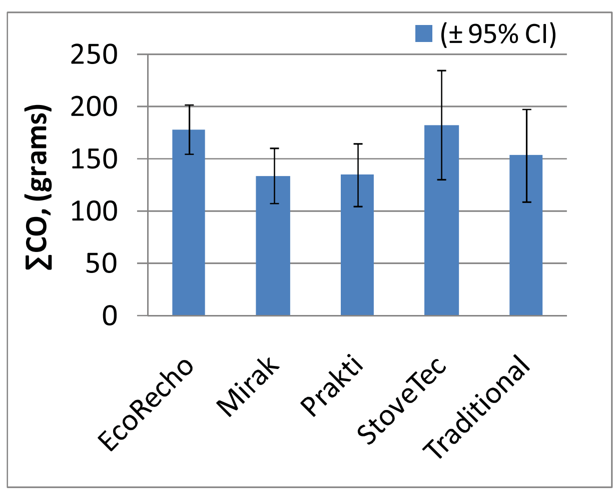

Fig. 11: Total CO Emissions over all Phases. Error bars are ± 95% confidence intervals.

3.2.2 Total Carbon Dioxide (CO_2)

In each WBT conducted, CO_2 emissions were monitored, recorded, and summed for each phase of the WBT. Those sums were then averaged across multiple tests to calculate the total CO_2 released per phase. Total CO_2 emission for the entire WBT, combining all phases, was calculated by summing these averaged phase totals. This summing of averages produces a propagation error, which was taken into account when calculating standard deviations and standard errors. As can be seen in Table 7, the simmer phase generally accounted for about half the total CO_2 emitted.

For the simmer phase, the Prakti had the lowest CO_2 emission, while the traditional stove had the highest (Fig. 12). However, results for total CO_2 emission for each stove for the simmer phase were not significantly different for all of the stoves at the p=0.05 level, meaning true differences between the stoves' emissions performance cannot be detected. Although the traditional stove had the highest average CO_2 emission for the simmer phase, its variability and the small sample size made it impossible to distinguish it from the Prakti even though the average CO_2 emissions for both stoves is quite different.

For the full WBT, the Prakti's CO_2 emissions were the lowest while the StoveTec's were the highest (Fig. 13). All stoves, except the StoveTec, had lower CO_2 emissions over the entire WBT than the traditional stove. Similar to the CO results, the traditional stove showed high variability, making it difficult to find a significant difference between its performance and that of the improved stoves. Over the entire WBT, at the p=0.05 level, the EcoRecho and Prakti stoves were significantly different from the StoveTec.

	Total CO_2 - Simmer (g)	**Total CO_2 – All Phases (g)**
EcoRecho	640	1376
Mirak	747	1577
Prakti	**542**	**1249**
StoveTec	802	**1842**
Traditional	**928**	1625

Table 7: Total CO_2 Emissions for Simmer Phase and over all Phases

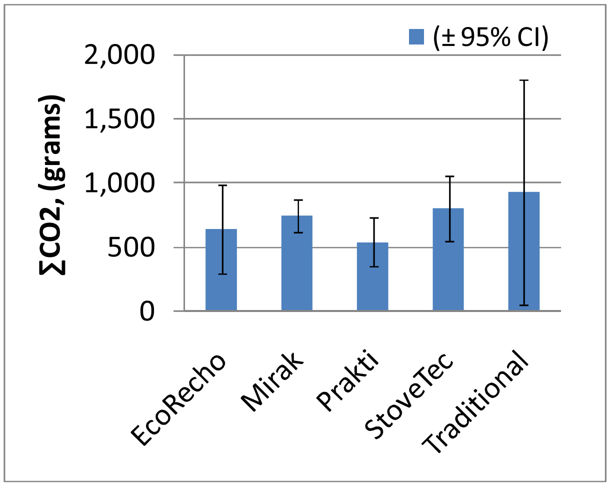

Fig. 12: Total CO_2 Emissions for the Simmer Phase. Error bars are ± 95% confidence intervals.

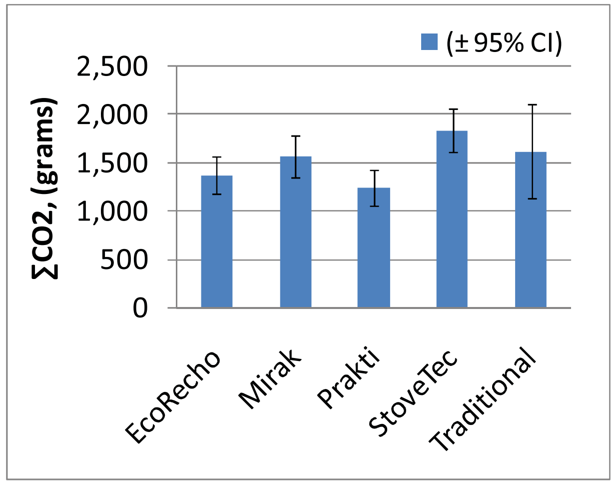

Fig. 13: Total CO_2 Emissions over all Phases. Error bars are ± 95% confidence intervals.

We include total CO_2 emission data because it is potentially useful for carbon finance projects. However, it should be noted CO_2 emission is a required outcome from the combustion of hydrocarbon fuels such as charcoal or fuelwood and, therefore, is not a completely undesirable outcome. Hydrocarbon fuels are largely made of carbon, which is released primarily as CO_2 or CO when combusted. Therefore, while it is more desirable to burn less fuel overall to decrease the total amount of emissions, 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). Higher CO_2 emissions mean the process of combustion was more complete and released less products of incomplete combustion such as toxic gases (CO being one of them) and particulates that cause health problems. The ratio of CO emission to CO_2 emission is presented in the next section for this reason.

3.2.3 Ratio of CO/CO_2

In each WBT conducted, the ratio of CO emission to CO_2 emission was calculated for each test phase and for all phases of the WBT. As can be seen in Table 8, for the simmer phase as well as overall, the Mirak had the lowest CO/CO_2 emission ratio and the EcoRecho had the highest. Over the entire WBT, the Mirak and EcoRecho were significantly different from one another, but middle ranks could not be distinguished at the $p=0.05$ level. For the simmer phase alone, stoves were not significantly different from one another at the $p=0.05$ level, meaning true differences between the stoves' total CO/CO_2 emission ratios were not detected.

	Total CO/CO_2 - Simmer (%)	Total CO/CO_2 – All Phases (%)
EcoRecho	**15.8**	**13.0**
Mirak	**8.0**	**8.5**
Prakti	12.7	10.9
StoveTec	10.8	9.9
Traditional	10.0	9.5

Table 8: CO/CO_2 Emission Ratio for Simmer Phase and over all Phases

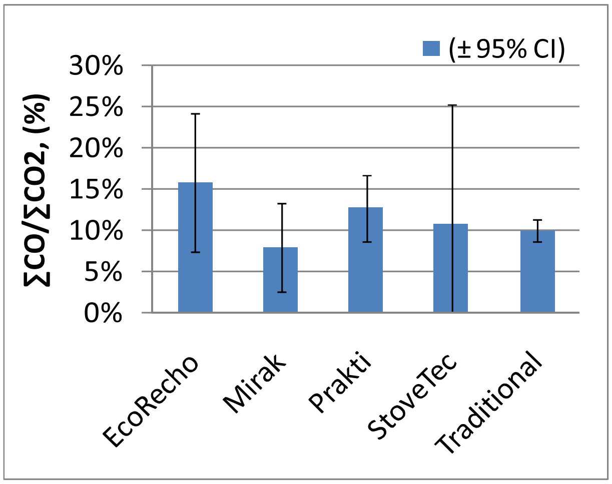

Fig. 14: CO/CO_2 Emission Ratios for the Simmer Phase. Error bars are ± 95% confidence intervals.

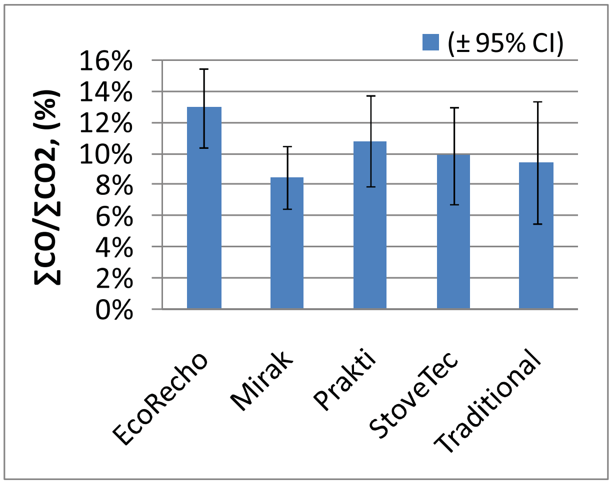

Fig. 15: Total CO/CO_2 Emission Ratios over all Phases. Error bars are ± 95% confidence intervals.

3.2.4 Emission Conclusions

CO emission over all phases of the WBT and over the simmer phase considered separately was not significantly different among the tested stoves. So, although Prakti and Mirak had the lowest average emissions, their results cannot be distinguished from those of the other stoves at the significance level of p=0.05. CO emissions from the simmer phase accounted for somewhat less than half the total CO emissions from the entire WBT.

CO_2 emissions over all phases of the WBT were the lowest for the Prakti and highest for the StoveTec. Over the entire WBT, at the p=0.05 level, the EcoRecho and Prakti stoves were significantly different from the StoveTec. However, similar to CO emissions, CO_2 emissions for the separately considered simmer phase were not significantly different among the tested stoves.

The Mirak had the lowest CO/CO_2 emission ratio and the EcoRecho had the highest. Over the entire WBT, at the p=0.05 level, the CO/CO_2 emission ratios of the Mirak and EcoRecho were significantly different from each other, but middle ranks could not be distinguished. CO/CO_2 ratios for the simmer phase alone were not significantly different at the p=0.05 level.

In considering both CO emissions and the CO/CO_2 ratio, the Mirak stove performed the best, although the difference was only significant when comparing the best and worst performers: middle ranks were not statistically significant.

3.3 Usability

In this section, we provide comments and observation on the ease of using the stove. Except where noted, the comments are from testers in the laboratory performing the WBT, 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 the making of *sospwa* by Haitian women in the spring of 2010. That report is 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. This problem occurred nearly every time they used the stove and caused multiple failed tests as the clogging completely cut off the airflow and put out the fire. The holes are difficult to unclog: testers ultimately resorted to using tongs to periodically unclog holes during the test. The door does not allow for partial opening, so testers kept it completely open. The handles were solid and could handle dumping ash multiple times. The EcoRecho had the most stable platform, consisting of prongs that could be lifted so that the pot could be placed on the prongs or on the charcoal directly. The appeal of the prongs was the stability they gave the pot, the ability to feed charcoal into the pan without having to lift the pot, and not smothering the fire with the pot.

- **Mirak**: As charcoal dies down, the pot sinks into the charcoal, cutting off airflow. Testers were able to mitigate the problem by putting large pieces of charcoal on the sides so it would allow for airflow. Because charcoal burned unevenly, the pot tended to tilt. With a bigger pan allowing the charcoal to spread out, testers found the stove does not light as well, and testers were often afraid of smothering the fire. In noting the temperature changes with Mirak, our testers found the temperature "scissored up" as opposed to climbing consistently. This may be because testers had to remove the pot from the stove to add more charcoal, which dropped the temperature of the water slightly each time they added fuel. Testers liked that the Mirak had a detachable pan to dump the remaining charcoal without having to move the entire stove.

- **Prakti:** The four prong platform is a bit unstable (not perfectly even) compared to the stable three prong platform of other stoves. The handles are small and fall down to rest against the side of the stove, making them hard to maneuver and causing them to become extremely hot. The door works well and is easy to use. The coals were easy to light because of the shallow chamber. Testers liked the shape and size of the stove and found it to be sturdy. They also thought the ash pan was a good one. They did find, however, the four prongs made it more difficult to add charcoal because there was less space through which to add additional fuel.

- **StoveTec**: The testers had trouble with the door, which fell off easily and was difficult to fit in its grooves. During hot and cold starts, the door was 85% open as fully opening the door caused it to fall off. The handles sometimes fell off when dumping charcoal out. The Stove Tec's interior clay slowly kept falling apart. During one failed test, the clay block shifted and sealed off air supply. Testers also found it difficult to get new coals lit when adding them. The stove remained very hot for hours after the test was completed.

- **Traditional:** The traditional stove is widespread in Haiti. Since the stove has been widely adopted, it is assumed to be highly usable and fit Haitian needs well. Therefore, we highlight positive aspects of the usability of the traditional stove because those are the characteristics that could potentially lead people to keep using the stove even if it is less efficient. The traditional stove had the benefit of simplicity. The stove is generally stable, has sturdy legs, and a large pan that can support various pot sizes and shapes. It had no doors which made it easy to use, but it also had no way to control the airflow to control the power setting without having to remove the pot to add or remove charcoal. An advantage of the traditional stove was the holes around the entire pan of the stove; they would not get plugged up with char, and they maintained sufficient airflow to prevent the fire from being smothered by the pot. Since the pot sits directly on the charcoal, testers had to put bigger pieces on the outer circle with smaller pieces on the inside so that the pot would not tilt. The large pan allowed for large amounts of charcoal to be added, and made it convenient to add and remove charcoal. Sometimes it was difficult to light the charcoal because the large pan allowed the charcoal to move around if it was not completely full. The metal handles are sturdy and protrude from the stove, increasing stove usability. Since the handles are metal they become hot during testing so testers had to use gloves or wait until the stove was cool to handle the stove.

In addition to comments of usability of each stove, we note how each stove compared to the traditional stove. When comparing the EcoRecho to the traditional stove, the EcoRecho had the stable prong platform, which is not present in the traditional stove. However, the holes of the traditional stove were large enough that they never plugged up or caused failed tests as in the EcoRecho. When comparing the Mirak to the traditional stove, the detachable pan used to dump the charcoal was an advantage, although the traditional stove was light enough to lift the entire stove. However, the pan of the Mirak would limit airflow as the pot sunk into charcoal. This problem was not observed in the traditional stove because the square pan was larger and the holes surround the entire pan, so the pot would not cover the entire top of the stove. When comparing the Prakti to the traditional stove, the Prakti had a door that worked well, was easy to use, and allowed for a range of airflow. Also, the ash pan was convenient and effective. However, the handles on the Prakti are small and fall down to rest against the side of the stove. The traditional stove's handles are larger and easier to handle, protrude out away from the stove, and cool down quickly. When comparing the StoveTec to the traditional stove, the StoveTec had a prong platform that increased the stability of the pot, and ensured that the charcoal wasn't smothered by the pot, in comparison with the traditional stove where the pot sits directly on the charcoal. However, the traditional stove's usability was simpler than the StoveTec, which translated into fewer problems during testing.

4. CONCLUSION

In regards to efficiency, all stoves offered improvement over the traditional stove. There is a tradeoff, though, in time to boil, as all improved stoves took much longer to bring water to a boil than the traditional stove. Overall, in terms of both thermal efficiency and specific fuel consumption, the Prakti and the EcoRecho performed the best. However, as described above, in many instances, differences between their performance and the performance of the StoveTec or Mirak were not statistically significant.

In terms of CO emissions and the CO/CO_2 ratio, the Mirak had the lowest emissions, although differences were statistically significant only when compared to the stove with the highest emissions, the EcoRecho.

For usability, we have included tester observations and comments in order to provide feedback to stove designers, but no stove emerged as clearly superior to the others.

These WBTs provide a good initial comparison of stove performance under controlled conditions. In the future, additional tests per stove would be useful to increase the sample sizes, and possibly reduce the confidence intervals, to be better able to make comparisons between stoves. However, even when results aren't statistically significant due to large confidence intervals, observed differences between stoves may be practically significant for real-world performance in the field. Also, to better predict how stoves will perform in terms of efficiency, emissions, and usability under Haitian conditions, we are complementing the WBTs with Controlled Cooking Tests (CCTs) using a protocol based on observations of Haitian cooking.

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Appendix A: Summary of Data for WBT

Table A1: Number of Tests per Phase

	Cold	Hot	Simmer	Entire WBT
EcoRecho	4	4	3	11
Mirak	5	3	3	11
Prakti	5	4	3	12
StoveTec	4	5	3	12
Traditional	4	3	3	10

Table A2: Time to Boil (mean ± SD)

	Cold Start (minutes)	Hot Start (minutes)
EcoRecho	55.2 ± 24.2	32.1 ± 3.5
Mirak	54.1 ± 17.3	42.1 ± 9.7
Prakti	51.3 ± 6.7	33.3 ± 18.3
StoveTec	59.8 ± 11.6	29.9 ± 6.6
Traditional	36.5 ± 16.8	24.0 ± 2.8

Table A3: Thermal Efficiency (mean ± SD)

	Simmer	Entire WBT
EcoRecho	37.5% ± 13.5%	31.6% ± 17.1%
Mirak	34.1% ± 6.2%	28.6% ± 7.7%
Prakti	46.2% ± 2.2%	37.3% ± 8.5%
StoveTec	36.6% ± 4.2%	30.5% ± 8.4%
Traditional	28.5% ± 2.1%	22.2% ± 3.1%

Table A4: Specific Fuel Consumption (mean ± SD)**

	Simmer (grams)	Entire WBT (grams)
EcoRecho	324 ± 127	479 ± 129
Mirak	289 ± 104	507 ± 124
Prakti	378 ± 302	539 ± 305
StoveTec	346 ± 91.7	572 ± 106
Traditional	808 ± 290	979 ± 290

**Temperature-Corrected

Table A5: Total CO Emission (mean ± SD)

	Simmer (grams)	Entire WBT (grams)
EcoRecho	98.6 ± 13.3	179 ± 19.3
Mirak	59.1 ± 13.2	134 ± 23.8
Prakti	68.7 ± 12.1	136 ± 27.4
StoveTec	83.5 ± 36.6	183 ± 43.1
Traditional	91.6 ± 31.6	154 ± 34.4

Table A6: Total CO_2 Emission (mean ± SD)

	Simmer (grams)	Entire WBT (grams)
EcoRecho	640 ± 140	1376 ± 158
Mirak	747 ± 52.8	1577 ± 207
Prakti	542 ± 77.0	1249 ± 170
StoveTec	802 ± 103	1842 ± 198
Traditional	928 ± 354	1625 ± 379

Table A7: Total CO/CO_2 Emission (mean ± SD)

	Simmer	Entire WBT
EcoRecho	15.8% ± 3.4%	13.0% ± 2.0%
Mirak	8.0% ± 2.2%	8.5% ± 1.9%
Prakti	12.7% ± 1.6%	10.9% ± 2.6%
StoveTec	10.8% ± 5.8%	9.9% ± 2.6%
Traditional	10.0% ± 0.6%	9.5% ± 3.1%

Appendix B: Change to Equation in WBT Protocol

The WBT was designed for wood-burning stoves and cannot be exactly applied to charcoal-burning stoves. We made the following modification in the WBT protocol equation to accommodate charcoal stoves.

When calculating equivalent dry fuel consumed for all phases of the WBT, the wood-burning protocol incorporates the energy required to turn the leftover wood into char. However, we used charcoal instead of wood and because charcoal is essentially char already, we assumed the energy content of the leftover charcoal was the same as the initial charcoal, allowing the change in carbon (ΔC_c) to equal zero. Also, due to differences in the energy content between charcoal and wood, we replaced the coefficient of 1.12 with 1.08. This changed the equation (for example in the cold start phase) from:

$$F_{cd} = F_{cm} * (1 - 1.12 * m) - 1.5 * \Delta C_c$$

to:

$$F_{cd} = F_{cm} * (1 - 1.08 * m)$$

where F_{cd} is the equivalent dry fuel consumed, F_{cm} is the fuel consumed, m is the moisture content of the fuel, and ΔC_c is the net change in char during the test.

The WBT Version 3.0 approximates the heat of vaporization h_{fg}, the energy required to evaporate water, as 2260 kJ/kg. The WBT protocol also remarks that this value is approximately 12% of the calorific value of dry wood $q_{dry\ wood}$,

$$0.12 * q_{dry\ wood} = h_{fg}$$

$$0.12 * q_{dry\ wood} = 2260 \text{ kJ/kg}$$

$$q_{dry\ wood} = \frac{2260 \text{ kJ/kg}}{0.12} = 18800 \text{ kJ/kg}$$

Additionally, the WBT protocol states that char has roughly 150% of the calorific content of dry wood,

$$q_{char} = 1.5 * q_{dry\ wood}$$

Since the heat of vaporization of water is a constant value,

$$x * q_{char} = h_{fg}$$

$$x * \left(1.5 * q_{dry\ wood}\right) = h_{fg}$$

$$x = \frac{2260 \text{ kJ/kg}}{(1.5 * 18800 \text{ kJ/kg})}$$

$$x = .08 = 8\%$$

Therefore, the coefficient in the equation for equivalent dry fuel consumed changed from 1.12 to 1.08,

$$F_{cd} = F_{cm} * (1 - 1.08 * m)$$

to account for using charcoal (essentially char) instead of wood.

For further information on the WBT protocol, see the Shell Foundation Household Energy Project WBT, version 3.0, found at: http://ehs.sph.berkeley.edu/hem/?page_id=38.

Appendix C: 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

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

where N is the number of measurements or sample size and x_i = 1,2, ... N are the individual measurements that are 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). Average values and sample standard deviations for each performance metric (time to boil, thermal efficiency, specific fuel consumption, carbon monoxide emission, carbon dioxide emission, and the ratio of carbon monoxide to carbon dioxide) are presented in Appendix A for reference.

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

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{N}}. \quad (2)$$

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 this uncertainty 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, by observing error bars that do not overlap.

When it is assumed that the measurements are normally distributed but the sample size is small (<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

$$\bar{x} \pm t_p \sigma_{\bar{x}} \quad (3)$$

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); $t_{.95}$ (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

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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.