DRAFT Report on Results of WBT for Charcoal Stoves for Haiti

October 6, 2010

DISCLAIMER

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 LBL stove testing facility using a modified form of Version 3 of the Shell Foundation Household Energy Project Water Boiling Test (WBT). **Stoves were tested for time to boil, thermal efficiency, and specific fuel consumption, as well as emissions of CO and CO2**. 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 the testing, we attempted to obtain those stoves that were being either considered for distribution by NGOs operating in Haiti or that are already widely available in Port au Prince.

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

Fig. 1: From left to right: traditional stove, EcoRecho, Prakti, 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 were told 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.
C. Prakti LeoChar. 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.
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.
E. Mirak. 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 half spherical, and the pot sits directly on the charcoal.

Although the StoveTec comes with a skirt that can be used for added efficiency, we chose not to use the skirt during testing. Because we were concerned that the skirt may not be commonly used, we thought it better to evaluate the stove without it. 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 was 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 that 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 but not for charcoal.

2.3 Test System

All testing was performed under controlled conditions at Lawrence Berkeley National Laboratory. The test system consists of stove platform and an exhaust hood which draws gasses upward where they are mixed and sampled. Both CO and CO2 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.

2.4 Protocol

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 room temperature water was brought to a boil.

2. Hot start (high power): Immediately following the cold start, the water is replaced with a new batch of 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.

These phases were used for simultaneous collection of data on data of thermal efficiency and emissions. When ventilation doors were available, we kept them open for the high power operation, and 50-60% open during the low power (simmer) operation.

The same flat-bottom, 15" diameter aluminum pot, purchased in Port-au-Prince, was used for all tests.

The WBT was designed for wood-burning stoves and cannot be exactly applied to charcoal-burning stoves. We made the following adjustments to accommodate charcoal stoves. These adjustments 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, the wood-burning protocol incorporates the energy required to turn the leftover wood into char. However, as charcoal was used instead of wood, it was determined that this term in the equation was not applicable and therefore was removed. This removal changed the equation from:

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

to:

$$F_{cd} = F_{cm} * (1 - 1.12 * m)$$

2.5 Analysis

For each metric, we report stove performance on the WBT both as a whole, averaged or summed over all three phases, as well as average performance solely on 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, in addition to presentation of results from all phases of the WBT combined, we have isolated the results of the simmer phase, separate from the cold and hot start portions of the WBT. This presentation will enable readers may 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 one standard deviation above and below the mean so that variation in results is clearly visible. Because of the small number of tests, variability was sometimes quite high. In the presence of large variability, it can be difficult to determine whether apparent differences observed in experiments actually represent true differences in real-world performance. Therefore, we have conducted hypothesis testing to identify whether these differences are statistically significant at the p=0 .05 level. When significant differences were found at the group level, we followed up with pair-wise analysis to identify which pairs of stoves were significantly different at the 0.05 level.[1] We do note, as a caveat, that .05 is a very conservative p-value, and it is likely that more stoves would be significantly different at a higher value such as 0.10.

3. RESULTS

Results are grouped into three categories:

- **Efficiency:** thermal efficiency, temperature-corrected specific fuel consumption, and time to boil
- **Emissions**: CO and CO2
- **Usability**: observations of ease of stove use from stove testers at LBNL

Equations for the various metrics are not presented 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.asp?id=42.

3.1 Efficiency

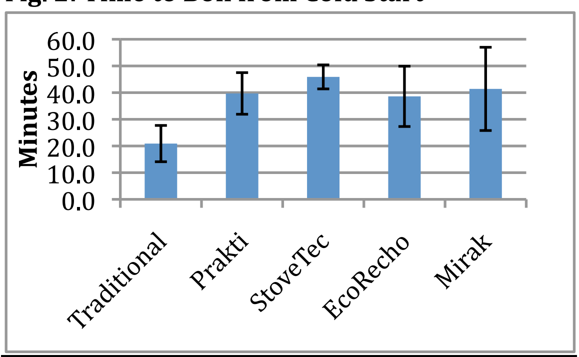
3.1.1 Time to Boil

As expected, the traditional stove brought water to a boil more quickly than any of the improved stoves. Water heated on the traditional stove boiled in only 20.9 minutes, yet the same amount of water took 38.6 minutes to boil in the next fasted stove (the EcoRecho), a difference of almost 18 minutes. Although all of the improved stoves were much slower than the traditional stove, they performed similarly to each other with averages ranging from 38.6 to 45.9, a difference of 7.3 minutes.

Table 1: Time to Boil from Cold Start

	Time to Boil (minutes)	Rank (Fastest to slowest)
Traditional	20.9	**1**
Prakti	39.7	3
StoveTec	45.9	**5**
EcoRecho	38.6	2
Mirak	41.4	4

Fig. 2: Time to Boil from Cold Start



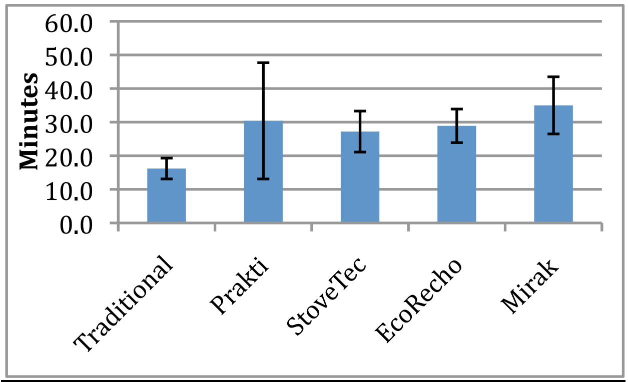
[1] For those not familiar with hypothesis testing, these tests are done by first posing a 'null hypothesis' proposing that stove performance is actually identical and that observed differences are the result of random variation. Statistical analysis is then conducted, and the hypothesis is only disproved,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

In the hot start boiling, in which room temperature water is placed on already heated coals, the results are similar. Once again, the traditional stove was much 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 12 to 48 minutes.

Table 2: Time to Boil from Hot Start

	Time to Boil (minutes)	Rank (Fastest to slowest)
Traditional	16.2	**1**
Prakti	30.4	4
StoveTec	27.2	2
EcoRecho	28.9	3
Mirak	35.0	**5**

Fig 3: Time to Boil from Hot Start



3.1.2 Thermal Efficiency

Thermal efficiency is the "ratio of the work done by heating and evaporating water to the energy consumed by burning wood." (WBT, p. 25) Calculations for determining thermal efficiency can be found in the WBT Protocol.

Table 3: Thermal Efficiency

	Efficiency in Simmer Phase	Thermal Efficiency – Entire WBT
Traditional	0.272	0.2
Prakti	0.441	0.345
StoveTec	0.35	0.282
EcoRecho	0.358	0.327
Mirak	0.326	0.266

Fig. 4: Thermal Efficiency Over Entire WBT

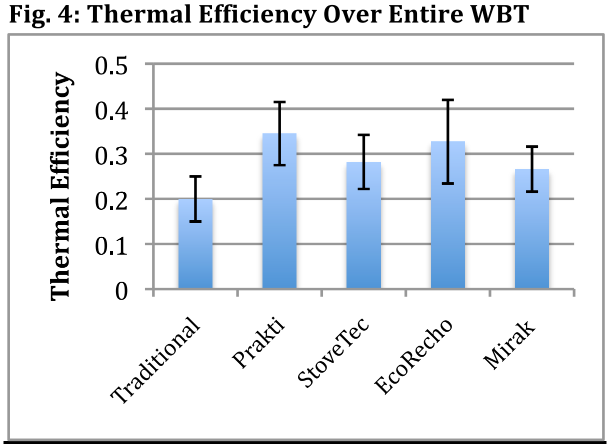


Table 3 above shows the thermal efficiency for the simmer phase as well as the average efficiency over all phases of the WBT. Average thermal efficiency results of the four stoves were better than that of the traditional stove. Results were significant at the 0.05 level for the WBT and the 0.10 level 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. As can be seen from the graph, all stoves performed at a higher efficiency than the traditional stove, with the Prakti and EcoRecho the most efficient and the traditional and Mirak the least efficient. To assess whether differences between stoves were significant, we performed pairwise comparisons across the improved stoves (leaving out the traditional), at the 0.05 level, which is admittedly conservative. At the 0.05 level, only the best (Prakti) and worst (Mirak) can be distinguished from each other.

When the simmer phase is broken out by itself (Fig. 5, below), it is clear that the traditional stove fares the worst. Considering the simmer phase only, at the .05 level, the EcoRecho and the Prakti stoves fare best, and both significantly outperform the traditional stove and the Mirak stove. Again, a higher significance level would likely have yielded other significant pairwise differences.

The graph illustrating simmering thermal efficiency over the three tests (Fig. 6, below) is provided to illustrate the variability in results between tests. Considering the unaveraged individual data points, the EcoRecho, for example, 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 that 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.

Fig. 5: Thermal Efficiency of Simmer Phase

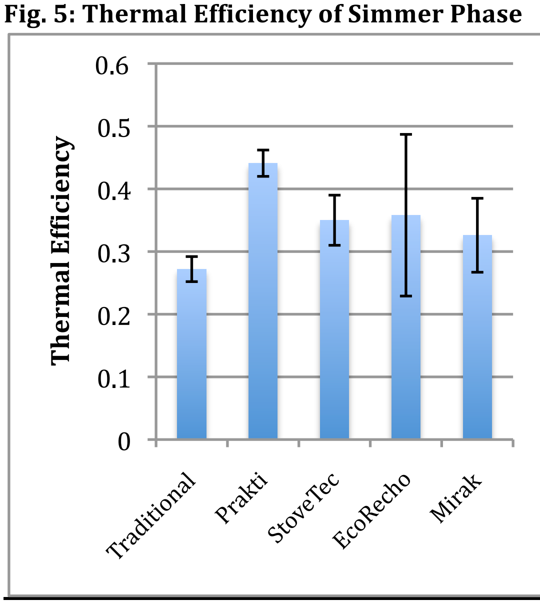
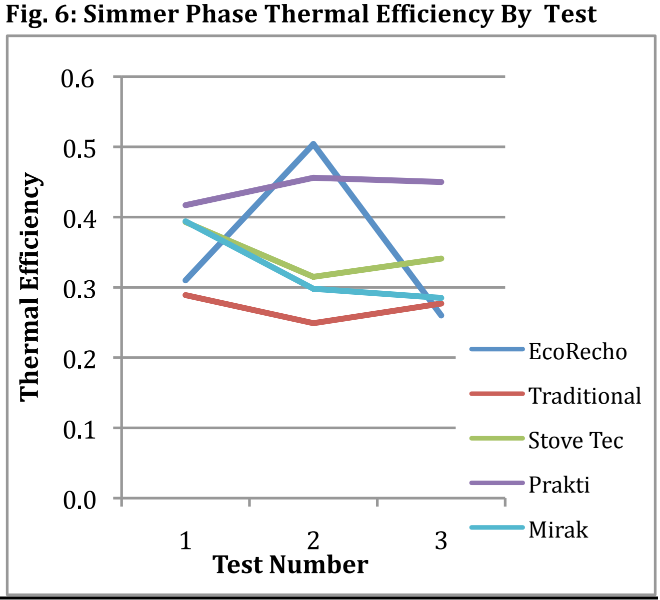


Fig. 6: Simmer Phase Thermal Efficiency By Test



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 high-power WBT, it is a measure of the amount of wood required to produce one liter (or kilo) of boiling water starting with cold stove."

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

Table 5: Temperature Adjusted Specific Fuel Consumption

	Simmer (g)	Total (g)
Traditional	**846.2**	**1034.2**
Prakti	395.6	577.7
StoveTec	362.2	621.0
EcoRecho	339.5	**514.8**
Mirak	**303.2**	536.3

Fig 7: Temperature Adjusted Specific Fuel Consumption

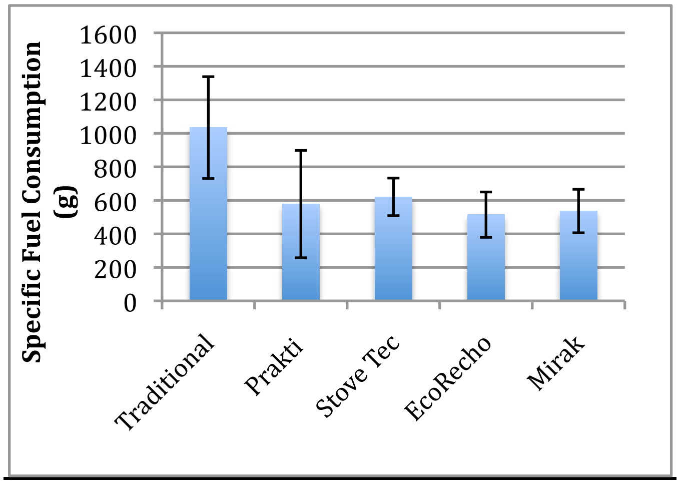


Fig. 8: Simmer Phase Specific Fuel Consumption

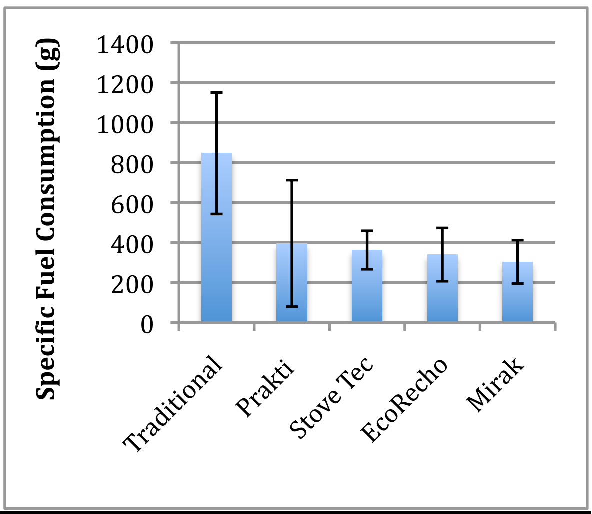
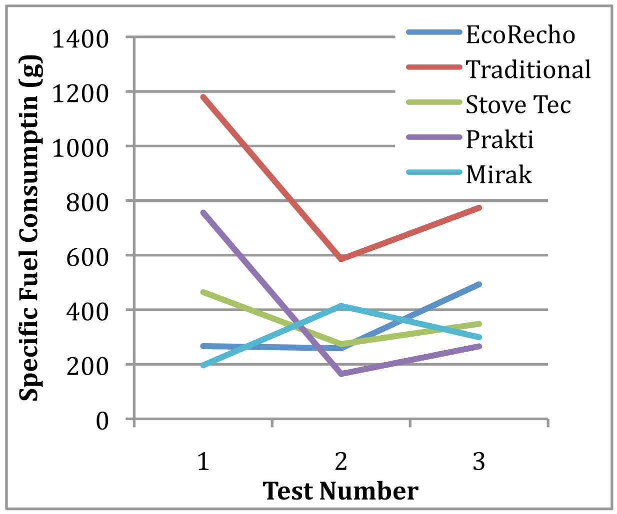


Fig. 9: Simmer Phase Sp. Fuel Consumption By Test



As can be seen in the table of temperature adjusted specific fuel consumption (Table 5), the simmer phase accounted for a large portion of the fuel consumed for each stove. Specific fuel consumption results showed so much variation that results for the total average specific fuel consumption for the entire WBT were not significantly different from one another. It is clear, however, that all improved stoves used considerably less fuel than the traditional stove, most using a little more than half that of the traditional stove.

When broken into phases, there was no significant difference in stove performance (including the traditional stove) for the hot-start phase. The findings for the simmer and cold phases, however, were significant at the .06 and .11 level, respectively, meaning that across the five stoves, at least one was different from the others in terms of average specific fuel consumption over those phases. Due to software limitations, pair-wise comparisons were limited to the 0.05 level and smaller, which precluded analysis for all phases.

Although pair-wise comparisons were not possible, one can see in the graph showing simmer specific fuel consumption by test (Fig. 9) that the traditional stove performed much worse than the improved stoves. Were pair-wise comparisons possible, the traditional stove would have likely been significant at the 0.10 level. Figure 9 also shows that 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 such that, 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.

The variation in the results for the Prakti stove are particularly large (standard deviation of 320.1 g of total fuel consumption of 577.7 g), and the results as a whole showed more variation than the other tests with several outliers. Because we do not know exactly what led to these outliers, we did not feel justified in throwing them out. 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 from both hot and cold starts is much higher for all improved stoves than for the traditional stove. This difference is worrisome because of the importance that stove users often place on the amount of time that it takes them to cook: 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 this concern over 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 winner in terms of time-savings.

Thermal efficiency results were significant at the p=0.05 level for both average performance across all phases and for the simmer phase individually. Thermal efficiency was highest for Prakti and EcoRecho and lowest for Mirak. When differences between stoves are analyzed, only the highest and lowest thermal efficiencies are significantly different while middle ranks are not.

The findings for specific fuel consumption were far more uncertain than those for thermal efficiency. Significant differences in performance were not observed for the full WBT. When the phases were separated, the cold phase was significant at the p=0.06 level, and the simmer phase was significant at the p=0.11 level, but pair-wise differences were insignificant at the p=0.05 level. Overall, specific fuel consumption was lowest/best for the Prakti and EcoRecho, and highest/worst for the StoveTec and traditional.

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

3.2 Emissions

3.2.1 Total Carbon Monoxide (CO)

In each WBT that was 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 per phase and standard deviation that is reported below. Total CO emissions 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. Results for total CO emissions over the entire WBT were not significantly different from one another, meaning that true difference between 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 stoves.

Results of the simmer phase considered separately were found to be significant. The Mirak again performs the best, while the EcoRecho performs the worst. In the simmer phase, the carbon monoxide emissions of the highest emitter (the EcoRecho) are significantly different than those of the lowest emitters (Mirak and Prakti). However, the middle ranks cannot be distinguished from one another.

As can be seen in the error bars of the graph of CO emissions of the simmer phase (Fig. 9) both the StoveTec and Traditional stoves had large variation in their emissions, making it difficult to assess whether they are significantly different in their performance than the other stoves.

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

	Total CO – Simmer Phase (g)	**Total CO – All Phases (g)**
Traditional	91.6	153.6
Prakti	68.7	135.6
StoveTec	83.5	**182.5**
EcoRecho	**98.6**	178.6
Mirak	**59.1**	**134.1**

Fig. 10: Total CO Emissions – Simmer Phase

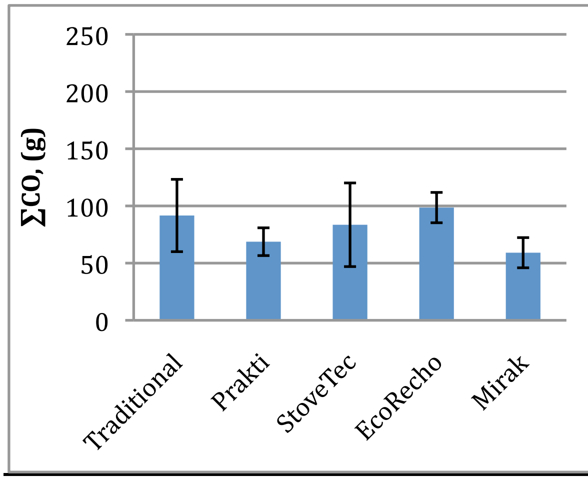
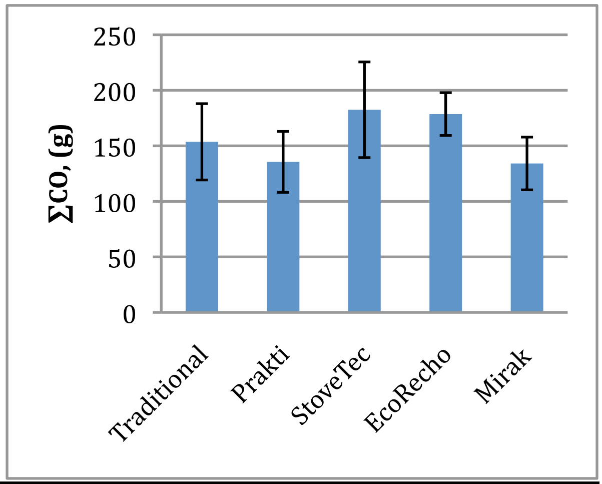


Fig. 11: Total CO Emissions over all Phases



3.2.2 Total CO_2

In each WBT that was 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 per phase and standard deviation that is reported below. Total CO_2 emissions 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. As can be seen in Table 7, the emissions from the simmer phase generally accounted for about half the total CO_2 emissions.

Differences between total CO_2 emissions were significant both for the full WBT and for the simmer phase considered individually. For the full WBT, the Prakti had the lowest emissions, while the StoveTec stove had the highest. The difference in emissions between the StoveTec and both the Prakti and the EcoRecho was significant, but no other pairs could be distinguished.

For the simmer phase, the Prakti again performed the best, while the traditional stove fared the worst. The differences between the Prakti and the StoveTec and Mirak, respectively, were significant. No other pairs could be distinguished. Although the traditional stove had the highest average emissions for the simmer phase, its variability made it impossible to distinguish from the Prakti even though the average emissions for both stoves are quite different.

As with 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. However, as the table shows, all stoves except the StoveTec did have lower emissions over the entire WBT than the traditional stove.

Table 7: Total CO2 Emissions for Simmer Phase and Full WBT

	Total CO2 - Simmer (g)	Total CO2 – All Phases (g)
Traditional	**928.4**	1625.3
Prakti	**541.6**	**1249.1**
StoveTec	802.2	**1841.8**
EcoRecho	639.7	1376.3
Mirak	747.1	1576.7

Fig 12: Total CO2 Emission – Simmer Phase

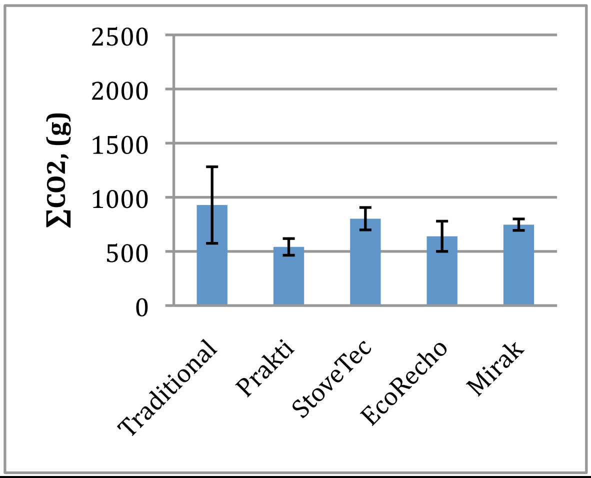
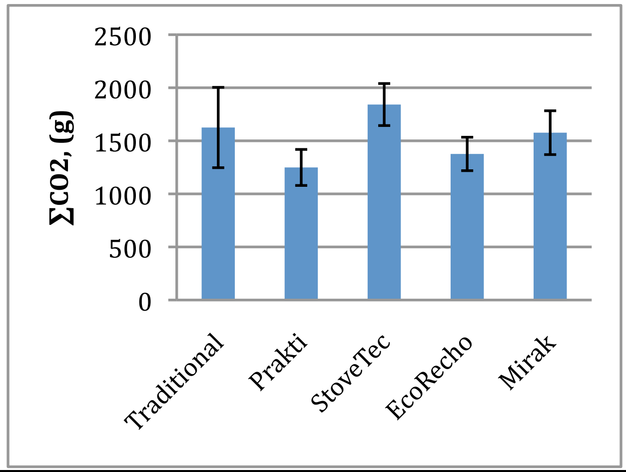


Fig 13: Total CO2 Emissions over all Phases



3.2.3 Emission Conclusions

The carbon monoxide results over all phases of the WBT were 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 our chosen significance level.

Differences between CO results from the simmer phase, which accounts for somewhat less than half the total CO emissions from the entire WBT, were significant. The Mirak and Prakti had the lowest emissions, which were significantly lower than the stove with the highest emissions (EcoRecho). Middle ranks could not be distinguished.

Differences between CO_2 results were significant for both the simmer phase and the full WBT. The Prakti stove had the lowest emissions for both the simmer and the full WBT. For the simmer test, the emissions of the Prakti were significantly lower than the StoveTec and Mirak, and in the full WBT, Prakti emissions were significantly lower than StoveTec. No other pairs could be distinguished.

In considering emissions of both CO and CO_2, the Prakti stove performed the best, although the difference was usually 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 *sos pwa* by Haitian women in spring of this year. That report is online available 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

- **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. 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.

- **Mirak** – As charcoal dies down, the pot sinks in, which cuts off airflow. Testers were able to mitigate the problem by putting large pieces on the sides so it would allow for airflow. Because charcoal burned unevenly, pot tended to tilt. Testers found this stove hard to light. With a bigger pan allowing the charcoal to spread out, it does not light as well, and testers were often afraid of smothering the fire. In noting the temperature changes with Mirak, our testers found that the temperature "scissored up" as opposed to climbing consistently. This may be because, in order to add more charcoal, testers had to remove the pot from the stove, which dropped the temperature of the water slightly each time they added fuel.

- **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 multiple ash dumpings. This stove was the easiest to feed when pieces of charcoal were large.

- **Prakti** - The four prong platform is a bit unstable (not perfectly even) compared to the stable 3-prong platform of other stoves. The handles are small and fall down to rest against the side of the stove, which makes them hard to maneuver. They also then get extremely hot, which makes them difficult to use. The door works well and is easy to use. The coals were easy to light because of the shallow chamber. Testers also 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, that the four prongs made it more difficult to add charcoal because there was less space through which to add additional fuel.

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 specific fuel and thermal efficiency, the Prakti and the EcoRecho performed the best. However, as described above, in many instances, their performance was not statistically significantly different from the StoveTec or the Mirak.

In terms of emissions of both CO and CO2, the Prakti performed the best, although differences were usually statistically significant only when compared to the stove with the highest emissions.

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. However, to better predict how stoves will perform in terms of emissions, efficiency, and usability under Haitian conditions, we are complementing the WBT's with Controlled Cooking Test (CCT) using a protocol based on observations of Haitian cooking. This second round of stove testing will include a larger number of stoves in order to compare most if not all stoves being considered for large-scale stove dissemination projects in Haiti.

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