Independent Laboratory Test Results for Household Cook Stoves for Developing Countries

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Abstract

We tested 132 combinations of household cook stoves, fuels, and operating conditions in the laboratory. Our testing included 22 stoves, 7 fuels, 2 fuel moisture levels, various operating conditions, and 3 test conditions (high power - cold start, high power - hot start, and low power). We measured power, energy efficiency, fuel use, and emissions of carbon monoxide, particulate matter, carbon dioxide, methane, total hydrocarbons, black carbon, elemental carbon, and organic carbon. We measured light absorption and light scattering of particulate emissions. For each pollutant, we report emission rates per time, and we report emission factors based on fuel energy, cooking energy, fuel mass, and cooking task. For each stove, we describe results and observations during testing. Our independent test results and extensive data set will be used by our partners in the PCIA (Partnership for Clean Indoor Air) who are disseminating stoves in the field, and by the GACC (Global Alliance for Clean Cookstoves) Standards and Testing Working Group that is developing improved standards for testing cook stoves. We offer recommendations for improving test methods. Our laboratory test results are not a substitute for field test results, but our testing complements field testing, and we recommend increased coordination between laboratory and field testing in the future.

1. Introduction

The PCIA (Partnership for Clean Indoor Air), supported by the USEPA (United States Environmental Protection Agency), was initiated in 2002, and the worldwide organization has grown to 467 partners who are involved in all aspects of improving cook stoves for developing countries. In addition to many other activities, PCIA/USEPA has sponsored laboratory and field testing of cook stoves. We (Jetter and Kariher, 2009) conducted a previous laboratory evaluation of cook stoves. MacCarty et al. (2010) published results from numerous laboratory tests, many of which were supported by USEPA, and Johnson et al. (2011 *add ref. if available*) recently conducted field evaluations supported by USEPA. Besides the USEPA-supported studies, several other laboratory and field evaluations of cook stoves have recently been published, including Johnson et al. (2008 and 2010), MacCarty et al. (2008), Roden et al. (2009), and Yuntenwi et al. (2008). With the 2010 launch of the GACC (Global Alliance for Clean Cookstoves), “a major global cookstove renaissance” (Smith 2010) offers the opportunity to build on the work of PCIA, PCIA Partners, and other institutions involved in developing cook stoves. The recently formed GACC Standards and Testing Working Group recognizes the need to build on prior work to improve laboratory and field evaluation of household cook stoves for developing countries, and the need to build capacity in developing countries for evaluating and improving cook stoves. During May to October, 2010, we conducted the most extensive round of laboratory, cook stove testing to date. Our objective was to provide independent test results, in the form of a large and convenient data set, to our partners in the PCIA, who are disseminating stoves in the field. These data will also be used by the GACC Standards and Testing Working Group in the development of improved protocols and standards for testing cook stoves.

2. Materials and Methods

2.1 Stoves Tested

We tested the 22 stoves shown in Figure 1. Stoves were selected for the study based on quantity disseminated, previous test results, innovation, and interest from PCIA partners. Three of the wood-burning stoves (D, P, and V in the figure) were variations of the "rocket" stove design described by MacCarty et al. (2008). Three of the stoves (C, G, and S in the figure) were variations of the "TLUD" (top-lit up-draft) design described by Roth (2011). If a pot skirt (a device for increasing heat transfer to the pot) was available for the stove, we tested with the skirt. Following are descriptions for the stoves shown in Figure 1. Information on the number of stoves disseminated and on cost is included, if that information was provided by the manufacturer.

A. Ceramic Jiko. "Jiko" means stove in Swahili. This is a typical, small, metal-clad, ceramic charcoal stove with variations used in many countries in Africa. A ceramic grate for holding the charcoal fuel is considered an improvement over the common, metal charcoal stove. A ceramic jiko will typically last longer than a metal jiko.

B. Metal Jiko. This is a typical, common, small, metal, charcoal stove with variations used in many countries in Africa and around the world.

C. Belonio Rice Husk Gas Stove. Alexis Belonio, Central Philippine University, designed this stove to burn waste rice husks that are abundantly available in many rice-growing regions of the world. The stove is a batch-loaded, TLUD design, and it has an AC (alternating current)-powered fan to provide forced draft. A detailed, operation manual was provided with the stove. Retail cost is approximately US$40.

D. Onil (HELPS International) Stove. Don O'Neal, HELPS International engineer/volunteer, initially developed this stove to reduce serious burns, especially to children, caused by traditional stoves and open cooking fires. The stove has a chimney and it has a rocket combustion chamber made of ceramic material. The stove body is made of pre-cast concrete parts, and the stove is assembled on site. A flat, steel top, called a plancha, is useful for making tortillas and for frying foods. The top has removable, steel rings to enable the bottom of a cooking pot to be directly exposed to hot combustion gases.

E. Protos Stove. This stove was developed by BSH Bosch und Siemens Hausgeräte GmbH, Germany, to use plant oil as fuel. A fuel tank is pressurized with an air pump to deliver fuel to an oil burner. Approximately 500 stoves per year have been disseminated. Provided with the stove were an operation manual, DVD, a "simmer plate" that can be placed between the burner and pot to reduce cooking power, and tools for cleaning the burner assembly. Production cost is approximately US$50.

Figure 1. Stoves tested

F. Mayon Turbo Stove 7000. This stove was developed by REAP (Resource Efficient Agricultural Production) Canada to burn rice hulls and other crop residues. Fuel is loaded into a hopper, and continuous feeding is possible (unlike other stoves that burn rice hulls with batch loading). The stove is made of steel. Approximately 500 stoves per year have been disseminated in The Philippines and The Gambia. Retail cost is approximately US$15.

G. Oorja Stove. This stove was initially developed by BP (British Petroleum), and was further developed and is now being disseminated by First Energy Private Limited in India. Mukunda et al. (2010) reported on the development of this stove. Biomass pellets made from agriculture residues are used as fuel. A small electrical fan powered by a rechargeable battery provides forced draft. A fan speed controller has a switch with a low and a high position. The combustion chamber is made of ceramic material clad with metal on the outside, and a heat shield is made of stainless steel. An operation manual and an extra rechargeable battery were provided with the stove. Over 400,000 stoves have been disseminated in India.

H. KCJ (Kenya Ceramic Jiko) Standard Stove. This metal-clad, ceramic, charcoal stove has been disseminated in large quantities (~500,000/yr) in Africa by the organization, Practical Action. Retail cost is approximately US$6.

I. GERES NLS (New Lao Stove). This metal-clad, ceramic, stove was developed by GERES (Groupe Energies Renouvelables, Environnement et Solidarités - a French non-profit NGO) and has been disseminated in large quantities (>250,000/yr) in Cambodia. The stove is primarily used with charcoal fuel, but it is designed to also use wood fuel. A ceramic piece between the fuel grate and pot is removable for adding fuel during operation of the stove. We tested the stove with charcoal fuel. Retail cost is approximately US$3.50.

J. StoveTec Prototype Charcoal Stove. This prototype, metal-clad, ceramic stove was adapted from a StoveTec Wood/Charcoal Stove. The stove was provided with a special cooking pot with an integral skirt and fins on the bottom for improved heat transfer. The fuel chamber had a vertical, cylindrical core made of perforated metal to provide air flow to the burning charcoal.

K. Jinqilin CKQ-80I Stove. This stove was developed by the Linhong Company in China and is manufactured by Shanzi Jinqilin Energy Technology Co., Ltd. Approximately 6,000 stoves per year have been disseminated in China. Corn cobs are primarily used as fuel, but straw briquettes and wood may also be used. The stove is a gasifier (Roth 2011) design with separate controls for primary and secondary air. A hand-operated shuttle mechanism enables continuous feeding of fuel. The stove has a chimney and an AC-powered fan that provides forced draft. The top of the stove has removable, cast-iron rings to enable the bottom of a cooking pot to be directly exposed to hot combustion gases. Retail cost is approximately US$100.

L. 3-Stone Fire. This is the most commonly used traditional method of cooking. Two variations of the 3-stone fire were tested as baselines cases. A "carefully tended" 3-stone fire was constantly tended during the test, and fuel-wood sticks were slowly fed into the fire so that only the ends of the sticks burned. A "minimally tended" 3-stone fire was only periodically tended, and fuel-wood sticks were added to the fire in batches approximately every 10 minutes.

M. Upesi Portable Stove. This metal-clad, ceramic, wood-burning stove has been disseminated in Africa by Practical Action in quantities of approximately 30,000 per year. Retail cost is approximately US$9.50.

N. Kenya Uhai Stove. This metal-clad, ceramic, charcoal stove has been disseminated in Africa by Practical Action in quantities of approximately 1,000 per year. It is different than other ceramic-lined charcoal stoves we tested, because the cooking pot rests directly on the ceramic liner, rather than on metal pot rests, and because the ceramic liner has a lip that reduces the size of the opening on top. Retail cost is approximately US$11.

O. Gyapa Stove. This metal-clad, ceramic, charcoal stove is made in Ghana by small-scale metal workers and ceramicists, and it has been disseminated by Enterprise Works in Ghana. An instruction sheet was provided with the stove.

P. Envirofit G-3300 Stove. This mass-produced stove was initially developed by Colorado State University and is disseminated by Envirofit International. At the time of our testing, approximately

15,000 stoves had been disseminated in 7 months. The stove has a rocket combustion chamber made of high-temperature alloy steel. A removable grate is made of cast iron. The stove was tested with a G-33SKT pot skirt accessory. An instructional video on a CD (compact disk) was provided with the stove. Retail cost for the stove is approximately US$31, not including the pot skirt accessory.

Q. Sampada Gasifier Stove. This stove was developed by ARTI (Appropriate Rural Technology Institute) and is distributed by Samuchit Enviro-Tech Private Limited in India. The stove is designed to burn wood or other biomass and to produce charcoal. The outer body of the stove is stainless steel, and the inner parts are non-stainless steel. An instruction sheet and instructional video on CD were provided with the stove. Retail cost for the stove is approximately US$38.

R. Berkeley-Darfur Stove. Ashok Gadgil, Lawrence Berkeley National Laboratory, initiated the development of this stove that is disseminated by the Darfur Stoves Project (Amrose et al., 2008). The design was adapted from the Tara Stove, originally made in India. The Berkeley-Darfur stove has a cast iron grate, and other components are made from sheet metal and are efficiently shipped flat to Darfur where they are assembled into stoves. Approximately 9,000 stoves were disseminated in 2010. We tested this stove with a round-bottomed, cast aluminum pot, as shown in Figure 1, that the stove was designed for. Production cost for the stove is approximately US$25, and the stoves have been disseminated free of cost in Darfur.

S. StoveTec Prototype TLUD Stove. This prototype stove was adapted from a StoveTec Wood-Charcoal Stove. The stove is a batch-loaded, TLUD design, and the fuel is wood pellets. Natural draft (convection) provides air flow for combustion. A pot skirt was provided with the stove.

T. Philips Power Stove HD4012. This stove is disseminated by Philips Electronics India Ltd. The stove was designed to use wood and other biomass fuels. A rechargeable battery and fan provide forced-draft air to the combustion chamber. Whereas the Philips HD4010 we previously tested (Jetter and Kariher 2009) was self-powered (a thermoelectric device used heat from the stove to recharge the battery and power the fan), the HD4012 requires a source of electricity to recharge the battery and/or power the fan. The base of the stove is injection-molded plastic, the upper body is made of stainless steel, and the combustion chamber is made of thin ceramic tiles. An operation manual was provided with the stove. Retail cost is approximately US$89.

U. Philips Natural Draft Stove HD4008. This is another stove disseminated by Philips Electronics India Ltd. The stove was designed to use wood and other biomass fuels. Natural draft (convection) provides air flow for combustion. The base of the stove is made of coated steel, the upper body is made of galvanized steel, and the combustion chamber and top are made of steel. An operation manual was provided with the stove. Retail cost is approximately US$31.

V. StoveTec Greenfire Wood Stove. This mass-produced stove was developed by Aprovecho Research Center, and is disseminated by StoveTec. The stove has a rocket combustion chamber made of ceramic material, and the top of the stove is made of cast iron. A pot skirt was provided with the stove. Operating instructions were printed on the carton containing the stove, and a user's manual was available online. StoveTec has disseminated approximately 35,000 stoves, including all other models, per year. Wholesale cost for the model we tested is approximately US$9 in quantities of approximately 3,000.

2.2 Fuels Tested. Fuels were tested for moisture content using ASTM Standard Method D4442-07 (ASTM, 2007), and fuels were analyzed for heat of combustion using ASTM Standard Method ASTM D5865-10 (ASTM, 2010). Moisture content was measured on each day the fuel was used for testing. The following fuels were used in the tests:

Wood fuel. We used Red Oak (*Quercus rubra*), a common hardwood, for testing wood fueled stoves. We obtained one large, freshly cut "green" log, and cut the wood into the desired size (1.5 x 1.5 cm in cross-section, after drying). We air dried the wood until it reached the desired moisture content (30% on a wet basis) for high-moisture content fuel, hereafter called “wet” fuel. Then we packed half of the wood into air-tight drums and stored the drums in a freezer to prevent mold from growing on the wood while maintaining the high moisture content. We air dried the other half until it reached equilibrium (10% on a wet basis) for low-moisture content fuel, hereafter called “dry” fuel. We removed high-moisture wood from the freezer, as needed, and thawed it to ambient temperature (inside a sealed plastic bag) before using it for testing stoves. We recommend this method for preparing uniform fuel wood with controlled moisture content. We recommend using a larger size (2 x 2 cm in cross-section, after drying) in future testing, because we think a larger size would be more representative of wood commonly used in the field.

Charcoal fuel. We used lump charcoal, rather than compressed briquettes, because lump charcoal is typically used in the field. Our lump charcoal, obtained from a commercial supplier, was made in Mexico from cord wood (not from lumbar scraps). We obtained fuel with higher moisture content by placing the dry charcoal in a humidification chamber at nearly 100% RH (relative humidity) for at least 48 hours. The charcoal was non-uniform in size and shape, but we used charcoal with a minimum dimension of approximately 1 cm and a maximum dimension of approximately 6 cm. In the future, we will experiment with screening the charcoal for better uniformity, and we will experiment with sprinkling the charcoal with water to obtain charcoal with higher moisture content.

Charcoal igniting material. Charcoal fuel is ignited with many different materials. We used a solid material, commercially available for the purpose of igniting charcoal, made from 90% wood fiber and 10% recycled newsprint, wood waste and paraffin wax. All charcoal was ignited with approximately 45 g of this material, except charcoal fuel for the StoveTec charcoal stove was ignited with charcoal lighter fluid, as recommended by the manufacturer.

Pellet fuel. We tested the StoveTec prototype TLUD stove with Douglas fir wood pellets obtained from a commercial supplier, and we tested the Oorja stove with Oorja biomass pellets provided by the manufacturer. We obtained fuel with higher moisture content by sprinkling pellets with water and sealing in an air-tight container for at least 24 hours. We calculated the amount of water to add to obtain the desired moisture content (15% on a wet basis).

Corn cob fuel. We obtained dry corn cobs from a commercial supplier. We obtained fuel with a higher moisture content by sprinkling cobs with water and sealing in an air-tight container for at least 24 hours. We calculated the amount of water to add to obtain the desired moisture content (30% on a wet basis).

Rice hull fuel. We obtained dry rice hull fuel from a commercial supplier, and we obtained fuel with higher moisture content by sprinkling rice hulls with water and sealing in an air-tight container for at least

24 hours. We calculated the amount of water to add to obtain the desired moisture content (18% on a wet basis). We found that the rice hulls did not readily absorb water, and we had to vigorously mix the fuel and water to obtain the desired moisture content.

Plant Oil. The Protos stove was designed to burn various plant oils, but we used rapeseed (canola) oil, because of availability, as recommended by the manufacturer.

2.3 Test System

Our test system, shown in Figure S1 (supplementary information, referenced in Appendix), consisted of a hood for collecting emissions from the stoves, a HEPA filter for removing particles from dilution air, an air duct for sampling air pollutants, and a blower for drawing air through the hood, HEPA filter, and duct. Air flow was adjusted so that all emissions were collected by the hood, but the velocity of air currents near the stove was less than 0.25 ms^{-1} to minimize the effect on performance of the stove. Air velocity in the duct was measured with an Ultratech (Garner, NC) pitot tube array, and air mass flow was determined by measurements of air velocity, temperature, and pressure. Additional dilution air was desired for the instruments listed in the figure. We used a Hildemann dilution sampling system (Hildemann et al., 1989), with automated control of air flow rates, to provide a dilution ratio of ten to one.

2.4 Sampling and Analysis

CO (carbon monoxide) and CO_2 (carbon dioxide) were measured in real time with an infrared analyzer, Model 200, California Analytical (Orange, California). THCs (total hydrocarbons) were measured in real time with an FID (flame ionization detector) analyzer, Model 300-HFID, California Analytical. CH_4 (methane) was measured in real time with a separate FID analyzer, Model 300M-HFID, California Analytical. $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm) was isokinetically sampled and collected on Teflon membrane filters with a URG (University Research Glassware, Chapel Hill, NC) cyclone and filter pack. Filters were equilibrated at 35% relative humidity and 23°C in an environmental chamber and were weighed with a micro balance, Model MC5, Sartorius (Goettingen, Germany). $PM_{2.5}$ was also collected on quartz fiber filters and was analyzed for OC/EC (organic carbon/elemental carbon) with a thermal-optical analyzer, Model 4L, Sunset Laboratory, (Forest Grove, Oregon). Sub-micrometer particles were measured with an SMPS (scanning mobility particle sizer) spectrometer, consisting of a Model 3080 Electrostatic Classifier and a Model 3010 Condensation Particle Counter, TSI (Shoreview, Minnesota). BC (black carbon) was measured in real-time with an Aethalometer, Model AE51, Magee Scientific (Berkeley, California). BC was also measured on the Teflon membrane filters with a Transmissometer, Model OT21, Magee Scientific. Aerosol light absorption and scattering were directly measured in real time with a photo-acoustic soot spectrometer, three-wavelength, Model PASS-3, Droplet Measurement Technology (Boulder, Colorado). Results for emissions of OC, EC, and BC, and for aerosol light absorption and scattering, will be reported in a subsequent publication.

2.5 Test Protocol. We used the WBT (Water Boiling Test) Version 4, posted on the PCIA web site, www.pciaonline.org. We measured pollutant emissions during the three phases of the WBT, and we separately report emissions for each of the three phases: (1) high power, cold start, (2) high power, hot start, and (3) low power, simmer.

We used a modified procedure for charcoal stoves, similar to the procedure used in our previous testing (Jetter and Kariher, 2009), because charcoal fuel takes longer to ignite than other fuels we used. Charcoal stoves typically produce a large amount of smoke during a cold start. For this reason, stoves are typically started outdoors and are brought indoors after the charcoal is hot and stops smoking. Although the hot charcoal produces little smoke, it produces a large amount of CO, so charcoal stoves should only be used in very well ventilated areas. We used 45 g of the solid, charcoal igniting material (described above) arranged in the same triangular shape, as recommended by the manufacturer of the material, for each cold start. We placed the pot on the stove after the charcoal was ignited and the igniting material stopped flaming. During the cold start, we measured the relatively high emissions of $PM_{2.5}$ from the igniting process. For the hot start phase of the WBT, we weighed the hot charcoal remaining from the cold start phase, and we left the hot charcoal in place in the stove. We added charcoal if needed during the hot start phase. Emissions measured during the hot start phase included the relatively low $PM_{2.5}$ emissions and relatively high CO emissions.

3. Results and Discussion

We report data in the supplementary information, referenced in the Appendix. Figures in the supplementary information are identified by the letter S and are abbreviated in brackets, for example Figure S2 is abbreviated [S2]. Error bars in the figures represent plus or minus one standard deviation. Each figure is accompanied by the tabulated data.

3.1 Fuel moisture. We found that various amounts of low-moisture (dry) fuel were required for starting and maintaining combustion in stoves tested with high-moisture (wet) fuel. Fuel moisture content is reported as the average (on a mass basis) of wet and dry fuels used for each stove/fuel combination tested. For example, the target moisture content for wet wood fuel was 30%, but the values shown in [S2] are somewhat lower, because of the additional dry fuel required to perform the tests. Average moisture content for dry wood fuel was 9.5%. Average moisture content for dry charcoal [S3] was 5.1%. We found that the charcoal did not absorb much moisture during storage at nearly 100% relative humidity, and the average moisture content of the wet charcoal [S4] was 7.8%. Hot charcoal remaining after the cold start (and used during the hot start and simmer) was assumed to have zero moisture content. Fuel moisture content for other fuels is shown in [S5].

3.2 Fuel energy content. Heat of combustion values, based on our measurements, were used for the WBT calculations and are shown in [S6].

3.3 Power and time-to-boil. Fire power [S7] is the fuel energy used by the stove per time. Cooking power [S8] is the useful energy into the cooking pot per time. Cooking power is shown in the figure for the cold start and hot start, but not for the simmer, because cooking power cannot be accurately measured during the simmer phase of the WBT. Time-to-boil, as defined in the WBT, is shown in Figures S9-S10. Cooking power is correlated with time-to-boil, as shown in [S11]. Some of the stoves we tested did not have enough cooking power to consistently boil 5 liters of water, as preferred in the WBT protocol. For the lower powered stoves, we used a smaller pot with 2 liters of water. Using the appropriate pot for the cooking power of the stove resulted in more consistent results for time-to-boil and other WBT parameters. We recommend this approach in the ongoing revision of the WBT.

3.4 Efficiency. Thermal efficiency [S12] is the ratio of useful energy (to the cooking pot) to total energy (released by the fuel). Thermal efficiency is shown in the figure for the cold start and hot start, but not for the simmer, because the useful energy to the cooking pot cannot be accurately measured during the simmer phase of the WBT. Compared to the 3-stone fire, most of the stoves we tested had better thermal efficiency. $CO_2/(CO_2+CO)$ as carbon [S13] is a proxy for combustion efficiency. Compared to the 3-stone fire, some of the stoves had better combustion efficiency, although most of the charcoal stoves had worse combustion efficiency.

3.5 Fuel use. Fuel burning rates are shown in [S14-S16]. Specific fuel consumption, as shown in [S17-S19], is defined by the WBT as the mass of fuel used per liter of water remaining in the pot at the end of the test. If a stove has a long time-to-boil, then less water remains in the pot at the end of the test (due to loss from steam), and specific fuel consumption tends to be higher. Similarly, if a stove cannot be controlled during the low-power simmer phase to maintain the water at the target temperature below the boiling point, then less water remains at the end of the test, and specific fuel consumption tends to be higher. Specific energy consumption [S20] is similarly affected by the water remaining in the pot at the end of the test.

3.6 Air pollutant emissions. We report data for air pollutants [S21-S68] as emission rates per time and as emission factors based on fuel energy, cooking energy, fuel mass, and WBT cooking tasks (cold start, hot start, simmer). Pollutant emissions are reported in terms of mass, except UFP (ultra-fine particles – particles less than 100 nm) emissions are reported in terms of number of particles. The smallest particle size for the SMPS was 14.6 nm. PM (particulate matter) has typically been considered the best single indicator of air pollutant emissions for stoves. For example, the USEPA regulates emissions from wood-fueled heating stoves in the U.S. based only on PM emission rates per time (USEPA, 1988). Our measured $PM_{2.5}$ emission rates for household cook stoves are shown in Figure 2 and tabulated values are provided in [S29]. Compared with the 3-stone fire, most of the stoves we tested had lower emissions of $PM_{2.5}$, although there were exceptions, as discussed in the following results for each stove. For comparison, the USEPA limit for PM emissions from heating stoves is 7.5 g/min, but heating stoves have greater heating capacity than household cook stoves. Nevertheless, we found some cook stove tests exceeded the limit, as shown in Figure 2. Compared with the 3-stone fire, charcoal stoves generally had relatively low emissions of $PM_{2.5}$, but high emissions of CO [S21].

3.7 Results and discussion for each stove.

3-Stone Fire. For this study, the distance between the testing surface (floor) and the cooking pot was 19 cm, while in our previous study (Jetter and Kariher, 2009), the distance was 9 cm. We chose a greater distance, similar to MacCarty et al. (2008), because we thought it would reduce emissions of air pollutants. We thought combustion would be improved by providing more space for mixing of combustion gases and by reducing the quenching of flames on the cooking pot. Compared with our previous results for the carefully-tended fire with dry fuel, we found that combustion efficiency [S13] was higher, as expected, and $PM_{2.5}$ emissions [S35] were lower, but the time-to-boil [S9] was longer, thermal

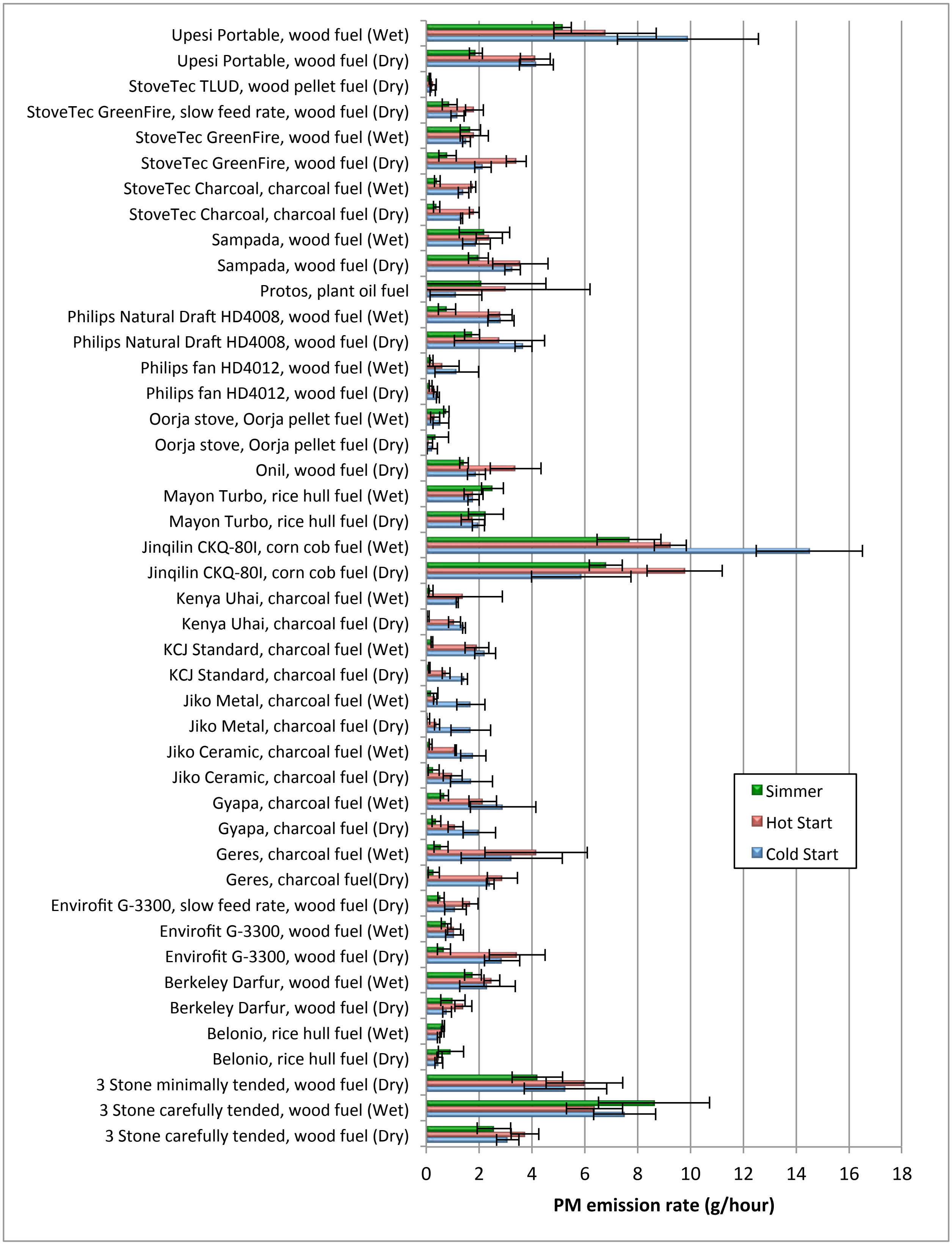

Figure 2. PM$_{2.5}$ emission rate (per time)

efficiency [S12] was lower, and specific fuel consumption [S17] was higher. The greater distance between floor and cooking pot resulted in improved combustion efficiency at the expense of heat transfer efficiency. Compared with the carefully tended 3-stone fire with dry fuel, the 3-stone fires with minimal tending and with wet fuel had worse emissions of air pollutants, as expected. $PM_{2.5}$ emissions [S29] were particularly high with wet fuel. We found it was not possible to test with wet fuel with minimal tending, because the 3-stone fire required constant tending to maintain combustion with wet fuel.

Belonio Rice Husk Gas Stove. We tested the smaller size stove (of two models) with a reactor diameter of 12 cm and height of 40 cm. This stove was designed for low power, and it had the lowest cooking power [S8] during the hot start phase of all the stoves we tested. It was the only stove we tested with the pot lid on, because it would not bring 2 liters of water to a full boil with the lid off. We tested with the pot lid off during the simmer phase. The stove had a control for varying the rotational speed of the fan, but we tested with nearly full fan speed during simmer. We found that if we set the fan speed too low, the flame went out, and a large amount of smoke was produced. We found the rice hull fuel easy to ignite, and the stove required no tending while the batch of fuel burned for up to 30 minutes. Compared with most non-charcoal stoves we tested, $PM_{2.5}$ emissions [S31] were low, but CO emissions [S23] were high. The stove requires electricity to operate the fan, and an interruption of power causes the flame to go out and a large amount of smoke to be produced. The ability to use abundantly available, waste rice hulls as fuel is an important advantage of this stove.

Berkeley-Darfur Stove. Compared with the 3-stone fire, maximum cooking power [S8] was similar, thermal efficiency [S12] was much better, and fuel consumption [S17] was much lower. Compared with the 3-stone fire, pollutant emissions per WBT task [S27, 35, 43, 51, 59, 67] were lower. Compared to the Envirofit and StoveTec rocket stoves operated at a medium power level (see below), the Berkeley-Darfur stove had a similar cooking power and had similar pollutant emissions. However, the two rocket stoves had somewhat lower pollutant emissions with wet fuel.

Envirofit G-3300 Stove. Compared with the 3-stone fire, maximum cooking power [S8] was higher and time-to-boil [S9] was faster; however, the manufacturer recommended that this stove be operated at a lower cooking power for reduced emissions. We tested the Envirofit G-3300 at maximum power and also at a medium power level (denoted by "slow feed rate" in the supporting information). We burned four wood fuel sticks at a time for maximum power, and we burned three sticks at a time for medium power. The medium power level for the Envirofit stove was similar to the maximum cooking power [S8] for the 3-stone fire. Compared with the 3-stone fire, thermal efficiency [S12] was much better and fuel consumption [S17] was much lower at all power levels. Pollutant emissions per WBT task [S27, 35, 43, 51, 59, 67] were lower at all power levels. Pollutant emissions were lower at the medium power level than at maximum power, as expected. Compared with the 3-stone fire, the Envirofit stove had much lower emissions, especially with wet fuel. Our results were consistent with Yuntenwi et al. (2008), who found that, compared with a 3-stone fire, a rocket stove was less susceptible to higher emissions with increased moisture content of fuel. We tested another rocket stove, the StoveTec Greenfire, at a medium power level, and we found that performance was similar for the two stoves. The Envirofit G-33SKT pot skirt, shown in Figure 1, was designed to adjust to fit pots of various sizes (similar to the design of certain vegetable steamers), but we found that the adjustable, overlapping leaves easily became mispositioned, and that caused awkward placement of the cooking pot into the skirt.

GERES NLS (New Lao Stove). This charcoal stove had the highest cooking power [S8] of all the stoves we tested. Compared with most charcoal stoves we tested, thermal efficiency [S12] and specific fuel consumption [S18] were approximately in the middle of the range of values, CO emissions per energy to the cooking pot [S23] with dry fuel were low, and $PM_{2.5}$ emissions per energy to the cooking pot [S31] were approximately in the middle of the range of values for the cold start, and were high for the hot start. The GERES stove was the only charcoal stove we tested that did not have a means for restricting the air flow to underneath the burning charcoal to reduce power during the simmer phase of the WBT. Most charcoal stoves we tested had a hinged door for this purpose. We used a sheet of aluminum foil to restrict air flow during the simmer phase, but a hinged door would have been more convenient.

Gyapa Stove. Compared with other charcoal stoves we tested, cooking power [S8], thermal efficiency [S12], fuel consumption [S18], and CO and $PM_{2.5}$ emissions per energy to the cooking pot [S23, 31] were approximately in the middle of the range of values, except CO emissions during the hot start were high, and $PM_{2.5}$ emissions with wet fuel during the hot start were high.

Ceramic Jiko and Metal Jiko. Compared with the small, metal jiko we tested, the small, ceramic jiko had slightly higher cooking power [S8] and faster time-to-boil [S10], but thermal efficiency [S12] and fuel consumption [S18] were nearly the same. Although the ceramic jiko is usually considered to be an improvement over the common, metal jiko, we found that the ceramic jiko we tested did not have lower emissions of CO and $PM_{2.5}$ [S23, 31]. The ceramic jiko is likely to be more durable than the metal jiko. Compared with most other charcoal stoves we tested, both jiko's had lower cooking power [S8], lower thermal efficiency [S12] during the cold start, and higher fuel consumption [S18] during the cold start and simmer. CO emissions per energy to the cooking pot [S23] were high for both jikos with dry fuel during the cold start. $PM_{2.5}$ emissions [S31] were high for both jikos for the cold start.

KCJ (Kenya Ceramic Jiko) Standard Stove. Compared with other charcoal stoves we tested, cooking power [S8] was in the middle of the range of values, thermal efficiency [S12] was high (especially during the hot start with dry fuel), fuel consumption [S18] was low, and CO and $PM_{2.5}$ emissions per energy to the cooking pot [S23, 31] were approximately in the middle of the range of values.

Kenya Uhai Stove. Compared with other charcoal stoves we tested, cooking power [S8] was in the middle of the range of values, thermal efficiency [S12] was high (especially during the cold start), fuel consumption [S18] was low, CO emissions [S23] were low, and $PM_{2.5}$ emissions [S31] were low for the cold start.

Jinqilin CKQ-80I Stove. Compared with other stoves we tested, this corn-cob fueled stove had cooking power [S8] in the middle of the range of values. Thermal efficiency [S12] was low, as we have found for other stoves with a relatively large amount of thermal mass (Jetter and Kariher, 2009), and specific energy consumption [S20] was high. CO emissions [S23] were high and were in the same range as emissions from charcoal stoves. Furthermore, CO emissions with wet fuel during the cold start were the highest compared to all stoves we tested. $PM_{2.5}$, THC, and CH_4 emissions [S31, 47, 55] were also among the highest for all stoves we tested and were especially high with wet fuel during the cold start. We attempted to reduce emissions by adjusting the controls for primary and secondary air. We were trained and assisted by a consultant with experience operating and testing the stove in China. We adjusted the controls while observing the real-time air pollutant monitors, but we were not able to reduce emissions to a lower level. We found that the primary air control was easy to inadvertently close, and when primary air flow was momentarily interrupted, then the flame went out, and a very large amount of smoke was produced. Our consultant mentioned that he observed that stove users in China typically left the ash access door open about 1 cm, and we found this provided enough air via natural convection to sustain the flame in the event the primary air was inadvertently shut off.

Mayon Turbo Stove 7000. Cooking power [S8] for this rice-husk fueled stove was higher than for the Belonio Rice Husk stove, and power was sufficient to bring 5 liters of water to a full boil. Compared with the Belonio stove, thermal efficiency [S12] was lower, fuel consumption [S19] was higher, CO emissions [S23] were lower, and $PM_{2.5}$ emissions [S31] were higher. Operation of the stove requires that the user tap on the side of the fuel hopper to feed fuel to the combustion area, and the power level of the stove is controlled by the amount of tapping. We found that more frequent tapping on the hopper to feed a smaller amount of fuel at a time resulted in lower emissions, and we tapped approximately every two minutes during the testing. The fuel was easy to ignite. An important advantage of this stove is the ability to burn abundantly available, waste rice hulls, and it does not require electricity to operate a fan.

Onil (HELPS International) Stove. The stove we tested was assembled on site by a representative from HELPS International. We used the same red oak fuel used for testing other stoves, except we used split wood, rather than sawed wood, as requested by the HELPS representative. Maximum cross-section dimension of the split wood was 4 cm. During the hot start, cooking power [S8] was adequate to boil 5 liters of water in 34.5 minutes, but during the cold start, the time-to-boil [S9] was 51.0 minutes. Combustion efficiency [S13] was quite good compared to other stoves we tested, but thermal efficiency [S12] was low. The slow time-to-boil and the low thermal efficiency were caused by the relatively large thermal mass of the plancha and ceramic combustion chamber. Thermal efficiency was better for the Onil stove than for another plancha stove we previously tested (Jetter and Kariher, 2009), likely because the removable rings in the plancha provided improved heat transfer to the pot. Compared with other wood-fueled stoves we tested, fuel consumption [S17] was high, because of the low thermal efficiency. Compared with the 3-stone fire, emissions of CO [S27], THC [S51], and CH_4 [59] were substantially lower, but emissions of $PM_{2.5}$ [S35] were similar. We attempted to test the Onil stove with wet fuel, but found that time-to-boil for 5 liters of water was greater than 60 minutes. We may test this stove with wet fuel with a smaller pot in the future. A notable advantage of the Onil stove is the chimney that reduces indoor air pollution. Plancha stoves have other advantages not captured by the WBT, such as the ability to cook tortillas, fry foods, heat multiple pots, and heat the indoor living space; however, the plancha stoves we tested were not well suited for boiling water. The GACC Standards and Testing Working Group is considering alternative test methods for plancha stoves.

Oorja Stove. Cooking power [S8] was less than 1,000 watts for this pellet-fueled stove, so we tested the stove with the smaller sized pot and 2 liters of water. Thermal efficiency [S12] for the Oorja stove was approximately two times that of the 3-stone fire. Compared with other stoves we tested, combustion efficiency [S13] was high, and emissions of pollutants [S31, 47, 55, 63] were much lower than for the 3-stone fire. Compared to other stoves we tested, we found greater variation in emissions, and this might have been caused by an intermittent problem with the fan speed controller. During our testing, we observed that the fan speed occasionally slowed, and then the power level of the stove dropped. When this problem occurred, we bypassed the fan speed controller and applied battery voltage directly to the fan. We found that if electrical power to the fan was interrupted, such as when a battery was momentarily removed, then the flame went out and a large amount of smoke was produced. An extra rechargeable battery received with the stove was defective and would not hold a charge. The stove required no tending while the batch of fuel burned for up to 70 minutes.

Philips Power Stove HD4012. Compared to other wood-burning stoves we tested, this stove had the highest cooking power [S8] and fastest time-to-boil [S9]. Thermal efficiency [S12] was high, combustion efficiency [S13] was high, and emissions of all pollutants were very low. The excellent performance of the stove was consistent with the performance of the Philips HD4010 stove we previously tested (Jetter and Kariher, 2009). Compared to the Philips HD4008 natural draft stove, the HD4012 fan stove had much lower emissions of $PM_{2.5}$ [S35], but similar emissions of UFPs [S67]. The rechargeable battery in the HD4012 is not removable, and the stove must be plugged into a source of electricity to recharge the battery. The Philips stove requires wood fuel to be cut into shorter pieces approximately 10 cm long, compared with other stoves we tested that can use long, wood fuel sticks.

Philips Natural Draft Stove HD4008. We found that we operated this stove at a higher fuel burning rate [S14] with wet fuel than with dry fuel to maintain combustion. For this reason, cooking power [S8] was higher and time-to-boil [S9] was faster with wet fuel. Compared with the 3-stone fire, thermal efficiency [S12] was more than twice as high, fuel consumption [S17] was much lower, and CO emissions [S27] were lower. $PM_{2.5}$ emissions [S35] for the HD4008 and the 3-stone fire were similar with dry fuel, but the HD4008 had much lower emissions than the 3-stone fire with wet fuel. The Philips natural draft stove also requires wood fuel to be cut into shorter pieces approximately 10 cm long, compared with other stoves we tested that can use long, wood fuel sticks.

Protos Stove. Cooking power [S8] was less than 1,000 watts for this liquid-fueled stove, so we tested the stove with the smaller sized pot and 2 liters of water. Firepower [S7] and the fuel burning rate [S16] remained the same during the cold start, hot start, and simmer, but we reduced the cooking power during the simmer phase by placing the “simmer plate” (provided with the stove) between the burner and the pot. The stove required approximately 30 mL of alcohol fuel to preheat the burner before operation with plant oil fuel. Compared with the 3-stone fire, thermal efficiency [S12] was more than twice as high, and compared to all the stoves we tested, combustion efficiency [S13] was high, and CO emissions [S23] were low. However, $PM_{2.5}$ emissions [S31] were high, and variation in $PM_{2.5}$ emissions was high, likely due to malfunction of the burner. We cleaned the burner after every test (less than 1.5 hours of stove operation), even though the manufacturer recommended cleaning the burner after every five hours of operation. We completely disassembled the burner assembly, cleaned the burner using the tools provided with the stove for this purpose, and then reassembled the burner, as recommended by the manufacturer. Nevertheless, the burner orifice occasionally became partially obstructed with a resulting reduction of cooking power. When the orifice became obstructed, we cleaned it with the fine wire tool (provided with the stove) while the stove was in operation, as recommended. During this process, occasionally the flame went out. Sometimes, we were able to reignite the burner, but occasionally we were not able to reignite, and then the bottom of the pot and the stove were sprayed with fuel oil from the burner. We did not use the test data for results reported here for the cases when we were not able to reignite the burner. The manufacturer was consulted and responded that the stove we tested had a defective burner and that the problem has since been corrected.

Sampada Gasifier Stove. Compared to other wood-fueled stoves we tested, cooking power [S8] was approximately in the middle of the range of values. Thermal efficiency [S12] for the Sampada stove was better than for the 3-stone fire, but not as good as for some of the other wood-fueled stoves. Compared with the 3-stone fire, fuel consumption [S17] was lower at high power (cold start and hot start) but was nearly the same at low power (simmer). Compared with the 3-stone fire, emissions of CO [S27] and $PM_{2.5}$ [S35] were lower, especially with wet fuel. The Sampada had a vertical tube in the center of the combustion space that was supported by the bottom of the stove. During our testing, the bottom of the stove warped due to combustion heat, and then the vertical tube slanted to one side. The manufacturer was consulted and responded that the bottom of the stove is now made of thicker metal to overcome the problem. The Sampada stove requires wood fuel to be cut into shorter pieces approximately 20 cm long, compared with other stoves we tested that can use long wood fuel sticks.

StoveTec Prototype Charcoal Stove. Compared with other charcoal stoves we tested, cooking power [S8] was approximately in the middle of the range of values. Thermal efficiency [S12] for the StoveTec stove was comparable to other charcoal stoves we tested for the hot start, but thermal efficiency for the cold start cannot be compared to the other stoves because of the different igniting material (charcoal lighter fluid) that was used for the StoveTec stove. Compared to other charcoal stoves we tested, fuel consumption [S18] was low, and emissions of CO [S23] and $PM_{2.5}$ [S31] were low, although emissions for the cold start cannot be compared to the other stoves because of the different igniting material used. For this prototype stove, the vertical, cylindrical core in the charcoal chamber was made out of perforated mild steel, but for a production stove, this part would likely need to be made of a different material that could better withstand the high temperature of charcoal combustion.

StoveTec Greenfire Wood Stove. Compared with the 3-stone fire, maximum cooking power [S8] was higher and time-to-boil [S9] was faster. We tested the StoveTec stove at maximum power and also at a medium power level (denoted by “slow feed rate” in the supporting information), for comparison with another rocket stove, the Envirofit G-3300. We burned four wood fuel sticks at a time for maximum power, and we burned three sticks at a time for medium power. The medium power level for the StoveTec stove was similar to the maximum cooking power [S8] for the 3-stone fire. Compared with the 3-stone fire, thermal efficiency [S12] was much better and fuel consumption [S17] was much lower at all power levels. Pollutant emissions per WBT task [S27, 35, 43, 51, 59, 67] were lower at all power levels. Pollutant emissions were lower at the medium power level than at maximum power. Compared with the 3-stone fire, the StoveTec stove had much lower emissions, especially with wet fuel. We found that performance for the StoveTec and Envirofit rocket stoves was, in general, similar. We found that the StoveTec stove developed thin, hairline cracks in the ceramic combustion chamber during testing. Cracks formed on stress relief grooves, but also on other areas of the cylindrical combustion chamber. It is not likely that these very small cracks affected performance during the testing.

StoveTec Prototype TLUD Stove. Cooking power [S8] was less than 1,000 watts for this TLUD stove, so we tested it with the smaller pot with 2 liters of water. Compared with all the stoves we tested, this stove had the highest thermal efficiency [S12]. Compared with all stoves, combustion efficiency [S13] was also high, energy consumption [S20] was low, and emissions of all pollutants were low. Among the stoves we tested, this stove was exceptional, because it performed so well with natural draft (without a fan), although it required processed fuel (wood pellets). The stove required no tending while the batch of fuel burned for approximately two hours. We attempted to test the stove with wet fuel, but we found that combustion could not be maintained, a typical characteristic for natural draft TLUD stoves.

Upesi Portable Stove. Compared with the 3-stone fire, cooking power [S8] was similar, and hence time-to-boil [S9] was similar. Thermal efficiency [S12] for the Upesi stove was a little better than for the 3-stone fire, but thermal efficiency for the Upesi stove was the lowest of all the non-chimney, wood-burning stoves we tested. Likewise, fuel consumption [S17] for the Upesi stove was a little lower than for the 3-stone fire, but fuel consumption for the Upesi stove was the highest of the non-chimney, wood-burning stoves we tested. CO emissions per mass of fuel [S24] were a little higher for the Upesi than for the 3-stone fire, but since the Upesi used a little less fuel, total CO emissions [S27] were similar for the Upesi stove and 3-stone fire. $PM_{2.5}$ emissions [S35] were also similar for the Upesi stove and 3-stone fire. CH_4 emissions [S55] with wet fuel were higher for the Upesi stove than for the 3-stone fire. In summary, the Upesi stove did not demonstrate much of an improvement over the 3-stone fire in terms of fuel use or emissions. The Upesi stove is constructed from relatively heavy ceramic material – a heat sink that causes lower thermal efficiency. Nevertheless, the Upesi stove partially encloses the fire, so it may have advantages over a 3-stone fire. The stove may help prevent burns and house fires, and it may perform better than a 3-stone fire outdoors under windy conditions. The Upesi may provide better support for a round-bottomed pot than the typical 3-stone fire, and pot support is important for cooking certain foods that are viscous and require stirring.

4. Conclusions

Our independent laboratory test results and extensive data set will be used by our partners in PCIA who are disseminating stoves in the field, and by the GACC Standards and Testing Working Group that is developing improved protocols and standards for testing cook stoves.

Laboratory test results are often not predictive of field test results, especially when laboratory and field test conditions are dissimilar (Roden et al., 2006; Bailis et al., 2007; Johnson et al., 2008; Roden et al., 2009). Roden et al. (2009) concluded: "To promote a better understanding of real-world emissions, field testing needs to identify the critical conditions and variables governing emissions, and laboratory testing needs to be designed to emulate these conditions." Johnson et al. (2010) propose that performance testing can be improved with an approach "…based on replication of the distribution of emission rates and combustion efficiencies seen during daily cooking activities in homes." We concur that expanded field testing campaigns are needed to provide critical information on actual use conditions that cannot be obtained from laboratory tests. We also recommend further laboratory testing research, coordinated with field research to emulate field conditions, to provide cost-effective evaluation of cook stoves with control of variables that is difficult or impossible to achieve in the field.

Here, we began to evaluate cook stoves under conditions that may be more representative of field use. Compared with previous laboratory studies, our test results for variations of the baseline, 3-stone fire are more consistent with field results. Several previous studies (Smith et al., 2000; Bhattacharya et al., 2002; Johnson et al., 2008; Roden et al., 2009) found proxy combustion efficiencies measured in the laboratory to be 96-97%, while a recent field study found combustion efficiency to be 93% (Johnson et al., 2011). This discrepancy is important, because a small difference in combustion efficiency makes a large difference in pollutant emissions. We found combustion efficiency [S13] measured in the laboratory to be as low as 93.5% for the 3-stone fire tested under conditions that may be more typical of field use. In the future, we will experiment with variation of the distance between the floor and pot, and with the inclusion of smoldering combustion based on activity data from the field.

We tested two rocket stoves, the Envirofit G-3300 and the StoveTec GreenFire, under three power levels, rather than the two power levels specified in the WBT. Testing stoves under a range of power levels may improve capability to correlate laboratory results with field results.

Some studies have aggregated results from the three phases of the WBT for the purpose of benchmarking (MacCarty et al., 2010), or for easier comparison of laboratory results between tests (Yuntenwi et al., 2008), or for comparison of laboratory and field results (Roden et al., 2009). Here, we present separate data for the three phases of the WBT, because it may provide a better opportunity to correlate laboratory results with field results. For example, if field testing indicates a stove is usually operated at low power, then it would be appropriate to compare field results with laboratory results for the stove operated at low power during the WBT.

We found that stoves that used processed fuels or batch fuel loading (Belonio, Oorja, Protos, StoveTec TLUD, and all charcoal stoves) required less operator attention than other stoves that required manual fuel feeding. The Philips HD4012 power stove required manual fuel feeding, but forced draft provided consistent combustion conditions, and compared with other manually fed stoves, performance was less dependent on the operator. Since operator behavior can have a large effect on test results, it will likely be easier to obtain consistent results between laboratory and field tests for stoves that require less operator attention. For example, Johnson et al. (2011 *add reference if available*) recently reported consistent results between laboratory and field tests for the Oorja stove.

Appendix. Supplementary information

Supplementary information referred to in this article can be found in the online version at: *(add)*

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