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Pollutant Emissions and Energy Efficiency under Controlled Conditions for Household Biomass Cookstoves and Implications for Metrics Useful in Setting International Test Standards

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ABSTRACT: Realistic metrics and methods for testing household biomass cookstoves are required to develop standards needed by international policy makers, donors, and investors. Application of consistent test practices allows emissions and energy efficiency performance to be benchmarked and enables meaningful comparisons among traditional and advanced stove types. In this study, twenty-two cookstoves burning six fuel types (wood, charcoal, pellets, corn cobs, rice hulls, and plant oil) at two fuel moisture levels were examined under laboratory-controlled operating conditions as outlined in the Water Boiling Test (WBT) protocol, Version 4. Pollutant emissions (carbon dioxide, carbon monoxide, methane, total hydrocarbons, and ultrafine particles) were continuously monitored. Fine particle mass was measured gravimetrically for each WBT phase. Additional measurements included cookstove power, energy efficiency, and fuel use. Emission factors are given on the basis of fuel energy, cooking energy, fuel mass, time, and cooking task or activity. The lowest PM_{2.5} emissions were 74 mg MJ_{delivered}⁻¹ from a technologically advanced cookstove compared with 700-1400 mg MJ_{delivered}⁻¹ from the base-case open 3-stone cookfire. The highest thermal efficiency was 53% compared with 14-15% for the 3-stone cookfire. Based on these laboratory-controlled test results and observations, recommendations for developing potentially useful metrics for setting international standards are suggested.

INTRODUCTION

Solid fuel combustion emissions from household cooking and heating are a leading risk factor for disease in the developing world, accounting for approximately 4% of all lost healthy life years and some 2 million premature deaths in low- and middle-income countries¹. Demand for fuelwood resources for household energy impacts terrestrial ecology and land-use patterns in a number of regions within the developing world, and fuel gathering typically requires many hours per week for poor populations². Potential climate effects are of concern due to the greenhouse gas and carbonaceous aerosol emissions from household combustion of biomass fuel³. Evidence suggests that widespread deployment of cookstoves with energy and combustion efficiency improvements over traditional technology could potentially help mitigate adverse human health, energy, and climate consequences⁴. Studies of stoves with chimneys show some success

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4 in reducing exposures and health impacts, but also indicate that additional reduction in emissions could potentially
5 achieve even greater benefits⁵. However, wide-scale adoption of cookstoves built with improved combustion technologies
6 and low emissions faces substantial challenges, including the lack of widely available and accepted cookstove emissions
7 and energy efficiency standards and testing protocols⁶. Such standards are required for (i) informing governments,
8 donors, and investors interested in promoting and supporting only high-quality stoves, (ii) improving comparisons among
9 fuels and stoves operating under pertinent task-, energy efficiency-, and combustion-related test variables, and (iii)
10 developing certification procedures, performance benchmarks, and meaningful test infrastructure for the global cookstove
11 market. Standards can provide incentive for stove developers to innovate and improve performance. Standards are not
12 developed in this study but may be developed through a standards organization. Metrics are suggested for possible use in
13 standards, as discussed below.
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21 A variety of protocols and metrics are used to evaluate cookstoves and quantify their combustion emissions. Many
22 studies utilize the “hood method” to capture, dilute, and measure air pollutant emissions from cookstoves⁷⁻²⁰, while some
23 measure the emissions directly from the flue if there is a chimney¹⁷⁻²⁰ or from a chamber after re-directing the emissions²¹⁻
24 ²⁵. These studies certainly provide a valuable body of knowledge, but the numerous test procedures have led to
25 inconsistencies in reporting, making the sparse published data difficult to compare from one laboratory to the next.
26 Moreover, the combustion and fuel conditions, chemical and physical analysis techniques, reporting metrics, and pollutant
27 types measured in these studies vary substantially. This general lack of consistency has hampered the development of
28 sound policies regarding cookstove use and dissemination. Further complicating the picture is that the emissions from
29 cookstove testing under field and laboratory conditions can differ²⁶⁻²⁸.
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37 The development of international cookstove standards will require some degree of laboratory control to rapidly and
38 accurately assess energy- and task-specific emissions performance as cookstove design and technology improve. Many
39 earlier emissions characterization efforts successfully applied controlled laboratory conditions to examine cookstoves
40 from Asia^{8-12,17-21,29-33}, South Africa⁷, and Guatemala²², where populations rely heavily on their use. More recent
41 controlled laboratory experiments were conducted to investigate the effects of fuel species, fuel combinations and fuel
42 moisture content on stove emissions and energy efficiency^{13-15,23-25}. Multiple stove design technologies were examined in
43 these experiments, and test results for fifty stoves were compiled for the purpose of defining composite performance
44 benchmarks¹⁶, but a different approach is recommended here, as described below.
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51 The present study provides a more extensive analysis of emissions and fuel use from a wider range of newer cookstove
52 technologies than past studies. Twenty-two cookstoves burning six fuels (cookstove dependent) at two moisture content
53 levels are examined under laboratory-controlled operating conditions. Pollutant emissions are sampled using established
54 hood and dilution methods. Real-time measurements of carbon dioxide (CO₂), carbon monoxide (CO), methane (CH₄),
55 total hydrocarbon (THC), fine particulate matter, and ultrafine particle (UFP) emissions are provided. In the interest of
56 developing a novel and versatile emissions database for cookstoves, emissions rates and factors are calculated on the basis
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of cooking energy delivered, cooking task, fuel energy and fuel mass. Cooking power, energy efficiency, and fuel use are also calculated. Using these laboratory-controlled test results and observations as a basis, useful metrics for developing and setting international standards for cookstove emissions and energy efficiency are discussed.

MATERIALS AND METHODS

Cookstove Systems. For this study, a cookstove system was defined by the cookstove type (including chimney, if so equipped), fuel (composition, moisture content, and size), cooking pot, pot skirt (device for improving heat transfer) if available from the stove manufacturer, and operating procedure. The twenty-two cookstove types, six fuels, moisture contents (low and high), cooking pot water volumes, and combustion chamber materials (metal or ceramic) are listed in Table 1. A total of forty-four system combinations were tested for the present study (see the Supporting Information for more details). Some low-power stoves did not consistently boil 5L of water—the WBT-specified default volume. For these stoves, a 2L pot was used instead. Two cookstoves were equipped with chimneys (~2m height). Natural-draft (also termed natural convection) stoves dominated the cookstove matrix; four forced-draft (fan-provided air) stoves were also tested. Twelve stoves with batch fuel loading (e.g., charcoal stoves) required less time for tending than others that required manual fuel feeding. Four stoves were variations of the “rocket” stove design¹³, and eight were variations of the “gasifier” design³⁴. The only traditional cooking system tested was a 3-stone cookfire. This particular system is treated as the base-case in this study because it is traditionally the most widely used. For the “carefully tended” 3-stone cookfire, fuelwood sticks were arranged in a radial pattern with the fire at the center, and sticks were continually fed into the center so that the ends of the sticks consistently burned. In the “minimally tended” mode, fuel wood was loaded in batches approximately every 10 minutes, and the fire was untended between loadings. Apart from the 3-stone cookfire, each cookstove was operated in one mode generally following manufacturers’ instructions. Table 1 provides identifiers that refer to cookstove photos and descriptions in the Supporting Information.

Fuels. Fuels were selected based on the stove type and typical field conditions. Fuel types include wood, charcoal, pellets, corn cobs, rice hulls and plant oil (Table 1). For wood-fired stoves, red oak (*Quercus rubra*) sticks of ~10% and ~30% moisture (wet basis) were used. Wood fuels sometimes required light processing including cutting or chopping. Fuel variables are described in the Supporting Information. Fuel moisture content was measured using ASTM Standard Method D4442-07³⁵. Fuel heat of combustion was measured using ASTM Standard Method ASTM D5865-10³⁶. Per WBT specification, the lower heating value of each fuel was used (see the Supporting Information).

Test Protocol. The WBT protocol (Version 4)³⁷ was used to determine cookstove power, energy efficiency, and fuel use. Pollutant emissions were simultaneously measured and reported for each of the three WBT test phases: (1) high-power, cold-start; (2) high-power, hot-start; and (3) low-power, simmer. Phases (1) and (2) were defined by the duration between fire ignition and the water boiling point. Phase (1) began with the cookstove, pot, and water at ambient temperature. Phase (2) immediately followed with the cookstove hot but the pot and water at ambient temperature. Phase (3) was

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4 defined by a 30-minute time period with the nominal water temperature maintained at 3°C below the boiling point. A
5 modified procedure was used for charcoal stoves¹⁵ (see the Supporting Information). Two wood-fueled rocket stoves
6 (Envirofit G-3300 and StoveTec GreenFire) were tested at an additional medium-power level. The power level was
7 controlled by simply changing the fuel feed rate. The WBT protocol specifies that the cooking pot be uncovered during
8 testing. Results are reported as averages with standard deviations for the tests performed in triplicate (or more).
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12 **Cookstove Emissions Testing Facility.** A schematic diagram of the emissions testing system and a thorough description
13 of the facility are provided in the Supporting Information. Briefly, stove emissions were collected into a stainless steel
14 hood connected to a dilution tunnel ($\sim 47 \text{ m}^3 \text{ min}^{-1}$), from which pollutant emissions were sampled. An induced-draft
15 blower maintained negative pressure in the entire system and provided filtered dilution air and hood air flows. A second
16 stage of dilution ($\sim 1:10$) was provided by a modified dilution sampling system^{38,39}, which was required for the Scanning
17 Mobility Particle Sizer (SMPS) and certain optical and carbonaceous aerosol measurements to be reported in a subsequent
18 publication. In this study, total emissions—those from the stove body and flue for stoves with chimneys—were measured
19 for all cookstove systems.
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23 **Emissions Characterization.** CO, CO₂, THC_s, and CH₄ were continuously monitored with infrared and flame ionization
24 detector (FID) analyzers (Models 200, 300-HFID, and 300M-HFID; California Analytical; Orange, California).
25 Continuous measurements were recorded every ten seconds. PM_{2.5} (particulate matter with aerodynamic diameter ≤ 2.5
26 μm) mass was measured gravimetrically with a microbalance (Model MC5; Sartorius; Göttingen, Germany). The PM_{2.5}
27 was sampled isokinetically and collected on polytetrafluoroethylene (PTFE) membrane filters positioned downstream of a
28 PM_{2.5} cyclone (URG, Chapel Hill, NC). Filters were equilibrated at 35% relative humidity and 23°C in an environmental
29 chamber prior to weighing. A particle mobility diameter range of 14.6-661 nm was measured with a SMPS, consisting of
30 an electrostatic classifier and condensation particle counter (Models 3080 and 3010; TSI; Shoreview, Minnesota). UFP
31 emissions over the 14.6-100 nm range were reported on a particle number basis. The SMPS conducted a full scan every
32 150 seconds, and some short-duration emission events may have been missed. Emissions were quantified using the mass-
33 flow method which requires continuous monitoring of the dilution tunnel air flow and temperature over the WBT
34 measurement period³⁷.
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38 Controlled laboratory measurements of cookstove emissions sometimes poorly predict field-based emissions^{26-28, 40}. Some
39 studies combine data from WBT phases for benchmarking purposes¹⁶ or for comparing intra-study laboratory and field
40 data²⁸, but these data are based on cookstove usage patterns that may not be reflective of actual field use. To improve the
41 ability to compare laboratory and field measurements, WBT phase-specific emissions data are reported in this study,
42 because each WBT phase simulates, to some extent, different cookstove use. For example, data from the high-power
43 phase of the WBT may be useful for comparison with data from field tests if a cookstove is usually operated at high-
44 power in the field. Thus, cookstove emissions data by WBT phase are likely to be useful in developing international
45 standards. The entire testing database (see the Supporting Information) is provided by the WBT phases for this study. The
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4 high-power, cold-start phase is selected for further detailed evaluation below, because (i) emissions tend to be high during
5 this phase, especially for stoves with large thermal mass, and (ii) thermal energy delivered to the cooking pot is not
6 adequately measured in the lower power phase of the WBT. Eventually, a practical method may be developed for
7 accurately measuring cooking energy delivered during low-power so that thermal efficiency can be used as a metric for all
8 phases. Pollutant emissions are analyzed further below.
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11 12 **RESULTS**

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15 For each cookstove system, figures and tables showing CO, PM_{2.5}, CO₂, THC, and CH₄ mass emission factors—on the
16 basis of time, fuel energy, cooking energy, fuel mass, and WBT cooking tasks (cold-start, hot-start, simmer)—are
17 provided in the Supporting Information. Emissions are reported on an equivalent dry fuel mass basis as defined by the
18 WBT. UFP number emissions, cookstove power, WBT time-to-boil, efficiency, and fuel use are also included. Emission
19 factors may be used to approximate pollutant exposures, to support regional air quality inventories, and for dispersion
20 model input.
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26 **Cooking Power and Time-to-Boil Relationship.** Figure 1 shows how average cooking power correlates to the time-to-
27 boil for a given pot and volume of water (2L and 5L) and includes data for the cold- and hot-start phases. Cooking power
28 is measured in watts (W) and is defined as the useful cooking energy delivered per unit time, whereas time-to-boil as
29 defined by the WBT is the elapsed time required to boil a specific volume of water. Figure 1 shows that the time-to-boil
30 is a power function of cooking energy and illustrates why the cookstove pot and water volume tested must be appropriate
31 for the stove cooking power. For example, if the pot and volume of water are too large, then the time-to-boil is too long
32 and inconsistent between test replications due to phase change and evaporation⁴¹. Appropriate use of stove cooking
33 power also produces more consistent task-based results for other WBT parameters such as specific fuel consumption and
34 emissions. Additional test results for fire power (energy released by the fuel per time), cooking power, and time-to-boil
35 are reported in the Supporting Information.
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43 **Stove Efficiencies.** Modified combustion efficiency (MCE, defined as $\text{CO}_2/(\text{CO}_2+\text{CO})$ on a molar basis) is considered a
44 reasonable proxy for true combustion efficiency (ratio of energy released by combustion to energy in the fuel)⁴². MCE is
45 equivalent to nominal combustion efficiency (NCE), as used in some literature⁹. Heat transfer efficiency (HTE) refers to
46 the fraction of the heat released by combustion that is used in cooking. Overall thermal efficiency (OTE), the product of
47 MCE and HTE, is the ratio of cooking energy delivered to fuel energy and is an indicator of stove energy efficiency (see
48 the Supporting Information). Figure 2 compares MCE and OTE for the high-power (cold-start) phase of the WBT
49 considering low-moisture fuel; the most efficient stoves are in the upper right corner. Figures 2-5 report test replication
50 error as \pm one standard deviation as specified by the WBT. Cookstoves and their performance are often classified⁷⁻³⁴
51 using fuel type, combustion chamber type, chimney use, heat transfer devices (e.g., pot skirt), draft type (forced or natural
52 convection), fuel feeding or loading method, design, or other characteristics (Table 1). Figures 2-5 present testing results
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4 for the individual cookstove systems using the following classification scheme: *3-stone fire, charcoal, forced-draft,*
5 *natural-draft, and liquid-fuel.* Although instructive for comparing results, we caution that stove classifications can be
6 problematic for standards development (e.g., different benchmarks for stoves with and without chimneys have been
7 proposed¹⁶ but not widely adopted). Classification schemes are non-ideal due to poorly represented and defined stove
8 variations within classes and the inability of novel cookstove technologies to properly fit into what was previously
9 defined. Thus, appropriate standards are best specified based on absolute performance metrics as discussed below.

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14 Cookstoves that achieve both high MCE and OTE show less fuel use and decreased pollutant emission factors. Baseline
15 3-stone fires (both minimally and carefully tended cases) had approximately 96-97% MCE and approximately 14-15%
16 OTE. Several cookstoves (Sampada, Mayon, StoveTec, Berkeley, Envirofit) with similar MCE as the 3-stone fire show at
17 least two-fold greater OTE. Since these cookstoves consume less fuel, they generally produce lower emissions per given
18 cooking task (as discussed below), but have little or no reductions in emissions per unit fuel. Charcoal stoves show
19 generally low but highly varied MCE due to high CO emissions and nonuniform lump charcoal fuel structure,
20 respectively. Between test replications, airflow differences through the combustion chamber are likely caused by
21 nonuniform charcoal fuel structure. Not all forced-draft stoves exhibit the high MCE they are typically noted for. Forced-
22 draft stoves with fans require electrical energy from household power, rechargeable batteries, or thermoelectric systems
23 (no thermoelectric stove was tested for this study). A natural-draft cookstove with a top-lit up-draft (TLUD) design, see
24 Roth³⁴, had the highest MCE and OTE, but requires processed, low-moisture, pellet fuel. Assuming unequal variance, the
25 Student's *t*-test (all *p*-values subsequently reported are based on this statistical test) indicated a significant difference ($p \leq$
26 0.024) between the OTE of the TLUD stove and that of every other stove. Compared with the open-fire base-case,
27 advanced cookstoves (Oorja, Protos, Philips fan, StoveTec TLUD) show improvements in combustion efficiency as
28 indicated by MCE. Relatively minor improvements in combustion efficiency can result in large emissions reductions
29 assuming OTE is maintained. The natural-draft chimney stove (Onil) shows a high MCE but relatively low OTE due to
30 the large thermal mass steel griddle top (termed "plancha" in Latin America). These stoves are used for boiling water but
31 are also used for preparing a variety of foods (e.g., tortillas) and for warmth (space heating). It is noteworthy that the
32 WBT does not apply when stoves are used for purposes other than boiling water. Additional WBT phase-based data for
33 MCE, OTE, and fuel use are provided in the Supporting Information.

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48 **Emissions of CO and PM_{2.5}.** Figure 3 shows the CO and PM_{2.5} emissions per unit cooking energy delivered for low-
49 moisture fuel during the WBT high-power (cold-start) phase. The low emissions stoves reside in the bottom left corner of
50 the figure. The majority of cookstoves emits less CO and PM_{2.5} per unit energy delivered than the 3-stone fire base-case.
51 Two forced-draft stoves (Philips fan, Oorja) and the TLUD-type stove had notably low emissions. A significant
52 difference ($p \leq 0.018$) was observed for the TLUD stove CO emissions compared with every other stove. Charcoal stoves
53 emit high CO levels during all three WBT phases and high PM emissions during the cold-start phase due to the charcoal
54 ignition process. After ignition, charcoal stoves can produce high levels of hazardous, odorless CO with much less
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4 warning in the form of irritating smoke compared to wood stoves and thus should be tested and used in well ventilated
5 areas only. An intermittent problem with the liquid-fuel stove burner caused high PM emissions variability and possibly
6 higher than expected PM emissions.
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9 Compared with the high-power level, the two rocket stoves operated at medium power show higher MCE and OTE
10 (Figure 2) and lower CO and PM_{2.5} mass emissions when normalized to cooking energy delivered (Figure 3). The
11 difference in MCE for the two power levels was significant ($p = 0.0005$) for the StoveTec stove. These rocket stoves can
12 thus achieve lower emissions for a given cooking task at less than maximum power. This comparison demonstrates the
13 value of evaluating cookstoves at an additional power level for developing international standards. United States
14 Environmental Protection Agency (USEPA) certification testing requires four power levels for residential, wood-fueled,
15 heating stoves⁴³. An additional benefit of stove testing at multiple power levels is the ability to better correlate laboratory
16 results with field results⁴².
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23 Figure 4 shows the CO and PM_{2.5} emissions per liter of water simmered per hour for low-moisture fuel considering the
24 WBT low-power phase. The majority of cookstoves emit less CO and PM_{2.5} per unit volume of water per time than the 3-
25 stone fire base-case. A forced-draft stove (Philips fan) had notably low emissions. Charcoal stoves emit lower PM levels
26 during the WBT low-power phase (Figure 4) than during the high-power cold-start phase (Figure 3). Again, an
27 intermittent problem with the liquid-fuel stove burner caused high PM emissions variability and possibly higher than
28 expected PM emissions.
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34 **UFP Emissions.** Figure 5 shows the UFP number and PM_{2.5} mass emissions per cooking energy delivered for low-
35 moisture fuel and the high-power (cold-start) phase. UFPs are of interest because they can penetrate deep into the airways
36 of the human respiratory tract to the alveoli, where they may cause adverse biological effects⁴⁴. Presently, there are no
37 USEPA standards or WHO guidelines related to UFPs, although European Union vehicle emissions legislation does
38 consider UFPs. The majority of cookstoves tested show lower UFP emissions compared with the 3-stone fire.
39 Intermittent malfunction of a fan speed controller likely produced highly variable UFP emissions for the Oorja stove. A
40 natural-draft TLUD stove shows the lowest mean UFP and PM_{2.5} mass emissions. The UFP emissions of the TLUD stove
41 were significantly lower ($p = 0.0007$) than those of the forced-draft Philips fan stove. Forced-draft stoves emit relatively
42 less PM_{2.5} mass but show an increase in UFP numbers⁴⁵; in this case, gas phase nucleation may be occurring in an
43 environment where fewer accumulation mode particles produce less surface area for condensation and growth⁴⁶.
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51 DISCUSSION

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53 The extensive testing and metrics analysis performed as part of this study allows for further insight critical to advancing
54 the development of realistic international cookstove testing and emissions standards. This study considers multiple
55 cookstove performance metrics (see the Supporting Information) and recommends potential metrics for future cookstove
56 standards. Pollutant emissions per cooking energy delivered⁴⁷ (in units of g MJ_{delivered}⁻¹) and OTE are recommended
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4 measures for the high-power WBT phases because they are based on the fundamental desired output – cooking energy –
5 that enables valid comparisons between all stoves and fuels⁹. For high-power WBT phases, the cooking energy delivered
6 is determined by (i) the sensible heat that raises the pot water temperature and (ii) the latent heat that produces steam. A
7 relatively small quantity of energy is unaccounted for (as loss from the pot), but OTE is measured accurately. This is not
8 so for the low-power WBT phase, despite the previous use of the OTE metric, because (i) relatively constant water
9 temperatures result in limited or no measured sensible heat and (ii) highly variable steam production produces variation in
10 measured latent heat. Furthermore, the unaccounted energy can be substantial relative to the latent heat. Thus, alternative
11 metrics are recommended for the low-power phase due to the lack of a method for measuring energy delivered during
12 low-power. Development of a practical method for accurately measuring cooking energy delivered during the low-power
13 phase would enable the use of the same metrics for all WBT phases. Until such a method is developed, specific energy
14 consumption (SEC – in units of MJ L⁻¹ h⁻¹) and specific emission rate (SER– in units of g L⁻¹ h⁻¹) are recommended as
15 standard measures for the WBT low-power phase. SEC is energy utilization and SER is emissions per liter of water
16 maintained at the WBT-specified temperature per unit time. The importance of documenting cooking power for the
17 purpose of meeting end-user needs is noted. Time-to-boil may also be reported if the pot type and water volume are
18 specified, but time-to-boil can be a misleading indicator due to the nonlinear correlation with cooking power, as illustrated
19 in Figure 1 and discussed above.

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21 Baldwin⁴⁷ proposed “cooking process efficiency” as an ultimate metric that may include, for example, the use of a
22 pressure cooker to improve process efficiency. Cooking process efficiency also includes “control efficiency” which
23 indicates the ability to provide “...only as much heat as needed to cook the food...”⁴⁷. The WBT protocol specifies a
24 “turn-down ratio” metric—the ratio of high-power to low-power—indicating the extent to which a stove can be controlled.
25 However, this WBT standard measure is limited in that it does not account for the wide range of power offered by some
26 stoves nor does it indicate a stove’s ability to respond rapidly to power level adjustments—issues that a revised WBT may
27 consider.

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43 This study attempted to test realistic cookstove systems to improve relevance to field conditions, as discussed above, but
44 further investigation is needed. Laboratory testing provides a cost-effective means of evaluating cookstoves while
45 controlling variables that are difficult or impossible to control in the field. Despite its advantages controlled laboratory
46 testing cannot fully duplicate field testing, but should emulate field conditions to the greatest extent possible²⁸. Expanded
47 field research is needed to provide critical information on actual use conditions that cannot be duplicated from controlled
48 tests. Thus, there is a need for future emphasis on coordination between controlled and field testing. Development of test
49 protocols is needed for stoves performing tasks substantially different than boiling water, such as the griddle stoves
50 discussed above.

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Despite a lack of correlation with emissions of some other pollutants that also affect health⁴⁸ and climate⁴⁰, CO and PM
emission measurements continue to be widely acquired for cookstoves due to their relative simplicity and availability.

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4 CO and PM measurements are likely to be required as part of any standardization process. The USEPA uses gravimetric
5 PM measurement for its National Ambient Air Quality Standards and for its certification programs, which include
6 measuring emissions from residential, wood-fueled, heating stoves sold in the U.S.⁴³. The gravimetric method is
7 generally considered more accurate and reliable⁴⁹ compared with relatively low-cost optical methods typically used in the
8 developing world for PM measurement. Nevertheless, light-scattering instruments can be useful for obtaining real-time
9 emissions data needed for improving cookstove designs and for better understanding human exposures to air pollutants.
10 A relatively low-cost gravimetric measurement method for PM is needed to enable widespread testing capacity to evaluate
11 stoves against international standards. Emissions of other important organic and inorganic pollutants also require
12 characterization using newly-developed, low-cost, accurate, and rapid analytical methods.
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19 Cookstoves with chimneys can produce fugitive emissions from the stove body into the indoor environment. Despite the
20 difficulty of mimicking fugitive emissions in laboratories, future evaluations of chimney stoves should consider both
21 indoor fugitive and total emissions consistent with the present study. Indoor emissions have a greater effect on household
22 air quality and human health, while total emissions have a greater effect on outdoor air quality and climate. Oddly, more
23 performance data are currently available for newer biomass stoves than for the traditional and modern stoves dominating
24 usage worldwide. To better align expectation levels with realized stove improvements, future performance evaluations
25 must include “best-case” liquid- and gas-fueled stoves⁵⁰ as well as more types of “worst-case” traditional solid-fuel
26 stoves, based on the same absolute performance metrics.
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33 **Outlook.** The WBT protocol is currently being revised, and work is needed to finalize the revision³⁷. With the 2010
34 launch of the Global Alliance for Clean Cookstoves (GACC), “a major global cookstove renaissance”⁵¹ offers the
35 opportunity to build on the foundational work of the Partnership for Clean Indoor Air (PCIA) and partner organizations
36 around the world – see background in the Supporting Information. The GACC Standards and Testing Working Group
37 recognized the need to build on prior work to improve controlled and field evaluation of household cookstoves and the
38 need to build capacity in the developing world for evaluating and improving cookstoves⁵². Stakeholders present at the
39 2011 PCIA Forum in Lima, Peru, including some members of the Standards and Testing Working Group, drafted the
40 “Lima Consensus”⁵³, an agreement to establish an interim rating system for the evaluation of cookstove models “that
41 reflects the varying tiers of performance in the areas of fuel efficiency, indoor air quality, PM_{2.5} and CO emissions, and
42 safety.” A rating system was proposed to be stove- and fuel-neutral, simply rating stove/fuels by a number of criteria that
43 will better communicate the performance of existing stove models and drive innovation to improve stove performance.
44 Building on the Lima Consensus, an International Organization for Standardization (ISO) International Workshop
45 Agreement (IWA) was finalized and unanimously affirmed by more than 80 stakeholders present at The Hague,
46 Netherlands on February 28-29, 2012. Recommendations from this work were adopted in the IWA entitled *Guidelines for*
47 *Evaluating Cookstove Performance*⁵⁴. This agreement is an important step toward developing the methods and metrics to
48 be used in international cookstove standards. Results from this study are mapped to Tiers defined in the IWA (see the
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4 Supporting Information). Emissions standards will also depend on assessing what is needed to protect health. This is
5 currently being addressed under the World Health Organization's Air Quality Guidelines program⁵⁵. Other important
6 cookstove characteristics that were not evaluated in this study include safety, durability, cost, controllability, and user
7 acceptability. Evaluation methods and metrics for these other important characteristics need to be further developed.
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11 **Supporting Information.** Additional information is provided on the cookstoves, fuels, pots, facility, and test protocol
12 used in this study, as well as supplemental technical discussion. A database is provided for cookstove systems tested,
13 which includes results for fuel moisture, fuel energy, cookstove power, WBT time-to-boil, efficiency, fuel use, and
14 emissions of CO, PM_{2.5}, CO₂, THC, CH₄, and UFPs. This information is available free of charge via the Internet at
15 <http://pubs.acs.org/> .
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32

33 **DISCLAIMER**

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35 This document has been reviewed in accordance with USEPA policy and approved for publication. Mention of trade
36 names or commercial products does not constitute endorsement or recommendation for use. The views expressed in this
37 article are those of the authors and do not necessarily reflect the views or policies of the USEPA.
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Table 1. Fuels and Cookstoves Tested

Fuel	Tested with Low-/ High-moisture fuel	Cookstove	Cooking pot, water volume (liters)	Combustion chamber material	Chimney	Pot skirt	Forced-draft	Batch fuel	Rocket-type	Gasifier-type	Supporting Info I.D.
Wood	L/H	3-stone, carefully tended	Standard, 5	None							A
	L	3-stone, minimally tended	Standard, 5	None				•			A
	L/H	Berkeley Darfur	Rnd-btm. Alum., 5	Metal			•				B
	L/H	Envirofit G-3300	Standard, 5	Metal			•			•	C
	L	Onil	Standard, 5	Ceramic	•					•	D
	L/H	Philips HD4008	Standard, 5	Metal						•	E
	L/H	Philips HD4012	Standard, 5	Ceramic			•			•	F
	L/H	Sampada	Standard, 5	Metal						•	G
	L/H	StoveTec GreenFire	Standard, 5	Ceramic			•			•	H
	L/H	Upesi Portable	Rnd-btm. Alum., 5	Ceramic						•	I
Charcoal	L/H	GERES	Standard, 5	Ceramic				•			J
	L/H	Gyapa	Standard, 5	Ceramic				•			K
	L/H	Jiko, ceramic	Standard, 2	Ceramic				•			L
	L/H	Jiko, metal	Standard, 2	Metal				•			M
	L/H	KCJ Standard	Standard, 5	Ceramic				•			N
	L/H	Kenya Uhai	Standard, 5	Ceramic				•			O
	L/H	StoveTec prototype	"Superpot", 5	Ceramic			•	•	•		P
Rice hulls	L/H	Belonio Rice Husk Gasifier	Standard, 2	Metal			•	•		•	Q
	L/H	Mayon Turbo	Standard, 5	Metal						•	R
Pellets, Oorja	L/H	Oorja	Standard, 2	Ceramic			•	•		•	S
Pellets, wood	L	StoveTec TLUD prototype	Standard, 2	Metal			•	•		•	T
Corn cobs	L/H	Jinqilin CKQ-80I	Standard, 5	Metal	•		•			•	U
Plant oil	n/a	Protos	Standard, 2	n/a				•			V

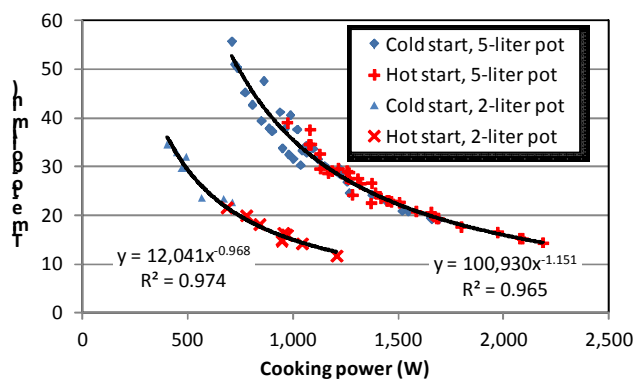


Figure 1. Time-to-boil versus cooking power for all cookstove systems evaluated

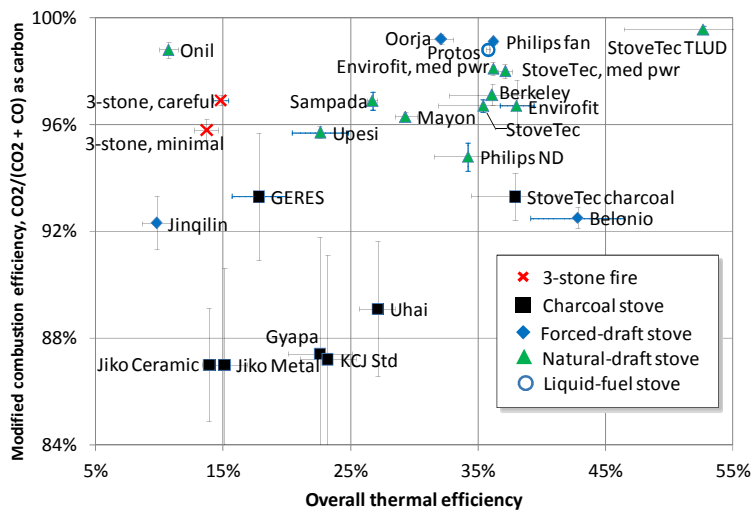


Figure 2. MCE versus OTE for low-moisture fuel during the high-power (cold-start) phase of the WBT.

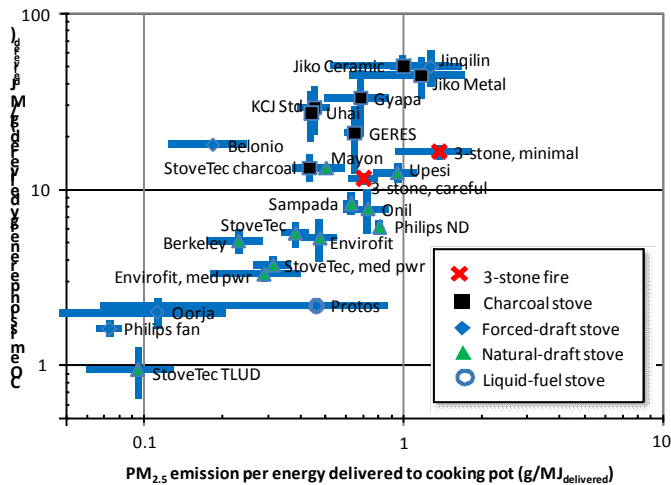


Figure 3. CO compared to PM_{2.5} emissions per energy delivered to the cooking pot for low-moisture fuel during the high-power (cold-start) phase of the WBT.

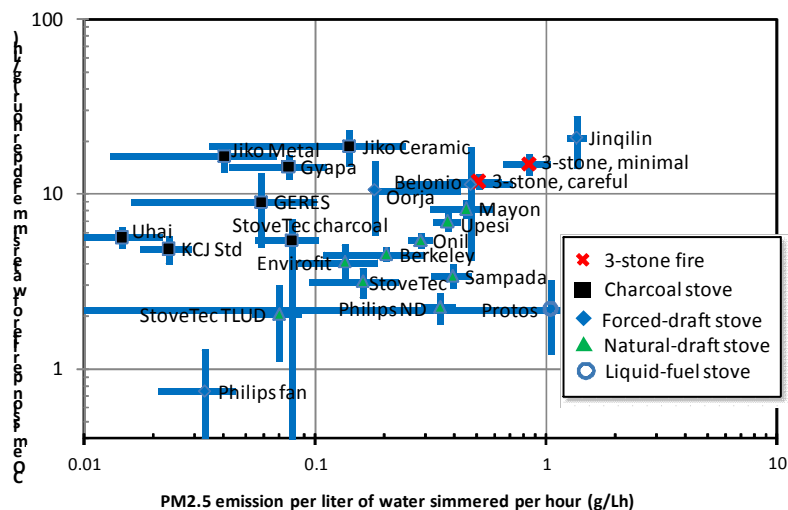


Figure 4. CO compared to PM_{2.5} emissions per liter of water simmered per hour for low-moisture fuel during the low-power phase of the WBT.

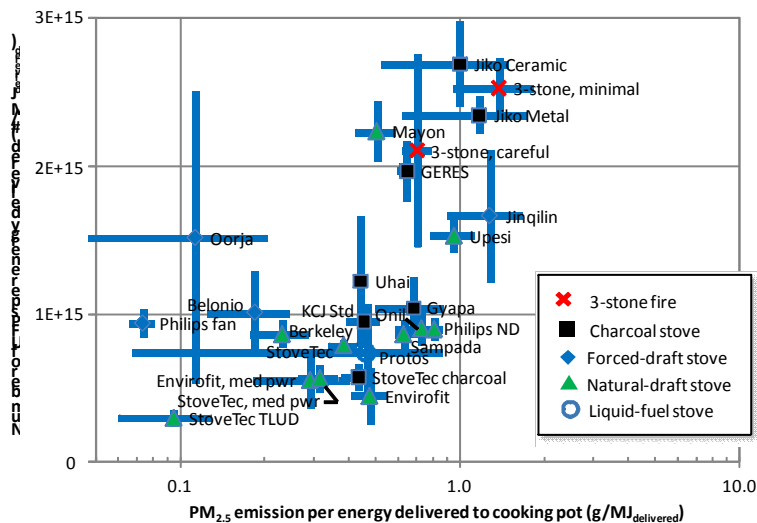


Figure 5. Number of UFPs compared to PM_{2.5} emissions per energy delivered to the cooking pot for low-moisture fuel during the high-power (cold-start) phase of the WBT.

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