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Test Report

InStove 60-Liter Institutional Stove with Wood Fuel

Air Pollutant Emissions and Fuel Efficiency

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Executive Summary

The U.S. Environmental Protection Agency's (EPA's) cookstove testing program was first developed to assist the EPA-led Partnership for Clean Indoor Air (1) and is now part of the U.S. Government's commitment to the Global Alliance for Clean Cookstoves (the Alliance) (2). Goals of the testing program are to:

1. Support the development of testing protocols and standards for cookstoves through ISO (International Organization for Standardization) TC (Technical Committee) 285: Clean Cookstoves and Clean Cooking Solutions (3).
2. Support the development of international Regional Testing and Knowledge Centers (many sponsored by the Alliance) for scientifically evaluating and certifying cookstoves to international standards (4).
3. Provide an independent source of data to Alliance partners.

This work supports EPA's mission to protect human health and the environment. Household air pollution, mainly from solid-fuel cookstoves in the developing world, is estimated to cause approximately 4 million premature deaths per year (5), and emissions of black carbon and other pollutants from cookstoves affect regional and global climate (6). An Alliance-coordinated multi-national multi-disciplinary approach, including the development of standards and testing, is designed to improve global health and the environment through clean cooking solutions (7).

This report provides testing results for a cookstove system consisting of the stove, cooking pot, fuel, and operating procedure. A detailed description of the system is provided in the body of the report. During testing, the stove was operated as intended by the manufacturer. Actual performance of a cookstove used in the field may vary if the system is different (e.g., a different fuel is used) or is not operated as intended.

The cookstove system was tested using the Water Boiling Test (WBT) Version 4.2.3 (8) and following the ISO IWA (International Workshop Agreement) 11-2012, Guidelines for Evaluating Cookstove Performance (9) (10), unanimously affirmed by more than 90 stakeholders at the ISO International Workshop on Cookstoves on February 28-29, 2012, in The Hague, Netherlands. IWA 11:2012 provides guidelines for rating cookstoves on tiers of performance for four important indicators: [1] Efficiency/fuel use, [2] Total Emissions, [3] Indoor Emissions, and [4] Safety; and the guidelines are being used while further development of testing protocols and standards is underway through ISO Technical Committee 285 (3). For measuring air pollutant emissions, the "total capture" method (also known as the "hood" method) was used, as described on Pages 60-61 of the WBT protocol (8) and similar to EPA Method 5G (11). The protocol specifies that the stove be tested at high power (cold- and hot-start phases) and low power (simmer phase). The cold-start phase begins with the stove at ambient temperature, and the hot-start phase begins with the stove at operating temperature. During both phases, the stove is operated at high power to heat water in the pot from ambient to boiling temperature. During the simmer phase, the stove is operated at low power to maintain the target water temperature at 3 °C below the boiling point. Fuel burning rates determine the power levels. During testing, variation in fuel burning rates between test replications is minimized. Actual performance of a cookstove used in the field may vary if the stove is operated at different fuel burning rates and hence at different power levels.

Test results summarized on Page iv were obtained in accordance with IWA 11:2012 guidelines, and tier ratings range from 0 (baseline) to 4 (best). Tier 0 represents the performance of typical traditional open three-stone fires used for cooking, and Tier 4 represents aspirational goals for solid-fuel cookstoves. Efficiency/fuel use, total emissions, and indoor emissions are tested at high- and low-power operating conditions, and sub-tier values and ratings are reported for the two power levels, while the overall rating is the lowest sub-tier rating, as specified in the IWA. Sub-tier values and ratings for many different stove types are compared in Figures 4 and 6-9 of this report. Following are brief descriptions of performance indicators specified in the IWA.

Efficiency/fuel use is an important indicator, especially for cookstoves used in areas where fuel is scarce or expensive or where forest degradation is an issue due to unsustainable harvesting of wood for fuel. Greater fuel efficiency is desirable, but increased efficiency does not always correlate with reduced emissions of air pollutants. Efficiency/fuel use tier levels are based on thermal efficiency at high power and specific energy use at low power, per the IWA.

Total emissions of air pollutants from cookstoves have potential impact on human health and climate change. CO (carbon monoxide) and $PM_{2.5}$ (fine particulate matter) are indicator pollutants specified in IWA 11:2012, and emissions of additional pollutants are quantified in this report, including gaseous pollutants CO_2 (carbon dioxide), THC (total hydrocarbons), CH_4 (methane), and NO_X (nitrogen oxides), as well as particulate OC (organic carbon), EC (elemental carbon), and BC (black carbon). Total emission tier levels are based on the mass of pollutant emitted per unit of useful energy delivered at high power and the specific emission rate at low power, per the IWA.

Indoor emissions have a potential direct impact on human health, and emissions may be reduced by stoves with cleaner combustion and/or with chimneys (flues). Stoves without chimneys are tested for total emissions into the indoor space, and stoves with chimneys are tested for fugitive emissions from the stove. Indoor emissions tier levels are based on emission rates, per the IWA.

Safety is also an important indicator included in IWA 11:2012 for evaluation of stoves for protection from risk of burns and other injuries, but safety is not evaluated in this report.

Cooking power is not an IWA performance indicator, but it is reported in the summary because it can be important for meeting user needs.

Fuel burning rates are reported to define the test conditions.

IWA tier ratings are based on the performance of the stove system operated as intended with low-moisture fuel. Additional test results are provided in this report for energy efficiency, fuel use, and air pollutant emissions for both low- and high-moisture fuel. Discussion of results, observations, and quality assurance are also included in the report.

Stove Manufacturer & Model	**InStove** Cottage Grove, OR, USA **60-Liter Institutional Stove** Serial No. 1079
Testing Center	EPA-Research Triangle Park, North Carolina, USA
Test Protocol	WBT Version 4.2.3, EPA Rev. 4 [see Reference (8)]
Fuel Used	Red oak wood, 7.2% moisture (wet basis), 2 x 2 x 36 cm
Pot Used	Flat-bottomed pot supplied with stove, tested with 40 liters of water

Test results were obtained in accordance with ISO (International Organization for Standardization) IWA (International Workshop Agreement) 11:2012. See previous page for brief description.

		Metric	Value	Unit	Sub-Tier
Efficiency / Fuel Use					
Tier	**4**	High Power Thermal Efficiency	56	%	4
		Low Power Specific Energy Use	0.005	MJ / (min L)	4
Total Emissions					
Tier	**3**	High Power CO	2.9	g / $MJ_{delivered}$	4
		Low Power CO	0.02	g / (min L)	4
		High Power $PM_{2.5}$	155	mg / $MJ_{delivered}$	3
		Low Power $PM_{2.5}$	0.3	mg / (min L)	4
Indoor Emissions					
Tier	**4**	High Power CO	0.01	g / min	4
		Low Power CO	0.009	g / min	4
		High Power $PM_{2.5}$	1.0	mg / min	4
		Low Power $PM_{2.5}$	0.3	mg / min	4

Tiers 0 → 4 (best)

	Value	Unit
Cooking Power (average of Cold Start and Hot Start phases)	3,703	W
Fuel burning rate (average for Cold Start, based on equivalent dry fuel consumed)	22.2	g / min
Fuel burning rate (average for Hot Start, based on equivalent dry fuel consumed)	22.7	g / min
Fuel burning rate (average for Simmer, based on equivalent dry fuel consumed)	11.3	g / min

Acronyms and Abbreviations

Alliance	Global Alliance for Clean Cookstoves
ASTM	American Society for Testing and Materials (now known as ASTM International)
BC	black carbon
C	carbon
C_3H_8	propane
CH_4	methane
cm	centimeter
CO	carbon monoxide
CO_2	carbon dioxide
EC	elemental carbon
EPA	U.S. Environmental Protection Agency
g	gram(s)
HEPA	high-efficiency particulate air
ISO	International Organization for Standardization
IWA	International Workshop Agreement
kg	kilogram(s)
kJ	kilojoule(s)
L	liter(s)
MCE	modified combustion efficiency
Met Lab	Metrology Laboratory
mg	milligram(s)
min	minute(s)
MJ	megajoule(s)
$MJ_{delivered}$	megajoule(s) of useful energy delivered
mm	millimeter(s)
n.a.	not applicable
NIOSH	National Institute for Occupational Safety and Health
NO_X	nitrogen oxides
OC	organic carbon
$PM_{2.5}$	particulate matter with an aerodynamic diameter ≤ 2.5 micrometers
PTFE	polytretrafluoroethylene
QA	quality assurance
RTP	Research Triangle Park
SD	standard deviation
SOP	Standard Operating Procedure
TC	Technical Committee
TC	total carbon
THC	total hydrocarbon
W	Watt(s)
WBT	Water Boiling Test

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Cookstove Testing Program

The U.S. Environmental Protection Agency's (EPA's) cookstove testing program was first developed to assist the EPA-led Partnership for Clean Indoor Air (1) and is now part of the U.S. Government's commitment to the Global Alliance for Clean Cookstoves (the Alliance) (2). Goals of the testing program are to:

1. Support the development of testing protocols and standards for cookstoves through ISO (International Organization for Standardization) TC (Technical Committee) 285: Clean Cookstoves and Clean Cooking Solutions (3).
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Description of Cookstove System Tested

A cookstove system consists of the stove, cooking pot, fuel, and operating procedure. The default operating procedure used for testing is the written instructions provided by the manufacturer, or operation as intended by the manufacturer. Actual performance of a cookstove used in the field may vary if the system is not operated as intended.

Development and dissemination. Damon Ogle and Fred Colgan developed the 60-liter Institutional Stove while associated with Aprovecho Research Center in Cottage Grove, Oregon, USA. In 2012, Colgan and Ogle founded Institutional Stove Solutions (InStove) to further develop and disseminate the technology. InStove manufactures stoves in Cottage Grove and has established a factory in Afikpo, Nigeria. InStove institutional stoves are designed for use in developing-world institutional settings, primarily refugee camps, schools, clinics, hospitals, and orphanages. More than 1,000 stoves have been disseminated in 20 countries, according to InStove (12).

Type of stove. The InStove 60-Liter Institutional Stove is a natural-draft type of cookstove designed for wood or other biomass fuel. Electrical power is not required for natural-draft stoves (power is required for some forced-draft stoves). As shown in Figure 1, a chimney provides draft and may be used to vent emissions to outside the cooking space. A rocket-type combustion chamber is located under the cooking pot. A "sunken-pot" design provides an integral pot skirt to enhance heat transfer to the sides, as well as the bottom, of the pot. The stove is designed to burn fuel sticks of wood or other biomass (e.g., biomass briquettes) that are manually fed into an opening in the lower front of the stove. Cooking power is controlled by the amount of fuel fed into the combustion chamber. A cap on top of the chimney prevents rain from entering the stove. The stove is designed to be manufactured in a small factory. InStove has developed drinking-water pasteurization and hospital-grade autoclave systems for use with the stove, but EPA tested the stove with only the cooking pot.

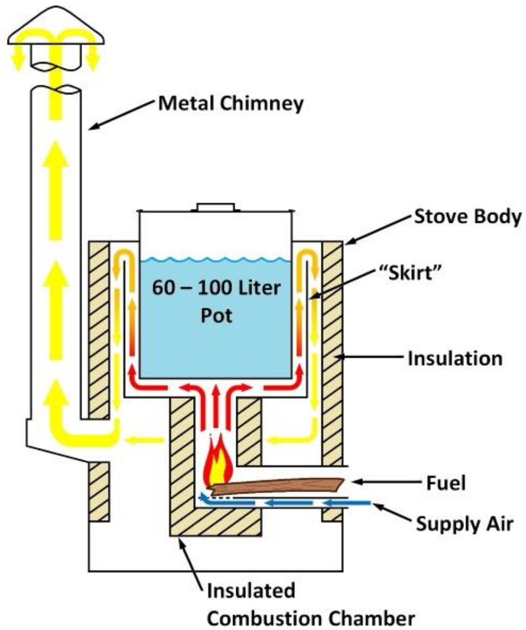

Figure 1. *Side-view cross-section diagram showing internal design. Credit: InStove*

Construction materials. The InStove body is built from a 55-gallon steel drum that is coated to prevent corrosion. The combustion chamber is constructed from high-temperature 310 stainless steel and 601 nickel alloys. Chimney and rain cap are galvanized steel, and the pot and lid are aluminum. Weight of the stove without the pot is 33 kg.

Figure 2. *InStove 60-Liter Institutional Stove*

Dimensions.
Stove height: 88 cm
Stove body diameter: 59 cm
Combustion chamber internal diameter: 14 cm
Combustion chamber internal height: 22 cm
Chimney internal diameter: 15 cm
Chimney length: 152 cm
Height of chimney top from floor: 198 cm
Fuel opening: 16.5 cm x 6.5 cm
Height of fuel opening from floor: 20 cm
Pot dimensions: see below

Accessories. The stove was supplied with a cooking pot, pot lid, chimney, and rain cap.

Cooking pot. The flat-bottomed pot supplied with the stove was used for the tests. Weight of the pot is 4.1 kg, and weight of the pot lid is 0.6 kg. Full capacity is approximately 55 liters, and the pot was used with 40 liters of water for the tests – the water was level with the top of the stove body, as shown in Figure 1. The stove system was tested without the lid on the pot, per the test protocol (described below). The pot material is aluminum. Outside diameter is 41.3 cm, and inside diameter is 40.5 cm at the top of the pot. Outside diameter at the bottom is 40 cm. Height is 45 cm. The pot and stove are designed to function together, and performance may vary if the stove is used with a different cooking pot.

Fuel. A hardwood, Red Oak (*Quercus rubra*), was obtained from a local supplier. Bark was removed, and the wood was saw-cut to dimensions of 2 cm x 2 cm x 36 cm. Wood was air dried, and high-moisture fuel was preserved in air-sealed containers in a freezer. Moisture content is reported on a wet basis in Tables 1-3 for low-moisture fuel and in Tables 7-9 for high-moisture fuel. Performance may vary if the stove is used with a different type of fuel.

Operating procedure. Operating and safety instructions were supplied with the stove, and the instructions were followed during testing.

Cost. According to InStove information (12), retail cost is approximately US$850 for the 60-liter institutional stove.

Quantity disseminated. According to InStove information (12), more than 1,000 stoves have been disseminated.

Lifetime. Estimated typical lifetime is approximately five years, but lifetime may vary depending on hours of use, fuel quality, environmental conditions, and other factors. In the future, a durability testing protocol may be developed through ISO TC 285, and durability testing may provide more comparable and quantitative results than the estimated lifetime.

Test Protocol

The cookstove system was tested using the Water Boiling Test (WBT) Version 4.2.3 (8) and following the ISO IWA (International Workshop Agreement) Guidelines for Evaluating Cookstove Performance (9) (10). Further development of testing protocols and standards is underway through ISO Technical Committee 285 (3). For measuring air pollutant emissions, the "total capture" method (also known as the "hood" method) was used, as described on Pages 60-61 of the WBT protocol (8) and similar to EPA Method 5G (11). Emissions were captured in a fume hood and were drawn under negative pressure through a primary dilution tunnel and then through a secondary tunnel with additional high-efficiency particulate air (HEPA)-filtered dilution air. Total emissions were measured per the ISO IWA by capturing both chimney emissions and fugitive emissions from the stove body with a fume hood. Indoor emissions were measured per the ISO IWA by capturing only fugitive emissions from the stove body with a hood. For quantification of total emissions, gaseous air pollutants were sampled from the primary dilution tunnel, and particulate pollutants were sampled from the secondary dilution tunnel. For quantification of indoor emissions, both gaseous and particulate pollutants were sampled from the primary dilution tunnel.

The WBT protocol specifies that the stove be tested at high power (cold- and hot-start phases) and low power (simmer phase). The cold-start phase begins with the stove at ambient temperature, and the hot-start phase begins with the stove at operating temperature. During both phases, the stove is operated at high power to heat water in the pot from ambient to boiling temperature. During the simmer phase, the stove is operated at low power to maintain the target water temperature at 3 °C below the boiling point. Fuel burning rates determine the power levels. During testing, variation in fuel burning rates between test replications is minimized. Actual performance of a cookstove used in the field may vary if the stove is operated at different fuel burning rates and hence at different power levels.

During each of the three separate phases of the test protocol, $PM_{2.5}$ (particulate matter with an aerodynamic diameter ≤ 2.5 micrometers) was isokinetically sampled and collected on polytretrafluoroethylene (PTFE)-membrane filters for gravimetric analysis and on quartz-fiber filters for OC (organic carbon) and EC (elemental carbon) analyses. Gravimetric analysis was performed with a microbalance in a temperature- and humidity-controlled room. OC and EC analyses was performed using National Institute for Occupational Safety and Health (NIOSH) Method 5040 (13), including analysis of gas-phase samples collected on quartz fiber filters downstream of PTFE membrane filters to account for the gas-phase absorption artifact (14). BC (black carbon) concentrations were measured in real-time with a microAeth® Model AE51 (AethLabs, San Francisco, CA, USA) aethalometer. Gaseous pollutant concentrations were measured in real-time with continuous emission monitors. CO (carbon monoxide) and CO_2 (carbon dioxide) were measured with non-dispersive infrared analyzers, THC (total hydrocarbons) and CH_4 (methane) were measured with flame-ionization detection analyzers, and nitrogen oxides (NO_X) were measured with a chemiluminescence analyzer.

Fuel moisture content was measured using the oven-drying method (15), and fuel heat of combustion was measured using the calorimeter method (16).

Test Results

A summary of results is presented in accordance with ISO IWA 11:2012 (9) on Page iv of this report. IWA tier ratings are based on the performance of the stove system operated as intended with low-moisture wood fuel.

InStove test results are compared with previously published results (17) in Figures 3-9. Key indicators of performance shown in the figures are described in Jetter et al. 2012 (17). Error bars on the data points for the InStove stove indicate standard deviations or 95% confidence intervals (using the t-distribution), as specified in the figures. For reference, data points for the 3-stone fire are indicated by red-colored X markers. Two data points are shown on each graph for a carefully-tended and a minimally-tended 3-stone fire. The carefully-tended fire performed better than the minimally-tended fire in all measures (17). Data points (blue diamonds indicated by the letter “P”) are indicated for comparison with the Philips Model HD4012 – a well-known and relatively high-performing forced-draft solid-fuel household stove. Data points for other stoves with previously published results are not identified in Figures 3-9, but stoves are identified in the journal article (17). All data shown in the figures are for stoves tested with low-moisture solid fuels, as described in the published results (17).

Cooking power versus fire power (in measurement units of Watts) data are shown in Figure 3 for high-power (average of cold-start and hot-start phases of the WBT). Cooking power is the rate of useful energy delivered to the contents of the cooking pot, while fire power is the rate of fuel energy used. Adequate cooking power is important for user acceptability, and cooking power is correlated with "time-to-boil" (17). The ratio of cooking power to fire power is thermal efficiency – shown in Figure 4.

Specific energy use during low-power (simmer phase of the WBT) **versus thermal efficiency during high-power** (average of cold-start and hot-start phases of the WBT) data are shown in Figure 4. These metrics are used to determine IWA Tier ratings, and the IWA Sub-Tiers are indicated in the figure.

Low-power versus high-power MCE (modified combustion efficiency) data are shown in Figure 5. MCE is defined as [CO_2/(CO_2 + CO)] on a molar basis and is considered a reasonable proxy for true combustion efficiency. MCE is not used to determine IWA Tier ratings, but stoves with higher MCEs tend to have lower emissions of air pollutants. Best performance is indicated in the upper right corner of the graph.

CO versus $PM_{2.5}$ emissions per useful energy delivered ($MJ_{delivered}$) to the water in the cooking pot during high-power phases of the WBT data are shown in Figure 6. Pollutant emissions per useful energy delivered and thermal efficiency are key IWA metrics because they are based on the fundamental desired output – cooking energy – that enables valid comparisons between all stoves and fuels.

CO versus $PM_{2.5}$ emissions per minute per liter of water simmered during the low-power phase of the WBT data are shown in Figure 7. Useful cooking energy is not accurately measured during the low-power test phase of the WBT (17), therefore the specific emission rate is used as the metric, per the IWA.

CO versus $PM_{2.5}$ indoor emission rates during high-power phases of the WBT data are shown in Figure 8.

CO versus $PM_{2.5}$ indoor emission rates during low-power data are shown in Figure 9.

Tabulated data for the InStove with low-moisture wood fuel, including data for test replicates, are shown in Tables 1-3 for parameters of the Water Boiling Test (8) and emissions of $PM_{2.5}$ and gaseous air pollutants, as described in Jetter et al. 2012 (17). Test Numbers shown in the column headings may not be sequential, because tests were rejected if quality assurance requirements were not met (see Quality Assurance/Quality Control section, below). The number of acceptable test replicates performed was seven for low-power, nine for high-power hot-start, and ten for high-power cold-start test phases. A sufficient number of replicates was performed to reduce 95% confidence intervals for ISO IWA tier ratings (Figures 4, 6, and 7).

OC and EC particulate emissions data are reported for low-moisture fuel in Table 4. Mass fractions of organic and elemental carbon to total carbon in particulate matter are reported in Table 5.

BC emissions data are reported for low-moisture fuel in Table 6.

Test Results for High-Moisture Fuel

Tabulated data for the InStove 60-Liter Institutional Stove with high-moisture fuel are shown in Tables 7-12 in the same format as Tables 1-6, as described in the previous section for low-moisture fuel. Four test replicates were performed to enable the calculation of standard deviations as an indicator of test variability. A side-by-side comparison of data for low- and high-moisture fuels is provided in Tables 13-15. Results for high-moisture "green" wood fuel are indicated by the green background color in the tables, while results for low-moisture (dry) fuel are indicated by the tan color. Moisture content was approximately 30 percent (wet basis) for high-moisture wood fuel, but some low-moisture fuel was required for starting the fire and maintaining combustion. Fuel moisture content is reported as the average (on a mass basis) of low- and high-moisture fuels, as described in Jetter et al. – see Supporting Information (17).

Test Results for Indoor Emissions

Data for indoor (fugitive) emissions tests per the ISO IWA with low-moisture fuel are shown in Table 16. The chimney effectively vented most of the emissions, and no visible smoke was emitted from the stove body during the tests. One test was performed to confirm and quantify the low level of fugitive emissions, and results are reported in the table.

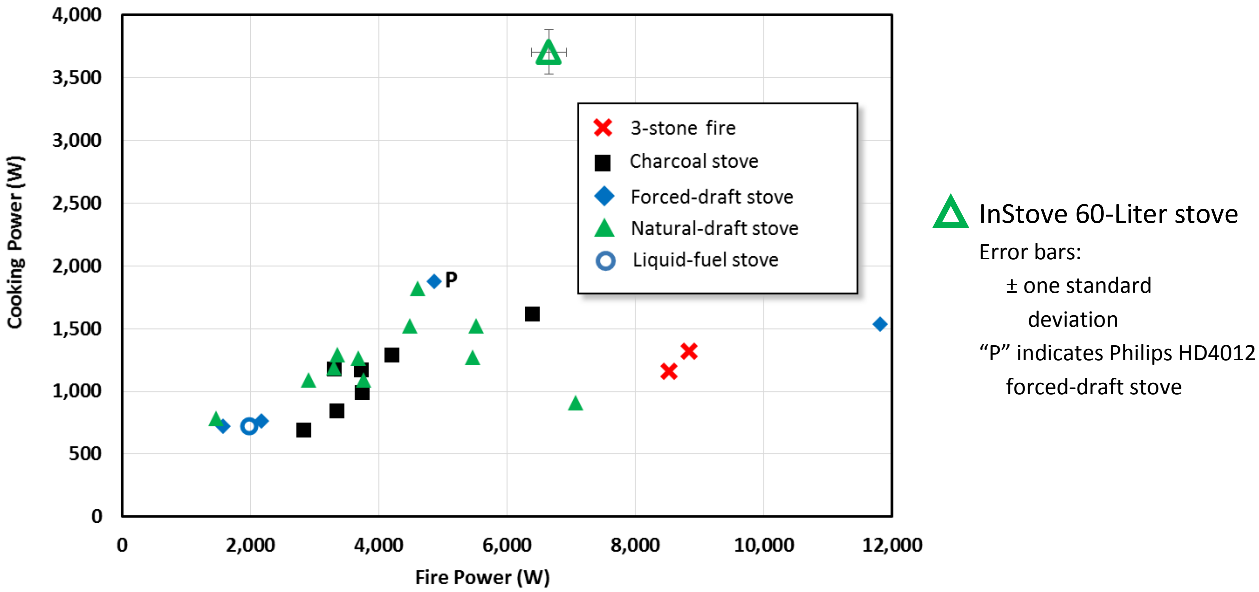

Figure 3. *Cooking power versus fire power during high-power*

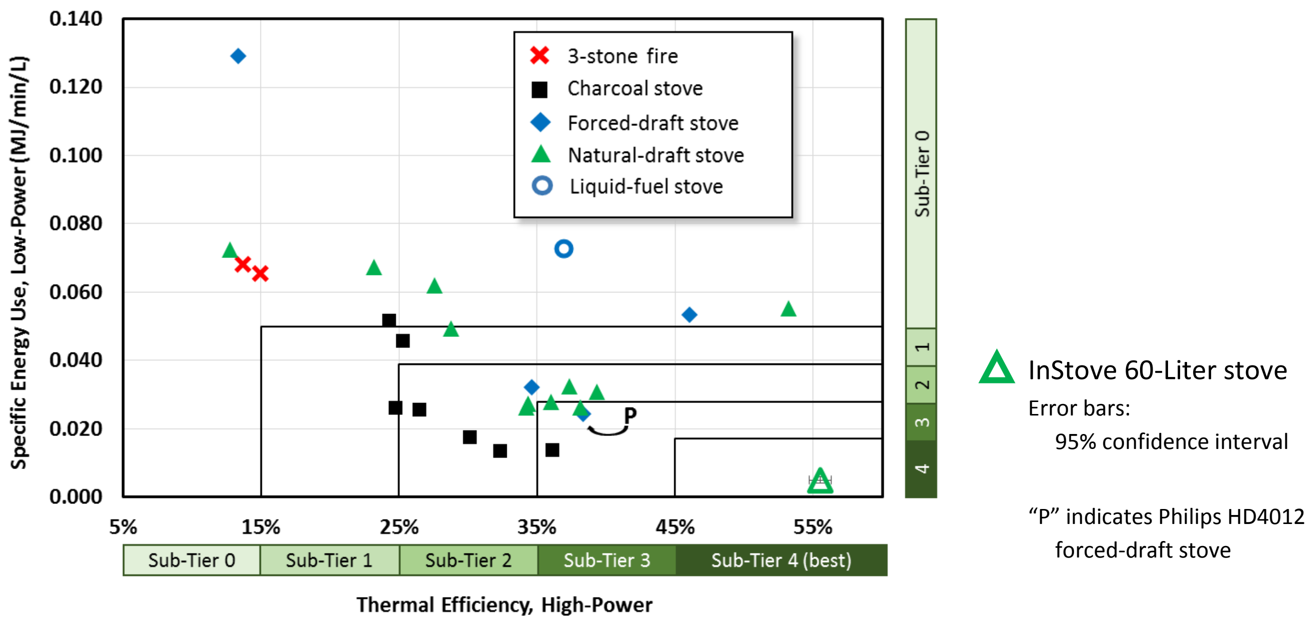

Figure 4. *Specific energy use during low-power versus thermal efficiency during high-power*

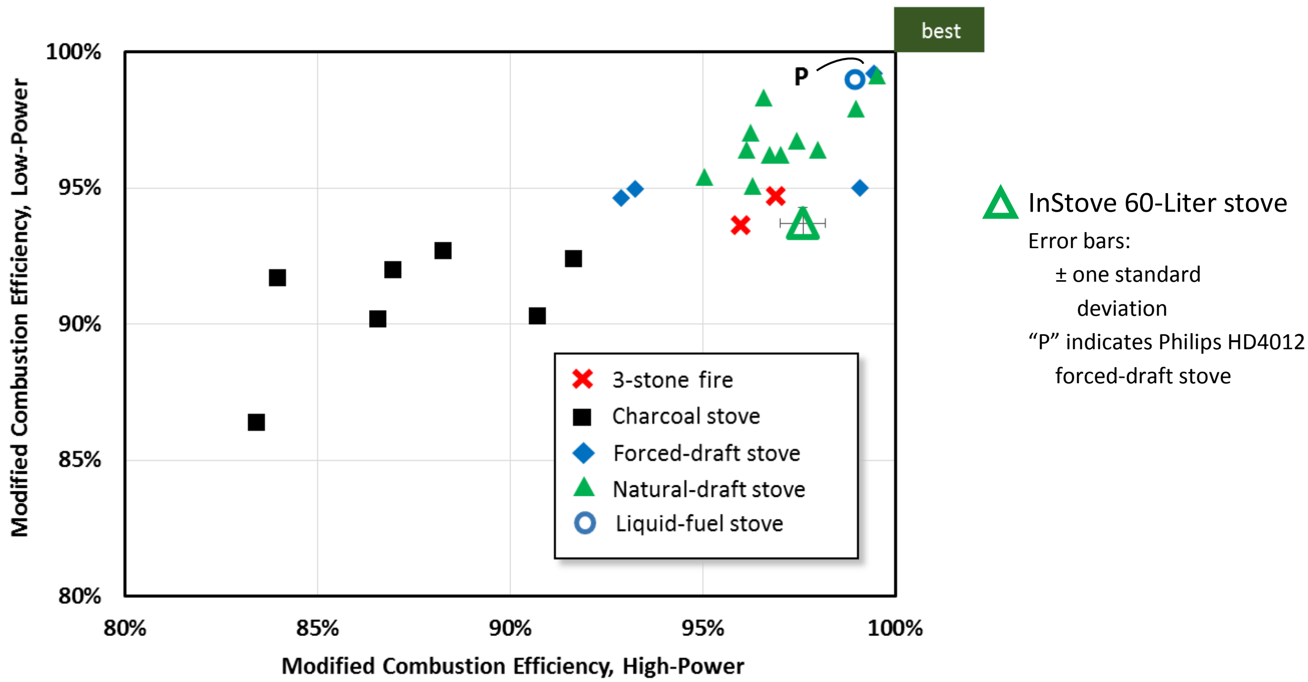

Figure 5. *Modified combustion efficiency, low-power versus high-power*

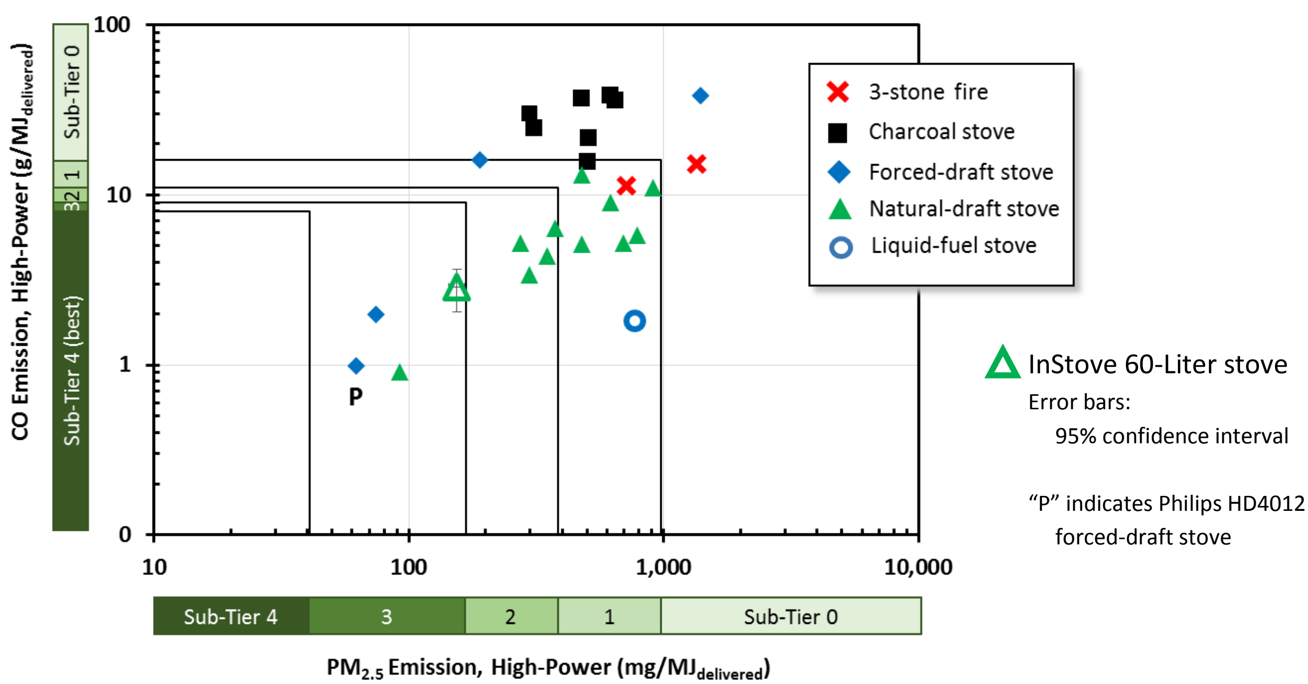

Figure 6. *CO versus $PM_{2.5}$ emissions per useful energy delivered to water in the cooking pot during high-power*

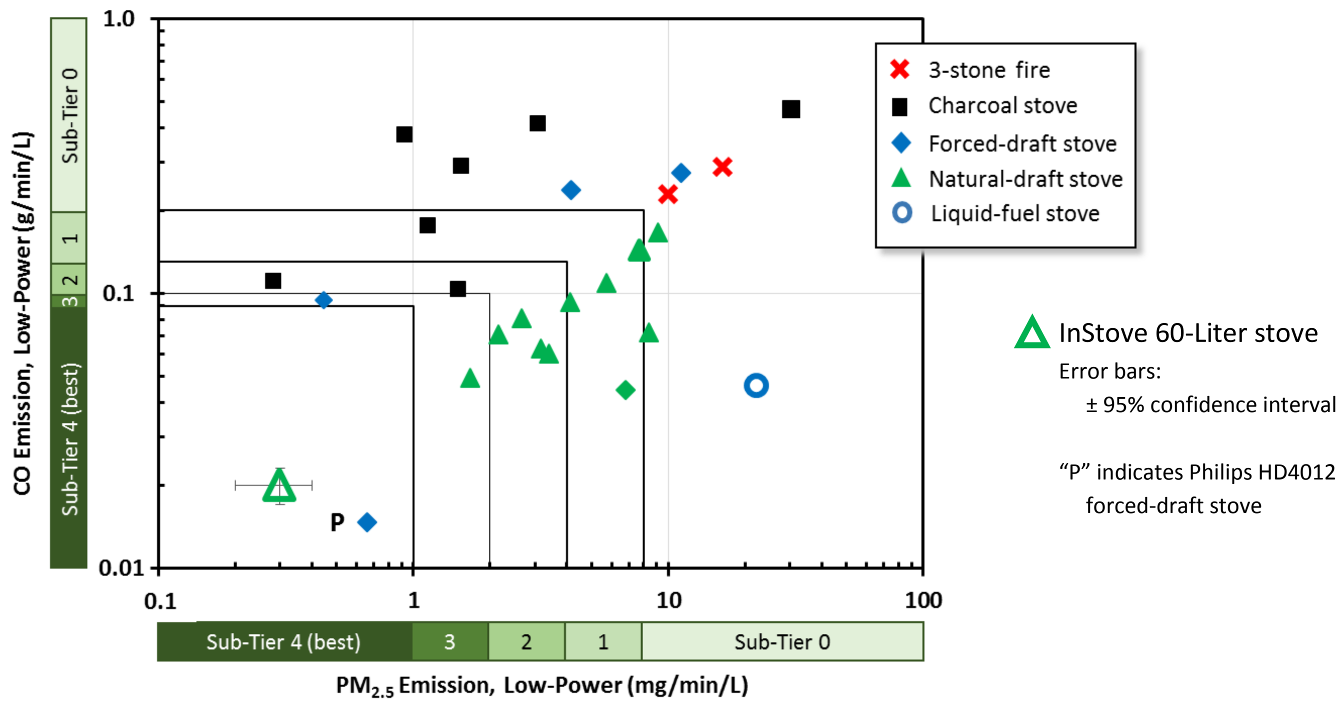

Figure 7. *CO versus $PM_{2.5}$ emissions per liter of water simmered per minute during low-power*

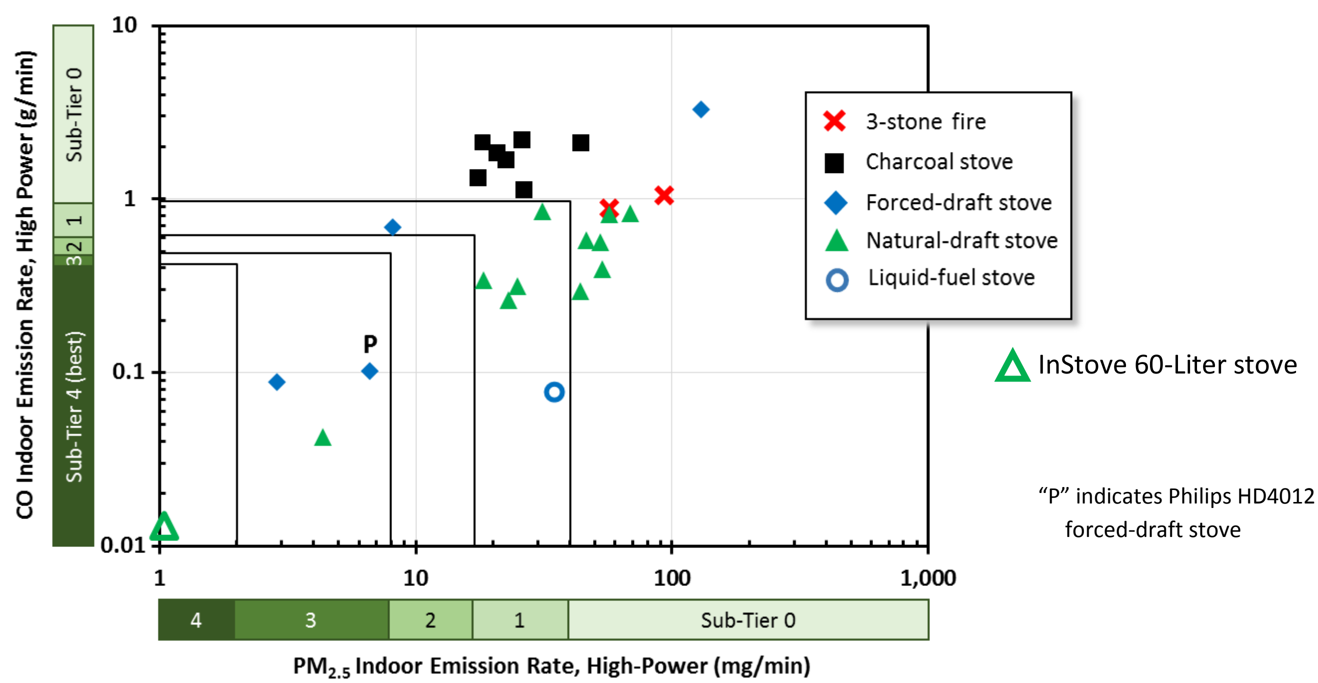

Figure 8. *CO versus $PM_{2.5}$ indoor emission rates during high-power*

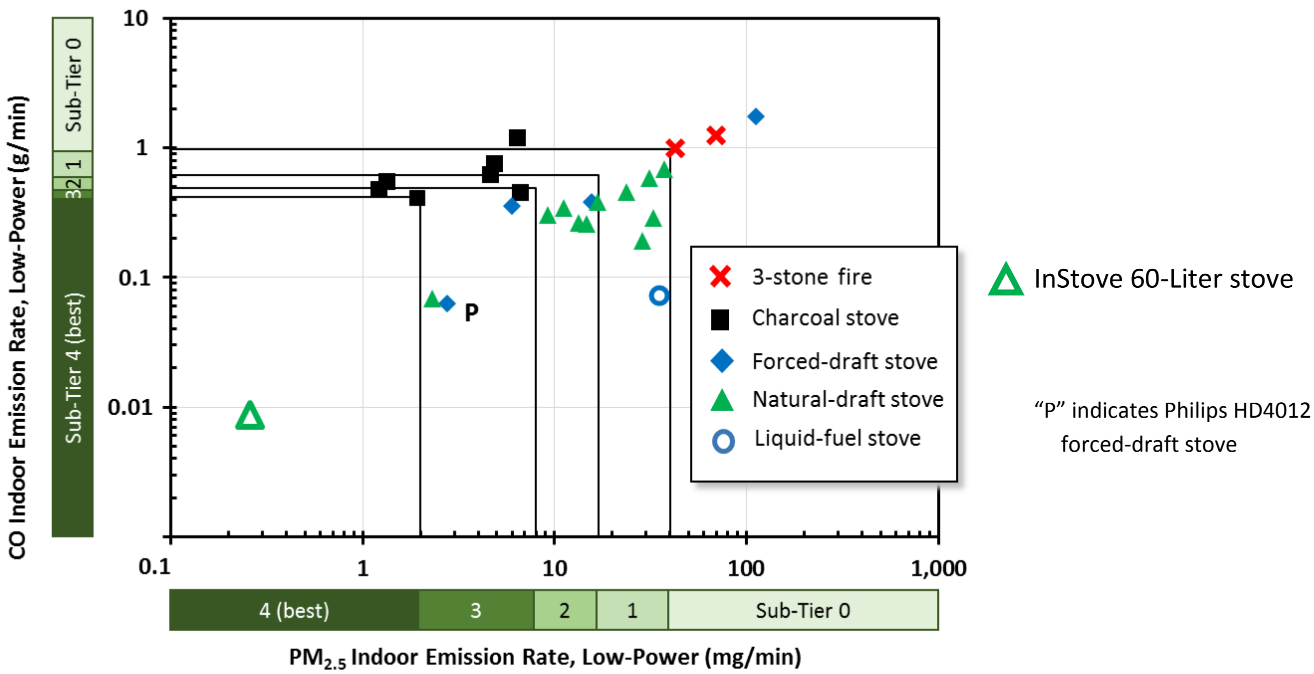

Figure 9. *CO versus $PM_{2.5}$ indoor emission rates during low-power*

Discussion of Results and Observations

As shown in the Results Summary, the InStove's cooking power was approximately 3,700 W (average of cold-start and hot-start test phases of the WBT). As shown in Figure 3, cooking power for the institutional stove was much greater than household stoves previously tested. The InStove is rated at Tier 4 for Efficiency/Fuel Use, as shown in Figure 4. MCE for the InStove was in the same range as other natural draft stoves at high power and somewhat less at low power, as shown in Figure 5.

The InStove is rated at Tier 3 for Total Emissions, as shown in the Results Summary. CO emissions are rated at Sub-Tier 4, and $PM_{2.5}$ emissions are rated at Sub-Tiers 3 and 4 for high- and low-power, respectively. The overall Tier rating is based on the lowest Sub-Tier rating, per the IWA. As shown in Figures 6 and 7, many previously tested forced-draft and natural-draft stoves were rated at Sub-Tier 4 for CO emissions, but fewer stoves were rated at Sub-Tiers 3 or 4 for $PM_{2.5}$ emissions. The InStove is rated at the same Sub-Tiers for Total Emissions as the previously tested Philips HD4012 stove.

As shown in the Results Summary, the InStove is rated at Tier 4 for Indoor Emissions. Indoor Emissions Tiers are based on emission rates (pollutant mass per time) into the household space, as shown in Figures 8 and 9. Since the InStove has an effective chimney, fugitive emissions from the stove body are very low. Fugitive emissions of CO and $PM_{2.5}$ (Table 16) were approximately 1-3% of total emissions (Tables 1-3).

The fraction of organic to total carbon in $PM_{2.5}$ was greater at low-power than at high-power with low-moisture fuel, as shown in Table 5. Elemental carbon is generally considered a reasonable proxy for black carbon, but black carbon is not scientifically well defined yet. Black carbon emissions can be operationally defined by an aethalometer instrument, as presented in Table 6. Discrepancies in mass between EC and BC and between TC and $PM_{2.5}$ may sometimes be observed due to the different methods and measurement uncertainties.

A comparison of performance with low- and high-moisture fuel, as shown in Tables 13-15, indicated mixed results. Thermal efficiency was nearly the same with low- and high-moisture fuels, but specific energy use was better with low-moisture fuel. During the high-power test phases, fire power and emission rates for $PM_{2.5}$ and CO were higher with low-moisture fuel, but during the low-power phase, fire power and the $PM_{2.5}$ emission rate were lower with low-moisture fuel. Emission rates of THC and CH_4 were generally lower with low-moisture fuel. Emissions of OC, EC, and BC were less during the low-power than during the high-power test phases for both low- and high-moisture fuel (Tables 14 and 15).

Real-time data for total emissions for a typical test sequence are shown in Figure 10. Data are shown for pollutant concentrations measured in the dilution tunnel, and pot water temperature indicates the three phases of WBT test sequence. Concentrations fluctuated over time as fuel was fed into the stove. CO_2 concentration indicates the rate of fuel consumption. CO, THC, CH_4, and NO_X concentrations were clearly above background levels (measured before and after the test. THC concentrations were reported as C_3H_8 (propane).

Real-time data for indoor (fugitive) emissions are shown in Figure 11. CO concentrations were clearly above background levels, and fluctuating emissions occurred over the entire test cycle – not just during start-up. Occasionally, THC peak concentrations were above background levels, but concentrations averaged over the test phases were not significantly above background levels. CH_4 and NO_X concentrations were not above background levels and are not shown in the figure.

The InStove performed without any problems during testing. The InStove is simple to operate – similar to typical rocket stoves. With its relatively lightweight metal components, the InStove is portable. Stoves are manufactured in small factories, and the InStove has a good-quality manufactured appearance. For more information, see the InStove web site (12).

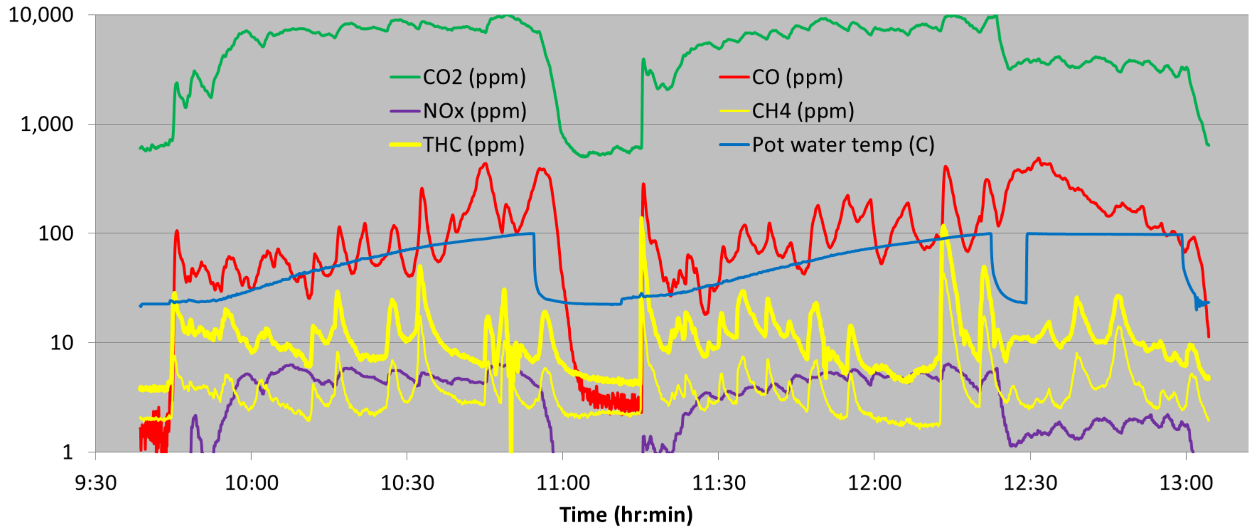

Figure 10. *Real-time data for total emissions for a typical test sequence*

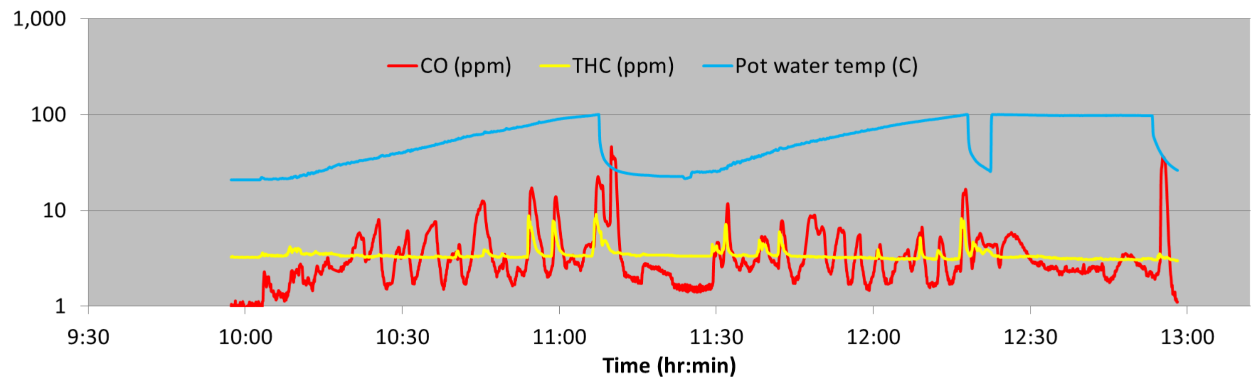

Figure 11. *Real-time data for indoor (fugitive) emissions*

Quality Assurance/Quality Control

A Quality Assurance Project Plan (QAPP) meeting EPA requirements (18) was prepared and was reviewed by an EPA Quality Manager. Specifically, work was in compliance with Category II Quality Assurance Project Plan requirements "…for important, highly visible Agency projects involving areas such as supporting the development of environmental regulations and standards" (19).

In February 2014, EPA QA staff conducted a technical systems audit (TSA) of this project. The purpose of this TSA was to conduct an independent and objective assessment of on-site activities through an in-depth evaluation of technical system documents, on-site laboratory work, equipment, procedures, and record keeping activities to ensure (1) that environmental data collection activities and the resulting data comply with the project's QAPP; (2) that these activities are implemented effectively; and (3) that these activities are suitable to achieve the project's data quality goals.

The TSA was conducted in accordance with principles described in *Guidance on Technical Audits and Related Assessments for Environmental Data Operations* (20). The technical basis of the TSA was the

QAPP entitled *Cookstove Testing for Air Pollutant Emissions, Energy Efficiency, and Fuel Use, Revision 1*, September 2013.

In general, the audit findings were positive in nature and indicated that the project was implemented as described in the QAPP. Note that the term "findings" as used in this document was consistent with the QA/G-7 definition and does not necessarily imply non-conformance. There were no findings that indicated a quality problem requiring corrective action. All phases of the implementation were found to be acceptable and to be performed in a manner consistent with the QAPP and with EPA quality assurance requirements.

An important indicator of overall data quality for cookstove performance testing is the carbon mass balance. Carbon measured in the emissions is compared with carbon measured in the fuel consumed. A percent difference based on carbon in the fuel is calculated for each test phase. A positive result indicates that more carbon was measured in the fuel than in the emissions, and a negative result indicates that less carbon was measured in fuel than in emissions. The absolute value of the percent difference is used as a quality indicator and is considered to be excellent when ≤ 10%, good when ≤ 15%, acceptable when ≤ 20%, and unacceptable when > 20%. A continuous improvement process is used in pursuit of excellent results, and tests are rejected when the carbon balance is > 20%. Carbon-balance results are shown in Table 17. Measurement uncertainties for both emissions and fuel are reflected in the carbon-balance results. Negative values in Table 17 indicate potential positive bias for carbon measured in emissions and/or negative bias for carbon measured in fuel. Test replicates were rejected if the carbon balance was unacceptable, and data were rejected if measurement quality objectives (described below) were unacceptable.

The carbon balance is an overall indicator of many of the critical measurements included as measurement quality objectives listed in Table 18. Test results included in this report were based on measurements that met or exceeded these quality objectives. Data were rejected if measurements did not meet acceptance criteria.

Tables

Following are tabulated data and information, as described above.

***Table 1.** Low-moisture fuel, high-power cold-start – WBT, $PM_{2.5}$, and gaseous pollutant parameters*

Parameter	Units	Average	SD	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
Fuel moisture (wet basis)	%	7.2	0.7	8.0	7.3	6.6	6.4	6.5	6.2	7.5	7.8	7.9	7.4
Fuel consumed (raw)	g	1817	62	1812	1840	1763	1860	1925	1821	1689	1854	1808	1801
Equivalent dry fuel consumed	g	1607	99	1435	1671	1613	1691	1768	1671	1522	1620	1544	1529
Time to boil 40 liters of water, 25 to 100°C	min	72.71	6.01	62.97	76.30	67.18	75.33	78.68	77.22	72.68	80.63	71.00	65.05
Thermal efficiency	%	55.0	1.6	57.6	54.4	54.9	53.4	53.4	54.4	53.7	54.3	57.1	57.0
Fuel burning rate	g/min	22.2	1.2	22.8	21.9	24.0	22.5	22.5	21.6	20.9	20.1	21.7	23.5
Temperature-corrected specific fuel consumption	g/liter	40.3	1.9	36.5	40.9	40.2	41.2	41.8	40.6	43.5	41.2	38.8	38.6
Temperature-corrected specific energy use	kJ/liter	718	34	673	722	709	726	738	716	785	745	684	681
Fire power	W	6574	329	6995	6442	7062	6603	6609	6363	6305	6047	6396	6914
Cooking power	W	3620	249	4026	3507	3880	3523	3530	3464	3387	3286	3653	3940
Modified combustion efficiency	%	97.6	0.9	98.6	96.0	97.4	97.0	96.8	97.9	97.8	97.0	98.6	98.7
$PM_{2.5}$ temperature-corrected total mass	mg	2295	211	2305	2357	2501	2254	2333	1877	2275	2680	2145	2221
mass per effective volume of water boiled	mg/liter	60.1	6.0	58.7	60.8	64.9	58.2	60.3	48.8	66.9	69.6	55.4	57.2
mass per fuel mass (raw)	mg/kg	1316	114	1274	1351	1477	1286	1325	1105	1387	1474	1219	1259
mass per equivalent dry fuel mass	mg/kg	1491	135	1608	1487	1614	1415	1442	1204	1538	1688	1428	1482
mass per fuel energy	mg/MJ	83.7	6.9	87.3	84.3	91.5	80.2	81.7	68.2	85.2	93.4	80.9	84.0
mass per useful energy delivered (to water in pot)	mg/MJ	152.1	12.9	151.7	154.8	166.5	150.2	153.0	125.3	158.5	171.9	141.6	147.4
mass per time	mg/hour	1982	205	2199	1955	2326	1906	1945	1563	1933	2034	1863	2091
CO temperature-corrected total mass	g	45.0	16.9	20.0	70.8	44.4	54.9	56.8	36.3	38.8	59.3	n.a.[1]	23.8
mass per effective volume of water boiled	g/liter	1.18	0.44	0.51	1.83	1.15	1.42	1.47	0.94	1.14	1.54	n.a.[1]	0.61
mass per fuel mass (raw)	g/kg	25.8	9.6	11.1	40.6	26.3	31.3	32.3	21.4	23.6	32.6	n.a.[1]	13.5
mass per equivalent dry fuel mass	g/kg	28.8	10.1	14.0	44.7	28.7	34.4	35.1	23.3	26.2	37.3	n.a.[1]	15.9
mass per fuel energy	g/MJ	1.62	0.58	0.76	2.53	1.63	1.95	1.99	1.32	1.45	2.07	n.a.[1]	0.90
mass per useful energy delivered (to water in pot)	g/MJ	2.98	1.10	1.32	4.65	2.96	3.66	3.73	2.42	2.70	3.80	n.a.[1]	1.58
mass per time	g/hour	38.2	12.9	19.1	58.7	41.3	46.4	47.4	30.2	32.9	45.0	n.a.[1]	22.4
CO_2 temperature-corrected total mass	g	2685	219	2167	2636	2567	2747	2716	2633	2728	2992	2850	2818
mass per effective volume of water boiled	g/liter	70.4	6.8	55.2	68.0	66.6	70.9	70.2	68.5	80.2	77.7	73.6	72.6
mass per fuel mass (raw)	g/kg	1541	131	1198	1510	1516	1567	1543	1550	1663	1646	1620	1597
mass per equivalent dry fuel mass	g/kg	1743	128	1511	1663	1657	1723	1679	1689	1844	1884	1897	1881
mass per fuel energy	g/MJ	97.9	7.6	82.1	94.3	93.9	97.7	95.2	95.7	102.1	104.3	107.5	106.6
mass per useful energy delivered (to water in pot)	g/MJ	178	14	143	173	171	183	178	176	190	192	188	187
mass per time	g/hour	2314	164	2067	2186	2388	2322	2264	2193	2318	2271	2476	2653

Table 1 continued on next page

Table 1 continued from previous page

Parameter	Units	Average	SD	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
THC (as C3H8) temperature-corrected total mass	g	0.82	0.42	0.86	0.70	0.58	0.36	0.69	0.49	1.21	1.65	n.a.[2]	n.a.[2]
mass per effective volume of water boiled	g/liter	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.01	0.04	0.04	n.a.[2]	n.a.[2]
mass per fuel mass (raw)	g/kg	0.47	0.24	0.47	0.40	0.34	0.21	0.39	0.29	0.74	0.91	n.a.[2]	n.a.[2]
mass per equivalent dry fuel mass	g/kg	0.53	0.27	0.60	0.44	0.38	0.23	0.42	0.31	0.82	1.04	n.a.[2]	n.a.[2]
mass per fuel energy	g/MJ	0.03	0.02	0.03	0.02	0.02	0.01	0.02	0.02	0.05	0.06	n.a.[2]	n.a.[2]
mass per useful energy delivered (to water in pot)	g/MJ	0.05	0.03	0.06	0.05	0.04	0.02	0.04	0.03	0.08	0.11	n.a.[2]	n.a.[2]
mass per time	g/hour	0.69	0.32	0.82	0.58	0.54	0.31	0.57	0.40	1.03	1.25	n.a.[2]	n.a.[2]
CH_4 temperature-corrected total mass	g	0.21	0.06	0.12	0.26	0.19	0.16	0.23	0.18	n.a.[3]	n.a.[3]	0.31	n.a.[3]
mass per effective volume of water boiled	g/liter	0.005	0.002	0.003	0.007	0.005	0.004	0.006	0.005	n.a.[3]	n.a.[3]	0.008	n.a.[3]
mass per fuel mass (raw)	g/kg	0.12	0.04	0.07	0.15	0.11	0.09	0.13	0.11	n.a.[3]	n.a.[3]	0.18	n.a.[3]
mass per equivalent dry fuel mass	g/kg	0.13	0.04	0.09	0.16	0.12	0.10	0.14	0.12	n.a.[3]	n.a.[3]	0.21	n.a.[3]
mass per fuel energy	g/MJ	0.008	0.002	0.005	0.009	0.007	0.006	0.008	0.007	n.a.[3]	n.a.[3]	0.012	n.a.[3]
mass per useful energy delivered (to water in pot)	g/MJ	0.014	0.004	0.008	0.017	0.012	0.011	0.015	0.012	n.a.[3]	n.a.[3]	0.020	n.a.[3]
mass per time	g/hour	0.18	0.05	0.12	0.21	0.17	0.14	0.19	0.15	n.a.[3]	n.a.[3]	0.27	n.a.[3]
NO_X temperature-corrected total mass	g	1.26	0.17	0.86	1.34	1.29	1.19	1.23	n.a.[4]	1.24	1.42	1.38	1.37
mass per effective volume of water boiled	g/liter	0.033	0.005	0.022	0.035	0.034	0.031	0.032	n.a.[4]	0.036	0.037	0.036	0.035
mass per fuel mass (raw)	g/kg	0.72	0.10	0.47	0.77	0.76	0.68	0.70	n.a.[4]	0.76	0.78	0.79	0.77
mass per equivalent dry fuel mass	g/kg	0.82	0.10	0.60	0.85	0.83	0.75	0.76	n.a.[4]	0.84	0.89	0.92	0.91
mass per fuel energy	g/MJ	0.05	0.01	0.03	0.05	0.05	0.04	0.04	n.a.[4]	0.05	0.05	0.05	0.05
mass per useful energy delivered (to water in pot)	g/MJ	0.08	0.01	0.06	0.09	0.09	0.08	0.08	n.a.[4]	0.09	0.09	0.09	0.09
mass per time	g/hour	1.09	0.14	0.82	1.11	1.20	1.01	1.02	n.a.[4]	1.05	1.08	1.20	1.29

[1] CO concentration measurement failed acceptance criteria
[2] THC analyzer malfunctioned
[3] CH_4 analyzer malfunctioned
[4] NOx analyzer malfunctioned

Table 2. *Low-moisture fuel, high-power hot-start – WBT, $PM_{2.5}$, and gaseous pollutant parameters*

Parameter	Units	Average	SD	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7[1]	Test 8	Test 9	Test 10
Fuel moisture (wet basis)	%	7.3	0.7	8.0	7.3	6.6	6.4	6.5	7.5	8.1	7.9	7.4
Fuel consumed (raw)	g	1724	73	1782	1743	1725	1643	1801	1583	1691	1761	1785
Equivalent dry fuel consumed	g	1513	78	1409	1580	1577	1486	1651	1425	1475	1500	1515
Time to boil 40 liters of water, 25 to 100°C	min	66.81	5.25	59.20	69.48	72.83	61.42	73.22	60.43	69.45	67.95	67.33
Thermal efficiency	%	56.0	1.1	55.5	55.9	55.5	57.2	55.1	54.2	56.3	56.3	57.7
Fuel burning rate	g/min	22.7	1.0	23.8	22.7	21.7	24.2	22.6	23.6	21.2	22.1	22.5
Temperature-corrected specific fuel consumption	g/liter	39.4	1.3	38.1	39.6	39.1	37.5	39.7	42.0	38.6	39.3	40.5
Temperature-corrected specific energy use	kJ/liter	700	27	702	699	690	661	700	759	681	693	714
Fire power	W	6729	363	7301	6688	6368	7117	6633	7098	6247	6494	6615
Cooking power	W	3765	201	4055	3737	3537	4070	3655	3846	3519	3653	3815
Modified combustion efficiency	%	97.6	0.8	98.6	96.3	97.1	97.7	97.3	96.9	98.2	98.4	98.1
$PM_{2.5}$ temperature-corrected total mass	mg	2359	316	2265	2018	2391	2483	2501	2982	2446	2265	1877
mass per effective volume of water boiled	mg/liter	62.0	10.8	57.9	52.7	61.6	64.2	64.5	87.2	63.0	58.2	48.9
mass per fuel mass (raw)	mg/kg	1385	247	1200	1205	1442	1550	1490	1869	1424	1263	1025
mass per equivalent dry fuel mass	mg/kg	1573	246	1518	1330	1577	1713	1625	2076	1632	1482	1208
mass per fuel energy	mg/MJ	88.2	13.3	82.5	75.4	89.4	97.1	92.1	115.0	90.3	84.0	68.5
mass per useful energy delivered (to water in pot)	mg/MJ	158.4	26.1	148.5	134.9	160.9	169.8	167.2	212.2	164.2	149.3	118.7
mass per time	mg/hour	2148	382	2167	1814	2049	2488	2200	2937	2080	1963	1630
CO temperature-corrected total mass	g	40.9	13.1	19.3	60.8	48.1	37.5	45.0	50.7	n.a.[2]	29.2	36.6
mass per effective volume of water boiled	g/liter	1.08	0.37	0.49	1.59	1.24	0.97	1.16	1.48	n.a.[2]	0.75	0.95
mass per fuel mass (raw)	g/kg	24.2	8.5	10.2	36.3	29.0	23.4	26.8	31.8	n.a.[2]	16.3	20.0
mass per equivalent dry fuel mass	g/kg	27.2	8.8	12.9	40.1	31.7	25.8	29.2	35.3	n.a.[2]	19.1	23.5
mass per fuel energy	g/MJ	1.53	0.50	0.70	2.27	1.80	1.46	1.66	1.95	n.a.[2]	1.08	1.33
mass per useful energy delivered (to water in pot)	g/MJ	2.75	0.92	1.26	4.06	3.23	2.56	3.01	3.61	n.a.[2]	1.93	2.31
mass per time	g/hour	37.3	12.0	18.4	54.6	41.2	37.5	39.6	50.0	n.a.[2]	25.3	31.8
CO_2 temperature-corrected total mass	g	2602	224	2203	2514	2543	2511	2592	2499	2752	2841	2963
mass per effective volume of water boiled	g/liter	68.1	6.2	56.3	65.6	65.5	64.9	66.9	73.1	70.9	72.9	77.2
mass per fuel mass (raw)	g/kg	1520	137	1167	1502	1533	1567	1545	1566	1602	1583	1618
mass per equivalent dry fuel mass	g/kg	1730	129	1476	1657	1677	1732	1684	1740	1836	1858	1907
mass per fuel energy	g/MJ	97.1	8.0	80.2	93.9	95.0	98.2	95.5	96.3	101.6	105.3	108.1
mass per useful energy delivered (to water in pot)	g/MJ	174	13	144	168	171	172	173	178	185	187	187
mass per time	g/hour	2353	159	2107	2261	2179	2515	2280	2461	2339	2462	2574

Table 2 continued on next page

Table 2 continued from previous page

Parameter	Units	Average	SD	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7[1]	Test 8	Test 9	Test 10
THC (as C3H8) temperature-corrected total mass	g	1.15	1.02	0.64	0.41	0.64	0.44	0.74	2.33	n.a.[3]	2.90	n.a.[3]
mass per effective volume of water boiled	g/liter	0.03	0.03	0.02	0.01	0.02	0.01	0.02	0.07	n.a.[3]	0.07	n.a.[3]
mass per fuel mass (raw)	g/kg	0.68	0.59	0.34	0.24	0.38	0.27	0.44	1.46	n.a.[3]	1.62	n.a.[3]
mass per equivalent dry fuel mass	g/kg	0.77	0.68	0.43	0.27	0.42	0.30	0.48	1.62	n.a.[3]	1.90	n.a.[3]
mass per fuel energy	g/MJ	0.04	0.04	0.02	0.02	0.02	0.02	0.03	0.09	n.a.[3]	0.11	n.a.[3]
mass per useful energy delivered (to water in pot)	g/MJ	0.08	0.07	0.04	0.03	0.04	0.03	0.05	0.17	n.a.[3]	0.19	n.a.[3]
mass per time	g/hour	1.06	0.93	0.61	0.37	0.54	0.44	0.65	2.29	n.a.[3]	2.51	n.a.[3]
CH_4 temperature-corrected total mass	g	0.26	0.16	0.05	0.18	0.30	0.20	0.28	n.a.[4]	n.a.[4]	0.53	n.a.[4]
mass per effective volume of water boiled	g/liter	0.007	0.004	0.001	0.005	0.008	0.005	0.007	n.a.[4]	n.a.[4]	0.014	n.a.[4]
mass per fuel mass (raw)	g/kg	0.15	0.09	0.03	0.11	0.18	0.12	0.17	n.a.[4]	n.a.[4]	0.29	n.a.[4]
mass per equivalent dry fuel mass	g/kg	0.17	0.10	0.03	0.12	0.19	0.14	0.18	n.a.[4]	n.a.[4]	0.34	n.a.[4]
mass per fuel energy	g/MJ	0.01	0.01	0.00	0.01	0.01	0.01	0.01	n.a.[4]	n.a.[4]	0.02	n.a.[4]
mass per useful energy delivered (to water in pot)	g/MJ	0.02	0.01	0.00	0.01	0.02	0.01	0.02	n.a.[4]	n.a.[4]	0.03	n.a.[4]
mass per time	g/hour	0.23	0.13	0.05	0.17	0.25	0.20	0.25	n.a.[4]	n.a.[4]	0.46	n.a.[4]
NO_X temperature-corrected total mass	g	1.15	0.14	0.88	1.10	1.09	1.09	1.17	1.20	1.20	1.30	1.36
mass per effective volume of water boiled	g/liter	0.030	0.004	0.023	0.029	0.028	0.028	0.030	0.035	0.031	0.033	0.035
mass per fuel mass (raw)	g/kg	0.68	0.08	0.47	0.66	0.66	0.68	0.70	0.75	0.70	0.72	0.74
mass per equivalent dry fuel mass	g/kg	0.77	0.09	0.59	0.73	0.72	0.75	0.76	0.83	0.80	0.85	0.87
mass per fuel energy	g/MJ	0.04	0.01	0.03	0.04	0.04	0.04	0.04	0.05	0.04	0.05	0.05
mass per useful energy delivered (to water in pot)	g/MJ	0.08	0.01	0.06	0.07	0.07	0.07	0.08	0.09	0.08	0.09	0.09
mass per time	g/hour	1.04	0.11	0.84	0.99	0.93	1.09	1.03	1.18	1.02	1.12	1.18

[1] Test 6 discontinued after the cold-start phase
[2] CO concentration measurement failed acceptance criteria
[3] THC analyzer malfunctioned
[4] CH_4 analyzer malfunctioned

Table 3. *Low-moisture fuel, low-power (30-min simmer) – WBT and pollutant emission parameters*

Parameter	Units	Average	SD	Test 2[1]	Test 3	Test 4	Test 5	Test 7[2]	Test 8	Test 9[3]
Fuel moisture (wet basis)	%	7.2	0.7	7.3	6.6	6.4	6.5	7.5	8.1	7.9
Fuel consumed (raw)	g	286	14	288	296	294	266	276	279	306
Equivalent dry fuel consumed	g	338	40	322	328	350	316	292	338	419
Fuel burning rate	g/min	11.3	1.3	10.7	10.9	11.7	10.5	9.7	11.2	14.0
Specific fuel consumption	g/liter	9.2	0.9	8.7	8.7	9.3	8.4	8.9	9.0	11.2
Specific energy use	kJ/liter	162	16	153	153	164	149	161	159	197
Fire power	W	3318	381	3157	3215	3435	3100	2929	3286	4105
Modified combustion efficiency	%	93.7	0.6	94.2	93.7	93.6	94.6	92.8	93.8	93.5
$PM_{2.5}$ total mass	mg	309	100	252	255	193	311	504	354	295
mass per volume of water remaining	mg/liter	8.5	3.3	6.8	6.8	5.1	8.3	15.4	9.5	7.9
mass per fuel mass (raw)	mg/kg	1089	384	874	863	658	1169	1828	1269	964
mass per equivalent dry fuel mass	mg/kg	939	385	782	778	552	984	1727	1049	704
mass per fuel energy	mg/MJ	52.7	21.0	44.3	44.1	31.3	55.7	95.6	58.1	39.9
mass per time	mg/hour	618	199	503	510	387	622	1008	703	590
CO total mass	g	20.9	3.2	18.6	20.8	21.4	17.8	19.7	n.a.[4]	26.8
mass per volume of water remaining	g/liter	0.57	0.09	0.50	0.55	0.57	0.47	0.60	n.a.[4]	0.72
mass per fuel mass (raw)	g/kg	72.4	8.1	64.6	70.5	72.7	67.0	71.6	n.a.[4]	87.7
mass per equivalent dry fuel mass	g/kg	61.7	4.2	57.7	63.6	61.0	56.4	67.6	n.a.[4]	64.1
mass per fuel energy	g/MJ	3.48	0.21	3.27	3.60	3.46	3.20	3.74	n.a.[4]	3.63
mass per time	g/hour	41.7	6.4	37.2	41.7	42.8	35.7	39.4	n.a.[4]	53.7
CO_2 total mass	g	505	70	478	486	496	489	397	583	607
mass per volume of water remaining	g/liter	13.7	1.5	12.9	12.9	13.2	13.0	12.1	15.6	16.2
mass per fuel mass (raw)	g/kg	1763	222	1660	1644	1685	1838	1441	2090	1983
mass per equivalent dry fuel mass	g/kg	1494	118	1484	1481	1415	1547	1361	1726	1448
mass per fuel energy	g/MJ	84.1	6.3	84.1	84.0	80.2	87.7	75.3	95.6	82.1
mass per time	g/hour	1009	139	956	972	991	978	794	1157	1213
THC (as C3H8) total mass	g	0.72	0.36	0.58	0.35	0.48	0.62	1.36	1.05	0.57
mass per volume of water remaining	g/liter	0.02	0.01	0.02	0.01	0.01	0.02	0.04	0.03	0.02
mass per fuel mass (raw)	g/kg	2.53	1.34	2.00	1.18	1.62	2.34	4.94	3.77	1.88
mass per equivalent dry fuel mass	g/kg	2.19	1.28	1.79	1.07	1.36	1.97	4.66	3.11	1.37
mass per fuel energy	g/MJ	0.12	0.07	0.10	0.06	0.08	0.11	0.26	0.17	0.08
mass per time	g/hour	1.43	0.71	1.15	0.70	0.95	1.24	2.72	2.09	1.15

Table 3 continued on next page

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Parameter	Units	Average	SD	Test 2[1]	Test 3	Test 4	Test 5	Test 7[2]	Test 8	Test 9[3]
CH_4 total mass	g	0.30	0.08	0.37	0.24	0.36	0.36	n.a.[5]	n.a.[5]	0.20
mass per volume of water remaining	g/liter	0.008	0.002	0.010	0.006	0.009	0.009	n.a.[5]	n.a.[5]	0.005
mass per fuel mass (raw)	g/kg	1.06	0.30	1.28	0.83	1.21	1.34	n.a.[5]	n.a.[5]	0.65
mass per equivalent dry fuel mass	g/kg	0.90	0.29	1.14	0.75	1.02	1.13	n.a.[5]	n.a.[5]	0.48
mass per fuel energy	g/MJ	0.05	0.02	0.06	0.04	0.06	0.06	n.a.[5]	n.a.[5]	0.03
mass per time	g/hour	0.61	0.15	0.73	0.49	0.71	0.71	n.a.[5]	n.a.[5]	0.40
NO_X total mass	g	0.17	0.04	0.14	0.16	0.14	0.16	0.15	0.20	0.24
mass per volume of water remaining	g/liter	0.005	0.001	0.004	0.004	0.004	0.004	0.005	0.005	0.006
mass per fuel mass (raw)	g/kg	0.59	0.11	0.50	0.53	0.48	0.59	0.55	0.72	0.78
mass per equivalent dry fuel mass	g/kg	0.50	0.07	0.45	0.48	0.40	0.50	0.52	0.59	0.57
mass per fuel energy	g/MJ	0.028	0.004	0.025	0.027	0.023	0.028	0.029	0.033	0.032
mass per time	g/hour	0.34	0.07	0.29	0.31	0.28	0.31	0.30	0.40	0.48

[1] Test 1 rejected due to carbon balance out of limits
[2] Test 6 discontinued after the cold-start phase
[3] Test 10 rejected due to carbon balance out of limits
[4] CO concentration measurement failed acceptance criteria
[5] CH_4 analyzer malfunctioned

Table 4. *Low-moisture fuel – emissions of OC (organic carbon) and EC (elemental carbon) in $PM_{2.5}$*

Parameter	Units	Average	SD	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
High-power cold-start													
OC temperature-corrected total mass	mg	539	134	384	604	619	555	622	275	534	760	491	549
mass per effective volume of water boiled	mg/liter	14.1	3.5	9.8	15.6	16.1	14.3	16.1	7.2	15.7	19.7	12.7	14.2
mass per fuel mass (raw)	mg/kg	309	75	212	346	365	317	353	162	326	418	279	311
mass per equivalent dry fuel mass	mg/kg	349	81	268	381	399	348	384	177	361	479	327	367
mass per fuel energy	mg/MJ	19.6	4.5	14.6	21.6	22.6	19.7	21.8	10.0	20.0	26.5	18.5	20.8
mass per useful energy delivered (to water in pot)	mg/MJ	35.7	8.6	25.3	39.7	41.2	37.0	40.8	18.4	37.2	48.7	32.4	36.5
mass per time	mg/hour	463	105	367	501	575	469	518	229	454	577	427	517
EC temperature-corrected total mass	mg	1205	76	1247	1126	1152	1167	1201	1145	1131	1307	1225	1346
mass per effective volume of water boiled	mg/liter	31.5	1.9	31.8	29.1	29.9	30.1	31.1	29.8	33.3	33.9	31.6	34.7
mass per fuel mass (raw)	mg/kg	691	32	689	646	680	666	682	674	690	719	697	763
mass per equivalent dry fuel mass	mg/kg	784	64	870	711	743	732	743	735	765	823	816	899
mass per fuel energy	mg/MJ	44.0	3.4	47.2	40.3	42.1	41.5	42.1	41.6	42.4	45.6	46.2	50.9
mass per useful energy delivered (to water in pot)	mg/MJ	79.9	4.4	82.1	74.0	76.7	77.7	78.8	76.45	78.8	83.8	80.9	89.3
mass per time	mg/hour	1042	109	1190	934	1071	986	1002	954	961	992	1064	1268
High-power hot-start													
OC temperature-corrected total mass	mg	582	262	340	206	594	722	684	n.a.[1]	1110	575	625	387
mass per effective volume of water boiled	mg/liter	15.5	7.8	8.7	5.4	15.3	18.7	17.6	n.a.[1]	32.5	14.8	16.0	10.1
mass per fuel mass (raw)	mg/kg	345	170	180	123	358	451	407	n.a.[1]	695	334	348	211
mass per equivalent dry fuel mass	mg/kg	390	184	228	136	392	498	444	n.a.[1]	772	383	409	249
mass per fuel energy	mg/MJ	21.9	10.3	12.4	7.7	22.2	28.2	25.2	n.a.[1]	42.8	21.2	23.2	14.1
mass per useful energy delivered (to water in pot)	mg/MJ	39.4	19.0	22.3	13.8	40.0	49.4	45.7	n.a.[1]	78.9	38.6	41.2	24.5
mass per time	mg/hour	534	264	326	185	509	724	601	n.a.[1]	1093	489	541	336
EC temperature-corrected total mass	mg	1297	61	1369	1270	1261	1279	1316	n.a.[1]	1278	1392	1320	1188
mass per effective volume of water boiled	mg/liter	34.0	1.9	35.0	33.1	32.5	33.1	34.0	n.a.[1]	37.4	35.9	33.9	30.9
mass per fuel mass (raw)	mg/kg	758	51	725	759	760	798	784	n.a.[1]	801	810	735	648
mass per equivalent dry fuel mass	mg/kg	863	50	918	837	832	883	855	n.a.[1]	890	928	863	764
mass per fuel energy	mg/MJ	48.4	2.3	49.8	47.4	47.1	50.0	48.5	n.a.[1]	49.3	51.4	48.9	43.3
mass per useful energy delivered (to water in pot)	mg/MJ	86.8	5.2	89.7	84.9	84.8	87.5	88.0	n.a.[1]	90.9	93.4	87.0	75.1
mass per time	mg/hour	1176	93	1310	1142	1080	1282	1158	n.a.[1]	1259	1183	1144	1032

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Parameter	**Units**	**Average**	**SD**	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 7**	**Test 8**	**Test 9**	**Test 10**
Low-power (30-minute simmer)													
OC total mass	mg	93.5	66.7	n.a.[2]	84.0	68.2	58.0	60.6	n.a.[1]	240.4	95.0	48.1	n.a.[3]
mass per volume of water remaining	mg/liter	2.6	2.1	n.a.[2]	2.3	1.8	1.5	1.6	n.a.[1]	7.3	2.5	1.3	n.a.[3]
mass per fuel mass (raw)	mg/kg	331	246	n.a.[2]	292	231	197	228	n.a.[1]	872	340	157	n.a.[3]
mass per equivalent dry fuel mass	mg/kg	292.2	240.9	n.a.[2]	260.9	208.1	165.5	191.6	n.a.[1]	823.5	281.0	115.0	n.a.[3]
mass per fuel energy	mg/MJ	16.4	13.3	n.a.[2]	14.8	11.8	9.4	10.9	n.a.[1]	45.6	15.6	6.5	n.a.[3]
mass per time	mg/hour	187	133	n.a.[2]	168	136	116	121	n.a.[1]	481	188	96	n.a.[3]
EC total mass	mg	105	52	n.a.[2]	66	80	42	179	n.a.[1]	71	148	149	n.a.[3]
mass per volume of water remaining	mg/liter	2.8	1.4	n.a.[2]	1.8	2.1	1.1	4.8	n.a.[1]	2.2	4.0	4.0	n.a.[3]
mass per fuel mass (raw)	mg/kg	370	193	n.a.[2]	230	269	143	672	n.a.[1]	258	530	486	n.a.[3]
mass per equivalent dry fuel mass	mg/kg	310	152	n.a.[2]	206	243	120	565	n.a.[1]	243	438	355	n.a.[3]
mass per fuel energy	mg/MJ	17.4	8.6	n.a.[2]	11.7	13.7	6.8	32.0	n.a.[1]	13.5	24.2	20.1	n.a.[3]
mass per time	mg/hour	209	104	n.a.[2]	132	159	84	357	n.a.[1]	142	294	297	n.a.[3]

[1] Test 6 discontinued after the cold-start phase
[2] Test 1 rejected due to carbon balance out of limits
[3] Test 10 rejected due to carbon balance out of limits

Table 5. *Low-moisture fuel – $PM_{2.5}$ mass fractions of organic carbon to total carbon (OC/TC) and elemental carbon to total carbon (EC/TC)*

	High-Power Cold-Start	High-Power Hot-Start	Low-Power (Simmer)
Mass fraction of OC/TC	0.309	0.310	0.471
Mass fraction of EC/TC	0.691	0.690	0.529

Table 6. *Low-moisture fuel – emissions of BC (black carbon) measured with aethalometer*

Parameter	Units	Average	SD	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
High-power cold-start													
BC temperature-corrected total mass	mg	1138	125	1382	1029	1129	1080	1158	972	1075	1320	1119	1118
mass per effective volume of water boiled	mg/liter	29.8	3.1	35.2	26.6	29.3	27.9	29.9	25.3	31.6	34.3	28.9	28.8
mass per fuel mass (raw)	mg/kg	652	58	764	590	667	616	658	572	656	726	636	634
mass per equivalent dry fuel mass	mg/kg	741	97	964	649	729	678	716	624	727	831	745	746
mass per fuel energy	mg/MJ	41.6	4.8	52.3	36.8	41.3	38.4	40.6	35.4	40.3	46.0	42.2	42.3
mass per useful energy delivered (to water in pot)	mg/MJ	75.4	7.6	90.9	67.6	75.2	72.0	75.9	64.9	74.9	84.6	73.9	74.2
mass per time	mg/hour	985	141	1318	854	1050	913	965	810	914	1001	972	1053
High-power hot-start													
BC temperature-corrected total mass	mg	1082	282	1149	532	1172	1237	744	n.a.[1]	1446	1222	1230	1002
mass per effective volume of water boiled	mg/liter	28.5	8.1	29.4	13.9	30.2	32.0	19.2	n.a.[1]	42.3	31.5	31.6	26.1
mass per fuel mass (raw)	mg/kg	633	177	609	318	706	772	444	n.a.[1]	906	711	686	547
mass per equivalent dry fuel mass	mg/kg	722	200	770	351	773	854	484	n.a.[1]	1007	815	805	645
mass per fuel energy	mg/MJ	40.5	11.0	41.8	19.9	43.8	48.4	27.4	n.a.[1]	55.8	45.1	45.6	36.5
mass per useful energy delivered (to water in pot)	mg/MJ	72.6	20.1	75.3	35.6	78.8	84.6	49.8	n.a.[1]	102.9	82.0	81.1	63.4
mass per time	mg/hour	986	287	1100	478	1004	1239	655	n.a.[1]	1425	1039	1066	870
Low-power (30-minute simmer)													
BC total mass	mg	74.5	49.4	n.a.[2]	28.4	44.2	24.9	62.1	n.a.[1]	79.7	148.8	133.1	n.a.[3]
mass per volume of water remaining	mg/liter	2.0	1.3	n.a.[2]	0.8	1.2	0.7	1.7	n.a.[1]	2.4	4.0	3.5	n.a.[3]
mass per fuel mass (raw)	mg/kg	261	171	n.a.[2]	99	150	85	233	n.a.[1]	289	533	435	n.a.[3]
mass per equivalent dry fuel mass	mg/kg	217	134	n.a.[2]	88	135	71	196	n.a.[1]	273	440	318	n.a.[3]
mass per fuel energy	mg/MJ	12.2	7.4	n.a.[2]	5.0	7.6	4.0	11.1	n.a.[1]	15.1	24.4	18.0	n.a.[3]
mass per time	mg/hour	149	98	n.a.[2]	57	88	50	124	n.a.[1]	159	295	266	n.a.[3]

[1] Test 6 discontinued after the cold-start phase
[2] Test 1 rejected due to carbon balance out of limits
[3] Test 10 rejected due to carbon balance out of limits

Table 7. *High-moisture fuel, high-power cold-start – WBT, $PM_{2.5}$, and gaseous pollutant parameters*

Parameter	Units	Average	SD	Test 1	Test 2	Test 3	Test 4
Fuel moisture (wet basis)	%	17.1	1.1	16.0	18.1	18.0	16.3
Fuel consumed (raw)	g	2172	19	2173	2182	2190	2145
Equivalent dry fuel consumed	g	1650	20	1678	1647	1636	1637
Time to boil 40 liters of water, 25 to 100°C	min	79.60	9.99	80.45	77.63	92.28	68.02
Thermal efficiency	%	53.9	0.5	53.4	53.9	54.5	53.8
Fuel burning rate	g/min	21.0	2.6	20.9	21.2	17.7	24.1
Temperature-corrected specific fuel consumption	g/liter	42.0	0.3	42.3	42.3	41.9	41.6
Temperature-corrected specific energy use	kJ/liter	753	7	759	759	749	745
Fire power	W	6264	775	6247	6346	5285	7179
Cooking power	W	3376	403	3335	3422	2882	3865
Modified combustion efficiency	%	98.4	0.0	98.4	98.4	98.4	98.5
$PM_{2.5}$ temperature-corrected total mass	mg	2384	255	2549	2237	2645	2105
mass per effective volume of water boiled	mg/liter	61.9	6.7	66.1	58.3	68.7	54.4
mass per fuel mass (raw)	mg/kg	1118	116	1209	1040	1226	998
mass per equivalent dry fuel mass	mg/kg	1473	156	1565	1378	1640	1308
mass per fuel energy	mg/MJ	81.0	7.6	85.4	75.2	89.5	74.1
mass per useful energy delivered (to water in pot)	mg/MJ	152	16	163	142	168	136
mass per time	mg/hour	1837	105	1959	1754	1745	1889
CO temperature-corrected total mass	g	30.2	2.1	30.6	30.5	32.3	27.4
mass per effective volume of water boiled	g/liter	0.78	0.06	0.79	0.80	0.84	0.71
mass per fuel mass (raw)	g/kg	14.2	0.9	14.5	14.2	15.0	13.0
mass per equivalent dry fuel mass	g/kg	18.7	1.3	18.8	18.8	20.1	17.0
mass per fuel energy	g/MJ	1.03	0.05	1.03	1.03	1.09	0.96
mass per useful energy delivered (to water in pot)	g/MJ	1.93	0.12	1.96	1.94	2.06	1.76
mass per time	g/hour	23.3	1.4	23.5	24.0	21.3	24.6
CO_2 temperature-corrected total mass	g	2935	124	2972	2977	3037	2755
mass per effective volume of water boiled	g/liter	76	3	77	78	79	71
mass per fuel mass (raw)	g/kg	1377	48	1410	1385	1408	1306
mass per equivalent dry fuel mass	g/kg	1814	73	1825	1834	1884	1712
mass per fuel energy	g/MJ	100	2	100	100	103	97
mass per useful energy delivered (to water in pot)	g/MJ	188	7	190	189	193	178
mass per time	g/hour	2274	197	2284	2335	2004	2472
THC (as C_3H_8) temperature-corrected total mass	g	3.14	0.27	3.14	3.39	3.29	2.77
mass per effective volume of water boiled	g/liter	0.08	0.01	0.08	0.09	0.09	0.07
mass per fuel mass (raw)	g/kg	1.47	0.11	1.49	1.57	1.52	1.31
mass per equivalent dry fuel mass	g/kg	1.94	0.16	1.93	2.09	2.04	1.72
mass per fuel energy	g/MJ	0.11	0.01	0.11	0.11	0.11	0.10
mass per useful energy delivered (to water in pot)	g/MJ	0.20	0.02	0.20	0.22	0.21	0.18
mass per time	g/hour	2.43	0.20	2.41	2.65	2.17	2.48
CH_4 temperature-corrected total mass	g	0.78	0.03	0.75	0.80	0.76	0.81
mass per effective volume of water boiled	g/liter	0.020	0.001	0.020	0.021	0.020	0.021
mass per fuel mass (raw)	g/kg	0.37	0.01	0.36	0.37	0.35	0.38
mass per equivalent dry fuel mass	g/kg	0.48	0.02	0.46	0.50	0.47	0.50
mass per fuel energy	g/MJ	0.027	0.001	0.025	0.027	0.026	0.028
mass per useful energy delivered (to water in pot)	g/MJ	0.050	0.002	0.048	0.051	0.049	0.052
mass per time	g/hour	0.61	0.09	0.58	0.63	0.50	0.72
NO_X temperature-corrected total mass	g	1.35	0.15	1.31	1.40	1.53	1.17
mass per effective volume of water boiled	g/liter	0.035	0.004	0.034	0.037	0.040	0.030
mass per fuel mass (raw)	g/kg	0.63	0.06	0.62	0.65	0.71	0.55
mass per equivalent dry fuel mass	g/kg	0.83	0.09	0.80	0.86	0.95	0.73
mass per fuel energy	g/MJ	0.046	0.005	0.044	0.047	0.052	0.041
mass per useful energy delivered (to water in pot)	g/MJ	0.09	0.01	0.08	0.09	0.10	0.08
mass per time	g/hour	1.04	0.04	1.00	1.10	1.01	1.05

Table 8. *High-moisture fuel, high-power hot-start – WBT, $PM_{2.5}$, and gaseous pollutant parameters*

Parameter	Units	Average	SD	Test 1	Test 2	Test 3	Test 4
Fuel moisture (wet basis)	%	16.6	1.5	15.7	15.8	18.8	16.0
Fuel consumed (raw)	g	2026	43	1971	2074	2018	2040
Equivalent dry fuel consumed	g	1562	66	1538	1618	1479	1613
Time to boil 5 liters of water, 25 to 100°C	min	72.68	8.59	68.10	84.58	73.02	65.03
Thermal efficiency	%	55.6	2.5	56.6	53.8	58.6	53.3
Fuel burning rate	g/min	21.7	2.5	22.6	19.1	20.3	24.8
Temperature-corrected specific fuel consumption	g/liter	41.1	1.7	40.3	43.0	39.2	41.8
Temperature-corrected specific energy use	kJ/liter	736	29	724	769	702	748
Fire power	W	6475	758	6757	5700	6043	7400
Cooking power	W	3594	389	3822	3067	3544	3944
Modified combustion efficiency	%	98.4	0.3	98.4	98.7	97.9	98.5
$PM_{2.5}$ temperature-corrected total mass	mg	2083	585	1920	1644	2943	1824
mass per effective volume of water boiled	mg/liter	54.0	15.3	49.8	42.7	76.6	47.1
mass per fuel mass (raw)	mg/kg	1015	288	964	775	1431	891
mass per equivalent dry fuel mass	mg/kg	1327	429	1235	993	1953	1127
mass per fuel energy	mg/MJ	73.0	23.1	67.4	54.2	106.5	63.8
mass per useful energy delivered (to water in pot)	mg/MJ	132	37	122	103	186	118
mass per time	mg/hour	1716	506	1674	1140	2374	1677
CO temperature-corrected total mass	g	30.7	6.4	30.9	25.6	39.7	26.5
mass per effective volume of water boiled	g/liter	0.80	0.17	0.80	0.66	1.03	0.69
mass per fuel mass (raw)	g/kg	15.0	3.2	15.5	12.1	19.3	13.0
mass per equivalent dry fuel mass	g/kg	19.5	4.9	19.9	15.5	26.3	16.4
mass per fuel energy	g/MJ	1.07	0.26	1.08	0.84	1.44	0.93
mass per useful energy delivered (to water in pot)	g/MJ	1.95	0.40	1.96	1.61	2.51	1.72
mass per time	g/hour	25.3	5.9	26.9	17.7	32.0	24.4
CO_2 temperature-corrected total mass	g	2896	146	2944	3012	2948	2682
mass per effective volume of water boiled	g/liter	75	4	76	78	77	69
mass per fuel mass (raw)	g/kg	1410	71	1478	1419	1433	1309
mass per equivalent dry fuel mass	g/kg	1831	130	1895	1819	1956	1656
mass per fuel energy	g/MJ	101	6	103	99	107	94
mass per useful energy delivered (to water in pot)	g/MJ	184	7	187	189	186	174
mass per time	g/hour	2374	206	2566	2088	2377	2464
THC (as C_3H_8) temperature-corrected total mass	g	2.68	0.40	2.53	2.60	3.26	2.34
mass per effective volume of water boiled	g/liter	0.07	0.01	0.07	0.07	0.08	0.06
mass per fuel mass (raw)	g/kg	1.31	0.19	1.27	1.22	1.59	1.14
mass per equivalent dry fuel mass	g/kg	1.70	0.32	1.63	1.57	2.17	1.44
mass per fuel energy	g/MJ	0.09	0.02	0.09	0.09	0.12	0.08
mass per useful energy delivered (to water in pot)	g/MJ	0.17	0.02	0.16	0.16	0.21	0.15
mass per time	g/hour	2.20	0.34	2.20	1.80	2.63	2.15
CH_4 temperature-corrected total mass	g	0.69	0.13	0.60	0.57	0.83	0.75
mass per effective volume of water boiled	g/liter	0.018	0.003	0.015	0.015	0.022	0.019
mass per fuel mass (raw)	g/kg	0.33	0.06	0.30	0.27	0.41	0.37
mass per equivalent dry fuel mass	g/kg	0.44	0.09	0.38	0.34	0.55	0.47
mass per fuel energy	g/MJ	0.02	0.01	0.02	0.02	0.03	0.03
mass per useful energy delivered (to water in pot)	g/MJ	0.04	0.01	0.04	0.04	0.05	0.05
mass per time	g/hour	0.57	0.14	0.52	0.39	0.67	0.69
NO_X temperature-corrected total mass	g	1.27	0.07	1.30	1.30	1.31	1.16
mass per effective volume of water boiled	g/liter	0.033	0.002	0.034	0.034	0.034	0.030
mass per fuel mass (raw)	g/kg	0.62	0.04	0.65	0.61	0.64	0.56
mass per equivalent dry fuel mass	g/kg	0.80	0.07	0.84	0.79	0.87	0.71
mass per fuel energy	g/MJ	0.044	0.003	0.046	0.043	0.047	0.040
mass per useful energy delivered (to water in pot)	g/MJ	0.080	0.004	0.082	0.082	0.083	0.075
mass per time	g/hour	1.04	0.10	1.13	0.90	1.06	1.06

Table 9. *High-moisture fuel, low-power (30-min simmer) – WBT and pollutant emission parameters*

Parameter	**Units**	**Average**	**SD**	**Test 1**	**Test 2**	**Test 3**	**Test 4**
Fuel moisture (wet basis)	%	17.4	3.8	14.2	17.1	22.8	15.4
Fuel consumed (raw)	g	421	29	378	426	442	439
Equivalent dry fuel consumed	g	427	16	416	447	433	412
Fuel burning rate	g/min	14.2	0.6	13.8	14.9	14.4	13.7
Specific fuel consumption	g/liter	11.5	0.5	11.2	12.1	11.8	11.1
Specific energy use	kJ/liter	207	9	200	217	212	199
Fire power	W	4254	170	4127	4454	4335	4100
Modified combustion efficiency	%	95.7	0.8	96.5	94.7	95.5	96.2
$PM_{2.5}$ total mass	mg	573	92	568	663	615	448
mass per volume of water remaining	mg/liter	15.5	2.5	15.3	17.9	16.7	12.1
mass per fuel mass (raw)	mg/kg	1367	241	1500	1557	1392	1021
mass per equivalent dry fuel mass	mg/kg	1338	174	1363	1482	1419	1087
mass per fuel energy	mg/MJ	73.6	8.4	74.4	80.9	77.4	61.6
mass per time	mg/hour	1146	185	1132	1326	1230	896
CO total mass	g	19.2	5.3	14.3	25.4	21.7	15.4
mass per volume of water remaining	g/liter	0.52	0.14	0.38	0.69	0.59	0.42
mass per fuel mass (raw)	g/kg	45.4	11.3	37.7	59.7	49.2	35.1
mass per equivalent dry fuel mass	g/kg	44.7	10.6	34.3	56.9	50.1	37.4
mass per fuel energy	g/MJ	2.46	0.56	1.87	3.10	2.73	2.12
mass per time	g/hour	38.4	10.6	28.5	50.9	43.4	30.8
CO_2 total mass	g	664	57	614	707	719	616
mass per volume of water remaining	g/liter	18.0	1.6	16.5	19.1	19.5	16.6
mass per fuel mass (raw)	g/kg	1579	118	1624	1661	1628	1403
mass per equivalent dry fuel mass	g/kg	1553	85	1475	1581	1659	1494
mass per fuel energy	g/MJ	85.5	4.1	80.5	86.3	90.5	84.7
mass per time	g/hour	1327	115	1225	1415	1438	1231
THC (as C_3H_8) total mass	g	1.30	0.14	1.42	1.37	1.10	1.31
mass per volume of water remaining	g/liter	0.035	0.004	0.038	0.037	0.030	0.035
mass per fuel mass (raw)	g/kg	3.11	0.52	3.74	3.22	2.50	2.98
mass per equivalent dry fuel mass	g/kg	3.05	0.36	3.40	3.07	2.54	3.18
mass per fuel energy	g/MJ	0.17	0.02	0.19	0.17	0.14	0.18
mass per time	g/hour	2.60	0.27	2.82	2.74	2.21	2.62
CH_4 total mass	g	0.35	0.01	0.35	0.34	0.34	0.37
mass per volume of water remaining	g/liter	0.0094	0.0004	0.0095	0.0091	0.0092	0.0099
mass per fuel mass (raw)	g/kg	0.83	0.07	0.93	0.79	0.76	0.83
mass per equivalent dry fuel mass	g/kg	0.82	0.06	0.85	0.75	0.78	0.89
mass per fuel energy	g/MJ	0.045	0.004	0.046	0.041	0.042	0.050
mass per time	g/hour	0.70	0.03	0.70	0.67	0.67	0.73
NO_X total mass	g	0.27	0.03	0.26	0.27	0.31	0.25
mass per volume of water remaining	g/liter	0.007	0.001	0.007	0.007	0.008	0.007
mass per fuel mass (raw)	g/kg	0.64	0.06	0.69	0.63	0.69	0.56
mass per equivalent dry fuel mass	g/kg	0.63	0.05	0.63	0.60	0.71	0.60
mass per fuel energy	g/MJ	0.035	0.003	0.034	0.033	0.039	0.034
mass per time	g/hour	0.54	0.05	0.52	0.54	0.61	0.49

Table 10. *High-moisture fuel – emissions of $PM_{2.5}$ OC (organic carbon) and EC (elemental carbon)*

Parameter	Units	Average	SD	Test 1	Test 2	Test 3	Test 4
High-power cold-start							
OC temperature-corrected total mass	mg	716	167	734	694	921	514
mass per effective volume of water boiled	mg/liter	18.6	4.4	19.1	18.1	23.9	13.3
mass per fuel mass (raw)	mg/kg	335	76	348	323	427	244
mass per equivalent dry fuel mass	mg/kg	442	103	451	427	571	319
mass per fuel energy	mg/MJ	24.3	5.4	24.6	23.3	31.2	18.1
mass per useful energy delivered (to water in pot)	mg/MJ	45.7	10.4	47.0	44.1	58.5	33.1
mass per time	mg/hour	544	61	564	544	608	461
EC temperature-corrected total mass	mg	1163	107	1309	1076	1177	1091
mass per effective volume of water boiled	mg/liter	30.2	2.8	34.0	28.0	30.6	28.2
mass per fuel mass (raw)	mg/kg	546	53	621	500	546	517
mass per equivalent dry fuel mass	mg/kg	719	64	804	663	730	678
mass per fuel energy	mg/MJ	39.6	3.2	43.8	36.2	39.8	38.4
mass per useful energy delivered (to water in pot)	mg/MJ	74.4	6.8	83.8	68.5	74.8	70.3
mass per time	mg/hour	901	109	1006	844	777	979
High-power hot-start							
OC temperature-corrected total mass	mg	449	284	314	298	875	310
mass per effective volume of water boiled	mg/liter	11.7	7.4	8.1	7.7	22.8	8.0
mass per fuel mass (raw)	mg/kg	219	138	158	140	426	151
mass per equivalent dry fuel mass	mg/kg	288	195	202	180	581	191
mass per fuel energy	mg/MJ	15.8	10.6	11.0	9.8	31.7	10.8
mass per useful energy delivered (to water in pot)	mg/MJ	28.5	17.9	19.9	18.7	55.3	20.1
mass per time	mg/hour	368	228	274	206	706	285
EC temperature-corrected total mass	mg	1144	149	1154	996	1345	1081
mass per effective volume of water boiled	mg/liter	29.7	3.9	29.9	25.9	35.0	27.9
mass per fuel mass (raw)	mg/kg	557	78	579	469	654	528
mass per equivalent dry fuel mass	mg/kg	726	125	743	601	892	668
mass per fuel energy	mg/MJ	40.0	6.6	40.5	32.8	48.7	37.8
mass per useful energy delivered (to water in pot)	mg/MJ	72.6	9.4	73.1	62.5	85.0	70.0
mass per time	mg/hour	943	174	1006	690	1084	993
Low-power (30-minute simmer)							
OC total mass	mg	198	46	260	203	156	173
mass per volume of water remaining	mg/liter	5.35	1.22	7.00	5.50	4.24	4.68
mass per fuel mass (raw)	mg/kg	478	149	688	477	353	395
mass per equivalent dry fuel mass	mg/kg	465	114	625	454	360	420
mass per fuel energy	mg/MJ	25.6	6.1	34.1	24.8	19.6	23.8
mass per time	mg/hour	396	91	519	407	312	346
EC total mass	mg	175	93	80	227	278	113
mass per volume of water remaining	mg/liter	4.73	2.54	2.16	6.13	7.55	3.06
mass per fuel mass (raw)	mg/kg	408	204	212	532	630	258
mass per equivalent dry fuel mass	mg/kg	404	207	193	507	642	275
mass per fuel energy	mg/MJ	22.2	11.2	10.5	27.6	35.0	15.6
mass per time	mg/hour	349	187	160	453	556	227

Table 11. *High-moisture fuel – $PM_{2.5}$ mass fractions of organic carbon to total carbon (OC/TC) and elemental carbon to total carbon (EC/TC)*

	High-Power Cold-Start	High-Power Hot-Start	Low-Power (Simmer)
Mass fraction of OC/TC	0.381	0.282	0.532
Mass fraction of EC/TC	0.619	0.718	0.468

Table 12. *High-moisture fuel – emissions of BC (black carbon) measured with aethalometer*

Parameter	Units	Average	SD	Test 1	Test 2	Test 3	Test 4
High-power cold-start							
BC temperature-corrected total mass	mg	1137	100	1203	1088	1235	1020
mass per effective volume of water boiled	mg/liter	29.5	2.6	31.2	28.4	32.1	26.4
mass per fuel mass (raw)	mg/kg	533	45	570	506	572	484
mass per equivalent dry fuel mass	mg/kg	702	61	739	671	766	634
mass per fuel energy	mg/MJ	38.6	2.8	40.3	36.6	41.8	35.9
mass per useful energy delivered (to water in pot)	mg/MJ	72.6	6.1	77.0	69.3	78.5	65.8
mass per time	mg/hour	877	52	924	854	815	916
High-power hot-start							
BC temperature-corrected total mass	mg	970	227	916	764	1294	907
mass per effective volume of water boiled	mg/liter	25.2	5.9	23.7	19.8	33.7	23.4
mass per fuel mass (raw)	mg/kg	473	113	460	360	629	443
mass per equivalent dry fuel mass	mg/kg	617	170	589	461	859	560
mass per fuel energy	mg/MJ	34.0	9.2	32.1	25.2	46.8	31.8
mass per useful energy delivered (to water in pot)	mg/MJ	61.6	14.3	58.0	47.9	81.8	58.7
mass per time	mg/hour	801	211	798	529	1043	834
Low-power (30-minute simmer)							
BC total mass	mg	146	63	90	137	237	120
mass per volume of water remaining	mg/liter	4.0	1.7	2.4	3.7	6.4	3.3
mass per fuel mass (raw)	mg/kg	343	133	239	322	536	275
mass per equivalent dry fuel mass	mg/kg	341	143	217	306	546	292
mass per fuel energy	mg/MJ	18.7	7.7	11.8	16.7	29.8	16.6
mass per time	mg/hour	292	127	180	274	474	241

Table 13. *Comparison of low- and high-moisture fuel – WBT, $PM_{2.5}$ and gaseous pollutant parameters*

Parameter	**Units**	**High-power cold-start**		**High-power hot-start**		**Low-power 30-minute simmer**	
Fuel moisture (wet basis)	**%**	**7.2**	**17.1**	**7.3**	**16.6**	**7.2**	**17.4**
Fuel consumed (raw)	g	1817	2172	1724	2026	286	421
Equivalent dry fuel consumed	g	1607	1650	1513	1562	338	427
Time to boil 40 liters of water, 25 to 100°C	min	72.71	79.60	66.81	72.68	n.a.[1]	n.a.[1]
Thermal efficiency	%	55.0	53.9	56.0	55.6	n.a.[1]	n.a.[1]
Fuel burning rate	g/min	22.2	21.0	22.7	21.7	11.3	14.2
Temperature-corrected specific fuel consumption	g/liter	40.3	42.0	39.4	41.1	9.2	11.5
Temperature-corrected specific energy use	kJ/liter	718	753	700	736	162	207
Fire power	W	6574	6264	6729	6475	3318	4254
Cooking power	W	3640	3376	3765	3594	n.a.[1]	n.a.[1]
Modified combustion efficiency	%	97.6	98.4	97.6	98.4	93.7	95.7
$PM_{2.5}$ temperature-corrected total mass	mg	2295	2384	2359	2083	309	573
mass per effective volume of water	mg/liter	60.1	61.9	62.0	54.0	8.5	15.5
mass per fuel mass (raw)	mg/kg	1316	1118	1385	1015	1089	1367
mass per equivalent dry fuel mass	mg/kg	1491	1473	1573	1327	939	1338
mass per fuel energy	mg/MJ	83.7	81.0	88.2	73.0	52.7	73.6
mass per useful energy delivered (to water in pot)	mg/MJ	152.1	152	158.4	132	n.a.[1]	n.a.[1]
mass per time	mg/hour	1982	1837	2148	1716	618	1146
CO temperature-corrected total mass	g	45.0	30.2	40.9	30.7	20.9	19.2
mass per effective volume of water	g/liter	1.18	0.78	1.08	0.80	0.57	0.52
mass per fuel mass (raw)	g/kg	25.8	14.2	24.2	15.0	72.4	45.4
mass per equivalent dry fuel mass	g/kg	28.8	18.7	27.2	19.5	61.7	44.7
mass per fuel energy	g/MJ	1.62	1.03	1.53	1.07	3.48	2.46
mass per useful energy delivered (to water in pot)	g/MJ	2.98	1.93	2.75	1.95	n.a.[1]	n.a.[1]
mass per time	g/hour	38.2	23.3	37.3	25.3	41.7	38.4
CO_2 temperature-corrected total mass	g	2685	2935	2602	2896	505	664
mass per effective volume of water	g/liter	70.4	76	68.1	75	13.7	18.0
mass per fuel mass (raw)	g/kg	1541	1377	1520	1410	1763	1579
mass per equivalent dry fuel mass	g/kg	1743	1814	1730	1831	1494	1553
mass per fuel energy	g/MJ	97.9	100	97.1	101	84.1	85.5
mass per useful energy delivered (to water in pot)	g/MJ	178	188	174	184	n.a.[1]	n.a.[1]
mass per time	g/hour	2314	2274	2353	2374	1009	1327
THC (as C_3H_8) temperature-corrected total mass	g	0.82	3.14	1.15	2.68	0.72	1.30
mass per effective volume of water	g/liter	0.02	0.08	0.03	0.07	0.02	0.04
mass per fuel mass (raw)	g/kg	0.47	1.47	0.68	1.31	2.53	3.11
mass per equivalent dry fuel mass	g/kg	0.53	1.94	0.77	1.70	2.19	3.05
mass per fuel energy	g/MJ	0.03	0.11	0.04	0.09	0.12	0.17
mass per useful energy delivered (to water in pot)	g/MJ	0.05	0.20	0.08	0.17	n.a.[1]	n.a.[1]
mass per time	g/hour	0.69	2.43	1.06	2.20	1.43	2.60
CH_4 temperature-corrected total mass	g	0.21	0.78	0.26	0.69	0.30	0.35
mass per effective volume of water	g/liter	0.005	0.020	0.007	0.018	0.008	0.009
mass per fuel mass (raw)	g/kg	0.12	0.37	0.15	0.33	1.06	0.83
mass per equivalent dry fuel mass	g/kg	0.13	0.48	0.17	0.44	0.90	0.82
mass per fuel energy	g/MJ	0.01	0.03	0.01	0.02	0.05	0.05
mass per useful energy delivered (to water in pot)	g/MJ	0.01	0.05	0.02	0.04	n.a.[1]	n.a.[1]
mass per time	g/hour	0.18	0.61	0.23	0.57	0.61	0.70
NO_X temperature-corrected total mass	g	1.26	1.35	1.15	1.27	0.17	0.27
mass per effective volume of water	g/liter	0.033	0.035	0.030	0.033	0.005	0.007
mass per fuel mass (raw)	g/kg	0.72	0.63	0.68	0.62	0.59	0.64
mass per equivalent dry fuel mass	g/kg	0.82	0.83	0.77	0.80	0.50	0.63
mass per fuel energy	g/MJ	0.05	0.05	0.04	0.04	0.03	0.03
mass per useful energy delivered (to water in pot)	g/MJ	0.08	0.09	0.08	0.08	n.a.[1]	n.a.[1]
mass per time	g/hour	1.09	1.04	1.04	1.04	0.34	0.54

[1]Not applicable to the low-power 30-minute simmer phase

__Table 14.__ Comparison of low- and high-moisture fuel – $PM_{2.5}$ organic and elemental carbon emissions

Parameter	Units	High-power cold-start		High-power hot-start		Low-power 30-minute simmer	
Fuel moisture (wet basis)	**%**	**7.2**	**17.1**	**7.3**	**16.6**	**7.2**	**17.4**
OC temperature-corrected total mass	mg	539	716	582	449	93.5	198
mass per effective volume of water	mg/liter	14.1	18.6	15.5	11.7	2.6	5.35
mass per fuel mass (raw)	mg/kg	309	335	345	219	331	478
mass per equivalent dry fuel mass	mg/kg	349	442	390	288	292.2	465
mass per fuel energy	mg/MJ	19.6	24.3	21.9	15.8	16.4	25.6
mass per useful energy delivered	mg/MJ	35.7	45.7	39.4	28.5	n.a.	n.a.
mass per time	mg/hour	463	544	534	368	187	396
EC temperature-corrected total mass	mg	1205	1163	1297	1144	105	175
mass per effective volume of water	mg/liter	31.5	30.2	34.0	29.7	2.8	4.73
mass per fuel mass (raw)	mg/kg	691	546	758	557	370	408
mass per equivalent dry fuel mass	mg/kg	784	719	863	726	310	404
mass per fuel energy	mg/MJ	44.0	39.6	48.4	40.0	17.4	22.2
mass per useful energy delivered	mg/MJ	79.9	74.4	86.8	72.6	n.a.	n.a.
mass per time	mg/hour	1042	901	1176	943	209	349
Mass fraction of OC/TC	-	0.309	0.381	0.310	0.282	0.471	0.532
Mass fraction of EC/TC	-	0.691	0.619	0.690	0.718	0.529	0.468

__Table 15.__ Comparison of low- and high-moisture fuel – emissions of black carbon (aethalometer)

Parameter	Units	High-power cold-start		High-power hot-start		Low-power 30-minute simmer	
Fuel moisture (wet basis)	**%**	**7.2**	**17.1**	**7.3**	**16.6**	**7.2**	**17.4**
BC temperature-corrected total mass	mg	1138	1137	1082	970	74.5	146
mass per effective volume of water	mg/liter	29.8	29.5	28.5	25.2	2.0	4.0
mass per fuel mass (raw)	mg/kg	652	533	633	473	261	343
mass per equivalent dry fuel mass	mg/kg	741	702	722	617	217	341
mass per fuel energy	mg/MJ	41.6	38.6	40.5	34.0	12.2	18.7
mass per useful energy delivered	mg/MJ	75.1	72.6	72.6	61.6	n.a.	n.a.
mass per time	mg/hour	985	877	986	801	149	292

Table 16. *Results from indoor (fugitive) emissions tests*

Parameter	Units	High-power cold-start	High-power hot-start	Low-power 30-min simmer
Fuel moisture (wet basis)	%	8.4	8.4	8.4
Fuel consumed (raw)	g	1797	1679	351
Equivalent dry fuel consumed	g	1554	1446	395
Time to boil 40 liters of water, 25 to 100°C	min	61.84	49.47	n.a.[1]
Thermal efficiency	%	56.2	56.1	n.a.[1]
Fuel burning rate	g/min	23.8	29.3	13.2
Temperature-corrected specific fuel consumption	g/liter	37.0	36.5	10.4
Temperature-corrected specific energy use	kJ/liter	669	660	187
Fire power	W	7166	8832	3961
Cooking power	W	4029	4958	n.a.[1]
$PM_{2.5}$ temperature-corrected total mass	mg	60	56	7.8
mass per effective volume of water	mg/liter	1.5	1.4	0.21
mass per fuel mass (raw)	mg/kg	35	33	22.3
mass per equivalent dry fuel mass	mg/kg	41	38	19.9
mass per fuel energy	mg/MJ	2.3	2.1	1.1
mass per useful energy delivered (to water in pot)	mg/MJ	4.0	3.8	n.a.[1]
mass per time	mg/hour	58.6	67.4	15.7
CO temperature-corrected total mass	g	0.81	0.63	0.26
mass per effective volume of water	g/liter	0.020	0.016	0.007
mass per fuel mass (raw)	g/kg	0.48	0.37	0.74
mass per equivalent dry fuel mass	g/kg	0.55	0.44	0.66
mass per fuel energy	g/MJ	0.030	0.024	0.036
mass per useful energy delivered (to water in pot)	g/MJ	0.054	0.043	n.a.[1]
mass per time	g/hour	0.79	0.77	0.52

[1]Not applicable to the low-power 30-minute simmer phase

Table 17. *Carbon balance, percent difference based on fuel carbon*

Fuel Moisture	Test phase	Units	Test 1 08/21/2014	Test 2 02/11/2015	Test 3 02/12/2015	Test 4 02/13/2015	Test 5 02/20/2015
Low	High-power cold-start	%	16.0	5.4	7.0	2.9	5.2
	High-power hot-start	%	18.0	6.2	5.7	3.1	5.4
	Low-power (simmer)	%	rejected[1]	13.7	13.4	17.2	10.2
			Test 6 02/23/2015	Test 7 05/06/2015	Test 8 05/08/2015	Test 9 05/12/2015	Test 10 05/13/2015
Low	High-power cold-start	%	5.7	-3.0	-6.2	-5.1	-3.8
	High-power hot-start	%	n.a.[2]	1.6	-10.7	-3.1	-6.0
	Low-power (simmer)	%	n.a.[2]	19.3	-6.9	15.1	rejected[1]
			Test 1 05/18/2015	Test 2 05/19/2015	Test 3 05/20/2015	Test 4 05/29/2015	
High	High-power cold-start	%	-4.0	-4.2	-7.9	6.6	
	High-power hot-start	%	-8.1	-4.3	-12.2	9.6	
	Low-power (simmer)	%	13.8	6.6	4.7	15.9	

[1] Rejected due to carbon balance out of limits

[2] Test 6 discontinued after the cold-start phase

Table 18. *Measurement quality objectives for critical measurements.*
All data included in this report were based on measurements that met or exceeded acceptance criteria.

Measurement	Reference	Indicators	Acceptance Criteria
Water and Fuel Mass, Electronic Balance	EPA RTP Met Lab SOP, MS-0501.0	Accuracy Precision	± 1 g ± 1 g
Water Temperature, Thermocouple	EPA RTP Met Lab SOP, TH-0301.0	Accuracy Precision	± 0.5 ˚C ± 0.5 ˚C
Fuel Heat of Combustion	ASTM D5865-13	Accuracy Precision	± 0.5% ± 0.5%
Fuel Moisture Content Mass, Electronic Balance	ASTM D4442-07	Accuracy Precision	± 1g ± 0.5g
$PM_{2.5}$ Mass, Microbalance	EPA Method 5	Accuracy Precision	± 0.01 mg ± 0.01 mg
$PM_{2.5}$ Mass, Sampling Air Flow	EPA RTP Met Lab SOP FV-0237.1	Accuracy Precision	± 1 lpm ± 1 lpm
PM OC/EC Mass	NIOSH Method 5040	Accuracy Precision	± 16.7% ± 10%
THC Concentration CH_4 Concentration	EPA Method 25A	Calibration linearity Zero bias Span bias Zero drift Span drift	± 2% of scale ± 5% of scale ± 5% of scale ± 3% of scale ± 3% of scale
CO Concentration	EPA Method 10		
CO_2 Concentration	EPA Method 3A		
NO_X Concentration	EPA Method 7E		
Duct Gas Velocity	EPA Methods 1 & 2	Accuracy Precision	± 5% of reading ± 5% of reading
Duct Gas Temperature Thermocouple	EPA RTP Met Lab SOP, TH-0301.0	Accuracy Precision	± 1 ˚C ± 1 ˚C

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