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Test Report

CleanCook Model A1 Stove with Alcohol Fuel

Air Pollutant Emissions and Fuel Efficiency

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Notice

The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development, has financially supported the testing described here. This document has been reviewed by the Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation by the EPA for use.

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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, the Netherlands. IWA 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 that specify tier ratings ranging 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 – typically attainable levels for liquid/gas-fuel stoves. 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 3 and 5-8 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. The specific energy use sub-tier rating is not included for the CleanCook A1 stove, as explained in the Discussion of Results section of this report.

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). Emission tier levels are based on the mass of pollutant emitted per 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 body. 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 alcohol fuel. Discussion of results, observations, and quality assurance are also included in the report.

Stove Manufacturer & Model	**Dometic AB** Sweden **CleanCook A1 Single-Burner Stove** Serial No. 147 2900009
Testing Center	EPA-Research Triangle Park, North Carolina, USA
Test Protocol	WBT Version 4.2.3, EPA Rev. 4 [see Reference (8)]
Fuel Used	Denatured alcohol (ethanol/methanol)
Pot Used	Standard flat-bottom 3L pot with 2L of water, without a pot skirt

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

		Metric	Value	Unit	Sub-Tier
Efficiency / Fuel Use					
Tier	**4**	High Power Thermal Efficiency	56.2	%	4
		Low Power Specific Energy Use	n.a.[1]	MJ / (min L)	n.a.[1]
Emissions					
Tier	**4**	High Power CO	1.51	g / $MJ_{delivered}$	4
		Low Power CO	0.04	g / (min L)	4
		High Power $PM_{2.5}$	1.5	mg / $MJ_{delivered}$	4
		Low Power $PM_{2.5}$	< 0.02[2]	mg / (min L)	4
Indoor Emissions					
Tier	**4**	High Power CO	0.06	g / min	4
		Low Power CO	0.06	g / min	4
		High Power $PM_{2.5}$	0.1	mg / min	4
		Low Power $PM_{2.5}$	< 0.03[2]	mg / min	4

Tiers 0 → 4 (best)

	Value	Unit
Cooking Power (average of Cold Start and Hot Start phases)	712	W
Fuel burning rate (average for Cold Start, based on equivalent dry fuel consumed)	3.6	g / min
Fuel burning rate (average for Hot Start, based on equivalent dry fuel consumed)	3.8	g / min
Fuel burning rate (average for Simmer, based on equivalent dry fuel consumed)	3.4	g / min

[1] Not applicable – see Discussion of Results section of this report

[2] Limit of detection

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(s)
CO	carbon monoxide
CO_2	carbon dioxide
CPC	condensation particle counter
EC	elemental carbon
EPA	U.S. Environmental Protection Agency
FOB	free on board
g	gram(s)
h	hour(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	polytetrafluoroethylene
RTP	Research Triangle Park
SD	standard deviation
SMPS	Scanning Mobility Particle Sizer
SOP	Standard Operating Procedure
TC	Technical Committee
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 International Organization for Standardization (ISO) TC (Technical Committee) 285: Clean Cookstoves and Clean Cooking Solutions (3).
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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).

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. Project Gaia, Gettysburg, Pennsylvania, USA, developed the portable alcohol-fueled CleanCook Model A1 stove in partnership with the Swedish manufacturer, Dometic AB, and the stove is manufactured in Slovakia. Similar Models Nova 1 and Nova 2 are manufactured in South Africa. CleanCook stoves are designed for use in the developing world, and stoves have been disseminated in Ethiopia, Nigeria, Brazil, Haiti, Kenya, Madagascar, South Africa, Malawi, Mozambique, Tanzania, and Guatemala.

Type of stove. The CleanCook Model A1 stove shown in Figure 1 is an unpressurized liquid-fuel type of stove designed for alcohol (ethanol and/or methanol) fuel. Evaporating liquid fuel burns as a gas, and no pressurized container or wick is required. Alcohol is contained in a fuel tank filled with an absorptive ceramic fiber material – adding a non-alcohol liquid fuel (such as kerosene) can damage the fuel container. Capacity of the fuel tank is 1.2 liters. A pot support with an integral wind screen attaches to the top of the stove. CleanCook stoves are mass produced. The Model A1 that was tested has a single burner and a mechanical regulator – a lever moves a metal disk that uncovers an opening for evaporating fuel. The regulator can be used to adjust or extinguish the flame. The stove does not include an ignition device –

the burner must be lit with a match or other source of flame. Models A2 and M2 (not tested) have two burners.

Construction materials. The A1 stove body is constructed of aluminum with a baked enamel finish. Burner, fuel tank, and pot support components are stainless steel, an inner chassis is galvanized steel, and handles are aluminum. A similar single-burner Model M1 (not tested) has all stainless steel components and is designed primarily for use with methanol fuel, since methanol is more corrosive than ethanol. Weight of the A1 stove including an empty fuel tank is 2.2 kilograms (kg). Weight of the empty fuel tank is 0.6 kg.

Figure 1. *CleanCook A1 alcohol stove and fuel tank*

Dimensions.
Stove height: 16 cm
Stove width: 34 cm
Stove depth: 29 cm
Fuel tank outside diameter: 22 cm
Fuel tank opening inside diameter: 8 cm
Fuel tank height: 6 cm

Accessories. No accessories were supplied with the stove.

Cooking pot. A default standard flat-bottomed pot was used for the tests. This pot has a weight of approximately 553 grams (g). Full capacity is approximately 3.5 liters, and the pot is used with two liters of water for the tests. The WBT protocol recommends 2.5 liters of water, but two liters is used, because 2.5 liters of water can boil over the top of the 3.5-liter standard pot. Material is stainless steel. Outside diameter of the rolled edge at the top of the pot is 216 millimeters (mm), and inside diameter of the pot at the top is 200 mm. Outside diameter at the bottom is 196 mm. Height (not including handles) is 98 mm. The pot was obtained from the CICCI Company (Copenhagen, Denmark) that has provided supplies for emergency relief and development projects around the world. Performance may vary if the stove is used with a different cooking pot.

Fuel. Denatured alcohol (52.5-55.0 % methanol, 42.5-46.5 % ethanol, <1.0 % methyl isobutyl ketone, <0.5 % acetic acid, <0.5 % heptane) was obtained from a local supplier. Performance may vary if the stove is used with a different type of fuel (e.g., 95% ethanol, 5% methanol).

Operating procedure. A laminated card with operating and safety instructions was supplied with the stove. Operating instructions were followed during testing.

Cost. Commercial unsubsidized prices posted by Project Gaia for August–September 2015 are FOB (free on board) factory, on a full container basis, shipped from South Africa, as follows. Cost for the Nova 1 (similar to the A1) is US$34.00, and cost for the two-burner Nova 2 (Similar to the A2) is US$53.50.

Quantity disseminated. Approximate quantities disseminated, according to Project Gaia, are as follows:

Ethiopia: 10,000
Nigeria: 4,000
Haiti: 2,200
Mozambique: 35,000
Kenya: 600
Tanzania: 150
South Africa: 300
Brazil: 300
Guatemala: 50
Madagascar: 450

Lifetime. According to Project Gaia information, expected typical lifetime is six years for the aluminum body stove and 10+ years for the stainless steel stove. 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 estimated lifetime.

Test Protocol

The cookstove system was tested using the Water Boiling Test (WBT) Version 4.2.3 (8) and following the ISO 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. Gaseous and particulate air pollutants were sampled from the primary dilution tunnel for testing of this stove/fuel. 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 polytetrafluoroethylene (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 were performed using National Institute for Occupational Safety and Health (NIOSH) Method 5040 (11), including analysis of gas-phase samples collected on quartz fiber filters downstream of PTFE membrane filters to account for the gas-phase absorption artifact (12). 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.

Test Results

A summary of results is presented in accordance with ISO International Workshop Agreement (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 according to the manufacturer's instructions with alcohol fuel.

CleanCook stove test results are compared with previously published results (14) in Figures 2-8. Key indicators of performance shown in the figures are described in Jetter et al. 2012 (14). Error bars on the data points for the CleanCook stove indicate 95% confidence intervals constructed with the t-distribution. 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 (14). Data points (blue diamonds indicated by the letter "P") are identified for the Philips HD4012 stove for comparison, because the HD4012 is a well-known and relatively high-performing forced-draft solid-fuel stove typically used for a performance reference. Data points for other stoves with previously published results are not identified in Figures 2-8, but stoves are identified in the journal article (14). All data shown in the figures for solid-fuel stoves are for test results with low-moisture fuels, as described in the published results (14).

Cooking power versus fire power data (in measurement units of Watts (W)) are shown in Figure 2 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" (14). The ratio of cooking power to fire power is thermal efficiency – shown in Figure 3.

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 3. These metrics are used to determine IWA Tier ratings, and the IWA Sub-Tiers are indicated in the figure. Low-power specific-energy-use tiers were established in IWA 11:2012 based on data mainly from stoves tested with five liters (L) of water, and it is now recognized that the specific energy use tiers are not applicable for stoves tested with less than five liters of water. It is expected that this issue will be revisited by ISO TC 285, and in the interim, we will use only the thermal efficiency for tier ratings for stoves, such as the CleanCook, tested with less than five liters of water. In Figure 3, the data point for the CleanCook stove is located on the bottom of the chart off the scale for Specific Energy Use, but the data point is shown on the correct scale for Thermal Efficiency, for comparison with data for previously tested stoves.

Low-power versus high-power MCE (modified combustion efficiency) data are shown in Figure 4. 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 (megaJoules ($MJ_{delivered}$)) to the water in the cooking pot during high-power phases of the WBT are shown in Figure 5. 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 (min) per liter of water simmered during the low-power phase of the WBT are shown in Figure 6. Useful cooking energy is not accurately measured during the low-power test phase of the WBT (14), therefore the specific emission rate is used as the metric, per the IWA. For the CleanCook stove, the average $PM_{2.5}$ emission parameter values were below the limits of detection, so the data point is located on the left side of the chart off the scale for $PM_{2.5}$ Emission, but on the scale for CO Emission for comparison with data from previously tested stoves. The $PM_{2.5}$ limit of detection values are included in Table 3.

CO versus $PM_{2.5}$ indoor emission rates during high-power phases of the WBT are shown in Figure 7.

CO versus $PM_{2.5}$ indoor emission rates during low-power are shown in Figure 8. For the CleanCook stove, the average $PM_{2.5}$ emission parameter values were below the limits of detection, so the data point is located on the left side of the chart off the scale for $PM_{2.5}$ Indoor Emission Rate, but on the scale for CO Indoor Emission Rate for comparison with data for previously tested stoves.

Tabulated data for the CleanCook with alcohol 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 (14). 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). Reasons for rejection of data are included in notes preceding Tables 1-4 and accompanying Tables 5-6.

OC and EC particulate emissions are reported in Table 4.

BC emissions are reported in Table 5.

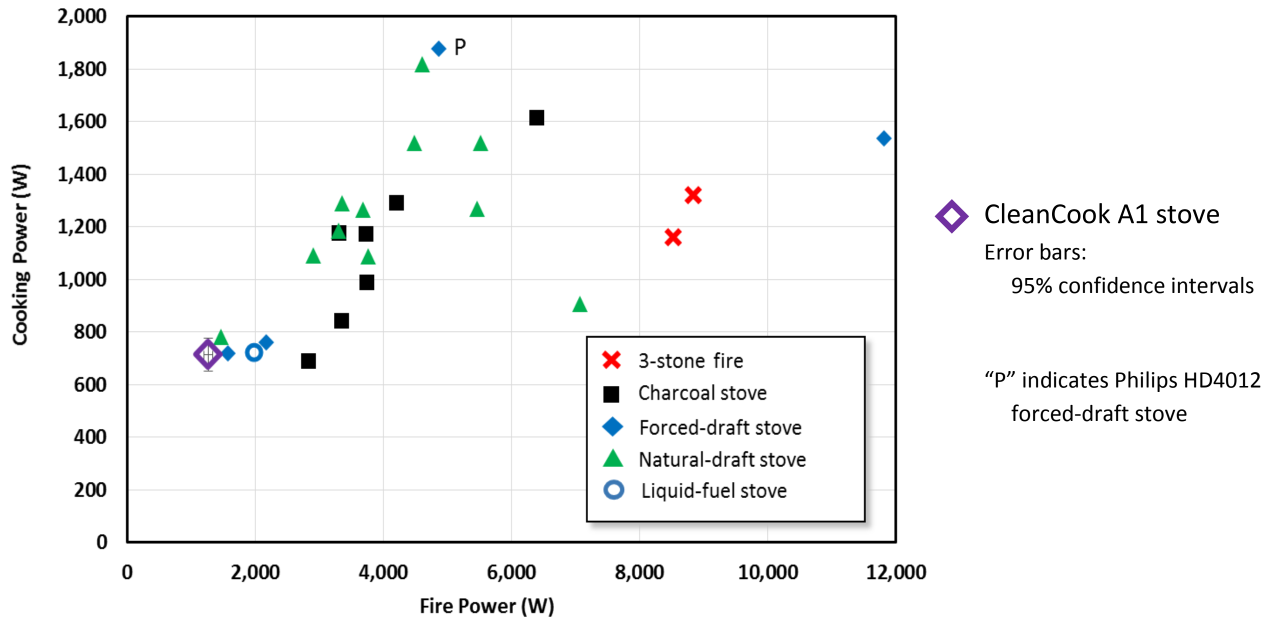

Figure 2. *Cooking power versus fire power during high-power*

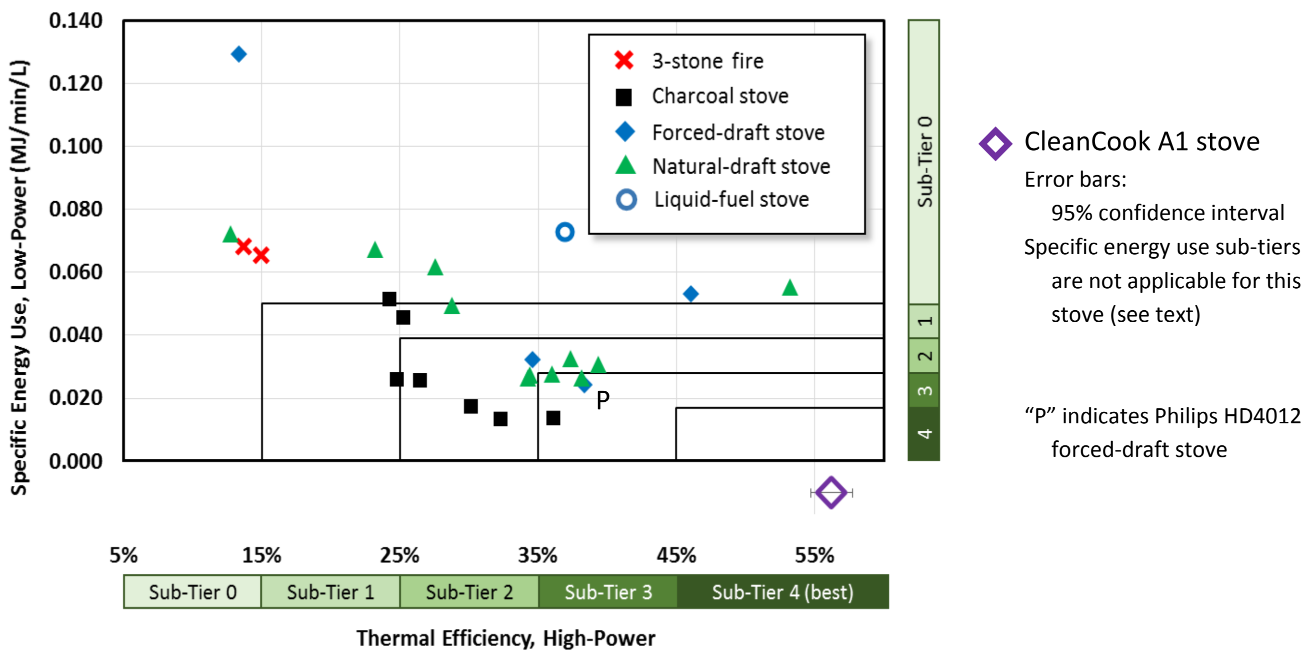

Figure 3. *Specific energy use during low-power versus thermal efficiency during high-power*

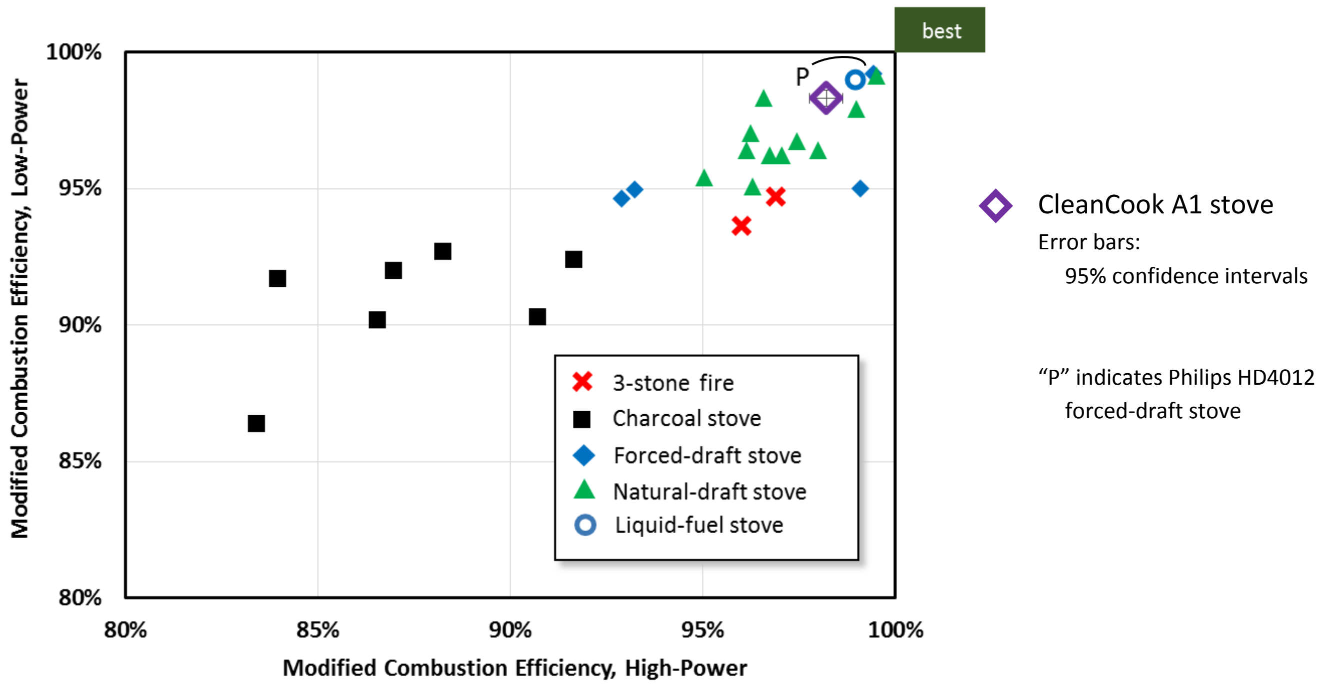

__Figure 4.__ Modified combustion efficiency, low-power versus high-power

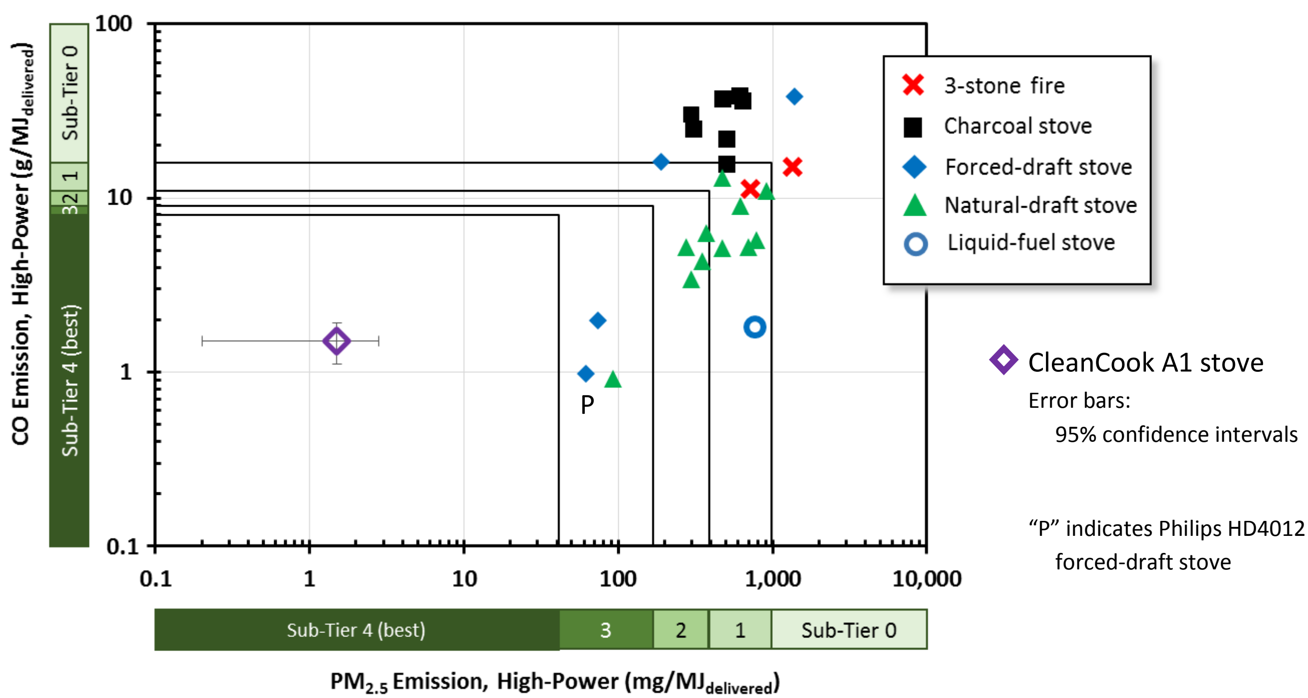

__Figure 5.__ CO versus $PM_{2.5}$ emissions per useful energy delivered to water in the cooking pot during high-power

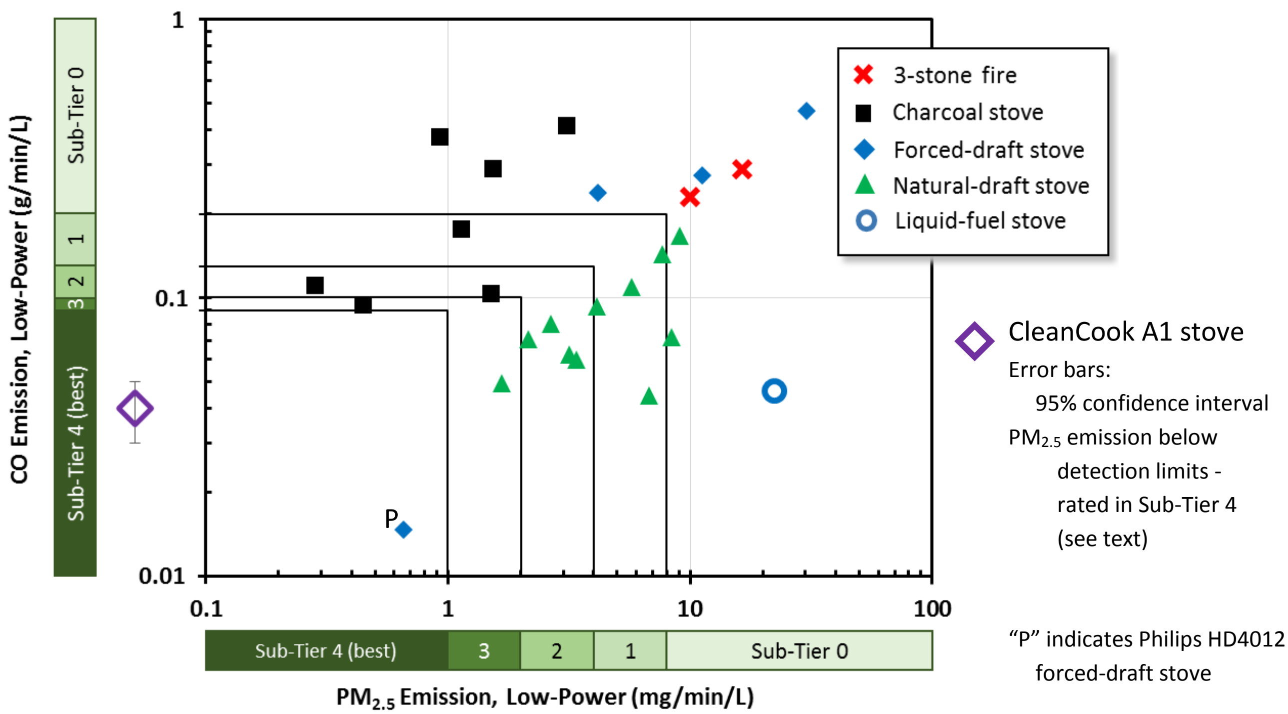

Figure 6. *CO versus $PM_{2.5}$ emissions per liter of water simmered per minute during low-power*

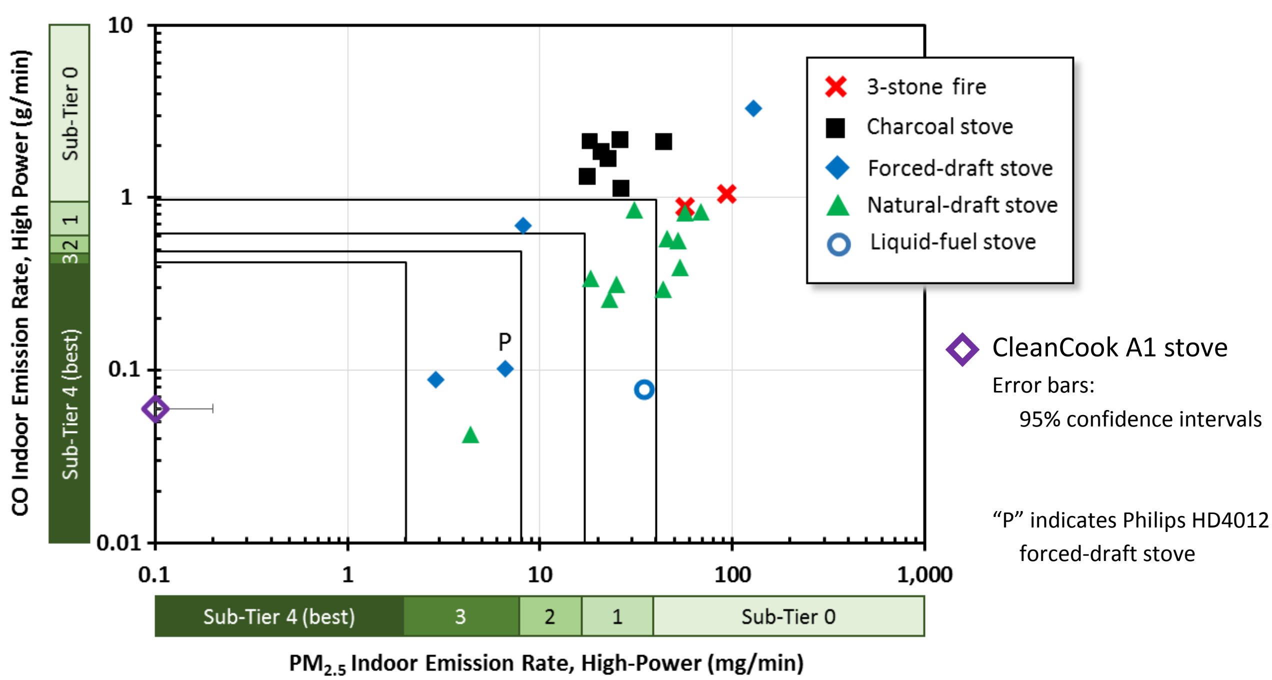

Figure 7. *CO versus $PM_{2.5}$ indoor emission rates during high-power*

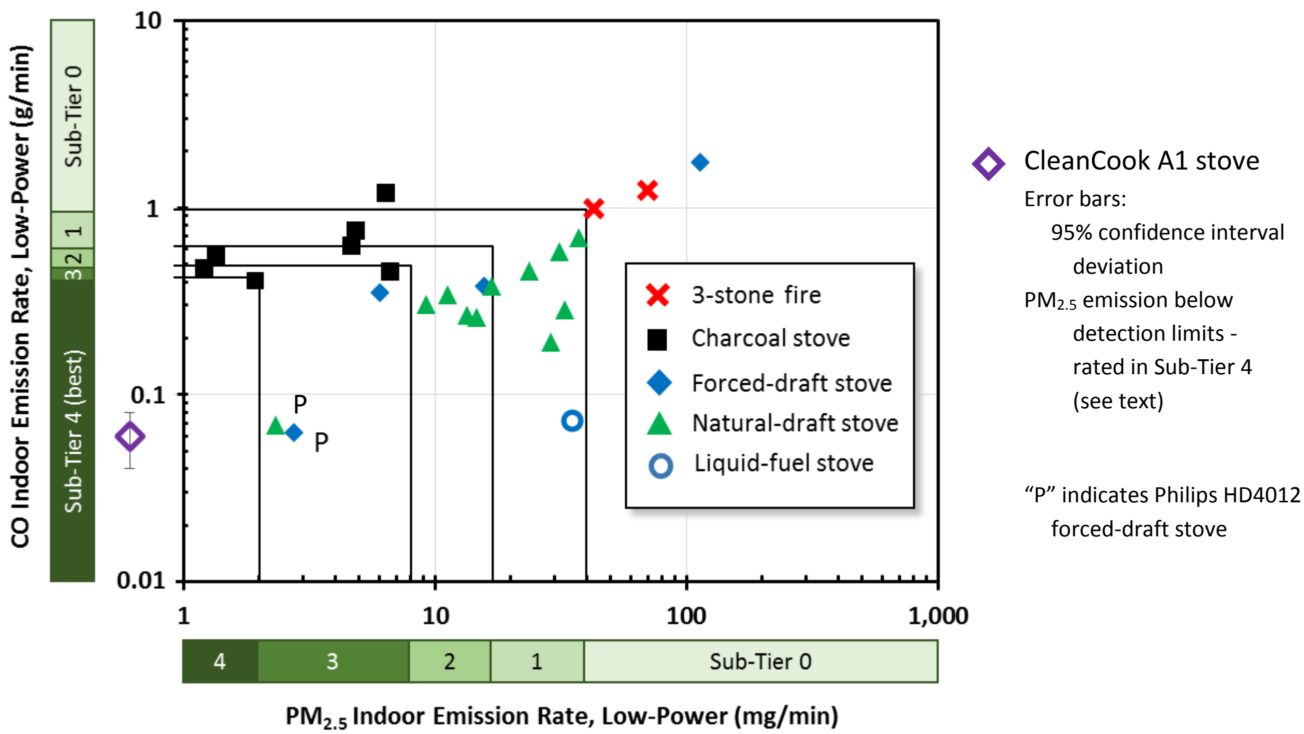

Figure 8. *CO versus $PM_{2.5}$ indoor emission rates during low-power*

Discussion of Results and Observations

As reported in the Results Summary, the Dometic CleanCook A1's cooking power was 712 W (average of cold-start and hot-start test phases of the WBT). Also reported in the Summary, the fuel burning rate for the low-power simmer phase was only slightly lower than the burning rate at high-power. The fuel burning rate could be turned down lower if the control was very carefully adjusted, but in daylight or in lighted room conditions, the alcohol flame was difficult to adjust because it was almost invisible, and the control lever had a narrow range of movement between nearly full power and extinguishing the flame. When the stove was operated at high power, the stove body and fuel tank warmed up – increasing the evaporation rate of the fuel. If the control was then adjusted for a lower power level with the warm stove, the power continued to decrease over time as the stove cooled down and the fuel evaporation rate decreased.

If the CleanCook is operated in a dark or dimly lit area, then the flame is more visible, and the cooking power is easier to adjust. The shape of the flame is best centered on the pot when the stove is level. The flame is usually blue in color, except a yellow flame was observed when the fuel tank was nearly empty.

As fuel evaporates, it provides evaporative cooling of the fuel canister. When the fuel canister is nearly empty, evaporative cooling diminishes, and the fuel tank becomes hotter.

As shown in Figure 2, cooking power for the CleanCook was low compared to many of the other stoves tested, and fire power for the CleanCook was very low because of the stove's relatively high thermal efficiency. Due to the low cooking power, five liters of water in a standard seven-liter pot with no lid could not be heated to the boiling temperature, so the CleanCook was tested with two liters of water in a standard three-liter pot. Since low-power specific energy use is not applicable for stoves tested with less than five liters of water, as discussed above, the data point shown in Figure 3 for the CleanCook stove is shown off the low-power scale but on the correct scale for high-power thermal efficiency. The CleanCook is rated at Sub-Tier 4 for Thermal Efficiency, and thermal efficiency for the CleanCook was higher than for stoves previously tested, as shown in Figure 3.

MCE was approximately 98% at both low- and high-power, as shown in Figure 4 – not quite as good as a pressurized liquid-fuel stove, one forced-draft solid-fuel stove, and one natural-draft solid-fuel stove previously tested. The CleanCook's evaporative burner has the advantage of simplicity, but some other types of burners may have provided better mixing of air and combustion gases, resulting in greater MCE, as shown in the figure.

The CleanCook is rated at Tier 4 for Emissions, as shown in the Results Summary, with all Sub-Tier 4 ratings, per the IWA. As shown in Figures 5 and 6, CO emissions were similar to some previously tested stoves, but $PM_{2.5}$ emissions were much lower than previously tested stoves. In Figure 6, the data point for the CleanCook stove is shown off the scale for low-power $PM_{2.5}$ emissions, because emissions were less than 0.02 milligrams (mg)/min/L – the limit of detection for the specific emission rate for this stove.

The CleanCook is also rated at Tier 4 for Indoor Emissions, as shown in the Results Summary, with all Sub-Tier 4 ratings, per the IWA. Indoor Emissions Tiers are based on emission rates (pollutant mass per time) into the household space. A stove with an effective chimney could have relatively high Total Emissions (low Tier rating) but low Indoor Emissions (high Tier rating). The CleanCook does not have a chimney, but the stove is rated at Tier 4 due to low emissions. Emission rates during high-power for the CleanCook, as shown in Figure 7, were similar to emission rates for other low-emission stoves for CO and were much lower than other emission rates for $PM_{2.5}$. In Figure 8, the data point for the CleanCook stove is shown off the scale for low-power $PM_{2.5}$ emissions, because emissions were less than 0.03 mg/min – the limit of detection for the emission rate for this stove.

Particulate OC and EC were analyzed, but measurements for all test replicates were below the detection limit values shown in Table 4.

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. 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. Particulate BC was analyzed with the aethalometer, but measurements for all test replicates were below the detection limit values shown in Table 5.

Average cooking power was slightly greater during the hot-start test phase (see Table 2) than during the cold-start (Table 1), because the fuel evaporation rate increased after the stove body and fuel tank warmed up.

Real-time data for a typical test sequence are shown in Figure 9. Data are shown for pollutant concentrations measured in the dilution tunnel, and the pot water temperature indicates the three phases of the WBT protocol sequence. Concentrations were remarkably consistent over time compared to the fluctuating concentrations typically observed when testing most solid-fuel stoves. CO_2 concentration indicates the rate of fuel consumption. CO and THC concentrations were clearly above background levels (measured before and after the test), while CH_4 and NO_X concentrations were only slightly above background levels. THC concentrations increased between test phases when the flame was extinguished due to evaporative emissions of the alcohol fuel. THC emission rates (reported as propane (C_3H_8), but composition is unknown) during combustion (averaged over all tests) were approximately 0.3 g/h, but peak emission rates due to evaporation were approximately 10 g/h.

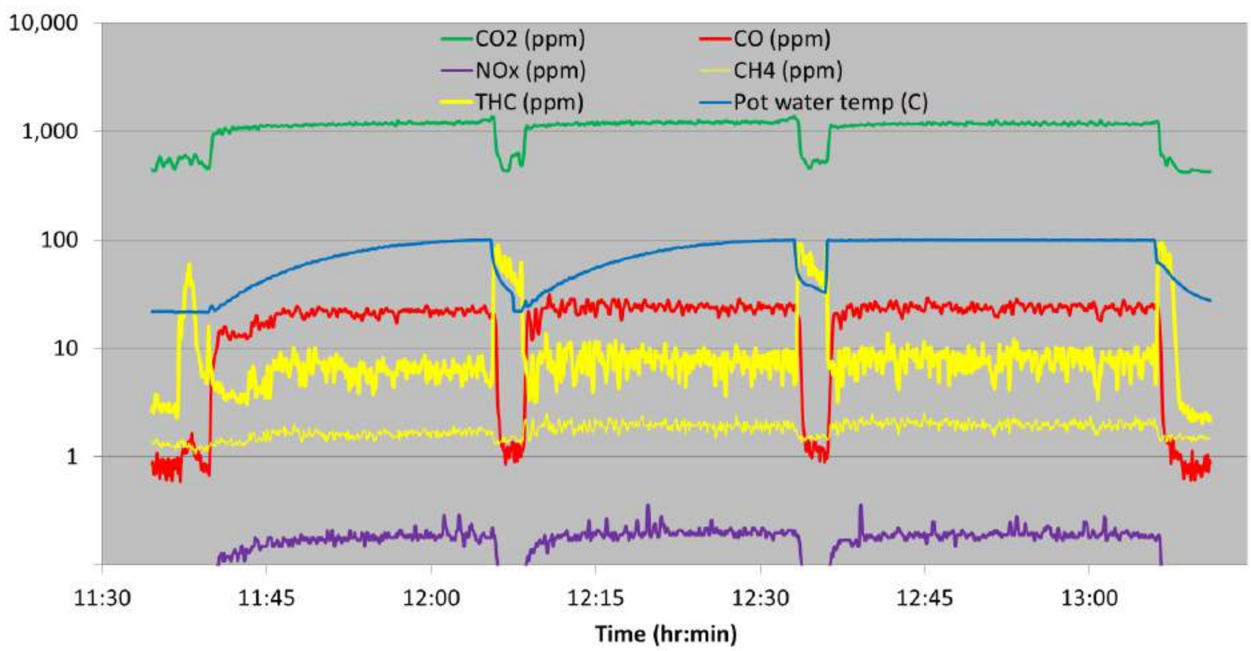

Figure 9. *Real-time data for a typical test sequence*

The CleanCook performed without any problems during testing, and the stove was simple to operate. Dometic has experience developing successful stoves for the marine market, and the CleanCook has a high-quality manufactured appearance. For more information, see the Dometic web site (14) and the CleanCook web site (15).

Quality Assurance/Quality Control

A Quality Assurance Project Plan meeting EPA requirements (16) 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" (17).

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 7. Measurement uncertainties for both emissions and fuel are reflected in the carbon-balance results. Consistently negative values in Table 7 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 or any other measurement quality objectives were unacceptable.

The carbon balance is an overall indicator of many of the critical measurements included as measurement quality objectives listed in Table 7. 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

On the following pages are tabulated data and information, as described above.

Table 1 notes:

[1] Test 1 rejected due to carbon balance out of limits
[2] Value was less than the limit of detection
[3] CO_2 concentration measurement failed acceptance criteria
[4] CH_4 analyzer malfunctioned
[5] NO_X concentration measurement failed acceptance criteria

Table 2 notes:

[1] Test 8 interrupted by a fire drill
[2] Value was less than the limit of detection
[3] CO_2 concentration measurement failed acceptance criteria
[4] NO_X concentration measurement failed acceptance criteria

Table 3 notes:

[1] Test 1 rejected due to carbon balance out of limits
[2] Test 8 interrupted by a fire drill
[3] Average value was less than the average limit of detection
[4] Not applicable because the average value was less than the average limit of detection
[5] Value was less than the limit of detection
[6] CO_2 concentration measurement failed acceptance criteria
[7] NO_X concentration measurement failed acceptance criteria

Table 4 notes:

[1] For all test replicates, values were less than limits of detection

Table 1. *High-power cold-start – WBT and pollutant emission parameters*

Parameter	Units	Average	SD	Test 2[1]	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Fuel consumed	g	90.3	8.4	91.9	79.9	103.8	94.1	96.5	83.3	80.4	92.5
Time to boil 2 liters of water, 25 to 100°C	min	24.38	4.39	23.21	20.00	32.25	25.21	28.68	20.62	20.04	25.00
Thermal efficiency	%	56.3	1.6	57.8	57.8	54.5	55.0	54.6	57.9	57.7	55.0
Fuel burning rate	g/min	3.6	0.3	3.8	3.9	3.1	3.6	3.3	3.9	3.8	3.6
Temperature-corrected specific fuel consumption	g/liter	48.0	5.6	49.1	41.6	56.6	50.0	53.2	43.1	41.2	49.0
Temperature-corrected specific energy use	kJ/liter	978	114	1001	848	1154	1019	1084	878	839	998
Fire power	W	1227	98	1291	1313	1050	1216	1120	1311	1303	1210
Cooking power	W	692	73	747	759	572	669	611	759	751	665
Modified combustion efficiency	%	98.2	0.4	98.2	98.6	97.8	98.4	98.3	98.8	98.1	97.5
$PM_{2.5}$ temperature-corrected total mass	mg	1.8	2.0	< 1.1[2]	< 1.0[2]	1.5	4.9	3.4	< 1.3[2]	3.9	< 1.1[2]
mass per effective volume of water boiled	mg/liter	1.0	1.1	< 0.6[2]	< 0.6[2]	0.8	2.7	1.9	< 0.7[2]	2.1	< 0.6[2]
mass per fuel mass	mg/kg	20.5	22.9	< 12.6[2]	< 13.3[2]	14.7	53.9	36.2	< 15.8[2]	50.3	< 12.1[2]
mass per fuel energy	mg/MJ	1.0	1.1	< 0.6[2]	< 0.7[2]	0.7	2.6	1.8	< 0.8[2]	2.5	< 0.6[2]
mass per useful energy delivered (to water in pot)	mg/MJ	1.8	2.0	< 1.1[2]	< 1.1[2]	1.3	4.8	3.3	< 1.3[2]	4.3	< 1.1[2]
mass per time	mg/hour	4.4	5.0	< 2.9[2]	< 3.1[2]	2.7	11.6	7.2	< 3.7[2]	11.6	< 2.6[2]
CO temperature-corrected total mass	g	1.46	0.47	1.46	0.94	2.14	1.33	1.47	0.89	1.35	2.13
mass per effective volume of water boiled	g/liter	0.81	0.27	0.81	0.50	1.22	0.74	0.83	0.48	0.72	1.17
mass per fuel mass	g/kg	16.64	4.37	16.50	12.13	21.47	14.73	15.57	11.13	17.59	23.96
mass per fuel energy	g/MJ	0.82	0.21	0.81	0.60	1.05	0.72	0.76	0.55	0.86	1.18
mass per useful energy delivered (to water in pot)	g/MJ	1.46	0.41	1.40	1.03	1.93	1.31	1.40	0.94	1.50	2.14
mass per time	g/hour	3.57	0.83	3.77	2.81	3.98	3.16	3.08	2.58	4.05	5.12
CO_2 temperature-corrected total mass	g	124	15	n.a.[3]	106	148	129	135	112	110	129
mass per effective volume of water boiled	g/liter	68	10	n.a.[3]	57	84	72	76	61	59	71
mass per fuel mass	g/kg	1430	33	n.a.[3]	1374	1480	1430	1429	1411	1436	1448
mass per fuel energy	g/MJ	70	2	n.a.[3]	67	73	70	70	69	70	71
mass per useful energy delivered (to water in pot)	g/MJ	125	6	n.a.[3]	117	133	127	128	120	122	129
mass per time	g/hour	307	21	n.a.[3]	319	275	307	283	327	331	309
THC (as C_3H_8) temperature-corrected total mass	g	0.12	0.07	0.12	0.05	0.19	0.06	0.09	0.06	0.10	0.25
mass per effective volume of water boiled	g/liter	0.06	0.04	0.07	0.02	0.11	0.03	0.05	0.03	0.05	0.14
mass per fuel mass	g/kg	1.31	0.76	1.40	0.59	1.92	0.69	1.00	0.72	1.31	2.83
mass per fuel energy	g/MJ	0.06	0.04	0.07	0.03	0.09	0.03	0.05	0.04	0.06	0.14
mass per useful energy delivered (to water in pot)	g/MJ	0.11	0.07	0.12	0.05	0.17	0.06	0.09	0.06	0.11	0.25
mass per time	g/hour	0.28	0.16	0.32	0.14	0.36	0.15	0.20	0.17	0.30	0.61
CH_4 temperature-corrected total mass	g	0.02	0.01	0.03	0.01	0.04	n.a.[4]	n.a.[4]	0.01	0.02	0.03
mass per effective volume of water boiled	g/liter	0.01	0.01	0.02	0.01	0.02	n.a.[4]	n.a.[4]	0.01	0.01	0.02
mass per fuel mass	g/kg	0.26	0.09	0.31	0.17	0.38	n.a.[4]	n.a.[4]	0.16	0.21	0.31
mass per fuel energy	g/MJ	0.01	0.00	0.02	0.01	0.02	n.a.[4]	n.a.[4]	0.01	0.01	0.02
mass per useful energy delivered (to water in pot)	g/MJ	0.02	0.01	0.03	0.01	0.03	n.a.[4]	n.a.[4]	0.01	0.02	0.03
mass per time	g/hour	0.06	0.02	0.07	0.04	0.07	n.a.[4]	n.a.[4]	0.04	0.05	0.07
NO_X temperature-corrected total mass	g	0.01	0.00	n.a.[5]	0.01	0.02	0.01	0.01	0.01	0.01	0.01
mass per effective volume of water boiled	g/liter	0.01	0.00	n.a.[5]	0.01	0.01	0.01	0.01	0.01	0.01	0.01
mass per fuel mass	g/kg	0.15	0.02	n.a.[5]	0.15	0.16	0.16	0.13	0.18	0.16	0.16
mass per fuel energy	g/MJ	0.01	0.00	n.a.[5]	0.01	0.01	0.01	0.01	0.01	0.01	0.01
mass per useful energy delivered (to water in pot)	g/MJ	0.01	0.00	n.a.[5]	0.01	0.01	0.01	0.01	0.01	0.01	0.01
mass per time	g/hour	0.03	0.00	n.a.[5]	0.03	0.03	0.03	0.03	0.04	0.04	0.03

*See preceding notes.

Table 2. *High-power hot-start – WBT and pollutant emission parameters*

Parameter	Units	Average	SD	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 9[1]
Fuel consumed	g	91.4	8.9	81.8	80.9	86.0	107.0	97.2	95.8	87.2	95.1
Time to boil 2 liters of water, 25 to 100°C	min	23.42	3.75	19.83	19.19	21.10	29.28	25.54	27.41	20.77	24.24
Thermal efficiency	%	56.2	1.9	57.7	58.7	58.3	53.5	55.8	54.6	56.6	54.4
Fuel burning rate	g/min	3.8	0.2	4.0	4.1	4.0	3.6	3.7	3.5	4.1	3.8
Temperature-corrected specific fuel consumption	g/liter	49.5	6.2	42.2	42.7	46.2	59.9	53.7	53.8	46.3	51.2
Temperature-corrected specific energy use	kJ/liter	1009	126	859	869	942	1221	1093	1097	944	1043
Fire power	W	1301	75	1351	1389	1348	1211	1262	1177	1382	1293
Cooking power	W	732	64	779	815	786	648	704	643	782	703
Modified combustion efficiency	%	98.1	0.6	98.2	98.4	98.2	97.4	98.3	98.4	98.8	97.2
$PM_{2.5}$ temperature-corrected total mass	mg	1.1	2.5	< 1.3[2]	< 1.3[2]	7.2	1.9	< 1.1[2]	< 1.1[2]	< 1.3[2]	< 1.1[2]
mass per effective volume of water boiled	mg/liter	0.6	1.4	< 0.7[2]	< 0.7[2]	4.0	1.1	< 0.6[2]	< 0.6[2]	< 0.7[2]	< 0.6[2]
mass per fuel mass	mg/kg	13.1	30.3	< 16.0[2]	< 16.5[2]	86.5	18.1	< 11.5[2]	< 11.2[2]	< 15.2[2]	< 12.2[2]
mass per fuel energy	mg/MJ	0.6	1.5	< 0.8[2]	< 0.8[2]	4.2	0.9	< 0.6[2]	< 0.6[2]	< 0.7[2]	< 0.6[2]
mass per useful energy delivered (to water in pot)	mg/MJ	1.1	2.6	< 1.4[2]	< 1.4[2]	7.3	1.7	< 1.0[2]	< 1.0[2]	< 1.3[2]	< 1.1[2]
mass per time	mg/hour	3.1	7.2	< 3.8[2]	< 4.0[2]	20.6	3.9	< 2.6[2]	< 2.4[2]	< 3.7[2]	< 2.8[2]
CO temperature-corrected total mass	g	1.60	0.60	1.48	1.11	1.36	2.57	1.50	1.36	0.93	2.46
mass per effective volume of water boiled	g/liter	0.89	0.35	0.79	0.60	0.75	1.48	0.85	0.77	0.51	1.36
mass per fuel mass	g/kg	17.69	5.40	18.75	14.18	16.22	24.64	15.76	14.34	11.01	26.66
mass per fuel energy	g/MJ	0.87	0.26	0.92	0.70	0.80	1.21	0.77	0.70	0.54	1.31
mass per useful energy delivered (to water in pot)	g/MJ	1.56	0.51	1.60	1.19	1.37	2.26	1.39	1.29	0.95	2.41
mass per time	g/hour	4.04	1.16	4.48	3.48	3.86	5.27	3.51	2.98	2.69	6.09
CO_2 temperature-corrected total mass	g	129	12	123	n.a.[3]	114	149	138	132	116	132
mass per effective volume of water boiled	g/liter	72	8	66	n.a.[3]	63	85	78	75	63	73
mass per fuel mass	g/kg	1428	69	1564	n.a.[3]	1359	1425	1457	1393	1369	1429
mass per fuel energy	g/MJ	70	3	77	n.a.[3]	67	70	71	68	67	70
mass per useful energy delivered (to water in pot)	g/MJ	126	7	133	n.a.[3]	114	131	128	125	119	129
mass per time	g/hour	325	26	373	n.a.[3]	324	305	325	290	334	326
THC (as C_3H_8) temperature-corrected total mass	g	0.13	0.11	0.12	0.08	0.11	0.26	0.05	0.05	0.04	0.33
mass per effective volume of water boiled	g/liter	0.07	0.06	0.06	0.04	0.06	0.15	0.03	0.03	0.02	0.18
mass per fuel mass	g/kg	1.43	1.10	1.49	1.00	1.35	2.49	0.49	0.56	0.49	3.57
mass per fuel energy	g/MJ	0.07	0.05	0.07	0.05	0.07	0.12	0.02	0.03	0.02	0.18
mass per useful energy delivered (to water in pot)	g/MJ	0.13	0.10	0.13	0.08	0.11	0.23	0.04	0.05	0.04	0.32
mass per time	g/hour	0.33	0.25	0.36	0.24	0.32	0.53	0.11	0.12	0.12	0.82
CH_4 temperature-corrected total mass	g	0.03	0.01	0.03	0.03	0.04	0.05	0.02	0.01	0.01	0.04
mass per effective volume of water boiled	g/liter	0.01	0.01	0.01	0.02	0.02	0.03	0.01	0.01	0.00	0.02
mass per fuel mass	g/kg	0.29	0.14	0.34	0.36	0.43	0.44	0.18	0.12	0.10	0.39
mass per fuel energy	g/MJ	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.00	0.02
mass per useful energy delivered (to water in pot)	g/MJ	0.03	0.01	0.03	0.03	0.04	0.04	0.02	0.01	0.01	0.04
mass per time	g/hour	0.07	0.03	0.08	0.09	0.10	0.10	0.04	0.03	0.02	0.09
NO_X temperature-corrected total mass	g	0.02	0.00	0.02	n.a.[4]	0.02	0.02	0.02	0.01	0.01	0.02
mass per effective volume of water boiled	g/liter	0.01	0.00	0.01	n.a.[4]	0.01	0.01	0.01	0.01	0.01	0.01
mass per fuel mass	g/kg	0.19	0.05	0.29	n.a.[4]	0.24	0.18	0.16	0.15	0.16	0.17
mass per fuel energy	g/MJ	0.01	0.00	0.01	n.a.[4]	0.01	0.01	0.01	0.01	0.01	0.01
mass per useful energy delivered (to water in pot)	g/MJ	0.02	0.00	0.02	n.a.[4]	0.02	0.02	0.01	0.01	0.01	0.02
mass per time	g/hour	0.04	0.01	0.07	n.a.[4]	0.06	0.04	0.04	0.03	0.04	0.04

*See preceding notes.

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

Parameter	Units	Average	SD	Test 2[1]	Test 3	Test 4	Test 5	Test 6	Test 7	Test 9[2]
Fuel consumed	g	101.3	9.3	97.9	96.2	88.1	99.2	100.6	114.0	113.0
Fuel burning rate	g/min	3.4	0.3	3.3	3.2	2.9	3.3	3.3	3.8	3.8
Specific fuel consumption	g/liter	76.5	8.5	71.8	71.3	65.7	75.4	75.3	88.0	88.0
Specific energy use	kJ/liter	1559	173	1463	1454	1338	1536	1535	1794	1794
Fire power	W	1145	104	1108	1089	997	1120	1135	1287	1278
Modified combustion efficiency	%	98.2	0.6	98.4	98.0	98.0	98.7	98.6	98.6	97.1
$PM_{2.5}$ total mass	mg	< 0.9[3]	n.a.[4]	< 0.9[5]	< 0.7[5]	2.2	< 0.9[5]	< 0.9[5]	< 0.9[5]	< 0.9[5]
mass per volume of water remaining	mg/liter	< 0.7[3]	n.a.[4]	< 0.7[5]	< 0.6[5]	1.7	< 0.7[5]	< 0.7[5]	< 0.7[5]	< 0.7[5]
mass per fuel mass	mg/kg	< 9.0[3]	n.a.[4]	< 9.3[5]	< 7.8[5]	25.2	< 9.5[5]	< 9.4[5]	< 8.3[5]	< 8.3[5]
mass per fuel energy	mg/MJ	< 0.4[3]	n.a.[4]	< 0.5[5]	< 0.4[5]	1.2	< 0.5[5]	< 0.5[5]	< 0.4[5]	< 0.4[5]
mass per time	mg/hour	< 1.8[3]	n.a.[4]	< 1.8[5]	< 1.5[5]	4.4	< 1.9[5]	< 1.9[5]	< 1.9[5]	< 1.9[5]
CO total mass	g	1.70	1.61	1.46	1.74	1.74	1.26	1.27	1.40	3.00
mass per volume of water remaining	g/liter	1.28	0.49	1.07	1.29	1.30	0.96	0.95	1.08	2.34
mass per fuel mass	g/kg	16.70	5.22	14.93	18.04	19.77	12.69	12.61	12.30	26.54
mass per fuel energy	g/MJ	0.82	0.26	0.73	0.89	0.97	0.62	0.62	0.60	1.30
mass per time	g/hour	3.39	1.22	2.92	3.47	3.48	2.51	2.53	2.80	5.99
CO_2 total mass	g	145	11	n.a.[6]	134	137	146	137	159	156
mass per volume of water remaining	g/liter	110	10	n.a.[6]	99	102	111	102	123	121
mass per fuel mass	g/kg	1426	74	n.a.[6]	1393	1557	1467	1360	1396	1380
mass per fuel energy	g/MJ	70	4	n.a.[6]	68	76	72	67	69	68
mass per time	g/hour	289	21	n.a.[6]	268	274	290	273	318	311
THC (as C_3H_8) total mass	g	0.14	0.13	0.08	0.15	0.12	0.07	0.06	0.10	0.42
mass per volume of water remaining	g/liter	0.11	0.10	0.06	0.11	0.09	0.05	0.04	0.07	0.32
mass per fuel mass	g/kg	1.34	1.09	0.79	1.52	1.32	0.68	0.57	0.84	3.68
mass per fuel energy	g/MJ	0.07	0.05	0.04	0.07	0.06	0.03	0.03	0.04	0.18
mass per time	g/hour	0.28	0.25	0.15	0.29	0.23	0.14	0.11	0.19	0.83
CH_4 total mass	g	0.03	0.02	0.05	0.05	0.03	0.02	0.01	0.02	0.05
mass per volume of water remaining	g/liter	0.02	0.01	0.04	0.03	0.02	0.01	0.01	0.01	0.04
mass per fuel mass	g/kg	0.33	0.17	0.53	0.47	0.37	0.17	0.15	0.15	0.44
mass per fuel energy	g/MJ	0.02	0.01	0.03	0.02	0.02	0.01	0.01	0.01	0.02
mass per time	g/hour	0.07	0.03	0.10	0.09	0.07	0.03	0.03	0.03	0.10
NO_x total mass	g	0.02	0.00	n.a.[7]	0.03	0.02	0.02	0.02	0.02	0.02
mass per volume of water remaining	g/liter	0.01	0.00	n.a.[7]	0.02	0.01	0.01	0.01	0.01	0.01
mass per fuel mass	g/kg	0.18	0.05	n.a.[7]	0.28	0.20	0.16	0.15	0.15	0.16
mass per fuel energy	g/MJ	0.01	0.00	n.a.[7]	0.01	0.01	0.01	0.01	0.01	0.01
mass per time	g/hour	0.04	0.01	n.a.[7]	0.05	0.04	0.03	0.03	0.03	0.04

*See preceding notes.

Table 4. Emissions of OC (organic carbon) and EC (elemental carbon)

Parameter	Units	Average[1]
High-power cold-start		
OC temperature-corrected total mass	mg	< 0.9
mass per effective volume of water boiled	mg/liter	< 0.5
mass per fuel mass	mg/kg	< 9.8
mass per fuel energy	mg/MJ	< 0.5
mass per useful energy delivered (to water in pot)	mg/MJ	< 0.9
mass per time	mg/hour	< 2.1
EC temperature-corrected total mass	mg	< 0.9
mass per effective volume of water boiled	mg/liter	< 0.5
mass per fuel mass	mg/kg	< 9.8
mass per fuel energy	mg/MJ	< 0.5
mass per useful energy delivered (to water in pot)	mg/MJ	< 0.9
mass per time	mg/hour	< 2.1
High-power hot-start		
OC temperature-corrected total mass	mg	< 0.9
mass per effective volume of water boiled	mg/liter	< 0.5
mass per fuel mass	mg/kg	< 9.9
mass per fuel energy	mg/MJ	< 0.5
mass per useful energy delivered (to water in pot)	mg/MJ	< 0.9
mass per time	mg/hour	< 2.3
EC temperature-corrected total mass	mg	< 0.9
mass per effective volume of water boiled	mg/liter	< 0.5
mass per fuel mass	mg/kg	< 9.9
mass per fuel energy	mg/MJ	< 0.5
mass per useful energy delivered (to water in pot)	mg/MJ	< 0.9
mass per time	mg/hour	< 2.3
Low-power (30-minute simmer)		
OC total mass	mg	< 0.9
mass per volume of water remaining	mg/liter	< 0.7
mass per fuel mass	mg/kg	< 8.9
mass per fuel energy	mg/MJ	< 0.4
mass per time	mg/hour	< 1.8
EC total mass	mg	< 0.9
mass per volume of water remaining	mg/liter	< 0.7
mass per fuel mass	mg/kg	< 8.9
mass per fuel energy	mg/MJ	< 0.4
mass per time	mg/hour	< 1.8

[1] For all test replicates, values were less than limits of detection

Table 5. Emissions of BC (black carbon) measured with aethalometer

Parameter	Units	Average[1]
High-power cold-start		
BC temperature-corrected total mass	mg	< 0.6
mass per effective volume of water boiled	mg/liter	< 0.3
mass per fuel mass	mg/kg	< 7.2
mass per fuel energy	mg/MJ	< 0.4
mass per useful energy delivered (to water in pot)	mg/MJ	< 0.6
mass per time	mg/hour	< 1.5
High-power hot-start		
BC temperature-corrected total mass	mg	< 0.6
mass per effective volume of water boiled	mg/liter	< 0.3
mass per fuel mass	mg/kg	< 6.7
mass per fuel energy	mg/MJ	< 0.3
mass per useful energy delivered (to water in pot)	mg/MJ	< 0.6
mass per time	mg/hour	< 1.5
Low-power (30-minute simmer)		
BC total mass	mg	< 0.8
mass per volume of water remaining	mg/liter	< 0.6
mass per fuel mass	mg/kg	< 7.6
mass per fuel energy	mg/MJ	< 0.4
mass per time	mg/hour	< 1.5

[1] For all test replicates, values were less than limits of detection

Table 6. *Carbon balance, percent difference based on fuel carbon*

Test phase	Units	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
		08/24/12	08/28/12	09/04/12	03/14/14	10/16/14	10/17/14	10/20/14	10/22/14	10/22/14
High-power cold-start	%	n.a.[1]	-8.3	-4.8	-14.1	-9.3	-9.4	-7.5	-10.2	-12.2
High-power hot-start	%	-20.0	-6.6	-4.3	-10.5	-11.4	-6.4	-4.2	n.a.[2]	-11.3
Low-power (simmer)	%	n.a.[1]	-7.5	-7.1	-19.6	-11.9	-3.7	-6.5	n.a.[2]	-7.6

[1] Test phase rejected due to carbon balance out of limits

[2] Test 8 interrupted by a fire drill

Table 7. *Measurement quality objectives for critical measurements*

All data included in this report were based on measurements that met or exceeded these objectives.

Measurement	Reference	Indicators	Acceptance Criteria
Water and Fuel Mass, Electronic Balance	EPA RTP[5] Met Lab[3] SOP[4], 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[1] D5865-04	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
SMPS[6] sample flow rate	EPA RTP Met Lab SOP, FV-0205.3	Flow cal., Classifier Flow cal., CPC[2]	± 1% of target ± 10% target
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

[1]American Society for Testing and Materials (now known as ASTM International.
[2]Condensation particle counter
[3]Metrology Laboratory
[4]Standard Operating Procedure
[5]Research Triangle Park
[6]Scanning mobility particle sizer

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