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Test Report

BioLite™ HomeStove™ with Wood 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 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 (International Organization for Standardization) 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 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). The WBT protocol specifies that the stove is 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 ISO IWA 11:2012 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. 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 3 & 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.

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 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	**BioLite™** New York, NY, USA **HomeStove™** H504T3-01
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, average moisture content 8.4%, dimensions: 2 x 2 x 36 cm
Pot Used	Standard flat-bottom 7L pot with 5L of water, with pot skirt

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	**2**	High Power Thermal Efficiency	33	%	2
		Low Power Specific Energy Use	0.027	MJ / (min L)	3
Total Emissions					
Tier	**3**	High Power CO	1.0	g / $MJ_{delivered}$	4
		Low Power CO	0.07	g / (min L)	4
		High Power $PM_{2.5}$	155	mg / $MJ_{delivered}$	3
		Low Power $PM_{2.5}$	1.4	mg / (min L)	3
Indoor Emissions					
Tier	**2**	High Power CO	0.07	g / min	4
		Low Power CO	0.28	g / min	4
		High Power $PM_{2.5}$	12.3	mg / min	2
		Low Power $PM_{2.5}$	6.0	mg / min	3

Tiers 0 → 4 (best)

	Value	Unit
Cooking Power (average of Cold Start and Hot Start phases)	1313	W
Fuel burning rate (average for Cold Start, based on equivalent dry fuel consumed)	11.7	g / min
Fuel burning rate (average for Hot Start, based on equivalent dry fuel consumed)	14.3	g / min
Fuel burning rate (average for Simmer, based on equivalent dry fuel consumed)	6.4	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
CPC	condensation particle counter
EC	elemental carbon
EPA	Environmental Protection Agency
g	gram
HEPA	high-efficiency particulate air
ISO	International Organization for Standardization
IWA	International Workshop Agreement
kg	kilogram
kJ	kilojoule
L	liter
MCE	modified combustion efficiency
Met Lab	Metrology Laboratory
mg	milligram
min	minute
MJ	megajoule
$MJ_{delivered}$	megajoule of useful energy delivered
mm	millimeter
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
RTP	Research Triangle Park
SD	standard deviation
SMPS	Scanning Mobility Particle Sizer
SOP	Standard Operating Procedure
TC	Technical Committee
TC	total carbon
THC	total hydrocarbon
W	Watt
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:

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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. The HomeStove, shown in Figure 1, was developed by BioLite, New York, NY, USA, and is manufactured in China. The stove is designed for dissemination in the developing world.

Type of stove. The HomeStove is a forced-draft (fan) type of stove, and it may also be classified as a rocket-type stove. If the fan fails, then the stove will operate as a natural-draft rocket stove, albeit at a lower level of performance. A thermoelectric generator, powered by the heat from combustion, provides electrical power to the fan and may be used as an auxiliary source of electricity for low-power applications such as charging a mobile device (e.g., cellular phone) or operating a light emitting diode (LED). The stove is designed to burn wood fuel sticks that are manually fed into an opening in the lower front of the stove. The fan operates automatically with no user controls and no rechargeable battery.

Construction materials. The base, lower combustion chamber, and top are constructed of cast iron. The outer shell and upper combustion chamber are stainless steel. A molded polymer housing located on the back side of the stove contains the fan and electronics. Total weight of the stove is 8.3 kg.

Dimensions.
Height (not including pot skirt): 30.4 cm
Height (including pot skirt): 38.1 cm
Outside diameter of base: 27.5 cm
Outside diameter of top: 27.5 cm
Fuel/air inlet opening: 12 cm wide x 9.5 cm high
Inside diameter of upper combustion chamber: 7.7 cm

Figure 1. *BioLite HomeStove with pot skirt*

Accessories. An adjustable pot skirt was supplied with the stove, and the stove was tested with the skirt. Pot skirts tend to improve performance by enhancing heat transfer from the combustion gases to the cooking pot. Performance may vary if the stove is used without the skirt.

Cooking pot. A default standard flat-bottomed pot was used for the tests. This pot has a weight of approximately 815 grams. Full capacity is approximately 7 liters, and the pot is used with 5 liters of water for the tests. Material is stainless steel. Outside diameter of the rolled edge at the top of the pot is 257 mm, and inside diameter of the pot at the top is 244 mm. Outside diameter at the bottom is 243 mm. Height (not including handles) is 162 mm. The pot was obtained from the CICCI company (Copenhagen, Denmark) that provides supplies for emergency relief and development projects around the world. 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 long for low-moisture fuel and dimensions of 1 cm x 2 cm x 36 cm long for high-moisture fuel. 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. At the time of testing, a manual was not available for the stove, but manufacturer representatives demonstrated its operation for the EPA testing team. During tests, fuelwood sticks were manually fed into the stove at a consistent burning rate, as reported in the results section.

Cost. The manufacturer declined to share this information.

Quantity disseminated. The manufacturer declined to share this information.

Lifetime. Expected typical lifetime is five years, according to the manufacturer. 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). 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 HEPA-filtered dilution air. Gaseous air pollutants were sampled from the primary dilution tunnel, and particulates were sampled from the secondary tunnel. The WBT protocol specifies that the stove is 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 for Low-Moisture Fuel

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

BioLite HomeStove test results are compared with previously published results (11) in Figures 2-8. Key indicators of performance shown in the figures are described in Jetter et al. 2012 (11). Error bars on the data points for the HomeStove indicate ± one standard deviation. 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 (11). Data points (blue diamonds indicated by the letter "P") are indicated for the Philips HD4012 stove for comparison, because it is a well-known and relatively high-performing forced-draft stove. Data points for other stoves with previously published results are not identified in Figures 2-8, but stoves are identified in the journal article (11). All data shown in the figures are for stoves tested with low-moisture fuels, as described in the published results (11).

Figure 2 shows cooking power versus fire power (in units of measurement of Watts) during 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" (11). The ratio of cooking power to fire power is thermal efficiency – shown in Figure 3.

Figure 3 shows 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). These metrics are used to determine IWA Tier ratings, and the IWA Sub-Tiers are indicated in the figure.

Figure 4 shows low-power versus high-power MCE (modified combustion efficiency). 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.

Figure 5 shows CO (carbon monoxide) versus $PM_{2.5}$ (particulate matter with an aerodynamic diameter ≤ 2.5 micrometers) emissions per useful energy delivered to the water in the cooking pot during high-power phases of the WBT. 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.

Figure 6 shows CO versus $PM_{2.5}$ emissions per minute per liter of water simmered during the low-power phase of the WBT. Useful cooking energy is not accurately measured during the low-power test phase of the WBT (11), therefore the specific emission rate is used as the metric, per the IWA.

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

Figure 8 shows CO versus $PM_{2.5}$ indoor emission rates during the low-power phase of the WBT.

Tabulated data for the BioLite HomeStove with low-moisture fuel, including data for test replicates, are shown in Tables 1-3. The tables include data for parameters of the Water Boiling Test (8) and of emissions of $PM_{2.5}$ and gaseous air pollutants, as described in Jetter et al. 2012 (11). 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).

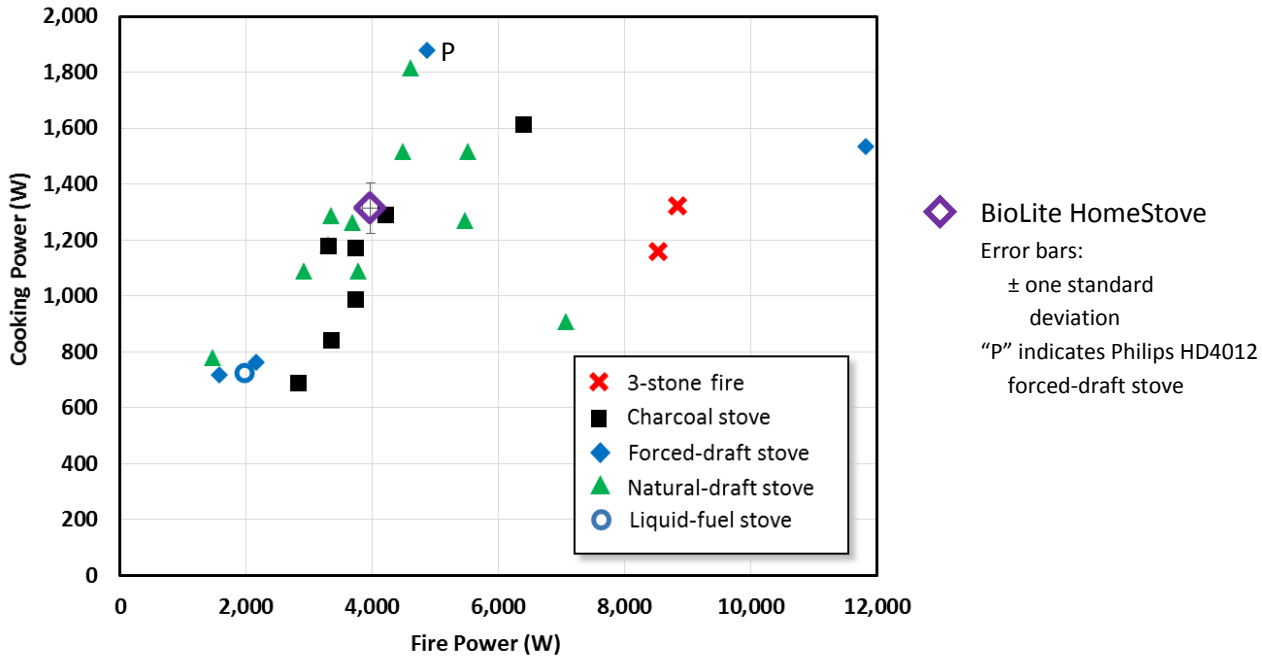

Figure 2. *Cooking power versus fire power during high-power*

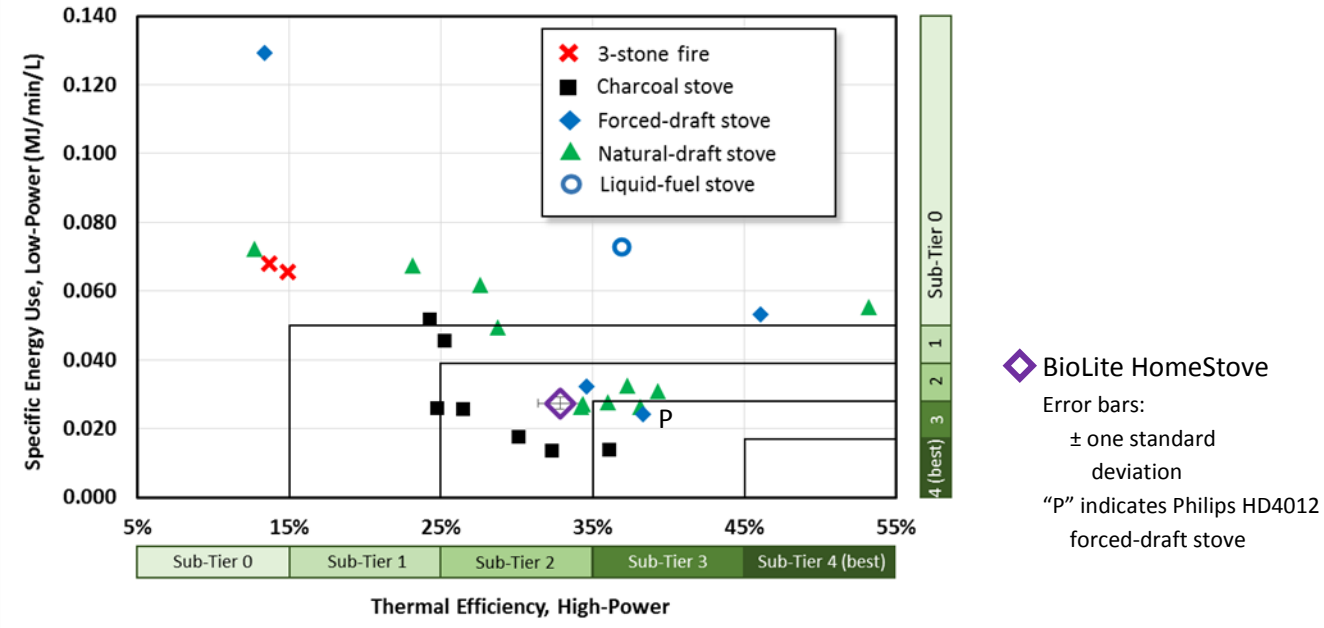

Figure 3. *Specific energy consumption during low-power versus thermal efficiency during high-power*

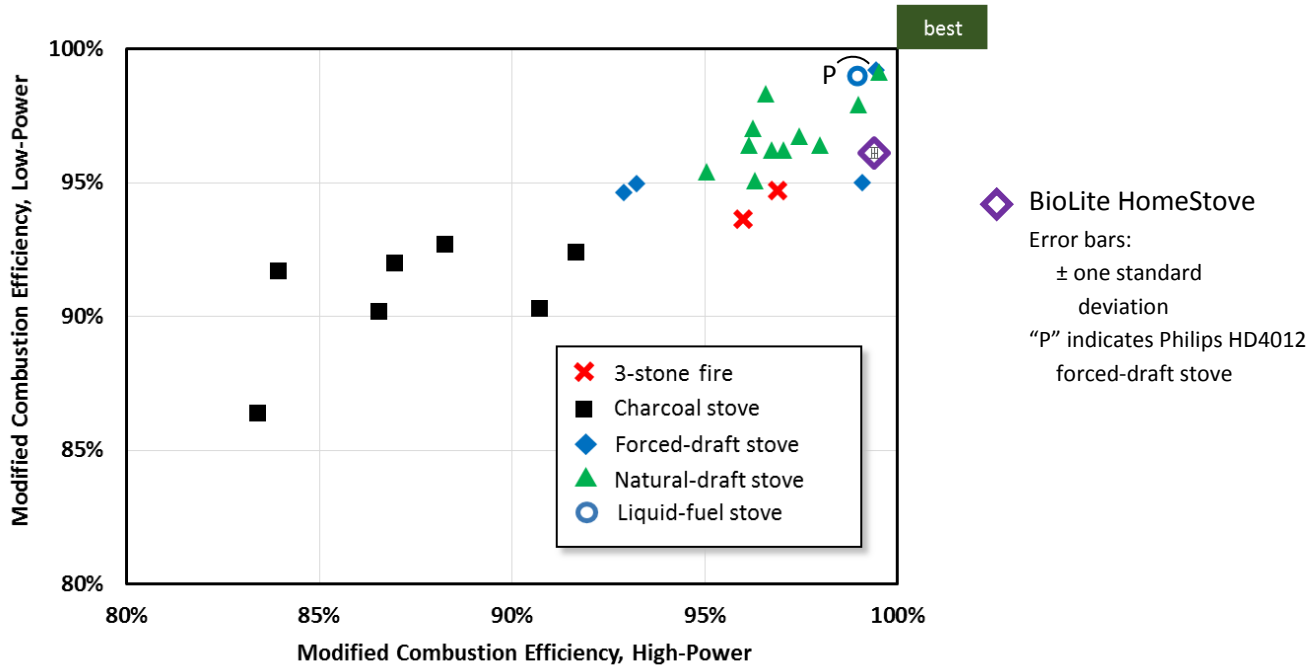

Figure 4. *Modified combustion efficiency, low-power versus high-power*

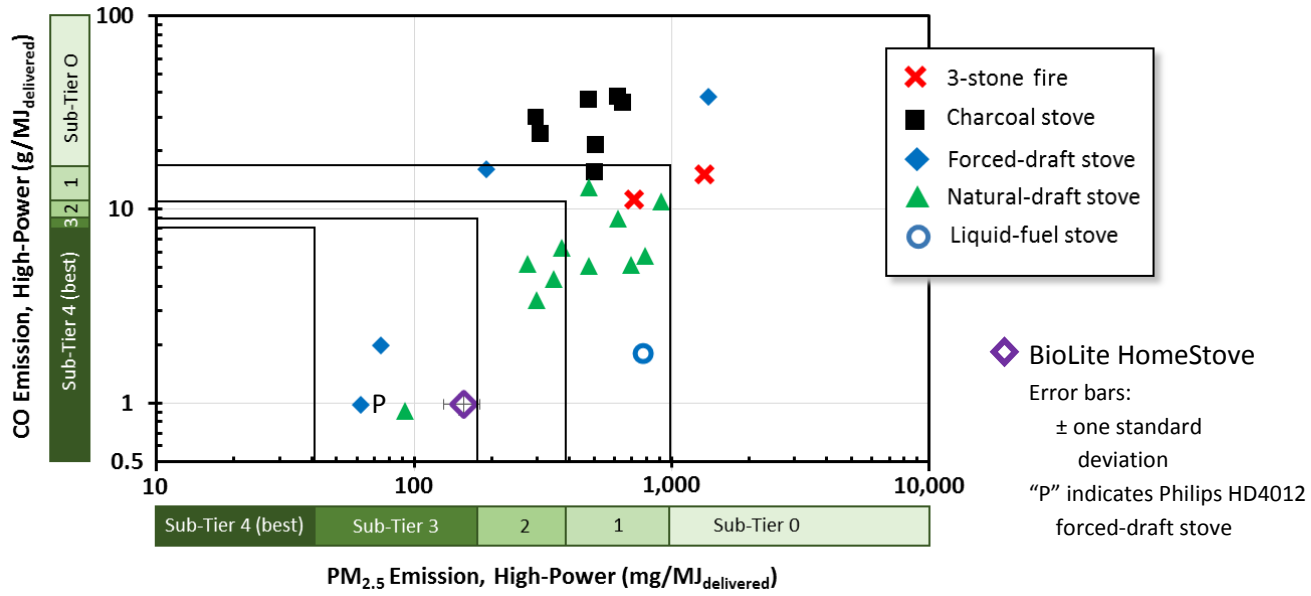

Figure 5. *CO versus $PM_{2.5}$ emissions per useful energy delivered to water in the cooking pot during high-power*

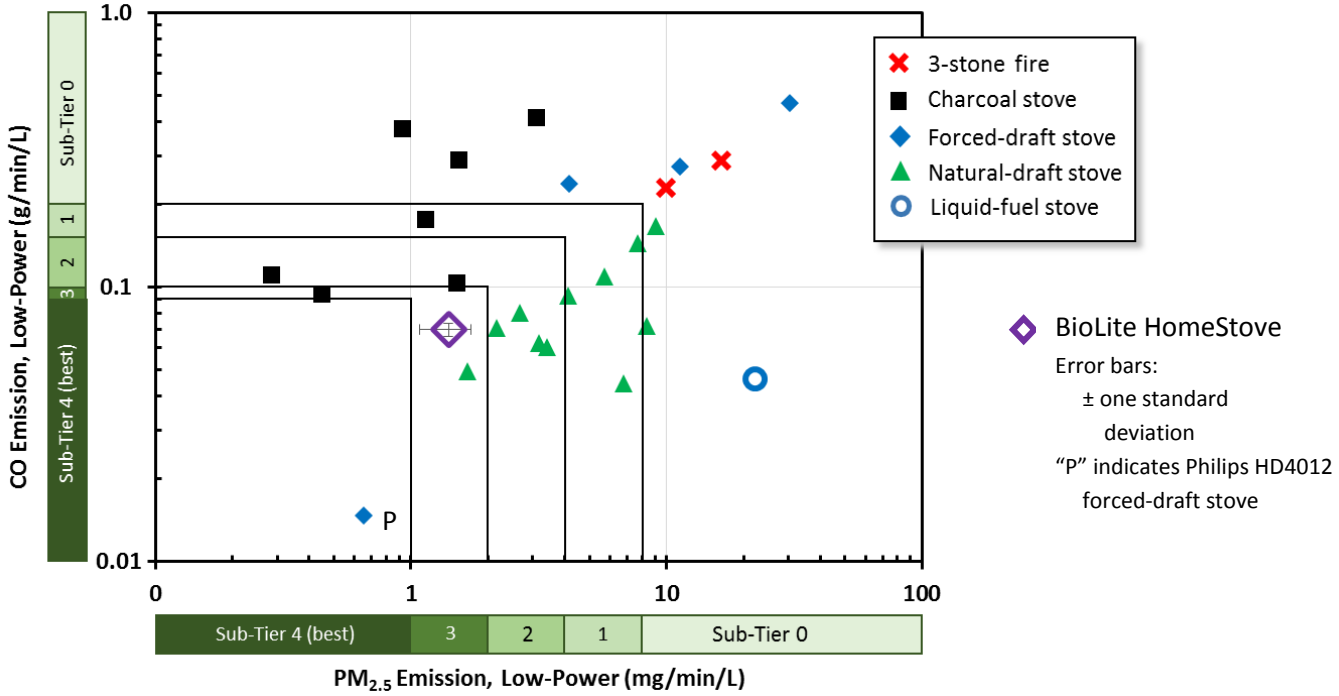

Figure 6. *CO versus $PM_{2.5}$ emissions per liter of water simmered per minute during low-power*

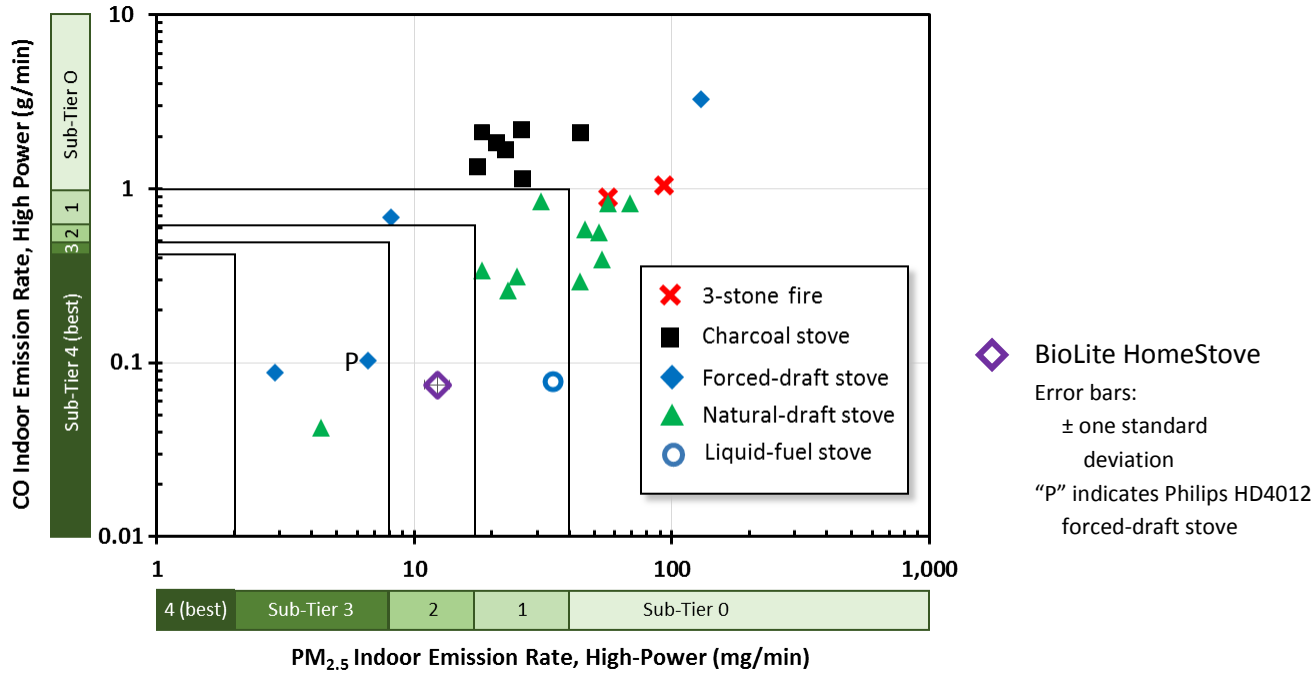

Figure 7. *CO versus $PM_{2.5}$ indoor emission rates during high-power*

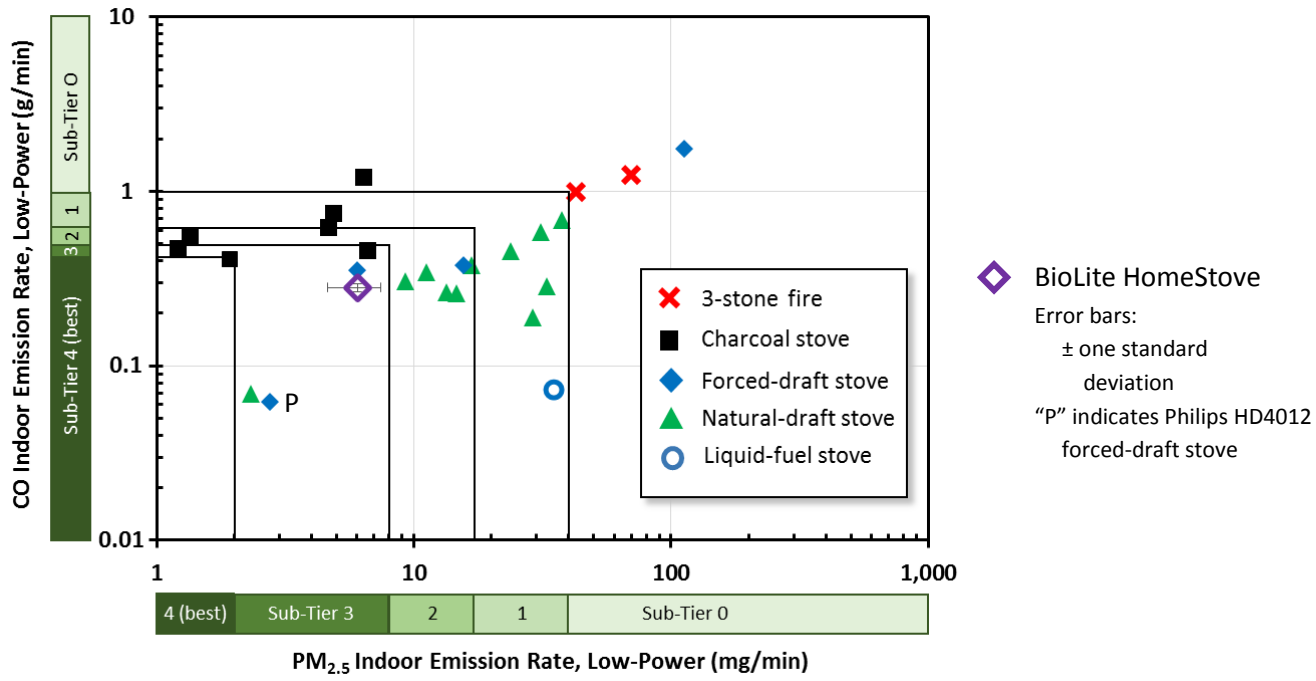

Figure 8. *CO versus $PM_{2.5}$ indoor emission rates during low-power*

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

Parameter	Units	Average	SD	Test 2[1]	Test 3	Test 4
Fuel moisture (wet basis)	%	8.3	1.02	7.2	8.8	9.0
Fuel consumed (raw)	g	488.9	5.3	484.5	494.8	487.3
Equivalent dry fuel consumed	g	354.1	25.4	375.1	361.4	325.8
Time to boil 5 liters of water, 25 to 100°C	min	28.74	2.0	28.96	30.57	26.69
Thermal efficiency	%	31.0	1.7	29.9	30.1	33.0
Fuel burning rate	g/min	11.7	0.5	12.3	11.3	11.7
Temperature-corrected specific fuel consumption	g/liter	69.7	5.0	73.9	71.2	64.2
Temperature-corrected specific energy use	kJ/liter	1277	92	1353	1304	1175
Fire power	W	3582	160	3753	3437	3556
Cooking power	W	1110	71	1124	1033	1174
Modified combustion efficiency	%	99.4	0.1	99.3	99.4	99.5
$PM_{2.5}$ temperature-corrected total mass	mg	264.0	42.8	245.9	312.9	233.3
mass per effective volume of water boiled	mg/liter	54.6	8.9	51.0	64.7	48.1
mass per fuel mass (raw)	mg/kg	566.6	85.6	534.5	663.6	501.7
mass per equivalent dry fuel mass	mg/kg	783.1	112.8	690.3	908.6	750.3
mass per fuel energy	mg/MJ	42.8	6.2	37.7	49.6	41.0
mass per useful energy delivered (to water in pot)	mg/MJ	138.3	23.1	125.9	165.0	124.1
mass per time	mg/hour	549.3	56.5	509.4	614.0	524.5
CO temperature-corrected total mass	g	2.20	0.29	2.53	2.08	1.98
mass per effective volume of water boiled	g/liter	0.45	0.06	0.52	0.43	0.41
mass per fuel mass (raw)	g/kg	4.72	0.68	5.50	4.40	4.26
mass per equivalent dry fuel mass	g/kg	6.50	0.55	7.10	6.03	6.37
mass per fuel energy	g/MJ	0.36	0.03	0.39	0.33	0.35
mass per useful energy delivered (to water in pot)	g/MJ	1.15	0.13	1.30	1.10	1.05
mass per time	g/hour	4.59	0.59	5.24	4.08	4.46
CO_2 temperature-corrected total mass	g	565	12	574	551	568
mass per effective volume of water boiled	g/liter	117	3	119	114	117
mass per fuel mass (raw)	g/kg	1,213	40	1,249	1,169	1,222
mass per equivalent dry fuel mass	g/kg	1,680	127	1,613	1,601	1,827
mass per fuel energy	g/MJ	92	7	88	87	100
mass per useful energy delivered (to water in pot)	g/MJ	296	6	294	291	302
mass per time	g/hour	1,183	98	1,190	1,082	1,277
THC (as C_3H_8) temperature-corrected total mass	g	0.25	0.02	0.24	0.24	0.27
mass per effective volume of water boiled	g/liter	0.05	0.00	0.05	0.05	0.06
mass per fuel mass (raw)	g/kg	0.54	0.04	0.53	0.51	0.59
mass per equivalent dry fuel mass	g/kg	0.75	0.11	0.68	0.70	0.88
mass per fuel energy	g/MJ	0.04	0.01	0.04	0.04	0.05
mass per useful energy delivered (to water in pot)	g/MJ	0.13	0.01	0.12	0.13	0.15
mass per time	g/hour	0.53	0.07	0.50	0.48	0.61
CH_4 temperature-corrected total mass	g	0.06	0.01	0.05	0.06	0.05
mass per effective volume of water boiled	g/liter	0.01	0.00	0.01	0.01	0.01
mass per fuel mass (raw)	g/kg	0.12	0.02	0.10	0.14	0.12
mass per equivalent dry fuel mass	g/kg	0.17	0.03	0.13	0.19	0.18
mass per fuel energy	g/MJ	0.01	0.00	0.01	0.01	0.01
mass per useful energy delivered (to water in pot)	g/MJ	0.03	0.00	0.02	0.03	0.03
mass per time	g/hour	0.12	0.02	0.10	0.13	0.12
NO_X temperature-corrected total mass	g	0.24	0.00	0.24	0.24	0.23
mass per effective volume of water boiled	g/liter	0.05	0.00	0.05	0.05	0.05
mass per fuel mass (raw)	g/kg	0.51	0.01	0.52	0.51	0.50
mass per equivalent dry fuel mass	g/kg	0.71	0.04	0.67	0.69	0.75
mass per fuel energy	g/MJ	0.04	0.00	0.04	0.04	0.04
mass per useful energy delivered (to water in pot)	g/MJ	0.12	0.00	0.12	0.13	0.12
mass per time	g/hour	0.50	0.03	0.50	0.47	0.52

[1] Test 1 rejected and not included due to improper ignition of fuel

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
Fuel moisture (wet basis)	%	8.5	0.87	8.8	7.2	8.8	9.0
Fuel consumed (raw)	g	436.5	13.2	426.5	449.0	423.9	446.7
Equivalent dry fuel consumed	g	311.7	28.4	311.0	349.4	280.6	305.9
Time to boil 5 liters of water, 25 to 100°C	min	21.03	2.7	21.56	24.46	17.93	20.18
Thermal efficiency	%	34.7	2.3	33.9	31.9	37.3	35.7
Fuel burning rate	g/min	14.3	0.6	13.8	13.7	15.0	14.6
Temperature-corrected specific fuel consumption	g/liter	61.9	5.9	62.1	69.5	55.2	60.9
Temperature-corrected specific energy use	kJ/liter	1134	108	1137	1273	1010	1116
Fire power	W	4355	186	4222	4181	4574	4442
Cooking power	W	1515	165	1431	1336	1707	1586
Modified combustion efficiency	%	99.5	0.1	99.4	99.5	99.7	99.5
$PM_{2.5}$ temperature-corrected total mass	mg	327.9	92.7	277.7	462.9	258.9	312.2
mass per effective volume of water boiled	mg/liter	67.9	19.4	57.8	96.1	53.2	64.7
mass per fuel mass (raw)	mg/kg	779.8	200.2	678.8	1075.0	637.7	727.8
mass per equivalent dry fuel mass	mg/kg	1084.6	205.7	930.8	1381.5	963.5	1062.7
mass per fuel energy	mg/MJ	59.2	11.2	50.8	75.5	52.6	58.0
mass per useful energy delivered (to water in pot)	mg/MJ	172.4	43.4	150.0	236.2	141.0	162.6
mass per time	mg/hour	925.8	153.9	772.6	1135.7	866.6	928.2
CO temperature-corrected total mass	g	1.55	0.40	1.88	1.63	0.97	1.72
mass per effective volume of water boiled	g/liter	0.32	0.08	0.39	0.34	0.20	0.36
mass per fuel mass (raw)	g/kg	3.70	0.93	4.61	3.79	2.40	4.01
mass per equivalent dry fuel mass	g/kg	5.16	1.19	6.31	4.87	3.63	5.85
mass per fuel energy	g/MJ	0.28	0.06	0.34	0.27	0.20	0.32
mass per useful energy delivered (to water in pot)	g/MJ	0.82	0.21	1.02	0.83	0.53	0.89
mass per time	g/hour	4.40	0.94	5.24	4.00	3.26	5.11
CO_2 temperature-corrected total mass	g	488	36	482	503	442	526
mass per effective volume of water boiled	g/liter	101	8	100	104	91	109
mass per fuel mass (raw)	g/kg	1,165	57	1,177	1,168	1,088	1,225
mass per equivalent dry fuel mass	g/kg	1,637	118	1,614	1,501	1,645	1,789
mass per fuel energy	g/MJ	89	6	88	82	90	98
mass per useful energy delivered (to water in pot)	g/MJ	258	14	260	257	241	274
mass per time	g/hour	1,404	146	1,340	1,234	1,479	1,563
THC (as C_3H_8) temperature-corrected total mass	g	0.22	0.03	no[1]	0.19	0.24	0.24
mass per effective volume of water boiled	g/liter	0.05	0.01	no[1]	0.04	0.05	0.05
mass per fuel mass (raw)	g/kg	0.52	0.08	no[1]	0.44	0.58	0.56
mass per equivalent dry fuel mass	g/kg	0.75	0.17	no[1]	0.56	0.88	0.81
mass per fuel energy	g/MJ	0.04	0.01	no[1]	0.03	0.05	0.04
mass per useful energy delivered (to water in pot)	g/MJ	0.12	0.02	no[1]	0.10	0.13	0.12
mass per time	g/hour	0.65	0.17	no[1]	0.46	0.79	0.71
CH_4 temperature-corrected total mass	g	0.03	0.01	0.04	0.03	0.02	0.03
mass per effective volume of water boiled	g/liter	0.01	0.00	0.01	0.01	0.00	0.01
mass per fuel mass (raw)	g/kg	0.07	0.03	0.10	0.06	0.04	0.07
mass per equivalent dry fuel mass	g/kg	0.10	0.03	0.14	0.08	0.06	0.11
mass per fuel energy	g/MJ	0.01	0.00	0.01	0.00	0.00	0.01
mass per useful energy delivered (to water in pot)	g/MJ	0.02	0.01	0.02	0.01	0.01	0.02
mass per time	g/hour	0.08	0.03	0.12	0.07	0.06	0.09
NO_X temperature-corrected total mass	g	0.21	0.02	0.19	0.23	0.20	0.22
mass per effective volume of water boiled	g/liter	0.04	0.00	0.04	0.05	0.04	0.05
mass per fuel mass (raw)	g/kg	0.50	0.03	0.47	0.54	0.48	0.52
mass per equivalent dry fuel mass	g/kg	0.70	0.05	0.64	0.69	0.73	0.76
mass per fuel energy	g/MJ	0.04	0.00	0.03	0.04	0.04	0.04
mass per useful energy delivered (to water in pot)	g/MJ	0.11	0.01	0.10	0.12	0.11	0.12
mass per time	g/hour	0.60	0.06	0.53	0.57	0.65	0.66

[1] THC data rejected and not included because it did not meet QA acceptance criteria per Table 17.

Table 3. *Low-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)	%	8.5	0.87	8.8	7.2	8.8	9.0
Fuel consumed (raw)	g	193.3	21.1	193.7	222.3	183.7	173.4
Equivalent dry fuel consumed	g	193.2	11.4	184.8	207.5	197.2	183.4
Fuel burning rate	g/min	6.4	0.4	6.2	6.9	6.6	6.1
Specific fuel consumption	g/liter	44.9	2.8	43.2	48.4	45.7	42.2
Specific energy use	kJ/liter	822	51	791	887	837	773
Fire power	W	1966	114	1880	2105	2015	1866
Modified combustion efficiency	%	96.1	0.2	95.7	96.3	96.3	96.1
$PM_{2.5}$ total mass	mg	181.1	42.9	156.9	160.0	162.2	245.3
mass per volume of water remaining	mg/liter	42.0	9.6	36.7	37.3	37.6	56.5
mass per fuel mass (raw)	mg/kg	956.8	312.6	809.8	719.8	882.8	1414.9
mass per equivalent dry fuel mass	mg/kg	944.9	263.6	848.8	771.0	822.5	1337.4
mass per fuel energy	mg/MJ	51.6	14.4	46.4	42.1	44.9	73.0
mass per time	mg/hour	362.3	85.7	313.7	319.1	325.8	490.7
CO total mass	g	8.42	0.47	9.07	8.24	7.96	8.39
mass per volume of water remaining	g/liter	1.96	0.12	2.12	1.92	1.85	1.93
mass per fuel mass (raw)	g/kg	43.91	5.02	46.81	37.08	43.35	48.39
mass per equivalent dry fuel mass	g/kg	43.73	4.47	49.07	39.72	40.39	45.74
mass per fuel energy	g/MJ	2.39	0.24	2.68	2.17	2.21	2.50
mass per time	g/hour	16.84	0.92	18.14	16.44	16.00	16.78
CO_2 total mass	g	325	6	320	333	323	323
mass per volume of water remaining	g/liter	76	2	75	78	75	74
mass per fuel mass (raw)	g/kg	1,694	157	1,652	1,499	1,760	1,865
mass per equivalent dry fuel mass	g/kg	1,685	74	1,732	1,605	1,640	1,763
mass per fuel energy	g/MJ	92	4	95	88	90	96
mass per time	g/hour	650	10	640	664	650	647
THC (as C_3H_8) total mass	g	0.58	0.11	no[1]	0.56	0.69	0.48
mass per volume of water remaining	g/liter	0.13	0.03	no[1]	0.13	0.16	0.11
mass per fuel mass (raw)	g/kg	3.01	0.67	no[1]	2.51	3.77	2.74
mass per equivalent dry fuel mass	g/kg	2.93	0.51	no[1]	2.69	3.52	2.59
mass per fuel energy	g/MJ	0.16	0.03	no[1]	0.15	0.19	0.14
mass per time	g/hour	1.15	0.22	no[1]	1.11	1.39	0.95
CH_4 total mass	g	0.19	0.04	0.20	0.13	0.20	0.21
mass per volume of water remaining	g/liter	0.04	0.01	0.05	0.03	0.05	0.05
mass per fuel mass (raw)	g/kg	0.99	0.27	1.05	0.60	1.10	1.20
mass per equivalent dry fuel mass	g/kg	0.98	0.23	1.10	0.64	1.03	1.14
mass per fuel energy	g/MJ	0.05	0.01	0.06	0.03	0.06	0.06
mass per time	g/hour	0.37	0.07	0.41	0.27	0.41	0.42
NO_X total mass	g	0.12	0.01	0.12	0.13	0.13	0.11
mass per volume of water remaining	g/liter	0.03	0.00	0.03	0.03	0.03	0.02
mass per fuel mass (raw)	g/kg	0.63	0.04	0.60	0.60	0.69	0.62
mass per equivalent dry fuel mass	g/kg	0.62	0.02	0.62	0.64	0.64	0.59
mass per fuel energy	g/MJ	0.03	0.00	0.03	0.03	0.04	0.03
mass per time	g/hour	0.24	0.02	0.23	0.26	0.26	0.22

[1] THC data rejected and not included because it did not meet QA acceptance criteria per Table 17.

OC (organic carbon) and EC (elemental carbon) particulate emissions were measured using NIOSH Method 5040 (12), and results are reported for low-moisture fuel in Table 4. Particulate samples were collected on quartz fiber filters, and gas-phase samples were also collected on quartz fiber filters downstream of PTFE membrane filters to account for the gas-phase absorption artifact (13). Mass fractions of organic and elemental carbon to total carbon in particulate matter are reported in Table 5.

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
High-power cold-start							
OC temperature-corrected total mass	mg	91.7	16.5	no[1]	73.6	106.0	95.7
mass per effective volume of water boiled	mg/liter	19.0	3.4	no[1]	15.3	21.9	19.7
mass per fuel mass (raw)	mg/kg	196.8	33.3	no[1]	160.0	224.7	205.7
mass per equivalent dry fuel mass	mg/kg	274.0	58.4	no[1]	206.6	307.7	307.7
mass per fuel energy	mg/MJ	15.0	3.2	no[1]	11.3	16.8	16.8
mass per useful energy delivered (to water in pot)	mg/MJ	48.1	9.4	no[1]	37.7	55.9	50.9
mass per time	mg/hour	191.8	34.3	no[1]	152.5	207.9	215.1
EC temperature-corrected total mass	mg	241.2	55.2	no[1]	230.5	301.0	192.2
mass per effective volume of water boiled	mg/liter	49.9	11.4	no[1]	47.8	62.2	39.7
mass per fuel mass (raw)	mg/kg	517.6	113.5	no[1]	501.2	638.4	413.3
mass per equivalent dry fuel mass	mg/kg	713.2	140.2	no[1]	647.3	874.2	618.0
mass per fuel energy	mg/MJ	38.9	7.7	no[1]	35.4	47.7	33.8
mass per useful energy delivered (to water in pot)	mg/MJ	126.3	29.2	no[1]	118.0	158.8	102.2
mass per time	mg/hour	500.2	81.7	no[1]	477.7	590.7	432.1
High-power hot-start							
OC temperature-corrected total mass	mg	89.8	43.8	53.3	153.5	75.2	77.4
mass per effective volume of water boiled	mg/liter	18.6	9.1	11.1	31.9	15.4	16.1
mass per fuel mass (raw)	mg/kg	213.1	98.8	130.3	356.4	185.2	180.4
mass per equivalent dry fuel mass	mg/kg	295.0	117.4	178.6	458.1	279.8	263.4
mass per fuel energy	mg/MJ	16.1	6.4	9.8	25.0	15.3	14.4
mass per useful energy delivered (to water in pot)	mg/MJ	47.1	21.6	28.8	78.3	40.9	40.3
mass per time	mg/hour	251.6	94.4	148.3	376.6	251.6	230.1
EC temperature-corrected total mass	mg	311.6	95.3	256.8	448.4	237.4	303.6
mass per effective volume of water boiled	mg/liter	64.6	19.9	53.4	93.1	48.7	63.0
mass per fuel mass (raw)	mg/kg	740.4	206.9	627.9	1041.2	584.8	707.8
mass per equivalent dry fuel mass	mg/kg	1029.0	219.8	860.9	1338.1	883.5	1033.4
mass per fuel energy	mg/MJ	56.2	12.0	47.0	73.1	48.3	56.4
mass per useful energy delivered (to water in pot)	mg/MJ	163.7	45.0	138.7	228.8	129.3	158.1
mass per time	mg/hour	878.0	166.9	714.6	1100.0	794.6	902.6
Low-power (30-minute simmer)							
OC total mass	mg	89.3	39.0	54.7	78.5	78.6	145.3
mass per volume of water remaining	mg/liter	20.7	8.9	12.8	18.3	18.2	33.5
mass per fuel mass (raw)	mg/kg	475.2	249.1	282.1	352.9	427.9	838.0
mass per equivalent dry fuel mass	mg/kg	466.1	221.8	295.7	378.0	398.7	792.1
mass per fuel energy	mg/MJ	25.5	12.1	16.2	20.6	21.8	43.3
mass per time	mg/hour	178.6	78.0	109.3	156.5	157.9	290.6
EC total mass	mg	80.1	12.4	84.4	89.4	61.7	84.8
mass per volume of water remaining	mg/liter	18.6	2.9	19.7	20.9	14.3	19.5
mass per fuel mass (raw)	mg/kg	415.7	64.1	435.6	402.2	336.0	489.1
mass per equivalent dry fuel mass	mg/kg	415.7	69.8	456.6	430.8	313.1	462.3
mass per fuel energy	mg/MJ	22.7	3.8	24.9	23.5	17.1	25.2
mass per time	mg/hour	160.2	24.5	168.8	178.3	124.0	169.6

[1] Test 1 rejected and not included due to improper ignition of fuel

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	0.275	0.224	0.527
Mass fraction of EC/TC	0.725	0.776	0.473

BC (black carbon) was measured with a microAeth® Model AE51 (AethLabs, San Francisco, CA, USA) aethalometer, and results are reported for low-moisture fuel in Table 6.

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
High-power cold-start							
BC temperature-corrected total mass	mg	259.7	72.9	no[1]	239.3	340.6	199.2
mass per effective volume of water boiled	mg/liter	53.7	15.1	no[1]	49.6	70.4	41.1
mass per fuel mass (raw)	mg/kg	557.0	150.4	no[1]	520.2	722.4	428.5
mass per equivalent dry fuel mass	mg/kg	767.2	192.8	no[1]	671.9	989.1	640.8
mass per fuel energy	mg/MJ	41.9	10.5	no[1]	36.7	54.0	35.0
mass per useful energy delivered (to water in pot)	mg/MJ	136.0	38.7	no[1]	122.5	179.6	106.0
mass per time	mg/hour	537.4	116.0	no[1]	495.8	668.4	447.9
High-power hot-start							
BC temperature-corrected total mass	mg	333.1	101.0	305.9	473.2	232.6	320.7
mass per effective volume of water boiled	mg/liter	69.0	21.1	63.7	98.2	47.8	66.5
mass per fuel mass (raw)	mg/kg	791.9	220.7	747.9	1098.9	573.0	747.7
mass per equivalent dry fuel mass	mg/kg	1098.8	229.5	1025.5	1412.3	865.7	1091.7
mass per fuel energy	mg/MJ	60.0	12.5	56.0	77.1	47.3	59.6
mass per useful energy delivered (to water in pot)	mg/MJ	175.1	48.0	165.3	241.5	126.7	167.0
mass per time	mg/hour	936.1	166.2	851.2	1161.0	778.6	953.5
Low-power (30-minute simmer)							
BC total mass	mg	78.9	12.2	90.9	78.1	62.4	84.3
mass per volume of water remaining	mg/liter	18.3	2.9	21.3	18.2	14.5	19.4
mass per fuel mass (raw)	mg/kg	411.5	76.9	469.4	351.1	339.5	486.0
mass per equivalent dry fuel mass	mg/kg	410.9	79.7	492.0	376.1	316.3	459.3
mass per fuel energy	mg/MJ	22.4	4.4	26.9	20.5	17.3	25.1
mass per time	mg/hour	157.8	24.2	181.8	155.7	125.3	168.5

[1] Test 1 rejected and not included due to improper ignition of fuel

Test Results for High-Moisture Fuel

Tabulated data for the BioLite HomeStove 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. 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 (11).

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)	%	17.6	2.47	19.9	19.2	14.5	16.7
Fuel consumed (raw)	g	843.4	61.4	860.3	886.1	752.7	874.4
Equivalent dry fuel consumed	g	561.7	26.9	556.1	568.5	528.8	593.4
Time to boil 5 liters of water, 25 to 100°C	min	58.38	2.0	56.80	61.15	57.06	58.49
Thermal efficiency	%	25.5	0.6	25.0	25.2	25.4	26.3
Fuel burning rate	g/min	9.3	0.3	9.5	9.1	8.9	9.6
Temperature-corrected specific fuel consumption	g/liter	119.5	6.4	118.9	122.7	110.8	125.5
Temperature-corrected specific energy use	kJ/liter	2189	118	2179	2249	2029	2300
Fire power	W	2829	104	2912	2765	2717	2922
Cooking power	W	721	36	728	696	690	769
Modified combustion efficiency	%	98.5	0.1	98.4	98.4	98.4	98.7
$PM_{2.5}$ temperature-corrected total mass	mg	628.5	59.6	683.6	565.2	636.6	no[1]
mass per effective volume of water boiled	mg/liter	138.1	12.4	150.1	125.3	138.9	no[1]
mass per fuel mass (raw)	mg/kg	783.8	116.2	815.8	654.9	880.7	no[1]
mass per equivalent dry fuel mass	mg/kg	1178.8	136.9	1262.0	1020.8	1253.6	no[1]
mass per fuel energy	mg/MJ	64.3	7.5	68.8	55.7	68.4	no[1]
mass per useful energy delivered (to water in pot)	mg/MJ	255.3	29.7	275.2	221.2	269.4	no[1]
mass per time	mg/hour	648.7	85.6	722.1	554.6	669.4	no[1]
CO temperature-corrected total mass	g	9.52	0.83	9.67	10.59	9.19	8.64
mass per effective volume of water boiled	g/liter	2.10	0.18	2.12	2.35	2.00	1.94
mass per fuel mass (raw)	g/kg	11.75	0.98	11.54	12.27	12.71	10.48
mass per equivalent dry fuel mass	g/kg	17.63	1.56	17.85	19.13	18.10	15.44
mass per fuel energy	g/MJ	0.96	0.09	0.97	1.04	0.99	0.84
mass per useful energy delivered (to water in pot)	g/MJ	3.78	0.40	3.89	4.14	3.89	3.20
mass per time	g/hour	9.78	0.68	10.21	10.39	9.66	8.87
CO_2 temperature-corrected total mass	g	975	51	964	1,015	907	1,013
mass per effective volume of water boiled	g/liter	215	14	212	225	198	227
mass per fuel mass (raw)	g/kg	1,203	48	1,151	1,176	1,255	1,229
mass per equivalent dry fuel mass	g/kg	1,803	24	1,780	1,833	1,787	1,810
mass per fuel energy	g/MJ	98	1	97	100	97	99
mass per useful energy delivered (to water in pot)	g/MJ	386	9	388	397	384	375
mass per time	g/hour	1,002	37	1,018	996	954	1,040
THC (as C_3H_8) temperature-corrected total mass	g	1.39	0.31	1.53	1.59	1.52	0.94
mass per effective volume of water boiled	g/liter	0.31	0.07	0.34	0.35	0.33	0.21
mass per fuel mass (raw)	g/kg	1.73	0.41	1.83	1.84	2.10	1.14
mass per equivalent dry fuel mass	g/kg	2.59	0.61	2.83	2.87	2.98	1.68
mass per fuel energy	g/MJ	0.14	0.03	0.15	0.16	0.16	0.09
mass per useful energy delivered (to water in pot)	g/MJ	0.56	0.14	0.62	0.62	0.64	0.35
mass per time	g/hour	1.43	0.32	1.62	1.56	1.59	0.96
CH_4 temperature-corrected total mass	g	0.30	0.09	0.29	0.40	0.31	0.19
mass per effective volume of water boiled	g/liter	0.07	0.02	0.06	0.09	0.07	0.04
mass per fuel mass (raw)	g/kg	0.36	0.11	0.34	0.46	0.43	0.23
mass per equivalent dry fuel mass	g/kg	0.55	0.16	0.53	0.71	0.61	0.33
mass per fuel energy	g/MJ	0.03	0.01	0.03	0.04	0.03	0.02
mass per useful energy delivered (to water in pot)	g/MJ	0.12	0.04	0.12	0.15	0.13	0.07
mass per time	g/hour	0.30	0.08	0.30	0.39	0.33	0.19
NO_X temperature-corrected total mass	g	0.42	0.04	0.42	0.44	0.37	0.45
mass per effective volume of water boiled	g/liter	0.09	0.01	0.09	0.10	0.08	0.10
mass per fuel mass (raw)	g/kg	0.52	0.02	0.50	0.51	0.51	0.55
mass per equivalent dry fuel mass	g/kg	0.78	0.04	0.77	0.80	0.73	0.81
mass per fuel energy	g/MJ	0.04	0.00	0.04	0.04	0.04	0.04
mass per useful energy delivered (to water in pot)	g/MJ	0.17	0.01	0.17	0.17	0.16	0.17
mass per time	g/hour	0.43	0.03	0.44	0.44	0.39	0.47

[1] $PM_{2.5}$ data rejected and not included due to a damaged filter

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 4[1]
Fuel moisture (wet basis)	%	19.0	1.02	19.8	19.3	17.8
Fuel consumed (raw)	g	678.7	44.2	630.9	718.0	687.3
Equivalent dry fuel consumed	g	451.5	36.7	409.2	471.4	473.9
Time to boil 5 liters of water, 25 to 100°C	min	38.00	3.2	34.33	40.20	39.48
Thermal efficiency	%	27.7	0.9	28.7	27.5	26.9
Fuel burning rate	g/min	11.4	0.1	11.6	11.4	11.3
Temperature-corrected specific fuel consumption	g/liter	92.2	7.6	83.8	98.6	94.3
Temperature-corrected specific energy use	kJ/liter	1690	140	1535	1806	1728
Fire power	W	3488	44	3536	3478	3449
Cooking power	W	966	44	1015	955	928
Modified combustion efficiency	%	98.9	0.1	98.8	98.9	99.0
$PM_{2.5}$ temperature-corrected total mass	mg	305.1	23.0	291.0	292.7	331.7
mass per effective volume of water boiled	mg/liter	64.8	4.7	61.3	63.0	70.2
mass per fuel mass (raw)	mg/kg	469.0	46.9	474.8	419.6	512.8
mass per equivalent dry fuel mass	mg/kg	705.0	57.3	732.1	639.1	743.7
mass per fuel energy	mg/MJ	38.5	3.1	39.9	34.9	40.6
mass per useful energy delivered (to water in pot)	mg/MJ	139.0	11.9	139.2	127.0	150.9
mass per time	mg/hour	483.2	40.3	508.7	436.8	504.1
CO temperature-corrected total mass	g	5.29	0.33	5.22	5.66	5.01
mass per effective volume of water boiled	g/liter	1.13	0.08	1.10	1.22	1.06
mass per fuel mass (raw)	g/kg	8.12	0.38	8.51	8.11	7.74
mass per equivalent dry fuel mass	g/kg	12.23	0.95	13.12	12.36	11.23
mass per fuel energy	g/MJ	0.67	0.05	0.72	0.67	0.61
mass per useful energy delivered (to water in pot)	g/MJ	2.41	0.12	2.50	2.46	2.28
mass per time	g/hour	8.39	0.76	9.12	8.44	7.61
CO_2 temperature-corrected total mass	g	748	64.64	674	784	787
mass per effective volume of water boiled	g/liter	159	14.87	142	169	167
mass per fuel mass (raw)	g/kg	1,147	62.39	1,099	1,124	1,218
mass per equivalent dry fuel mass	g/kg	1,724	36.94	1,695	1,712	1,766
mass per fuel energy	g/MJ	94	2.02	92	93	96
mass per useful energy delivered (to water in pot)	g/MJ	340	17.97	322	340	358
mass per time	g/hour	1,182	13.85	1,178	1,170	1,197
THC (as C_3H_8) temperature-corrected total mass	g	0.60	0.10	0.71	0.58	0.51
mass per effective volume of water boiled	g/liter	0.13	0.02	0.15	0.12	0.11
mass per fuel mass (raw)	g/kg	0.92	0.20	1.16	0.83	0.78
mass per equivalent dry fuel mass	g/kg	1.40	0.34	1.79	1.27	1.14
mass per fuel energy	g/MJ	0.08	0.02	0.10	0.07	0.06
mass per useful energy delivered (to water in pot)	g/MJ	0.27	0.06	0.34	0.25	0.23
mass per time	g/hour	0.96	0.25	1.24	0.87	0.77
CH_4 temperature-corrected total mass	g	0.13	0.04	0.17	0.14	0.09
mass per effective volume of water boiled	g/liter	0.03	0.01	0.04	0.03	0.02
mass per fuel mass (raw)	g/kg	0.21	0.07	0.28	0.19	0.14
mass per equivalent dry fuel mass	g/kg	0.31	0.12	0.44	0.30	0.21
mass per fuel energy	g/MJ	0.02	0.01	0.02	0.02	0.01
mass per useful energy delivered (to water in pot)	g/MJ	0.06	0.02	0.08	0.06	0.04
mass per time	g/hour	0.22	0.08	0.30	0.20	0.14
NO_X temperature-corrected total mass	g	0.33	0.05	0.28	0.38	0.33
mass per effective volume of water boiled	g/liter	0.07	0.01	0.06	0.08	0.07
mass per fuel mass (raw)	g/kg	0.51	0.04	0.46	0.54	0.52
mass per equivalent dry fuel mass	g/kg	0.76	0.06	0.71	0.83	0.75
mass per fuel energy	g/MJ	0.04	0.00	0.04	0.05	0.04
mass per useful energy delivered (to water in pot)	g/MJ	0.15	0.01	0.13	0.16	0.15
mass per time	g/hour	0.52	0.04	0.49	0.56	0.51

[1] Test 3 rejected and not included due to burning rate too high

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
Fuel moisture (wet basis)	%	22.01	0.48	22.45	22.09	21.49
Fuel consumed (raw)	g	327.4	20.1	306.7	346.8	328.6
Equivalent dry fuel consumed	g	234.4	4.6	230.9	232.6	239.6
Fuel burning rate	g/min	7.9	0.2	7.7	8.0	8.0
Specific fuel consumption	g/liter	55.5	1.4	53.9	55.9	56.6
Specific energy use	kJ/liter	1017	26	987	1025	1038
Fire power	W	2414	55	2350	2451	2440
Modified combustion efficiency	%	97.3	0.4	97.1	97.7	96.9
$PM_{2.5}$ total mass	mg	346.3	40.6	299.6	365.7	373.6
mass per volume of water remaining	mg/liter	82.0	10.5	69.9	87.9	88.3
mass per fuel mass (raw)	mg/kg	1056.1	80.0	977.0	1054.5	1136.9
mass per equivalent dry fuel mass	mg/kg	1476.4	154.7	1297.9	1572.2	1559.1
mass per fuel energy	mg/MJ	80.5	8.4	70.8	85.8	85.0
mass per time	mg/hour	701.2	88.4	599.3	757.1	747.2
CO total mass	g	7.52	1.45	7.50	6.08	8.99
mass per volume of water remaining	g/liter	1.78	0.33	1.75	1.46	2.12
mass per fuel mass (raw)	g/kg	23.12	5.04	24.46	17.54	27.34
mass per equivalent dry fuel mass	g/kg	32.05	5.68	32.49	26.16	37.50
mass per fuel energy	g/MJ	1.75	0.31	1.77	1.43	2.05
mass per time	g/hour	15.19	2.69	15.00	12.60	17.97
CO_2 total mass	g	418	22	400	411	443
mass per volume of water remaining	g/liter	99	6	93	99	105
mass per fuel mass (raw)	g/kg	1,279	84	1,305	1,185	1,347
mass per equivalent dry fuel mass	g/kg	1,783	59	1,734	1,767	1,848
mass per fuel energy	g/MJ	97	3	95	96	101
mass per time	g/hour	846	43	801	851	886
THC (as C_3H_8) total mass	g	1.12	0.43	0.75	1.02	1.59
mass per volume of water remaining	g/liter	0.27	0.10	0.17	0.25	0.38
mass per fuel mass (raw)	g/kg	3.41	1.27	2.44	2.94	4.84
mass per equivalent dry fuel mass	g/kg	4.75	1.73	3.24	4.38	6.64
mass per fuel energy	g/MJ	0.26	0.09	0.18	0.24	0.36
mass per time	g/hour	2.26	0.85	1.50	2.11	3.18
CH_4 total mass	g	0.28	0.13	0.19	0.22	0.43
mass per volume of water remaining	g/liter	0.07	0.03	0.04	0.05	0.10
mass per fuel mass (raw)	g/kg	0.84	0.39	0.61	0.63	1.30
mass per equivalent dry fuel mass	g/kg	1.17	0.53	0.81	0.93	1.78
mass per fuel energy	g/MJ	0.06	0.03	0.04	0.05	0.10
mass per time	g/hour	0.56	0.26	0.37	0.45	0.85
NO_X total mass	g	0.16	0.02	0.15	0.17	0.17
mass per volume of water remaining	g/liter	0.04	0.00	0.03	0.04	0.04
mass per fuel mass (raw)	g/kg	0.50	0.03	0.47	0.50	0.53
mass per equivalent dry fuel mass	g/kg	0.70	0.06	0.63	0.74	0.72
mass per fuel energy	g/MJ	0.04	0.00	0.03	0.04	0.04
mass per time	g/hour	0.33	0.04	0.29	0.36	0.35

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	402.6	92.4	501.4	388.1	318.3	no[1]
mass per effective volume of water boiled	mg/liter	88.5	20.5	110.1	86.0	69.4	no[1]
mass per fuel mass (raw)	mg/kg	496.1	88.7	598.4	449.7	440.4	no[1]
mass per equivalent dry fuel mass	mg/kg	751.2	155.6	925.7	700.9	626.9	no[1]
mass per fuel energy	mg/MJ	41.0	8.5	50.5	38.2	34.2	no[1]
mass per useful energy delivered (to water in pot)	mg/MJ	162.8	34.9	201.9	151.9	134.7	no[1]
mass per time	mg/hour	415.1	101.9	529.7	380.8	334.7	no[1]
EC temperature-corrected total mass	mg	165.2	67.5	225.5	178.0	92.3	no[1]
mass per effective volume of water boiled	mg/liter	36.4	14.9	49.5	39.5	20.1	no[1]
mass per fuel mass (raw)	mg/kg	201.0	70.8	269.1	206.2	127.6	no[1]
mass per equivalent dry fuel mass	mg/kg	306.5	118.0	416.2	321.4	181.7	no[1]
mass per fuel energy	mg/MJ	16.7	6.4	22.7	17.5	9.9	no[1]
mass per useful energy delivered (to water in pot)	mg/MJ	66.5	26.0	90.8	69.6	39.1	no[1]
mass per time	mg/hour	169.9	70.7	238.2	174.6	97.0	no[1]
High-power hot-start							
OC temperature-corrected total mass	mg	107.0	45.4	137.2	129.1	no[2]	54.8
mass per effective volume of water boiled	mg/liter	22.8	9.7	28.9	27.8	no[2]	11.6
mass per fuel mass (raw)	mg/kg	164.6	71.8	223.9	185.1	no[2]	84.7
mass per equivalent dry fuel mass	mg/kg	250.0	114.6	345.3	282.0	no[2]	122.9
mass per fuel energy	mg/MJ	13.6	6.3	18.8	15.4	no[2]	6.7
mass per useful energy delivered (to water in pot)	mg/MJ	48.9	21.3	65.6	56.0	no[2]	24.9
mass per time	mg/hour	172.0	80.3	239.9	192.7	no[2]	83.3
EC temperature-corrected total mass	mg	207.1	11.0	197.4	219.0	no[2]	205.0
mass per effective volume of water boiled	mg/liter	44.0	2.8	41.6	47.2	no[2]	43.4
mass per fuel mass (raw)	mg/kg	317.7	4.1	322.0	314.0	no[2]	317.0
mass per equivalent dry fuel mass	mg/kg	478.2	18.4	496.5	478.3	no[2]	459.7
mass per fuel energy	mg/MJ	26.1	1.0	27.1	26.1	no[2]	25.1
mass per useful energy delivered (to water in pot)	mg/MJ	94.2	0.9	94.4	95.0	no[2]	93.3
mass per time	mg/hour	327.8	16.7	345.0	326.9	no[2]	311.6
Low-power (30-minute simmer)							
OC total mass	mg	225.1	44.9	187.6	274.9	212.8	no[3]
mass per volume of water remaining	mg/liter	53.4	11.5	43.8	66.1	50.3	no[3]
mass per fuel mass (raw)	mg/kg	684.0	95.8	611.7	792.7	647.6	no[3]
mass per equivalent dry fuel mass	mg/kg	960.9	195.1	812.7	1181.9	888.1	no[3]
mass per fuel energy	mg/MJ	52.4	10.6	44.3	64.5	48.4	no[3]
mass per time	mg/hour	456.6	100.6	375.2	569.1	425.6	no[3]
EC total mass	mg	76.1	32.0	97.9	91.1	39.4	no[3]
mass per volume of water remaining	mg/liter	18.0	7.6	22.9	21.9	9.3	no[3]
mass per fuel mass (raw)	mg/kg	233.9	102.8	319.3	262.6	119.8	no[3]
mass per equivalent dry fuel mass	mg/kg	326.7	141.5	424.1	391.5	164.3	no[3]
mass per fuel energy	mg/MJ	17.8	7.7	23.1	21.4	9.0	no[3]
mass per time	mg/hour	154.4	65.6	195.8	188.5	78.7	no[3]

[1] Data rejected and not included due to a damaged filter

[2] Test 3 rejected and not included due to fuel burning rate too high

[3] Test 4 rejected and not included due to fuel burning rate too high

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	0.709	0.341	0.747
Mass fraction of EC/TC	0.291	0.659	0.253

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	246.9	101.5	264.5	200.6	142.8	379.7
mass per effective volume of water boiled	mg/liter	54.7	23.1	58.1	44.5	31.2	85.2
mass per fuel mass (raw)	mg/kg	301.5	116.9	315.7	232.4	197.6	460.3
mass per equivalent dry fuel mass	mg/kg	452.6	172.9	488.4	362.3	281.3	678.3
mass per fuel energy	mg/MJ	24.7	9.4	26.6	19.8	15.3	37.0
mass per useful energy delivered (to water in pot)	mg/MJ	96.5	35.0	106.5	78.5	60.4	140.7
mass per time	mg/hour	254.0	105.0	279.4	196.8	150.2	389.5
High-power hot-start							
BC temperature-corrected total mass	mg	216.8	26.2	187.3	225.7	no[1]	237.4
mass per effective volume of water boiled	mg/liter	46.1	5.8	39.5	48.6	no[1]	50.2
mass per fuel mass (raw)	mg/kg	332.1	31.6	305.6	323.5	no[1]	367.0
mass per equivalent dry fuel mass	mg/kg	498.8	30.9	471.3	492.8	no[1]	532.3
mass per fuel energy	mg/MJ	27.2	1.7	25.7	26.9	no[1]	29.0
mass per useful energy delivered (to water in pot)	mg/MJ	98.5	9.2	89.6	97.9	no[1]	108.0
mass per time	mg/hour	341.7	17.2	327.5	336.8	no[1]	360.8
Low-power (30-minute simmer)							
BC total mass	mg	81.4	21.8	95.3	92.5	56.2	no[2]
mass per volume of water remaining	mg/liter	19.3	5.2	22.2	22.2	13.3	no[2]
mass per fuel mass (raw)	mg/kg	249.5	71.5	310.8	266.9	171.0	no[2]
mass per equivalent dry fuel mass	mg/kg	348.4	98.9	412.8	397.9	234.5	no[2]
mass per fuel energy	mg/MJ	19.0	5.4	22.5	21.7	12.8	no[2]
mass per time	mg/hour	164.9	45.4	190.6	191.6	112.4	no[2]

[1] Test 3 rejected and not included due to fuel burning rate too high

[2] Test 4 rejected and not included due to fuel burning rate too high

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

Parameter	Units	High-power cold-start		High-power hot-start		Low-power 30-minute simmer	
Fuel moisture (wet basis)	**%**	**8.3**	**17.6**	**8.5**	**19.0**	**8.5**	**22.0**
Fuel consumed (raw)	g	488.9	843.4	436.5	678.7	193.3	327.4
Equivalent dry fuel consumed	g	354.1	561.7	311.7	451.5	193.2	234.4
Time to boil 5 liters of water, 25 to 100°C	min	28.74	58.38	21.03	38.00	n.a.[1]	n.a.[1]
Thermal efficiency	%	31.0	25.5	34.7	27.7	n.a.[1]	n.a.[1]
Fuel burning rate	g/min	11.7	9.3	14.3	11.4	6.4	7.9
Temperature-corrected specific fuel consumption	g/liter	69.7	119.5	61.9	92.2	44.9	55.5
Temperature-corrected specific energy use	kJ/liter	1277	2189	1134	1690	822	1017
Fire power	W	3582	2829	4355	3488	1966	2414
Cooking power	W	1110	721	1515	966	n.a.[1]	n.a.[1]
Modified combustion efficiency	%	99.4	98.5	99.5	98.9	96.1	97.3
$PM_{2.5}$ temperature-corrected total mass	mg	264.0	628.5	327.9	305.1	181.1	346.3
mass per effective volume of water	mg/liter	54.6	138.1	67.9	64.8	42.0	82.0
mass per fuel mass (raw)	mg/kg	566.6	783.8	779.8	469.0	956.8	1056.1
mass per equivalent dry fuel mass	mg/kg	783.1	1178.8	1084.6	705.0	944.9	1476.4
mass per fuel energy	mg/MJ	42.8	64.3	59.2	38.5	51.6	80.5
mass per useful energy delivered (to water in pot)	mg/MJ	138.3	255.3	172.4	139.0	n.a.[1]	n.a.[1]
mass per time	mg/hour	549.3	648.7	925.8	483.2	362.3	701.2
CO temperature-corrected total mass	g	2.20	9.52	1.55	5.29	8.42	7.52
mass per effective volume of water	g/liter	0.45	2.10	0.32	1.13	1.96	1.78
mass per fuel mass (raw)	g/kg	4.72	11.75	3.70	8.12	43.91	23.12
mass per equivalent dry fuel mass	g/kg	6.50	17.63	5.16	12.23	43.73	32.05
mass per fuel energy	g/MJ	0.36	0.96	0.28	0.67	2.39	1.75
mass per useful energy delivered (to water in pot)	g/MJ	1.15	3.78	0.82	2.41	n.a.[1]	n.a.[1]
mass per time	g/hour	4.59	9.78	4.40	8.39	16.84	15.19
CO_2 temperature-corrected total mass	g	565	975	488	748	325	418
mass per effective volume of water	g/liter	117	215	101	159	76	99
mass per fuel mass (raw)	g/kg	1,213	1,203	1,165	1,147	1,694	1,279
mass per equivalent dry fuel mass	g/kg	1,680	1,803	1,637	1,724	1,685	1,783
mass per fuel energy	g/MJ	92	98	89	94	92	97
mass per useful energy delivered (to water in pot)	g/MJ	296	386	258	340	n.a.[1]	n.a.[1]
mass per time	g/hour	1,183	1,002	1,404	1,182	650	846
THC (as C_3H_8) temperature-corrected total mass	g	0.25	1.39	0.22	0.60	0.58	1.12
mass per effective volume of water	g/liter	0.05	0.31	0.05	0.13	0.13	0.27
mass per fuel mass (raw)	g/kg	0.54	1.73	0.52	0.92	3.01	3.41
mass per equivalent dry fuel mass	g/kg	0.75	2.59	0.75	1.40	2.93	4.75
mass per fuel energy	g/MJ	0.04	0.14	0.04	0.08	0.16	0.26
mass per useful energy delivered (to water in pot)	g/MJ	0.13	0.56	0.12	0.27	n.a.[1]	n.a.[1]
mass per time	g/hour	0.53	1.43	0.65	0.96	1.20	2.26
CH_4 temperature-corrected total mass	g	0.06	0.30	0.03	0.13	0.19	0.28
mass per effective volume of water	g/liter	0.01	0.07	0.01	0.03	0.04	0.07
mass per fuel mass (raw)	g/kg	0.12	0.36	0.07	0.21	0.99	0.84
mass per equivalent dry fuel mass	g/kg	0.17	0.55	0.10	0.31	0.98	1.17
mass per fuel energy	g/MJ	0.01	0.03	0.01	0.02	0.05	0.06
mass per useful energy delivered (to water in pot)	g/MJ	0.03	0.12	0.02	0.06	n.a.[1]	n.a.[1]
mass per time	g/hour	0.12	0.30	0.08	0.22	0.37	0.56
NO_X temperature-corrected total mass	g	0.24	0.42	0.21	0.33	0.12	0.16
mass per effective volume of water	g/liter	0.05	0.09	0.04	0.07	0.03	0.04
mass per fuel mass (raw)	g/kg	0.51	0.52	0.50	0.51	0.63	0.50
mass per equivalent dry fuel mass	g/kg	0.71	0.78	0.70	0.76	0.62	0.70
mass per fuel energy	g/MJ	0.04	0.04	0.04	0.04	0.03	0.04
mass per useful energy delivered (to water in pot)	g/MJ	0.12	0.17	0.11	0.15	n.a.[1]	n.a.[1]
mass per time	g/hour	0.50	0.43	0.60	0.52	0.24	0.33

[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*

Parameter	Units	High-power cold-start		High-power hot-start		Low-power 30-minute simmer	
Fuel moisture (wet basis)	**%**	**8.3**	**17.6**	**8.5**	**19.0**	**8.5**	**22.0**
OC temperature-corrected total mass	mg	91.7	402.6	89.8	107.0	89.3	225.1
mass per effective volume of water	mg/liter	19.0	88.5	18.6	22.8	20.7	53.4
mass per fuel mass (raw)	mg/kg	196.8	496.1	213.1	164.6	475.2	684.0
mass per equivalent dry fuel mass	mg/kg	274.0	751.2	295.0	250.0	466.1	960.9
mass per fuel energy	mg/MJ	15.0	41.0	16.1	13.6	25.5	52.4
mass per useful energy delivered	mg/MJ	48.1	162.8	47.1	48.9	n.a.	n.a.
mass per time	mg/hour	191.8	415.1	251.6	172.0	178.6	456.6
EC temperature-corrected total mass	mg	241.2	165.2	311.6	207.1	80.1	76.1
mass per effective volume of water	mg/liter	49.9	36.4	64.6	44.0	18.6	18.0
mass per fuel mass (raw)	mg/kg	517.6	201.0	740.4	317.7	415.7	233.9
mass per equivalent dry fuel mass	mg/kg	713.2	306.5	1029.0	478.2	415.7	326.7
mass per fuel energy	mg/MJ	38.9	16.7	56.2	26.1	22.7	17.8
mass per useful energy delivered	mg/MJ	126.3	66.5	163.7	94.2	n.a.	n.a.
mass per time	mg/hour	500.2	169.9	878.0	327.8	160.2	154.4
Mass fraction of OC/TC	-	0.275	0.709	0.224	0.341	0.527	0.747
Mass fraction of EC/TC	-	0.725	0.291	0.776	0.659	0.473	0.253

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)	**%**	**8.3**	**17.6**	**8.5**	**19.0**	**8.5**	**22.2**
BC temperature-corrected total mass	mg	259.7	246.9	333.1	216.8	78.9	81.4
mass per effective volume of water	mg/liter	53.7	54.7	69.0	46.1	18.3	19.3
mass per fuel mass (raw)	mg/kg	557.0	301.5	791.9	332.1	411.5	249.5
mass per equivalent dry fuel mass	mg/kg	767.2	452.6	1098.8	498.8	410.9	348.4
mass per fuel energy	mg/MJ	41.9	24.7	60.0	27.2	22.4	19.0
mass per useful energy delivered	mg/MJ	136.0	96.5	175.1	98.5	n.a.	n.a.
mass per time	mg/hour	537.4	254.0	936.1	341.7	157.8	164.9

Discussion of Results and Observations

As shown in the Results Summary, the BioLite HomeStove's cooking power was 1313 W (average of cold-start and hot-start test phases of the WBT) with low-moisture fuel. As shown in Figure 2, cooking power for the HomeStove was similar to that of the 3-stone fire, while fire power for the HomeStove was less due to its better efficiency. The HomeStove is rated at Tier 2 for Efficiency/Fuel Use, as shown in Figure 3. MCE was better at high-power than at low-power, as shown in Figure 4. The previously tested Philips HD4012 forced-draft stove had better thermal efficiency (without a pot skirt) and better MCE at low-power, but it required extra fuelwood preparation (10 cm or less in length), while the HomeStove has the advantage of using fuelwood sticks with long lengths – similar to fuelwood used in many traditional stoves.

The HomeStove is rated at Tier 3 for 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 5 and 6, 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 HomeStove is rated at the same Sub-Tiers for Emissions as the previously tested Philips HD4012 stove.

As shown in the Results Summary, the HomeStove is rated at Tier 2 for Indoor Emissions, and the lowest Sub-Tier value is for high-power $PM_{2.5}$ emissions, as shown in Figure 7. 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 HomeStove does not have a chimney.

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.

As expected, performance was generally better with low-moisture fuel than with high-moisture fuel, as shown in Tables 13-15. With low-moisture fuel, fuel consumption was lower, thermal efficiency was higher, cooking power was higher, and air pollutant emissions were mostly lower. Emissions of particle-phase organic carbon were lower with low-moisture fuel, and emissions of elemental and black carbon were somewhat lower with high-moisture fuel, as shown in Tables 14-15.

Average cooking power was greater during the hot-start test phase (see Tables 2 and 8) than during the cold-start (Tables 1 and 7), because the stove's thermal mass absorbs more heat during cold-start.

The HomeStove performed without any problems during testing. The HomeStove is simple to operate – similar to typical rocket stoves. With its cast iron components, the HomeStove is similar in weight to some portable stoves with ceramic components, and it is heavier than previously tested portable metal stoves. BioLite has experience developing the successful CampStove for the recreational market, and the HomeStove has a high-quality manufactured appearance. For more information, see the BioLite web site (14).

Quality Assurance/Quality Control

A Quality Assurance Project Plan meeting EPA requirements (15) 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" (16).

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 16. Test replicates were rejected if the carbon balance or any other measurement quality objectives (described below) were unacceptable.

Table 16. *Carbon balance, percent difference based on fuel carbon*

Fuel Moisture	Test phase	Units	Test 1	Test 2	Test 3	Test 4
			06/07/2013	06/20/2013	06/21/2013	06/25/2013
Low	High-power cold-start	%	Rejected[1]	10.6	11.4	-1.2
	High-power hot-start	%	10.7	16.7	8.9	1.0
	Low-power (simmer)	%	0.9	8.3	6.8	-0.2
			07/09/2013	07/10/2013	02/21/2014	02/28/2014
High	High-power cold-start	%	3.1	0.0	-0.7	1.1
	High-power hot-start	%	8.2	7.4	Rejected[2]	4.2
	Low-power (simmer)	%	4.6	3.4	-7.2	Rejected[3]

[1] Rejected due to improper ignition of fuel

[2] Rejected due to fuel burning rate too high

[3] Rejected due to fuel burning rate too high

The carbon balance is an overall indicator of many of the critical measurements included as measurement quality objectives listed in Table 17. 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.

Table 17. *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 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 D5865-04	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 sample flow rate	EPA RTP Met Lab SOP, FV-0205.3	Flow cal., Classifier Flow cal., CPC	± 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

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