# [Insert lab logo]

Laboratory Testing of the [insert Stove name]

In compliance with ISO 19867-1:2018

Including fuel use and emissions

Prepared by [insert writer’s name], [insert writer’s position], on [insert date]

Prepared for: [insert client]

# [Insert picture of stove]

Figure 1 [Stove name] [brief stove description].

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# List of acronyms

|  |  |
| --- | --- |
| # | number count |
| ARC | Aprovecho Research Center |
| BC | Black Carbon |
| C | degrees of temperature Celsius |
| cal | calibration |
| CI | Confidence Interval |
| cm | centimeter |
| CO | carbon monoxide |
| CO2 | carbon dioxide |
| g | gram of mass |
| H | hydrogen |
| Hg | mercury |
| hr | hour |
| ISO | International Organization for Standardization |
| J | joule |
| kW | kilowatt |
| L/min | liters per minute |
| LEMS | Laboratory Emissions Monitoring System |
| m/s | meters per second |
| mg | milligram |
| min | minute |
| MJ | Megajoule |
| MJd | megajoules delivered |
| N | nitrogen |
| NVLAP | National Voluntary Laboratory Accreditation Program (USA) |
| O | oxygen |
| PM2.5 | Particulate Matter with aerodynamic diameter ≤ 2.5 micrometers |
| ppm | parts per million |
| QC | Quality Control |
| Rel | relative |
| RH | Relative Humidity |
| SD | Standard Deviation |
| µg | micro-gram |

# Executive Summary

The [insert stove name] was received at the [insert lab name] Laboratory on [insert date]. Standard laboratory tests were carried out using the ARC Laboratory Emissions Monitoring System (LEMS) and the ISO 19867-1:2018 Water Heating Test at three power levels. This report contains quality control documentation to validate the test data against ISO quality requirements. *[Insert brief description of stove, how it was fed, and what fuel/species was used]. The primary ISO metrics are provided in* Table 1 *and are shown against the ISO 19867-3:2018 Voluntary Tiers of Performance. The stove was rated Tier [insert tier value] for thermal efficiency with and without char, Tier [insert tier value] for PM2.5 emissions, and Tier [insert tier value] for CO emissions.*

Table 1 Summary of results

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Metric** | | **Test Sequence Phase** | | | | **Tier Rating** |
| **High** | **Medium** | **Low** | **Combined** |
| Thermal Efficiency without char (%) | Mean | 52.1 | - | - | 52.1 | 4 |
| SD | 2.6 | - | - | 2.6 |
| 90% CI | 40.6 - 63.6 | - | - | 40.6 - 63.6 |
| Thermal Efficiency with char (%) | Mean | 54 | - | - | 54 | 4 |
| SD | 2.5 | - | - | 2.5 |
| 90% CI | 43.0 - 65.1 | - | - | 43.0 - 65.1 |
| Char Energy Productivity (%) | Mean | 3.8 | - | - | 3.8 | N/A |
| SD | 0.4 | - | - | 0.4 |
| Char Mass Productivity (%) | Mean | 1.9 | - | - | 1.9 | N/A |
| SD | 0.2 | - | - | 0.2 |
| Cooking Power (kW) | Mean | 2.1 | - | - | N/A | |
| SD | 0.1 | - | - |
| Fuel Burning Rate (g/min) | Mean | 12.8 | - | - | N/A | |
| SD | 1 | - | - |
| PM2.5 per useful energy (mg/MJ) | Mean | - | - | - | - | nan |
| SD | - | - | - | - |
| 90% CI | - | - | - | - |
| CO per useful energy (g/MJ) | Mean | 3.9 | - | - | 3.9 | 5 |
| SD | 0.6 | - | - | 0.6 |
| 90% CI | 1.2 - 6.5 | - | - | 1.2 - 6.5 |
| Safety | Score |  | | | | N/A |
| Durability | Score |  | | | | N/A |

# 1. Introduction

## 1.1 Description of the cookstove system tested

A cookstove system consists of the stove, cooking vessel, pot skirt, 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 tested.

The [insert stove name] is a [insert stove fed type (continuously fed or batch fed)], [insert stove type (rocket, TLUD, sunken pot, etc] stove. The [inset stove name] stands at [insert stove height] cm tall. The system consists of a [description of what the system includes (brief stove description, if there’s a skirt, if there’s a removable combustion chamber, if there’s grate, f there’s a stick shelf, if there’s a pot, etc.)]. The [insert pot diameter] cm [insert pot brand/source if known] [insert pot capacity] L pot [insert a description of how the pot goes on the stove if it sits on top, what supports it, what’s the air gap. If it’s sunken, how big is the gap]. [Insert explanation of why the pot goes on the stove the way it does – ideal heat transfer, ease of use, copy of local custom, etc.]. [Insert any safety features added to the stove and how they protect the user]. [Insert any other notable information regarding the stove system]

# 2. Methods

### 2.1 Stove and operating procedures

The [insert stove name] stove is a [insert stove fed type (continuously fed or batch fed)]. To operate the stove at different power levels, the amount of [insert method for changing power (air control, feed rate/number of stick, or combustion chamber size. If the stove is a single powered stove, replace this sentence with an explanation of how it is single powered] varied. Testing was conducted with [insert fuel dimension and type (wood, pellets, charcoal, etc)]. For the high power tests, [insert number of sticks used or weight of fuel] were used. For the medium power tests, [insert number of sticks used or weight of fuel] were used. For the low power tests, [insert number of sticks used or weight of fuel] were used. [Insert feeding methodology, how was the fuel fed to the stove]. Power was monitored by the operator using the LEMS, adjusting [insert ‘feed rate’, ‘air control’, or ‘feed rate and air control’ depending on what was used] to maintain power.

#### 2.1.1 Starting sequence

To light the fire, [insert weight of kindling] of kindling [insert accelerant type and if the kindling was soaked or the accelerant was added on top] were placed in the stove and arranged for optimal burning. On ignition, the desired fuel load was placed on top of the kindling [change description for batch fed stoves].

### 2.1.2 Fuel

The stove was loaded with pieces of [insert type of fuel and species] that had dimensions of [insert dimensions of fuel] and a moisture content of [insert moisture content] (wet basis). The fuel had a lower heating value of *[insert lower heating value* J/g (dry sample). Moisture and higher heating value measurements were made at [insert lab name] using [insert methodology for moisture and higher heating value measurements]. The elemental composition of the fuel was determined at [insert source].

The fuel was sourced from [insert where wood was bought (local market name, area location)] and consists of off [describe what the fuel consists of (construction cutoffs, fallen wood/branches, market quality fuel, etc.). The [insert fuel species] was [cut or sorted] to a particular [cross section and shape or size distribution]. A cross section of [insert standard lab cross section] cm is the standard lab size used by the [insert lab name] lab in the absence of other field-based specifications.

The Higher Heating Value of the [dry wood or other fuel] was [insert higher heating value] J/g as determined by [insert source. Either calorimeter or similar measurement or trusted source], and the Higher Heating Value of the made charcoal was [insert higher heating value] J/g.

The Lower Heating Value of both the wood and the charcoal was calculated based on the method specified in the ISO protocol, which depends on the chemical composition of the fuel. The percentage of H, O, and N of the wood was [assumed or measured] to be [insert percentage H], [insert percentage O], and [insert percentage N] respectively. The charcoal the percentages were assumed to be [insert percentage H], [insert percentage O], and insert percentage N] respectively ([insert source if used, Baldwin, 1987 is a reliable source]). The resulting Lower Heating Value of the wood was [insert lower heating value] J/g, and for the charcoal it was [insert lower heating value] J/g.

The Effective Heating Value of the wood was found to be [insert higher heating value] J/g using the calculation specified in the ISO protocol which is dependent on moisture content.

### 2.1.3 The cooking vessel

A [insert pot diameter] cm diameter by [insert pot height] cm tall [flat bottom or round bottom] pot was used. The pot is constructed of [insert wall thickness] mm [insert pot material]. It was filled with [insert liters of water used] L of water, a value that is consistent with local practices. *[Insert if a pot skirt was or was not used during the test].*

## 2.2 Laboratory operational conditions

The environmental conditions of the laboratory were measured before and after each test. The air temperature was between [insert lowest temperature] C and [insert highest temperature] C. The RH was between [insert lowest RH] % and [insert highest RH] %. The atmospheric pressure was between [insert lowest atmospheric pressure] in Hg and [insert highest atmospheric pressure] in Hg. [Insert if the wind speed was measured or not. If it was, insert the measurement. If it was not, insert the justification (indoor measurement with windows and doors closed had an assumed 0 windspeed)].

## 2.3 Testing Procedure

### 2.3.1 Standard ISO protocol

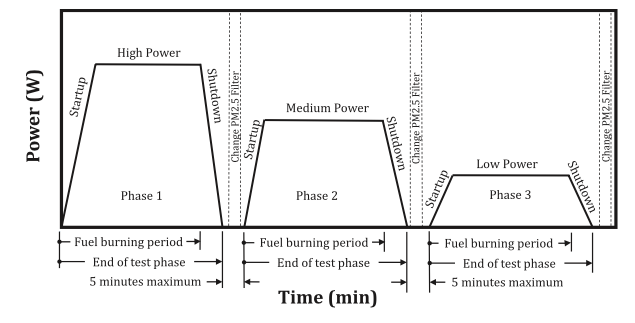


Figure 2 Diagram of the testing phases for a stove tested at three power levels (ISO, 2018).

ISO 19867-1:2018 provides a laboratory test for cookstoves to be evaluated with performance metrics such as thermal efficiency and emissions released per unit energy delivered to the cooking pot. The procedure primarily involves heating or boiling and evaporating water, but each test phase is carried out for 30 minutes (plus shutdown time) at an attempted constant power level. The simulated cooking task for all three power levels is to heat water in a pot. Energy that goes into the pot is accounted for by measuring, over the test period, the temperature rise of the water and the amount of water that evaporates. The mass of emissions released by the stove is measured during the full combustion cycle, which includes the startup phase, the steady state phase, and the shutdown phase. The ISO protocol calls for each power level test to be carried out in sequence. The high power test is therefore done with the stove body at room temperature, and the medium and low power tests are therefore done with the stove body heated by the fire to well above ambient temperature. The heated condition is referred to as a hot start.

### 2.3.2 Deviations from the standard ISO protocol

[If no deviation were performed, state ‘No deviations’. If deviations to the standard protocol were performed, list the deviation, justification for the change, and observed impact to the test.]

## 2.4 Emissions and Fuel Measurements

Evaluation of a cookstove with ISO 19867-1:2018 consists of measurements that are related to fuel use, emissions, safety, and durability. The instruments used to take the measurements are described in the following sections.

### 2.4.1 Fuel use

The direct measurements needed to evaluate the fuel use of a cookstove during the test are the mass of the water that was heated in the pot, the mass of water that was evaporated out of the pot, the mass of fuel used, and the temperature change of the water in the pot. Physical constants related to the fuel that are also needed are the lower heating value and moisture content of the fuel, as well as the water boiling temperature and its latent heat of evaporation. For these tests, a balance with 1 g resolution was used to obtain the masses, a silicone shielded thermocouple was used to obtain the water temperature, a bomb calorimeter was used to measure the higher heating value of the fuel, an *elemental analyzer* was used to determine the lower heating value of the fuel, and [‘an oven was used to dry the fuel in order to determine its moisture content.’ or ‘a moisture meter was used on the ends and middle of three fuel pieces to determine the moisture content.’].

### 2.4.2 Emissions

Emissions measurements were made with the ARC Laboratory Emissions Monitoring System (LEMS). The LEMS has been manufactured by ARC since 2009 and is in use in laboratories worldwide. The LEMS is a total capture dilution tunnel emissions sampler with a pump and filter system for measuring PM2.5 mass, a light scattering sensor for detecting PM2.5 emissions events against time, and integrated CO and CO2 gas sensors that are calibrated against reference gasses. The dimensions of the hood, the length of the dilution tunnel, and the location of the sample ports are in compliance with ISO 19867-1:2018.

The gas and PM2.5 sensors measure concentrations (mass/volume). The volumetric flow rate through the dilution tunnel, which is needed to calculate emission factors (mass/useful energy delivered) and rates (mass/time), is determined through a measurement of the gas temperature within the tunnel and the differential pressure across a Nailor FSA-06 Pitot static flow grid. The flow grid and its pressure transducer are calibrated against a Dwyer inclined oil manometer. The flow grid pressure amplification factor is calibrated via a velocity traverse using a Dwyer standard Pitot static tube and an ARC manufactured support bracket. The temperature sensors are calibrated against the theoretical phase change temperatures of water at local atmospheric pressure.

The CO sensor is an Alphasense CO-AF with a range of 0 to 5000 ppm. The calibrated range is from 0 to 500 ppm using reference gas from Mesa labs certified to within 1% of nominal. The temperature of the sample gas is measured near the sample port using an LM35 thermistor. The temperature induced zero and span drift of the Alphasense CO-AF is controlled in post processing based on a separate LM35 temperature measurement of the sample gas within the CO sensor housing. The lower limit of detection of the CO emissions factor (energy delivered basis) using the LEMS dilution tunnel is within Tier 5.

The CO2 sensor is a CozIR-A GC-00022 with a range of 0 to 10,000 ppm. The calibrated range is 0 to 8000 ppm using reference gas from Mesa labs certified to within 1% of nominal. The CozIR has onboard temperature compensation.

The pump and filter PM2.5 mass measurement system includes a rotometer to monitor the sample flow rate. The sample flow rate is controlled by a critical orifice. The rotometer and critical orifice are calibrated against a Bubble-O-Meter Quad manually operated bubble meter with volume graduations that are NIST traceable. The pre- and post-test masses of the 47 mm glass fiber filter are measured with a 0.01 mg resolution balance (Citizen CX265). It features an internal calibration weight. The accuracy and precision of the balance are monitored with an NVLAP (National Voluntary Laboratory Accreditation Program) certified external calibration weight that has a mass of 0.5 g +- 10 ug. A filter is used for each test phase, and the filters are conditioned for moisture load level in a desiccator prior to each measurement of their mass. The lower limit of detection for the gravimetric PM2.5 measurement of emissions factors (energy delivered basis) using the LEMS dilution tunnel is within Tier 4 at 0.01 mg balance resolution when the sample flow rate is about 33 L/min.

## 2.5 Metrics

The three primary performance metrics are thermal efficiency and fugitive emissions of CO and PM2.5 released per unit energy delivered to the cooking pot. Fugitive emissions are the emissions that escape from a cookstove into the surrounding space of the cooking environment, as opposed to total emissions which includes emissions that are removed via a chimney. These metrics have been mapped against Voluntary Tiers of Performance in ISO Technical Report 19867-3:2018. The maximum Tier score is 5 and the minimum score is 0. Separate tier ratings are specified for each metric. A Tier score of 0 indicates no improvement over the open fire. A Tier score of 5 for Thermal Efficiency means that the stove has the highest performance when compared against existing technology. A Tier of 5 for PM2.5 or CO means that almost all users would not face adverse health effects from the stove as tested. Actual field use is known to result in higher emissions for many stove and fuel types. ISO 19867-3 also includes tier ratings for safety and durability.

Thermal efficiency is defined as the quotient of energy delivered to the water in the cooking vessel over the energy expended by the fire. For biomass burning stoves, thermal efficiency is presented with and without an energy credit given for the char that is produced by the stove. Thermal Efficiency without char is applicable when users do not use the char remaining after cooking as fuel. Thermal Efficiency with char is applicable when users use the char remaining after cooking as fuel.

The amount of charcoal produced by biomass burning stoves is quantified as “Char mass productivity” and “Char energy productivity”. Both metrics are expressed as percentages. Char mass productivity is the mass of charcoal created divided by the mass of the wood consumed. Char energy productivity is similarly defined, but on an energy basis.

Emissions per energy delivered to the cooking pot is a derived metric. It is calculated by dividing the mass of the emissions that were released by the stove by the amount of energy that the stove delivered to the cooking pot.

The firepower of the stove is presented because it often influences the emission rates. The firepower is the rate of energy released by the fire. The burn rate of the fuel on a dry fuel basis is shown for the same reason.

The cooking power is presented and is defined as the rate of energy that goes into the cooking pot and is used to compare stoves on the basis of their potential to complete a cooking task within a specified time.

The measured emissions rates are presented because they may be used to estimate room emissions concentrations using models such as the single-zone box model. An implementation of the box model is available at aprovecho.org under the “Project Planning” menu item.

## 2.6 Voluntary Tiers of Performance

To better understand the results of this stove testing report, the essential definitions of the Voluntary Tiers of Performance for emissions that are presented in ISO 19867-3:2018 are paraphrased here. The Tiers of performance for PM2.5 are based on the relative risk that children face of contracting an acute lower respiratory tract infection when exposed to a particular level of PM2.5. A Tier score of 5 corresponds to a relative risk of 1 (no extra risk compared to breathing clean air), and Tier 0 corresponds to a relative risk greater than 3.15. Tiers 1 to 4 represent a range of relative risk between Tiers 0 and 5.

The Tiers for CO have four different mappings because less is known about the effects of low, chronic dosages. The primary mapping is the percent of homes that meet the WHO 24-hour air quality guideline of 6 ppm. Tier 1 is greater than or equal to 20% of homes meet the guideline, Tier 4 is greater than or equal to 80% of homes, with Tiers 2 and 3 evenly spaced. Tier 5 is greater than or equal to 90% of homes.

The secondary mapping for CO is the percent of homes in which the cook is exposed to less than an average of 230 mg/m3 (200 ppm) during the cooking event. After 2-3 hours at this level of exposure the cook experiences, according to footnote b of Table 11 in ISO 19867-3:2018, a “slight headache and impaired judgment”. For Tier 1 it is greater than or equal to 90% of homes, for Tier 2 it is greater than or equal to 97.1% of homes, and for the higher Tiers it is all above 99%.

The third and fourth mappings for CO show the estimated 24 hr concentration and the cooking event concentration for 50% of homes that use a cookstove with the given emission rate.

### 2.6.1 Statistical analysis and repeatability quality standard

For each metric, the report includes the confidence interval of the average (labeled conservative bound and upper bound in the tables in the Results section). The confidence interval was calculated using Student’s t-distribution at a confidence level of 90%. The ISO 19867-3:2018 Voluntary Tiers of Performance were calculated using the conservative bound of the confidence interval for each metric.

[Insert: ‘At least 5 test replicates were conducted for each power level (high, medium, and low) per ISO 19867-1:2018, “A minimum of five replicate tests shall be performed for each cookstove/fuel combination, and the number of replicates shall be reported. If greater statistical confidence is desired to meet user needs (e.g. for rating against performance targets), then more than five replicate tests should be conducted.”

Although not a requirement of the ISO standard,[insert lab name] desired greater statistical confidence, so additional tests were made until the range of the 90% confidence interval was less than 1/2 of the range of the Tier that contained the conservative bound of the confidence interval.’ If a higher statistical confidence was achived.]

# 3. Results

The results of each individual test are reported (Appendix A). The average results for each power level, and the average of the three power levels are shown in Table 2. *The simple arithmetic mean was used to report the average of the three power levels in the absence of field derived weighting factors.*

For each metric, in addition to the average result, the report includes the confidence interval (labeled CI in the Tables) and the standard deviation of the test replicates (labeled SD). The confidence interval was calculated using the Student’s t-distribution at a confidence level of 90%.

Table 2 Summary of results

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Metric** | | **Test Sequence Phase** | | | | **Tier Rating** |
| **High** | **Medium** | **Low** | **Combined** |
| Thermal Efficiency without char (%) | Mean | 52.1 | - | - | 52.1 | 4 |
| SD | 2.6 | - | - | 2.6 |
| 90% CI | 40.6 - 63.6 | - | - | 40.6 - 63.6 |
| Thermal Efficiency with char (%) | Mean | 54 | - | - | 54 | 4 |
| SD | 2.5 | - | - | 2.5 |
| 90% CI | 43.0 - 65.1 | - | - | 43.0 - 65.1 |
| Char Energy Productivity (%) | Mean | 3.8 | - | - | 3.8 | N/A |
| SD | 0.4 | - | - | 0.4 |
| Char Mass Productivity (%) | Mean | 1.9 | - | - | 1.9 | N/A |
| SD | 0.2 | - | - | 0.2 |
| Cooking Power (kW) | Mean | 2.1 | - | - | N/A | |
| SD | 0.1 | - | - |
| Fuel Burning Rate (g/min) | Mean | 12.8 | - | - | N/A | |
| SD | 1 | - | - |
| PM2.5 per useful energy (mg/MJ) | Mean | - | - | - | - | nan |
| SD | - | - | - | - |
| 90% CI | - | - | - | - |
| CO per useful energy (g/MJ) | Mean | 3.9 | - | - | 3.9 | 5 |
| SD | 0.6 | - | - | 0.6 |
| 90% CI | 1.2 - 6.5 | - | - | 1.2 - 6.5 |
| Safety | Score |  | | | | N/A |
| Durability | Score |  | | | | N/A |

# 4. Discussion

## 4.1 Interpretation of data and limitations

Testing a described stove system with repeatable methods provides a basis for comparison across stoves. When another stove is tested in the same manner, statistically significant differences can be determined. Analyzing stove performance at different power levels provides information on how the stove performs over a range of operating conditions.

Cooking in the field can be different in many ways. These test results and Tier ratings are therefore not intended to serve as the sole basis for decisions about which technologies/fuels to promote for a given setting, since the performance of a given technology will likely differ under real-use conditions. The best way to assess real-world impacts of a stove intervention or program is through field studies, see ISO 19869:2019, as well as other existing methods.

In addition to the limitations arising from differences from real-world performance, laboratory test metrics (efficiency, emissions, safety, and durability) do not inform other factors that are critical to the impacts a product, program, or intervention may achieve. These factors include, but are not limited to, geographic/cultural suitability, price-affordability, acceptability to the target user group, and other socio-economic factors.

# 5. References

ISO, 2018. International Standards Organization, “Cookstoves and clean cooking solutions – harmonized laboratory test protocols part 1: Standard test sequence for emissions and performance, safety and durability, ISO 19867-1:2018”. 2018

# 

# Appendix A - Detailed Test Data

Table 3 Low-power test replicate results for performance and emissions

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Metric** | **Units** | **Mean** | **SD** | **Test 1** | **Test 2** |
| Fuel mass, dry | kg | - | - | - | - |
| Fuel moisture content (wet basis) | % | 16.2 | 0 | 16.3 | 16.3 |
| Thermal efficiency with char | % | - | - | - | - |
| Thermal efficiency without char | % | - | - | - | - |
| Char energy productivity | % | - | - | - | - |
| Char mass productivity | % | - | - | - | - |
| Fuel burning rate (dry basis) | g/min | - | - | - | - |
| Cooking power | kW | - | - | - | - |
| Modified combustion efficiency | N/A | - | - | - | - |
| PM2.5 total mass | N/A | - | - | - | - |
| PM2.5 mass per dry fuel mass | N/A | - | - | - | - |
| PM2.5 mass per fuel energy | N/A | - | - | - | - |
| PM2.5 mass per useful energy delivered | N/A | - | - | - | - |
| PM2.5 mass per time | N/A | - | - | - | - |
| CO total mass | N/A | - | - | - | - |
| CO mass per dry fuel mass | N/A | - | - | - | - |
| CO mass per fuel energy | N/A | - | - | - | - |
| CO mass per useful energy delivered | N/A | - | - | - | - |
| CO mass per time | N/A | - | - | - | - |
| CO2 total mass | N/A | - | - | - | - |
| CO2 mass per dry fuel mass | N/A | - | - | - | - |
| CO2 mass per fuel energy | N/A | - | - | - | - |
| CO2 mass per useful energy delivered | N/A | - | - | - | - |
| CO2 mass per time | N/A | - | - | - | - |
| BC total mass | N/A | - | - | - | - |
| BC mass per dry fuel mass | N/A | - | - | - | - |
| BC mass per fuel energy | N/A | - | - | - | - |
| BC mass per useful energy delivered | N/A | - | - | - | - |
| BC mass per time | N/A | - | - | - | - |

Table 4 Medium-power test replicate results for performance and emissions

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Metric** | **Units** | **Mean** | **SD** | **Test 1** | **Test 2** |
| Fuel mass, dry | kg | - | - | - | - |
| Fuel moisture content (wet basis) | % | 16.2 | 0 | 16.3 | 16.3 |
| Thermal efficiency with char | % | - | - | - | - |
| Thermal efficiency without char | % | - | - | - | - |
| Char energy productivity | % | - | - | - | - |
| Char mass productivity | % | - | - | - | - |
| Fuel burning rate (dry basis) | g/min | - | - | - | - |
| Cooking power | kW | - | - | - | - |
| Modified combustion efficiency | N/A | - | - | - | - |
| PM2.5 total mass | N/A | - | - | - | - |
| PM2.5 mass per dry fuel mass | N/A | - | - | - | - |
| PM2.5 mass per fuel energy | N/A | - | - | - | - |
| PM2.5 mass per useful energy delivered | N/A | - | - | - | - |
| PM2.5 mass per time | N/A | - | - | - | - |
| CO total mass | N/A | - | - | - | - |
| CO mass per dry fuel mass | N/A | - | - | - | - |
| CO mass per fuel energy | N/A | - | - | - | - |
| CO mass per useful energy delivered | N/A | - | - | - | - |
| CO mass per time | N/A | - | - | - | - |
| CO2 total mass | N/A | - | - | - | - |
| CO2 mass per dry fuel mass | N/A | - | - | - | - |
| CO2 mass per fuel energy | N/A | - | - | - | - |
| CO2 mass per useful energy delivered | N/A | - | - | - | - |
| CO2 mass per time | N/A | - | - | - | - |
| BC total mass | N/A | - | - | - | - |
| BC mass per dry fuel mass | N/A | - | - | - | - |
| BC mass per fuel energy | N/A | - | - | - | - |
| BC mass per useful energy delivered | N/A | - | - | - | - |
| BC mass per time | N/A | - | - | - | - |

Table 5 High-power test replicate results for performance and emissions

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Metric** | **Units** | **Mean** | **SD** | **Test 1** | **Test 2** |
| Fuel mass, dry | kg | 0.2 | 0 | 0.2 | 0.2 |
| Fuel moisture content (wet basis) | % | 16.2 | 0 | 16.3 | 16.3 |
| Thermal efficiency with char | % | 54 | 2.5 | 52.3 | 55.8 |
| Thermal efficiency without char | % | 52.1 | 2.6 | 50.2 | 53.9 |
| Char energy productivity | % | 3.8 | 0.4 | 4.1 | 3.5 |
| Char mass productivity | % | 1.9 | 0.2 | 2 | 1.7 |
| Fuel burning rate (dry basis) | g/min | 12.8 | 1 | 13.4 | 12.1 |
| Cooking power | kW | 2.1 | 0.1 | 2.2 | 2.1 |
| Modified combustion efficiency | mol/mol | 1 | 0 | 1 | 1 |
| PM2.5 total mass | g | - | - | - | - |
| PM2.5 mass per dry fuel mass | g/kg | - | - | - | - |
| PM2.5 mass per fuel energy | g/MJ | - | - | - | - |
| PM2.5 mass per useful energy delivered | mg/MJ | - | - | - | - |
| PM2.5 mass per time | mg/min | - | - | - | - |
| CO total mass | g | 9.5 | 1.6 | 8.3 | 10.6 |
| CO mass per dry fuel mass | g/kg | 39 | 7.8 | 33.6 | 44.5 |
| CO mass per fuel energy | g/MJ | - | - | - | - |
| CO mass per useful energy delivered | g/MJ | 3.9 | 0.6 | 3.5 | 4.3 |
| CO mass per time | g/min | 0.5 | 0.1 | 0.5 | 0.5 |
| CO2 total mass | g | 460 | 7.8 | 465.5 | 454.5 |
| CO2 mass per dry fuel mass | g/kg | 1888.3 | 22.2 | 1872.6 | 1904.1 |
| CO2 mass per fuel energy | g/MJ | - | - | - | - |
| CO2 mass per useful energy delivered | g/MJ | 188.4 | 6.7 | 193.2 | 183.7 |
| CO2 mass per time | g/min | 24 | 1.6 | 25.1 | 22.9 |
| BC total mass | N/A | - | - | - | - |
| BC mass per dry fuel mass | N/A | - | - | - | - |
| BC mass per fuel energy | N/A | - | - | - | - |
| BC mass per useful energy delivered | N/A | - | - | - | - |
| BC mass per time | N/A | - | - | - | - |

# Appendix B - Time Resolved CO and CO2 Data for Each Test

[Insert subtractbkg\_1.png file in the first test replicate file]

Figure 3 Time resolved CO and CO2 concentrations in the dilution tunnel for the first test replicate

[Insert subtractbkg\_1.png file in the second test replicate file]

Figure 4 Time resolved CO and CO2 concentrations in the dilution tunnel for the second replicate

[Insert subtractbkg\_1.png file in the third test replicate file]

Figure 5 Time resolved CO and CO2 concentrations in the dilution tunnel for the third replicate

[Insert subtractbkg\_1.png file in the fourth test replicate file (if performed)]

Figure 6 Time resolved CO and CO2 concentrations in the dilution tunnel for the fourth replicate

[Insert subtractbkg\_1.png file in the fifth test replicate file (if performed)]

Figure 7 Time resolved CO and CO2 concentrations in the dilution tunnel for the fifth replicate

# Appendix C - Quality Control

The variability in results between repeated tests is due to a combination of variability in the performance of the cookstove system, operating conditions, limitations of measurement techniques, and instrument performance. Cookstove systems, especially those using solid fuels, can have variable performance that is reflected in variable results, but the variability due to operating conditions and measurement techniques can be minimized by following the test protocols as closely as possible. Measurement bias and variability from instrument performance can also be minimized through careful maintenance, calibration and proper usage. Nevertheless, measurement instruments have limits to their precision, accuracy, and reliability, which inherently contribute to measurement variability and uncertainty. The level of confidence required (which is directly related to the level of precision, accuracy, and resolution needed) depends not only on protocol parameters but also on the goal of the tests being conducted. Reporting instrument performance metrics provides an indication of the quality of measurements and the degree to which the instrumentation has the ability to accurately resolve the relevant stove performance metrics.

The ISO protocol contains measurement acceptance criteria that are used to assure that high quality data are obtained. Two tables from the standard containing most of the acceptance criteria are recreated here for reference (Table 6, Table 7). Full quality control data is available upon request.

Table 6 Measurement acceptance criteria (ISO, 2018)

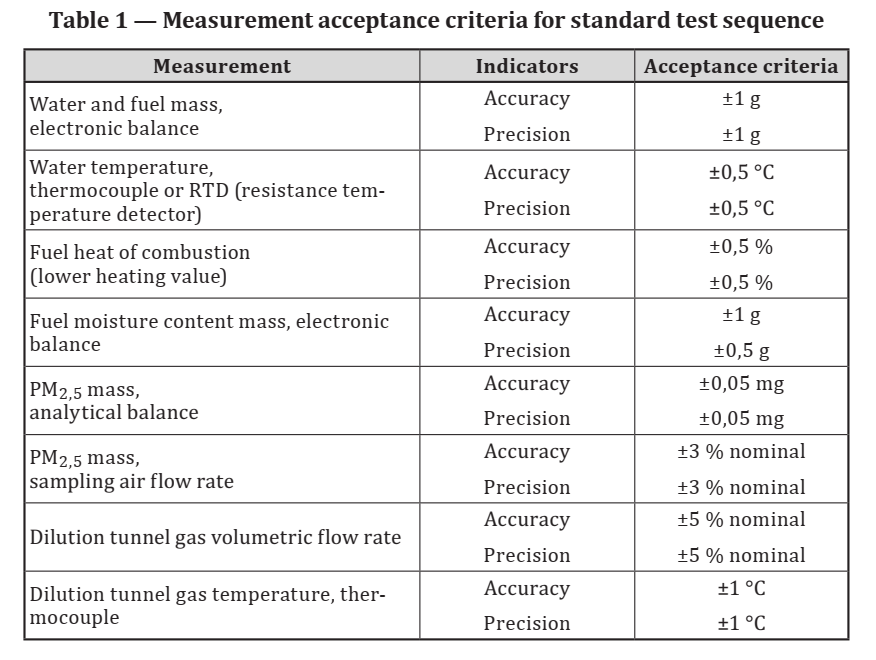
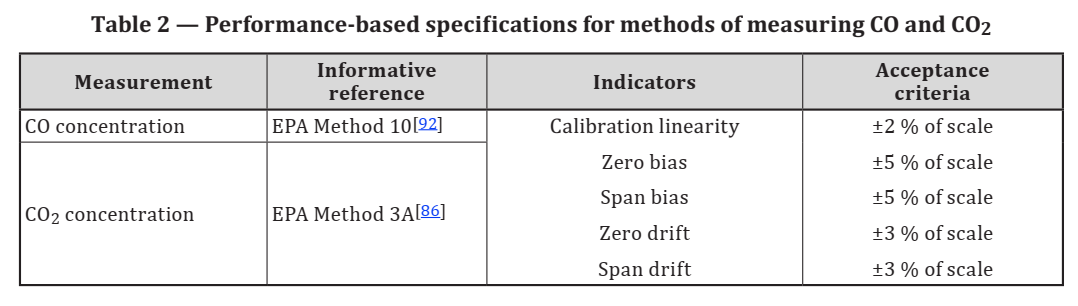


Table 7 Measurement acceptance criteria for CO and CO2 (ISO, 2018)



The quality control data presented here are included to show that the test results are based on measurements that meet the quality control acceptance criteria. Table 9 shows all quality control checks that were taken before, during, and after each test to ensure that the data collected is accurate.

The first section of Table 9 details the information of the stove tested, the fuel species used, the data, and other details for reference.

The second section of Table 9 details the quality control checks performed to ensure the PM2.5 measurements were accurate during each test. A leak check was performed before each test on each gravimetric train used. This leak check involved applying a negative pressure to the system using the gravimetric pump and measuring the change in pressure in the system over a given time. Acceptance criteria is defined as within 3% of the nominal flow rate which is controlled by a critical orifice rated for 16.7 L/min at sea level. Additional checks were made for each power level tested. The mass scattering cross section is not a part of the ISO standard. It is the relationship between the measurement of the light scattering PM2.5 sensor included internally in the ARC LEMS and the gravimetric measurements. A mass scattering cross section that is outside of the typically observed range may indicate other errors and is therefore included in the verification checks.

The balance used to weigh the filters has a precision and accuracy of +/- 20 ug as determined by repeated measurements of a NVLAP certified reference mass over a period of several weeks. ISO requires that the net filter weight be greater than 10 times the precision and accuracy of the balance. The ‘filter mass threshold’ confirms if this criteria has been met. The ISO protocol requires measuring the filters after conditioning in a desiccator, and then again after 6 more hours of conditioning until the average weight of the sets agree within 0.05 mg. The set till convergence in Table 9 tracks the number of times the filter was conditioned and weighed until convergence criteria was met for the clean (tare) filter and the loaded (gross) filter. Before each set, a certified 5 mg weight was weighed to test the calibration of the scale. If the set of weights closely agreed with the certified mass, the balance cal check was marked as ‘Pass’. Additionally, before each weighing set, the desiccator temperature and relative humidity that the filter was conditioned at was recorded.

Quality control measures related to the performance of the dilution tunnel are shown in in the third section of Table 9. The “average flow rate” is shown along with the standard deviation of the time resolved measurement. If 2x the standard deviation of the flow rate is less than 5% of the average, then the acceptance criteria for the precision of the dilution tunnel volumetric flow rate is met. This measure indicates that approximately 95% of the time resolved measurements are within 5% of the average, and indicates that the flow is constant to within the acceptance criteria of the ISO standard.

The “hood flow capture” metric indicates whether or not the capture efficiency test was performed during the test series. The standard indicates that a visual inspection must be performed to determine whether smoke leaves the hood face during operation.

Results of the pressure sensor leak checks are show. These checks were performed by applying negative and positive pressure to the respective sides of the flow grid with the ISO acceptance criteria that the leak rate shall be less than +/- 3%. The calibration factor used for the flow grid and the static pressure within the dilution tunnel as determined by a velocity traverse is included for reference.

The CO and CO2 sensors were bias checked immediately before the tests were carried out. Zero and span bias checks were carried out before each test. When the bias checks are carried out before and after a single test the drift can be calculated over the single test. When the bias checks are carried out over the period of several tests the drift is calculated over the period of several tests. Acceptance criteria for bias and leak checks are show in Table 7.

Before each test, a leak check was performed on the gas sampling system to ensure that the sample was not contaminated with additional ambient air. A positive pressure was applied to the system and the change in pressure was observed over a period of time. According to the ISO protocol, the acceptance criteria was 0.1% of the sampling flow rate at operating pressure.

Environmental conditions are shown in Table 9 in the final section. The standard dictates that the test must be carried out in an environment with a temperature between 5 and 40 C, and with a wind speed of less than 1 m/s as determined before and after the test. The humidity and ambient pressure are recorded, but no acceptance criteria are given in the Standard.

Background concentrations of CO, CO2, and PM2.5 are shown as evidence that they were measured. The average value before and after the test is subtracted from the values obtained during the test period, as specified in the Standard. The CO and CO2 concentrations are measured before and after the test, since the LEMS measures them at a frequency of between 1 Hz and 0.25 Hz. During tests of Tier 5 stoves, the PM2.5 background is determined using a second filter that is run during the measurement period. The filters are weighed with a 1 ug resolution balance.

The carbon balance during each test is shown in Table 8. It is not a required metric of the standard, but it is highly recommended within the standard for quality assurance. Values above 1g/g and below 0.1 g/g can indicate measurement errors.

Table 8 Background emissions and carbon balance results for each test.

|  |  |  |  |
| --- | --- | --- | --- |
| **Background Emissions** | | | |
| CO Concentration Before Test | ppm | 0.299 | -0.386 |
| CO2 Concentration Before Test | ppm | 753.921 | 735.86 |
| PM Concentration Before Test | Mm^-1 | 10709.702 | 11285.426 |
| CO Concentration After Test | ppm | 1.301 | 1.224 |
| CO2 Concentration After Test | ppm | 736 | 725.344 |
| PM Concentration After Test | Mm^-1 | 11000.724 | 11624.305 |
| **Carbon Balance** | | | |
| **High Power** | | | |
| Carbon In High Power | g | 121.899 | 117.356 |
| Carbon Out High Power | g |  |  |
| Carbon In to Carbon Out | g/g |  |  |
| **Medium Power** | | | |
| Carbon In Medium Power | N/A |  |  |
| Carbon Out Medium Power | N/A |  |  |
| Carbon In to Carbon Out | N/A |  |  |
| **Low Power** | | | |
| Carbon In Low Power | N/A |  |  |
| Carbon Out Low Power | N/A |  |  |
| Carbon In to Carbon Out | N/A |  |  |

The current values for the low frequency calibrations are shown in Table 10. The low frequency calibrations are: the dilution tunnel flow rate accuracy, as determined by a Pitot tube velocity traverse, the accuracy of the PM2.5 sample flow rate through the filter, as determined with a Buck mini-Buck calibrator manual bubble meter, the accuracy and precision of the temperature measurement of the test water and dilution tunnel gas, as determine by ice and boiling water reference, and the accuracy and precision of the electronic balances that are used to measure the water and fuel masses, as determined with a set of reference weights totaling 3500 g.

Table 9 Quality control activity results before, during, and after each test.

|  |  |  |  |
| --- | --- | --- | --- |
| **Stove Information** | | | |
| Stove type/model | |  |  |
| Location | |  |  |
| Fuel species | | df | df |
| Date | |  |  |
| **PM2.5 Quality Control** | | | |
| Gravimetric A Leak Rate | l/min | 0.000000 |  |
| Gravimetric A Leak Check | Pass/Fail | PASS |  |
| Gravimetric B Leak Rate | l/min | 0.001307 |  |
| Gravimetric B Leak Check | Pass/Fail | PASS |  |
| **High Power** | | | |
| Mass Scattering Cross Section High Power | m^2/g | nan | nan |
| Net Filter Weight High Power | g | 1.0 | 1.0 |
| Balance Cal Check High Power | pass/fail | pass | pass |
| Filter Mass Threshold High Power | pass/fail | PASS | PASS |
| Tare Sets Till Convergence High Power | # |  |  |
| Gross Sets Till Convergence High Power | # |  |  |
| Gravimetric A Flow Rate Check High Power | pass/fail |  |  |
| Gravimetric B Flow Rate Check High Power | pass/fail |  |  |
| Desicator Temperature High Power | C | 22 |  |
| Desicator Relative Humidity High Power | % | 22 |  |
| **Medium Power** | | | |
| Mass Scattering Cross Section Medium Power | N/A |  |  |
| Net Filter Weight Medium Power | N/A |  |  |
| Balance Cal Check Medium Power | pass/fail | fail |  |
| Filter Mass Threshold Medium Power | N/A |  |  |
| Tare Sets Till Convergence Medium Power | # |  |  |
| Gross Sets Till Convergence Medium Power | # |  |  |
| Gravimetric A Flow Rate Check Medium Power | pass/fail |  |  |
| Gravimetric B Flow Rate Check Medium Power | pass/fail |  |  |
| Desicator Temperature Medium Power | C |  |  |
| Desicator Relative Humidity Medium Power | % |  |  |
| **Low Power** | | | |
| Mass Scattering Cross Section Low Power | N/A |  |  |
| Net Filter Weight Low Power | N/A |  |  |
| Balance Cal Check Low Power | pass/fail |  |  |
| Filter Mass Threshold Low Power | N/A |  |  |
| Tare Sets Till Convergence Low Power | # |  |  |
| Gross Sets Till Convergence Low Power | # |  |  |
| Gravimetric A Flow Rate Check Low Power | pass/fail |  |  |
| Gravimetric B Flow Rate Check Low Power | pass/fail |  |  |
| Desicator Temperature Low Power | C |  |  |
| Desicator Relative Humidity Low Power | % |  |  |
| **Dilution Tunnel Quality Control** | | | |
| Hood Total Capture | pass/fail |  |  |
| Flow Grid Calibration Factor | N/A |  |  |
| Negative Pressure Leak Rate | % |  |  |
| Negative Pressure Leak Check | pass/fail |  |  |
| Positive Pressure Leak Rate | % |  |  |
| Positive Pressure Leak Check | pass/fail |  |  |
| Static Pressure of Dilution Tunnel | N/A |  |  |
| **High Power** | | | |
| Dilution Tunnel Average Flow Rate High Power | m^3/sec | 0.131 | 0.13 |
| Dilution Tunnel Standard Deviation High Power | m^3/sec | 0.002 | 0.002 |
| Dilution Tunnel Flow Check | pass/fail | PASS | PASS |
| **Medium Power** | | | |
| Dilution Tunnel Average Flow Rate Medium Power | N/A |  |  |
| Dilution Tunnel Standard Deviation Medium Power | N/A |  |  |
| Dilution Tunnel Flow Check | N/A |  |  |
| **Low Power** | | | |
| Dilution Tunnel Average Flow Rate Low Power | N/A |  |  |
| Dilution Tunnel Standard Deviation Low Power | N/A |  |  |
| Dilution Tunnel Flow Check | N/A |  |  |
| **Gas Sensor Quality Control** | | | |
| Gas Sensor Leak Rate | N/A |  |  |
| Gas Sensor Leak Check | Pass/Fail |  |  |
| **CO** | | | |
| Zero Bias | N/A |  |  |
| Span Bias | N/A |  |  |
| Zero Drift | N/A |  |  |
| Span Drift | N/A |  |  |
| Zero Bias QC | Pass/Fail |  |  |
| Span Bias QC | Pass/Fail |  |  |
| Zero Drift QC | Pass/Fail |  |  |
| Span Drift QC | Pass/Fail |  |  |
| **CO2** | | | |
| Zero Bias | N/A |  |  |
| Span Bias | N/A |  |  |
| Zero Drift | N/A |  |  |
| Span Drift | N/A |  |  |
| Zero Bias QC | Pass/Fail |  |  |
| Span Bias QC | Pass/Fail |  |  |
| Zero Drift QC | Pass/Fail |  |  |
| Span Drift QC | Pass/Fail |  |  |
| **Environmental Quality Control** | | | |
| Initial Wind Speed | m/s | 0 | 0 |
| Final Wind Speed | m/s | 0 | 0 |
| Wind Speed Check | pass/fail | PASS | PASS |
| Initial Room Temperature | C | 16 | 12 |
| Final Room Temperature | C | 16 | 12 |
| Temperature Check | pass/fail | PASS | PASS |

Table 10 Current values of low frequency calibrations

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Low Frequency Lab Instruments Calibration Status |  |  |  |  |  |  |
| Measurement | Instrument | Indicator | Acceptance Criteria | Actual Value | Last Calibration Date | Start Date of Record |
| Water and fuel mass | MyWeigh CTS 30000 | Accuracy | 1 g | <0.5 |  |  |
|  |  | Precision | 1 g | <0.5 |  |  |
| Water temperature | Type K thermocouple, silicone shielded and sealed, LEMS DAQ | Accuracy | 0.5 C | 0.2 |  |  |
|  |  | Precision | 0.5 C | <0.5 |  |  |
| Fuel moisture content mass | Citizen CN 3Z | Accuracy | 1 g | 0.1 |  |  |
|  |  | Precision | 0. 5 g | 0.1 |  |  |
| PM2.5 Mass, sampling air flow | Critical orifice, Lenox Laser, 1387 micron | Accuracy | 3% nominal | 1.2% nominal |  |  |
|  |  | Precision | 3% nominal | <3% | Every test |  |
| Dilution tunnel gas volumetric flow rate | Nailor FSA-06 Pitot tube array | Accuracy | 5% nominal |  |  |  |
|  |  | Precision | 5% nominal |  | Every test |  |
| Dilution tunnel gas temperature | RTD LM 35, stainless steel shielded and sealed, LEMS DAQ | Accuracy | 1.0 C |  |  |  |
|  |  | Precision | 1.0 C | <1.0 |  |  |