

The Water Boiling Test

Version 4.2.3

*Cookstove Emissions and Efficiency
in a Controlled Laboratory Setting*

Released 19 March 2014

Summary of updates 4.2.3:

The spreadsheet has been updated to include:

- Options to use carbon balance and total capture methods for emissions,
- More worksheets for up to 10 test replicates,
- Corrections of remaining calculation errors,
- Updates to the input and calculations of duct temperature
- Formatting improvements, and
- A new worksheet to facilitate uploading to the clean cooking catalog.

The protocol document has been updated to include instructions for these new features. For a complete description of updates, please reference the document “WBT 4.2.3 Spreadsheet Changes” located on the Testing Protocols website at <http://www.cleancookstoves.org/our-work/standards-and-testing/learn-about-testing-protocols/>.

Summary of major updates 4.2 (Released 26 January 2013):

Addresses comments from public comment period ending December 1, 2009. The comment period was organized by U.S. Environmental Protection Agency, Partnership for Clean Indoor Air (PCIA), with updates coordinated by PCIA and the Global Alliance for Clean Cookstoves (Alliance).

Updated to reflect International Organization for Standardisation (ISO) International Workshop Agreement (IWA).

Calculation errors have been corrected.

Language and formatting updates to improve clarity and readability.

Appendices 2 and 4 are being updated to reflect these changes, and an updated version to the WBT will be released.

Responses to comments from technical committee may be found at:

<http://www.cleancookstoves.org/our-work/standards-and-testing/learn-about-testing-protocols/>

Table of Contents

I.	Introduction and Background	2
A.	Benefits and limitations of the WBT	2
B.	Emission testing.....	3
C.	Interpretation of Water Boiling Test measures	3
D.	Document structure	4
II.	Water Boiling Test (WBT) Overview	5
A.	Emission testing.....	5
III.	Preparing the Laboratory	6
A.	Calibration	6
B.	Obtain the required equipment	6
C.	Obtain the calculation spreadsheet	7
D.	Determine the local boiling point.....	7
E.	Set up emission measurements, optional	7
IV.	Preparing for Testing	8
A.	Safety and Health	8
B.	Testing a New Stove	8
C.	Selecting Fuel and Pot(s) for Testing.....	8
D.	Daily Preparation.....	9
V.	Water Boiling Test Protocol.....	10
A.	Time Required	10
B.	Important Considerations for Testing	10
C.	Preparation for each set of 3 Water Boiling Tests	10
D.	Preparation for each Water Boiling Test.....	12
E.	Instructions for WBT Phases	13
	WBT Phase 1: High Power (Cold Start)	13
	WBT Phase 2: High Power (Hot Start).....	16
	WBT Phase 3: Low Power (Simmering).....	18

F.	Completion	20
VI.	Interpreting Results of the Water Boiling Test.....	22
A.	Commonly used measures	22
B.	Cautions.....	22
C.	Stove characteristics.....	22
D.	Efficiency metrics	23
E.	Emission metrics.....	24
F.	Additional measures.....	24
	Appendix 1. Preparation for the Water Boiling Test	25
1.1	Holding the Thermocouple in the Pot	25
1.2	Determining Local Boiling Point	26
1.3	Determining Fuel Moisture Content	26
	Appendix 2. Modifications to the Water Boiling Test	28
2.1	Non-Wood Fuels.....	28
2.2	Multi-pot stoves	29
	High-power tests.....	29
	Low-power test.....	30
	Appendix 3. History of the Water Boiling Test	31
	Appendix 4. Calculation of WBT Performance Metrics.....	33
4.1	Variables that are Constant Throughout All Three Phases	33
4.2	Variables for High Power Phase (Cold Start).....	35
4.3	Variables for High Power Phase (Hot Start)	46
4.4	Variables for Low Power Phase (Simmering)	48
4.5	IWA Performance Metrics.....	52
4.6	IWA Performance Tiers.....	55
	Appendix 5. Statistics Lessons for Performance Testing	57
	Appendix 6. Emission Measurement.....	59
6.1	Which pollutants should be measured?	59

6.2 Capturing the exhaust 59

6.3 Data collection 61

6.4 Relating pollutant concentrations to fuel burned 62

 Exhaust flow..... 62

 Carbon balance 62

6.5 Pollutant measurements..... 63

 Carbon monoxide 64

 Method 1: Electrochemical (real-time) 64

 Method 2: Non-dispersive infrared (real-time)..... 64

 Particulate matter..... 64

 Method 1: Gravimetric (integrated)..... 64

 Method 2: Optical (real-time) 65

 Other methods 65

 Carbon dioxide..... 65

 Method 1: Non-dispersive infrared (NDIR, real-time)..... 65

 Method 2: Inference based on oxygen content 66

 Exhaust flow rate 66

 Oxygen content..... 66

6.6 A caution about packaged analyzers..... 67

6.7 Data acquisition 67

6.8 Summary 68

6.9 Citations 68

Appendix 7. Data entry sheets 71

Appendix 8. Remaining challenges for the WBT and Testing Protocols..... 76

 Needs for additional protocols 76

 Additional studies to address remaining questions..... 76

 Additional diagnostic measures 77

 Wood type and moisture content..... 77

<i>Water Boiling Test, version 4.2.3</i>	6
Pot insulation	78
Test sequence	78
Thermal efficiency.....	78
Humidity in ambient air	79
Power to Boil.....	81
Appendix 9 – Requirements for Testing for ISO International Workshop Agreement	82

I. INTRODUCTION AND BACKGROUND

The Water Boiling Test (WBT) is a simplified simulation of the cooking process. It is intended to measure ***how efficiently a stove uses fuel to heat water in a cooking pot*** and the ***quantity of emissions produced while cooking***.

A. BENEFITS AND LIMITATIONS OF THE WBT

The WBT test for efficiency can be performed throughout the world with simple equipment. (If emissions are measured, more complex equipment is required.) Its primary benefits are:

- Provide initial or laboratory assessments of stove performance in a controlled setting
- Compare the effectiveness of different designs at performing similar tasks
- Evaluate stove changes during development
- Select the most promising products for field trials
- Ensure that manufactured stoves meet intended performance based on designs

All standardized tests involve trade-offs. When conditions are highly controlled and variability is reduced, a test is better able to detect small changes. However, a more controlled test is often less representative of actual cooking. Controlled tests are appropriate to compare various technical aspects of stove design and pre-field evaluations of performance. While lab-based tests allow differentiation between stoves, field-based tests give better indication of performance during actual use.

The Water Boiling Test was developed to assess stove performance in a controlled manner, and thus it is probably less like local cooking than other tests described below. Although the WBT is a useful tool for the reasons given above, it's important to remember its limitations. It is an approximation of the cooking process and is conducted in controlled conditions by trained technicians. Laboratory test results might differ from results obtained when cooking real foods with local fuels, even if efficiency and emissions were measured in exactly the same way for both tests. In order to confirm desired impacts (whether it is fuel conservation, smoke reduction, or other impacts), stoves must be measured under real conditions of use.

To understand how stoves perform with local foods, cooking practices, and fuels, stove testers may use the Controlled Cooking Test (CCT) that has been developed in parallel with the WBT. The CCT is still a lab test but is conducted by preparing a standardized version of a local meal. The Uncontrolled Cooking Test (UCT) which is conducted in the field during which the cooks choose any meal they want, operate the stove in any manner they feel is appropriate and using any pots they feel suited to the tasks. A Kitchen Performance Test (KPT), which compares fuel consumption in households using the improved stove to households using a traditional stove, should be conducted to evaluate changes in fuel consumption among stove-users. This field test includes two qualitative surveys: the first helps implementers (project designers, manufacturers, distributors, or investors) to assess household cooking behavior and practices prior to the introduction of a new stove and the other provides follow-up data 3-6 months after the stove has been introduced in a household. The KPT also includes a procedure to compare fuel consumption in households using different types of stoves. Field tests are also important for demonstrating results for carbon credits and estimating

contributions to greenhouse gas emissions or air pollution. ***Field testing is critical to justify claims about real impacts on fuel consumption, greenhouse gas emissions, or air pollution resulting from the stoves.*** This document describes the Water Boiling Test only. Instructions for the other lab-based tests, the Controlled Cooking Test, Uncontrolled Cooking Test, and Kitchen Performance Test are given in separate documents, with updates made available at www.cleancookstoves.org.

This test was originally designed for stoves that burn wood, but has been adapted to accommodate other types of stoves and fuels. See Appendix 2 for a discussion of the use of non-woody fuels.

Advanced testers who are interested in evaluating additional variables that may impact stove performance may consult comments posted at www.cleancookstoves.org.

B. EMISSION TESTING

Fuel efficiency was a primary driver for early cookstove programs. We now know that air pollutants emitted from solid-fuel use have many health and environmental impacts. This document contains instructions for measuring pollutants emitted by the stove during the cooking process, but these steps can be omitted for those without the necessary equipment. Efficiency and emissions must be tested with the same protocol, because changes in stove operation and design affect both.

While fuel consumption is a relatively simple measurement, determining pollutant measurements is significantly more complicated. In addition to guidelines for measuring fuel efficiency, the WBT also provide guidelines for measuring pollutants and obtaining performance metrics for the stove. Combining these metrics with efficiency measurements, we can determine another useful parameter: emissions per task. The WBT measures of emissions: not *what people are exposed to*, but *what pollutants leave the stove*. This is a more direct way to compare two stoves than indoor air concentration. Other organizations have developed important protocols for determining indoor exposures. Computational models have also been developed to estimate indoor air concentrations based on stove emissions and other parameters.

C. INTERPRETATION OF WATER BOILING TEST MEASURES

An excellent stove will have good measures of efficiency, emissions, and other performance such as time-to-boil. Intermediate stoves may not perform as well in one of these categories. Stove programs, distributors, and users have individual priorities, which should be communicated to testers and designers. Results may vary with tester experience, and testing should be done by well-trained technicians. The Alliance is working with the global network of regional testing and knowledge centers (RTKCs) to ensure trained technicians to perform the WBT.

D. DOCUMENT STRUCTURE

The main chapter in this document includes only the protocol (steps) that testers will perform repeatedly. Other instructions, the detailed equations implemented in the Water Boiling Test, and some historical notes are given in the Appendices, which are listed below.

Appendix 1 (Preparation for the Water Boiling Test) should be read carefully before performing any tests.

Appendix 2 (Modifications to the Water Boiling Test) is needed if common cooking practices include non-wood stoves or multi-pot stoves.

Appendix 3 (History of the Water Boiling Test), Appendix 4 (Calculations Used to Determine Performance Metrics), and Appendix 8 (Outstanding Issues with the WBT) may be of interest to testers who wish to understand the history and technical issues of the test.

Appendix 4 (Calculation of WBT Performance Metrics) explains the equations that are used to calculate the performance metrics in the Excel workbook.

Appendix 5 (Statistics Lessons for Performance Testing) should be read by all testers at some time, although it is not necessary to begin exploring testing.

Appendix 6 (Emission Measurement) should be read carefully to perform emission measurements.

Appendix 7 (Data Entry Forms) provides forms that can be printed for hand recording of data.

Appendix 8 (Remaining Challenges for the WBT and Testing Protocols) may be of interest to testers who wish to understand remaining technical issues to be resolved.

Appendix 9 (Requirements for Testing for ISO International Workshop Agreement) describes recent developments for international standards for cookstove performance and testing requirements in the ISO IWA.

II. WATER BOILING TEST (WBT) OVERVIEW

The WBT consists of three phases that immediately follow each other. These are discussed below and shown graphically in Figure 1. The entire WBT should be conducted at least three times for each stove, which constitutes a WBT test set. The test workbook for WBT 4.2.3 can accommodate results for up to 10 tests.

- 1) For the **cold-start high-power phase**, the tester begins with the stove at room temperature and uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. The tester then replaces the boiled water with a fresh pot of ambient-temperature water to perform the second phase.
- 2) The **hot-start high-power phase** is conducted after the first phase while stove is still hot. Again, the tester uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. Repeating the test with a hot stove helps to identify differences in performance between a stove when it is cold and when it is hot. This is particularly important for stoves with high thermal mass, since these stoves may be kept warm in practice.
- 3) The **simmer phase** provides the amount of fuel required to simmer a measured amount of water at just below boiling point for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world.

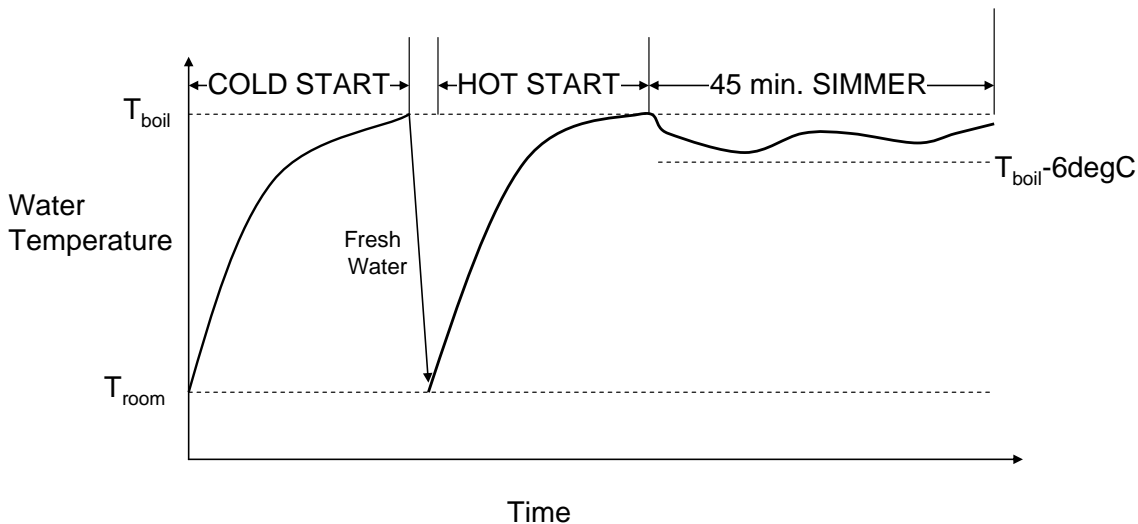


Figure 1. Temperature during the three phases of the water boiling test. (Figure credit: Nordica MacCarty)

A full stove test should always include all three test phases. A quick test for a laboratory's internal use may include only the cold-start and simmer phases if the stove has low mass (no ceramic) and previous WBTs have shown that the cold-start and hot-start phases produce the same results.

A. EMISSION TESTING

This basic testing protocol includes optional instructions (Appendix 6) for measuring carbon monoxide (CO), particulate matter (PM), and carbon dioxide (CO₂) concentrations in the stove's exhaust. Other pollutants may also be measured.

III. PREPARING THE LABORATORY

This section describes steps needed to prepare your laboratory for testing. Calibration should be done regularly. The other steps need to be done only once at each location.

A. CALIBRATION

Equipment, including the thermocouple, scales, emission equipment, should be regularly calibrated to ensure standardization of results. Air flow measuring stations in dilution tunnels can be calibrated using a pitot tube. Thermocouples can be calibrated using thermometric fixed points (i.e. ice bath and boiling water). Filter sampling systems should be leak checked under negative pressure. Barometric pressure sensors can be calibrated using an automated pressure calibrator. Relative humidity sensors can be calibrated using aqueous salt solutions. Balances and stopwatches can be checked for accuracy with test masses and a reference clock, respectively. For emissions equipment, calibration can be done with zero checks and using compressed gases. All major components should be checked to ensure operability and repaired when required. Laboratory equipment maintenance should be conducted as recommended by the manufacturer and on an as-needed basis.

Consult other resources, for example U.S. EPA Standard Operating Procedures, for further information and guidelines about frequency of calibration.

B. OBTAIN THE REQUIRED EQUIPMENT

- Scale with a capacity of at least 6 kg and accuracy of ± 1 gram
- Heat resistant material to protect scale
- Digital Thermometer, accurate to 0.5 degree C, with thermocouple probe suitable for immersion in liquids
- Wood moisture meter OR oven for drying wood and scale for weighing (moisture meter is less accurate, especially for very wet wood)
- Timer
- Tape measure for measuring wood and stove (cm)
- Standard pots: pots that are used in your region and have a volume of about 7 liters (for 5-L tests) or 3.5 liters (for 2.5-L tests). For each size, you should choose a standard shape (height and circumference) that is used in your area.
- Wood or metal fixture for holding thermocouple in water (see Appendix 1.1)
- Small shovel/spatula to remove charcoal from stove
- Tongs for handling charcoal
- Dust pan for transferring charcoal
- Metal tray to hold charcoal for weighing
- Heat resistant gloves
- (Optional) Emissions equipment (See Appendix 6)

C. OBTAIN THE CALCULATION SPREADSHEET

Measurements from the WBT can be recorded in the Excel workbook titled

WBT_data-calculation_sheet_4.2.3.xls

which is provided at the Standards and Testing protocols website: <http://www.cleancookstoves.org/our-work/standards-and-testing/learn-about-testing-protocols/>. This spreadsheet uses the equations in Appendix 4. You may also do the calculations by hand, by following the equations in Appendix 4. The WBT and Excel workbook may be updated and WBT_data-calculation_sheet_4.2.3.xls may not be the most current version. **Please make sure you have the latest version of the workbook and protocol by visiting the website.**

This document assumes that you will be using the Excel spreadsheet. It indicates the sheets within the spreadsheet where the data will be entered like this: [*NameOfSheet*] sheet. For example, results of the tests are shown in the [*Results*] sheet.

The [*IWA Summary*] sheet is the latest IWA Tier Reporting form previously available only as a separate Word document, now included as part of the template for easy communication of results.

You will not need to use the [*Calorific values*] and [*Lists*] sheets. These sheets contain data that are used for calculations throughout the spreadsheet.

The [*Catalog Import Data*] sheet contains summary metrics from the spreadsheet which allows for direct upload into the Clean Cooking Catalog located at <http://catalog.cleancookstoves.org/>. Do not edit the information on this worksheet or change its location (last), as this will result in an error in test result upload.

D. DETERMINE THE LOCAL BOILING POINT

See Appendix 1.2.

E. SET UP EMISSION MEASUREMENTS, OPTIONAL

See Appendix 6.

IV. PREPARING FOR TESTING

A. SAFETY AND HEALTH

To ensure the safety and health of the tester, a breathing mask and eye protection should be used.

B. TESTING A NEW STOVE

Perform at least one *practice test* on each type of stove. The tester should perform enough tests to become familiar with the testing procedure and with the characteristics and operation of the stove. This will provide an indication of how much fuel is required to boil the required amount of water.

New stoves should also be seasoned (used a few times) prior to testing as stove performance can vary based on how often the stove has been used. New stoves often have ceramic components which contain unknown amounts of moisture. It is helpful to run the stove first to drive off any moisture before conducting any tests. If a scale is available to weigh the stove, the stove should be run until the weight of the stove stabilized. This should be done with a small fire because large ceramic components can easily be damaged if fired quickly.

C. SELECTING FUEL AND POT(S) FOR TESTING

- 1) Determine the *type and characteristics of fuel* you will use. The type, size and moisture content of fuel have a large effect on the outcome of stove performance tests. For that reason, ***all tests of a single stove, or all tests to compare designs or stoves, must be done with fuel of the same type and moisture content, and similar size.*** Obtain all of the fuel from the same source if possible.

There isn't a prescribed standard dimension or level of moisture for all tests. Testers may use fuel (type, size, moisture content) that is readily available in their area. See also section on page 20 on "Changes to Testing Conditions to Improve Repeatability" for discussion on standard fuel types, dimensions, and moisture content.

Solid fuel should be well dried and uniform in size. Remember that wood of 3-4 cm in diameter may take from 3-8 months to dry fully, although dung or crop residues may take less time. Drying can be accelerated by circulating air through stored wood. Document the fuel type, moisture content, and size.

Fuel between 1.5 cm x 1.5 cm to 3 cm x 3 cm is suggested. If comparability between labs is a goal for your tests, use wood with cross-sectional dimensions of 1.5 cm x 1.5 cm.

- 2) Determine the *type of pot* you will use, and record its size and shape. The 7-liter pot should be used except for the following situations:
 - a) The stove is designed for a much smaller pot and cannot boil 5 liters of water (use the 3.5-liter pot),
or
 - b) It is extremely uncommon to boil as much as 5 liters of water in your region (use the 3.5-liter pot);
or
 - c) The stove is designed for a specific pot (use the pot for which it was designed).

If you use the 7-liter pot, use 5 liters of water for each phase of the WBT. If you use the 3.5-liter pot, use 2.5 liters of water for each phase

Although some of the WBT metrics are normalized to the amount of water boiled, results should not be compared for stoves of different sizes. Conducting tests with a standard sized pot improves repeatability and comparability. See also Box on page X “Changes to Testing Conditions to Improve Repeatability.”

D. DAILY PREPARATION

Preparation for each day’s testing may be done the previous day.

- 1) *Find your space.* Make sure that there is adequate space and sufficient time to conduct the test without being disturbed. Testing should be done indoors in a room that is protected from wind, but with sufficient ventilation to vent harmful stove emissions. Wind or air draft changes heat transfer between the stove and the pot and will affect the results of the test, and should be avoided.
- 2) *Prepare fuel.* Prepare and weigh one bundle of fuel for each WBT that will be conducted. Each bundle should be at least **5 kg**. More fuel may be needed for some stoves, including high mass stoves. If kindling will be used to start the fire, it should be prepared ahead of time and included in the pre-weighed bundles of fuel.
- 3) *Determine moisture content* of the fuel to be used. See the guidelines in Appendix 1.2.
- 4) *Prepare water.* At least **10 liters of water** (or 5 liters for small pots) for each pot being used are required for the three phases of the WBT. If water is scarce in your area, water used one day may be cooled and reused in the next day’s testing. Water should be at ambient temperature prior to the test. Do not start any tests with water that is hotter than room temperature.

V. WATER BOILING TEST PROTOCOL

A. TIME REQUIRED

It will take 1½ - 2 hours to do the high (cold and hot starts) and low power phases for one stove. It will take 4 ½ - 6 hours to do one set of three WBTs for one stove.

B. IMPORTANT CONSIDERATIONS FOR TESTING

- 1) The *cooking system* includes a stove, a fuel, a pot, and an operator. All four affect the performance of the system.
- 2) No test should require the stove to perform a task that would not occur during its normal operation.
- 3) You should use the *same fuel and pot* for each test if you wish to compare designs or stoves. However, you should never use a fuel or pot for which a stove was not designed.
- 4) The *operation of the stove* has a large effect on the outcome of stove performance tests. All tests of a single stove, and all tests to evaluate design improvements, must be done with consistent operation of the stove. Document the operation with written procedures, photos, and videos (if possible).

C. PREPARATION FOR EACH SET OF 3 WATER BOILING TESTS

- 1) Create a new Excel workbook for each set of three tests by making a copy of “WBT_data-calculation_sheet_4.2.3.xls”. Excel files should *always* have a unique name or code number.

You, the tester, should fill out all **gray cells** and **cells with listboxes** (choices). Other cells are calculations.

- 2) Fill out the [*General Information*] sheet. A copy of this sheet is given in Appendix 7 if you wish to fill it out by hand. This sheet asks you to record:
 - a) Test and Stove Description
 - **Name of Tester(s)**
 - **Test Number or Code**
 - **Test Dates**
 - **Test Year**
 - **Test Location**
 - **Replicate Test Number (if you are performing more than 3 sets of tests)**
 - **Altitude**

- **Stove Type/Model**
 - **Manufacturer**
 - **Description and Notes about the stove***
 - **Description of Pot(s)**
- b) Ambient Conditions
- **Air relative humidity (%)**
 - **Local boiling point of water (determined using Appendix 1.2) (°C)**
- c) Emission Testing (optional)
- **Atmospheric pressure (kPa)**
 - **Pitot delta-P**
 - **Hood flow rate (m³/hr)**
- d) **Notes or description about stove or operation not included elsewhere on this form**, especially fuel addition, during the high-power and simmering tests (you should know this from your practice tests) weigh the dry pots without lid and the char container
- e) Fuel description
- **General description of fuel**
 - **Fuel type (select from list)**
 - **Fuel description (select from list)**
 - **Average length (cm)**
 - **Cross-sectional dimensions (cm x cm)**
 - **Gross, Net and Char calorific values and char content (by your own measurement or filled in automatically based on selected fuel type)**
 - **Description of fire starter, small wood, or kindling**
- f) Description of operation the high-power test
- **How is fire started?**
 - **When do you add new fuel to the fire?**
 - **How much fuel do you add at one time?**
 - **How often do you feed the fire without adding fuel (e.g. push sticks)?**
 - **Do you control the air above or below the fire? If so, what do you do?**
- g) Description of operation during the simmering test
- **How is fire started?**
 - **When do you add new fuel to the fire?**
 - **How much fuel do you add at one time?**
 - **How often do you feed the fire without adding fuel (e.g. push sticks)?**
 - **Do you control the air above or below the fire? If so, what do you do?**

* *Guidance for stove description: Photograph the stove, if possible. Use a tape measure to record the dimensions of the stove. A cross sectional drawing of the stove with dimensions may be useful. Identify the materials used for stove construction. Use an additional sheet if necessary.*

- 3) Fill out the [Fuel Moisture] sheet if you are using a handheld moisture meter. A copy of this sheet is given in Appendix 7 if you wish to fill it out by hand, but you will need to enter the values in the worksheet to obtain the calculated moisture content.
- 4) Determine whether your fuel is fed **continuously** or in a **batch**. Many wood and crop waste stoves are continuous feed, while most charcoal and liquid-fuel stoves are loaded with fuel before the test. The two types of fuel-feeding have some separate instructions.
- 5) Do not proceed if wind will affect your testing location.

D. PREPARATION FOR EACH WATER BOILING TEST

- 1) If you wish to record data by hand at first, print a [Test Entry] Sheet or from Appendix 7. If you wish to record the data directly in the workbook, you will be entering data into the [Test-1], [Test-2] or [Test-3] (up to 10 tests possible) sheets, for each replicate of the WBT.

Prepare one pot (or more if testing multi-pot stoves) for the cold start test. Record the **dry weight of each pot (g)**. Fill each pot with 5 kg (5 liters) of clean room temperature water. If using the smaller standard pot, fill each pot with 2.5 kg or 2.5 liters of water. The amount of water should be determined by placing the pot on the scale and adding water until the total weight of pot and water together is 5 kg (or 2.5 kg) more than the weight of the pot alone.

If the stove cannot accommodate the standard pot and the pot that is used cannot accommodate 5 (or 2.5) kg of water, OR if a multi-pot stove is used with non-standard pots that cannot accommodate 5 (or 2.5) kg of water, fill each pot about 2/3 full and record the change in procedure in the comment space. Use the same amount of water for each phase and each test.

Record the **weight of pot(s) with water (g), Cold Start High Power, Start**.

- 2) If you have enough pots, prepare additional pots and water for the hot start test. If not enough pots are available, measure out the needed volumes of water in another container.
- 3) Measure and record the ambient conditions: **air temperature (°C), wind conditions (select from list)**.
- 4) (Optional for emission measurements) Record **background concentrations** for **CO₂ (ppm), CO (ppm), and particulate matter concentrations (µg/m³)**.

In earlier versions of the spreadsheet, fuel description and calorific value were entered on the Test Entry sheets. In this version these values are taken from the [General Information] sheet. The same fuel type, size, and moisture content must be used for the three replicates of the WBT.

E. INSTRUCTIONS FOR WBT PHASES

Remaining data for the three phases of the test should be recorded on the Test Entry form. The stove should begin at room temperature.

WBT PHASE 1: HIGH POWER (COLD START)

Instruction	Data, Cold Start High Power section	Units
1. Prepare the timer (do not start it yet).		
2. Continuous: Weigh the bundle of fuel plus kindling.	Weight of fuel, Start	g
Batch: (Includes charcoal, ethanol, kerosene, and LPG stoves) Weigh the stove loaded with fuel.	Weight of fuel, Start	g
3. Place the pot on the stove. Using the wooden fixtures, place a thermometer in each pot so that water temperature may be measured in the center, 5 cm from the bottom. If there are additional pots, use the additional thermometers if possible. Measure the initial water temperature in each pot. Confirm that it does not vary substantially from the ambient temperature. There should NOT be a lid on the pot while conducting the WBT.	Water temperature, Start	°C
4. Optional for emission measurements: Record background concentrations and duct temperature. For real-time emission measurements, begin recording the particulate matter measurement. For filter-based measurements, turn on flow to the particulate matter filter. Begin recording the emission measurement for CO and CO ₂ .	Background CO₂ Background CO Background PM Duct Temperature <i>Real-time emission measurements recorded by emissions equipment</i>	ppm ppm µg/m ³ °C

Continuous Measurement of Temperature: The water temperature may be continuously recorded if a device is available to do so.

Lids: While a lid helps to retain heat and is often used in actual cooking tasks, it does not affect the transfer of heat from the stove to the pot. Lids may increase the variability of the WBT results, making it harder to compare results from different tests.

5. Start the fire in a reproducible manner according to local practices. (This procedure should be documented.)		
6. Once the fire has caught, start the timer and record the starting time. Bring the first pot rapidly to a boil without being excessively wasteful of fuel using wood from the pre-weighed bundle. Control the fire with the means commonly used locally. (This procedure should be documented.)	Time, Start	hr:min
7. When the water in the first pot reaches the pre-determined local boiling temperature as shown by the digital thermometer, rapidly do steps 7.a – 7.f.		
a. Record the time at which the water in the primary pot (Pot # 1) first reaches the local boiling temperature. Record this temperature also.	Time, Finish Water temperature, Finish	hr:min °C
b. Optional for emission measurements: Turn off flow to the particulate matter filter (for filter-based measurements). Remove and properly store filter and then replace filter.		
c. Continuous: Remove all wood from the stove and extinguish the flames. Flames can be extinguished by blowing on the ends of the sticks or placing them in a bucket of ash or sand; do not use water – it will affect the weight of the wood. Knock all loose charcoal from the ends of the wood into the container for weighing charcoal. Weigh the unburned wood removed from the stove together with the remaining wood from the pre-weighed bundle. Extract all remaining charcoal from the stove. Weigh this remaining charcoal with the charcoal that was knocked off the sticks.	Weight of fuel, Finish Weight of charcoal+containe r, Finish	g g g

Emissions During Fuel Measurements: This procedure is not included in the emission measurement because it is not part of normal operation.

Alternative Method to Weigh Charcoal: If your scale can handle the weight of the stove, then you can weigh the whole stove with the charcoal rather than removing the charcoal.

<p>Batch: Remove all the remaining from the stove and extinguish the flames. Carefully separate the charcoal and the wood and weigh them separately.</p>	<p>Weight of fuel, Finish. Weight of charcoal, Finish</p>	<p>g</p>
<p>d. For multi-pot stoves, measure the water temperature from each pot (the primary pot should be at the boiling point).</p>	<p>Water temperature, Pot #2 – 4, Finish</p>	<p>°C</p>
<p>e. Weigh each pot, with its water.</p>	<p>Weights of Pot with water, Finish</p>	<p>g</p>
<p>f. Discard the hot water.</p>		

This completes the high power cold-start phase. Next, begin the high power-hot start phase, immediately while the stove is still hot. **Be careful not to burn yourself!**

Alternative Methods to Charcoal Measurements for Batch-bed Stoves: In previous versions, the charcoal was not weighed separately. Reflecting the recommendation from several commenters, these instructions have been modified to better account for remaining wood and charcoal. Procedures for batch-fed stoves are being developed including methodology to properly account for energy and carbon remaining. Alternatively, the remaining fuel can be ground to be made more uniform, and then analyzed for heating value and carbon content.

WBT PHASE 2: HIGH POWER (HOT START)

Instruction	Data, Hot Start High Power section	Units
1. Reset the timer (do not start it yet).		
2. If the pot for the hot start phase has not been prepared in advance, refill the pot with 5 (or 2.5) kg of fresh ambient-temperature water. Weigh the pot (with water) and measure the initial water temperature. For multi-pot stoves, fill the additional pots, weigh them and record their weights.	Weight of pot(s) with water, Start	g
3. Continuous: Record the weight of the second bundle of fuel plus kindling. Batch: Weigh the stove loaded with fuel.	Weight of fuel, Start Weight of fuel, Start	g g
4. Place the pot on the stove and replace the thermometer in the pot. Measure the initial water temperature in each pot. Confirm that it does not vary substantially from the ambient temperature.	Water temperature, Start	°C
5. Optional for emission measurements: For filter-based measurements, turn on flow to the particulate matter filter.	Real-time emission measurements recorded by emissions equipment	
6. Start the fire using fuel from the second pre-weighed bundle designated for this phase of the test. Follow the ignition procedure used in Phase 1.		

Continuous Measurement of Temperature: The water temperature may be continuously recorded if a device is available to do so.

<p>7. Once the fire has caught, start the timer. Record the starting time. Bring the first pot rapidly to a boil without being excessively wasteful of fuel using wood from the second pre-weighed bundle. Control the fire using the procedure used in Phase 1.</p>	<p>Time, Start</p>	<p>hr:min</p>
<p>8. When the water in the first pot reaches the pre-determined local boiling temperature as shown by the digital thermometer, rapidly do steps 8.a – 8.e.</p>		
<p>a. Record the time at which the water in the primary pot (Pot # 1) first reaches the local boiling temperature. Record this temperature also.</p>	<p>Time, Finish Water temperature, Finish</p>	<p>hr:min °C</p>
<p>b. Optional for emission measurements: Turn off flow to the particulate matter filter (for filter-based measurements). Remove and properly store filter and then replace filter.</p>		
<p>c. Continuous: Remove all wood from the stove and extinguish the flames. Knock all loose charcoal from the ends of the wood into the combustion area (you will not weigh the charcoal at this stage).</p> <p>Weigh the unburned wood removed from the stove together with the remaining wood from the second pre-weighed bundle.</p> <p>Batch: Weigh the stove loaded with fuel. Record zero for the weight of charcoal.</p>	<p>Weight of fuel, Finish</p> <p>Weight of fuel, Finish. Weight of charcoal = 0, Finish</p>	<p>g</p> <p>g</p> <p>g</p>
<p>d. For multi-pot stoves, measure the water temperature from each pot (the primary pot should be at the boiling point).</p>	<p>Water temperature, Pot #2 – 4, Finish</p>	<p>°C</p>
<p>e. Weigh each pot, with its water.</p>	<p>Weights of Pot with water, Finish</p>	<p>g</p>
<p>9. Return the unburned wood to the stove. Proceed immediately with the low power test.</p>		

Speed and Safety: Speed and safety are important during Step 8 because the water temperature should stay as close as possible to boiling in order to proceed directly to the simmer phase. The pot of hot water may be temporarily covered with a lid and placed on a hot plate (if available).

Multi-pot Stoves: Final temperature and weight of additional pots may be recorded. However, metrics to evaluate energy delivered to additional pots need to be more fully developed. See discussion of multi-pot stove testing in Appendix 2 and the discussion of additional metrics in Appendix 8.

WBT PHASE 3: LOW POWER (SIMMERING)

This portion of the test is designed to test the ability of the stove to shift into a low power phase following a high-power phase in order to simmer water for 45 minutes using a minimal amount of fuel. For multi-pot stoves, **only the primary pot will be assessed for simmering performance.**

Instruction	Data, Simmer Test section	Units
1. Reset the timer (do not start it yet).		
2. Record the weight of the pot with water.	<i>Weight of pot with water, Start</i>	g
3. Continuous: Record the weight of fuel remaining from the hot start high power phase plus the third bundle of fuel plus kindling.	<i>Weight of fuel, Start</i>	g
Batch: Record the weight of the stove loaded with fuel remaining from the hot start high power phase	<i>Weight of fuel, Start</i>	g
4. Relight the hot wood that was replaced. Follow the ignition procedure used in Phase 1.		
5. Optional for emission measurements: For filter-based measurements, turn on flow to the particulate matter filter.	<i>Real-time emission measurements recorded by emissions equipment</i>	
6. Once the fire has caught, reset and start the timer. Record the starting time.	<i>Time, Start</i>	hr:min
7. Place the pot on the stove and replace the thermometer in the pot.		

8. For 45 minutes maintain the fire at a level that keeps the water temperature as close as possible to 3 degrees below the boiling point. The test is invalid if the temperature in the pot drops more than 6°C below the local boiling temperature.

9. After 45 minutes rapidly do steps 6.a – 6.d:

a. Record the time. Record the final water temperature – it should still be about 3 °C below the established boiling point.

Time, Finish g
Water temperature, Finish °C

b. **Optional for emission measurements:** Turn off flow to the particulate matter filter (for filter-based measurements). Remove and properly store filter.

c. **Continuous:** Remove all wood from the stove and extinguish the flames. Knock all loose charcoal from the ends of the wood into the charcoal container.

Weigh the unburned wood removed from the stove together with the remaining wood from the second pre-weighed bundle.

Weight of fuel, Finish g

Extract all remaining charcoal from the stove. Weigh this remaining charcoal with the charcoal that was knocked off the sticks.

Weight of charcoal+container, Finish g

Batch: Remove all the remaining from the stove and extinguish the flames. Carefully separate the charcoal and the unburned wood and weigh them separately.

Weight of wood, Finish g
Weight of charcoal+container, Finish g

d. Weigh the pot with the remaining water.

Weight of pot with water, Finish g

Maintaining Temperature: Many stoves lack adequate turndown ability, which makes it difficult to maintain the desired temperature without the fire going out (especially after the initial fuel load has been consumed). In this case, use the minimum amount of wood necessary to keep the fire from dying completely. Water temperatures in this case will be higher than 3° below boiling, but the test is still valid. The tester should not attempt to reduce power by splitting the wood into smaller pieces.

Alternative Methods to Charcoal Measurements for Batch-bed Stoves: In previous versions, the charcoal was not weighed separately. Reflecting the recommendation from several commenters, these instructions have been modified to better account for remaining wood and charcoal. Procedures for batch-fed stoves are being developed including methodology to properly account for energy and carbon remaining. Alternatively, the remaining fuel can be ground to be made more uniform, and then analyzed for heating value and carbon content.

Changes to Testing Conditions to Improve Repeatability

The WBT is designed to test many stoves in many places, but comparisons become less reliable as testing conditions vary. You should identify the reasons for testing when deciding on the form of the test. If you are using the WBT as a preliminary measure of stove performance during the design phase, then adapt the protocol to local conditions. Some laboratories may be using tests to compare the performance of their stoves with other available stove models. In these situations, some changes may be made to the test to improve repeatability. However, we caution that these changes may make the stove perform differently than it would in practice. If laboratory tests are very different from real operation, then comparisons done in the laboratory may lead to incorrect conclusions about stoves in real operation. Any specific changes to the WBT should be noted in the documentation for each test.

1. Fuel

a. Type: Wood with high heat content (between 20-21 MJ/kg), and without excessive pitch content, should be used for all tests. Choose one wood which is used widely in the region.

b. Dimensions: Different sizes of solid fuels have different burning characteristics. Some laboratories have used wood with cross-sectional dimensions of 1.5 cm x 1.5 cm.

c. Moisture content: All testing should be carried out with wood of low moisture content (values used have been 6.5% or 10% on a wet basis). This reduces variability but may make combustion unlike field conditions.

2. Initial Water Temperature: A fixed initial temperature can be chosen for the water rather than relying on ambient temperature (15 °C has been used).¹

3. Cooking Pot: The tests should be conducted with either a large standard pot (with a 7 liter capacity) or a small standard pot (with a 3 liter capacity), depending on the size of the stove.

F. COMPLETION

The three phases described above complete the WBT. Be sure that you have entered all the data required.

For testing results that are not proprietary, the workbook can be directly uploaded into the Clean Cooking Catalog using the following steps:

1. Ensure you have not made edits to or moved the location of the [*Catalog Import Data*] sheet on the workbook.
2. Visit the Submit Test Results page at <http://catalog.cleancookstoves.org/content/test-results/new>.
3. In the source data section, upload the completed WBT 4.2.3 results spreadsheet.

¹ The temperature-corrected time to boil and specific consumption should still use a reference temperature of 25 C for comparability with other tests.

4. Complete information on publication (if applicable).
5. Click “Submit test result” to share the information on the Catalog.

For any questions or comments on submitting test results, please contact catalog@cleancookstoves.org.

VI. INTERPRETING RESULTS OF THE WATER BOILING TEST

This section discusses how to interpret the stove performance metrics produced by the Water Boiling Test. The calculation of these measures is done according to the equations in Appendices 4 and 6.

Each of these metrics is valuable, and it is up to each stove program to determine which metrics are most important to their program.

A. COMMONLY USED MEASURES

The measures that most stove programs use are summarized here.

Stove characteristics: burning rate, firepower, turn-down ratio

Efficiency and performance measures: time to boil, specific fuel consumption , thermal efficiency

Emission measures: emissions per fuel burned, emissions per MJ, emissions per task

B. CAUTIONS

Results for high-power and low-power tests may vary greatly. Stoves often perform well on the high-power test and poorly on the low-power test or vice versa. Testers should examine the results of both types of tests rather than relying on the totals.

Although some of the metrics are normalized to the amount of water boiled, comparisons for stoves of different sizes should be done with caution.

Reports from the individual phases (cold-start high-power, hot-start high-power, and simmer) may be less accurate than the overall total. This is especially true because the tester doesn't weigh the charcoal after the hot-start test, so estimates of the fuel used during the hot-start and simmer tests are not exact.

C. STOVE CHARACTERISTICS

Burning Rate – A measure of the average grams of wood burned per minute during the test. When compared between tests, this compares how consistently the user was operating the stove. When compared between stoves, this measure indicates how rapidly the stove consumes fuel.

Firepower – Firepower is a measure of how quickly fuel was burning, reported in Watts (Joules per second). It is affected by both the stove (size of fuel entrance/combustion chamber) and user operation (rate of fuel feeding). Generally it is a useful measure of the stove's heat output, and an indicator of how consistently

the operator ran the stove over multiple tests. A higher or lower value is not necessarily preferable, but rather is an indicator of the size of the stove.

Turn-Down Ratio – Turn-Down ratio indicates how much the user adjusted the heat between high power and low power phases. A higher value indicates a higher ratio of high power to low power, and could signal a greater range of power control in the stove. However, this value reflects only the amount of power control that was actually used.

D. EFFICIENCY METRICS

Time to Boil – The time it took for pot #1 to reach boiling temperature from the starting temperature.

Temperature Corrected Time to Boil – The time it took for pot #1 to reach boiling temperature, corrected to reflect a temperature rise of 75 deg C from start to boil. This measure can be compared across tests and stoves to determine the “speed” of the stove at high power, often an important factor to cooks.

Thermal Efficiency (IWA Metric for High Power) – Thermal efficiency is a measure of the fraction of heat produced by the fuel that made it directly to the water in the pot. The remaining energy is lost to the environment. So a higher thermal efficiency indicates a greater ability to transfer the heat produced into the pot. While thermal efficiency is a well-known measure of stove performance, a better indicator may be specific consumption, especially during the low power phase of the WBT. This is because a stove that is very slow to boil may have a very good looking TE because a great deal of water was evaporated. However the fuel used per water remaining may be too high since so much water was evaporated and so much time was taken while bringing the pot to a boil.

Specific Fuel Consumption – This is a measure of the amount of fuel required to boil (or simmer) 1 liter of water. It is calculated by the equivalent dry fuel used minus the energy in the remaining charcoal, divided by the liters of water remaining at the end of the test. In this way, the fuel used to produce a useful liter of “food” and essentially the time taken to do so is accounted for.

Specific Fuel Consumption is listed as the *IWA metric for Low Power*, which is reported in MJ/(min·L).

Temp-Corrected Specific Fuel Consumption – This is the previous measure, also corrected as if the temperature rise from start to boil was 75 degrees C, in order to easily compare different tests that may have had different starting or boiling temperatures. It is best to always look at the temperature corrected value rather than the uncorrected value. A higher T-C SC indicates more fuel required to complete the same task of producing a liter of boiled (or simmered) water.

Temp-Corrected Specific Energy Consumption – This is the same measure as the previous, but reported as energy (kilojoules) rather than fuel (grams). This allows for a direct comparison between different fuels, such as various types of wood, charcoal, dung, etc.

Benchmark Values – The benchmark values combine the phases of cold start, hot start and simmer into one value for the overall test. It is the average of temp-corrected specific consumption (or emission) in cold and hot start, added to simmer. Having one overall value to look at can be helpful in comparing a large number of stove designs.

E. EMISSION METRICS

These emissions metrics can be used for CO₂, CO, PM, or other species. Across the different emission metrics, emissions are reported as mass on an equivalent dry basis. If ultra-fine particles (particles less than 100 nm) are measured, this result can be reported as number of particles.

Emissions per MJ delivered to pot (IWA Metric for High Power Total Emissions, CO and PM) – This metric is preferable for high-power phases because it reports emissions in terms of the desired output, cooking energy, and enables comparisons between stoves and fuels. The cooking energy delivered to the pot is measured as the sensible heat that raised the pot water temperature and the latent heat that produced steam.

Emission rate (emissions per time) (IWA Metric for Indoor Emissions, CO and PM) – This metric specifies the mass emitted over the duration of a phase. The overall emission rate to determine the IWA Tier is based on whichever is greater of the high power or low power CO emission rate. The high power emission rate is the average of the hot start and cold start phases.

Specific emission rate (Emissions per time per liter of water) (IWA Metric for Low Power Total Emissions, CO and PM) – This metric is preferable for the low-power phase because of the difficulty in calculating the cooking energy delivered to the pot due to limited or no measured sensible heat (relatively constant water temperatures) and variation in measured latent heat (highly variable steam production).

Emissions per task and Emissions per weight of fuel burned – These are also often reported, however these metrics have less comparability between different stoves.

F. ADDITIONAL MEASURES

These additional measures may be found on the individual test sheets [Test-1], [Test-2], and [Test-3].

Water vaporized from all pots - If this value is high compared with other stoves, then high thermal efficiency may not be a good measure of strong performance. It could mean only that the stove is boiling off too much water.

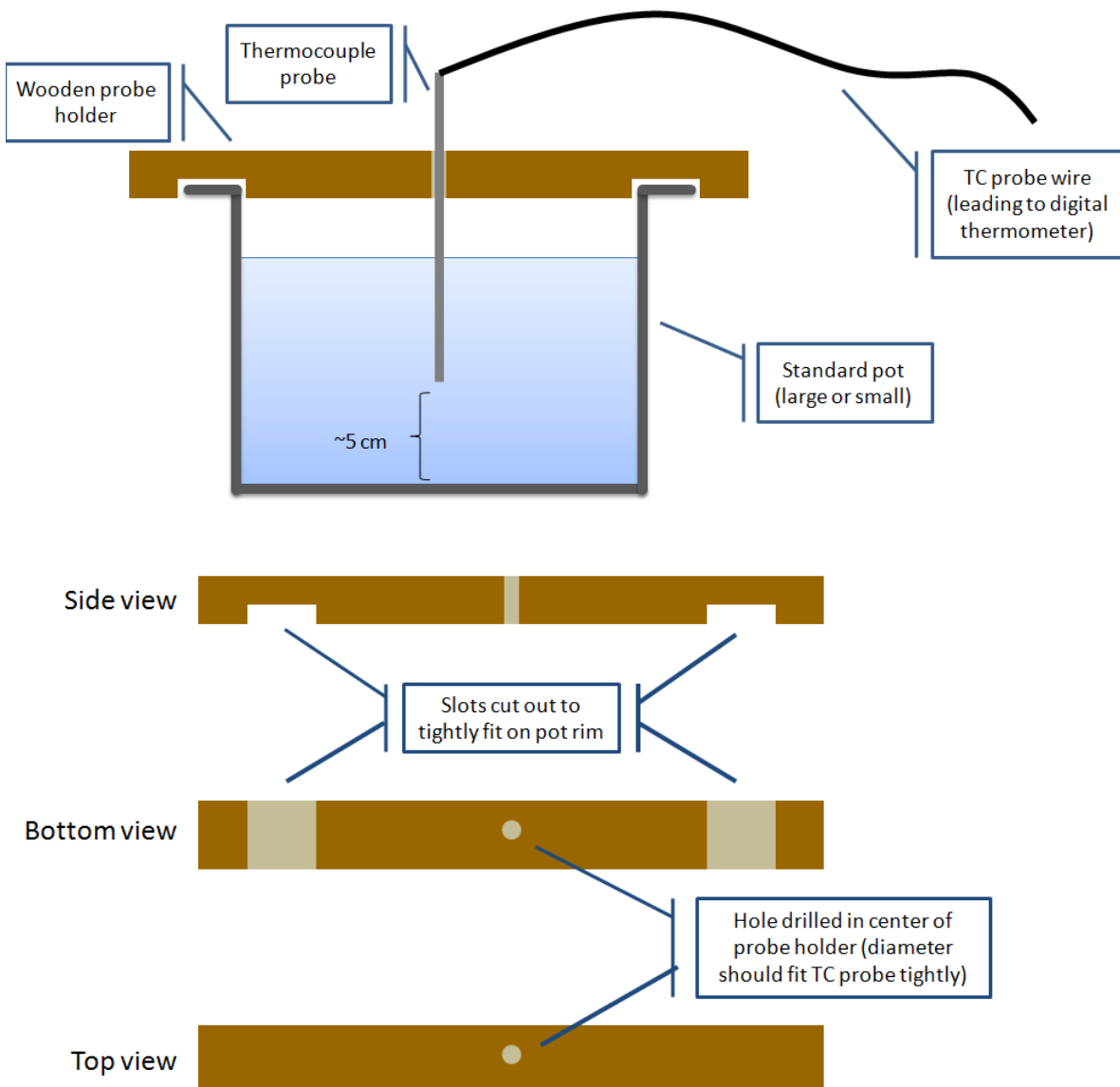
Water temperature in additional pots – High temperatures indicate that the stove is successful in heating multiple pots.

APPENDIX 1. PREPARATION FOR THE WATER BOILING TEST

This appendix provides guidance on initial setup of the equipment for the Water Boiling Test. It also discusses two methods that are needed to perform the WBT, local boiling point and fuel moisture content.

1.1 HOLDING THE THERMOCOUPLE IN THE POT

The diagram below shows a wooden probe holder to keep the thermocouple (TC) probe in the pot. The dimensions are not critical, but the probe holder should be made so that the TC probe fits into it tightly and the probe holder fits securely on the pot



1.2 DETERMINING LOCAL BOILING POINT

The local boiling point of water is the point at which the temperature no longer rises, no matter how much heat is applied. The local boiling temperature is influenced by several factors including altitude, minor inaccuracies in the thermometer, and weather conditions. For these reasons, the local boiling temperature cannot be assumed to be 100° C. For a given altitude h (in meters), the boiling point of water may be estimated by the following formula:

$$T_b = \left(100 - \frac{h}{300}\right)^\circ \text{C}$$

However, it is better to determine the local boiling point empirically using the following procedure:

- 1) Choose whether you will use the large or small standard pot. Measure 5 liters of water for the large standard pot (or 2.5 liters for the small standard pot). Bring it to a rolling boil. Make sure that the stove's power output is high, and the water is fully boiling!
- 2) Using the same thermometer that will be used for testing, measure the boiling temperature when the thermometer is positioned in the center, 5 cm above the pot bottom. You may find that even at full boil, when the temperature no longer increases, it will still oscillate several tenths of a degree above and below the actual boiling point.
- 3) Record the temperature over a five minute period at full boil and note the maximum and minimum temperatures observed during this period. The maximum and minimum temperatures should then be averaged. This result will be recorded as the "local boiling temperature" on the [*General Information*] sheet in the Excel work book whenever you do a test.

1.3 DETERMINING FUEL MOISTURE CONTENT

Well-dried fuel contains 10-20% water while fresh cut wood may contain more than 50% water by mass (wet basis). Ideally, fuel used for both testing stoves and for cooking by project beneficiaries should be dried as much as local environmental conditions allow. However, dried fuel is not always available and both stove testers and household cooks must use what they can get. In order to control for variations in fuel moisture content, stove testers should measure it and account for it in their stove performance calculations. Thus, you need to input moisture content in the [*Fuel Moisture*] sheet within the workbook.

There are two ways of defining fuel moisture content: on a wet basis and on a dry basis. In the former, the mass of water in the fuel is reported as a percentage of the mass of wet fuel and in the latter case, it is reported as a percentage of the mass of the dry fuel. The calculations for each are shown below followed by a plot showing how both wood moisture on a wet basis and wood mass vary with wood moisture defined on a dry basis for one kg of oven-dry wood. Unless otherwise specified, we will report wood moisture on a wet basis. The testers should always specify which basis they are using.

The two moisture contents are related in this way:

$$MC_{wet} = \frac{MC_{dry}}{1 + MC_{dry}}$$

Measuring moisture content can be done in two ways. The most precise way is to use the equations listed above by weighing a sample of the air-dry fuel (Mass of fuel)_{wet} and weighing it again after it has been completely dried (Mass of fuel)_{dry}. Take a small sample (200-300 g) of the fuel randomly from the stock of fuel to be used for the tests. Weigh the sample and record the mass. Dry the sample in an oven at a few degrees over 100 °C and weigh it again. This may be done at the testing site if an oven is available, or the wet sample may be weighed on-site and then stored carefully and dried later, when an oven is available.

To dry the sample, put it in an oven overnight and then remove it and weigh the sample every two hours on a sensitive scale (± 1 g accuracy) until the mass no longer decreases. The oven temperature should be carefully controlled so that it doesn't exceed 110°C (230°F). If the wood is exposed to temperatures near 200°C (390°F), it will thermally break down and lose matter that is not water, causing an inaccurate measurement of moisture content.

A second way to measure wood moisture is with a wood moisture meter. This device measures fuel moisture on a dry basis by measuring the conductivity between two sharp probes that are inserted in the wood. This is more convenient than oven-drying because the measurement can be rapidly done on site as the fuel is being prepared. The probes should be inserted parallel with the grain of the wood. The device may be adjusted for different species and calibrated for different ambient temperatures. The meter measures between 6% and 35-40% moisture (dry basis). If the sample of wood is wetter than the upper range of the meter, the meter will either show an error. Wood moisture can vary in a given piece of wood as well as among different pieces from a given bundle. When the meter is used, take three pieces of wood randomly from the bundle and measure each piece in three places. This yields nine measurements overall. The moisture of the bundle should be reported as the average of these nine measurements. Convert this average to a wet basis using the formula (this is done automatically in the computer spreadsheet). Record this average in the [*Fuel Moisture*] sheet.

Note – the moisture meter is not designed to measure non-woody fuels and should not be used on dung or crop residues. If dung or crop residues are used, then the oven-drying method is recommended. See Appendix 2 for further discussion.

APPENDIX 2. MODIFICATIONS TO THE WATER BOILING TEST

2.1 NON-WOOD FUELS

This WBT may be done with many different stove-fuel combinations, including stoves that burn liquid and gaseous fuels, as well as solid fuels like coal, charcoal, crop residues and dung. However, if fuels other than wood are used then there are some special factors to consider when filling the data entry and calculation forms. These are discussed below for each fuel.

Liquid and gaseous fuels

If liquid and/or gaseous fuels are used, the procedure is simplified because there is neither char nor ash to be measured. Moreover, many liquid and gaseous stoves are small enough to directly measure on a scale, so that fuel consumption can be very straightforward. However, if the stoves are too large to put on the scale, then fuel consumption may be difficult to assess. Similarly, if the gas is from a piped source (as with gas stoves in the US), then a flow meter may be needed to measure the quantity of fuel consumed. In addition, the tester must know the calorific value of the fuel. Even for fossil fuels, this can vary depending on exact mix of distillates. Some calorific values reported in the literature are given below, but we suggest the tester use a value measured locally if possible.

Fuel	Calorific value (MJ/kg)	Source
Kerosene	43.3	Zhang et al., 2000
	43.6	IEA, 2005
	43.1	Smith et al, 2001
LPG	49.0	Zhang et al., 2000
	47.1	IEA, 2005
	45.8	Smith et al, 2001
Natural gas	51.3	Zhang et al., 2000
Biogas	17.7	Smith et al, 2001
Ethanol (pure)	26.8	Schmer et al., 2007

Non-wood solid fuels:

With non-woody solid fuels two complications arise. The first is that the moisture meter used to measure wood moisture content cannot measure the moisture content of non-woody fuels. Therefore testers must use the oven method to determine moisture content. Second, the calorific value of the fuel, which is affected by the moisture content, must be determined. As with liquid and gaseous fuels, solid fuels have a range of calorific values. However, if possible, testers should try to ascertain the specific calorific value of their fuel through calorimetry. This procedure requires specialized equipment and training. If possible, testers should check with a local university to see if testing facilities are available. If testing can not be done locally, use values from previous studies. Some calorific values of non-woody solid fuels are given in the table below. An even larger number of calorific values, for both woody and non-woody fuels, are given in the accompanying Data and Calculations spreadsheet.

Fuel	Calorific value (MJ/kg)	Source
Charcoal	25.7 @ 1.7 % MC _{wet}	Smith et al, 2001
	27.6-31.5 @ ~5 % MC _{wet}	Pennise et al. 2002
Maize stalks	16.1 @ 9.1 % MC _{wet}	Zhang et al., 2000
	15.4 @ 5.0 % MC _{wet}	RWEDP, 1993
Wheat stalks	14.0 @ 7.3 % MC _{wet}	Zhang et al., 2000
	15.4 @ 5.0 % MC _{wet}	RWEDP, 1993
Rice stalks	13.0 @ 8.8 % MC _{wet}	Smith et al, 2001
	14.2 @ 5.0 % MC _{wet}	RWEDP, 1993
Dung	11.8 @ 7.3 % MC _{wet}	Smith et al, 2001
	15.4 @ 5.0 % MC _{wet}	RWEDP, 1993
Coal		
China	22.5	IEA, 2005
China	27.3 @ 2.1 % MC _{wet}	Zhang et al., 2000
China (washed)	30.1 @ 4.7 % MC _{wet}	Zhang et al., 2000
US	26.2	IEA, 2005
India	18.4	IEA, 2005
South Africa	23.5	IEA, 2005

2.2 MULTI-POT STOVES

Some stoves are designed to cook with more than one pot. If this is the case, the tester should use the number of pots that the stove can accommodate (the testing forms have space for up to four pots). The explicit calculations for multiple pots are explained below.

HIGH-POWER TESTS

In order to closely mirror the single pot test and ensure that the task can be completed in a reasonable amount of time, the high power tests are stopped when the primary pot (the pot closest to the source of heat) comes to a boil. The indicators of stove performance account for the water heated in the additional pots. To do so they are modified in the following way.

Calculations that are modified to account for multiple pots in the high power tests*

f_{cm}	Wood consumed, moist (grams)	Same as for single-pot stove
ΔC_c	Net change in char during test phase (grams)	Same as for single-pot stove
f_{cd}	Equivalent dry wood consumed (grams)	Same as for single-pot stove
w_{cv}	Water vaporized (grams)	$w_{cv} = \sum_{j=1}^4 (P_{j_{ci}} - P_{j_{cf}})$

w_{cr}	Effective mass of water boiled ("Boiled" water remaining at end of test) (grams)	$w_{cr} = \sum_{j=1}^4 \left((P_{j_{cf}} - P_j) * \left(\frac{T_{j_{cf}} - T_{j_{ci}}}{T_b - T_{j_{ci}}} \right) \right)$
t_c	Duration of phase (min)	Same as for single-pot stove
h_c	Thermal efficiency	$h_c = \frac{4.186 * \sum_{j=1}^4 (P_{j_{ci}} - P_j) * (T_{j_{cf}} - T_{j_{ci}}) + 2260 * (w_{cv})}{f_{cd} * LHV}$
r_{cb}	Burning rate (grams/min)	Same as for single-pot stove
SC_c	Specific fuel consumption (grams wood/grams water)	$SC_c = \frac{f_{cd}}{\sum_{j=1}^4 \left[(P_{j_{cf}} - P_j) * \left(\frac{T_{j_{cf}} - T_{j_{ci}}}{T_b - T_{j_{ci}}} \right) \right]}$
SC_c^T	Temp-corrected specific consumption (grams wood/grams water)	$SC_c^T = SC_c * \frac{75}{T_{cf} - T_{ci}}$
FP_c	Firepower (W)	Same as for single-pot stove
<p>* These calculations use the subscript-c for the cold-start test, however the modified hot-start calculations are identical.</p> <p>In each case, j is an index of each pot (1-4)</p> <p>The factor $\left(\frac{T_{j_{cf}} - T_{j_{ci}}}{T_b - T_{j_{ci}}} \right)$ is used to "discount" the water heated in additional pots that does not come to a full boil. For example, when calculating specific consumption, which, in this test, measures the amount of wood required to boil a unit amount of water, we want to give credit for the water heated in other pots, although it was not boiled. Since the energy (Q) required to bring water to a boil is a roughly linear function of the temperature change ($Q \propto \Delta T$) we discount the water that was not boiled by a factor that varies between zero and one, reflecting the fraction of sensible heat absorbed by the water relative to the heat required to boil it.</p>		

LOW-POWER TEST

In the low power test it is more difficult to incorporate the output from additional cooking pots. For this reason, multi-pot stoves may appear to be at a disadvantage in this part of the test, which assesses the ability of the stove to maintain a pot of water just below the boiling temperature. In lowering the power delivered to the primary cooking pot, the stove will probably not be able to deliver much heat to secondary pots. Fluctuations in temperature in the other pots will greatly complicate the assessment, thus they will be ignored. The Stove Performance Test used in assessing improved stoves in China adopts a similar procedure [10].

Of course, well-designed multi-pot stoves have the strength of providing high power to the primary cooking pot, while simultaneously providing low power to an additional pot (or pots). However, this test is designed to only bring the water in the primary pot to boiling temperatures and the stove performance indicators calculated from the results of the simmer test will only rely on the measurements taken from the primary pot. While this may not capture all of the strengths of the multi-pot stove, those strengths should be captured in the results of the high power test, as well as in the controlled cooking test and kitchen performance (field) tests, which also must be conducted to fully assess stove performance.

APPENDIX 3. HISTORY OF THE WATER BOILING TEST

The version numbers given in this discussion were assigned by the authors of the appendix. They were not assigned by the original authors. Version numbering should continue through future development of the WBT.

Versions 1 and 2: Volunteers in Technical Assistance (VITA), 1982-1985 provided the first committee-based recommendations for testing cooking stoves. The document outlined three tests: the Water Boiling Test, the Controlled Cooking Test, and the Kitchen Performance Test. It was first published in 1982 and revised in 1985.

VITA struggled with all of the questions we faced in developing the current document. The introduction to this document recommends: “The standard should represent a compromise between the widest possible range of applications, and the closest possible fit with actual cooking practices.” They also pointed out the difference between testing “done for local use only (for stove users and others) and testing where the results are intended to be transmitted to other places.”

A revision of the WBT and a lot of perspective were provided by Dr. Samuel Baldwin in his book, “Biomass stoves: Engineering design, development, and dissemination.”

Version 3: UC Berkeley and Aprovecho, 2003-2007, often known as the “UCB WBT”. Rob Bailis, Damon Ogle, Nordica MacCarty, and Dean Still (this was also distributed as Version 1.5 on the Berkeley site).

The Shell Foundation began an entrée into the stoves world around 2001, and noticed the need for benchmarks because many “improved” stoves didn’t work. They engaged Dr. Kirk Smith, of UC Berkeley, to update the WBT and includes the CCT and KPT. Dr. Smith engaged Rob Bailis (then a graduate student) and Aprovecho personnel to revise the WBT.

During this process, Dean Still and Damon Ogle of Aprovecho performed a literature review and examined national tests, including those of China and India. They contacted field organizations who were conducting stove projects to ask about typical pot sizes, water amounts, and simmering times. This was the source of the recommended 5 liters and the simmering length. The resulting WBT incorporated procedures that were perceived to be the best available. Over about a year, the WBT equations were completely rewritten and developed into a spreadsheet, first by Rob Bailis, then with input from Dean Still and Damon Ogle, and finally maintained by Nordica MacCarty. Several other people provided critiques of the spreadsheet and equations.

An eye-opening experience occurred at Aprovecho’s 2005 “Stove Camp”: none of six testing teams at this camp was completely successful in implementing the written protocol. This did not bode well for field testing. During subsequent training and testing around the world, particularly by Nordica MacCarty, small modifications to both the WBT protocol and spreadsheet to improve user-friendliness were implemented.

Version 4: ETHOS, PCIA, Global Alliance for Clean Cookstoves (2007-2013). Around 2007, it became apparent that wider community involvement in testing methods was needed. Both the method of testing and some of the calculations in the WBT had been critiqued, and the “right” answer was not always apparent. University laboratories began seeking precision and repeatability, sometimes producing recommendations for changes to the test that were quite possible in laboratory settings but not practical

for field testing. The group Engineers in Technical and Humanitarian Opportunities of Service (ETHOS), had held annual meetings on cookstove topics since 2001. It initiated a technical committee, led by Dr. Tami Bond of the University of Illinois, to address some of these issues.

Many people contributed to the document revisions, including the following. Extensive revisions were suggested by Crispin Pemberton-Pigott (New Dawn Engineering). Penn Taylor (Iowa State University) reworked all the equations for clarity and conformity with standard engineering practice. Cory Kreutzer and Morgan DeFoort (Colorado State University) developed their own Water Boiling Test, optimized for repeatability, and freely shared their protocol. All differences between that document and the present WBT were examined. Laura Fierce (University of Illinois) conducted an extensive comparison between these updates and the original Version 3 documents. Crispin Pemberton-Pigott also thoroughly reviewed the Iowa State University and Colorado State University documents. Nordica MacCarty and Dean Still (Aprovecho Research), co-authors of the Version 3 WBT, responded with field perspective and suggestions for changes. Michael Johnson (Berkeley Air Monitoring Group) contributed explanations for laboratory and field testing).

Tami Bond and Christoph Roden (University of Illinois) and Nordica MacCarty developed the emission testing recommendations, which are new to version 4. Wiecher Kamping (Phillips) made suggestions about carbon monoxide measurement. Jim Jetter (U.S. Environmental Protection Agency) provided a detailed description of stove operation which became the basis for the General Information sheet in the current Excel workbook.

Tom Miles and Erin Rasmussen maintained the Bioenergy Methods ListServ and Brenda Doroski and John Mitchell (U.S. Environmental Protection Agency, Partnership for Clean Indoor Air), were invaluable forums for discussion and collecting resources.

After the comment period ending in 2009, contributors to final comment reviews, revisions and refinements include Tami Bond(University of Illinois), Ryan Thompson (University of Illinois), David Sherman (University of Illinois, Michael Naleid (formerly Global Alliance for Clean Cookstoves, now Winrock), Ranyee Chiang (Global Alliance for Clean Cookstoves).

APPENDIX 4. CALCULATION OF WBT PERFORMANCE METRICS

Rob Bailis, formerly UC Berkeley, now Yale University

Nordica MacCarty, formerly Aprovecho Research Center, now Iowa State University

Penn Taylor, Iowa State University

Ryan Thompson, formerly Aprovecho Research Center, now University of Illinois, Urbana-Champaign

The WBT consists of three phases: a high-power phase with a cold start, a high power phase with a hot start, and a low power (simmer) phase. Each phase involves a series of measurements and calculations. The calculations for the one-pot test are described below. For stoves that accommodate more than one pot, the calculations will be adjusted to account for each pot. These adjustments are explained above in Appendix 2.2. The emissions are calculated using the carbon balance method which is explained in more detail in Appendix 6.

4.1 VARIABLES THAT ARE CONSTANT THROUGHOUT ALL THREE PHASES

<i>HHV</i>	Gross calorific value (dry wood) (kJ/kg)
<i>LHV</i>	Net calorific value (dry wood) (kJ/kg)
<i>MC</i>	Wood moisture content (% - wet basis)
<i>EHV</i>	Effective calorific value (accounting for moisture content of wood)
<i>LHV_{char}</i>	Net calorific value of char (kJ/kg)
<i>P1</i>	Dry mass of empty pot (grams)
<i>K</i>	Weight of empty container for char (grams)
<i>T_a</i>	Ambient Temperature (°C)
<i>T_b</i>	Local boiling point of water (°C)
<i>fuelFracC</i>	Fuel carbon fraction (%)
<i>charFracC</i>	Char carbon fraction (%)

EMISSION VARIABLES

<i>P_{atm}</i>	Atmospheric Pressure (kPa)
<i>Q</i>	Hood flow rate (m ³ /hr)
<i>CO_{2b}</i>	Background CO ₂ concentration (ppm)
<i>CO_b</i>	Background CO concentration (ppm)
<i>PM_b</i>	Background PM concentration (ug/m ³)

HHV – Higher heating value (also called gross calorific value). This is the theoretical maximum amount of energy that can be extracted from the combustion of the moisture-free fuel *if* it is completely combusted *and* the combustion products are cooled to room temperature such that the water produced by the reaction of the fuel-bound hydrogen is condensed to the liquid phase.

LHV – Lower heating value (also called net heating value). This is the theoretical maximum amount of energy that can be extracted from the combustion of the moisture-free fuel *if* it is completely combusted *and* the combustion products are cooled to room temperature but the water produced by the reaction of the fuel-bound hydrogen remains in the gas phase. For woodfuels, LHV typically differs from HHV by 1.32 MJ/kg.²

MC – This is the % wood moisture content on a wet basis, defined by the following formula:

$$MC = \frac{m_{fuel,wet} - m_{fuel,dry}}{m_{fuel,wet}}$$

MC is a decimal fraction which is formatted in the WBT spreadsheet as a percentage. Therefore, if the spreadsheet shows that MC = 15%, a value of MC=0.15 is used for the calculations.

This can be determined gravimetrically (by weighing a sample of wet fuel, drying the sample, and weighing it again) or through the use of a wood moisture meter (see description of test procedure).

If the Delmhorst J-2000 moisture meter is used in this test to measure wood moisture content, be aware that it provides moisture content on a *dry basis*. In order to use ‘m’ in the following analysis, the output of the instrument must be converted to moisture content on a *wet basis*. *Dry basis* must be converted to *wet basis* using the following equation:

$$MC_{wet} = \frac{MC_{dry}}{1 + MC_{dry}}$$

EHV – The effective calorific value of the fuel takes account of the energy required to heat and evaporate the moisture present in the fuel. *EHV* is not actually used in any WBT calculations. It is calculated in the following way:

$$EHV = LHV \cdot (1 - MC_{wet}) - MC_{wet} \cdot \Delta h_{H_2O}$$

where

Δh_{H_2O} = change in specific enthalpy of water

$$\Delta h_{H_2O} = h_{H_2O(gas),T_b} - h_{H_2O(liquid),T_{fuel,i}}$$

The specific enthalpy of the liquid water at the initial temperature and the water vapor at the local boiling temperature can be looked up in a table. A reasonable approximation is:

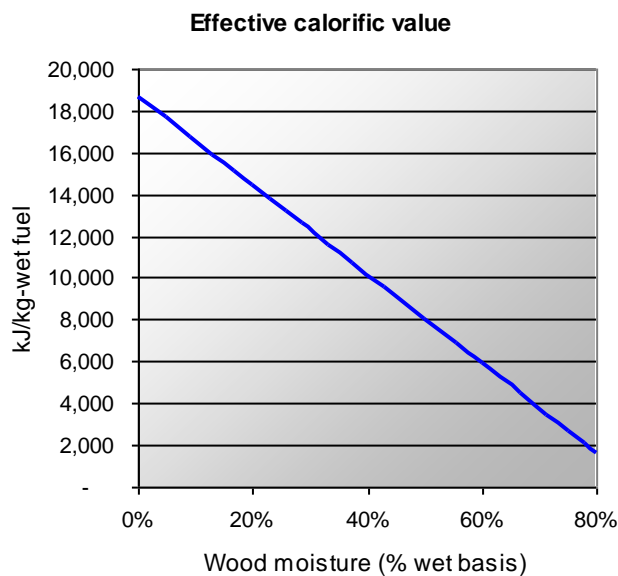
$$\Delta h_{H_2O} = \Delta h_{H_2O,fg} + h_{H_2O(liquid),T_b} - h_{H_2O(liquid),T_{fuel,i}} = \Delta h_{H_2O,fg} + C_{p,H_2O}(T_b - T_{fuel,i})$$

² Dry wood typically consists of 6% hydrogen by mass. Thus, one kg of dry wood contains 60 g of hydrogen, which reacts to form 540 g of H₂O. The difference in enthalpy between the liquid and gaseous phases of 540 g of water at room temperature is roughly 1.32 MJ, thus, for a typical sample of moisture-free wood, HHV and LHV differ by 1.32 MJ. In Baldwin (1986), the difference between HHV and LHV is given as 1.39 MJ/kg, but this applies to water vapor at 100 °C, which is not typically how LHV is defined [3, p. 55].

At common boiling temperatures, the specific heat capacity of liquid water (C_{p,H_2O}) is nearly constant at 4.2 kJ/kg*K, and the specific enthalpy of vaporization ($\Delta h_{H_2O,l,g}$) can be approximated at 2,260 kJ/kg. Therefore, the effective heating value can be calculated by:

$$EHV = LHV \cdot (1 - MC_{wet}) - MC_{wet} \cdot ((T_b - T_{fuel,i}) \cdot 4.2 + 2260)$$

The graph below shows EHV as a function of wood moisture content (wet basis) assuming an HHV of 20,000 kJ/kg (LHV of 18,680 kJ/kg), which is a typical value for hardwoods. Note that at 50% moisture, which is not uncommon for freshly cut (green) wood in moist climates, the effective energy content of the fuel is reduced by more than half.



P₁– This is the weight of the empty pot. For multi-pot stoves, P is followed by an index number 1 – 4.

k– This is the weight of the charcoal container that will be used to hold the char when it is removed from the stove and weighed.

T_b – This is the local boiling point of water, which should be determined empirically in order to account for variations as a result of altitude.

P_{atm} - This is the atmospheric pressure.

Q – This is the flow rate in the duct of the emissions collection hood system.

T_d – This is the temperature of the emission sample.

CO_{2b} – This is the average background CO₂ concentration to be taken before the test which will be subtracted from the average concentration measured during the test.

CO_b - This is the average background CO concentration to be taken before the test which will be subtracted from the average concentration measured during the test.

PM_b - This is the average background PM concentration to be taken before the test which will be subtracted from the average concentration measured during the test.

4.2 VARIABLES FOR HIGH POWER PHASE (COLD START)

Variables that are measured directly

f_{ci}	Mass of fuel before test (grams)
$P1_{ci}$	Mass of pot of water before test (grams)
$T1_{ci}$	Water temperature at start of test (°C)
$t_{c,i}$	Time at start of test (min)
f_{cf}	Mass of fuel after test (grams)
c_c	Mass char with dish after test (grams)
$P1_{cf}$	Mass of pot of water after test (grams)
$T1_{cf}$	Water temperature at end of test (°C)
t_{cf}	Time at end of test (min)

Variables that are calculated

f_{cm}	Fuel consumed, moist (grams)
Δc_c	Change in char during test (grams)
f_{cd}	Equivalent dry wood consumed (grams)
w_{cv}	Water vaporized (grams)
w_{cr}	Effective mass of water boiled (grams)
Δt_c	Time to boil (min)
Δt_c^T	Temperature corrected time to boil (min)
h_c	Thermal efficiency (%)
r_{cb}	Burning rate (grams/min)
SC_c	Specific fuel consumption (grams wood/liter water)
SC_c^T	Temp-corrected specific fuel consumption (grams wood/grams water)
	Temp-corrected specific energy consumption (kJ/liter water)
SET_c	
FP_c	Firepower (W)

Emission Variables that are Measured Directly

$CO_{2,c}$	Average CO ₂ concentration (ppm)
CO_c	Average CO concentration (ppm)
PM_c	Average PM concentration (ug/m ³)
T_{cd}	Average Duct Temperature (°C)

Emission Variables that are Calculated

V_c	Total exhaust flow (m ³)
CC_c	Exhaust carbon concentration (ppm)
C_c	Total carbon in exhaust (g/m ³)
f_{ce}	Dry fuel consumed estimated from emissions (grams)
CB_c	Hood carbon balance (%)
$EF_{CO_2,c}$	CO ₂ emission factor (grams emission/grams fuel)
$EF_{CO,c}$	CO emission factor (grams emission/grams fuel)
$EF_{PM,c}$	PM emission factor (grams emission/grams fuel)
$m_{CO_2,c}$	CO ₂ mass produced (grams)
$m_{CO,c}$	CO mass produced (grams)
$m_{PM,c}$	PM mass produced (grams)
$E_{CO_2,c}$	CO ₂ emission per water boiled (grams emission/liter water)
$E_{CO,c}$	CO emission per water boiled (grams emission/liter water)
$E_{PM,c}$	PM emission per water boiled (grams emission/liter water)

f_{cm} – The **fuel consumed (moist)** is the mass of wood used to bring the water to a boil, found by taking the difference of the pre-weighed bundle of wood and the wood remaining at the end of the test phase:

$$f_{cm} = f_{ci} - f_{cf}$$

Δc_c – The **net change in char during the test** is the mass of char created during the test, found by removing the char from the stove at the end of the test phase. Because it is very hot, the char will be placed in an empty pre-weighed container of mass k (to be supplied by testers) and weighing the char with the container, then subtracting the container mass from the total:

$$\Delta c_c = c_c - k$$

w_{cv} – The **mass of water vaporized** is a measure of the water lost through evaporation during the test. It is calculated by subtracting the initial weight of pot and water minus final weight of pot and water.

$$w_{cv} = P1_{ci} - P1_{cf}$$

w_{cr} – The **effective mass of water boiled** is the water remaining at end of the test. It is a measure of the amount of water heated to boiling. It is calculated by simple subtraction of final weight of pot and water minus the weight of the pot.

$$w_{cr} = P1_{cf} - P1$$

Δt_c – The **time to boil pot #1** is the difference between start and finish times:

$$\Delta t_c = t_{c,f} - t_{c,i}$$

Δt_c^T – The **temperature-corrected time to boil pot #1** is the same as above, but adjusts the result to a standard 75 °C temperature change (from 25 °C to 100 °C). This adjustment standardizes the results and facilitates a comparison between tests that may have used water with higher or lower initial temperatures.

$$\Delta t_c^T = \Delta t_c \cdot \frac{75}{T1_{cf} - T1_{ci}}$$

f_{cd} – The **equivalent dry fuel consumed** adjusts the amount of dry fuel that was burned in order to account for two factors: (1) the energy that was needed to remove the moisture in the fuel and (2) the amount of char remaining unburned. The mass of dry fuel consumed is the moist fuel consumed minus the mass of water in the fuel:

$$dry\ fuel = f_{cm} \cdot (1 - MC)$$

The energy that was needed to remove the moisture in the fuel ($\Delta E_{H_2O,c}$) is the mass of water in the fuel multiplied by the change in specific enthalpy of water.

$$\Delta E_{H_2O,c} = m_{H_2O,c} (C_p (T_b - T_{fuel,i}) + \Delta h_{H_2O,fg})$$

In similar fashion to the EHV equation above,

$$C_p \approx 4.186 \left[\frac{\text{kJ}}{\text{kgK}} \right] \quad \Delta h_{H_2O,fg} \approx 2,257 \left[\frac{\text{kJ}}{\text{kg}} \right] \quad T_{fuel,i} \approx T_a$$

The mass of water in the fuel is: $m_{H_2O,c} = f_{cm} \cdot MC$

Therefore,

$$\Delta E_{H_2O,c} = f_{cm} \cdot MC(4.186(T_b - T_a) + 2,257)$$

This quantity of energy is divided by the energy content of the fuel to determine the equivalent mass of fuel required to remove the moisture in the fuel:

$$\text{fuel to evap water} = \frac{\Delta E_{H_2O,c}}{LHV}$$

The fuel energy stored in the char remaining ($\Delta E_{char,c}$) is the mass of char multiplied by the energy content of the char:

$$\Delta E_{char,c} = \Delta c_c \cdot LHV_{char}$$

This quantity of energy is divided by the energy content of the fuel to determine the equivalent amount of unburned fuel remaining in the form of char:

$$\text{fuel in char} = \frac{\Delta E_{char,c}}{LHV}$$

Putting it all together we have:

$$f_{cd} = \text{dry fuel} - \text{fuel to evap water} - \text{fuel in char}$$

$$f_{cd} = f_{cm} \cdot (1 - MC) - \frac{f_{cm} \cdot MC(4.186(T_b - T_a) + 2,257)}{LHV} - \frac{\Delta c_c \cdot LHV_{char}}{LHV}$$

$$f_{cd} = \frac{f_{cm}(LHV(1 - MC) - MC(4.186(T_b - T_a) + 2,257)) - \Delta c_c \cdot LHV_{char}}{LHV}$$

h_c – Thermal efficiency: This is a ratio of the work done by heating and evaporating water to the energy consumed by burning fuel. It is an estimate of the total energy produced by the fire that is used to heat the water in the pot. It is calculated in the following way:

$$h_c = \frac{\Delta E_{H_2O,heat} + \Delta E_{H_2O,evap}}{E_{released,c}}$$

The energy to heat the water is the mass of water times specific heat capacity times change in temperature:

$$\Delta E_{H_2O,heat} = m_{H_2O} \cdot C_p \cdot \Delta T$$

As explained in the EHV equation above, the specific heat capacity can be approximated as:

$$C_p \approx 4.186 \left[\frac{kJ}{kgK} \right] \quad \text{and}$$

$$\Delta E_{H_2O,heat} = (P1_{ci} - P1) \cdot 4.186 \cdot (T1_{cf} - T1_{ci})$$

The energy to evaporate the water is the mass of water evaporated multiplied by the specific enthalpy of vaporization of water:

$$\Delta E_{H_2O,evap} = w_{cv} \cdot \Delta h_{H_2O,fg}$$

As explained in the EHV equation above, the specific enthalpy of vaporization can be approximated as:

$$\Delta h_{H_2O,fg} = 2,260 \left[\frac{kJ}{kg} \right] \quad \text{and}$$

$$\Delta E_{H_2O,evap} = w_{cv} \cdot 2,260$$

The energy consumed is the equivalent mass of dry fuel consumed multiplied by the heating value:

$$E_{released,c} = f_{cd} \cdot LHV$$

Putting it all together we have:

$$h_c = \frac{4.186(T1_{cf} - T1_{ci})(P1_{ci} - P1) + 2260 \cdot w_{cv}}{f_{cd} \cdot LHV}$$

The thermal efficiency is actually a unitless decimal fraction but it is formatted in Excel as a percentage.

r_{cb} – Burning rate: This is a measure of the rate of fuel consumption while bringing water to a boil. It is calculated by dividing the equivalent dry fuel consumed by the time of the test.

$$r_{cb} = \frac{f_{cd}}{\Delta t_c}$$

SC_{cold} - Specific fuel consumption: Specific consumption can be defined for any number of cooking tasks and should be considered “the fuel required to produce a unit output” whether the output is boiled water, cooked beans, or loaves of bread. In the case of the cold-start high-power WBT, it is a measure of the amount of wood required to produce one liter (or kilo) of boiling water starting with cold stove. It is calculated as:

$$SC_c = \frac{f_{cd}}{w_{cr}}$$

SC_c^T – Temperature corrected specific fuel consumption: This corrects specific consumption to account for differences in initial water temperatures. This facilitates comparison of stoves tested on different days or in different environmental conditions. The correction is a simple factor that “normalizes” the temperature change observed in test conditions to a “standard” temperature change of 75 °C (from 25 to 100). It is calculated in the following way:

$$SC_c^T = SC_c \cdot \frac{75}{T1_{cf} - T1_{ci}}$$

SE_c^T – Temperature corrected specific energy consumption: Similar to the temperature corrected specific fuel consumption, this metric is a measure of the amount of fuel energy required to produce one liter (or kilo) of boiling water starting with cold stove. It is the temperature corrected specific fuel consumption multiplied by the energy content of the fuel:

$$SE_c^T = SC_c^T \cdot \frac{LHV}{1000}$$

FP_c – Firepower: This is the fuel energy consumed to boil the water divided by the time to boil. It tells the average power output of the stove (in Watts) during the high-power test:

$$FP_c = \frac{f_{cd} \cdot LHV}{\Delta t_c \cdot 60}$$

Note, by using f_{cd} in this calculation, we have accounted for both the remaining char and the fuel moisture content:

V_c - Total exhaust flow: This the the total volume of air that passes through the collection hood. It is used to calculate the quantity of emissions that are collected by the hood. In this version of the WBT, stove emission quantities are calculated using the carbon balance method, and the total exhaust flow is not used to calculate the stove emission quantities. The total exhaust flow is the volumetric flow rate through the hood multiplied by the time of the test period:

$$V_c = Q \cdot \frac{\Delta t_c}{60}$$

CC_c - Exhaust carbon concentration: This is the average concentration of carbon atoms in the stove exhaust which accounts for the carbon atoms present in the CO₂, CO, and PM:

$$CC_c = CO2_{carbon,c} + CO_{carbon,c} + PM_{carbon,c}$$

One molecule of CO₂ contains one carbon atom. Therefore, the concentration of carbon from CO₂ [ppm_v] is the same as the concentration of CO₂. The CO₂ concentration is the difference between the concentration measured during the test and the background concentration:

$$CO2_{carbon,c} = CO2_c - CO2_b$$

The CO carbon concentration is calculated the same way:

$$CO_{carbon,c} = CO_c - CO_b$$

The PM is measured as a mass concentration $\left[\frac{\mu\text{g}}{\text{m}^3}\right]$. We assume that the PM is 80% carbon by mass, so the PM mass carbon concentration is:

$$PM_{\text{carbon},c} \left[\frac{\mu\text{g}}{\text{m}^3}\right] = 0.8 \cdot (PM_c - PM_b)$$

Now we need to convert the mass concentration $\left[\frac{\mu\text{g}}{\text{m}^3}\right]$ to [ppm_v]. The mass concentration of a gas is the mass of the gas per unit volume. The parts per million by volume of a gas is the volume fraction of space that the gas occupies multiplied by 1,000,000:

$$Conc_{\text{carbon}} \left[\frac{\text{g}}{\text{m}^3}\right] = \frac{m_{\text{gas}}}{V_{\text{Total}}} \quad Conc_{\text{carbon}} [\text{ppm}_v] = \frac{V_{\text{gas}}}{V_{\text{Total}}} \cdot 10^6$$

To convert from $\left[\frac{\text{g}}{\text{m}^3}\right]$ to [ppm_v] we use the ideal gas law to convert m_{gas} to V_{gas} :

$$P_{\text{Total}} V_{\text{gas}} = n_{\text{gas}} RT$$

The number of moles of the gas is equivalent to the mass of the gas divided by the molecular weight:

$$n_{\text{gas}} = \frac{m_{\text{gas}}}{MW_{\text{gas}}}$$

Substituting this into the ideal gas law we get:

$$P_{\text{Total}} V_{\text{gas}} = \frac{m_{\text{gas}}}{MW_{\text{gas}}} RT$$

Rearranging the ideal gas law to solve for V_{gas} we get:

$$V_{\text{gas}} = \frac{m_{\text{gas}} RT}{MW_{\text{gas}} P_{\text{Total}}}$$

$$R = \text{universal gas constant} = 0.008314 \left[\frac{\text{kPa} \cdot \text{m}^3}{\text{mol} \cdot \text{K}}\right]$$

$$T = \text{temperature of the gas in Kelvin} = T_d + 273.15$$

$$MW_{\text{gas}} = MW_{\text{carbon}} = 12 \left[\frac{\text{g}}{\text{mol}}\right]$$

$$P_{\text{Total}} = \text{atmospheric pressure} = P_{\text{atm}} [\text{kPa}]$$

$$V_{\text{gas}} = \frac{m_{\text{gas}} \cdot 0.008314 \cdot (T_d + 273.15)}{12 \cdot P_{\text{atm}}}$$

Then we substitute V_{gas} into the ppm_v equation to get:

$$PM_{\text{carbon},c} [\text{ppm}_v] = \frac{\frac{m_{\text{gas}} \cdot 0.008314 \cdot (T_d + 273.15)}{12 \cdot P_{\text{atm}}}}{\frac{m_{\text{gas}}}{MW_{\text{gas}} P_{\text{Total}}}} \cdot 10^6$$

$$PM_{\text{carbon},c} [\text{ppm}_v] = \left(\frac{m_{\text{gas}}}{V_{\text{Total}}}\right) \cdot \frac{0.008314 \cdot (T_d + 273.15) \cdot 10^6}{12 \cdot P_{\text{atm}}}$$

Then we substitute in the mass concentration of carbon:

Water Boiling Test, version 4.2.3

$$\left(\frac{m_{gas}}{V_{Total}}\right) \left[\frac{g}{m^3}\right] = \frac{PM_{carbon,c} \left[\frac{\mu g}{m^3}\right]}{10^6 \left[\frac{\mu g}{g}\right]} = \frac{0.8 \cdot (PM_c - PM_b)}{10^6} \left[\frac{g}{m^3}\right]$$

$$PM_{carbon,c} [ppm_v] = \frac{0.8 \cdot (PM_c - PM_b)}{10^6} \cdot \frac{0.008314 \cdot (T_d + 273.15) \cdot 10^6}{12 \cdot P_{atm}}$$

$$PM_{carbon,c} [ppm_v] = \frac{(PM_c - PM_b) \cdot 0.008314 \cdot (T_d + 273.15)}{15 \cdot P_{atm}}$$

Putting it all together we get:

$$CC_c = (CO_{2c} - CO_{2b}) + (CO_c - CO_b) + \frac{(PM_c - PM_b) \cdot 0.008314 \cdot (T_d + 273.15)}{15 \cdot P_{atm}}$$

C_c - Total carbon in exhaust: This is actually the mass concentration of carbon in the exhaust. It is calculated by using the ideal gas law to convert the volumetric exhaust carbon concentration [ppm_v] (CC_c calculated above) to a mass concentration. In the calculation of CC_c above, we show that the volumetric concentration [ppm_v] is related to the mass concentration $\left[\frac{g}{m^3}\right]$ by the formula:

$$Conc_{carbon} [ppm_v] = Conc_{carbon} \left[\frac{g}{m^3}\right] \cdot \frac{0.00831 \cdot (T_d + 273.15) \cdot 10^6}{12 \cdot P_{atm}}$$

Rearranging, we get:

$$Conc_{carbon} \left[\frac{g}{m^3}\right] = \frac{Conc_{carbon} [ppm_v]}{\frac{0.00831 \cdot (T_d + 273.15) \cdot 10^6}{12 \cdot P_{atm}}}$$

$$C_c = \frac{CC_c \cdot 12 \cdot P_{atm} \cdot 10^{-6}}{0.00831 \cdot (T_d + 273.15)}$$

f_{ce} - Dry fuel consumed estimated from emissions: This is the estimate of dry fuel consumed based on the total carbon mass collected in the emission hood. The total carbon mass is the mass concentration multiplied by the total volume collected. The total mass of carbon is divided by the fuel carbon fraction to calculate the total mass of fuel:

$$f_{ce} [g_{fuel}] = \frac{C_c \left[\frac{g_{carbon}}{m^3}\right] \cdot V_c [m^3]}{fuelFracC \left[\frac{g_{carbon}}{g_{fuel}}\right]}$$

CB_c - Hood carbon balance: This is the ratio of carbon collected in the emission hood to carbon consumed. The carbon balance is equivalent to the ratio of burned fuel collected in the emission hood to fuel consumed:

$$\begin{aligned} \text{Carbon Balance} &= \frac{\text{carbon emission collected}}{\text{total carbon consumed}} \\ &= \frac{(\text{dry fuel collected in emissions}) \cdot (\text{carbon fraction of fuel})}{(\text{dry fuel consumed}) \cdot (\text{carbon fraction of fuel})} \\ &= \frac{\text{dry fuel collected in emissions}}{\text{dry fuel consumed}} \end{aligned}$$

The dry fuel collected in the emissions is the quantity f_{ce} calculated above. The dry fuel consumed is determined by weighing the fuel and char before and after the test period. The dry fuel consumed is the moist fuel consumed minus the mass of moisture in the fuel minus the mass of fuel remaining in the form of char:

$$\text{dry fuel consumed} = f_{cm} \cdot (1 - MC) - \frac{\Delta c_c \cdot \text{charFracC}}{\text{fuelFracC}}$$

Therefore:

$$CB_c = \frac{f_{ce}}{f_{cm} \cdot (1 - MC) - \frac{\Delta c_c \cdot \text{charFracC}}{\text{fuelFracC}}}$$

The value of CB is a decimal fraction but the cell is formatted in Excel as a percent. The carbon balance indicates what fraction of the stove emissions are captured by the hood.

EF_{CO_{2,c}} - CO₂ emission factor: Average grams of CO₂ emitted per kilogram of fuel burned. It is calculated from the ratio of CO₂ concentration to carbon concentration.

$$\frac{\text{Conc}_{CO_2} [ppm_v]}{\text{Conc}_{carbon} [ppm_v]} = \frac{(CO_{2,c} - CO_{2,b})}{CC_c}$$

The parts per million by volume of a gas is the molar ratio of the gas multiplied by 1,000,000:

$$\text{Conc}_{carbon} [ppm_v] = \frac{n_{gas}}{n_{Total}} \cdot 10^6$$

Therefore, the volumetric concentration ratio of two gases is equivalent to the molar ratio:

$$\frac{\text{Conc}_{CO_2} [ppm_v]}{\text{Conc}_{carbon} [ppm_v]} = \frac{\frac{n_{CO_2} \cdot 10^6}{n_{Total}}}{\frac{n_{carbon} \cdot 10^6}{n_{Total}}} = \frac{n_{CO_2,c}}{n_{carbon,c}}$$

The moles of CO₂ in the numerator can be converted to grams of CO₂ by multiplying by the molecular weight of CO₂ (44 g/mol).

$$m_{CO_2} [g_{CO_2}] = n_{CO_2,c} [mol_{CO_2}] \cdot \frac{44 [g_{CO_2}]}{1 [mol_{CO_2}]}$$

The moles of carbon in the denominator can be converted to kilograms of fuel by first multiplying by the molecular weight of carbon (12 g/mol) to get grams of carbon, then dividing by the mass fraction of carbon to get grams of fuel, then dividing by 1000 to convert grams of fuel to kilograms of fuel.

$$m_{fuel} [kg] = n_{carbon} [mol_{carbon}] \cdot \frac{12 [g_{carbon}]}{1 [mol_{carbon}]} \cdot \frac{1 [g_{fuel}]}{fuelFracC [g_{carbon}]} \cdot \frac{1 [kg_{fuel}]}{1000 [g_{fuel}]}$$

Putting it all together we get:

$$EF_{CO_2,c} \left[\frac{g_{CO_2}}{kg_{fuel}} \right] = \frac{m_{CO_2} [g_{CO_2}]}{m_{fuel} [kg]} = \frac{n_{CO_2,c} [mol_{CO_2}] \cdot 44 \left[\frac{g_{CO_2}}{mol_{CO_2}} \right]}{n_{carbon,c} [mol_{carbon}] \cdot 12 \left[\frac{g_{carbon}}{mol_{carbon}} \right] \cdot \frac{1 [g_{fuel}]}{fuelFracC [g_{carbon}]} \cdot \frac{1 [kg_{fuel}]}{1000 [g_{fuel}]}}$$

And then we substitute back in:

$$\frac{n_{CO_2,c} [mol_{CO_2}]}{n_{carbon,c} [mol_{carbon}]} = \frac{(CO_2_c - CO_2_b)}{CC_c}$$

To arrive at:

$$EF_{CO_2,c} = \frac{(CO_2_c - CO_2_b)}{CC_c} \cdot \frac{44}{12} \cdot fuelFracC \cdot 1,000$$

EF_{CO,c} - CO emission factor: Average grams of CO emitted per kilogram of fuel burned. It is calculated the same way as EF_{CO₂,c} but the molecular weight of CO is used instead:

$$EF_{CO,c} = \frac{(CO_c - CO_b)}{CC_c} \cdot \frac{28}{12} \cdot fuelFracC \cdot 1,000$$

EF_{PM,c} - PM emission factor: Average grams of PM emitted per kilogram of fuel burned. It is calculated a little differently than EF_{CO₂,c} and EF_{CO,c} because the PM concentration is a mass concentration with units $\left[\frac{\mu g}{m^3} \right]$ not [ppm_v]. If we take the ratio of the mass concentration of PM to the mass concentration of carbon, we get:

$$\frac{(PM_c - PM_b) \left[\frac{\mu g_{PM}}{m^3_{air}} \right]}{C_c \left[\frac{g_{carbon}}{m^3_{air}} \right]} = \frac{(PM_c - PM_b)}{C_c} \left[\frac{\mu g_{PM}}{g_{carbon}} \right]$$

The numerator can be converted from micrograms to grams of PM by dividing by 1,000,000.

$$m_{PM} [g_{PM}] = \frac{m_{PM} [\mu g_{PM}]}{1,000,000 \left[\frac{\mu g_{PM}}{g_{PM}} \right]}$$

The denominator can be converted from grams of carbon to kilograms of fuel by first dividing by the fuel carbon fraction to get grams of fuel and then dividing by 1000 to convert from grams to kilograms:

$$m_{fuel} [kg_{fuel}] = \frac{m_{carbon} [g_{carbon}]}{fuelFracC \left[\frac{g_{carbon}}{g_{fuel}} \right] \cdot 1000 \left[\frac{g_{fuel}}{kg_{fuel}} \right]}$$

Putting it all together, we get:

$$EF_{PM,c} = \frac{m_{PM} [g_{PM}]}{m_{fuel} [kg_{fuel}]} = \frac{(PM_c - PM_b) \cdot fuelFracC \cdot 1,000}{C_c \cdot 1,000,000}$$

$m_{CO_2,c}$ - CO₂ mass produced: This is the total mass of CO₂ emitted during the test phase. It is the emission factor $EF_{CO_2,c} \left[\frac{g_{CO_2}}{kg_{fuel}} \right]$ multiplied by the dry fuel consumed [kg_{dryfuel}]. The dry fuel consumed is the moist fuel consumed minus the weight of moisture in the fuel minus the amount of fuel that remains in the form of char:

$$m_{CO_2,c} = EF_{CO_2,c} \cdot \left(f_{cm} \cdot (1 - MC) - \Delta c_c \cdot \frac{charFracC}{fuelFracC} \right) \cdot \frac{1}{1000}$$

$m_{CO,c}$ - CO mass produced: This is the total mass of CO emitted during the test phase. It is the emission factor $EF_{CO,c} \left[\frac{g_{CO}}{kg_{fuel}} \right]$ multiplied by the dry fuel consumed [kg_{dryfuel}]. The dry fuel consumed is the moist fuel consumed minus the weight of moisture in the fuel minus the amount of fuel that remains in the form of char:

$$m_{CO,c} = EF_{CO,c} \cdot \left(f_{cm} \cdot (1 - MC) - \Delta c_c \cdot \frac{charFracC}{fuelFracC} \right) \cdot \frac{1}{1000}$$

$m_{PM,c}$ - PM mass produced: This is the total mass of PM emitted during the test phase. It is the emission factor $EF_{PM,c} \left[\frac{g_{CO}}{kg_{fuel}} \right]$ multiplied by the dry fuel consumed [kg_{dryfuel}]. The dry fuel consumed is the moist fuel consumed minus the weight of moisture in the fuel minus the amount of fuel that remains in the form of char:

$$m_{PM,c} = EF_{PM,c} \cdot \left(f_{cm} \cdot (1 - MC) - \Delta c_c \cdot \frac{charFracC}{fuelFracC} \right) \cdot \frac{1}{1000}$$

$E_{CO_2,c}$ - CO₂ emission per water boiled: It is the total mass of CO₂ emitted divided by effective mass of water boiled, then multiplied by the approximate density of water:

$$E_{CO_2,c} \left[\frac{g_{CO_2}}{L_{H_2O}} \right] = \frac{m_{CO_2,c} [g_{CO_2}]}{w_{cr} [g_{H_2O}]} \cdot 1000 \left[\frac{g_{H_2O}}{L_{H_2O}} \right]$$

$E_{CO_2,c}$ - CO emission per water boiled: It is the total mass of CO emitted divided by effective mass of water boiled, then multiplied by the approximate density of water:

$$E_{CO,c} \left[\frac{g_{CO}}{L_{H_2O}} \right] = \frac{m_{CO,c} [g_{CO}]}{w_{cr} [g_{H_2O}]} \cdot 1000 \left[\frac{g_{H_2O}}{L_{H_2O}} \right]$$

$E_{PM,c}$ - PM emission per water boiled: It is the total mass of PM emitted divided by effective mass of water boiled, then multiplied by the approximate density of water:

$$E_{PM,c} \left[\frac{g_{PM}}{L_{H_2O}} \right] = \frac{m_{PM,c} [g_{PM}]}{w_{cr} [g_{H_2O}]} \cdot 1000 \left[\frac{g_{H_2O}}{L_{H_2O}} \right]$$

4.3 VARIABLES FOR HIGH POWER PHASE (HOT START)

In this test, measurements and calculations are identical to the cold start test except that the char remaining is not extracted and weighed. Simply substitute the subscript 'h' for the subscript 'c' in each variable as in the table below. Char remaining is assumed to be the same as the char remaining from the "cold start" phase.

Variables that are directly measured

f_{hi}	Mass of fuel before test (grams)
Pl_{hi}	Mass of pot of water before test (grams)
Tl_{hi}	Water temperature at start of test (°C)
$T_{h,i}$	Time at start of test (min)
f_{hf}	Mass of fuel after test (grams)
c_h	Mass char with dish after test (grams)
Pl_{hf}	Mass of pot of water after test (grams)
Tl_{hf}	Water temperature at end of test (°C)
t_{hf}	Time at end of test (min)

Variables that are calculated

f_{hm} Fuel consumed, moist (grams)

$$f_{hm} = f_{hi} - f_{hf}$$

Δc_h	Change in char during test (grams)	$\Delta c_h = \Delta c_c$
f_{hd}	Equivalent dry wood consumed (grams)	$f_{hd} = \frac{f_{hm}(LHV(1 - MC) - MC(4.186(T_b - T_a) + 2,257)) - \Delta c_h \cdot LHV_{char}}{LHV}$
w_{hv}	Water vaporized (grams)	$w_{hv} = P1_{hi} - P1_{hf}$
w_{hr}	Effective mass of water boiled (grams)	$w_{hr} = P1_{hf} - P1$
Δt_h	Time to boil (min)	$\Delta t_h = t_{h,f} - t_{h,i}$
Δt_h^T	Temperature corrected time to boil (min)	$\Delta t_h^T = \Delta t_h \cdot \frac{75}{T1_{hf} - T1_{hi}}$
h_h	Thermal efficiency (%)	$h_h = \frac{4.186(T1_{hf} - T1_{hi})(P1_{hi} - P1) + 2260 \cdot w_{hv}}{f_{hd} \cdot LHV}$
r_{hb}	Burning rate (grams/min)	$r_{hb} = \frac{f_{hd}}{\Delta t_h}$
SC_h	Specific fuel consumption (grams wood/liter water)	$SC_h = \frac{f_{hd}}{w_{hr}}$
SC_h^T	Temp-corrected specific fuel consumption (grams wood/grams water)	$SC_h^T = SC_h \cdot \frac{75}{T1_{hf} - T1_{hi}}$
SE_h^T	Temp-corrected specific energy consumption (kJ/liter water)	$SE_h^T = SC_h^T \cdot \frac{LHV}{1000}$
FP_h	Firepower (W)	$FP_h = \frac{f_{hd} \cdot LHV}{\Delta t_h \cdot 60}$

Emission Variables that are Measured Directly

CO_{2h}	Average CO_2 concentration (ppm)
CO_h	Average CO concentration (ppm)
PM_h	Average PM concentration ($\mu g/m^3$)
T_{hd}	Average Duct Temperature ($^{\circ}C$)

Emission Variables that are Calculated

V_h	Total exhaust flow (m^3)	$V_h = Q \cdot \frac{\Delta t_h}{60}$
-------	------------------------------	---------------------------------------

CC_h	Exhaust carbon concentration (ppm)	$CC_h = (CO_{2h} - CO_{2b}) + (CO_h - CO_b) + \frac{(PM_h - PM_b) \cdot 0.008314 \cdot (T_d + 273.15)}{15 \cdot P_{atm}}$
C_h	Total carbon in exhaust (g/m^3)	$C_h = \frac{CC_h \cdot 12 \cdot P_{atm} \cdot 10^{-6}}{0.00831 \cdot (T_d + 273.15)}$
f_{he}	Dry fuel consumed estimated from emissions (grams)	$f_{he} = \frac{C_h \cdot V_h}{fuelFracC}$
CB_h	Hood carbon balance (%)	$CB_h = \frac{f_{he}}{f_{hm} \cdot (1 - MC) - \frac{\Delta c_h \cdot charFracC}{fuelFracC}}$
$EF_{CO_2,h}$	CO ₂ emission factor (grams emission/grams fuel)	$EF_{CO_2,h} = \frac{(CO_{2h} - CO_{2b})}{CC_h} \cdot \frac{44}{12} \cdot fuelFracC \cdot 1,000$
$EF_{CO,h}$	CO emission factor (grams emission/grams fuel)	$EF_{CO,h} = \frac{(CO_h - CO_b)}{CC_h} \cdot \frac{28}{12} \cdot fuelFracC \cdot 1,000$
$EF_{PM,h}$	PM emission factor (grams emission/grams fuel)	$EF_{PM,h} = \frac{(PM_h - PM_b) \cdot fuelFracC \cdot 1,000}{C_h \cdot 1,000,000}$
$m_{CO_2,h}$	CO ₂ mass produced (grams)	$m_{CO_2,h} = EF_{CO_2,h} \cdot \left(f_{hm} \cdot (1 - MC) - \Delta c_h \cdot \frac{charFracC}{fuelFracC} \right) \cdot \frac{1}{1000}$
$m_{CO,h}$	CO mass produced (grams)	$m_{CO,h} = EF_{CO,h} \cdot \left(f_{hm} \cdot (1 - MC) - \Delta c_h \cdot \frac{charFracC}{fuelFracC} \right) \cdot \frac{1}{1000}$
$m_{PM,h}$	PM mass produced (grams)	$m_{PM,h} = EF_{PM,h} \cdot \left(f_{hm} \cdot (1 - MC) - \Delta c_h \cdot \frac{charFracC}{fuelFracC} \right) \cdot \frac{1}{1000}$
$E_{CO_2,h}$	CO ₂ emission per water boiled (grams emission/liter water)	$E_{CO_2,h} = \frac{m_{CO_2,h}}{w_{hr}} \cdot 1000$
$E_{CO,h}$	CO emission per water boiled (grams emission/liter water)	$E_{CO,h} = \frac{m_{CO,h}}{w_{hr}} \cdot 1000$
$E_{PM,h}$	PM emission per water boiled (grams emission/liter water)	$E_{PM,h} = \frac{m_{PM,h}}{w_{hr}} \cdot 1000$

4.4 VARIABLES FOR LOW POWER PHASE (SIMMERING)

In this test, the initial measurements are the same as in the high power tests, however the goal of this test is to maintain water at a high temperature with minimal power output from the stove. Since the goal differs, the interpretations of the calculations also differ from those of the high power phases. In addition,

one important assumption is made using data from the hot start high power test and one additional calculation is performed that does not appear in the high power tests. These are both explained below.

The assumption made in this test is based on the amount of char present at the start of the simmer phase. At the end of the hot start phase, when the water comes to a boil, it is quickly weighed without disturbing the char and then the fire is tended to maintain the water within a few degrees of boiling for 45 minutes. There will be char remaining in the stove from the wood that was used to bring the water to a boil during the hot start. Removing that char from the stove, weighing it, and relighting it disturbs the fire and may result in the water temperature dropping too far below boiling. Thus, the recommended procedure is to assume that the char present at the start of the simmer phase is the same as the char that was measured after the high power cold start test (Δc_s). While this is not entirely accurate, the error introduced by this assumption should be minimal – especially if the tester(s) followed an identical procedure in the cold start and hot start phases.

Variables that are directly measured

f_{si}	Starting mass of fuel (grams)
$P1_{si}$	Starting mass of pot with water (grams)
$T1_{si}$	Starting water temperature ($T_{si} = T1_{hf}$) (°C)
$t_{s,i}$	Time at start of simmer phase (min)
f_{sf}	Mass of unburned fuel remaining after test (grams)
c_s	Mass of charcoal and container after test (grams)
$P1_{sf}$	Mass of pot with water after test (grams)
$T1_{sf}$	Water temperature at end of test (°C)
$t_{s,f}$	Time at end of simmer phase (min)

Variables that are calculated

f_{sm}	Fuel consumed, moist (grams)	$f_{sm} = f_{si} - f_{sf}$
Δc_s	Change in char during test (grams)	$\Delta c_s = c_s - k$
f_{sd}	Equivalent dry fuel consumed (grams)	$f_{sd} = \frac{f_{sm}(LHV(1 - MC) - MC(4.186(T_b - T_a) + 2,257)) - \Delta c_s \cdot LHV_{char}}{LHV}$
w_{sv}	Water vaporized (grams)	$w_{sv} = P1_{si} - P1_{sf}$
w_{sr}	Effective mass of water simmered (grams)	$w_{sr} = P1_{sf} - P1$
Δt_s	Time to boil (min)	$\Delta t_s = t_{s,f} - t_{s,i}$
h_s	Thermal efficiency (%)	$h_s = \frac{4.186(T1_{sf} - T1_{si})(P1_{si} - P1 + w_{sr})/2 + 2260 \cdot w_{sv}}{f_{sd} \cdot LHV}$
r_{sb}	Burning rate (grams/min)	$r_{sb} = \frac{f_{sd}}{\Delta t_s}$

SC_s	Specific fuel consumption (grams wood/liter water)	$SC_s = \frac{f_{sd}}{w_{sr}}$
SE_s	Specific energy consumption (kJ/liter water)	$SE_s = SE_s \cdot \frac{LHV}{1000}$
FP_s	Firepower (W)	$FP_s = \frac{f_{sd} \cdot LHV}{\Delta t_s \cdot 60}$
TDR	Turn down ratio	$TDR = \frac{FP_c}{FP_s}$

Emission Variables that are Measured Directly

CO_{2s}	Average CO_2 concentration (ppm)
CO_s	Average CO concentration (ppm)
PM_s	Average PM concentration ($\mu\text{g}/\text{m}^3$)
T_{sd}	Average Duct Temperature ($^{\circ}\text{C}$)

Emission Variables that are Calculated

V_s	Total exhaust flow (m^3)	$V_s = Q \cdot \frac{\Delta t_s}{60}$
CC_s	Exhaust carbon concentration (ppm)	$CC_s = (CO_{2s} - CO_{2b}) + (CO_s - CO_b) + \frac{(PM_s - PM_b) \cdot 0.008314 \cdot (T_d + 273.15)}{15 \cdot P_{atm}}$
C_s	Total carbon in exhaust (g/m^3)	$C_s = \frac{CC_s \cdot 12 \cdot P_{atm} \cdot 10^{-6}}{0.00831 \cdot (T_d + 273.15)}$
f_{se}	Dry fuel consumed estimated from emissions (grams)	$f_{se} = \frac{C_s \cdot V_s}{fuelFracC}$
CB_s	Hood carbon balance (%)	$CB_s = \frac{f_{se}}{f_{sm} \cdot (1 - MC) - \frac{\Delta c_s \cdot charFracC}{fuelFracC}}$
$EF_{CO_{2,s}}$	CO_2 emission factor (grams emission/grams fuel)	$EF_{CO_{2,s}} = \frac{(CO_{2s} - CO_{2b})}{CC_s} \cdot \frac{44}{12} \cdot fuelFracC \cdot 1,000$
EF_{CO_s}	CO emission factor (grams emission/grams fuel)	$EF_{CO_s} = \frac{(CO_s - CO_b)}{CC_s} \cdot \frac{28}{12} \cdot fuelFracC \cdot 1,000$
$EF_{PM,s}$	PM emission factor (grams)	$EF_{PM,s} = \frac{(PM_s - PM_b) \cdot fuelFracC \cdot 1,000}{C_s \cdot 1,000,000}$

emission/grams fuel)

$m_{CO_2,s}$	CO ₂ mass produced (grams)	$m_{CO_2,s} = EF_{CO_2,s} \cdot \left(f_{sm} \cdot (1 - MC) - \Delta c_s \cdot \frac{\text{charFracC}}{\text{fuelFracC}} \right) \cdot \frac{1}{1000}$
$m_{CO,s}$	CO mass produced (grams)	$m_{CO,s} = EF_{CO,s} \cdot \left(f_{sm} \cdot (1 - MC) - \Delta c_s \cdot \frac{\text{charFracC}}{\text{fuelFracC}} \right) \cdot \frac{1}{1000}$
$m_{PM,s}$	PM mass produced (grams)	$m_{PM,s} = EF_{PM,s} \cdot \left(f_{sm} \cdot (1 - MC) - \Delta c_s \cdot \frac{\text{charFracC}}{\text{fuelFracC}} \right) \cdot \frac{1}{1000}$
$E_{CO_2,s}$	CO ₂ emission per water simmered (grams emission/liter water)	$E_{CO_2,s} = \frac{m_{CO_2,s}}{w_{sr}} \cdot 1000$
$E_{CO,s}$	CO emission per water simmered (grams emission/liter water)	$E_{CO,s} = \frac{m_{CO,s}}{w_{sr}} \cdot 1000$
$E_{PM,s}$	PM emission per water simmered (grams emission/liter water)	$E_{PM,s} = \frac{m_{PM,s}}{w_{sr}} \cdot 1000$

h_s – The thermal efficiency calculation for simmer is a little different than the high power calculation. For the high power thermal efficiency, the mass of water boiled is the water mass at the start of the test ($P1_{ci} - P1$). For the low power thermal efficiency, the effective mass of water simmered is the average of the starting and ending water masses in the pot:

$$= (P1_{si} - P1 + w_{sr})/2$$

This calculation difference is not important because the thermal efficiency should not be used to evaluate the low power stove performance. Because thermal efficiency accounts for sensible heat as well as evaporative losses, it rewards for the generation of steam. In most cooking conditions, excess steam production does not decrease cooking time, as the temperature in the pot is fixed at the boiling point. Thus, producing excess steam, while it does reflect fuel energy transferred to the cooking pot, is not necessarily a good indicator of stove performance. Instead, the Turndown Ratio and the IWA Low Power Specific Fuel Consumption should be used to evaluate low power stove performance.

TDR – Turndown Ratio is the ratio of average high firepower to average low firepower. It represents the degree to which the firepower of the stove can be controlled by the user:

$$TDR = \frac{FP_c}{FP_s}$$

There is no temperature-corrected specific consumption in the simmer phase because the change in temperature should be limited to a few degrees.

It is important to remember that the goal of this part of the test is to maintain the water at a temperature just under boiling, and one should interpret the results accordingly. Whereas the specific consumption in the high power phases (SC_c and SC_h) indicated the mass of fuel required to complete the task of boiling one liter (or kilogram) (including the evaporation of some water), the specific consumption in the simmer phase (SC_s) indicates the mass of fuel required to *maintain* each liter (or kilo) of water three degrees below boiling temperature. These are not directly comparable, but rather tell two different measures of stove performance. The same is true for other indicators, like burning rate and firepower.

4.5 IWA PERFORMANCE METRICS

High Power Thermal Efficiency (%): If the Hot Start phase is omitted, then the cold start efficiency is reported:

$$\text{High Power Thermal Efficiency} = h_c$$

If the Hot Start phase is not omitted, then the average of the cold start efficiency and hot start efficiency is reported:

$$\text{High Power Thermal Efficiency} = \frac{h_c + h_h}{2}$$

Low Power Specific Fuel Consumption (MJ/min/L): A more descriptive name for this metric is low power specific energy consumption rate. It is the energy consumed per liter of water simmered per minute. The energy consumed is the equivalent dry fuel consumed during simmer multiplied by the heat content of the fuel. By normalizing for the amount of water and the time of simmer, this metric can be used to compare stove performance even when the amount of water and length of the simmer is different between stoves.

$$\text{Low Power Specific Fuel Consumption} = \frac{f_{sd} \cdot \text{LHV}}{w_{sr} \cdot \Delta t_s \cdot 1000}$$

High Power CO (g/MJ_d): This metric is the CO emission per unit of energy delivered to the cooking pot:

$$\text{High Power CO} \left[\frac{\text{g}}{\text{MJ}} \right] = \frac{\text{CO emission [g]}}{\text{Energy delivered to pot [MJ]}}$$

The energy delivered to the cooking pot is the total energy consumed multiplied by the thermal efficiency. The total energy consumed is the equivalent dry fuel consumed during the high power phase(s) multiplied by the heat content of the fuel:

$$\text{Energy delivered to pot [MJ]} = h_c \cdot f_{cd} [\text{g}] \cdot \text{LHV} \left[\frac{\text{kJ}}{\text{kg}} \right] \cdot \frac{1}{1000} \left[\frac{\text{MJ}}{\text{kJ}} \right] \cdot \frac{1}{1000} \left[\frac{\text{kg}}{\text{g}} \right]$$

If the Hot Start phase is omitted, then the metric is calculated for the Cold Start:

$$\text{High Power CO} = \frac{m_{CO,c} \cdot 1000000}{h_c \cdot f_{cd} \cdot \text{LHV}}$$

If the Hot Start phase is not omitted, then the metric is calculated for the Cold Start and Hot Start and the average of the two is reported:

$$\text{High Power CO} = \frac{\frac{m_{\text{CO,c}} \cdot 1000000}{h_c \cdot f_{\text{cd}} \cdot \text{LHV}} + \frac{m_{\text{CO,h}} \cdot 1000000}{h_h \cdot f_{\text{hd}} \cdot \text{LHV}}}{2} = \frac{1000000}{\text{LHV} \cdot 2} \cdot \left(\frac{m_{\text{CO,c}}}{h_c \cdot f_{\text{cd}}} + \frac{m_{\text{CO,h}}}{h_h \cdot f_{\text{hd}}} \right)$$

Low Power CO (g/min/L): A more descriptive name for this metric is low power specific emission rate. It is the CO emission per liter of water simmered per minute. By normalizing for the amount of water and the time of simmer, this metric can be used to compare stove performance even when the amount of water and length of the simmer is different between stoves.

$$\text{Low Power CO} = \frac{m_{\text{CO,s}}}{\Delta t_s \cdot w_{s,r}} \cdot 1000$$

High Power PM (mg/MJ_a): This metric is the PM emission per unit of energy delivered to the cooking pot:

$$\text{High Power PM} \left[\frac{\text{mg}}{\text{MJ}} \right] = \frac{\text{PM emissions [mg]}}{\text{Energy delivered to pot [MJ]}}$$

The energy delivered to the pot is the total energy consumed multiplied by the thermal efficiency. The total energy consumed is the equivalent dry fuel consumed during the high power phase(s) multiplied by the heat content of the fuel:

$$\text{Energy delivered to pot [MJ]} = h_c \cdot f_{\text{cd}} [\text{g}] \cdot \text{LHV} \left[\frac{\text{kJ}}{\text{kg}} \right] \cdot \frac{1}{1000} \left[\frac{\text{MJ}}{\text{kJ}} \right] \cdot \frac{1}{1000} \left[\frac{\text{kg}}{\text{g}} \right]$$

If the Hot Start phase is omitted, then the metric is calculated for the Cold Start:

$$\text{High Power PM} = \frac{m_{\text{PM,c}} \cdot 10^9}{h_c \cdot f_{\text{cd}} \cdot \text{LHV}}$$

If the Hot Start phase is not omitted, then the metric is calculated for the Cold Start and Hot Start and the average of the two is reported:

$$\text{High Power PM} = \frac{\frac{m_{\text{PM,c}} \cdot 10^9}{h_c \cdot f_{\text{cd}} \cdot \text{LHV}} + \frac{m_{\text{PM,h}} \cdot 10^9}{h_h \cdot f_{\text{hd}} \cdot \text{LHV}}}{2} = \frac{10^9}{\text{LHV} \cdot 2} \cdot \left(\frac{m_{\text{PM,c}}}{h_c \cdot f_{\text{cd}}} + \frac{m_{\text{PM,h}}}{h_h \cdot f_{\text{hd}}} \right)$$

Low Power PM (mg/min/L): A more descriptive name for this metric is low power specific emission rate. It is the PM emission per liter of water simmered per minute. By normalizing for the amount of water and the time of simmer, this metric can be used to compare stove performance even when the amount of water and length of the simmer is different between stoves.

$$\text{Low Power PM} = \frac{m_{\text{PM,s}}}{\Delta t_s \cdot w_{s,r}} \cdot 1000000$$

Indoor CO Emissions (g/min): This metric reports the high power or low power CO emission rate into the kitchen, whichever is greater:

$$\text{Indoor CO Emissions} = \max (ER_{\text{CO,high}}, ER_{\text{CO,low}})$$

If the Hot Start phase is omitted, then the high power emission rate is calculated for the Cold Start:

$$ER_{CO,high} = \frac{m_{CO,indoor,c}}{\Delta t_c}$$

where $m_{CO,indoor,c}$ is the total mass of CO emitted into the kitchen during the test period.

If the Hot Start phase is not omitted, then the high power emission rate is calculated for the Cold Start and Hot Start and the average of the two is reported:

$$ER_{CO,high} = \frac{\frac{m_{CO,indoor,c}}{\Delta t_c} + \frac{m_{CO,indoor,h}}{\Delta t_h}}{2}$$

The low power emission rate is calculated from the simmer period:

$$ER_{CO,low} = \frac{m_{CO,indoor,s}}{\Delta t_s}$$

For non-chimney stoves that vent 100% of emissions into the kitchen, the total mass emitted into the kitchen is equal to the total mass emitted from the stove ($m_{CO,indoor,c}=m_{CO,c}$, $m_{CO,indoor,h}=m_{CO,h}$, $m_{CO,indoor,s}=m_{CO,s}$). For other stoves that vent outdoors, the fugitive emissions into the kitchen must be measured separately from the total emissions and the formula in the spreadsheet must be corrected accordingly.

Indoor PM Emissions (mg/min): This metric reports the high power or low power PM2.5 emission rate into the kitchen, whichever is greater:

$$Indoor\ PM\ Emissions = \max(ER_{PM,high}, ER_{PM,low})$$

It is calculated in the same manner as the Indoor CO Emissions except a factor of 1000 is added to convert grams to milligrams. If the Hot Start phase is omitted, then the high power emission rate is calculated for the Cold Start:

$$ER_{PM,high} = \frac{m_{PM,indoor,c}}{\Delta t_c} \cdot 1000$$

where $m_{PM,indoor,c}$ is the total mass of PM emitted into the kitchen during the test period.

If the Hot Start phase is not omitted, then the high power emission rate is calculated for the Cold Start and Hot Start and the average of the two is reported:

$$ER_{PM,high} = \frac{\frac{m_{PM,indoor,c}}{\Delta t_c} \cdot 1000 + \frac{m_{PM,indoor,h}}{\Delta t_h} \cdot 1000}{2}$$

The low power emission rate is calculated from the simmer period:

$$ER_{PM,low} = \frac{m_{PM,indoor,s}}{\Delta t_s} \cdot 1000$$

For non-chimney stoves that vent 100% of emissions into the kitchen, the total mass emitted into the kitchen is equal to the total mass emitted from the stove ($m_{PM,indoor,c}=m_{PM,c}$, $m_{PM,indoor,h}=m_{PM,h}$, $m_{PM,indoor,s}=m_{PM,s}$). For other stoves that vent outdoors, the fugitive emissions into the kitchen must be measured separately from the total emissions and the formula in the spreadsheet must be corrected accordingly.

4.6 IWA PERFORMANCE TIERS

The IWA Performance Metrics are grouped into tiers using the following table:

IWA VITA WBT Tiers	units	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
High Power Thermal Efficiency	%	< 0.15	≥ 0.15	≥ 0.25	≥ 0.35	≥ 0.45
Low Power Specific Consumption	MJ/min/L	> 0.05	≤ 0.05	≤ 0.039	≤ 0.028	≤ 0.017
High Power CO	g/MJd	> 16	≤ 16	≤ 11	≤ 9	≤ 8
Low Power CO	g/min/L	> 0.2	≤ 0.2	≤ 0.13	≤ 0.1	≤ 0.09
High Power PM	mg/MJd	> 979	≤ 979	≤ 386	≤ 168	≤ 41
Low Power PM	mg/min/L	> 8	≤ 8	≤ 4	≤ 2	≤ 1
Indoor Emissions CO	g/min	> 0.97	≤ 0.97	≤ 0.62	≤ 0.49	≤ 0.42
Indoor Emissions PM	mg/min	> 40	≤ 40	≤ 17	≤ 8	≤ 2
Safety	Johnsons	< 45	≥ 45	≥ 75	≥ 88	≥ 95

APPENDIX 5. STATISTICS LESSONS FOR PERFORMANCE TESTING

Rob Bailis, formerly UC Berkeley, now Yale University

At least three tests should be performed on each stove. If two models of stove are being compared, the testers should pay attention to the statistical significance of the results of the series of tests. For example, if testers want to compare an indicator of stove performance like *specific fuel consumption*, it is not possible to say conclusively that one stove is better than another with 100% surety. They can only declare one stove better than another with a certain level of confidence. This level depends on several factors, including the difference in the average *specific consumption* of each stove, the variability of the test results, and the number of tests that were performed.

While a full discussion of statistical theory is beyond the scope of this stove-testing manual, we will rely on some basic ideas of statistical theory to decide whether or not the results of these tests can be used to make claims about the relative performance of different stove models. For example, Table 1 shows data from a series of cold-start water boiling tests conducted at the Aprovecho Research Center on two different single-pot woodstoves. Each stove was tested three times. From the data, it is clear that the Stove-2 performs much better than Stove-1 in most indicators of stove performance. Notice however, that some indicators of stove performance, namely burning rate and firepower, show difference between stoves. This indicates the importance of considering a multiple indicators when defining stove performance.

TABLE 1: RESULTS OF THREE HIGH-POWER COLD START WATER BOILING TESTS ON TWO DIFFERENT STOVES. STATISTICS SHOULD ALSO BE COMPARED FOR OTHER TWO PHASES

	units	Stove-1			Stove-2			Statistics		
		Mean	SD	CoV	Mean	SD	CoV	% difference between Stove-1 and Stove-2	T-test	Significant with 95% confidence?
Wood consumed	g	837	34	4%	468	60	13%	-44%	7.55	YES
Time to boil 5 liters of water	min	36	3	7%	20	2	10%	-44%	6.89	YES
Thermal efficiency	--	0.19	0.01	4%	0.28	0.04	14%	49%	-3.30	YES
Rate of wood consumption	g/min	23	1	3%	24	4	18%	1%	-0.04	NO
Specific fuel consumption	g/liter	155	8	5%	91	11	12%	-41%	6.77	YES
Firepower	kW	6.6	0.2	3%	6.6	1.2	18%	1%	-0.04	NO

SD = Standard deviation; CoV = Coefficient of variation

Table 2, on the other hand, shows the impact of greater variability on the statistical confidence. The table shows the specific consumption derived from two pairs of stove comparisons based on three trials each. In both the higher and lower variability cases, the stoves have the same average specific consumptions, favoring the Stove-2 by 23% (104 compared to 134 g wood per liter of water boiled). However, in the lower variability case the coefficient of variation (CoV) is 6% and 9% for Stove-1 and Stove-2 respectively, while in the higher variability case the CoV is higher (9% and 13% respectively). In the lower variability case, the difference in the two stoves is statistically significant with 95% confidence, while in the higher variability

case, it is not. Thus, even though the specific fuel consumption of Stove-2 appears to be better than Stove-1 by over 20% we can not say with 95% confidence that Stove-2 is better based on the data with higher variability. In order to rectify the situation, we either need to lower our standards of confidence, or conduct additional tests. If we lower our standards, we can say the observed difference between Stove-1 and Stove-2 is significant with 90% confidence (a 10% chance of error). Alternatively, if we want to maintain the standard of 95% confidence, we can try conducting more tests. For example, if we perform additional tests and the standard deviation in the test results does not change from that shown in the higher variability case of Table 2, then 5 tests of each stove would be sufficient to declare that the observed difference of 23% between Stove-1 and Stove-2 is significant with 95% confidence.

If the CoV of the *benchmark* values for fuel use and energy use is greater than 25% among 3 tests, the tester should perform an additional test to increase confidence in comparisons. Frequently, these measures have a CoV of 10% or lower. Variability in emissions may be somewhat higher.

TABLE 2: HYPOTHETICAL TEST RESULTS SHOWING EFFECT OF DATA VARIABILITY ON STATISTICAL CONFIDENCE BASED ON THREE TESTS OF EACH STOVE

Specific Consumption	units	Stove-1			Stove-2			Statistics		
		Mean	SD	CoV	Mean	SD	CoV	% difference between Stove-1 and Stove-2	T-test	Significant with 95% confidence?
Lower variability	g/liter	134	8	6%	104	9	9%	-23%	3.4	YES
Higher variability	g/liter	134	12	9%	104	13	13%	-23%	2.4	NO

APPENDIX 6. EMISSION MEASUREMENT

Tami C. Bond and Christoph Roden, University of Illinois
Nordica MacCarty, Aprovecho Research

Measuring pollutants from stoves requires more commitment than the simple WBT for efficiency. Here, we discuss some of the considerations for setting up emission measurements. These concerns are often taken into account in designing measurement packages specifically for cookstoves. If you've purchased one of those, you can read this section for information. If you're interested in buying or setting up a measurement system, you should probably make sure you are aware of the issues discussed here. Before conducting the WBT with emissions measurements, testers should become familiar with these issues and using the equipment.

6.1 WHICH POLLUTANTS SHOULD BE MEASURED?

Many pollutants can be measured, but the most important are CO (carbon monoxide) and PM (particulate matter, smoke). CO has some short-term health-effects, and may have some long-term health effects. PM has both short-term and long-term health effects. You should measure both, although CO is relatively easy to measure and PM is more difficult. Your eyes can tell the difference between a stove that is quite smoky and one that is not very smoky. However, it is difficult to visually add all the smoke emitted over the course of a cooked meal. Also, smoke can be harder to see depending on its color, on lighting, and on contrast with background.

Other emissions are also of interest. For example, polyaromatic hydrocarbons (PAH) can have some specific health effects. Some reactive gases, known as volatile organic compounds (VOCs) could contribute to ozone formation. Non-CO₂ greenhouse gases (GHGs, like methane) may be of interest if your stove project could be funded for climate reasons. PM affects climate as well, especially the dark part (known as black carbon). Most of these pollutants are more challenging to measure, and are best done by a regional testing center.

6.2 CAPTURING THE EXHAUST

Emissions from solid-fuel burning are variable in both time and space. Measuring in only one place in the exhaust or over a short period of time, does not give accurate emission readings. Some method is needed to average over all events during combustion. Because the burning is so unsteady, you cannot take a one-time measurement with a gas probe as furnace technicians do. For example, a very large fraction of the pollutants are emitted during ignition or addition of wood. A one-time sample taken during this time would overestimate average emissions; a single sample that missed that time would understate the emission rate.

Pollutants change as they leave the hot combustion chamber. These changes might not affect CO concentrations, but they are quite important for PM. One of these changes is caused by "semi-volatile

organic compounds,” which act similarly to water. They are gaseous in the hot exhaust and then condense into particles as the exhaust cools down. Measuring realistic emissions requires waiting until the exhaust is cooled. If you measure hot exhaust, you can greatly underestimate the particle concentrations.

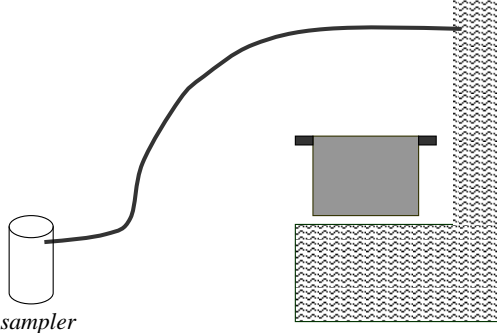
Stove exhaust is also wet. It contains water from the fuel, from combustion, and from the cooking pot. As you cool the exhaust, water condenses, and that liquid water can damage the pollutant measurements. The exhaust must be dried before you draw it through the measurements. In addition, water can be incorporated into particles if the relative humidity (moisture) in the exhaust is high. This gives the particles more apparent mass than they would have when dry, so that the particle concentration could be measured too high.

So, the sampling procedure must: (1) integrate the sample over the entire burn cycle; (2) integrate the sample over the entire exhaust plume; (3) cool and dry the exhaust; and (4) relate emissions to fuel burned. The first and last of these are usually done by choosing appropriate data collection and analysis, and will be discussed later.

Cooling and drying can be accomplished by one of two methods. **Dilution** with clean, dry air is the method we recommend. This cools the exhaust to near room temperature, and reduces the water vapor in the hot exhaust to concentrations where it will not condense. Another method, used in classic U.S. EPA stack sampling, consists of sampling with a **train** of processes: collecting PM from the hot exhaust, drying, cooling, and collecting additional condensed material in cold impingers. We consider the latter method too complex for most stove designers, and much modern sampling is conducted with dilution, anyway (Hildemann et al., 1989; U.S. EPA, 2000).

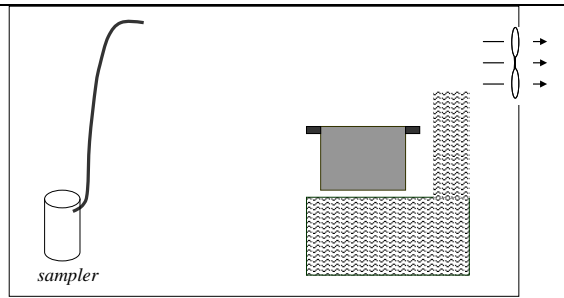
Some collection methods are shown in Table 1 on the next page. We recommend the **hood method** because cooling and drying are done simultaneously through natural dilution, and because the equations are easiest to implement. The laboratory air must be clean and dry if it is used as dilution. This means that the hood must capture all of the stove exhaust, or pollutants will accumulate in the room. Additional dilution with dry compressed air (not shown) may be needed if the surrounding air is very humid.

Table 1. Methods of collecting stove exhaust.

Description	Advantages/Disadvantages	Sketch
Direct stack sampling: Draw sample directly from chimney.	<p><i>Advantages:</i> Setup is extremely simple.</p> <p><i>Disadvantages:</i> No cooling or drying of air unless sampling “train” is used; doesn’t work for stoves without chimneys.</p>	
Room method: Measure room concentration indoors and the air exchange rate in a room, then calculate the emission	<p><i>Advantages:</i> The measurement and setup are fairly simple, as long as a suitable room is available.</p> <p><i>Disadvantages:</i> Requires extra equations to infer emission rate; not</p>	

rate.

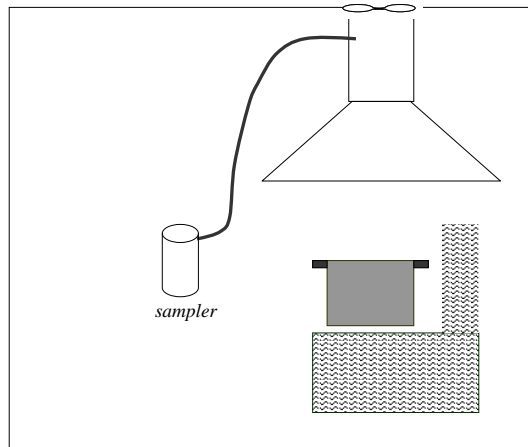
as easy to see immediate changes in the burning; assumes that air in room is mixed well and constant emissions when real conditions are more variable; Exposes stove operator to air pollutants, unless special breathing equipment is available.



Hood method: Capture all the exhaust in a hood, and measure the flow rate through the hood.

Advantages: Shows instant changes in burning; flow rate is easy to measure.

Disadvantages: Requires building an exhaust hood and adding a small fan; less portable.



6.3 INDOOR AND TOTAL EMISSIONS

Cookstoves with chimneys can be tested separately for indoor air emissions (from the stove, not from the chimney). To measure total emissions, emissions from the stove and from the chimney are captured through the hood and duct system. To measure indoor emissions, the steel hood is placed over the stove, and the chimney penetrates the hood. Emissions from the stove are measured, while emissions from the chimney are exhausted without being measured. For stoves without chimneys that are used indoors, indoor and total emissions are identical.

6.4 DATA COLLECTION

We stated earlier that the sampling procedure must integrate the sample over the entire burn cycle. For this, you need either measurements that record real-time data (that is, second by second), or an integrated sample (bag or filter) that collects samples from all times during the burning. In other words, you need to either collect data which you can average later, or you need to produce a physical average by collecting a small, continuous sample throughout the test. We highly recommend **real-time data collection**. Many of the pollutant measurements are real-time, anyway, and the data are extremely instructive for the varying combustion that occurs in wood stoves.

When we discuss specific pollutant measurements, we will indicate which methods provide real-time data and which are integrated by taking a physical sample over a long time period.

6.5 RELATING POLLUTANT CONCENTRATIONS TO FUEL BURNED

All instruments measure pollutant *concentrations*. While concentrations are directly relevant to human health, additional measurements or analysis are needed to relate the measured pollutants to the amount of fuel burned and the task performed. Pollutant per fuel burned is often given the name “emission factor.”

The *room method* requires some way to measure the room’s air exchange rate. Air exchange rate is affected by variation in room temperature, outdoor temperature, and wind pressure. The calculation of air exchange rate can be rather uncertain, which is why we don’t recommend the room method to evaluate emissions. If you are using a real-time CO device, the exchange rate can be inferred from the decay of the CO concentration after the test is complete.

Both *direct stack sampling* and the *hood method* can use two methods to relate concentrations to fuel burned: *exhaust flow* and *carbon balance*. Both have been used for stove testing: Ballard-Tremeer and Jawurek (1996) relied on exhaust flow, and the carbon balance method has been used by Zhang et al. (2000) and Roden et al. (2006). The best approach is using both and making sure the results match. Using only one is sufficient for field measurements.

EXHAUST FLOW

Principle: All the pollutants are collected in the hood or stack flow. The pollutant flow at any time is the total exhaust flow times the pollutant concentration.

Calculate total emitted pollutants:

$$E_{tot} = Q C_{pollutant} t_{test} \quad (1)$$

where E_{tot} is the total pollutants emitted during the test (g), Q is the flow rate through the hood or exhaust (m^3/sec), $C_{pollutant}$ is the average pollutant concentration in the exhaust gas (g/ m^3), and t_{test} is the test length (sec). This method is most accurate if Q is constant through the test. Otherwise, changing exhaust flow rates can cause a bias in the total.

Calculate emission factor:

$$EF = E_{tot} / F_{tot} \quad (2)$$

where E_{tot} comes from Equation 1 and F_{tot} is the total fuel burned, which must be measured separately. The WBT already measures total fuel burned, so this information is easily available in a laboratory setting.

Advantages: Calculations are very simple. This is the most accurate method if flow rate is kept constant.

Disadvantages: Requires accurate flow measurements, and accurate measurements of fuel.

CARBON BALANCE

Principle: All the carbon in the fuel is transformed to combustion products that contain carbon (CO_2 , CO, unburned hydrocarbons, and particulate matter). These can be used to infer the amount of fuel burned that corresponds to the amount of pollutant measured. By taking the ratio between the pollutant concentration and the carbon concentration in the exhaust air, one avoids the need to quantify ambient air mixed into the exhaust.

Calculate emission factor:

$$EF = \frac{C_{\text{pollutant}}}{C_{\text{carbon}} F_{\text{carbon}}} \quad (3)$$

where $C_{\text{pollutant}}$ is the average pollutant concentration in the exhaust gas (g/m^3), C_{carbon} is the average carbon concentration in the exhaust gas (g/m^3), and F_{carbon} is the mass fraction of carbon in the fuel. For wood fuel, F_{carbon} is about 0.5. C_{carbon} is determined by adding the contribution of each combustion products:

$$C_{\text{carbon}} = C_{\text{CO}_2} \frac{12}{44} + C_{\text{CO}} \frac{12}{28} + C_{\text{HC}} \frac{36}{44} + C_{\text{PM}} \frac{1}{1.4} \quad (4)$$

Each C in the equation above indicates concentrations in g/m^3 . The fractions account for the fact that part of each pollutant is not carbon. The "HC" term assumes that unburned hydrocarbons are measured as propane.

Advantages: No measurements of flow or fuel are needed. This is an advantage in field settings where such observations can be difficult; if you capture a representative sample of exhaust, a hood or exhaust stack is not even needed. Just as accurate as the exhaust-flow method if a hood is used and flow is constant.

Disadvantages: Requires an extra measurement of carbon dioxide. Less accurate than hood method if the sampled flow is not constant. Carbon content of fuel is often uncertain to 10%, which translates to an uncertainty in emission factor. Some measurement programs do not measure unburned hydrocarbons; however, these are small fractions of the total carbon.

6.6 POLLUTANT MEASUREMENTS

Here, we discuss measurements to quantify each combustion product. In this section, we will not list products made by specific companies, because such a list would be quickly outdated. Instead, we will discuss the *physical principles* of pollutant measurements. After you have considered the advantages and disadvantages of each type of measurement, choose one, and then seek an analyzer based on that physical principle. We do indicate approximate costs in \$US (as of 2009), which are part of the advantages or disadvantages.

In addition to pollutant measurements, the temperature, pressure, and relative humidity at the concentration measurement point should always be recorded before and after each test. If possible, these values should be monitored continuously throughout the test.

If you have real time measurements/data acquisition, emissions over time may be plotted.

CARBON MONOXIDE

Needed: *Always*

METHOD 1: ELECTROCHEMICAL (REAL-TIME)

Principle: CO causes a reaction within a chemical cell, which causes current to flow.

Advantages: Cheap (\$US 200-400)

Disadvantages: Relatively slow response time (~30 sec), temperature sensitivity, and cross-sensitivity to other gases; cells can be chosen to compensate for this sensitivity. Needs frequent calibration.

Recommendation: Good enough for in-field stove testing with frequent calibration.

METHOD 2: NON-DISPERSIVE INFRARED (REAL-TIME)

Principle: CO absorbs light at a specific wavelength.

Advantages: Rapid response (limited only by flow rate and cell volume); accurate.

Disadvantages: Expensive (\$US 5,000-10,000). [Note: These are getting cheaper—need more research.]

Recommendation: Should be used in testing labs that require high accuracy.

PARTICULATE MATTER

Needed: *Always*

METHOD 1: GRAVIMETRIC (INTEGRATED)

Principle: Draw the air sample through a filter (a membrane disk) that catches the particles. The filter must be weighed before and after measurement; hence the name “gravimetric.” The difference between the two weights is the total mass of collected particles.

Advantages: Considered a standard method; most accurate for absolute mass. Particulate matter can be analyzed with other techniques to obtain chemical composition.

Disadvantages: Not real-time (no immediate information or information on events). Expensive if you do not already have a balance; see discussion below. It is easy to contaminate filters in field settings.

Recommendation: Should be used in testing labs that require high accuracy, along with optical measurements that provide real-time information.

Required components: For each test: filters (~\$US 1-2 each) and petri dishes for storing filters (\$1 each). Single purchases: filter holders (\$50-500 each); pump (\$200-400 USD); measurement of flow rate through the filter (~\$100); balance (\$5,000-25,000 depending on needed accuracy, which depends on sample size); size-selective inlet (cyclone or impactor) to exclude larger particles (~\$1,000); glove box or environmental chamber to control humidity and temperature of weighing environment.

Equation to obtain concentration:

$$C_{PM} = \frac{M_{filter,after} - M_{filter,before}}{Q_{filter} t_{test}} \quad (5)$$

where M is the mass of the filter (g), Q_{filter} is the flow rate through the filter; and t_{test} is the test length (sec).

Brief instructions: Humidity and temperature of the air affect the filter weight; that's why the glove box or environmental chamber is needed. Be sure to equilibrate the filter (24 hours) to the box relative humidity prior to both weights. Keep new and sampled filters in individually sealed containers, handle the filter with forceps, wear gloves, and store the filter and container in a freezer once a sample has been collected. You should investigate standard operating procedures for filter weighing before starting such measurements.

METHOD 2: OPTICAL (REAL-TIME)

Principle: The mass of PM is inferred from how the particles interact with light. A beam of light is passed through exhaust air, and the reduction in transmitted light or increase in scattered light is measured.

Advantages: Rapid response; no post-analysis required.

Disadvantages: Cheaper than entire gravimetric setup (\$1000-5000), but still costly. Light interaction depends on the particles' size and composition, and for that reason, the relationship between optical methods and mass can be a large source of uncertainty. The name "optical" methods applies to three different methods of using light to measure particles; see Table 2 for comments.

Recommendation: We recommend scattering measurements for most in-field applications, because these are least sensitive to particle composition. However, the uncertainties in inferring mass should not be ignored, especially when comparing stoves.

OTHER METHODS

Research laboratories sometimes use other methods of measuring mass in real time. Here, we have not discussed the Tapered Element Oscillating Microbalance (TEOM) because it has difficulty measuring semi-volatile material. We have also not discussed real-time, size-resolved measurements such as the Scanning Mobility Particle Sizer (SMPS) or Electrical Low Pressure Impactor (ELPI), because we consider these too difficult to operate and maintain at the average stove lab.

CARBON DIOXIDE

Needed: *When using carbon balance method*

METHOD 1: NON-DISPERSIVE INFRARED (NDIR, REAL-TIME)

Principle: CO₂ absorbs light at a specific wavelength.

Advantages: This is the only reliable method for measuring carbon dioxide. Fortunately, these devices have become much cheaper (\$US 150-600).

Recommendation: You must use infrared measurements for CO₂.

Table 2. Three types of optical measurements

Measurement	Advantage	Disadvantage
Opacity (extinction, or scattering plus absorption)	Easiest and often cheapest	Absorbing (black) particles have much higher extinction than non-absorbing particles, so opacity-to-mass ratio varies widely
Scattering	Least sensitive to particle composition	Sensitive to particle size; can be most expensive
Absorption (filter transmittance or black smoke)	Most common measurement	Particles that do not absorb light will not be measured

METHOD 2: INFERENCE BASED ON OXYGEN CONTENT

Principle: Ambient air should have 20.9% oxygen content. Missing oxygen must have been turned into CO₂ or another combustion product.

Advantages: O₂ measurement is very simple.

Disadvantages: Requires knowledge of the carbon, hydrogen and oxygen composition of burning fuel. If the air has been diluted, CO₂ at the measurement point is low, and O₂ is high. In this situation, inferring a CO₂ measurement requires taking the small difference of two large numbers (ambient O₂ minus exhaust O₂), which is quite uncertain.

Recommendation: Do not use an O₂ balance to infer CO₂. Check whether CO₂ reading is “calculated” or “inferred;” if so, it is taken from an O₂ reading, with the associated uncertainties. However, an O₂ meter at the outlet of a combustion chamber can help you assess excess air and hence combustion quality.

EXHAUST FLOW RATE

Needed: When using exhaust flow to relate pollutant measurements to fuel use

An orifice, or a plate with a hole which causes a pressure drop, is a common way of measuring exhaust flow. For turbulent flow, the flow rate is proportional to the square root of the pressure drop. The pressure gauge needed is about \$US 60 US, and the orifice can be made very cheaply. The flow versus pressure relationship should be calibrated by comparing with a more accurate flow device. Before installing an orifice, you should consult an engineering text book to determine where to locate the pressure taps, and where to place the orifice.

Pitot tubes, used to measure velocity of fluid flow, can also measure exhaust flow using the pressure difference between a tap facing into the flow and a tap shielded from the flow. Another option that is designed for use in sheet metal ducts is called a “flow grid” (\$US 40). It uses the pitot-tube principle at four points in the flow.

OXYGEN CONTENT

Needed: To assess the amount of excess air in the stove’s combustion chamber, providing design input

Oxygen analyzers are frequently included in packaged combustion analyzers. An oxygen measurement made after the needed dilution is not useful for stove design. Instead, this measurement should occur directly downstream of the combustion chamber, or sometimes inside it. A program that assesses only the performance of stoves need not include an oxygen measurement. However, an oxygen measurement can provide critical input for a stove designer.

6.7 A CAUTION ABOUT PACKAGED ANALYZERS

Many packaged combustion analyzers are designed for assessing furnaces (natural-gas or oil) or automobiles. While these analyzers may appear convenient, some issues should be considered before purchasing them. (1) The combustion devices for which the packaged analyzers are designed have steadier combustion than cookstoves, so this emission testing equipment is often designed to take just a single sample, not a real-time sample. (2) Packaged analyzers are made to sample the concentrated exhaust in a stack, not diluted gas above a stove, so that their measurement ranges are usually higher than the ideal stove measurements. (3) These analyzers usually have no ability, or very crude ability, to sample particulate matter. Even “black smoke” measurements are taken over a small period of time and use the least desirable detection (see Table 2). (4) Finally, these analyzers frequently use the O₂-balance method to detect CO₂.

Packaged analyzers, especially those used for furnaces, may be appropriate for measuring combustion conditions within the stove. However, they should be used with caution unless they are designed for cookstove emission measurements.

6.8 DATA ACQUISITION

If pollutants are monitored in real-time, the real-time data will need to be recorded and averaged after the test. There are rugged, inexpensive dataloggers that collect real-time data and later can download it to a personal computer (or a Palm Pilot). To see your data while the measurement is being taken, a computerized data acquisition system is needed. This system will include a card that talks to the computer (“A/D” or analog-to-digital board), another board where the signals are collected, and software. The cost, *not* including the computer, ranges from \$US 250-1000.

Users need to be somewhat computer-literate to retrieve the data from the loggers and produce meaningful results. Dataloggers should include a training manual and a spreadsheet that does most of the work.

6.9 SUMMARY

Figure 2 (next page) shows the equipment we recommend to perform the simplest emission measurements. The equipment is also listed in Table 3, at the end of this Appendix. We recommend measuring both flow and carbon dioxide; the expense is not high and the additional information gives confidence. You can alter this measurement plan, keeping in mind the principles described above.

6.10 CITATIONS

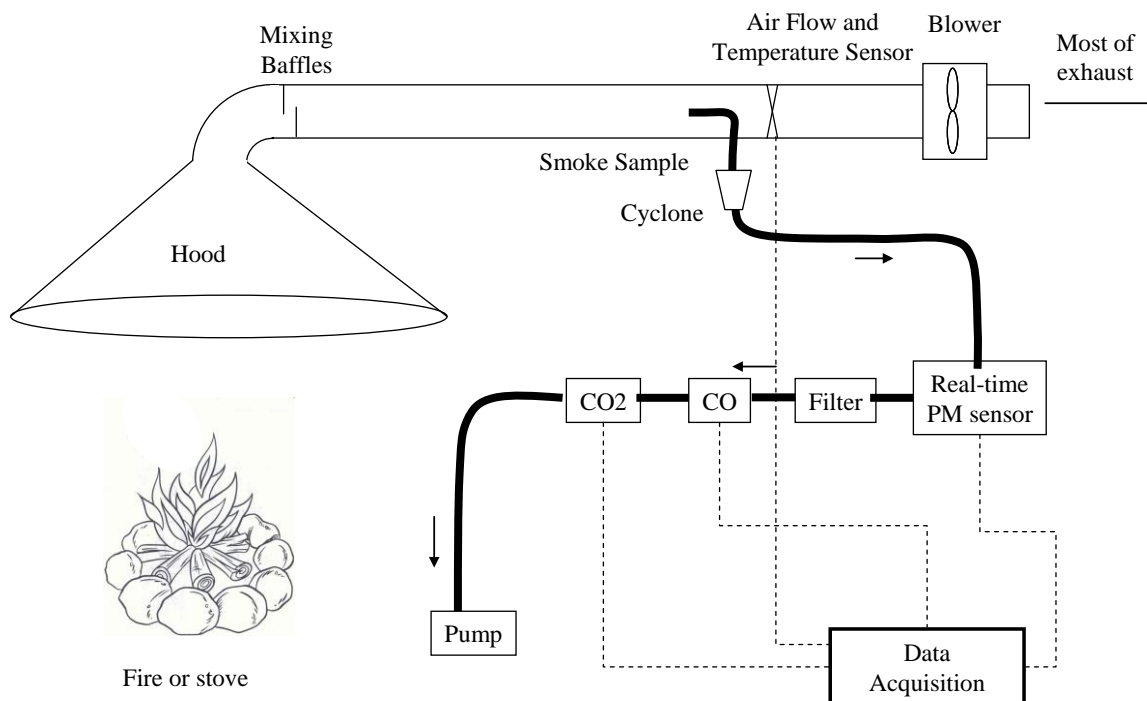
Ballard-Tremeer, G., and H.H. Jawurek (1996), Comparison of five rural, wood-burning cooking devices: efficiencies and emissions, *Biomass & Bioenergy*, 11 (5), 419-430.

Brockmann, J.E., Sampling and Transport of Aerosols, in *Aerosol Measurement: Principles, Techniques and Applications*, edited by K. Willeke, and P.A. Baron, pp. 77-111, Van Nostrand Reinhold, New York, 1993.

Roden, C.A., T.C. Bond, S. Conway, and A.B.O. Pinel (2006), Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves, *Environ. Sci. Tech.*, 40, 6750-6757.

Zhang, J., K.R. Smith, Y. Ma, S. Ye, F. Jiang, W. Qi, P. Liu, M.A.K. Khalil, R.A. Rasmussen, and S.A. Thorneloe (2000), Greenhouse gases and other airborne pollutants from household stoves in China: A database for emission factors, *Atmos. Env.*, 34, 4537-4549.

Figure 2. Setup for testing emissions. Thick solid lines show smoke collection; arrows indicate direction of airflow; dashed lines are electrical connections. See next page for further instructions and Table 3 for equipment discussion.



Notes:

- Hood should be at least 1 m above the stove top to avoid affecting the combustion. If you fear that some smoke may escape, you may enclose the fire or stove with light sheets of hanging cloth— *do not* extend the hood downward or you may affect the flow through the flame. BE SAFE— keep all enclosures well away from flames!!
- Sampling should be at least 8 duct-diameters downstream of the mixing baffles, and at least 2 duct-diameters upstream of the blower. For example, if the duct is 15 cm (6 inches) in diameter, the sample should be at least 90 cm from the baffles and at least 30 cm from the blower.
- Sample probe **must** be facing into the flow. Good practice says that sampling should be *isokinetic*— that is, the flow into the sample probe must be traveling at the same speed and direction as the flow in the collection duct. If you are **absolutely sure** that your stove exhaust *does not* contain particles lofted by a fan (i.e. your stove has natural draft), then the diameters of the particles will be quite small. In this case, the sampling velocity may vary by a factor of 3 from isokinetic, either up or down. For particles with diameters less than 500 nanometers, this introduces no more than a 2% error [Brockmann *et al.*, 1993, and equations therein].
- Prior to sample collection, all tubing must be made of stainless steel or conductive tubing to avoid particle loss and reaction with material deposited in the sampling system. Keep tubing as short as possible. Stainless steel is preferred over silicone tubing because of sampling issues with the latter.

Table 3. Equipment for simple emission measurement

Equipment (Range, if applicable)	Analysis Method/Purpose	Cautions
Exhaust hood, including blower and collection duct (80-150 m ³ /h)	Collect exhaust	Must not affect flow through stove
Flow grid	Measurement of flow through exhaust	Must be calibrated before use
Pressure transducers (2) (0-25 cm H ₂ O or 2500 Pa)	Measure pressure drop across flow grid, and pressure at concentration measurement	
Scattering measurement (0-5000 µg/m ³)	PM concentration	Scattering-to-mass ratio is uncertain. Repeatable to 10 µg/m ³ for particles of same composition.
Carbon monoxide (0-2000 ppm)	Electrochemical for simple measurements; non-dispersive infrared for very accurate lab	Calibrate frequently (need calibration gas). Should be repeatable to 10 ppm.
Carbon dioxide (0-5000 ppm)	Non-dispersive infrared	Don't use O ₂ balance. Need calibration gas. Should be repeatable to 10 ppm.
Measurement temperature (0-100 C)	Thermocouple	Should remain near room temperature
Measurement relative humidity	Capacitive sensor	Should remain below 50% RH
Real-time data acquisition		
Filter-based particulate matter setup	For accurate lab only; see discussion above for components	
Cyclone	Remove particles greater than 2.5 µm diameter from sample stream	Flow rate through cyclone affects size of particles removed. Non-stove applications may have significant PM>2.5 µm and this "cut size" should be revisited in another situation.
Pump	Draw air through sampling system	

APPENDIX 7. DATA ENTRY SHEETS

You may print these sheets to fill out by hand. To perform the calculations that result in WBT metrics, you should enter all the data in the Excel file “WBT_data-calculation_sheet_###.xls” (### is the version number, such as 4.2.3).

Water Boiling Test - General Information

Test & stove description

Name of Tester(s) _____

Test Number or Code _____

Test Dates _____

Test Year _____

Test Location _____

Replicate Test Number _____

Altitude (m) _____

Stove Type/Model _____

Manufactured by _____

Description and Notes _____

Description of Pot(s) _____

Ambient conditions

Air relative humidity (%) _____

Local boiling point (C) _____

Emission testing

Atmospheric P (kPa) _____

Pitot delta-P _____

Hood flow rate (m3/hr) _____

Notes or description about stove or operation not included elsewhere on this form

Description of operation during the high-power test

How is fire started? _____

When do you add new fuel to the fire? _____

How much fuel do you add at one time? _____

How often do you feed the fire without adding fuel (e.g. push sticks)? _____

Do you control the air above or below the fire? _____

If so, what do you do? _____

Version 4.2.3

Fuel description

Your general description _____

Fuel type (Select from list) _____

Fuel description (Select from list) _____

Average length (cm) _____

Cross-sectional dimensions (cm x cm) _____

Default values (looked up)

Gross calorific value _____ - HHV, kJ/kg

Net calorific value _____ - LHV, kJ/kg

Char calorific value _____ - LHV, kJ/kg

Char carbon content _____ 95% by mass

If possible, enter a calorific value from measurements of local fuel below.

Check box if you have a measured calorific value

Measured gross calorific value _____ HHV measured, kJ/kg

Measured net calorific value _____ LHV, kJ/kg

Assumed net calorific value _____ LHV, kJ/kg

Values to be used for tests

Gross calorific value _____ - HHV, kJ/kg

Net calorific value _____ - LHV, kJ/kg

Fuel carbon content _____ - by mass

Description of firestarter (e.g. paper, fluid) and small wood or kindling
(note: Kindling should be weighed and reported with wood)

Description of operation during the simmering test

How is fire started? _____

When do you add new fuel to the fire? _____

How much fuel do you add at one time? _____

How often do you feed the fire without adding fuel (e.g. push sticks)? _____

Do you control the air above or below the fire? _____

If so, what do you do? _____

Fuel moisture content worksheet

If you are determining fuel moisture with the Delmhorst J-2000 or similar handheld moisture meter, take 3 pieces of fuel at random from the stock used for each test and measure each in three places along its length. Enter the results in the gray spaces below. The worksheet will automatically calculate average moisture content on a dry and wet basis.

If you are using another means to determine fuel moisture, ignore this worksheet and enter the moisture in the proper space on each Test's data form.

Test-1	Instrument reading (% dry basis)		
	1	2	3
Piece 1			
Piece 2			
Piece 3			
Average moisture content (%)			
dry-basis			wet-basis

Test-2	Instrument reading (% dry basis)		
	1	2	3
Piece 1			
Piece 2			
Piece 3			
Average moisture content (%)			
dry-basis			wet-basis

Method used to obtain wood moisture:

The Delmhorst J-2000 moisture analyzer measures fuel moisture on a dry basis. To find moisture on a wet basis, use the following equation:

$$MC_{wet} = \frac{MC_{dry}}{1 + MC_{dry}}$$

This spreadsheet does this calculation automatically if a value is entered in the dry-basis space. Output requires moisture content on a wet basis, so the conversion is very important.

Test-3	Instrument reading (% dry basis)		
	1	2	3
Piece 1			
Piece 2			
Piece 3			
Average moisture content (%)			
dry-basis			wet-basis

Test-4	Instrument reading (% dry basis)		
	1	2	3
Piece 1			
Piece 2			
Piece 3			
Average moisture content (%)			
dry-basis			wet-basis

Test-5	Instrument reading (% dry basis)		
	1	2	3
Piece 1			
Piece 2			
Piece 3			
Average moisture content (%)			
dry-basis			wet-basis

Test-6	Instrument reading (% dry basis)		
	1	2	3
Piece 1			
Piece 2			
Piece 3			
Average moisture content (%)			
dry-basis			wet-basis

	Instrument reading (% dry basis)		
	1	2	3
Piece 1			
Piece 2			
Piece 3			
Average moisture content (%)			
dry-basis	<input type="text"/>		wet-basis <input type="text"/>

	Instrument reading (% dry basis)		
	1	2	3
Piece 1			
Piece 2			
Piece 3			
Average moisture content (%)			
dry-basis	<input type="text"/>		wet-basis <input type="text"/>

	Instrument reading (% dry basis)		
	1	2	3
Piece 1			
Piece 2			
Piece 3			
Average moisture content (%)			
dry-basis	<input type="text"/>		wet-basis <input type="text"/>

	Instrument reading (% dry basis)		
	1	2	3
Piece 1			
Piece 2			
Piece 3			
Average moisture content (%)			
dry-basis	<input type="text"/>		wet-basis <input type="text"/>

Fuel moisture content worksheet

Water Boiling Test - Test Entry Form Version 4.2.3

These values are not linked to the Test sheets. This sheet is provided so you can print an easy data entry form. You will have to enter these values in each Test sheet to obtain the calculations.

Air Temperature

Wind Conditions

Fuel Dimensions

Moisture Content (wet basis)

Dry Weight Pot 1

Dry Weight Pot 2

Dry Weight Pot 3

Dry Weight Pot 4

Weight Container for Char

Local Boiling Point *

* enter on General Information

Background CO2 (ppm)**

Background CO (ppm)**

Background PM (ug/m3)**

** For emission testing only

Name of Testers

Date

Stove Type/Model

Test Number

Location

Fuel Type

Notes

	Cold Start		Hot Start		Simmer	
	Start	End	Start	End	Start	End
Time	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Weight of Fuel	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Water Temperature, Pot 1	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Water Temperature, Pot 2	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Water Temperature, Pot 3	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Water Temperature, Pot 4	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Weight of Pot 1 with water	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Weight of Pot 2 with water	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Weight of Pot 3 with water	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Weight of Pot 4 with water	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Fire Starting Materials	<input type="text"/>		<input type="text"/>		<input type="text"/>	
Average CO2 (ppm)		<input type="text"/>		<input type="text"/>		<input type="text"/>
Average CO (ppm)		<input type="text"/>		<input type="text"/>		<input type="text"/>
Average PM (ug/m3)		<input type="text"/>		<input type="text"/>		<input type="text"/>
Average Duct Temperature		<input type="text"/>		<input type="text"/>		<input type="text"/>

APPENDIX 8. REMAINING CHALLENGES FOR THE WBT AND TESTING PROTOCOLS

The Water Boiling Test, and other standardized tests, are constantly being examined and improved. Below we discuss some questions of current interest in the Water Boiling Test, which may be updated in future versions. Laboratory studies are suggested that may resolve some of these issues or provide data to support discussions.

8.1 NEEDS FOR ADDITIONAL PROTOCOLS

Several performance measures are not addressed by the WBT protocol. For example, some stoves are used for space heating and the WBT does not consider efficiency of a stove for a combination of heating and cooking. Issues like safety and durability are also not addressed. The Biomass Stove Safety Protocol measures safety indicators. Certain stove types are not adequately addressed by this version of the WBT, for example plancha stoves, biochar producing stoves, and charcoal stoves.

These gaps may be addressed by expanding the scope of the WBT or developing separate protocols. The Alliance and its partners are working collaboratively to address some of these gaps, including protocols to address durability-related indicators and plancha stoves.

8.2 ADDITIONAL STUDIES TO ADDRESS REMAINING QUESTIONS

The introductory text of the WBT discusses some of the tradeoffs between laboratory and field testing, relating to repeatability and reflecting real use. The differences between laboratory and field testing may be minimized through studies to develop laboratory procedures that reflect burn cycles of actual use, evaluate the tradeoffs in repeatability and in-home performance, and develop practical protocols that are repeatable and that reflect real use. In addition, future discussions and studies can help to laboratory- and field-based protocols together into a single framework.

The current calculations for emissions use the carbon balance method. Future updates to the spreadsheet will include calculations using the total capture method.

The issue of whether or not to use a lid during the WBT has been the subject of much intense debate. Studies to evaluate each option for the variability and repeatability of results can help resolve these challenges. To improve comparability between different WBT results, standardizing the protocol is a high priority, but future studies may indicate that a switch to using a lid is beneficial.

Due to difficulties in separating and weighing charcoal, the current version of the WBT specifies that charcoal is not weighed after the high power hot start phase. There can be considerable differences in charcoal remaining after the cold and hot start phases, which affects the calculations of stove performance. This issue could be addressed by examining how large these differences are, whether the differences are larger in certain types of stoves, and evaluating the uncertainty based on the differences in charcoal remaining. If the contribution to uncertainty is high, the WBT may be modified so that charcoal is weighed after the high power hot start phase. This modification would delay the start of the low power simmering phase, but if the pot with boiling water can be kept insulated, that would mitigate this issue. This issue is relevant for stoves that are designed to produce charcoal that can then be used in other devices, for example gasifier stoves. For protocol updates to address these types of stoves, studies are needed that

identify evaluate how much charcoal remains and how much is used in practice and to reconsider the separation of the high power and low power phase for some stoves.

The caution that the hood extraction flow rate must not affect air flow through the stove should be quantified so that testers can perform measurements to evaluate this issue. As this is an important issue, the Global Alliance for Clean Cookstoves is seeking quantitative data on how hood extraction flow rate affects stove performance and suggestions on methods to ensure that hood extraction flow rate does not affect air flow through stove, including guidance on minimal height requirements from the stove to the hood and limits for air velocity.

Several commenters have suggested that a starting temperature for water should be specified for the high power hot and cold start phases. This requirement would add to the number of steps required for the WBT, and thus should be evaluated. A quantitative or empirical analysis is needed to compare the performance results for WBT 4.2, including temperature corrected values, with performance results with a specified starting temperature for water.

Stoves can heat up the surrounding environment significantly, owing to the fact that the construction is made of metal. The environment will likely be hotter at the start of the second phase compared to the first. The impact of the increased surrounding temperatures on stove performance has been suggested as an interesting area to evaluate, although it would be challenging to control ambient air temperatures and often testing labs only have one setup for conducting tests.

Future developments to the WBT spreadsheet and data collection may include standardized collection of real-time temperature and emissions data, collecting indoor and total emissions for chimney stoves, and improved integration with the Stove Performance Inventory.

The uncertainty and intrinsic error of the WBT results have not yet been completely and systematically evaluated, and this work is going by the Alliance and its partners. The results of this analysis may indicate areas of the protocol that need further refinement.

Further testing on starting and remaining fuel will be useful to evaluate fuel combustion and emissions, for example analysis of unburned gases, composition, density, or ash content.

8.3 ADDITIONAL DIAGNOSTIC MEASURES

Users have recommended several additional diagnostics that could be presented on the Results summary of the Water Boiling Test. These include the values discussed in “Additional Measures” in the section “Interpreting the Results of the Water Boiling Test.” Other measures mentioned include the amount of charcoal produced, energy efficiency measures for multi-pot stoves.

Interaction with field testers is needed to determine if these are useful to most testers.

8.4 WOOD TYPE AND MOISTURE CONTENT

The choice of wood for the WBT is a subject of active discussion. Some laboratories recommend manufactured, dry, square wood with relatively small cross-sections. Wood with these characteristics provides greater repeatability among tests. However, it is not similar to most wood used in the field.

Parametric testing should be conducted to compare measured performance for the same stove using manufactured or square wood and using representative wood.

8.5 POT INSULATION

(Morgan DeFoort, Colorado State University)

The use of insulation above the water is another change proposed to reduce variability. This insulation consists of any closed-cell foam capable of handling temperatures seen during testing. Ideally the foam is cut so that it fits inside the pot and sits on top of the water inside. This insulation reduces the water lost from the pot; it also reduces the pot's heat requirement, which could lead to unrepresentative operation. Adding such insulation decreases the amount of energy required, and will probably decrease the specific fuel consumption and emissions. Thus, results from a WBT with an insulated pot should not be compared with this version of the WBT.

Parametric testing should be conducted to determine whether a stove optimized with pot insulation results in an optimal stove for conditions without pot insulation.

8.6 TEST SEQUENCE

(Crispin Pemberton-Pigott, New Dawn Engineering)

The current test sequence of cold-start high-power, hot-start high-power, and finally simmering stores the maximum possible heat in the stove prior to the simmering test. This storage could give an unfair advantage to high-mass stoves, which can simmer water more easily using the stored heat. One suggestion is to alter the test sequence so that the simmer test occurs in the middle, so that simmering occurs with only the heat stored in the first cooking cycle. The practical disadvantage is that tests completed with the original test sequence will not be comparable. High-mass stoves may have an advantage during the simmering phase, but high-mass stoves have a disadvantage that is shown by comparing results of the cold- and hot-start phases.

Some exploratory tests using a cold-start, simmer, hot-start, simmer cycle could be accomplished to examine the differences in simmering results after each high-power test. In addition, a greater understanding of in-use fuel cycles should be brought to this question. How frequently are completely cold, high-mass stoves found in practice?

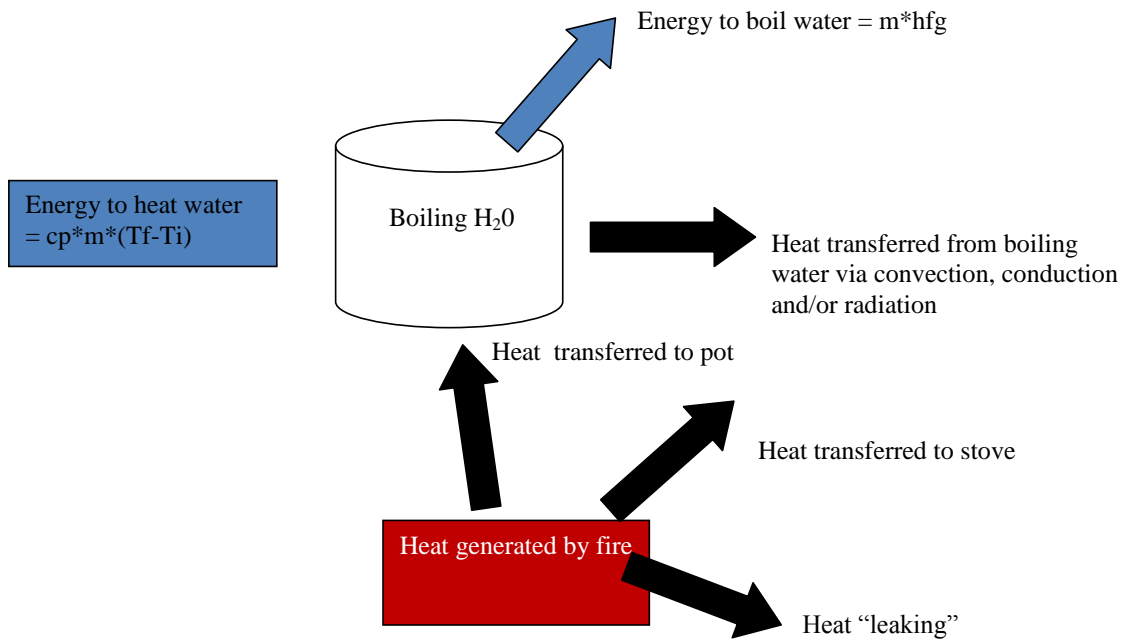
8.7 THERMAL EFFICIENCY

(Initial ideas from Crispin Pemberton-Pigott, New Dawn Engineering; description by Laura Fierce, University of Illinois)

Efficiency is one of the most common metrics taken from the Water Boiling Test. The test is supposed to help stove designers understand how well energy is transferred from the fuel to the cooking pot. However, the measurement of energy transfer is incomplete, leading to a misrepresentation of thermal efficiency.

A simple energy balance for the fire, stove and cooking pot is shown in the figure below. Blue indicates quantities currently used in the WBT to calculate energy transferred to the pot, red indicates quantities used to calculate energy generated by the fuel, and black indicates quantities that are not currently used in the calculations. The energy transferred to the water is actually the sum of the latent heat, sensible heat, and the heat transferred away from the pot via convection, conduction, and radiation. This latter heat is

not accounted for in the WBT calculation, but it is very important: at simmering, the stove's mission is to counterbalance this heat loss, not to evaporate water from the pot. Yet, the evaporation of water, rather than the heat loss from the pot, is measured. This mismatch between the measured quantity and the desired service also occurs during the high-power, water-heating tests, but the impact is not as great.



There has been a proposal to use the difference between high-power and low-power tests to provide a better measure of thermal efficiency. This proposal has not been thoroughly evaluated with laboratory experiments.

Improved calculations of thermal efficiency should be pursued and verified, particularly if they can be accomplished without a change in protocol. Thermal efficiency measures should be viewed with caution, particularly from the simmering test. A better measure is the quantity of fuel required to complete a task, known as specific consumption.

8.8 HUMIDITY IN AMBIENT AIR

(Robert van der Plas)

The emission testing setup given in this document assumes that laboratory air is clean and dry. However, many locations have very humid air. High relative humidity in ambient air contributes to two problems in emission testing. First, the laboratory air is too moist to dry the sample, which contains water from both the combustion and the cooking pot. Condensation may occur within the sampling system. Second, smoke particles increase in size when relative humidity is high, causing them to scatter more light. This increased scattering would be interpreted as a greater mass.

A subsequent investigation should identify the amount of dilution air required at specific humidities to avoid these problems, and include these recommendations in the document. A description of a dilution dryer should be included for environments that are too humid.

8.9 POWER TO BOIL

(H. S. Mukunda, CGPL, Indian Institute of Science, Bangalore)

A stove might operate inefficiently if too much power is provided for the needed task. Test results are highly dependent on the power level chosen. Some guidance should be provided for acceptable ranges of firepower needed to boil the standard 2.5L and 5L of water. We should collect data on observed firepower from regional testing laboratories to provide a range for users.

APPENDIX 9 – REQUIREMENTS FOR ISO INTERNATIONAL WORKSHOP AGREEMENT

9.1 BACKGROUND ON INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO) INTERNATIONAL WORKSHOP AGREEMENT (IWA)

In February 2012, more than 90 stakeholders from 23 countries met in The Hague to establish an ISO IWA³ that provides interim guidance for rating cookstoves on four performance indicators: efficiency, total emissions, indoor emissions, and safety. An IWA⁴ is an ISO document produced through workshop meeting(s) to address a rapidly emerging market need, and can be used as a precursor to International Standards. This cookstoves IWA serves as a guideline for governments, policy-makers, investors, manufacturers and others in the cookstoves community and it will inform the future work required in developing new or revised internationally agreed upon cookstove standards and protocols. This IWA, with unanimous support among meeting participants, represents a significant step forward in global efforts to scale up clean cookstoves and fuels. The ISO International Workshop was hosted by the Global Alliance for Clean Cookstoves and the Partnership for Clean Indoor Air, and chaired by the American National Standards Institute.

9.2 THE IWA FRAMEWORK AND WBT

Each of the four indicators has multiple Tiers of Performance (0 to 4) in order to highlight progress that has been made while encouraging further improvement. The process for defining tiers is outlined in the IWA supporting materials.⁵ The IWA outlines Tiers of Performance for two protocols (WBT 4.1.2⁶ and Biomass Stove Safety Protocol⁷), while also providing a framework for establishing Tiers of Performance for additional test protocols.

Because the current interim guidelines are based on the WBT, the guidelines are limited to the types of stoves that are suitable for the WBT, the indicators measured through the WBT, and the specifications of the test protocol. Thus, the scope and focus of the WBT must be clearly communicated to cookstoves stakeholders so that the guidelines are used appropriately. These issues are discussed in the “Workshop resolutions” section of the IWA. Additional protocols will need to be developed and refined and consensus on Tiers of Performance for additional protocols will need to be developed in order to expand these interim guidelines.

³ http://www.iso.org/iso/catalogue_detail?csnumber=61975 and <http://community.cleancookstoves.org/files/172>

⁴ ISO Deliverables/IWA International Workshop Agreement: http://www.iso.org/iso/home/standards_development/deliverables-all.htm?type=iwa

⁵ <http://www.pciaonline.org/files/10-Performance-Measures-web.pdf>

⁶ Water Boiling Test 4.1.2: http://www.pciaonline.org/files/WBT4.1.2_0_0.pdf

⁷ Biomass Stove Safety Protocol: <http://www.pciaonline.org/files/Stove-Testing-Safety-Guidelines.pdf>

9.3 TESTING REQUIREMENTS AND STANDARDIZED REPORTING

The IWA builds on the protocol specifications of the WBT by specifying minimum equipment or methodology in the IWA Section 3 “Framework for evaluating cookstove performance.” Two methodologies are acceptable for measuring indoor emissions:

- 1) capturing indoor emissions in a chamber with a controlled and measured air exchange rate, measured air volume, and well mixed air or
- 2) capturing indoor emissions in a hood and mixed with air in a dilution tunnel.

The following requirements are specified in the IWA for measuring emissions and indoor emissions:

- 1) for carbon monoxide emissions or room measurement, non-dispersive infrared (with calibration consistent with U.S. EPA 40 CFR Part 60, Appendix A, Method 10)⁸ or electrochemical cell (with pre/post calibration method)
- 2) for particulate matter emission or indoor air quality measurement:
 - a. real-time measurement of a particulate matter proxy via light scattering, and
 - b. PM_{2.5} gravimetric measurement such as U.S. EPA 40 CFR Part 60, Appendix A, Method 5
- 3) for emissions exhaust gas flow, constant volume pump or flow grid both with real-time temperature and pressure correction consistent with U.S. EPA CFR Part 60, Appendix A, Method 1 or 2d, or equivalent
- 4) for temperature measurement, type K thermocouple or equivalent
- 5) computer data logging of all measurements with a minimum time resolution of one measurement per ten seconds
- 6) for measuring fuel and water masses, a calibrated digital scale with 1 g resolution or better

To ensure standardized and transparent reporting of IWA Tiers, the Alliance, with review by Alliance partners, has developed requirements for organizations to report IWA tiers and testing for stoves. For reporting specific IWA Tiers of performance to donors, investors, or users, the following five (5) criteria must be met:

- 1) Methodology and equipment must meet the criteria outlined in the IWA document and any updates that have been reviewed by Alliance Partners during a public comment period or that have been established as part of international standards development.
- 2) The testing must be conducted using protocols that have been mapped to IWA Tiers. For protocols not currently mapped to IWA Tiers, Tiers of Performance must be reviewed by Alliance Partners, evaluated by a technical committee with representation from testing experts, manufacturers, and other stakeholders, and following any established procedures for developing international standards. The acceptability of a protocol for a particular stove and tier designation should be determined by the ability of the test procedure to repeat the performance metric within one-third of the distance between tiers, under conditions that are consistent with the test specification.
- 3) The testing data must be shared publically through the Stove Performance Inventory.

⁸ U.S. EPA 40 CFR Part 60: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&tpl=/ecfrbrowse/Title40/40cfr60_main_02.tpl

- 4) The testing for a stove must be conducted by technicians and a testing center with no financial stake in the stove being tested or an alternative stove. Testing centers should provide complete disclosure of personal or institutional investments in any stove or energy related technologies by the lab, its subsidiaries or parent organizations, or its personnel.
- 5) The stove(s) tested must be randomly selected from the production line and should not be a prototype under development.

9.4 SUBMISSIONS TO THE STOVE PERFORMANCE INVENTORY

The [SPI] sheet in the WBT spreadsheet is to facilitate submissions to the Stove Performance Inventory. This sheet has the same format as the Inventory spreadsheet. Most cells will be automatically filled in from the spreadsheet. **Gray cells and cells with listboxes** (choices) need to be filled in by the tester, including:

- **source:** If the data has been published in any reports or publications, provide the reference.
- **lead testing group:** Name of testing organization
- **lead testing group type:** Select from Consultant, Government, Manufacturer, National Laboratory, NGO, Private Research Group, University.
- **year:** Year in which testing took place
- **source link:** If the data has been published in any reports or publications, provide a URL.
- **source type:** Select from Conference paper, Conference proceedings, Peer-reviewed journal, Presentation, Report, None. Select None if the testing results have been submitted to the Inventory without an accompanying report.
- **stove characteristics:** for each column with a stove characteristic (columns J to AO, enter 1 if the tested stove has that characteristic and 0 if the tested stove doesn't have that characteristic.
- **primary and secondary fuel type:** Select the primary and secondary fuel types that the stove is designed for. Note, this is different from the fuel type used in the WBT.
- **test fuel reduced:** Select the type of fuel that was used in the WBT.
- **fuel calorific value STD:** If fuel calorific value was measured, enter the standard deviation for the fuel calorific value.
- **test region, country, altitude:** Select the test region from the list. Enter the country and altitude of the test center
- **environment testing details:** Enter any other information about the testing environment.
- **test notes:** Enter any other information about how the test was conducted.
- **IWA Safety (index):** If the Biomass Stove Safety Protocol was conducted for the tested stove, enter the safety index.

All other values are entered or calculated automatically, including the IWA metrics and tiers.