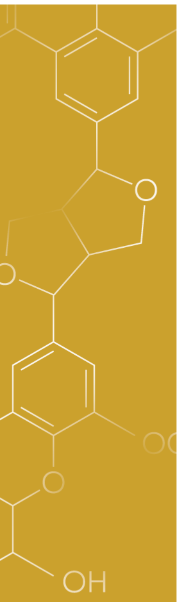

Stove Manufacturers Emissions & Performance Test Protocol (EPTP)

A protocol for testing stove fuel efficiency and emissions and a standard for improved stoves

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Stove Manufacturers Emissions & Performance Test Protocol (EPTP)

BACKGROUND

Millions of families around the world use biomass cook stoves. Widespread use, combined with increasing populations, has created growing health and environmental concerns in many nations.

In the face of these challenges, a number of researchers, grassroots organizations and businesses have increasingly focused on developing more fuel-efficient cook stoves with reduced emissions. These initiatives, some independent, some collaborative, have resulted in great strides in the development of improved cook stove technologies.

Along with the many new stove options, either available or in development, comes a need for ways to compare stove performance in fuel efficiency and emissions. Accurate and comparable measurements of stove performance help consumers, businesses, governments and non-governmental organizations make decisions about replacing traditional stoves with improved technologies.

Because of the diverse stove-improvement initiatives moving forward in tandem, however, to date no single governing standard for comparing stove performance has emerged.

To address this gap, researchers from the Engines and Energy Conversion Lab (EECL) at Colorado State University, Envirofit, Philips and Shell Foundation have collaborated to refine and standardize the well-known Water Boiling Test (WBT) to serve as a global standard.

OBJECTIVES

STANDARDIZED PROTOCOL

This document, detailing the Stove Manufacturers Emissions & Performance Test Protocol (EPTP), updates the WBT version 3.0 by Balis et. al. and provides a standardized protocol for measuring and comparing cook stove performance.

The EPTP is an approximation of real world cooking processes, which can be conducted on most stoves throughout the world. By using measured thermal efficiencies and emissions productions, the WBT can be used to roughly predict the performance of stoves for various cooking tasks.

To provide a more complete profile of fuel efficiency and emissions, this protocol measures multiple aspects of stove performance: fuel consumption, turndown ratio, thermal efficiency, carbon monoxide and particulate matter.

The EPTP is not intended to replace all other forms of stove assessment. It is designed as a simple method with which stoves made in different places and for different cooking applications can be compared through a standardized and replicable test. It intends to help stove designers understand how well energy is transferred from the fuel to the cooking pot and how this relates to carbon monoxide and particulate emissions. Data obtained from just a few days of testing will help in the development of better stoves, which can then be tested in the field by typical users cooking food.

PROPOSED GUIDELINES

The EPTP also proposes initial standards or guidelines for determining whether a stove design is “improved” over traditional or alternative stove designs. This new standard will provide a frame of reference for both stove designers and stove evaluators.

CHOOSING THE RIGHT TEST

Specific variables such as stove design, fuel type, altitude, climate, cooking application, and end-user cooking and fueling habits can dramatically affect overall stove performance. For this reason, no single test provides a complete measurement or predictor of stove field performance.

Used together, the following three tests do provide a more complete picture. While this standardized protocol focuses on the EPTP, it is important to understand how it relates to other tests of stove performance.

EMISSIONS & PERFORMANCE TEST PROTOCOL (EPTP)

The EPTP was developed to enable stove manufacturers a, standardized testing and comparison of fuel efficiency and emissions for different types of cook stoves. Performed in controlled laboratory conditions by trained technicians, it approximates cooking. As such, it is not intended to provide complete information about actual stove use by people cooking food in their homes. The emphasis of the EPTP is on stove performance rather than user performance or preferences.

The EPTP can prove especially useful during stove development, when evaluating and comparing different types of stoves, and when assessing how different stove accessories or configurations may affect stove performance.

CONTROLLED COOKING TEST (CCT)

Developed in parallel with the WBT, the CCT provides an understanding of how test stoves perform when actual end users, rather than lab technicians, cook food.

The CCT provides a bridge between true lab and field testing. This intermediate data can inform stove design, deployment and evaluation.

KITCHEN PERFORMANCE TEST (KPT)

A field test developed for use in conjunction with the WBT and CCT, the KPT compares fuel consumption in households using traditional stoves with households using alternative stoves, such as those that have been designed for improved fuel efficiency and/or lower emissions.

This test helps predict actual changes in fuel consumption among families who adopt a different stove.

OVERVIEW OF THE EPTP

TEST FUELS

This paper assumes wood as the test fuel throughout the discussion and protocol. The WBT was originally designed for woodstoves, but it has been adapted to accommodate other types of stoves and fuels. For a discussion of the use of non-woody fuels, including specific protocol modifications, please see Appendix B .

MEASUREMENTS

This protocol includes testing for both fuel efficiency and emissions; some researchers may test only for fuel efficiency, others for both. Measurements taken during an EPTP series include ambient temperature, average fuel dimensions, wood moisture content, test times, the weights of fuel, charcoal and water, and emissions of particulate matter and carbon monoxide.

TEST SEQUENCE

The EPTP consists of three phases. For each wood-fired stove tested, phases 1, 2 and 3 are performed three times in sequence. For each stove, it takes approximately 1½–2 hours to perform one complete high- and low-power test sequence.

Phase 1: Cold-start (CS), high-power test

In this first phase, the tester begins with the stove at room temperature and uses a pre-weighed bundle of wood or other fuel to heat a measured quantity of water to 90°C in a standard pot.

Phase 2: Hot-start (HS), high-power test

The second phase immediately follows the first test, while the stove is still hot. The tester first replaces water heated in phase 1 with a fresh pot of cold water at the established starting temperature. Again using a pre-weighed bundle of fuel, the tester heats the water to 90°C in a standard pot.

Repeating the heating test with a hot stove helps to identify performance differences when a stove is hot versus cold.

Phase 3: Simmer test

The third phase continues immediately from the second phase. Here, the tester determines the amount of fuel required to simmer a measured amount of water at just above 90°C for 45 minutes.

This step simulates the long cooking of legumes or pulses common throughout much of the world.

TEST VARIATIONS

For a discussion of test variations using two-pot stoves or other fuels, see Appendix B. Note that tests of gasifier, charcoal and coal stoves omit phase 2, the hot-start test, due to measurement and safety considerations.

NEW IN THE EPTP

The most recent modifications to the WBT, included in this standardized EPTP protocol, include:

- Floating a layer of foam insulation on top of the water in the test pot during the cold- and hot-start tests, to reduce vaporization;
- Using 90°C, rather than boiling, as the target temperature for the simmer test, to reduce variation in final temperature due to different boiling points based on geography and to reduce the likelihood of over-fueling;
- Using a starting water mass determined by stove firepower and the temperature of available water, to assure equal energy transfer during different test series;
- Holding the simmer test temperature as close to 90°C as possible, to minimize water loss through steam.
- Maintaining fuel moisture content between 4 and 10%

TEST OUTPUTS

The primary difference between the EPTP and earlier stove tests for thermal efficiency is in the concept of efficiency used. The EPTP standards are based on a concept of efficiency broader than Percent Heat Utilized (PHU). The EPTP test yields several quantitative outputs for comparison. The relative importance of each of these factors depends on the location and use case for a particular stove type.

For more information on each indicator, see Appendix F, which defines each measure and explains how it is calculated.

TEST DURATION

The reported test duration is the average time of the two high-power phases—cold start and hot start.

FUEL EFFICIENCY

Fuel consumption

Fuel consumption can be calculated from the following equation:

$$\frac{Fuel_{CS} + Fuel_{HS}}{2} + Fuel_{Simmer}$$

Averaging the two high-power phases (cold start, CS, and hot start, HS) accounts for the fact that a stove may require a different amount of fuel to complete a task, depending on the starting temperature of the stove.

Turndown ratio

The turndown ratio is a measure of the extent to which a stove's energy can be controlled. The turndown ratio can be found by taking the low-power-phase fuel consumption rate over the average fuel consumption rate of the two high-power phases.

$$\frac{\frac{Fuel_{CS}}{Time_{CS}}+\frac{Fuel_{HS}}{Time_{HS}}}{2}+\frac{Fuel_{Simmer}}{Time_{Simmer}}$$

Thermal efficiency

The thermal efficiency of a biomass cook stove indicates how well that stove can transfer the energy contained in the fuel to the cooking pot.

$$\frac{Thermal\ Efficiency_{CS}+Thermal\ Efficiency_{HS}}{2}$$

The thermal efficiency is only calculated for the high-power phases in this protocol. Because the point of vaporization varies from location to location, introducing uncertainty when calculating the energy required to induce phase change, low-power thermal efficiency is not calculated.

EMISSIONS

The concentration of pollutants in a room may be a better predictor of health effects than total mass emissions. Although the EPTP does not specify room concentration emissions levels, the EECL and Philips have developed suggested maximum concentration levels. See Improved Stove Testing Criteria for further information and calculation methods.

Total carbon monoxide (CO)

Total emissions are calculated using the following equation:

$$\frac{CO_{CS}+CO_{HS}}{2}+CO_{Simmer}$$

Averaging the two high-power phases (cold start, CS, and hot start, HS) accounts for the fact that a stove may sometimes be used before cooling completely from previous use. A stove with high thermal mass may have poor emissions during cold-start testing, but retained heat may improve its performance during hot-start testing.

Total particulate matter (PM)

Total emissions are calculated using the following equation:

$$\frac{PM_{CS}+PM_{HS}}{2}+PM_{Simmer}$$

As with calculating CO emissions, averaging the two high-power phases (CS and HS) accounts for the fact that a stove may sometimes be used before completely cooling from previous use. A stove with high thermal mass may have poor emissions during cold-start testing, but retained heat may improve its performance during hot-start testing.

EQUIPMENT & MATERIALS

EQUIPMENT

- Scale; capacity of at least 6 kg and accuracy of ± 1g
- Wood moisture meter; capable of measuring 6-40% humidity (optional)
- Thermocouple probe & data collection system
- Thermocouple holder (see Appendix E)
- Cooking pot (see Appendix D to determine required capacity)
- Pot insulation
- Implements to remove charcoal from stove
- Charcoal container

Note: For information on emissions testing and equipment, see Appendix A and the specific US Environmental Protection Agency (EPA) guidelines referenced therein.

CONSIDERATIONS

Stoves

Firepower

The range of energy that a stove will transfer depends on its size and firepower. It is up to the tester or stove manufacturer to determine which firepower range best represents a particular test stove model. The standard test protocol assumes a "medium" firepower stove.

Adapt the test to the test stove by choosing an appropriate starting fuel quantity and water mass. See Appendix D for more information.

Power control

Many stoves lack adequate turndown ability. The tester may find it impossible to maintain the desired temperature without the fire going out. This is most likely to happen after the initial load of charcoal in the stove has been consumed.

If this is the case, use the minimum amount of wood necessary to keep the fire from dying completely. Do not attempt to reduce power by splitting the wood into smaller diameter pieces as this will affect test results.

FUELS

Record the fuel type, average dimensions and moisture content for each test series.

Softwoods such as pine or Douglas fir constitute the standard fuel for the EPTP. Other woods and alternative fuels (Appendix B) may also be used in accordance with the stove manufacturers instructions. For meaningful comparison, however, only directly compare tests performed using the same fuel. Likewise, take measures to ensure uniformity in

- moisture content
- heating values
- dimensions

Fire starter

If using the same fire starter as test bulk fuel, include its mass when calculating total fuel consumption. If using a different fuel for fire starter, record its mass separately.

Moisture content

Record fuel moisture content for each test series.

The moisture content of a fuel varies greatly, depending on ambient conditions. For dimensional wood, this can strongly affect the outcomes of the EPTP. For consistent and optimal results, use dimensional wood with a dry moisture content of 4-10% for all testing.

If a moisture meter will not be used, the "oven-dry method" is an acceptable alternative.

Oven-drying fuel

For the oven-dry method, first measure the mass of a random sample of fuel at ambient moisture content, dry the fuel until no moisture remains, then measure the mass of the fuel sample again. Calculate fuel moisture content from the difference between pre- and post-measurement masses. See Appendix F for more calculations.

Note: to avoid catching the wood on fire during oven drying, closely monitor the temperature to keep it below pyrolysis temperatures. The temperature should not be permitted to get much above the boiling point to prevent other gases, such as CO_2, from being released.

Dimensions

Record the average fuel dimensions for each test series.

Recommended dimensions: 1.5 cm square

The physical dimensions of wood may affect EPTP results, particularly results for particulate matter. The effects on carbon monoxide emissions seem to be minimal [DeFoort M, L'Orange C. Submitted to Energy for Sustainable Development, Oct. 2009].

The physical dimensions of the fuel influence the rate of combustion and impact the emissions released. Cut fuel wood as close as possible to 1.5 cm square. If this is not possible, strive for uniformity in dimensions, whatever those might be [, 1979].

Lower heating value

The lower heating value of a fuel depends on both species and individual sample. Studies have shown that the coefficient of variation of heating values across wood species is about 10.5%, while that of individual samples is 4%.

Although softwoods are the recommended fuels for testing, alternative species with lower heating values close to that of Douglas fir are acceptable. The estimated lower heating value of the fuel used is to be recorded along with the method used to estimate it.

WATER TEMPERATURE AND MASS

The temperature of readily available water may change with season and test location. For consistency in the amount of energy transferred from the stove to the cooking pot, for each phase and between test series, use the tables in Appendix D to determine the correct starting water mass based on the temperature of available water. Equations for calculating the amount of water can be found in Appendix D.

Note: The initial temperature of water used must be between 4°C and 30°C.

POTS

Size and dimensions

Although the EPTP does not require a specific pot, choose a pot reasonable for the volume of water being used. Depending on the stove firepower and the temperature of available water, the test water volume might range from approximately 4 to 6L. (See Appendix D.) Choose a cooking pot of roughly equal height and diameter.

Material

The cooking pot to be used should be made of steel or aluminum.

POT INSULATION/LID

Using insulation at the water surface dramatically reduces water loss from the pot during testing, thereby minimizing the error in energy-related test metrics. For the EPTP, use insulation in the cooking pot for both high-power phases. Do not use insulation during the simmer test.

The insulation should be closed-cell foam (to minimize absorption), 1-3 cm thick, and capable of handling temperatures of at least 100° C. Cut the foam to a diameter 0.25-2 cm smaller than the pot diameter and make a small hole in the center for inserting the thermocouple probe into the pot. For the two high-power phases only, float the foam on the surface of the water, with the thermocouple probe inserted through the center. (See set-up diagram.)

THERMOCOUPLE HOLDER

During the test, the thermocouple will be placed such that the tip is approximately 5 cm from the bottom of the pot. In phases 1 & 2, it will be inserted through the insulating foam into the water.

Consistent thermocouple placement may be achieved in numerous ways. One of the most effective is by using a support that sits across the top of the pot and has a hole drilled through it for the thermocouple. See Appendix E for a diagram and more detail.

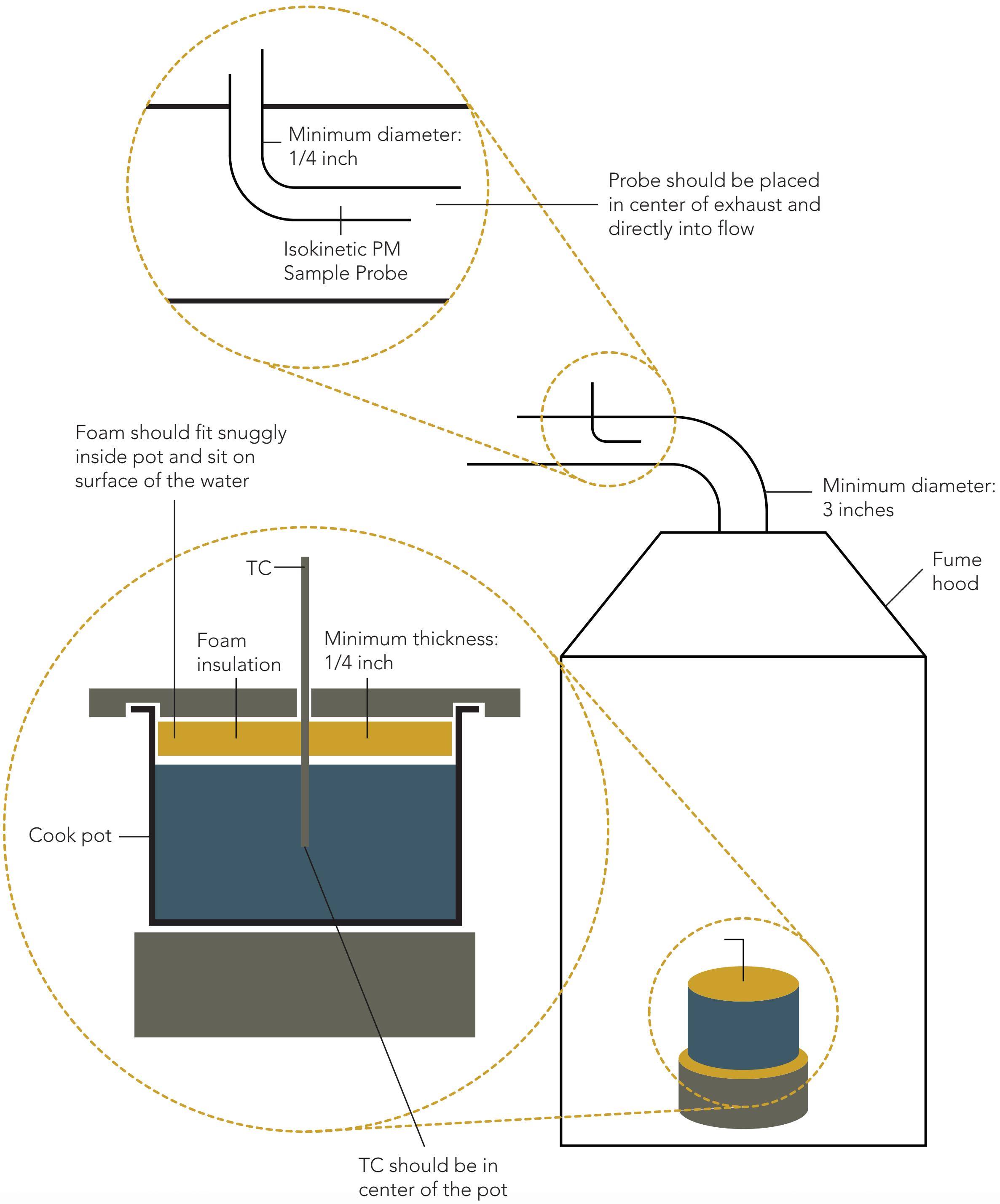
CHARCOAL CONTAINER

A lidded steel or aluminum pot serves well as a charcoal container because placing the lid on the pot quickly extinguishes any wood or charcoal that is still burning.

DATA COLLECTION SYSTEM

A data collection system is necessary for thermocouple, carbon monoxide, and time measurements. The data collection system should be sufficient to capture the transient nature of a stove. A system with a sampling frequency of 0.25 Hz for greater is sufficient.

SET-UP



Minimum diameter:
1/4 inch
Isokinetic PM
Sample Probe
Probe should be placed
in center of exhaust and
directly into flow
Foam should fit snuggly
inside pot and sit on
surface of the water
Minimum diameter:
3 inches
Fume
hood
TC
Foam
insulation
Minimum thickness:
1/4 inch
Cook pot
TC should be in
center of the pot

PROTOCOL

FUEL EFFICIENCY VERSUS EMISSION TESTING

A stove can be operated to optimize efficiency at the cost of emissions or vice versa. While the EPTP protocol may be used without testing emissions, the intent of the protocol is to measure both performance and emissions so as to support simultaneous improvement. For this reason, the EPTP calls for both emissions and performance testing. It does not, however, provide exhaustive details of equipment or protocols for CO, CO2 and particulate matter sampling. For additional information on emissions testing procedures, see Appendix A and the specific US Environmental Protection Agency (EPA) guidelines referenced therein.

TEST VARIATIONS

See Appendix B for information on test variations using two-pot stoves and gasifier, coal and charcoal stoves.

TEST PREPARATION

Prepare fuel supply

Prepare enough fuel to conduct at least three tests before starting the first test. As a rough guide, procure at least 15 kg of air-dried fuel for each stove in order to ensure enough fuel to test each stove three times. Large multi-pot stoves may require even more than 15 kg. To reduce test variation, if possible obtain all wood from the same source. It should be uniform in size and well dried, with a dry moisture content of 4-10%. See Appendix F for information on calculating moisture content.

Pre-weigh the bundles for each test. If kindling will be used to start the fire during testing, prepare it ahead of time and included in the pre-weighed bundles of fuel.

Ensure water supply and determine water mass for testing

See the tables in Appendix D to determine the appropriate mass of water for testing, which may range from approximately 2–13 kg. The correct starting water mass depends on the temperature of available water, which varies by location and season, and on the firepower of the test stove.

Perform practice testing

Perform at least one practice test on each type of stove in order to become familiar with the testing procedure and with the characteristics of the stove. This will also provide an indication of how much fuel is required to perform the test.

Assure sufficient space and time for testing

Make sure to have enough space and time to conduct the test without being disturbed. It will take 1½–2 hours to perform a complete testing sequence for a stove.

Perform testing indoors in a room protected from wind but with sufficient ventilation to vent harmful stove emissions. If testing for emissions, see Appendix A for additional set-up recommendations, including a semi-enclosed fume hood.

Initial steps

1. Fill out the first page of the Data & Calculations form. This includes information about the stove, fuel and test conditions. Number each series of tests for future reference.
2. Prepare three (3) bundles of fuel wood, including kindling for each of the phases of the test. The fuel should be relatively uniform in size and shape; split big pieces of wood and avoid using very small pieces (except for kindling).
3. Measure each of the following parameters and record them on the Data & Calculations form. Record these once for each series of tests.
   a. Air temperature.
   b. Average dimensions of wood (length x width x height). Use similarly sized wood for every test to reduce variation in test conditions. Ideally, use dimensional wood 1.5 cm square that is a length easy to manipulate within the test set-up. If the stove design requires a particular size of fuel, use the optimal size for the stove.
   c. Weight of each wood bundle. Weigh each bundle of wood, including any kindling that will be used.
   d. Wood moisture content (% - wet basis). Use a wood moisture meter or the oven-dry method (described above in Equipment and Materials considerations) to determine the moisture content of the test fuel wood. See Appendix F for calculations.

e. Weight of container to be used for charcoal. If using a lidded pot, decide in advance whether charcoal weight will be measured with or without the lid. Record the container weight accordingly.

f. Diagram or photograph of experimental set-up. Either photograph the experimental set-up or measure and record the stove dimensions and describe the stove and set-up in the space provided on the Data & Calculations sheet. Also record any stove identifiers.

4. Once all of the above parameters have been measured and recorded and the fuel is prepared, proceed with the test.

Phase 1: Cold start, high power

This phase measures the time and fuel required for a cold stove to heat a pot of water to 90°C and measures the emissions generated during that time.

Procedure

1. Record the starting water temperature, starting wood mass, and starting pot mass.
2. Fill pot with required amount of water based on initial water temperatures and stove firepower (Appendix D). Measure amount of water by mass, rather than volume, with an accuracy ±2 g.
3. Add insulation to pot and insert thermocouple through it such that thermocouple tip is approximately 5 cm from bottom of pot.
4. Begin measurement and collection of particulates.
5. Begin data acquisition (temperature, carbon monoxide, time) and record test start time.
6. Start stove using fire starter according to manufacturer's recommendations. If no recommendations are provided
   e. For natural draft stoves use wood shims or other thin wood pieces of repeatable dimensions.
   f. For charcoal and coal stoves use kerosene.
7. Feed fuel according to stove manufacturer's specifications. If fueling information is not provided, fuel in a way that rapidly raises the water temperature without wasting fuel.
8. When water in pot reaches 90°C
   a. Stop collection of particulates. (Make certain to do so before removing charcoal from the stove, since doing so agitates the charcoal and releases particulates that can skew emissions results.)
   b. Stop data acquisition.
   c. Record time at end of test.
   d. Remove all wood from stove and extinguish flames.
   e. Dislodge loose charcoal from wood into charcoal weighing container.
   f. Transfer all charcoal from stove into charcoal weight container.
9. Weigh all wood remaining from original bundle, including unburned wood removed from stove.
10. Weigh all collected charcoal and charcoal container.
11. Remove insulation from water surface and weigh cooking pot and water.
11. Discard hot water after weighing.

Data collection

Make certain to record on the Data & Calculation form:

- time to complete test
- temperature of water in pot
- amount of wood remaining
- weight of pot with remaining water
- amount of charcoal remaining

Phase 2: Hot start, high power

This phase measures the time and fuel required for a hot stove to heat a pot of water to 90°C and measures the emissions generated during that time.

Note: For gasifier, charcoal, and coal stoves, due to safety and measurement considerations, skip phase 2 entirely and proceed directly to phase 3. See Appendix B for details and protocol modifications.

Procedure

For wood-fired stoves, execute steps 1-5 as quickly as possible after finishing the cold start protocol, while the stove is still hot.

1. Fill pot with required amount of water based on initial water temperatures and stove firepower (Appendix D). Measure water by mass, rather than volume, with an accuracy ±2 g.
2. Add insulation to pot and insert thermocouple through it such that thermocouple tip is approximately 5cm from bottom of the pot.
3. Begin measurement and collection of particulates.
4. Begin data acquisition (temperature, carbon monoxide, time).
5. Record test start time.
6. Start stove using fire starter according to manufactures recommendations. If no recommendations are provided, for natural draft stoves use wood shims or other thin wood pieces of repeatable dimensions.
7. Feed fuel according to stove manufactures specifications. If fueling information is not provided, fuel in a way that rapidly raises water temperature without wasting fuel.
8. When the water in the pot reaches 90°C
   a. Stop collection of particulates. (Make certain to do so before dislodging charcoal from unburned wood into the stove, since doing so agitates the charcoal and releases particulates that can skew emissions results.)
   b. Stop data acquisition.
   c. Record time at end of test.
   d. Remove unburned wood from stove and dislodge loose charcoal into combustion chamber.
9. Weigh all fuel remaining from the original bundle, including unburned wood removed from the stove.
10. Remove insulation from water surface and weigh cooking pot and water.
11. Retain hot water for phase 3.

Data collection

Make certain to record on the Data & Calculation form

- time to complete test
- temperature of water in pot
- amount of wood remaining
- weight of pot with remaining water

Phase 3: Simmer, low power

The simmer test immediately follows the hot-start test and measures the stove's ability to shift from high to low power. The objective is to simmer water at or just above 90°C for 45 minutes using a minimal amount of fuel.

While maintaining a temperature just above 90°C facilitates comparability of test results, doing so is not required. The lower the temperature is maintained, the greater the fuel economy, but the ability to practically dial down temperature varies from one stove design to another.

Note: It is acceptable if temperatures vary up and down, but the test is invalid if the temperature in the pot drops below 90°C.

Procedure

Complete steps 1–6 as quickly as possible after the finishing phase 2, while the stove and water are still hot.

1. Begin measurement and/or collection of particulates.
2. Begin data acquisition (temperature, carbon monoxide, time).
3. Record test start time.
4. Return cooking pot to stove without insulation.
5. Place thermocouple into water such that tip is approximately 5 cm from bottom of pot.
6. If needed, restart stove.
7. Maintain fire such that water temperature holds at or above 90°C.
8. After holding the water temperature at or above 90°C for 45 minutes
    a. Stop collection of particulates.
    b. Stop data acquisition.
    c. Remove all fuel from stove and dislodge loose charcoal from fuel into charcoal weighing container.
    d. Transfer all charcoal from stove into charcoal weighing container.
9. Weigh all fuel remaining from original bundle.
10. Weigh cooking pot and water.
11. Weigh all collected charcoal and charcoal weighing container.

Data collection

Make certain to record on the Data & Calculation form:

- time to complete test
- temperature of water in pot
- amount of wood remaining
- weight of pot with remaining water
- amount of charcoal remaining

EMISSIONS AND PERFORMANCE STANDARDS FOR IMPROVED STOVES

These standards focus on fuel use and emissions only, for residential single-pot cookstoves. The stove manufacturers who developed the Stove Manufacturers Emissions and Performance Test Protocol (EPTP) have agreed upon these standards to serve as a minimum requirement to classify as stove as "improved." The standards are based on reasonably achievable technology improvements over typical baseline cooking methods.

STANDARDS

Fuel Use

Using the protocol outlined in the EPTP, a residential single-pot wood-burning cookstove must use no more than 850 grams of wood.

Carbon Monoxide Emissions

Using the protocol outlined in the EPTP, a residential single-pot wood-burning cookstove must emit no more than 20 grams of carbon monoxide.

Particulate Matter Emissions

Using the protocol outlined in the EPTP, a residential single-pot wood-burning cookstove must emit no more than 1500 grams of particulate matter, less than 10 microns in diameter.

BACKGROUND

Tests performed by Aprovecho Research Center in 2006, commissioned by the Shell Foundation, form the basis for these standards. Although those tests followed a somewhat different protocol than the EPTP (WBT 3.0), protocol differences primarily impact repeatability and consistency of the results, rather than numerical values, so the results are still applicable to proposed standards.

OTHER STOVE EVALUATION CRITERIA

Safety and durability

Safety and durability standards have been left to the individual stove manufacturers to determine.

Health effects

The improved stove testing standards listed above are not based on health effects data. The manufacturers advocate use of the concentration models presented in the EPTP to inform stove design and hope to eventually develop health-based standards.

OTHER FUELS AND STOVE TYPES

Standards for other fuels and stove sizes may be developed in the future by the manufactures with input from other manufactures and stakeholders.

APPENDIX A: EMISSIONS TESTING

While not all organizations will include emissions in stove performance testing, this appendix provides key information and considerations for testing emissions of stove gases and particulate matter. Additional information regarding equipment, sampling and measurement can be found in the US Environmental Protection Agency (EPA) guidelines referenced below.

GASEOUS EMISSIONS

In order to measure gaseous emissions from a cook stove, all emissions must be completely captured. Measuring the real-time carbon monoxide emissions collected requires an emissions analyzer.

Stove-testing considerations

Ideally, perform the WBT in a semi-enclosed hood for these reasons:

- Proper sampling of exhaust gas released from a cook stove requires collection of all emitted gases.
- The volume of fresh air provided for consumption must be sufficient and take into account that the airflow rate is governed by the rate of fuel being consumed.
- All emissions must be captured, and without affecting stove operation.
- The user must be able to access and manipulate the stove, pot, and fuel throughout the test.

The hood should contain a door so that the user can interact with the stove while minimizing the amount of unfiltered air passing into the collection system.

Sampling protocol and equipment

Transfer stove emissions collected in the hood to a duct of a size determined by flow-rate requirements. Properly sample across the entire duct diameter.

For duct sampling and flow rate measurement requirements, refer to EPA 40 CFR Part 60 Method 1 and 2d.

Emissions Analyzer

Analyze gas samples taken continuously throughout the test for carbon monoxide using a non-dispersive infrared spectrometer (NDIR) system or better for at least one test replicate. The remainder tests may be conducted with electrochemical or equivalent equipment. Data acquisition frequency should be sufficient to capture the quick fluctuations in performance typical of these stoves.

For NDIR spectrometer requirements and measurement methodology refer to EPA 40 CFR Part 60 Method 10.

PARTICULATE MATTER (PM)

Inhaled particles 10 microns and smaller are capable of creating health problems. The entire inhalable fraction should be considered when evaluating biomass cook stoves for potential health implications.

Stove-testing considerations

If measuring particulate emissions, sample continuously throughout each test phase. Be sure to stop collection of particulates, however, before removing fuel and charcoal from the stove. During these steps, agitation of the coals can introduce additional particulates into the airflow, skewing results.

Accounting for background PM

Since particulates in the ambient air can artificially raise the particulate count for a given test, HEPA filters should be used to treat the incoming air to remove background particulate matter.

If HEPA filters cannot be used, clearly note this on the PM data reports and take background PM samples at the beginning and end of each test day. The duration of the background PM measurement should be sufficient to collect a representative sample and reach the minimum detection limit of the system. In some cases, this may require a sampling duration of 20 minutes or longer.

Sampling

Obtaining reliable measurement of particulate matter requires isokinetic sampling. A cyclone that removes particles greater than 10 microns should be installed upstream of the sample filter.

Replicate tests can be performed using optical methods, provided at least one test is performed using gravimetric filter and optical systems running concurrently to correlate and calibrate optical and mass measurements.

For particulate sampling and measurement refer to EPA 40 CFR §1065.140, §1065.145, §1065.170, §1065.190, §1065.545, §1065.590, and §1065.595.

APPENDIX B: TEST VARIATIONS

STOVE TYPES

Gasifier / Charcoal / Coal

Stoves that are more traditionally batch fed, such as gasifier, charcoal, and coal stoves, introduce additional considerations to the standard test protocol.

For these stove types, modify the protocol as follows:

- Phase 2: hot start, high power
  Skip this phase entirely. Adding a fire starter such as kerosene to a hot stove can result in fuel vaporization and explosion when lit.
- Phase 1: cold start, high power / Phase 3: Simmer
  At the end of the cold-start phase, remove and weigh the pot of water. Return the pot and water to the stove immediately, and proceed directly to the simmer phase.
- Measurement and calculation of fuel use
  Due to practical considerations (such distinguishing burned from unburned pellets or re-lighting charcoal stoves) use the carbon-balance method described below to assess fuel consumption, rather than weighing remaining charcoal and fuel.

Carbon-balance method

Subtracting the total carbon in stove emissions from the amount of carbon in the starting fuel mass gives the amount of burned/unburned fuel at a given point in time. Using the carbon-balance method in stove testing, requires measuring all emitted CO and CO2 for all phases.

By using the molecular mass of CO (28g/mole) and CO2 (44g/mole) and the total mass of each gas during a test phase, a total mass of carbon burned can be found. By knowing the mass percent of carbon in a fuel, the total mass of any fuel can be found based on the captured emissions. The mass percent carbon of different biomass fuels can be found following ASTM method E870-82(1998)e1.

Two-pot stoves

Testing two-pot stoves requires only small modifications to the procedure for a single-pot stove. Test phases are concluded when the primary pot reaches 90°C.

For two-pot stoves, modify the standard protocol as follows:

- Pot designations
  Clearly designate and indicate on the Data & Calculations Form which pot is primary and which is secondary. Unless stipulated differently by the manufacturer, designate as primary the pot located closest to the heat source.
- Dry weight of standard pot without lid
  If more than one pot is used, record the dry weight of each pot. If the weights differ, clearly identify which pot will be considered primary and placed closest to the fire. Maintain this distinction throughout testing.
- Water mass
  Fill the second pot with water of the same temperature and mass as the primary pot.
- Data acquisition
  Stop data acquisition and record the test time when the primary pot reaches 90°C (procedure step 7).
- Calculating thermal efficiency
  Consider both pots when calculating thermal efficiency. Calculate the efficiency for each pot, and then take the sum of both to determine total efficiency.

Fuel types

The EPTP defers to individual stove manufactures to provide instruction on stove operation when using alternative fuels such as agriculture wastes, animal dung, etc. Emissions and performance numbers from EPTP tests using such fuels will vary greatly from tests which use standard fuels.

APPENDIX C: SAMPLE DATA SHEET

Name of Tester	Date	Air Temp	Average Dimensions of Fuel	Wood Moisture Content	Stove	Test Description	Labview File Number
				Filter Mass (Cold Start)	Filter Mass (Hot Start)	Filter Mass (Simmer)	FTIR File Name
				Filter # (Cold Start)	Filter # (Hot Start)	Filter # (Simmer)	

TEST DATA	
Time to Boil	minutes
Wood	grams
Carbon Monoxide	grams
Particulate Matter	milligrams

Measurements	Units	Cold Start High Power		Hot Start High Power		Simmer Test	
		Start	Finish	Start	Finish	Start	Finish
Time (24 hour units)	hr:min						
Weight of Wood	g						
Water Temperature POT 1	°C						
Water Temperature POT 2	°C						
Weight of Pot 1 with Water	g						
Weight of Pot 2 with Water	g						
Fire Starting Materials	---						
Weight of Charcoal and Container	g				Measure after simmer test		

APPENDIX D: DETERMINING MASS OF WATER FOR TESTING

To reduce test variability, keep the amount of energy transferred to the cooking pot constant for the cold- and hot-start phases and from test to test. Consistent energy transfer depends on:

- Stove size and firepower
  The range of energy that a stove will transfer depends on its size and firepower. These two factors determine an appropriate range of water volumes for a given test stove.
- Temperature of available water
  The temperature of readily available water may change with season and test location.

Use the tables below to determine the recommended starting mass of water based on the firepower of the test stove and the temperature of readily available water. Most stoves tested will be medium fire-power stoves.

Note: The initial temperature of water used must be between 4° C and 30° C.

Table 1: Single Family Stove (5kW or less)

Intial Water Temperature (°C)	Mass of Water Required (kg)	Intial Water Temperature (°C)	Mass of Water Required (kg)
4	4.36	18	5.21
5	4.41	19	5.28
6	4.46	20	5.36
7	4.52	21	5.44
8	4.57	22	5.52
9	4.63	23	5.60
10	4.69	24	5.68
11	4.75	25	5.77
12	4.81	26	5.86
13	4.87	27	5.95
14	4.93	28	6.05
15	5.00	29	6.15
16	5.07	30	6.25
17	5.14		

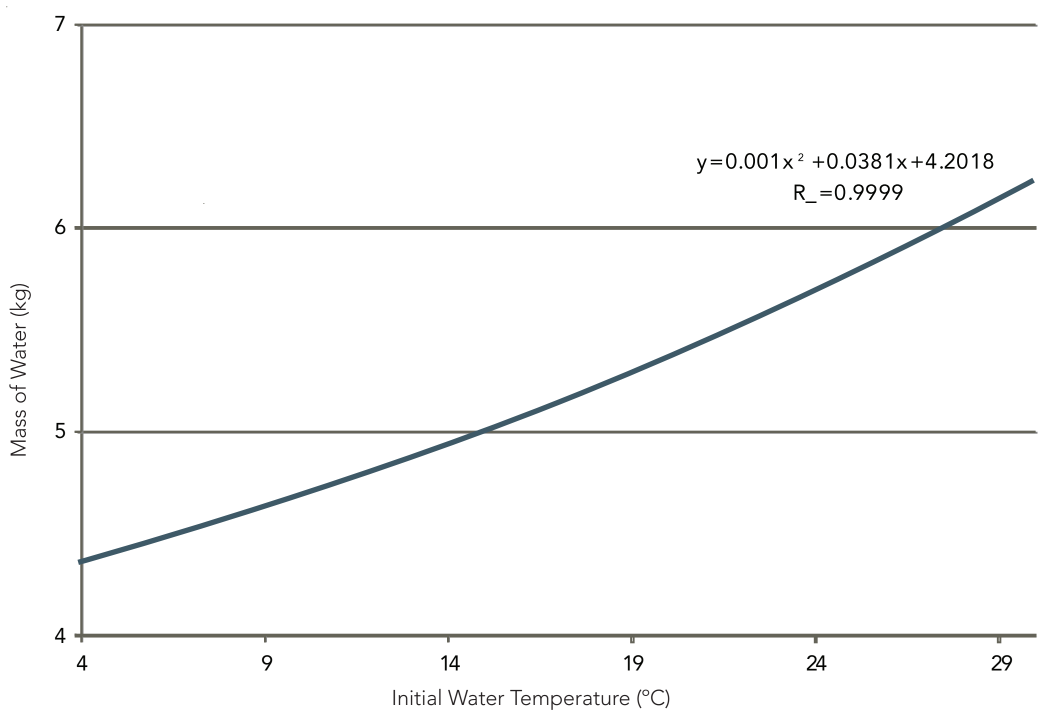
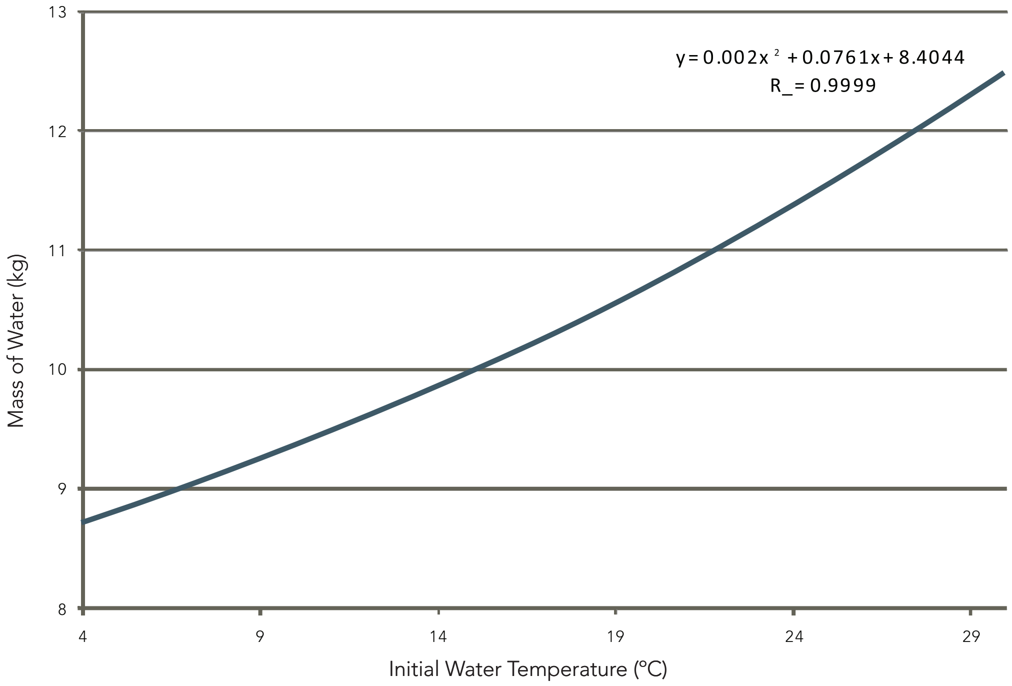


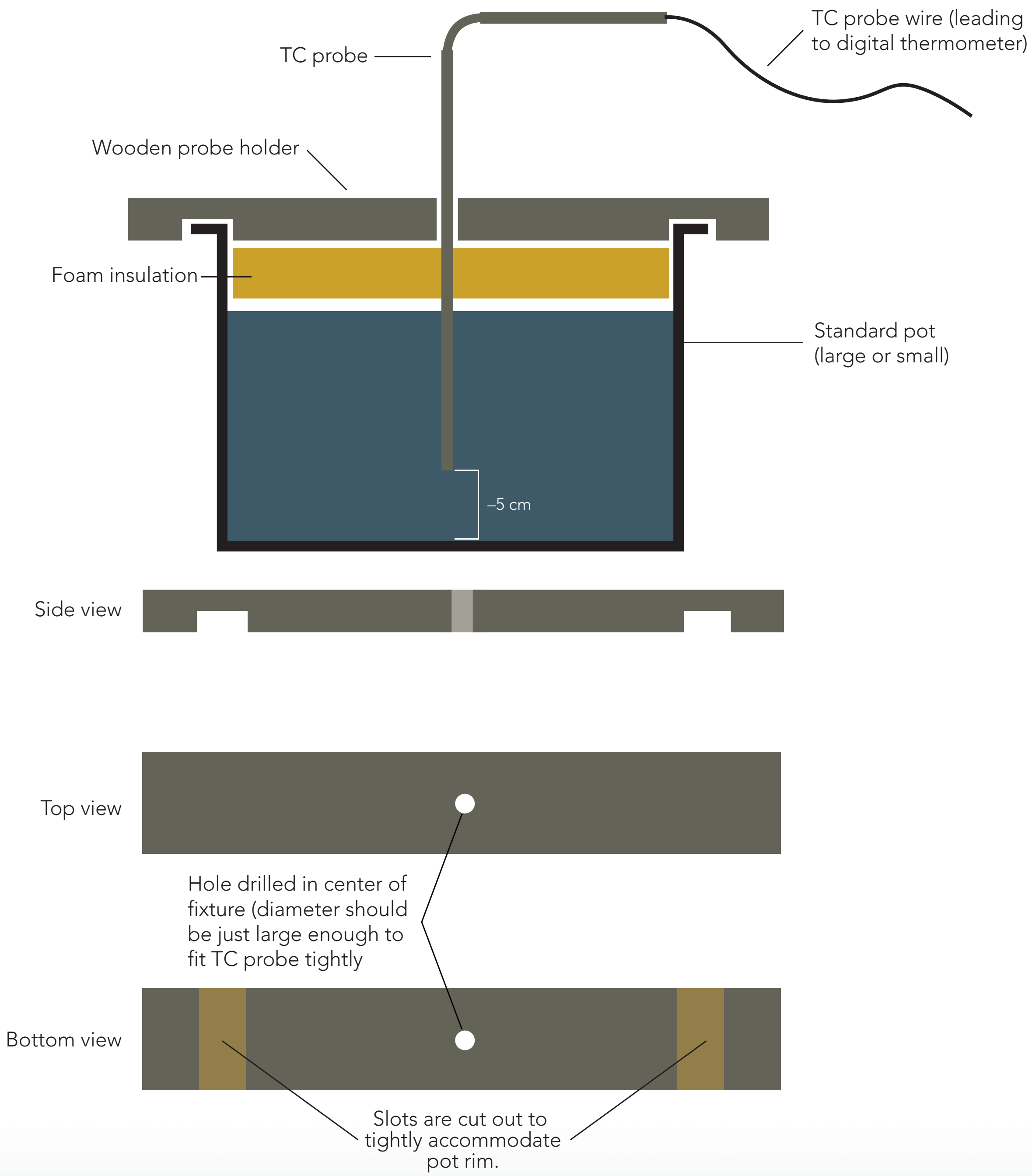
Table 2: Institutional Stoves (greater than 5kW)

Intial Water Temperature (°C)	Mass of Water Required (kg)	Intial Water Temperature (°C)	Mass of Water Required (kg)
4	8.72	18	10.42
5	8.82	19	10.56
6	8.93	20	10.71
7	9.04	21	10.87
8	9.15	22	11.03
9	9.26	23	11.19
10	9.38	24	11.36
11	9.49	25	11.54
12	9.62	26	11.72
13	9.74	27	11.91
14	9.87	28	12.10
15	10.00	29	12.30
16	10.14	30	12.50
17	10.27		



APPENDIX E: DIAGRAM OF THERMOCOUPLE HOLDER

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



APPENDIX F: CALCULATIONS USED IN THE EPTP

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 below.

MEASURED VARIABLES

F_i Mass of fuel prior to test

F_f Mass of fuel after test

M Moisture content of fuel (%), wet basis

T_i Water temperature prior to test

T_f Water temperature after test

t_i Time at start of test

t_f Time at end of test

C_i Mass of charcoal container prior to test

C_f Mass of charcoal and container after test

T_b Local boiling temperature of water

T_a Ambient temperature

P_e Instantaneous Pressure at exhaust sampling location

T_e Instantaneous Temperature at exhaust sampling location

CO_{ppm} Instantaneous carbon monoxide emission

MF_i Initial mass of particulate filter

MF_f Final mass of particulate filter

LHV Lower Heating Value

CALCULATED VARIABLES

F_{cd} Dry Fuel Consumed

t_c Test Duration

R_b Burning Rate

η_{th} Thermal Efficiency

FP_o Overall Firepower

FP_u Useful Firepower

C_c Charcoal Created

CO Mass of Carbon Monoxide Emitted

E_{ins} Maximum Instantaneous Carbon Monoxide Room Exposure (mg/m3)

E_{15} Maximum 15 minute Carbon Monoxide Room Exposure (mg/m3)

E_{60} Maximum 60 minute Carbon Monoxide Room Exposure (mg/m3)

PM Mass of Particulate Matter Emitted

NOMENCLATURE AND CALCULATIONS

t_c Test Duration

The test duration is simply the amount of time elapsed during the test. This parameter is only valuable for high power testing since low power testing is performed over a set duration.

$$t_c = t_f - t_i$$

C_c Charcoal Created

The charcoal created is the amount of charcoal accumulated during the test. This parameter is valuable only during the high power cold start test.

$$C_c = C_f - C_i$$

F_{cd} Dry Fuel Consumed

The fuel consumption for a given test is the mass of equivalent dry fuel that is burned over the duration of the test. This quantity is a calculated value and is adjusted for the humidity in the measured fuel. This parameter is valuable for both high and low power testing. The calculation of dry fuel consumed is accomplished using the following equation:

$$F_{cd} = \left(F_i - F_f\right) * \left(1 - \frac{M}{100}\right) - \left(F_i - F_f\right) * \left(\frac{M}{100}\right) * \left(\frac{\left(C_p * (T_b - T_a) + H_v\right)}{LHV_{wood}}\right) - \frac{LHV_{char}}{LHV_{wood}} * C_c$$

LHVchar and LHVwood represent the lower heating values of charcoal and wood respectively.

R_b Burning Rate

The burning rate is the average rate that dry fuel was consumed during the test. This parameter is valuable for both the high power and low power tests.

$$R_b = \frac{F_{cd}}{t_c}$$

η_{th} Thermal Efficiency

Thermal efficiency is a measure of both the combustion efficiency of the stove and heat transfer efficiency to the pot. This parameter is valuable for the high power tests and is calculated by dividing the amount of energy necessary to raise the water temperature of the pot from its initial to final value by amount of energy that is available through ideal combustion of the fuel used during the test:

$$\eta_{th} = \frac{C_p * m_w * \left(T_f - T_i\right) + H_v * \left(m_{w,i} - m_{w,f}\right)}{\left(F_i - F_f\right)\left(1 - \frac{M}{100}\right) * LHV_{wood} - \left(F_i - F_f\right) * \frac{M}{100} * \left(C_p * (T_b - T_a) + H_v\right) - LHV_{char} * C_c}$$

C_p is the heat capacity of water (4.186 J/g-K) and Hv is the enthalpy of vaporization of water (2260 J/g).

FP_o Overall Firepower

Overall firepower is a measure of the average rate of energy released from fuel combustion transferred to the pot, surroundings, and stove over the duration of the test. This parameter is valuable for both high and low power testing.

$$FP_o = \frac{LHV * F_{cd}}{t_c}$$

FP_u Useful Firepower

Useful firepower is the average rate of energy released from fuel combustion that is transferred to the pot over the duration of the test. This parameter is valuable for only high power testing.

$$FP_u = \eta_{th} * FP_o$$

CO Mass of Carbon Monoxide Emitted

The mass of carbon monoxide emitted is the total mass of carbon monoxide accumulated throughout the test. This parameter is valuable for both low and high power testing and is calculated from the instantaneous non-dispersive infrared analyzer carbon monoxide measurement. Specifically, the mass of carbon monoxide emitted is calculated using the following equations:

$$\dot{m}_{co,i} = Q * \frac{CO_{ppm,i}}{1E6} * \frac{P_{e,i}}{R_{co,i} * T_{e,i}}$$

$$CO = \Delta t * \sum_{i=0}^{n-1} \dot{m}_{co,i}$$

Q is the volumetric flow rate of the emissions collection hood, Δt is the time between sample points, and $\dot{m}_{co,i}$ is the instantaneous mass flow rate of carbon monoxide. Note that the second equation is a numerical integration of the mass flow rate function; any numerical integration method can be used although the Riemann Sum method is used here.

PM Mass of Particulate Matter Emitted

$$PM = MF_f - MF_i - \dot{m}_{bk} * t_c$$

$\dot{m}_{bk}$ is the average background particulate collection rate.

Oven-Dry Method

For the oven-dry method, first measure the mass of a random sample of fuel at ambient moisture content, dry the fuel until no moisture remains, and then measures the mass of the fuel sample again. Calculate fuel moisture content from difference between pre- and post-measurement masses.

$$\%MC = \frac{Mass_{original} - Mass_{dry}}{Mass_{original}} * 100$$

APPENDIX G: STATISTICAL CONSIDERATIONS

CALCULATING REQUIRED TEST REPLICATES

Biomass cook stove testing has a significant degree of uncertainty associated with it. Performing a number of test replicates can reduce this uncertainty. The need for replicate testing is especially important considering the small variations seen between stove models and parameters tested. Having low statistical confidence does not mean that the results are invalid; instead it should be taken as a reason for caution when evaluating data and planning future testing.

The number of test replicates required to determine significant difference in the performance of two test stoves can be calculated from the following equation.

$$n = \frac{2\left(Z_{1-\alpha/2} + Z_{1-\beta}\right)^2}{\left(\frac{\Delta\mu}{\sigma}\right)^2}$$

n number of samples required

α Type 1 error, probability of rejecting the null hypothesis when it is true

β Type 2 error, probability of not rejection null hypothesis when it is false

$\Delta\mu$ variation in means between sample and null hypothesis

σ standard deviation

α and β are inversely proportional to the number of test replicates required to achieve statistical significance. Minimizing these values reduces the probability of inaccurately judging the truth of the null hypothesis. Each term has an associated critical Z value which is a measure of the number of standard deviations between a point and the mean value. The Z value gives an indication of the percentage of data captured by a measurement. As the population standard deviation is unknown, the standard deviation of a sample can be used to determine the required number of test replicates to be conducted [van Belle, 2002]. The detection range and standard deviation can be normalized by the mean before being used in the previous equation.

EXAMPLE

For the equation above, using a coefficient of variation of 15% (based on biomass stove tests conducted at the Engines and Energy Conversion Lab), a desired detectable difference between stoves of at least 25%, an value of 0.05, and a α value of 0.1 (based on convention) indicates 7-8 replicates would be required.

It is important to explore how the assumed values used in the previous equation affect the number of test replicates required to achieve statistical significance. To arrive at the values in the following table, each parameter was varied independently of the others, and the number of test replicates required for statistical significance was calculated.

Changing the threshold for detectable difference between stoves caused the greatest variability. This example used a performance variation of 25% as a starting point for detectable difference. If a smaller difference were desired, however, the number of test replicates required for statistical difference would quickly become impractical. Based on the values in the table, the initial values used were reasonable for testing, but the desired $\Delta\mu$ should be carefully considered when planning future testing.

Table 3: Effect of equation parameters on required test replicates

	Variable Range	Replicate Range
α	0.01–0.1	5–10
β	0.01–0.15	5–12
σ	0.1–0.25	3–18
$\Delta\mu$	0.05–0.5	2–155

STATISTICAL CONFIDENCE

Table 4 shows how greater variability impacts 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 Stove-2 by 23% (104 vs134 g wood per liter of water boiled).

In the lower variability case, however, the coefficient of variation (CoV) is 6% and 9% for Stove-1 and Stove-2 respectively. 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.

This disparity can be resolved in two ways: by lowering the standard of confidence or by conducting additional tests. If the confidence standard is lowered, the observed difference between Stove-1 and Stove-2 could, for example, be stated with 90% confidence, meaning a 10% chance of error.

Alternatively, if the standard of 95% confidence were preserved, conducting more tests might increase statistical confidence. For example, if in performing additional tests the standard deviation in the test results did not change from that shown in the higher variability case in Table 5, 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.

Table 4: Hypothetical test results showing effect of data variability on statistical confidence based on three tests of each stove

		Stove-1			Stove-2			Statistics		
Specific Consumption	units	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 H: EVOLUTION OF THE EPTP

PROCEDURAL CHANGES

Measurements of stove performance at both high- and low-power output can give an indication of how a stove will behave in actual cooking conditions. As far back as 1985, a number of stove experts began to question the wisdom of relying solely on thermal efficiency calculations, and recommended an alternative standard.

The EPTP presented here is based on the original procedures proposed by VITA (1985) and Baldwin (1987), which were updated in 2007 (WBT 3.0) and updated again in 2009 (EPT) as outlined below.

Revisions 1–3 were implemented in 2007 by Rob Balis, Damon Ogle, Nordica MacCarty and Dean Still, with input from Kirk Smith and Rufus Edwards. This was WBT version 3.0 from January 2007.

1. Transitioning smoothly from high-power to low-power tests is difficult. Methods used in past testing procedures have suggested extinguishing and weighing wood and charcoal, weighing boiling hot water, and rearranging the fire and cooking pot in rapid succession, steps which are both risky and stressful. This revised version of the WBT follows the suggestions described in VITA Procedural Notes 3 [2], which allows for a more relaxed testing procedure with minimal loss in accuracy.
2. A hot-start test is incorporated in the high-power phase to account for differing performance of stoves kept hot throughout the day, important for massive stoves, whose performance may vary significantly between cold and hot starting conditions.
3. Simmering occurs for 45 minutes, rather than 30 minutes (as suggested in VITA, 1985), because the large amount of charcoal some stoves create during the high power phase can skew the results if the simmering test is too short. The presence of charcoal helps to keep small amounts of wood burning. A 45-minute simmering period is long enough for the stove at low power to establish a burning equilibrium, as excess charcoal made at high power is normally consumed within 30 minutes.

Revisions 4–6 were implemented in 2009 by Morgan Defoort, Christian L'Orange, Cory Kreutzer (CSU EECL) and Nathan Lorenz of Envirofit, and Wiecher Kamping of Philips Electronics.

4. During the low-power simmer test, the tester is instructed to try to keep the water temperature as close to 90°C as possible. Because different amounts of steam are produced at each degree point below boiling, it is desirable to minimize the variation in simmering temperature to ensure that tests are comparable.
5. The temperature range of the water has been changed to reduce variability between test replicates. This has been achieved in two ways: by lowering the final water temperature to 90°C and by using a starting water mass based on water temperature. Using 90°C, rather than "boiling," sets a more definitive end point to the test, since test duration is no longer influenced by the boiling point of a particular geographic location. Using a water mass determined by starting water temperature helps ensure all tests transfer equal amounts of energy, regardless of the temperature of available water.
6. A layer of foam insulation was introduced to the cold and hot starts to limit the amount of vaporization taking place. Although testing temperatures have been reduced to below the boiling point for most regions of the world, some vaporization will still occur.

APPENDIX I: EMISSIONS ROOM CONCENTRATIONS

The WBT emissions criteria currently in place only set a standard for total mass emissions produced during the test. While convenient for comparing stoves, it does not give represent the true health concerns of emissions exposure. Personal exposure depends on the emissions room concentration and the duration of exposure. The concentration of a gas in an enclosed space depends on the room size and the air exchange within. To directly compare results, the same room and air exchanges must be made.

IMPROVED STOVE CRITERIA

Maximum Instantaneous CO Concentration

The maximum instantaneous CO room concentration is never to exceed 200mg/m3. This value is an adaptation of the National Institute of Occupational Safety and Health CO ceiling. [World Health Organization]

Maximum 15 Minute Average CO Concentration

The maximum 15 minute average CO room concentration is not to exceed 100mg/m3. This value is an adaptation of the World Health Organization's 15 minute CO exposure guideline. The WHO CO exposure guideline is based on keeping an individual's carboxyhemoglobin percentage below 2.5%. [World Health Organization]

Maximum 60 Minute Average CO Concentration

The maximum 60 minute average CO room concentration is not to exceed 30mg/m3. This value is an adaptation of the World Health Organization's 15 minute CO exposure guideline. The WHO CO exposure guideline is based on keeping an individual's carboxyhemoglobin percentage below 2.5%. [World Health Organization]

E_{ins} Maximum Instantaneous Carbon Monoxide Room Exposure (mg/m^3)

Assuming a room size and a number of air exchanges per hour, the maximum instantaneous carbon monoxide room exposure can be calculated from the collection of instantaneous mass flow rates of carbon monoxide (previously defined). The rate of change of carbon monoxide concentration in the room is given by the following differential equation:

$$\frac{dQ_{co}}{dt} = \frac{\dot{m}_{co}}{V} - R_e Q_{co}$$

Where Q_{co} is the concentration of carbon monoxide in the room, R_e is the room air exchange rate, C_e is the stove exhaust carbon monoxide concentration, and V is the room size. Note that this equation assumes that gas mixing is instantaneous. An approximate solution to this differential equation is:

$$Q_{co,i} = Q_{co,i-1} * (1 - R_e * \Delta t) + \frac{\Delta t * \dot{m}_{co,i}}{\mathrm{V}}$$

Where $Q_{co,i}$ is the current instantaneous carbon monoxide room concentration, and $Q_{co,i\text{-}1}$ is the previous instantaneous carbon monoxide room concentration. Note that this solution includes the time necessary for removal of all carbon monoxide from the room and should therefore be extended beyond i = n test sample points to i=k, where k is defined below. From the approximate solution the maximum instantaneous carbon monoxide room exposure can be found using the following formula:

$$E_{ins} = \max\left(Q_{co,i}\right)\ for\ 0 \leq\ i \leq k$$

$$where\ k = n + \frac{3600sec}{\Delta t}$$

E_{15} Maximum 15 minute Carbon Monoxide Room Exposure (mg/m^3)

$$\alpha = \frac{900sec}{\Delta t}$$

$$Q_{15,i} = \frac{\sum_{p=i-\alpha}^{i} Q_{co,p}}{\alpha}\ for\ \alpha \leq i \leq k$$

$$E_{15} = \max\left(Q_{15,i}\right) for\ \alpha \leq i \leq k$$

E_{60} Maximum 60 minute Carbon Monoxide Room Exposure (mg/m^3)

$$\beta = \frac{3600sec}{\Delta t}$$

$$Q_{15,i} = \frac{\sum_{q=i-\alpha}^{i} Q_{co,q}}{\beta}\ for\ all\ \beta \leq i \leq k$$

$$E_{15} = \max\left(Q_{15,i}\right) for\ \beta \leq i \leq k$$

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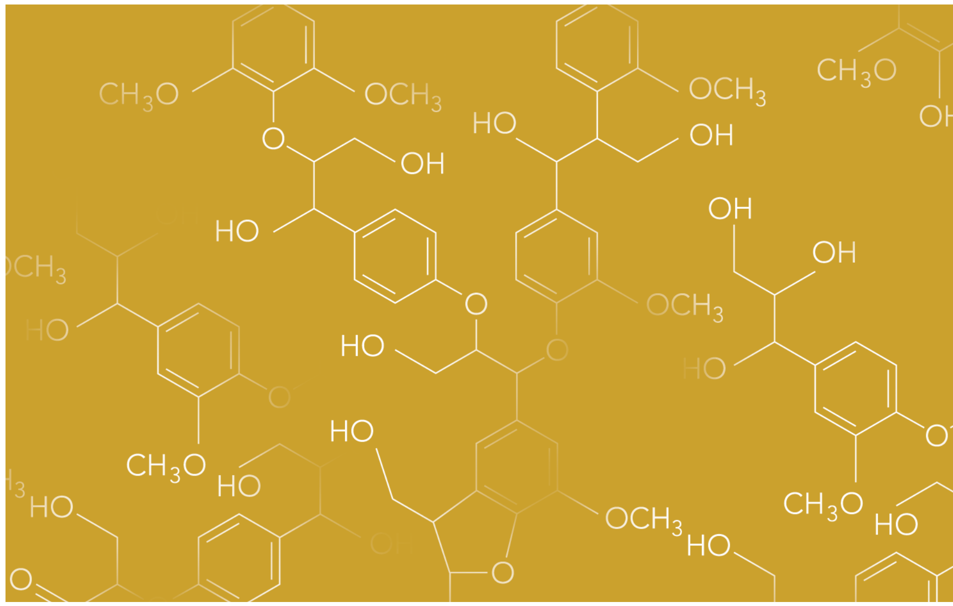

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