The Water Boiling Test (WBT)

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Introduction

This modified version of the well-known Water Boiling Test (WBT) is a rough simulation of the cooking process that is intended to help stove designers understand how well energy is transferred from the fuel to the cooking pot. It can be performed on most stoves throughout the world. The test is not intended to replace other forms of stove assessment; however, 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 is important to understand both the strengths and weaknesses of the WBT. Strengths include the WBT's simplicity and replicability. In addition, it provides a preliminary understanding of stove performance, which is very helpful during the design process. Data obtained from a just few days of testing will help in the development of better stoves, which can then to be tested by cooks in their intended environment. Visser (2003) has shown that by determining thermal efficiency at high and low power, as is done in this version of the WBT, fuel use can be roughly predicted for various cooking tasks.

However, the WBT also has weaknesses. In order to be applicable to many different types of stoves, the WBT is only a rough approximation of actual cooking. It is done in controlled conditions by trained technicians. Therefore, it can't provide much information about how the stove performs when cooking real foods. To get an understanding of how the stove performs cooking foods cooked by local people, stove testers should use the Controlled Cooking Test (CCT) that has been developed in parallel with this test. Similarly, the WBT can't be used to accurately predict actual changes in fuel consumption among families who adopt an improved stove. A Kitchen Performance Test (KPT), which compares fuel consumption in households using the improved to households using a traditional stove, should be conducted before drawing any conclusions about changes in fuel consumption among real stove-users. The KPT has also been developed to be used together with the CCT and WBT. Further discussion of the WBT and variations used in China and India is found in Appendix 1.

The WBT developed for the Shell HEH program consists of three phases that immediately follow each other.

1) In the first phase, the cold-start high-power test, the tester begins with the stove at room temperature and uses a pre-weighed bundle of wood or other fuel[1] to boil a measured quantity of water in a standard pot. The tester then replaces the boiled water with a fresh pot of cold water to perform the second phase of the test.

2) The second phase, the hot-start high-power test, follows immediately after the first test while stove is still hot. Again, the tester uses 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.

3) The third phase follows immediately from the second. Here, the tester determines the amount of fuel required to simmer a measured amount of water at just below boiling for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world.

This combination of tests measures some aspects of the stove's performance at both high and low power outputs, which are associated with the stove's ability to conserve fuel. However, rather than report a single number indicating the thermal efficiency of the stove, which is not necessarily a good predictor of stove performance,[2] this test is designed to yield several quantitative outputs. Different stove designers may find different outputs more or less useful depending on the context of their stove program. The outputs are:

- time to boil (adjusted for starting temperature);
- burning rate (adjusted for starting temperature);
- specific fuel consumption (adjusted for starting temperature);
- firepower
- turn-down ratio (ratio of the stove's high power output to its low power output); and
- thermal efficiency

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[1] This test was originally designed for woodstoves, but has been adapted to accommodate other types of stoves and fuels. See Appendix 3 for a discussion of the use of non-woody fuels.

[2] A direct calculation of thermal efficiency derived from the Water Boiling Test is not a good indicator of the stove's performance because it rewards the excess production of steam. Under normal cooking conditions, excess steam production wastes energy because it represents energy that is not transferred to the food. Temperatures within the cooking pot do not rise above the boiling point of water regardless of how much steam is produced. Thus, unless steam is required for the cooking process – for example in the steaming of vegetables [1], excess steam production should not be used to increase indicators of stove performance.

For more information on each indicator, see Appendix 2, which defines each measure and explains how it is calculated.

Before starting the tests…

The following five steps should be completed before beginning the actual tests.

1) Be sure that there is sufficient water and fuel. If possible, try to obtain all of the wood from the same source. It should be well-dried and uniform in size. If kindling is to be used to start the fire, it should also be prepared ahead of time and included in the pre-weighed bundles of fuel.

2) 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 boil the required amount of water. **As a rough guide, procure at least 15 kg of air-dried fuel for each stove in order to ensure that there is enough fuel to test each stove three times. Large multi-pot stoves may require even more than 15 kg.**

3) The practice tests should also be used to determine the **local boiling point of water**. The local boiling point of water is the point at which the temperature no longer rises, no matter how much heat is applied. This should be determined by the following procedure:

   - ⇒ 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!

   - ⇒ 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.

   - ⇒ The tester should 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 and this result recorded as the "local boiling temperature" on the data and calculation form. (this need only be done once for your test location - see note 2).

4) One full WBT requires at least 10 liters of cool water for each pot being used. If water is scarce in your area, water used one day may be cooled and reused in the next day's testing. But, do not start any tests with water that is significantly above room temperature.

5) 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. It will take 1½ - 2 hours to do the high and low power test for each stove. You will save time if you prepare enough bundles of fuel to conduct several tests before starting the first test.

Beginning of Testing Procedure

Equipment used for the Water Boiling Test:

- Scale with a capacity of at least 6 kg an accuracy of ±1 gram
- Heat resistant pad to protect scale
- Digital Thermometer, accurate to 1/10 of a degree, with thermocouple probe suitable for immersion in liquids
- Small shovel/spatula to remove charcoal from stove
- Wood moisture meter (optional)
- Tongs for handling charcoal
- Timer
- Dust pan for transferring charcoal
- Standard pot(s) (see note 1)
- Metal tray to hold charcoal for weighing
- Wood fixture for holding thermocouple probe in water (see diagram in Appendix 4)
- Heat resistant gloves
- At least 10 liters of clean water for each WBT (in locations where water is scarce, this may be cooled and reused for later tests)
- 2 bundles of air-dried fuelwood each weighing between 1 and 2 kg for each test (each stove is tested three times). More fuel may be needed for high-mass stoves.

Initial steps: to be done once for each tests

1. Fill out the first page of the Data and Calculations form. This includes information about the stove, fuel and test conditions. Number each series of tests for future reference.

2. Measure each of the following parameters. These should be recorded once for each series of tests. Record the measurements on page 1 of the Data and Calculation form.

    a) Air temperature.

    b) Average dimensions of wood (length x width x height). This is to give a rough idea of the size of fuel used for the test. You should use similarly sized wood for every test to reduce variation in test conditions. If the stove design requires a specific size of fuel then you should use the optimal size for the stove. Otherwise, use sticks 2-5 cm in diameter (see Note 3 for a discussion of the effects of fuel wood variation on stove performance).

c) Wood moisture content (% - wet basis): to be determined 1) By weighing a sample of fuel, drying the sample completely in a controlled manner, and weighing it again or 2) By using the wood moisture meter included in the testing kit. (See Note 4 and the section on variables and calculations below for full details of defining and measuring moisture content). The Data and Calculation form contains a special worksheet to record and process your measurements. See the form for a more detailed explanation.

d) Dry weight of standard supplied pot without lid. If more than one pot is used, record the dry weight of each pot. If the weights differ, be sure not to confuse the pots as the test proceeds. **Do not use pot lids for this, or any other phase of the WBT (see Note 5)**. The standard pot (supplied with the test equipment) should be used wherever possible (see notes). If it is not compatible with the stove, use a pot that is typically used and note its dimensions in the "comments" section of the Data and Calculations worksheet.

e) Weight of container to be used for charcoal.

f) Local boiling point of water determined by using the same digital thermometer and sensor that will be used in the testing (see Note 2).

g) If you have access to a camera (not included in standard kit), photograph the stove. If you don't have access to a camera, use a tape measure to record the dimensions of the stove and describe it in the space provided.

3. Prepare 2 bundles of fuel wood. These should be pre-weighed: one for each of the two measurement 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, which should also be prepared in advance if necessary) (see Note 3).

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

Phase 1: High Power

Data recorded in the remaining phases of the test should be recorded on page two of the Data and Calculation form.

1. Prepare the timer, but do not start it until fire has started.

2. Fill each pot with 5 kg (5 liters) of clean room temperature water (if using the smaller standard pot, fill the 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. Record the weight of pot and water in the Data and Calculations Sheet.

(If the stove can not accommodate the standard pot and the pot that is used can not accommodate 5 (or 2.5) kg of water, OR if a multi-pot stove is used with non-standard pots that can not accommodate 5 (or 2.5) kg of water, fill each pot ~2/3 full and record the change in procedure in the comment space. Record the weight of the pot(s) with the water on the Data and Calculation Form. Use the same amount of water for each test iteration.)

3. 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. Record the initial water temperature in each pot and confirm that it does not vary substantially from the ambient temperature.

4. The stove should be at room temperature. Start the fire in a reproducible manner according to local practices. Record any starting materials that are used other than the wood from the first bundle of pre-measured wood (e.g. paper or kerosene).

5. Once the fire has caught, record the starting time. Throughout the following "high power" phase of the test, control the fire with the means commonly used locally to bring the first pot rapidly to a boil without being excessively wasteful of fuel.

6. When the water in the first pot reaches the pre-determined local boiling temperature as shown by the digital thermometer, rapidly do the following:

   a. **Record** the time at which the water in the primary pot (Pot # 1) first reaches the local boiling temperature. Record this temperature also.

   b. 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.

   c. Weigh the unburned wood removed from the stove together with the remaining wood from the pre-weighed bundle. **Record** result on the Data and Calculation form.

   d. For multi-pot stoves, measure the water temperature from each pot (the primary pot should be at the boiling point). **Record** the temperatures on the Data and Calculation Form.

   e. Weigh each pot, with its water. **Record** these weights on the Data and Calculation form

f. Extract all remaining charcoal from the stove, place it with the charcoal that was knocked off the sticks and weigh it all. **Record** the weight of the charcoal + container on the Data and Calculation Form.

Summary

⇒ Make sure that you have recorded time and temperature of the boiling water in the first pot, the amount of wood remaining, the weight of Pot # 1 with the remaining water, and amount of charcoal remaining on the Data and Calculation Form. For multi-pot stoves, be sure that you have recorded the temperature that each additional pot reached **when Pot # 1 first came to its full boiling temperature**.

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

Phase 2: High Power (Hot Start)

1. Reset the timer, but do not start it until fire has started.

2. Refill the pot with 5 (or 2.5) kg of fresh cold water. Weigh the pot (with water) and measure the initial water temperature; **record** both measurements on the Data and Calculations sheet. For multi-pot stoves, fill the additional pots, weigh them and record their weights.

3. Light the fire using kindling and wood from the second pre-weighed bundle designated for this phase of the test.

4. Record the starting time, and bring the first pot rapidly to a boil without being excessively wasteful of fuel using wood from the second pre-weighed bundle.

5. Record the time at which the first pot reaches the local boiling point as indicated on the Data and Calculation form. Record this temperature for the first pot.

6. After reaching the boiling temperature, quickly do the following (speed is important at this stage because we want to keep the water temperature as close as possible to boiling in order to allow us to proceed directly to the simmer test):

   a. Remove the unburned wood from the stove. Knock off any loose charcoal, but try to keep it in the combustion area (you will not weigh the charcoal at this stage). Weigh the wood removed from the stove, together with the unused wood from the previously weighed supply. **Record** result on Data and Calculation form.

   b. **Record** the water temperature from other pots if more than one pot is used.

c. Weigh each pot, with it's water and **record** the weights. After weighing, immediately replace each pot on the stove (**remember, we want to keep the water temperature as close as possible to boiling in order to proceed directly to the simmer test!**).

7. Replace and relight the wood removed from the fire ***proceed immediately*** with the low power test.

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** (see the discussion of multi-pot stove-testing in Appendix 5).

Start of Low Power test

1. Reset the timer.

2. Replace the thermometer in the pot. Adjust the fire to keep the water as close to 3 degrees below the established boiling point as possible.

It is acceptable if temperatures vary up and down, but;

⇒ **The tester must vigilantly try to keep the simmering water as close as possible to 3 degrees C below the local boiling point (see notes 6 and 7).**

⇒ **The test is invalid if the temperature in the pot drops more than 6°C below the local boiling temperature.**

3. 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.

4. After 45 minutes rapidly do the following:

   a. Record the finish time of the test (this should be 45 minutes). Record this and all remaining measurements on the Data and Calculation Form under the heading "Finish: 45 minutes after Pot # 1 boils".

   b. Remove all wood from the stove and knock any loose charcoal into the charcoal container. Weigh the remaining wood, including the unused wood from the pre-weighed bundle.

   c. Record the final water temperature on Data and Calculation Form – it should still be roughly 3 °C below the established boiling point.

d. Weigh the pot with the remaining water. Record the weight on the Data and Calculation Form.

e. Extract all remaining charcoal from the stove and weigh it (including charcoal which was knocked off the sticks). Record the weight of pan plus charcoal.

This completes the WBT. The test should be conducted a total of three times for each stove.

Analysis

Input the results of this WBT into the Data and Calculation software. Output will be viewable in the "Results" worksheet.

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 performance of different stove models. For more discussion, see Appendix 6.

Notes on the WBT

1. **Pots:** The capacity, dimensions and material of the pot have a significant influence on stove performance. In order to maximize the comparability of the WBT across different types of stove ***we recommend that testers use one of two standard pots*** depending on the design and power output of the stove being tested. The recommended pots are 1) a large pot (with a 7 liter capacity) and 2) a small pot (with a 3.4 liter capacity)[INCLUDE A PHOTO OR SCHEMATIC OF THE POTS?]. Depending on the power output of the stove and cooking practices in the area where the stove is used, testers should use either the large or small standard pot unless the stove requires a specific pot in order to function properly. If testers use a non-standard pot, they should record the capacity, dimensions, weight, and material. Use of a non-standard pot may bias the results and make them difficult to compare to other WBTs.

2. **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. This should be determined empirically by the following procedure: Put 5 liters of water in the standard pot and bring it to a boil. Using the same thermometer that will be used for testing, measure the boiling temperature when the thermocouple is positioned in the center, roughly 5 cm above the pot bottom. The tester will find that even at full boil (when new higher temperatures are no longer observed), the temperature will oscillate several tenths of a degree above and below the actual boiling point. The tester should 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

and this result recorded as the "local boiling temperature" on the data and calculation form. (This need only be done once for your test location).

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:

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

3. **Fuels:** The type and size of fuel can affect the outcome of the stove performance tests. In order to minimize the variation that is potentially introduced by variations in fuel characteristics VITA (1985) recommends taking the following precautions:

    - Try to use only wood (or other fuel) that has been thoroughly air-dried. Wooden stocks 3-4 cm in diameter may take from 3-8 months to dry fully. Dung or crop residues take somewhat less time in dry conditions. For woodfuel, drying can be accelerated by ensuring that the wood is stored in a way that allows air to circulate through it.

    - Different sizes of solid fuels fuel have different burning characteristics. While stove users may not have the ability to optimize fuel size, testers should try to use only similar sizes of wood to minimize this source of variation.

4. **Moisture content of wood:** 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, there is a space for moisture content to be input in the Data and Calculation form and software.

    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 take care to specify which basis they are using.

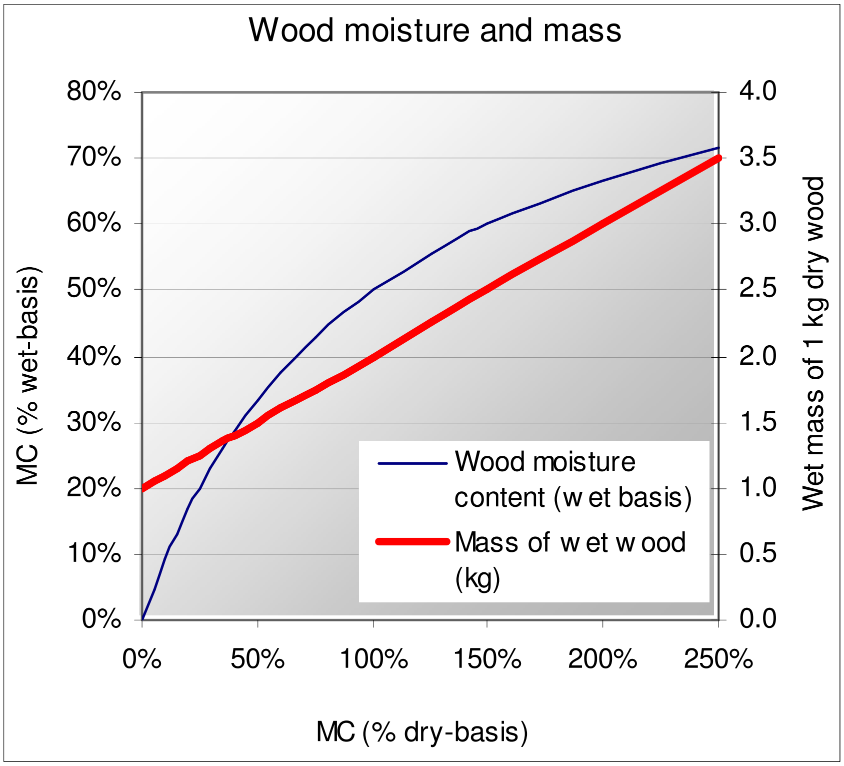
$$MC_{wet}(\%) = \frac{(\text{Mass of fuel})_{wet} - (\text{Mass of fuel})_{dry}}{(\text{Mass of fuel})_{wet}} * 100 \quad \text{and}$$

$$MC_{dry}(\%) = \frac{(\text{Mass of fuel})_{wet} - (\text{Mass of fuel})_{dry}}{(\text{Mass of fuel})_{dry}} * 100$$

The two moisture contents are related in this way: $MC_{wet} = \frac{MC_{dry}}{MC_{dry} + 1}$.

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 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 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 reads up between 6% and 40% moisture (dry basis). If the sample of wood is wetter than 40%, the meter will yield an error.[3] 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) $MC_{wet} = \frac{MC_{dry}}{MC_{dry}+1}$. Record this average in the Data and Calculation 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,

[3] 40% moisture on a dry basis is equivalent to roughly 29% moisture on a wet basis.

then the oven-drying method is recommended. See Appendix 3 for further discussion.

5. **Lids:** The WBT should be conducted without lids. This may seem counterintuitive, because lids generally improve the performance of the stove. However, the main purpose of the WBT is to quantify the way that heat is transferred from the stove to the cooking pot. While a lid helps to *retain heat* in the pot, and should therefore be used for any actual cooking task, it does not effect the *transfer of heat* from the stove to the pot. Hence, a lid is not needed for the WBT even if lids are commonly used among communities for which the improved stove is intended.

   In fact, lids can complicate the WBT by increasing the variability of the outcome and making it harder to compare results from different tests. As Baldwin writes, "If a lid is used then the amount of water evaporated and escaping is somewhat dependent on the tightness of the lid's fit to the pot, and very dependent on the firepower. If the firepower is so low that that the temperature is maintained a few degrees below boiling, effectively no water vapor will escape. If the firepower is high enough so that the water boils, the escaping steam will push the lid open and escape," (from Chapter 5, note 2, p. 263).

   The water lost has different effects on each indicator of stove performance. However, since it is difficult to standardize the lid's "tightness of fit", even for a standardized pot, we recommend testers not use the lid for the WBT. This should have little impact on the high power testing phase – indicators like specific consumption and thermal efficiency are both relatively insensitive to evaporated water.

   However, the indicators derived from the low power test are more sensitive to the amount of water evaporated. Again, from Baldwin, "By not using a lid, evaporation rates are higher and the stove must be run at a somewhat higher power to maintain the temperature than is the case with a lid" (p. 263).

6. **Power control:** Many stoves lack adequate turndown ability. The tester may find that it is impossible to maintain the desired temperature without the fire going out (especially after the initial load of charcoal in the stove has been consumed). If this is the case, the tester should 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 further splitting the wood into smaller diameter pieces.

7. **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 started to question the wisdom of relying solely on thermal efficiency calculations, and recommended that they be replaced by another standard:

…some of the procedures described here differed significantly from what has been recommended in the past. The main difference is in the concept of efficiency used. These standards are based on a broader description and justification of efficiency than Percent Heat Utilized (PHU). They interpret evaporation as a measure of energy wasted, not energy used [2, page ix].

The revised test presented here is based on the procedures proposed by VITA (1985) and Baldwin (1987), but has incorporated minor changes described below:

- Specific Consumption is defined as the ratio of the total amount of wood used to the amount of water "cooked" [3], but was modified for multi-pot stoves to reward heat transferred to secondary cooking pots (see Appendix 5).

- It can be difficult to make a smooth transition from high-power to low power tests. Methods used in past testing procedures have suggested extinguishing and weighing wood and charcoal as well as weighing boiling hot water, and rearranging the fire and cooking pot in rapid succession, which is 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.

- During the low power simmer test, the tester is instructed to try to keep the water temperature as close to 3°C below the predetermined boiling point as possible. Different amounts of steam are produced at each degree point below boiling. For this reason, it is necessary to minimize the variation in temperature to ensure that tests are comparable.

- A hot-start test is incorporated in the high power phase in order to account for the different performance of stoves that are kept hot throughout the day. This is important for massive stoves, whose performance may vary significantly between cold and hot starting conditions.

- Simmering occurs for 45 minutes rather than 30, (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.

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Appendix 1

Stove Performance Testing

Tests of stove performance range from lab-based water boiling and cooking tests to qualitative and quantitative surveys of stove users in the field. There are advantages and disadvantages to both types of tests. Lab-based tests are more appropriate at the early stages of stove development in order to compare various technical aspects of stove design. For example, Baldwin recommends lab-based tests for comparing and optimizing different dimensions and other design details of the stove. Lab-based tests are also more appropriate when comparing stoves that are used in different regions of the world. There is a great amount of variation in cooking practices, fuels, and household environments throughout the world's developing regions that makes direct comparisons of actual stoves in people's kitchen very difficult. Lab-based tests In order to accommodate the many aspects of stove performance testing that eliminate the variability in factors that may affect stove performance other than the physical characteristics of the stove itself.

In order to accommodate the many aspects of stove performance testing that designers of improved cookstoves face, the protocols described in this manual include procedures for two types of lab-based tests as well as a field test. The lab tests include a modified version of VITA's Water Boiling Test (WBT) and as well as a Controlled Cooking Test (CCT). The field test includes two qualitative surveys: the first helps project designers to assess household cooking practices prior to the introduction of the improved stove and the other provides them with follow-up data 3-6 months after the stove has been introduced to the family. The field test also includes a procedure to compare fuel consumption in households using different types of stoves. This test is critical if project designers wish to make justifiable claims about real impacts on fuel consumption resulting from the stoves that they are promoting. ***Such claims can not be based on lab-based tests alone***

While lab-based tests allow stove developers to differentiate between well-designed and poorly-designed stoves, they give little indication of how the stoves are actually used by the people who are targeted by stove projects. In order to know if stove projects are having the desired impact (whether it is fuel conservation, smoke reduction, or both), the stoves must be measured under real conditions of use.

Two major stove programs and their use of stove performance tests

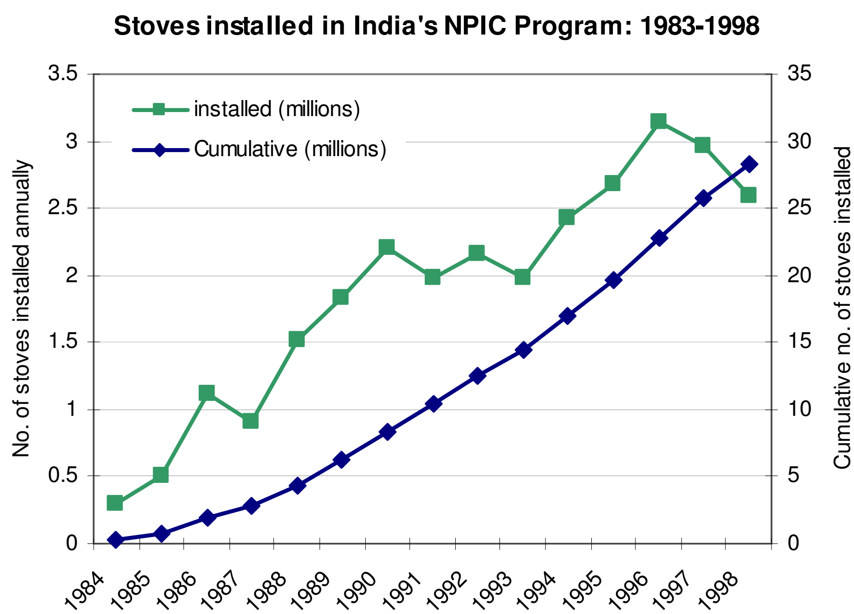
In addition to the tests introduced by VITA and elaborated by Baldwin, other large-scale efforts have been conducted to assess the performance of improved stoves and stove programs. Two of the most notable efforts are those that have been conducted over the past 20 years in India and China. Taken together, these programs represent the vast majority of improved stoves introduced globally: with well over 200 million stoves disseminated between them. These programs have undergone numerous changes since their inception in the early 1980s. A full review of these programs is beyond the scope of this document, but a brief review of each is given below, with attention to the stove performance monitoring methods that have been used. References are also provided for further reading.

India's National Improved Chula Program (NPIC)

This program, which has been underway for nearly two decades, had five stated objectives:

- to conserve and optimize the use of fuelwood, especially in the rural and semi-urban areas
- to help alleviate deforestation
- to reduce the drudgery associated with cooking, especially on women, and the health hazards caused by smoke and heat exposure in the kitchen
- to bring about improvements in household sanitation and general living conditions
- employment generation in rural areas

By 1999, NPIC activities had disseminated over 28 million stoves [4]. The graph below illustrates the number of stoves disseminated during the first 15 years of project activity.



Based on data from [4]

Despite the impressive numbers, NPIC is not considered an unqualified success. Firstly, the cumulative data hide the fact that most stoves have a limited lifetime –

typically no more than two years - so that the total number of stoves in use in 1998 was actually a small fraction of the cumulative number shown in the graph. Several other factors also contributed to NPIC's problems. These are summed up well in the following passage, which is taken from a recent World Bank report on India's experience with cookstoves in the context of indoor air pollution reduction:

> *In the early programs it was assumed that if improved stoves were presented to people, they would be quickly adopted and the intervention would lead to self- sustaining programs. This often did not happen for several reasons. One reason was that the energy efficiencies achieved in laboratories did not translate into similar efficiency gains in rural homes. Another reason lay in an obvious failure to identify the market for improved stoves; for example, some programs introduced stoves into regions where people purchased neither their traditional stoves nor fuelwood, thus having little appreciation of efficiency gains. The health benefits of the improved stoves were not well advertised. Finally, the price of an improved stove was a significant barrier to adoption, especially in areas where there was very little cash outlay for stoves or fuel [5].*

While each of these problems presents significant obstacles for stove project designers, the problem of linking lab-based efficiency to actual fuel consumption in rural homes is of greatest concern to the ideas presented in this document. We will discuss this issue in much more detail below.

NPIC reports claimed that each stove reduced fuelwood consumption by 30-40% relative to a traditional chulha, which represents roughly 700 kg of fuelwood family per year [6]. The World Bank reports more modest savings of 19-23% relative to traditional stoves. Kishore and Ramana also report smaller improvements. They cite one study that found savings of about 35 kg fuelwood per year and another that actually found a **net increase** in fuel consumption. The results of the latter study are shown in Table 1 below. These data are the result of fuel consumption surveys that followed VITA's kitchen performance test protocol [2, 4]. The results show that in many cases, NPIC stoves consumed more fuel than the traditional chulas that they were meant to replace.

Kishore and Ramana's review of the NPIC stove performance relied on field tests, but the NPIC program itself based its assessments of stove performance primarily on "thermal efficiency" tests. Thermal efficiency was defined as "the ratio of heat actually utilized to the heat theoretically produced by complete combustion of a given quantity of fuel," [6, p. 96]. In order to qualify for inclusion in NPIC, improved chulhas were required to have a minimum efficiency of 20% for fixed mud stoves and 25% for portable metal stoves. The lab-based tests that were used differ substantially from the WBT designed by VITA and presented below with slight modifications. See [6, Annex 2] for a full description of the procedure.

Table 1: Comparison of fuel consumption in Improved and Traditional Chulhas in 3 Indian States

	Improved chulha		Traditional chulha		
	No. of households	Wood consumption kg/day/stove[a]	No. of households	Wood consumption kg/day/stove[a]	Percent savings of improved chulha compared to traditional chulha
Tamil Nadu					
Manachai	14	5.99	8	5.34	**-12**
Muthupattai	10	7.27	10	4.77	**-62**
Rajasthan					
Motuka	11	7.2	12	5.91	**-22**
West Bengal					
Golti	14	9.34	14	11.65	19.8
Iswarigacha	15	7.34	13	7.83	6.3
Average					**-14**

From [4]

[a] Assuming six persons per family, one chulha per family and a calorific value of 17.6 MJ/kg for wood.

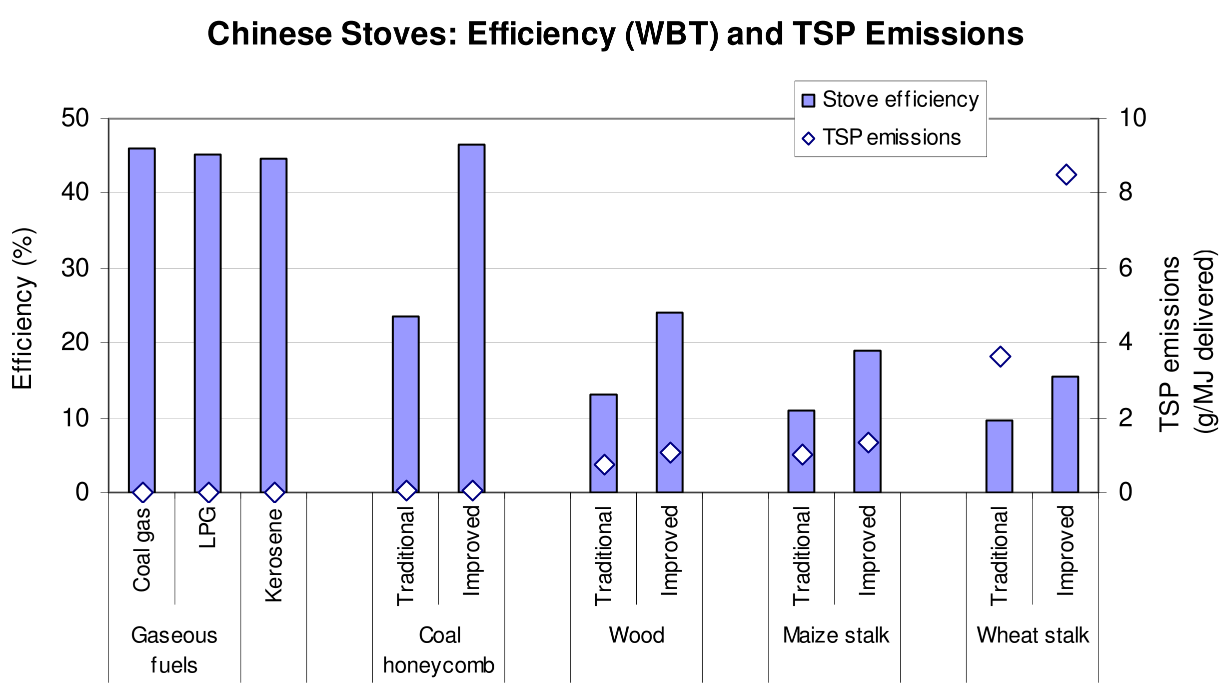
NPIC continued until 2002, when the Indian government devolved authority to the state level so that individual states in India are now responsible for implementing improved stove programs. Additionally, in recent years, many non-governmental agencies have become involved in stove development and dissemination, both in partnership with and independent of, state-run projects.

The Chinese National Improved Stove Program (CNISP)

China has undertaken the most extensive improved stove program in the world. Between its inception in 1983 and 1998, roughly 185 million stoves were disseminated in China [7]. Like India's NPIC, CNISP was originally intended to conserve biomass fuels and reduce the time and effort household members had to devote to meeting their energy needs.[4] Because of its sheer scale and the extent of social and economic changes China has undergone during the time that the program has been in place, the impact that CNISP has had is difficult to assess independent of other changes in rural China. Biomass fuel consumption in some rural areas has decreased, but this may be attributed to fuel switching rather than to gains in energy efficiency. Many rural families have begun using coal, electricity, or other fuels in addition to biofuels, which would likely result in decreased biofuel consumption regardless of the type of stove in use.

[4] One expert has pointed out that in addition to the goals of biofuel conservation and reduced workload on the rural household, China's stove program was also a state-driven effort to modernize biofuel consumption in order to reduce and/or delay growth in demand for fossil fuels among China's massive rural population [8].

As Smith indicated over 10 years ago, information about quantitative aspects of China's improved stoves is not widely available [8]. Data about the performance of stoves disseminated through CNISP are not widely published. Zhang and colleagues tested emissions and efficiencies of 28 fuel-stove combinations in China. They report average lab-based efficiencies derived from a 3 repetitions of a modified version of VITA's WBT [9]. A sample of their results are reproduced below in the graph below showing four pairs of traditional and improved Chinese stoves each using a different solid fuel: coal, wood, maize stalks and wheat stalks. Three popular fossil fuel options are also included for comparison. Notice the efficiency determined by the modified WBT is higher in improved stoves. However, the biomass stoves tested are far less efficient than liquid and gaseous fossil fuels. Another interesting result concerns health impact of stoves; the biofuels used in improved stoves appear to result in higher emissions of particulate matter (measured as *Total Suspended Particulates* or TSP). All of these stoves tested have chimneys, so the increase in TSP is not necessarily a cause for concern as long as the chimneys are functioning well, however it does indicate that higher overall efficiency in these improved stoves has likely been achieved at the expense of combustion efficiency.



Based on data from [9]

However, it is difficult to predict fuel consumption by rural families under real cooking conditions solely through the results of energy efficiency determined by WBTs. Unfortunately, few reports of actual fuel consumption by improved stoves in China have been published outside of China. The authors would welcome any information about field performance of improved stoves in China.

Appendix 2

An explanation of the calculations used in the WBT

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.

Variables that are constant throughout each phase of the test

HHV	Gross calorific value (dry wood) (MJ/kg)
LHV	Net calorific value (dry wood) (MJ/kg)
m	Wood moisture content (% - wet basis)
c_{eff}	Effective calorific value (accounting for moisture content of wood)
P	Dry weight of empty Pot (grams)
k	Weight of empty container for char (grams)
T_b	Local boiling point of water (deg C)

Explanations of Variables

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.[5]

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[5] 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 H_2O. 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 ºC, which is not typically how LHV is defined [3, p. 55].

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

$$m = \frac{(\text{mass of wet fuel}) - (\text{mass of dry fuel})}{\text{mass of wet fuel}} * 100$$

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).

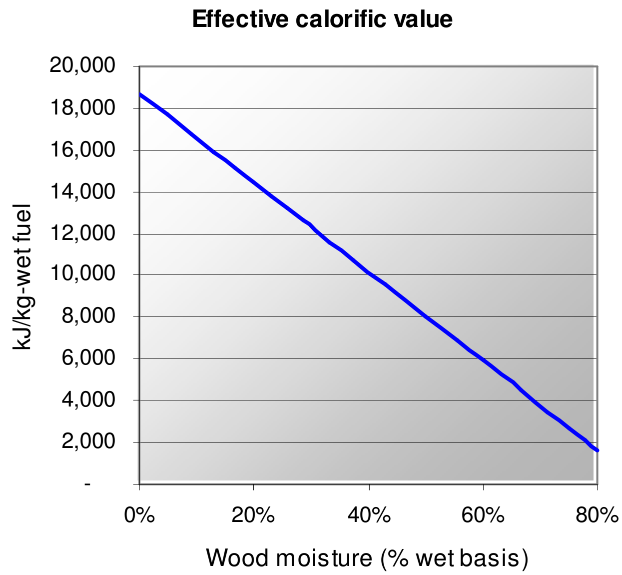
If the Delmhorst J-2000 moisture meter is used in this test to measure wood moisture content, be aware that it provides moisture content on a *dry basis*. In order to use 'm' in the following analysis, the output of the instrument must be converted to moisture content on a *wet basis*. *Dry basis* must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

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

c_{eff} **-** This is the effective calorific value of the fuel, with takes account of the energy required to heat and evaporate the moisture present. This is calculated in the following way:

$$c_{eff} = \frac{LHV * (\text{mass of dry fuel}) - (\text{mass of water in fuel}) * (80 * 4.186 + 2260)}{\text{mass of wet fuel}}$$

where 80ºC represents the typical change from ambient temperatures to the boiling point of water, 4.186 kJ/(kg•ºC) is the specific heat capacity of water, and 2260 kJ/kg is the energy required to evaporate one kilogram of water. The graph below shows c_{eff} 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.



P - This is the weight of the empty pot. For multi-pot stoves, this 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.

1. High power test (cold start)

Variables that are directly measured

f_{ci}	Weight of fuel before test (grams)
P_{ci}	Weight of Pot with water before test (grams)
T_{ci}	Water temperature before test (ºC)
t_{ci}	Time at start of test (min)
f_{cf}	Weight of wood after test (grams)
c_c	Weight of charcoal and container after test (grams)
P_{cf}	Weight of Pot with water after test (grams)
T_{cf}	Water temperature after test (ºC)
t_{cf}	Time at end of test (min)

Variables that are calculated

f_{cm}	Wood consumed, moist (grams)
Δc_c	Change in char during test phase (grams)
f_{cd}	Equivalent dry wood consumed (grams)
w_{cv}	Water vaporized (grams)
w_{cr}	Water remaining at end of test (grams)
Δt_c	Duration of phase (min)
h_c	Thermal efficiency
r_{cb}	Burning rate (grams/min)
SC_c	Specific fuel consumption (grams wood/grams water)
SC^T_h	Temp-corrected specific consumption (grams wood/grams water)
FP_c	Firepower (W)

Explanations of Calculations

f_{cm} – Wood consumed (moist): This is the mass of wood that was 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:

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

Δc_c – Net change in char during test phase: This 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 two masses.

$$\Delta c_c = c_c - k$$

f_{cd} – Equivalent dry wood consumed: This is a calculation that adjusts the amount of wood that was burned in order to account for two factors: (1) the energy that was needed to remove the moisture in the wood and (2) the amount of char remaining unburned. The calculation is done in the following way:

$$f_{cd} = f_{cm} * (1 - (1.12 * m)) - 1.5 * \Delta c_c$$

The factor of $1-(1.12*m)$ adjusts the mass of wood burned by the amount of wood required to heat and evaporate $m*f_{cm}$ grams of water. It takes roughly 2260 kJ to evaporate a kilogram of water, which is roughly 12% of the calorific value of dry wood. Thus if wood consists of m% moisture, the mass of wood that can effectively heat the pot of water is reduced by roughly $1-(1.12*m)$ because the water must be boiled away (see [3] for further discussion).

The factor of $1.5*\Delta c_c$ accounts for the wood converted into unburned char. Char has roughly 150% the calorific content of wood, thus the amount of wood heating the pot of water should be adjusted by $1.5*\Delta c_c$ to account for the remaining char. Note, in the simmer phase it is possible that there will be a net loss in the amount of char before and after the test, in which case Δc is negative and the equivalent dry wood increases rather than decreases.

W_{cv} – Water vaporized: This is a measure of the amount of water lost through evaporation during the test. It is calculated by simple subtraction of initial weight of pot and water minus final weight of pot and water.

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

w_{cr} – Water remaining at end of test: This 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.

$$w_{cr} = P_{cf} - P$$

Δt_c – Time to boil pot #1: This is simply the time taken to perform the test. It is a simple clock difference:

$$\Delta t_c = t_{cf} - t_{ci}$$

Δt^T_c – Temperature-corrected time to boil pot #1: this 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.

$$\Delta t^T_c = (t_{cf} - t_{ci}) \times 75/(T_{cf} - T_{ci})$$

h_c – Thermal efficiency: This is a ratio of the work done by heating and evaporating water to the energy consumed by burning wood. It is calculated in the following way.

$$h_c = \frac{4.186*(P_{ci}-P)*(T_{cf}-T_{ci})+2260*(w_{cv})}{f_{cd}*LHV}$$

In this calculation, the work done by heating water is determined by adding two quantities: (1) the product of the mass of water in the pot, $(P_{ci} - P)$, the specific heat of water (4.186 J/g°C), and the change in water temperature $(T_{cf} - T_{ci})$ and (2) the product of the amount of water evaporated from the pot and the latent heat of evaporation of water (2260 J/g). The denominator (bottom of the ratio) is determined by taking the product of the dry-wood equivalent consumed during this phase of the test and the LHV.

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

$$r_{cb} = \frac{f_{cd}}{t_{ci} - t_{cf}}$$

SC_c - Specific fuel consumption: Specific consumption can be defined for any number of cooking tasks and should be considered "the fuelwood 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 in this way:

$$SC_c = \frac{f_{cd}}{P_{cf} - P}$$

SC^T_c – 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 ºC (from 25 to 100). It is calculated in the following way.

$$SC^T{}_c = \frac{f_{cd}}{P_{cf} - P} * \frac{75}{T_{cf} - T_{ci}}$$

FP_c – Firepower: This is a ratio of the wood energy consumed by the stove per unit time. It tells the average power output of the stove (in Watts) during the high-power test.

$$FP_c = \frac{f_{cd} * LHV}{60 * (t_{ci} - t_{cf})}$$

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

High power test (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}	Weight of fuel before test (grams)
P_{hi}	Weight of Pot with water before test (grams)
T_{hi}	Water temperature before test (ºC)
t_{hi}	Time at start of test (min)
f_{hf}	Weight of wood after test (grams)
c_h	Weight of charcoal and container after test (grams)
P_{hf}	Weight of Pot with water after test (grams)
T_{hf}	Water temperature after test (ºC)
t_{hf}	Time at end of test (min)

Variables that are calculated

f_{hm}	Wood consumed, moist (grams)	$f_{hm} = f_{hf} - f_{hi}$
Δc_h	Net change in char during test phase (grams)	$\Delta c_h = c_c - k$ (assumed to be equal to cold start)
f_{hd}	Equivalent dry wood consumed (grams)	$f_{hd} = f_{hm} * (1-(1.12*m)) - 1.5*\Delta c_h$
w_{hv}	Water vaporized (grams)	$w_{hv} = P_{hi} - P_{hf}$
w_{hr}	Water remaining at end of test (grams)	$w_{hr} = P_{hf} - P$
Δt_h	Time to boil pot #1	$\Delta t_h = t_{hf} - t_{hi}$
$\Delta t^T{}_h$	Temp -adjusted time to boil pot #1	$\Delta t^T{}_h = (t_{hf} - t_{hi}) \times 75/(T_{hf} - T_{hi})$
h_h	Thermal efficiency	$h_h = \frac{4.186*(P_{hi}-P)*(T_{hf}-T_{hi})+2260*(w_{hv})}{f_{hd}*LHV}$
r_{hb}	Burning rate (grams/min)	$r_{hb} = \frac{f_{hd}}{t_{hi}-t_{hf}}$
SC_h	Specific fuel consumption (grams wood/grams water)	$SC_h = \frac{f_{hd}}{P_{hf}-P}$
$SC^T{}_h$	Temp-corrected specific consumption (grams wood/grams water)	$SC^T{}_h = \frac{f_{hd}}{P_{hf}-P} * \frac{75}{T_{hf}-T_{hi}}$

FP_h Firepower (W) $$FP_h = \frac{f_{hd} * LHV}{60 * (t_{hi} - t_{hf})}$$

Low power (simmering) test

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 when the water first boils. The low power phase starts by repeating the high power hot start test, however 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. 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_c). 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 bringing the water to a boil.

Variables that are directly measured

f_{si} Weight of unused fuel when the water first boils (grams)

P_{si} Weight of Pot with water when the water first boils (grams)

T_{si} Water temperature at boiling ($T_{si} = T_b$) (ºC)

t_{si} Time at start of simmer phase test (min)

f_{sf} Weight of unburned wood remaining after test (grams)

c_s Weight of charcoal and container after test (grams)

P_{sf} Weight of Pot with water after test (grams)

T_{sf} Water temperature at end of test (ºC)

t_{sf} Time at end of test (min)

Variables that are calculated

f_{sm}	Wood consumed, moist (grams)	$f_{sm} = f_{sf} - f_{si}$
Δc_s	Net change in char during test phase (grams)	$\Delta c_s = c_s - k - \Delta c_c$
f_{sd}	Equivalent dry wood consumed (grams)	$f_{sd} = f_{sm} * (1 - (1.12 * m)) - 1.5 * \Delta c_s$
w_{sv}	Water vaporized (grams)	$w_{sv} = P_{si} - P_{sf}$
w_{sr}	Water remaining at end of test (grams)	$w_{sr} = P_{sf} - P$
Δt_s	Duration of phase (min)	$\Delta t_s = t_{sf} - t_{si}$
h_s	Thermal efficiency	$h_s = \frac{4.186 * (P_{si} - P) * (T_{sf} - T_{si}) + 2260 * (w_{sv})}{f_{sd} * LHV}$
r_{sb}	Burning rate (grams/min)	$r_{sb} = \frac{f_{sd}}{t_{si} - t_{sf}}$
SC_s	Specific fuel consumption (grams wood/grams water)	$SC_s = \frac{f_{sd}}{P_{sf} - P}$
FP_s	Firepower (W)	$FP_s = \frac{f_{sd} * LHV}{60 * (t_{si} - t_{sf})}$
TDR	Turn-down ratio	$TDR = \frac{FP_h}{FP_s}$

There is no temp-corrected specific consumption in the simmer phase because the test starts at T_b and 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 tests (SC_c and SC_h) indicated the mass of fuel required to produce one liter (or kilogram) of boiling water, the specific consumption in the simmer phase (SC_s) indicates the mass of wood 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.

It is also important to acknowledge that over-reliance on thermal efficiency can lead to misleading results, particularly in the simmer phase. 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 wood energy transferred to the cooking pot, is not necessarily a good indicator of stove performance. As we state elsewhere, we wish to de-emphasize the role that thermal efficiency plays in discussions of stove performance and stress other, more informative indicators such as the burning rate and specific consumption at high and low power, and the turn-down ratio, which indicates the degree to which power output from the stove can be controlled by the user.

Appendix 3

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. For fossil fuels, this can vary depending on exact mix of distillates that are used. Some calorific values that have been reported in the literature are given below, but we suggest the tester use a locally specific value 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

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 can not 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.[6] If possible, testers should check with a local

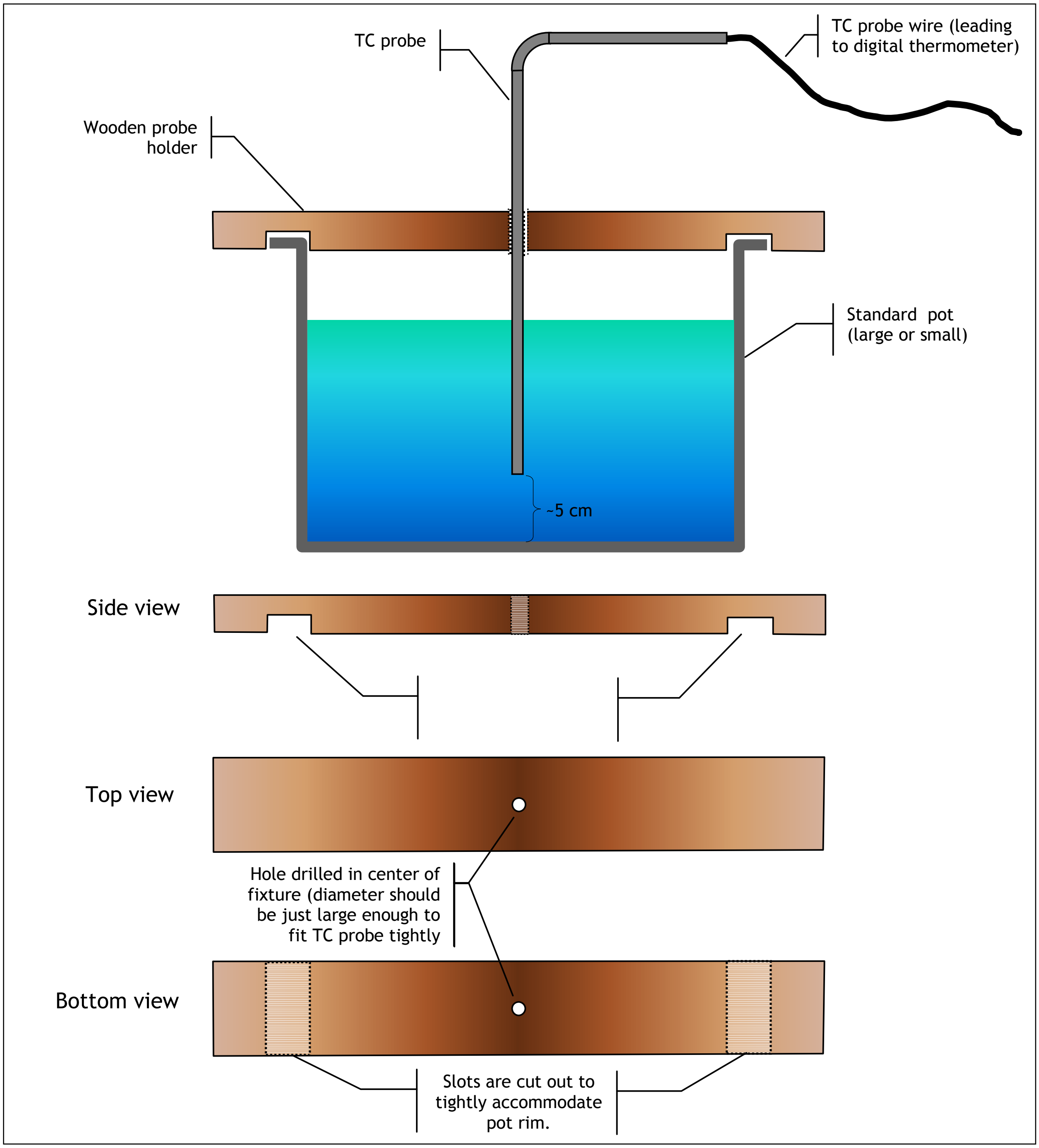
[6] See, for example, http://web.umr.edu/~gbert/cal/cal.html, for an explanation and a simulation of the procedure.

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 reported in previous household energy studies are given in the table below and have been included 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

Appendix 4

Diagram showing wooden fixture holding TC probe in pot. The dimensions are not critical, but the fixture should be made so that the TC probe fits into it tightly and the fixture itself fits securely on the pot.



Appendix 5

WBT Modifications for 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 Data and Calculation Form has space for up to four pots). The testing procedure will remain the same except for the additional measurements of weight and temperature. In addition, the calculations will be modified slightly.

To test stoves that accommodate multiple cooking pots, the data forms have been modified (see the file Template_for_multipot_WBT.xls). The modifications allow for weight and temperature of up to four pots to be recorded. The calculations are also modified to take these additional measurements into account. The modifications 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)	$w_{cv} = \sum_{j=1}^{4}(Pj_{ci} - Pj_{cf})$
w_{cr}	"Boiled" water remaining at end of test (grams)	$w_{cr} = \sum_{j=1}^{4}\left((Pj_{cf} - Pj) * \left(\frac{Tj_{cf} - Tj_{ci}}{T_b - Tj_{ci}}\right)\right)$
Δt_c	Duration of phase (min)	Same as for single-pot stove
h_c	Thermal efficiency	$h_c = \frac{\left[4.186 * \sum_{j=1}^{4}(Pj_{ci} - Pj) * (Tj_{cf} - Tj_{ci})\right] + 2260 * (w_{cv})}{f_{cd} * LHV}$
r_{cb}	Burning rate (grams/min)	Same as for single-pot stove

SC_c	Specific fuel consumption (grams wood/grams water)	$SC_c = \dfrac{f_{cd}}{\sum_{j=1}^{4}\left[(Pj_{cf} - Pj) * \left(\dfrac{Tj_{cf} - Tj_{ci}}{T_b - Tj_{ci}}\right)\right]}$
SC^T_c	Temp-corrected specific consumption (grams wood/grams water)	$SC^T{}_c = SC_c * \dfrac{75}{T_{cf} - T_{ci}}$
FP_c	Firepower (W)	Same as for single-pot stove

* These calculations use the subscript-c for the cold-start test, however the modified hot-start calculations are identical.

In each case, j is an index of each pot (1-4)

The factor $\left(\dfrac{Tj_{cf} - Tj_{ci}}{T_b - Tj_{ci}}\right)$ 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.

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, we acknowledge the strengths of well-designed multi-pot stoves, which lies in the stoves' ability to provide 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 6

Aspects of statistics to think about when conducting the WBT

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 2 shows data from a series of cold-start water boiling tests conducted at the Aprovecho Institute 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 2: Results of three high-power cold start Water Boiling Tests on two different stoves

		Stove-1			Stove-2			Statistics		
	units	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 $(\text{CoV} = \text{SD} \div \text{mean})$										

Table 3, 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 3, 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 3: 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