The Improved Water Boiling Test (EP-WBT)

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Introduction

This modified version of the well-known Water Boiling Test (WBT, based on version 3.0 by Balis et.al.) 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 standard which is should be used depends on the specifics of the desired data. The test is not intended to replace all 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 A.

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 fuel1 to heat a measured

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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 C for a discussion of the use of non-woody fuels.
quantity of water in a standard pot. The tester then replaces the heated 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 heat 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 for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world. Simmering at 90⁰C is desired to facilitate comparability of test results but is not required. The most economic fuel consumption will occur in stoves which can be dialed down to maintain this low temperature but this may not be practical with some stove designs.

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 reporting a single number indicating the thermal efficiency of the stove, which is not necessarily a good predictor of stove performance, this test is designed to yield several quantitative outputs. The relative importance of each of these factors depends on the location and situation under which the stove is to be used but initial guidelines for a stove to be considered “improved” can be found below.

The outputs are:

- test duration

The reported test duration is the average time of the high power phases.

- total CO emissions

Total emissions benchmarks are to be calculated from the following equation

\[
\frac{CO_{CS} + CO_{HS}}{2} + CO_{simmer}
\]

The averaging of the two high power phases (cold start, CS, and hot start, HS) is done to account for the fact that a stove may sometimes be used before cooling completely. A stove with high thermal mass may have poor emissions during cold start testing but will retain that heat and may improve its performance during hot start testing.

- total PM emissions

Total emissions benchmarks are to be calculated from the following equation

\[
\frac{PM_{CS} + PM_{HS}}{2} + PM_{simmer}
\]
The averaging of the two high power phases (cold start and hot start) is done to account for the fact that a stove may sometimes be used before cooling completely. A stove with high thermal mass may have poor emissions during cold start testing but will retain that heat and may improve its performance during hot start testing.

- fuel consumption

Fuel consumption can be calculated from the following equation

\[
\text{Fuel consumption} = \frac{\text{Fuel}_{CS} + \text{Fuel}_{HS}}{2} + \text{Fuel}_{Simmer}
\]

The averaging of the two high power phases is done to account for the fact that a stove may require a different amount of fuel to complete a task depending on the temperature of the stove.

- turndown ratio

The turndown ratio is a measure of how the energy of a stove can be controlled. The turndown ratio can be found from taking the ratio of fuel consumption rate of the low power phase over the average fuel consumption rate of the high power phases.

\[
\text{Turndown ratio} = \frac{\text{Fuel}_{CS}}{\text{Time}_{CS} \times \text{Time}_{HS}} \times \frac{\text{Fuel}_{Simmer}}{2} \times \frac{\text{Time}_{Simmer}}{\text{Fuel}_{Simmer}}
\]

- thermal efficiency

The thermal efficiency of a biomass cook stove indicates how well that stove can transfer the energy contained in the fuel into the cooking pot. The thermal efficiency is only calculated for the high power phases in this protocol. The low power thermal efficiency is not calculated due to the variation in vaporization which will be seen between locations and the uncertainty in calculating the energy required to induce phase change.

\[
\text{Thermal Efficiency}_{CS} + \text{Thermal Efficiency}_{HS}
\]

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

Further explanation of each performance guidelines and equations used for calculation can be found in Appendix B. The concentration of pollutants in a room may be a better predictor of health effects than total mass emissions. Although the WBT does not specify room concentration emissions levels the Engines and Energy Conversions Laboratory and Philips have developed suggested maximum concentration levels. For further information and calculations methods see Improved Stove Testing Criteria.
Before starting the tests...

The following four 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 perform the test. 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 temperature of water readily available will change with location and season. For this reason a range of acceptable water temperatures and the resultant mass of water to be used has been supplied. The mass of water to be used should be determined from Table 1.

4) 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.

Equipment used for the Water Boiling Test:

- Scale with a capacity of at least 6 kg and accuracy of ± 1g
- Thermocouple probe
- Pot insulation
- Charcoal container
- Wood moisture meter capable of measuring 6-40% humidity (optional)
- Cooking pot
- Implements to remove charcoal from stove

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.

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 5.1 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.

e. Weight of container to be used for charcoal.

f. Local boiling point of water.

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).

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

**Phase 1: High Power**

1. Fill pot with required amount of water from Table 1 based on initial water temperatures. The amount of water should be measured by mass rather than by volume with an accuracy ±2g.

2. Add insulation to pot and insert thermocouple through insulation so that the thermocouple is approximately 5cm from the bottom of the pot.

3. Begin measurement and/or collection of particulates.

4. Begin data acquisition (temperature, carbon monoxide, time, and time at start of test).

5. Start stove using fire starter according to manufactures recommendations.
a. If no recommendations are provided it is recommended to use wood shims, or other thin wood pieces of repeatable dimensions, for natural draft stoves and kerosene for charcoal and coal stoves

6. Fuel is to be feed according to stove manufactures specifications. If fueling information is not provided the stove should be run in such a manner to rapidly raise the water temperature without being wasteful of fuel.

7. When the water in the pot reaches 90°C stop collection of particulates.

8. Stop data acquisition and record time at end of test.

9. Remove all fuel from the stove and extinguish flames. Dislodge loose charcoal from the wood into charcoal weighing container.

10. Weigh all wood remaining from the original bundle.

11. Weigh all charcoal collected from stove in charcoal weighing container.

12. Remove insulation from water surface and weigh cooking pot and water. Discard hot water after weighing.

Summary

⇒ Make sure that you have recorded the time to complete the test, the temperature of the 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 the test is completed when the primary pot reaches 90°C. For more details see Appendix C.

⇒ 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)

Steps 1-5 should be completed as quickly as possible after the completion of the cold start while the stove is hot.

1. Fill pot with required amount of water from Table 1 based on initial water temperatures. The amount of water should be measured by mass rather than volume with an accuracy ±2g.

2. Add insulation to pot and insert thermocouple through insulation so that the thermocouple is approximately 5cm from the bottom of the pot.
3. Begin measurement and/or collection of particulates.

4. Begin data acquisition (temperature, carbon monoxide, time, and time at start of test).

5. Start stove using fire starters according to manufactures recommendations.
   a. If no recommendations are provided it is recommended to use wood shims, or other thin wood pieces of repeatable dimensions, for natural draft stoves and kerosene for charcoal and coal stoves.

6. Fuel is to be fed according to stove manufactures specifications. If fueling information is not provided the stove should be run in such a manner to rapidly raise the water temperature without being wasteful of fuel.

7. When the water in the pot reaches 90°C stop collection of particulates.

8. Stop data acquisition and record time at the end of test.

9. Remove all fuel from the stove and dislodge loose charcoal from the fuel while leaving charcoal in combustion chamber.

10. Weigh all fuel remaining from the original bundle.

11. Remove insulation from water surface and weigh cooking pot and water. Retain hot water for simmer phase.

**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.

Steps 1-10 should be completed as quickly as possible after the completion of the hot start while the stove and water are hot.

1. Begin measurement and/or collection of particulates

2. Begin data acquisition (temperature, carbon monoxide, time, and time at start of test).

3. Return cooking pot to stove without the insulation. Place thermocouple in water in such a way that the tip is approximately 5cm from the bottom of the pot. This may be done in many ways but a support sitting across the top of the pot with a hole drilled through it works well.
4. If needed restart stove. Maintain the fire such that the water is at a temperature above 90°C. Although it is not required to keep the temperature close to 90°C it is advisable.

5. After 45 minutes stop collection of particulates.

6. Stop data acquisition.

7. Remove all fuel from the stove and dislodge loose charcoal from the fuel into charcoal weighing container.

8. Weigh all fuel remaining from the original bundle.

9. Weigh cooking pot and water

10. Weigh all charcoal collected from stove in charcoal weighing container.

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

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

Analysis
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 E.

Notes on the WBT

1. Pots:

Although a specific pot is not specified, the pot used should be reasonable for the volume of water being used. The cooking pot to be used should be constructed of steel or aluminum. The cooking pot should be of a sauce pan style with roughly equal height and diameter dimensions.

2. Pot Insulation/Lid

The use of insulation dramatically reduces the amount of water that is lost from the pot during a test. Reducing water lost from the pot minimizes the error in energy related test metrics. All tests are to be completed using insulation in the cooking pot for both high power phases. Insulation is not to be used for the low power phase. The insulation must be 1cm-3cm thick of closed-cell foam capable of handling temperatures of at least 100°C. The foam should also be chosen so that it does not uptake water. The foam is to be cut to a diameter 0.25-2cm smaller then the pot diameter and should sit on the water surface.

3. Water Temperature
The temperature of water which is conveniently available may change with season and test location. It is desirable to keep the amount of energy which is transferred to the cooking pot constant for both the cold and hot start phases and between tests. To keep equal energy between tests the mass of water will change with its temperature. Equations for calculating energy transfer in water can be found in Appendix B and Table 1 can be used to determine the required amount of water for a given starting temperature. The initial temperature of water used must be between 4°C and 30°C.

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4. Fuels

A number of fuel types can be used for the Water Boil Test but softwoods such as pine or Douglas fir constitute the standard fuel. Because the results of the Water Boil Test are dependent upon the fuel type used it is recommended that only tests performed with the same fuel type be directly compared. In addition, fuels with comparable properties such as moisture content, heating values, and dimensions should be used if possible for comparability purposes. The fuel used is to be recorded. If the fire starter is the same material as the bulk fuel being used its mass should be included when calculating total fuel consumption. Otherwise the mass of the fire starter should be recorded separately.

4.1. Moisture Content

The moisture content of a fuel is extremely variable depending on ambient conditions. Unfortunately the moisture content of dimensional wood strongly affects the outcome of the Water Boil Test. For this reason it is recommended that all testing using dimensional wood be carried out at dry moisture contents between 4-10%. If a moisture meter is not to be used the “oven dry method” is an acceptable alternative. Equations required for calculation can be found in Appendix B. Fuel moisture content is to be recorded.

4.2. Lower Heating Value
The lower heating value of a fuel is dependent 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 whose lower heating value closely matches 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.

4.3. Dimensions

The physical dimensions of wood somewhat affect the results of the Water Boil Test. Wood dimensions seem to affect particulate matter although the effects on carbon monoxide emissions seem to be minimal (Insert Parametric Study Reference). For this reason it is recommended that the standard wood dimensions are 1.5 cm square for testing. The physical dimensions of the fuel being used influence the rate of combustion and impact the emissions being released. Although slight variations in dimension are acceptable fuel wood should be cut as close to 1.5cm square as possible. The dimensions of the fuel used are to be recorded.

5. Gaseous Emissions Testing Equipment

In order to measure gaseous emissions from a cook stove it is necessary for complete capture of all emissions. In addition, an emissions analyzer is required to measure the real-time carbon monoxide emissions collected. Requirements necessary for proper testing are given in the following sections.

5.1. Sampling Requirements

For the proper sampling of exhaust gas released from a cook stove all gases must be collected. The combustion process requires fresh air and the flow rate of this air through the stove is governed by the rate of fuel being consumed. Because fuel consumption is variable and dependent upon a number of factors it is necessary to flow a sufficient excess of air through the sampling system in order to capture all emissions while not affecting stove operation. In addition, particulates in the ambient air can artificially raise the particulate count for a given test. Finally, the user must be able to manipulate the stove, pot, and fuel being used during the test. For these reasons it is desirable to perform the Water Boil Test in a semi-enclosed hood. In addition, HEPA filters should treat the incoming air in order to remove background particulate matter. 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. Once stove emissions have been collected in a hood they are to be transferred to a duct whose size is chosen based on flow rate requirements. Thereafter, sampling from the duct occurs in a way that properly samples across the entire duct diameter. For duct sampling and flow rate measurement requirements refer to EPA 40 CFR Part 60 Method 1 and 2d. If HEPA filters cannot be used background PM measurements maybe taken. Background samples should be taken at the beginning and end of each test day and the fact background air was not filtered must be clearly noted on PM data reports if this is the case. The duration of the background measurement should be sufficient to collect a representative sample and to reach the minimum
detection limit of the system. In some cases this may require samples to be taken for 20 minutes or longer.

5.2. Emissions Analyzer

Continuous gas samples throughout the test are to be analyzed for carbon monoxide using a nondispersive infrared spectrometer (NDIR) system or better for at least one test replicate. The remainder tests can be conducted with electrochemical or equivalent equipment. Data acquisition frequency should be sufficient to capture the transient nature of a stove. For NDIR spectrometer requirements and measurement methodology refer to EPA 40 CFR Part 60 Method 10.

6. PM Testing Equipment

Continuous particulate sampling is to be performed throughout the test. In order to obtain reliable measurement of particulate matter, isokinetic sampling is required. In addition, a cyclone that removes particles greater than 10 microns should be installed upstream of the sample filter. All particles 10 microns and smaller are considered to be inhalable. To determine the health implications of particles from biomass cook stoves the entire inhalable fraction should be considered. 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. Replicate tests can be performed using optical methods if at least one test has gravimetric filter and optical systems running concurrently to correlate and calibrate optical and mass measurements.

7. 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.

8. 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. The tester should not attempt to reduce power by further splitting the wood into smaller diameter pieces.

9. 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.

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.

Revisions 4-6 were implemented in 2009 by Morgan Defoor and Nathan Lorenz of envirofit, and Wiecher Kamping of Philips electronics.

1. 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.

2. 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.

3. 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.

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. Different amounts of steam are produced at each degree point below boiling. For this reason, 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. By lowering the final water temperature to 90°C, as compared to “boiling”, a more definitive end point to the test is achieved.
The test duration is no longer dependent on the local boiling point of a location. By using a variable starting water temperature and water mass all tests can transfer equal amounts of energy regardless of the temperature of water available.

6. A layer of foam insulation was introduced to the cold and hot starts to limit the amount of vaporization which occurs. Although testing temperatures have been reduced below the boiling point for most regions of the world some vaporization will still occur.
REFERENCES


Appendix A

Stove Performance Testing

Biomass cook stove testing has been traditionally broken into two broad categories; laboratory and field testing. Although the same test protocol maybe used in each they may result in different results. This is due to the fact that the tests are often conducted with different goals in mind. Laboratory tests are more often conducted for stove development and research. The more controlled environment inherent in the laboratory allows for greater repeatability and accuracy. The laboratory also allows for easier comparison of stoves from different regions of the world. Field tests are more often conducted to determine how the stove is actually used and to determine in field emissions. The large degree of variability in the field makes it difficult to separate the performance of user from that of the stove.

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.

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. Although useful data is gained from both laboratory and field testing the results will vary. It is important to determine what information is of most importance and to choose the appropriate testing environment.

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.

![Graph](image)

**Stoves installed in India's NPIC Program: 1983-1998**

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 2 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 2: Comparison of fuel consumption in Improved and Traditional Chulhas in 3 Indian States

<table>
<thead>
<tr>
<th></th>
<th>Improved chulha</th>
<th>Traditional chulha</th>
<th>Percent savings of improved chulha compared to traditional chulha</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of households</td>
<td>Wood consumption kg/day/stove&lt;sup&gt;a&lt;/sup&gt;</td>
<td>No. of households</td>
</tr>
<tr>
<td>Tamil Nadu</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manachai</td>
<td>14</td>
<td>5.99</td>
<td>8</td>
</tr>
<tr>
<td>Muthupattai</td>
<td>10</td>
<td>7.27</td>
<td>10</td>
</tr>
<tr>
<td>Rajasthan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motuka</td>
<td>11</td>
<td>7.2</td>
<td>12</td>
</tr>
<tr>
<td>West Bengal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Golti</td>
<td>14</td>
<td>9.34</td>
<td>14</td>
</tr>
<tr>
<td>Iswarigacha</td>
<td>15</td>
<td>7.34</td>
<td>13</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From [4]

<sup>a</sup> 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.\(^2\) Because of its sheer

\(^2\) 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].
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.

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 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.

**Chinese Stoves: Efficiency (WBT) and TSP Emissions**

[Graph showing efficiency and TSP emissions for different stoves and fuel types.]

*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 B

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.

Variable Declaration

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
\[ F_{cd} \quad \text{Dry Fuel Consumed} \]
\[ t_c \quad \text{Test Duration} \]
\[ R_b \quad \text{Burning Rate} \]
\[ \eta_{th} \quad \text{Thermal Efficiency} \]
\[ FP_o \quad \text{Overall Firepower} \]
\[ FP_u \quad \text{Useful Firepower} \]
\[ C_c \quad \text{Charcoal Created} \]
\[ CO \quad \text{Mass of Carbon Monoxide Emitted} \]
\[ E_{ins} \quad \text{Maximum Instantaneous Carbon Monoxide Room Exposure (mg/m}^3\text{)} \]
\[ E_{15} \quad \text{Maximum 15 minute Carbon Monoxide Room Exposure (mg/m}^3\text{)} \]
\[ E_{60} \quad \text{Maximum 60 minute Carbon Monoxide Room Exposure (mg/m}^3\text{)} \]
\[ PM \quad \text{Mass of Particulate Matter Emitted} \]

**Nomenclature and Calculations**

\[ t_c \quad \text{Test Duration} \]

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

\[ t_e = t_f - t_i \]

**C_c \quad \text{Charcoal Created}**

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

\[ C_c = C_f - C_i \]

\[ F_{cd} \quad \text{Dry Fuel Consumed} \]
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:

\[ F_{cd} = (F_i - F_f) \cdot \left(1 - \frac{M}{100}\right) - (F_i - F_f) \cdot \left(\frac{M}{100}\right) \cdot \left(\frac{C_p \cdot \left(T_f - T_i\right) + H_v}{LHV_{wood}}\right) - \frac{LHV_{char}}{LHV_{wood}} \cdot C_v \]

Where LHV_{char} and LHV_{wood} are the lower heating values of charcoal and wood respectively.

R_b \hspace{1cm} \text{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.

\[ R_b = \frac{F_{cd}}{t_c} \]

\( \eta_{th} \hspace{1cm} \text{Thermal Efficiency} \)

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:

\[ \eta_{th} = \frac{C_p \cdot m_w \cdot (T_f - T_i) + H_v \cdot (m_{wt} - m_{wt_f})}{(F_i - F_f) \cdot \left(1 - \frac{M}{100}\right) \cdot LHV_{wood} - (F_i - F_f) \cdot \frac{M}{100} \cdot \left(C_p \cdot (T_f - T_i) + H_v\right) - \frac{LHV_{char}}{LHV_{wood}} \cdot C_v} \]

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

FP_o \hspace{1cm} \text{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.

\[ FP_o = \frac{LHV \cdot F_{cd}}{t_c} \]
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.

\[ FP_u = \eta_{ch} \times FP_o \]

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:

\[
\dot{m}_{\text{CO}} = \frac{Q \times CO_{\text{ppm}}}{100} \times \frac{P_{\text{ef}}}{R_{\text{CO}} \times T_{\text{ef}}}
\]

\[
CO = \Delta t \times \sum_{i=0}^{n-1} \dot{m}_{\text{CO, i}}
\]

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

PM  Mass of Particulate Matter Emitted

\[ PM = MR - MR - \bar{m}_{\text{bk}} \times FC \]

Where \(\bar{m}_{\text{bk}}\) is the average background particulate collection rate.

Oven-Dry Method

The oven-dry method takes a random sample of fuel at ambient moisture content and dries the fuel until no moisture remains. The moisture content can be calculated from the mass difference between pre and post measurements. It is important when using the oven-dry method to control the temperature to ensure pyrolysis temperatures are not reached.

\[ %MC = \frac{\text{Mass}_{\text{original}} - \text{Mass}_{\text{dry}}}{\text{Mass}_{\text{original}}} \times 100 \]
Appendix C

Test Variations

Stove Type

- Gasifier/Charcoal/Coal

Stoves which are more traditionally batch fed, such as gasifier, charcoal, and coal stoves, have difficulty being run using the standard test protocol. During the hot start phase when more kerosene is added, the fire starter most common with batch fed stoves, the fuel vaporizes and can explode when lit. For these stoves the test protocol should skip the hot start phase entirely. At the end of the cold start phase the pot of water should be removed, weighed, and replaced and then the test proceeds directly to the simmer phase. Because fuel is not removed between the two phases a combination of CO and CO2 measurements must be taken to calculate fuel use and all quantities which steam from fuel use. By measuring real time carbon emissions a fuel consumption rate can be found if the percent carbon in the fuel is known.

- 2 Pot Stove

Two pot stoves can follow nearly the same procedure as a single pot stove. The second pot should be filled with the same water temperature and mass as the primary pot. Test phases are concluded when the primary pot reaches the 90°C. When calculating thermal efficiency both pots should be considered. Efficiency of each pot is to be calculated individually with the total efficiency the sum of each pot. Unless stipulated differently by the manufacturer the pot closest to the heat source is to be considered the primary pot. If one pot is not clearly the primary pot the tester is to make a decision with the choice clearly indicated in the test data.

Fuel Type

- Wood Pellets
- Animal Dung
- Agricultural Waste

Stove Firepower

The amount of energy which is reasonable to ask a stove to transfer will depends on its size. An industrial stove will nearly never boil only 5kg of water. The test needs to be sized to the stove being tested. In addition to the standard test protocol two size ranges can be tested following the same procedure. It is up to the tester or stove manufacturer to determine which range is most applicable to the particular stove model being tested. The standard test protocol is the “medium” firepower stove.
### Low Firepower

<table>
<thead>
<tr>
<th>Initial Water Temperature (°C)</th>
<th>Mass of Water Required (kg)</th>
<th>Initial Water Temperature (°C)</th>
<th>Mass of Water Required (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.18</td>
<td>18</td>
<td>2.60</td>
</tr>
<tr>
<td>5</td>
<td>2.21</td>
<td>19</td>
<td>2.64</td>
</tr>
<tr>
<td>6</td>
<td>2.23</td>
<td>20</td>
<td>2.68</td>
</tr>
<tr>
<td>7</td>
<td>2.26</td>
<td>21</td>
<td>2.72</td>
</tr>
<tr>
<td>8</td>
<td>2.29</td>
<td>22</td>
<td>2.76</td>
</tr>
<tr>
<td>9</td>
<td>2.32</td>
<td>23</td>
<td>2.80</td>
</tr>
<tr>
<td>10</td>
<td>2.34</td>
<td>24</td>
<td>2.84</td>
</tr>
<tr>
<td>11</td>
<td>2.37</td>
<td>25</td>
<td>2.89</td>
</tr>
<tr>
<td>12</td>
<td>2.40</td>
<td>26</td>
<td>2.93</td>
</tr>
<tr>
<td>13</td>
<td>2.44</td>
<td>27</td>
<td>2.98</td>
</tr>
<tr>
<td>14</td>
<td>2.47</td>
<td>28</td>
<td>3.02</td>
</tr>
<tr>
<td>15</td>
<td>2.50</td>
<td>29</td>
<td>3.07</td>
</tr>
<tr>
<td>16</td>
<td>2.53</td>
<td>30</td>
<td>3.13</td>
</tr>
<tr>
<td>17</td>
<td>2.57</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The relationship between initial water temperature and mass of water required can be modeled by the quadratic equation:

\[ y = 0.0005x^2 + 0.019x + 2.101 \]

with an R² value of 0.9999.

---

### High Firepower

The mass of water required for high firepower is a linear function of the initial water temperature, as shown in the graph.

Graph equation:

\[ y = 0.0005x + 2.101 \]

R² value: 0.9999
<table>
<thead>
<tr>
<th>Initial Water Temperature (°C)</th>
<th>Mass of Water Required (kg)</th>
<th>Initial Water Temperature (°C)</th>
<th>Mass of Water Required (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>8.72</td>
<td>18</td>
<td>10.42</td>
</tr>
<tr>
<td>5</td>
<td>8.82</td>
<td>19</td>
<td>10.56</td>
</tr>
<tr>
<td>6</td>
<td>8.93</td>
<td>20</td>
<td>10.71</td>
</tr>
<tr>
<td>7</td>
<td>9.04</td>
<td>21</td>
<td>10.87</td>
</tr>
<tr>
<td>8</td>
<td>9.15</td>
<td>22</td>
<td>11.03</td>
</tr>
<tr>
<td>9</td>
<td>9.26</td>
<td>23</td>
<td>11.19</td>
</tr>
<tr>
<td>10</td>
<td>9.38</td>
<td>24</td>
<td>11.36</td>
</tr>
<tr>
<td>11</td>
<td>9.49</td>
<td>25</td>
<td>11.54</td>
</tr>
<tr>
<td>12</td>
<td>9.62</td>
<td>26</td>
<td>11.72</td>
</tr>
<tr>
<td>13</td>
<td>9.74</td>
<td>27</td>
<td>11.91</td>
</tr>
<tr>
<td>14</td>
<td>9.87</td>
<td>28</td>
<td>12.10</td>
</tr>
<tr>
<td>15</td>
<td>10.00</td>
<td>29</td>
<td>12.30</td>
</tr>
<tr>
<td>16</td>
<td>10.14</td>
<td>30</td>
<td>12.50</td>
</tr>
<tr>
<td>17</td>
<td>10.27</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ y = 0.002x^2 + 0.0761x + 8.4044 \]

\[ R^2 = 0.9999 \]
Appendix D

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 E

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 3 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 3: Results of three high-power cold start Water Boiling Tests on two different stoves

<table>
<thead>
<tr>
<th>Units</th>
<th>Stove-1</th>
<th>Stove-2</th>
<th>% difference between Stove-1 and Stove-2</th>
<th>T-test</th>
<th>Significant with 95% confidence?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood consumed</td>
<td>g</td>
<td>837</td>
<td>34 4%</td>
<td>-44%</td>
<td>7.55 YES</td>
</tr>
<tr>
<td>Time to boil 5 liters of water</td>
<td>min</td>
<td>36</td>
<td>3 7%</td>
<td>-44%</td>
<td>6.89 YES</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>g/min</td>
<td>0.19</td>
<td>0.01 4%</td>
<td>49%</td>
<td>-3.30 YES</td>
</tr>
<tr>
<td>Rate of wood consumption</td>
<td>g/min</td>
<td>23</td>
<td>1 3%</td>
<td>1%</td>
<td>-0.04 NO</td>
</tr>
<tr>
<td>Specific fuel consumption</td>
<td>g/liter</td>
<td>155</td>
<td>8 5%</td>
<td>-41%</td>
<td>6.77 YES</td>
</tr>
<tr>
<td>Firepower</td>
<td>kW</td>
<td>6.6</td>
<td>0.2 3%</td>
<td>1%</td>
<td>-0.04 NO</td>
</tr>
</tbody>
</table>

SD = Standard deviation; CoV = Coefficient of variation (CoV = SD ÷ mean)

Table 4, 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 cannot 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 4, 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

<table>
<thead>
<tr>
<th>Specific Consumption units</th>
<th>Stove-1</th>
<th>Stove-2</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>SD</td>
<td>CoV</td>
<td>Mean</td>
</tr>
<tr>
<td>Lower variability g/liter</td>
<td>134</td>
<td>8</td>
<td>6%</td>
</tr>
<tr>
<td>Higher variability g/liter</td>
<td>134</td>
<td>12</td>
<td>9%</td>
</tr>
</tbody>
</table>