The Water Boiling Test (WBT)

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VERC Training
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With help from Nordica McCarty
The Water Boiling Test (WBT)

- Standardized, reproducible lab test
- Boil and simmer water
- Measure the boil time, fuel use, efficiency, and optionally emissions
- Trained tester carefully tends the fire
- High and low power test phases
- Cold stove and hot stove test phases
- Allows for multiple pots on one stove
Stove Testing Continuum

- **WBT (Lab)**
  - Increasing cost
  - Increasing sample size and variability
  - Increasing measurement of in-home use
  - Increasing relation to WHO air quality guidelines

- **CCT**
  - Increasing control of variables
  - Increasing isolation of stove performance
  - Increasing quantification of emissions
  - Increasing intervention of testers

- **KPT (Field)**

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**Legend**
- **WBT** (Whole Body Thermal)
- **CCT** (Continuous Combustion Test)
- **KPT** (Kindling Proximate Test)
Purpose of WBT

- Effective design tool to evaluate design changes of a stove

- “…a simple method with which stoves made in different places and for different cooking applications can be compared through a standardized and replicable test.”
Advantages of the WBT

- Reproducible, standardized
- Stoves from around the world can be compared
- A target performance level (benchmark) can be set based on comparisons
- Effects stove design changes can be observed quite clearly and relatively quickly
Disadvantages of the WBT

- Not always reproducible
  When the tester or fuel changes

- Not representative of field use
  Only one simulated cooking task

- Hard to do for some stoves
  Batch-loading stoves: TLUD’s, charcoal
# WBT Procedure

<table>
<thead>
<tr>
<th>Phase</th>
<th>COLD START</th>
<th>HOT START</th>
<th>SIMMER</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Task</strong></td>
<td>Bring to Boil 5L in first pot</td>
<td>Bring to Boil fresh 5L in first pot</td>
<td>Simmer remaining 5L for 45 minutes</td>
</tr>
<tr>
<td><strong>Record</strong></td>
<td>Time Fuel Water Charcoal</td>
<td>Time Fuel Water</td>
<td>Time Fuel Water Charcoal</td>
</tr>
<tr>
<td></td>
<td><em>Assume Same Charcoal as Cold Start</em></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
WBT Procedure

- **Water Temperature**
  - COLD START
  - HOT START
  - Fresh Water

- **Time**
  - 45 min. SIMMER
  - $T_{\text{boil}} - 6$ degC

- **Symbols**
  - $T_{\text{boil}}$
  - $T_{\text{room}}$
WBT – Preparing for the Test

First do a practice test to:

- Get familiar with the stove
- Determine if the stove should be tested with 2.5 or 5 liters
- Determine how much fuel is required
- Determine boiling temperature of water
WBT – Preparing for the Test

Gather Supplies

1. Scale - 6000g range, 1g resolution
2. Temperature sensor – waterproof
3. Fixture for suspending temperature sensor
4. Wood moisture meter or oven for fuel MC
WBT – Preparing for the Test
Gather Supplies

5. Timer or watch
6. Pot – standard or dedicated, no lid
7. Heat resistant pad for scale
8. Charcoal scooper/tongs
9. Char tray
10. Heat resistant gloves
11. Water – room temp,
    - at least 10 liters
12. Fuel – air dried, uniform
    - 2 bundles ~ 2kg each
WBT – Preparing for the Test

Fill out page 1 of the Data and Calculation Sheet

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**SHELL FOUNDATION HEF PROJECT WATER BOILING TEST**

**DATA AND CALCULATION FORM** (the form can be used with stoves that cook between one and four pots)

Shaded cells require user input; unshaded cells automatically display outputs

**Qualitative data**

- **Name(s) of Tester(s):** Theomias
- **Test Number:** 1
- **Date:** February 2020
- **Stove type/model:** Thoro Stove Basic
- **Location:** Regional Testing Center of Heffa
- **Type of fuel:** Average Softwood (Coastal)
- **Wind conditions:** No wind

**Initial Test Conditions**

<table>
<thead>
<tr>
<th>Data</th>
<th>value</th>
<th>units</th>
<th>label</th>
<th>Data</th>
<th>value</th>
<th>units</th>
<th>label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temp</td>
<td>27.0</td>
<td>°C</td>
<td></td>
<td>Dry weight of Pot #1 (grams)</td>
<td>880</td>
<td>g</td>
<td>P1</td>
</tr>
<tr>
<td>Average dimensions of fuel</td>
<td>35.50</td>
<td>cm x cm x cm</td>
<td></td>
<td>Dry weight of Pot #2 (grams)</td>
<td>870</td>
<td>g</td>
<td>P2</td>
</tr>
<tr>
<td>Gross caloric value (dry fuel)</td>
<td>20.817</td>
<td>kcal/lit</td>
<td>HHV</td>
<td>Dry weight of Pot #3 (grams)</td>
<td>880</td>
<td>g</td>
<td>P3</td>
</tr>
<tr>
<td>Net caloric value (dry fuel)</td>
<td>19.497</td>
<td>kcal/lit</td>
<td>HHV</td>
<td>Dry weight of Pot #4 (grams)</td>
<td>800</td>
<td>g</td>
<td>P4</td>
</tr>
<tr>
<td>Wood moisture content (%)</td>
<td>15%</td>
<td>%</td>
<td></td>
<td>Weight of container for char (grams)</td>
<td>200</td>
<td>g</td>
<td></td>
</tr>
<tr>
<td>Effective calorific value</td>
<td>18.187</td>
<td>kcal/lit</td>
<td></td>
<td>Local boiling point</td>
<td>100.0</td>
<td>°C</td>
<td>T_e</td>
</tr>
</tbody>
</table>

**Description of stove and other comments:**

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**BASIC TEST DATA**
WBT – Preparing for the Test

Fill out page 1 of the Data and Calculation Sheet

Determining Moisture Content

Method 1:

- Use hand-held moisture to measure the $MC_{dry}$
- Then convert to $MC_{wet}$ using the Fuel Moisture Sheet of the Excel WBT spreadsheet

Method 2:

Oven drying method
WBT – Conducting the Test

Phase 1: High Power Cold Start

- Set the pots on the stove with 5000g of water with the temp sensor suspended in the water of Pot 1.

- Record:
  - Starting weight of pots with water
  - Starting water temperatures
  - Initial mass of the bundle of fuel

- Light the fire - record start time

- Tend fire and bring water to a boil
WBT – Conducting the Test

Phase 1: High Power Cold Start

- When Pot 1 boils record:
  - Time
  - Temperature of all pots
  - Pot plus water weights
  - Fuel remaining

- Break char off tips of burned sticks
- Put char on tray and record weight of char plus tray
WBT – Conducting the Test

Phase 2: High Power Hot Start

- Refill the pots with cool water and repeat the boil procedure starting with a hot stove.
- Use a new bundle of wood.
- This time, when Pot 1 boils, keep the char in the combustion chamber. DO NOT WEIGH THE CHAR.
- Weight the pots and place them back on the stove.
- Weigh the wood, place it back in the combustion chamber, then re-light it.
WBT – Conducting the Test
Phase 3: Low Power Simmer

- Record the start time once the fire is lit
- Transfer over the fuel weight, pot and water weight, and water temp from the results column at the end of the hot start
- Tend the fire to keep the water temp of Pot 1 at 3 degrees C below boiling for 45 min
- After 45 min of simmer record:
  - Final water temperature
  - Weight of Pot 1 plus water
  - Final weight of fuel and char remaining
WBT Results

Once you have tested the stove 3 times, copy the data from your data sheet to the Excel spreadsheet.

The performance metrics are listed on the Results sheet for each of the three phases: The important ones are:

1. Time to Boil (temp corrected)
2. Thermal Efficiency
3. Specific Fuel Consumption (temp corrected)
4. Firepower
5. Turndown Ratio
WBT Results

Temperature Corrected Time to Boil (min)

\[
= \frac{75}{T_{boil} - T_{init}} \times (t_{boil} - t_{start})
\]

Normalized to a standard change in temperature of 75 C
WBT Results

Thermal Efficiency (%)

\[
\text{Thermal Efficiency} = \left( \frac{\text{energy to heat water} + \text{energy to evap water}}{\text{energy released by fuel}} \right) \times 100
\]

High efficiency ≠ low fuel consumption

because high power stoves evaporate lots of water and also use lots of fuel
Temperature Corrected Specific Fuel Consumption (g/L)

\[
\text{Eq. dry wood consumed} = \frac{\text{dry wood mass}}{T_{\text{boil}} - T_{\text{init}}} * \frac{\text{equivalemt dry wood consumed (g)}}{\text{liters of water remaining (L)}}
\]

Best indicator of fuel consumption
WBT Results

Average Firepower (W)

\[
\text{Average Firepower (W)} = \frac{\text{total energy released by fuel during the test period (Joules)}}{\text{length of test period (seconds)}}
\]
WBT Results

Turndown Ratio

\[
\text{average boil firepower (W)} = \frac{\text{average simmer firepower (W)}}{\text{average simmer firepower (W)}}
\]

Indicates a stove’s ability to adjust the firepower to match low power and high power cooking tasks.
WBT Measuring Emissions
PEMS

- Portable Emissions Measurement System collects and measures real-time emissions

- This data is processed using the PEMS spreadsheet to provide WBT results in the form of:
  - Total Emissions (grams)
  - Emission Factors (grams emission per kg fuel burned)
  - Pollutant/CO₂ ratios
  - Specific Emissions (grams of emissions per liter of water cooked)
  - Emissions to Complete the WBT (grams) - used for benchmarking
### Total Emissions

<table>
<thead>
<tr>
<th></th>
<th>COLD START</th>
<th>SIMMER</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO</strong></td>
<td>16.52</td>
<td>27.75</td>
</tr>
<tr>
<td><strong>CO2</strong></td>
<td>293</td>
<td>449</td>
</tr>
<tr>
<td><strong>appx PM</strong></td>
<td>2220</td>
<td>1172</td>
</tr>
</tbody>
</table>

### Specific Emissions (Corrected for starting temp, moisture, and char and water remaining)

<table>
<thead>
<tr>
<th></th>
<th>COLD START</th>
<th>SIMMER</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO</strong></td>
<td>4.0</td>
<td>25.7</td>
</tr>
<tr>
<td><strong>CO2</strong></td>
<td>71.0</td>
<td>415.9</td>
</tr>
<tr>
<td><strong>appx PM</strong></td>
<td>537.5</td>
<td>1084.4</td>
</tr>
</tbody>
</table>

### Other Emission Measures

<table>
<thead>
<tr>
<th></th>
<th>COLD START</th>
<th>SIMMER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood (g) based on Carbon</td>
<td>174</td>
<td>269</td>
</tr>
<tr>
<td>CO/CO2 Ratio (molar)</td>
<td>8.8%</td>
<td>9.7%</td>
</tr>
<tr>
<td>EF-CO (g/kg) based on Carbon</td>
<td>94.85</td>
<td>103.21</td>
</tr>
<tr>
<td>EF-CO2 (g/kg) based on Carbon</td>
<td>1684</td>
<td>1671</td>
</tr>
<tr>
<td>EF-PM (g/kg) based on Carbon</td>
<td>12.75</td>
<td>4.36</td>
</tr>
</tbody>
</table>

### Standard Performance Measures

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CO to Cook 5L (20)</td>
<td>84.2</td>
</tr>
<tr>
<td>PM to Cook 5L (1500)</td>
<td>5398.6</td>
</tr>
<tr>
<td>CO2 to Cook 5L</td>
<td>1394.7</td>
</tr>
</tbody>
</table>
WBT Sample Size

- At least three full tests per stove design are recommended
- Then do more tests if necessary to achieve the desired statistical significance measured by the COV (Coefficient of Variation)

\[
COV = \frac{\text{standard deviation}}{\text{average value}} \times 100 \quad (\%)
\]

- COV is a measure of how much your results vary
- COV indicates how good you are at getting repeatable results
- For stove testing
  - COV = 5% is very good
  - COV = 10% or 25% is also acceptable
Do more tests to lower the COV

Sample size = 3

Sample size = 4

After doing a 4th test, the variation decreased for the cold start and hot start but not for the simmer
Regional Water Boiling Test (RWBT)

- Same control of variables as the WBT
  (same repeatability as WBT)
- Change the cooking task to be more realistic
  - Local pot (and lid)
  - Local fuel (as long as it doesn’t increase variability)
  - Simulate local cooking tasks
Stove Testing Continuum

WBT

Increasing cost
Increasing sample size and variability
Increasing measurement of in-home use
Increasing relation to WHO air quality guidelines

Lab

CCT

Increasing control of variables
Increasing isolation of stove performance
Increasing quantification of emissions
Increasing intervention of testers

Field

KPT

Increasing cost
Increasing sample size and variability
Increasing measurement of in-home use
Increasing relation to WHO air quality guidelines
Regional Water Boiling Test (RWBT) Advantages

- A lab test that is more representative of field results
  - better approximation of actual cooking

- Same repeatability as the WBT

- Prepares stoves for the CCT better
Regional Water Boiling Test (RWBT) Disadvantages

- Not internationally comparable

- Could be abused as a substitute for field data
Regional Water Boiling Test (RWBT) Example: RWBT for West Africa

Difference from WBT protocol: RWBT uses a pot has lid because cooks in West Africa usually use a lid to cook rice or beans.

During the WBT, simmering without a lid requires 1000 W firepower due to heat loss by evaporation

During the RWBT, simmering with a lid requires 100 W firepower by blocking evaporation

Excess firepower = wasted fuel. RWBT shows us which stoves can save fuel at low power. WBT does not test stove at low power.

The WBT does not evaluate the stove performance below 1000 W, so the RWBT is a more appropriate test for that cooking task.
Documentation

➢ www.aprovecho.org/lab/pubs/testing

Download testing protocols