Reporting Domestic Stove Performance
Towards a Shared Vocabulary:
Definitions and Metrics

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Building a lexicon of agreed terminology and definitions for testing stoves

There is a need for well-defined metrics, terms and methods for testing and certification of domestic cooking stoves. These are required in order to accurately discuss and report thermal efficiency, gas and particulate emissions, fuel consumption and possibly other criteria.

Stakeholders of Improved Cookstoves

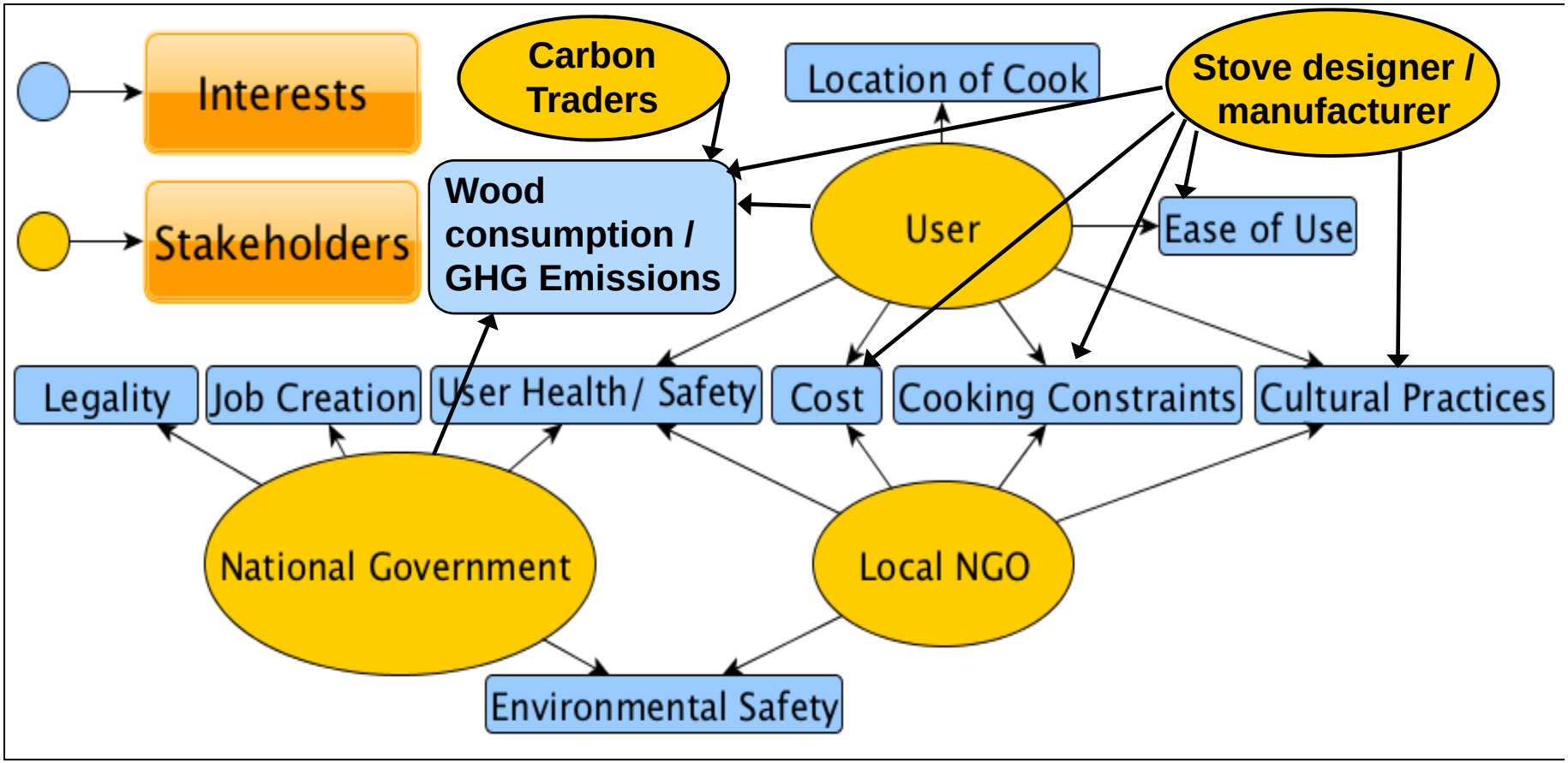

Figure credit: John Abelt, Caroline Bartholomew, Thomas Curley, Katelyn Ditzler, Dan Giannetto, Elizabeth Holohan, Chris Voltz, **January 11th, 2013 The University of Virginia, Project Proposal: STS 2500 / EVSC 1050**

Industry-wide assessment methods

- Who is going to use these product assessments?
- What metrics are most suited to these purposes and stakeholders?
- Who is defining these metrics and terms?
- Which terms already have standard definitions?
- What review process is in place that will update these metrics and refine the definitions?

Basic Metrics

fuels

combustion

emissions

safety

Basic Terms

cooking power

energy

energy efficiency

emission factor

heat gain

fuel consumption

fuel efficiency

heat transfer efficiency

More complex metrics

diverse cooking tasks

multiple fuels

affordability

traditions

stove acceptance

More complex terms

density of heat flow

heat flow rate cooking test

heat flux

turn down ratio

Towards a Common Terminology

Boil – To heat a container of (usually) water raising the temperature to the point at which evaporation begins.

Boiling – a condition where ware heated in a cooking vessel has additional heat supplied so as to create an overturning circulation of that water.

The timing of the boiling point is a problem unless continuous recording is part of test method. The change of boiling point with altitude a minor complicating factor. Pot lids don't change the indicated boiling point.

Boil, Rolling – variously defined; subject to opinion of the observer; synonyms: hard boil; full boil; vigorous boil.

Towards a Common Terminology

3-Star Rating system: A system used by the World Bank's Clean Stove Initiatives for classifying product performance into one of three categories (tiers) according to a set of performance targets. To qualify on a performance tier, the performance ratings for CO, PM emissions and overall thermal efficiency must each meet or exceed the respective requirements for that tier. Emissions are rated per MegaJoule of heat that is accumulated in the pot or pots. The thermal efficiency is the total heat accumulated divided by the energy available in the fuel consumed, **As Received**, per burn cycle expressed as a per cent.

Towards a Common Terminology

As Received (H_{AR}): The specific heating value of the **Fuel Consumed** expressed in unit [MJ/kg]. This specific heating value considers the Higher Heating Value (HHV) of dry fuel obtained by bomb calorimeter testing, a deduction for the combustion of fuel hydrogen to give the Lower Heating Value (LHV) and a further deduction to consider the fuel moisture content. A synonym is **Effective Heating Value (EHV).**

HHV of dry fuel by direct measurement using a bomb calorimeter [MJ/kg]

LHV of dry fuel = **HHV**(Dry) - 25.911 * 9$\boldsymbol{h}$ [MJ/kg]

$\mathbf{H_{AR}}$ of fuel = **HHV**(Dry) - 25.911 * ($\boldsymbol{w}$ + 9$\boldsymbol{h}$) [MJ/kg]

where $\boldsymbol{h}$ = the Hydrogen mass fraction of the dry fuel expressed as a percentage

$\boldsymbol{w}$ = the water mass fraction of the fuel (WWB) **As Received** expressed as a percentage

This formula, converted to other units [BTU/lb], [kCal/kg], is in common use, i.e. by the US-EPA and China.

Towards a Common Terminology

Baseline Emission Factor: When comparison is being made between a candidate technology and a product stove already in common use, the qualifying performance improvement may be expressed relative to the 'baseline product' rather than in absolute form.

Towards a Common Terminology

Biomass Fuels are those including but not limited to: wood, chopped wood products, processed wood products, crop residues, crop processing residues, wood pellets, biomass pellets, charcoal, torrefied biomass products, sawdust, leaves and grasses.

Burn Cycle: The combustion of fuel from ignition to extinction at any and all power levels required to perform a specified cooking cycle. The fuel load is normally adjusted to be at least adequate for the completion of the cycle. The product manufacturer may recommend a standard ignition or extinction method or methods.

Towards a Common Terminology

Compliant products are defined as those products that are capable of delivering adequate heat into one or more cooking vessels without exceeding the **emission factor** or **fuel consumption** thresholds necessary to achieve at least a 1-Star rating. Cooking stoves must deliver the heat in a controllable manner as required by the selected **Technical Test**.

Cooking Cycle: The cycle that uses the heat available from a **Burn Cycle** for the preparation of food or the heating of water. The whole **Cooking Cycle** is normally contained within the **Burn Cycle** though in special cases retained heat stoves might continue cooking after the fire has been extinguished. The product manufacturer may recommend a cooking power adjustment method or methods, for example exposing or shielding the bottom of a pot.

Towards a Common Terminology

Cooking Power Maximum (P_{MAX}): The measured maximum rate of heat gained by the pot during a high power section of the **Technical Test**, expressed in Joules per second or Watts. It is calculated as the differential maximum **Net Heat Gained** and includes the heat gained by the pot material.

Cooking Power Minimum (P_{MIN}): The measured minimum rate of heat gained by the pot during a low power section of the **Technical Test**, expressed in Joules per second or Watts. It is calculated as the differential minimum **Net Heat Gained** and includes the heat gained by the pot material.

Towards a Common Terminology

Cooking Stove: Any biomass fuelled cooking appliance that delivers heat at an acceptable rate into one or more cooking vessels, having the facility such that an operator can adjust the cooking power to high and low enough rates so as to properly cook the foods typically prepared in the geographical area of interest.

Cooking Test #: Any particular defined cooking cycle of food preparation, water heating or other home industry task that is typical of behaviour in the geographical area of interest each of which is given a different number. Common tasks are characterised, numbered and replicated in the laboratory using typical pots, fuels and behaviours and the performance measured. A **Technical Test** is a combination of **Cooking Tests**.

Towards a Common Terminology

Density of Heat Flow (HFR): Used as a synonym for **Heat Flow Rate** or **Heat Flux** expressed in units [J/cm^2/sec].

Effective Heating Value (EHV): Specific heat energy available from fuel containing moisture; synonym for **As Received (H_{AR})**, unit [MJ/kg].

Emission Factor (EF): The **mass of CO** (x) [g] or **mass of $PM_{2.5}$** (y) [mg] emitted during a burn cycle are determined and divided by the **net heat gained H_{NET}**, yielding emission factors **EF_{CO}** and **$EF_{PM2.5}$** respectively in units mass of emissions per net MegaJoule:

EF_{CO}	= x grams of CO/H_{NET}	[g/MJ]
$EF_{PM2.5}$	= y milligrams of $PM_{2.5}$/H_{NET}	[mg/MJ]

Towards a Common Terminology

Energy Consumed (H_F): The heat energy available [MJ] in the **Fuel Consumed**.

$$H_F = H_{AR} * F_C \text{ [MJ]}$$

where H_{AR} = the specific heating value of the fuel **As Received** and

F_C = the mass of **Fuel Consumed**

Fuel Consumed (F_C): The fuel consumption of a biomass burning stove is defined as the mass [kilograms] of new fuel drawn from a supply that is sourced outside the cooking system needed to conduct any one of a series of identical replications of a burn cycle, save the first.

Towards a Common Terminology

Fuel Consumption – The amount of new fuel required to initiate and complete a task within a sequence of repetitive uses. Residue of char or partially pyrolysed wood is a significant element of the calculation – is it discarded, or is it used in next fire-making cycle?

For calculating GHG emissions, the use of residual char for combustion in a secondary device or any non-combustion use is an important factor for some programmes.

Towards a Common Terminology

Fuel Remaining: Fuel which is unburned, partially or almost completely burn remaining after a burn cycle is complete, and which can be used in the same stove during the next replication of the cycle, is considered to be unburned fuel and is deducted from the amount of **Fuel Consumed**. If the properties of the fuel remaining after a test (to be re-used in the next fire) are substantially the same, there is no need to determine for the energy contained in such fuel. It is simply put into the subsequent fire. If local practice is to discard all **Fuel Remaining**, this behaviour may be copied if no behaviour change is expected in this regard.

Towards a Common Terminology

Geographic Community of Interest: A region, however defined, which is identified as a stove improvement area in which marketing and other activities are initiated. The cooking habits of the communities in the region are studied so that a laboratory test can be created which will predict whether and to what extent a candidate stove is an improvement over current products. The test will be reflective of an amalgam of local practices thus the evaluations vary from one place to another. Variations include the fuels, stoves, pots, foods and meal preparation methods. There may be several evaluation methods required for one area when multiple or specialised cooking appliances are in common use.

Towards a Common Terminology

Heat Available in the Fuel (H_F): The total heat available from the perfect combustion of the **Fuel Consumed** calculated from the heating value per unit mass **As Received** (AR). H_F is expressed in unit [MJ].

Heat Flow Rate (HFR): The rate at which heat enters a cooking vessel per unit area of heated surface, normally taken to be the area of the bottom of the vessel. It is a measure of cooking power per unit area expressed in units [J/s/cm^2] or [W/cm^2]. The measurement may be made for any diameter of pot used during a test cycle but is usually reported for the largest diameter. The diameter should be reported together with the **HFR** value, or indicated by clear implication in the body of the report. Sunken pots and skirted pots will be treated differently, with the heated surface area calculated appropriately.

This is also called the **Heat Flux** or the **Density of Heat Flow**, depending on which language is used. For example 热流密度 and Плотность теплового потока both mean the latter and are in common use. The ultimate meaning is the same: Joules per second per square meter [J/s/m2]. Using CGS it can be written [Watts/cm2].

Towards a Common Terminology

Heat Flow Rate Cooking Test (HFR Cooking Test): The burn cycle (including power variation and duration) of a **Cooking Test** is conducted without cooking food, but rather heating water in the same pot or pots normally used. It is a type of **WHT**. The heat gained by these pots is determined, swapping the pot for another one if the water reaches 70°C. The **HFR Cooking Tests** are conducted for each of the selected **Cooking Tests** that make up the **Technical Test** (which are always HFR tests). The **Technical Test** result is then validated by comparing it with the sum of the **HFR Cooking Tests**.

Heat Flux (HFR): Heat flow per unit Time per unit Area expressed in units [J/s/cm^2] or [W/cm^2]; used as a synonym for **Heat Flow Rate** and **Density of Heat Flow**.

Towards a Common Terminology

Net Heat Gained (H_{NET}): This variable is the heat retained by a cooking vessel during a burn cycle and is expressed in units of MegaJoules. It includes the heating of the pot and its contents plus the heat of evaporation of water, but excludes other heat flows through the pot, specifically radiative and convective losses from the pot sides and top.

Overall Energy Efficiency (η): Refer to **System Efficiency**

Overall Thermal Efficiency (η): Refer to **System Efficiency**

Towards a Common Terminology

Simmering – A state of equilibrium in which the cooking heat input is adjusted to keep the temperature close to or at boiling, with infrequent bubbles at the surface.

Towards a Common Terminology

$PM_{2.5}$: Fine particulate matter, such that the aerodynamic diameter of the particles is less than 2.5 μm.

Pot-swapping method: Water is heated in a series of pots which are replaced if the water reaches a predetermined temperature selected to avoid evaporation, normally 70°C. The pots and water masses and the change in temperature of both, and considering the Specific Heat of each, are used to calculate the total heat gained during a **Burn Cycle** or **Cooking Cycle**. This is a high precision variant of a **Water Boiling Test** that avoids the measurement complexities related to the evaporation of water. It can be used to precisely determine the **Heat Flow Rate**, the **System Efficiency** and **Cooking Power** at any fire power.

Towards a Common Terminology

Stove Testing Toolbox: This is an approach to testing whereby the methods for making individual measurements and calculation procedures **(Tools)** are agreed and published as validated procedures. Any test that is built up using a series of validated **Tools** from the **Toolbox** is accepted as producing valid results. Depending on the requirements of the customer, a laboratory is free to use any validated **Tool** or **Tool** combination without having to have the combined set of procedures externally reviewed as a separate method. The concept can be extended to cover all performance measurements including safety and social acceptability.

System Efficiency (η): The ratio of the useful heat energy gained by a cooking vessel divided by the energy originally available in the **Fuel Consumed** (as defined in 2.13) expressed as %. Synonyms include O**verall Thermal Efficiency** and **Overall Energy Efficiency**.

Towards a Common Terminology

Technical Test: A water heating test conducted under controlled conditions wherein the power and duration of two or more **Cooking Tests** is duplicated. It is a **Water Heating Test**. The purpose of the **Technical Test** is to reproduce, without cooking and without bringing water to a boil, a burn cycle that is representative of an amalgam of cooking cycles used in the geographic community of interest. A **Technical Test** is created by combining several **Cooking Tests**. A **Technical Test** is a combination, by simple average or weighted for frequency, of the durations and fire power(s) of two **Burn Cycles** within which the cooking takes place. The sum of the emissions and fuel consumption of two **Technical Tests** should be the same as the combined results of the component **HFR Cooking Tests** which, strictly speaking, are **Technical Tests** for a single cooking task.

Thermal Efficiency

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Thermal Efficiency (TE)

$= (M_2 - M_1)*\sigma / [(T_2 - T_1)*(M_{pot}* \theta_{pot} + M_w* \theta_w)]$

where

M_2, M_1 are the final and initial mass of fuel

σ is the lower heating value of the fuel

T_2, T_1 are the final and initial temperatures

M_{pot}, w and θ_{pot}, w are the mass and specific heats of the pot and water respectively.

For the practical purpose of not losing water mass and energy through evaporation, the final temperature should be in the range 60 to 70°C during this type of test.

Towards a Common Terminology

Turn Down Ratio (TDR): During the cooking of foods typical in the community of interest, the **Cooking Power Maximum P_{MAX}** and **Cooking Power Minimum P_{MIN}** are determined. These are the upper and lower limits of cooking power required in the **Geographic Community of Interest** to produce the meals. The ratio between these power levels is defined as the **Turn Down Ratio**. Specialised water heaters are not required to demonstrate any capacity to control the **Cooking Power** and thus do not have a **TDR**.

Towards a Common Terminology

Water Boiling Test (WBT): Any test of a stove or water heater that uses a pot or pots of water heated from an initial to a final temperature (sometimes but not necessarily to the boiling point) as a surrogate for cooking and for determining the quantity of heat delivered by the product to the cooking vessel or cooking surface.

Water Heating Test (WHT) – any test in which the heating of water is used for fundamental performance assessment; allows good precision while virtually eliminating evaporation.

System or thermal efficiency ➔ obtained by heating water from 30°C to 70°C

cooking power and heat flux ➔ rate of heat gain at different firepower levels

quantum of heat gained ➔ used to calculate specific emissions rates

Towards a Common Terminology

Water Heater: Any water heating appliance which can deliver heat at an acceptable rate into one or more water containers. It is distinct from a cooking appliance because it is normally not required to have a controllable rate of heating the container.

Conclusions: Metrics for Measuring the Performance of Domestic Combustion Stoves: Towards a Shared Vocabulary

- A lexicon should be compiled and maintained on an open access platform (a GACC wiki), as an ongoing community based activity.
- The stakeholders in or reasons for a particular metrics should be part of the definition.
- The list should be inclusive of all commonly used terms, rather than exclusive of overlapping or contradictory terms.
- Once definitions of certain terms ad metrics converge, transfer to a permanent agreed lexicon.
- Would the GACC be willing to host this lexicon?

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