Emission Testing for Real People

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This document is a compendium of thoughts based on my own emission testing background and discussions that have taken place on the Stoves list and at ETHOS meetings. I intend it to be an evolving document, so please comment. I really do want this to work for “real people,” so if you can’t understand something, ***let me know***.

1) Purpose

I am writing this document to collect thoughts and stimulate discussions among Stovers and other interested parties, and to lay out some of the issues for non-experts, particularly those working “on the ground” who might have occasion for stove testing. The ultimate goal is a document with a lot of community input on the topic of *emission* testing.

I assume that anyone with a testing lab is already aware of the issues I raise here. I don’t attempt to address any of the more complex source-characterization questions that abound in the academic literature. Many organizations are looking at efficiency and have established procedures for measuring it, so I am not going to address efficiency testing here, although it is a necessary component. I also ignore the very real concerns of safety, utility, and marketability. Of course, those should all be components of a stove assessment.

Why might we be concerned with accurate emission testing? After all, isn’t breathing any amount of smoke too much? Of course, that question could expand into a much longer discussion. My own opinion is that *while we are waiting* for 2-3 billion people to gain access to truly clean household energy, it is a reasonable goal to reduce exposures by a factor of 2, 5 or 10 if that effort can be undertaken rapidly and (relatively) cheaply.

The last statement—open for discussion, of course—sets the stage for the accuracy we want to achieve. Accuracy of 95% is not important; if a measure reduces emissions or exposure by only 5%, it’s not worth pursuing. We ought to be able to see factors of two, so I suggest that 25% accuracy[1] is a figure of merit. I don’t speak much about accuracy of each specific measurement in the following sections, but my consideration of “measurements worth making” is loosely based on the 25%.

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[1] Basically, I’d like two different means (50% and 100%) to be separated by 2-σ measurement uncertainty, meaning that that uncertainty should be about 25%. This value is entirely intuitive, and I admit to its sloppiness.

2) Operating the stove

One natural answer to “How should we operate the stove during testing?” is “Why, just like people do, of course.” But there is quite a wide range of what “people” do; even the fires of one experienced meal-cooker might vary from night to night, depending on fuels, meals, and obedience of children. There should be a determined wood size and loading schedule if one is to compare stoves on an emission basis. Some emission tests have been done by starting with enough wood to carry through the whole fire. I think that is a mistake; a lot of the PM emissions come from the heating of new or “green” wood added during the course of the fire, and overloading leads to high emissions as well, so the loading pattern is really important. Beyond that, what is *more* important is that you do the *same thing* every time if you want to compare stoves. The procedure used for testing emissions should be the same as the one used for efficiency if you are doing both measurements (and you probably should). I suggest some rules of thumb:

a) Develop a set of rules that seems reasonable for what you know about your region. These should include wood size, wood dryness, reloading rules, kindling method, power output (pot size, time to boil, etc) and length of time at each power output.
b) Be reasonable. Mimicking sensible practice is more important than adhering to every detail. For example, if one stove uses wood more slowly, don’t stuff it full of wood just because you had to do that with another one.
c) Write it down. Record your standard test procedure. Keep a log of changes in your procedure. Document a standard set of information (today’s wood size) for every test you do. Record the mistakes as well, as they are often useful in explaining differences between tests. *This* is more important than doing the same thing as everyone else in the world.
d) Communicate! Write, talk, post on what you’re doing, listen carefully to suggestions, and ignore them if they’re not right for your situation. Take the laugh test: ask women who do the cooking if your practice is anything like theirs. Cook on it yourself, and babysit while you’re doing it!

3) Emissions versus exposure

Your project might care far more about concentration than about emission rate. A stove with a chimney can have high emissions, but as long as they’re sent outside and the stove doesn’t leak to the room, room concentrations—and health-damaging exposures—can be kept low. If you’re worried about exposures for health purposes, it is enough to measure indoor pollutant concentration. In that case, you have to make sure that the concentration is evenly distributed throughout the room, which might require some small mixing fans. Or, you could also try to guess which location is most representative of exposures (e.g. cooking station, living area).

In rural areas, where concentrations dissipate after they exit the home, indoor concentrations are most important by far. In peri-urban or urban areas, or in any study interested in stove impacts beyond the user’s health, emissions are also of interest. Other organizations are presently working on the important protocols for measuring indoor exposures. This document will discuss measuring emissions: not *what people are exposed to*, but *what pollutants exit the stove*.

The room concentration does not tell you much about emission rate, because it's also affected by the room's air exchange rate. The same is true of any measurement in the exhaust: it's affected by how much fresh air has been mixed into the stove exhaust. Relating the pollutant measurement to the amount of fuel burned is a more direct way to compare two stoves. Other measures we might like are pollutant per meal cooked or per hour of use. In this case, we have to have some way of relating *measurements in the exhaust gas* to the *quantity of fuel that was burned*. We will talk about these ways later on.

4) What emissions should we measure?

Pretty much everyone agrees that we should measure CO (carbon monoxide) and PM (particulate matter). It's relatively easy to measure and it has some short-term (and maybe long-term) health effects. PM is much less easy to measure, and it has both short-term and long-term health effects.

Argument: Since you can see smoke, you don't have to measure it.
Response: That's true on a first-order basis. You can tell the difference between a stove that is really smoky and one that is not very smoky. However, it is hard to visually sum up all the smoke emitted over the course of a cooked meal. Also, smoke can be harder to see depending on its color, on lighting, and on contrast with background.

Argument: CO and PM are correlated well enough that we don't need to measure both.
Response: This could be true, and it would be useful if that were so. I personally have not seen enough convincing data. This relationship might hold on a "macro" level, but it needs to work for many stoves, fuels, *and operators* in order to be proven reliable. PM and CO are uncorrelated, and sometimes anti-correlated, on a real-time basis. That is shown in my data (see presentation at ETHOS meeting 01/2002) and also reported by Rob Bailis (UC Berkeley), among others.

There are some other emissions of interest. PAH (polyaromatic hydrocarbons) can have some specific health effects. Some reactive gases could contribute to ozone formation. Non-CO_2 greenhouse gases (GHGs) could be of interest if you think you might find a willing donor for your stove project. Most of these are challenging to measure, especially since you have to maintain calibration standards. They are best done by a well-equipped lab. I am writing here for people who want to ensure their stoves are improving, by measuring and reducing a couple of major pollutants. If you reduce the major products of incomplete combustion, it's likely (but not 100% certain) that you will reduce the other nasties as well.

5) The right sample

The combustion of solid fuel is irregular in both space and time. Emissions come out in little pockets (space-wise) and spurts (time-wise). Measuring in one spot at the top of a burner, or over a few seconds or even a minute, could give some false impressions unless the exhaust is quite steady and well-mixed, which rarely happens. We need some way of integrating over all the events that happen in a stove. Also, the exhaust changes as it comes out of the stove. This might affect CO concentrations only a little, but it is really important for PM; some material is a gas in the hot exhaust and condenses into particles as it cools down (just like water). In order to measure realistic emissions *or* exposure, you really need to measure after the exhaust is cooled.

Dean Still (Aprovecho) has used the garbage bag technique—collecting some exhaust, after dilution, in a large bag and then measuring it. This is a reasonable way to get a first-order measurement of emissions (none, some, lots). It might not be sufficient for comparing stoves overall, and it is a bit awkward for repetitive testing. You need some continuous garbage bag that does you the favor of adding up emissions. There are various ways of doing this, and it's useful to consider all the testing needs at once.

To relate to fuel burned, we could use a few methods:

a) Measure the concentration indoors and the air exchange rate in a room, then back out emission rate. Advantages: The measurement and setup are pretty simple. Disadvantages: Requires solving a couple of equations if you want to get total emissions; not as easy to see immediate changes in the burning; assumes that air in room is mixed well.
b) Capture all the exhaust in a hood, and measure the flow rate through the hood. Multiply flow by pollutant concentration, add up over time, divide by fuel burned. Advantages: Shows instant changes in burning; flow rate is pretty easy to measure. Disadvantages: Requires building an exhaust hood and putting in a light fan. (Don't let this sound discouraging; it shouldn't be too hard if scrap metal is easily available. The fan you need is smaller and lighter than even a home furnace fan.)
c) Capture the exhaust in either a hood or a large room, and measure CO_2 in the sample. CO_2+CO accounts for most of the carbon that came out of the fuel. Advantages: Shows both instant changes in burning *and* burning rate. Disadvantages: It is somewhat expensive to measure CO_2.

I do both (b) and (c) and make sure the results match, but you probably don't need to be so picky. Let the high-end labs worry about that. There are a few other kinds; "dilution tunnels" are favored for EPA testing, for example; and "dilution plenums" (sucking the exhaust into a stainless steel cavern and letting it sit before sampling it) have been used by many in the academic set. These can be pretty expensive.

6) Today's measurements

Now we're getting into the nitty-gritty—exactly *what* do we use to measure? Inexpensive combustion analyzers are made to assess furnaces (natural-gas or oil) or automobiles. Compared to the combustion we're interested in, these combustion types are far more steady, and the exhaust gas is less diluted. For that reason, the ideal analyzers *do not exist* (yet). I will talk about those ideal analyzers later on. This section is about what we can do *now*.

Because the burning is so unsteady, you can't take a one-time measurement with a gas probe as furnace technicians do. This is a problem, because most emission testing equipment is designed only for that purpose. You need either *real-time, recordable* measurements, or *an integrated sample* (bag or filter) that contains samples from each portion of the burn. I highly recommend real-time data. It is extremely instructive. In this section, the only integrated sample I discuss is particulate matter; that's because real-time PM measurements are still expensive.

Carbon monoxide
CO is most cheaply measured with an electrochemical sensor. The problems with this method are slow response time in the temperature sensitivity, and cross-sensitivity to other gases, but it is probably good enough for stove-testing purposes. The CITY[2] sensor has been recommended by people I trust, and it is fairly cheap (<$200). A more accurate method is NDIR (non-dispersive infrared), but it is more expensive. Note that Onset[3] makes an all-in-one CO meter and data logger. I recommend getting the sensor and data logger separately because you have more control of how the exhaust is forced over the sensor.

Exhaust flow, for option (c) in Section 5.
A pitot tube is the standard method of measuring flow. It is based on the idea that moving air creates a slightly higher pressure when it has to stop. A reasonable alternative, and one designed for application in sheet-metal ducts, is the flow grid. It is like a set of four averaging pitot tubes. These can be had for about $40 and the pressure gauge you need to measure the output is another $40.

Carbon dioxide, for option (b) in Section 5.
CO_2 is harder to measure than CO; it can't be measured with the cheap electrochemical cells. The best current method is NDIR (again, non-dispersive infrared). Telaire[4] makes cheap CO_2 devices (about $500), but someone needs to fiddle with them to optimize them for this application. Here, another problem is available ranges. The best range is probably 0-1% CO_2 by volume (0-10,000 ppm), but most CO_2 monitors are either 0-3,000 ppm or 0-10%. You can also infer the CO_2 from an O_2 measurement.[5]

Particulate matter
Standard methods of measuring emitted PM usually involve sucking the sample through a filter that catches the particles. You weigh the filter before and after, and the difference is the mass of particles. I don't, absolutely don't, recommend this (and I will probably be disowned by numerous regulators). To make this method work, you need either an expensive balance of fabulous precision, or a huge sample. Differences in the humidity (dryness of the air) affect the weight too, so you need humidity control, and so on. Many other effects can change the collected particle mass between the time of sampling and the time of weighing, especially since the particles tend to be very reactive particles. Finally, there's no immediate feedback—you don't get to know what you just measured until much later.

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[2] www.citytech.com

[3] www.onsetcomp.com

[4] www.telaire.com

[5] Some people (Colorado State) have suggested that they will look into the feasibility of O2 measurements for this purpose.

In defense of filter samples, they are well accepted and cheaper than real-time data. If you do use “filter samples,” be sure to dry (“desiccate” in lab terms) the filter prior to both weighings. Also be sure to seal the containers and to keep them as cold as possible. Other material you will need includes a pump, a way to calibrate flow rate, and plastic holders for the filters.

Optical methods have drawbacks, but I recommend them anyway because they are easy to use and *do* give immediate feedback. “Optical” means that the mass of PM is inferred from how the particles interact with light: pass a beam of light through an exhaust and see how it changes. How particles affect light depends on their size and composition, and for that reason, many studies have shown that a poor relationship between “extinction” (the quantity of light wiped out) and particle mass. A better measure is “scattering”—how much light bounces off the particles. A number of devices measure real-time scattering.[6] At this point, they are all rather expensive ($3000-5000 US).

<u>*Data acquisition*</u>

If you choose real-time monitoring, you will need a way to log the data. The HOBO dataloggers from Onset[3] are great, rugged, inexpensive ($~200 US) little units that collect real-time data and later send it to a personal computer (or a Palm Pilot). LabView from National Instruments[7] is the standard for laboratory data acquisition, and allows you to see your data as they are taken. The minimum cost to set up LabView is about $1000, and the package can easily get more expensive.

An equally challenging problem is that users need to be computer-literate to deal with retrieving the data from the loggers and producing meaningful results. Dataloggers cannot be sent to the field without a training manual and a spreadsheet that does most of the work.

7) *The perfect measurements*

Perfect measurements, or at least measurements that are good enough for routine stove testing, are probably not far away. What’s missing from the present measurement suite?

<u>Physical equipment</u>

- Inexpensive ways of measuring particulate matter in real-time. In my view, this is the *top priority* for measurement development. Kirk Smith (UC Berkeley) has supported an effort to address this problem, and his device may be nearly ready for use.

- CO and CO_2 measurement with NDIR, optimized for the correct ranges. CO_2 measurements will be the easiest way to produce emission rates in a wide range of testing situations. My group is doing some work on making this measurement inexpensively.

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[6] e.g. www.tsi.com (SideTrak), www.thermo.com (DataRam), Radiance Research nephelometer

[7] www.ni.com

- Simple hoods that collect exhaust in a variety of field situations, operable on low or no power; *or*, agreement on a chamber procedure to follow

- Methods of calibrating pollutant measurements

Activities

- Putting simple measurements "through the paces" by comparing with academically-accepted measurements and determining reasons for differences

- Community agreement on protocols. Aprovecho's push to revamp the water boiling test for efficiency has set the bar for a model to follow.

- Lab tests should support real-practice field tests and not vice versa!

8) Special requests

This is only the second edition of "Real People." More feedback is needed. In addition to general input, I think that this document still needs:

- Reader-friendly diagrams

- Suggestions for manufacturers and suppliers in countries outside the U.S.