Emissions Performance and User Acceptance of a Catalytic Biomass Cookstove in Rural Guatemala

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Stove Construction. The prototype catalytic stoves were built using inexpensive materials and consisted of five primary components: the stove exterior, the interior combustion chamber/chimney, the cooking surface/drip pan, the catalytic monolith, and an ash pan. An inexpensive, mass-market, steel 5-gal bucket was used as the stove exterior; a fuel inlet was cut in the bucket. The interior combustion chamber/chimney was made of 304 stainless steel, hand rolled into shape, and riveted together. Once formed, the combustion chamber/chimney was riveted to the base of the stove. Cement mixed with vermiculite was poured into the base of stove to prevent heat loss from the fire to the ground beneath. The oxidation catalyst, suspended within the stove, was made from a cordierite monolith (Applied Ceramics Inc.) that was coated with potassium titanate catalyst ($K_2Ti_2O_5$). The stove was packed with high-temperature fiber insulation between the combustion chamber/chimney and the exterior. The drip pan was made of cast iron using sand casting and was affixed to the top of the stove using bolts. The ash pan, which facilitates easy clean up, was made of 304 stainless steel and was held together with spot welds.

Field Trial Emissions Measurements. The experimental configuration for emissions sampling is shown in Figure S1. CO and CO_2 concentrations were measured in real time using a TSI IAQ-CALC 7545 (TSI Inc., USA). Emissions were drawn through the probe using a constant-flow SKC sampling pump (SKC Inc., USA) and drawn through a BGI Triplex cyclone (BGI, USA) at 1.5 liters per minute to remove particles larger than 2.5 microns in diameter. The sample was then pulled through a PTFE filter to collect $PM_{2.5}$. PTFE filters were weighed before and after sampling in a temperature- and humidity-controlled room on a microbalance with 0.1 μg resolution (Mettler Toledo, USA). Background emissions were measured by using a PATS+ particle monitor ($PM_{2.5}$) and a TSI IAQ-CALC 7545 (CO/CO_2) for 10 minutes before and after stove operation. The average background concentrations were subtracted from emissions sampling data to account for the ambient. Household air pollution (HAP) was measured as follows. $PM_{2.5}$ concentration was measured at 1 minute intervals using a PATS+ (Berkeley Air Monitoring Group). CO and CO_2 concentrations were measured at 1 second intervals using a Dwyer CMT200 CO Transmitter and an Airsense 310e CO_2 sensor. Data was logged using a HOBO 4-Channel Analog Data Logger (UX120-006M). The sensors, data logger, and rechargeable Li-ion battery supply were housed in a sealed, moisture-resistant enclosure. The CO and CO_2 sensors were calibrated using known concentrations of CO (100 ppm) in air, CO_2 (10,000 ppm) in air, and zero air. Beyond the calibrations performed by the manufacturer, the $PM_{2.5}$ sensor was co-located with gravimetric $PM_{2.5}$ measurements to determine an adjustment factor of 1.68 should be applied to the PM mass calculation to get a corrected $PM_{2.5}$ concentration.

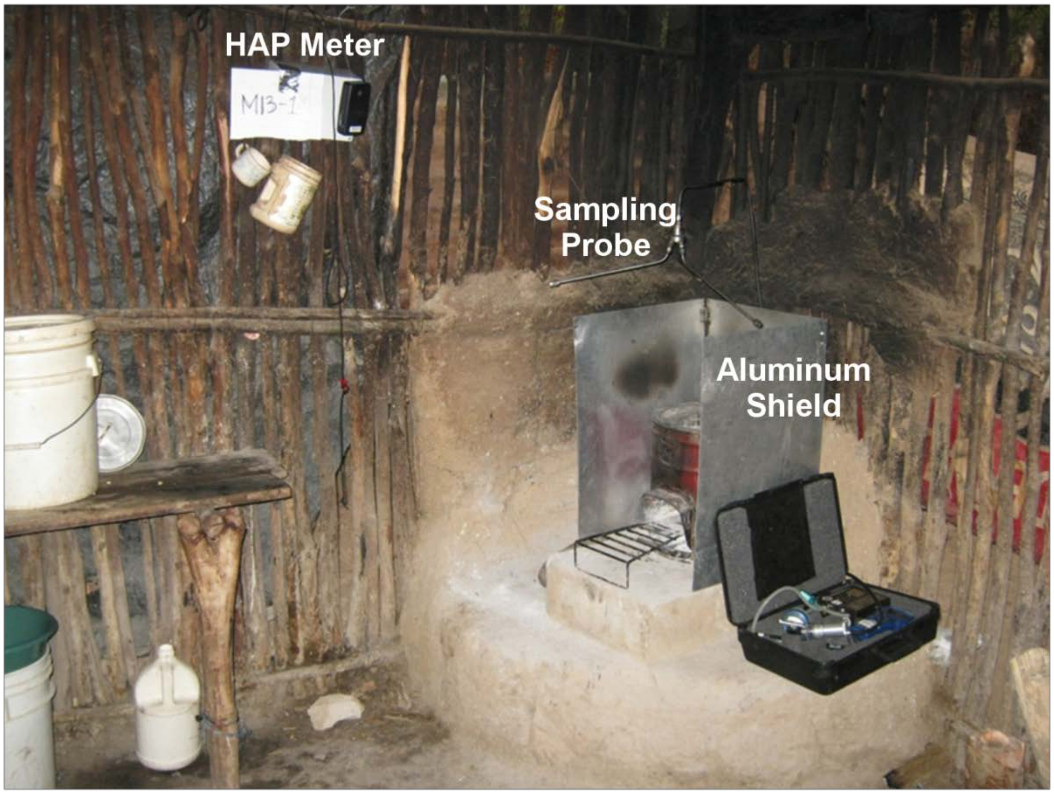

Figure S1. Stove emissions sampling configuration.

Household air pollution (HAP) data was collected by measuring PM, CO, and CO_2 concentrations within a user's home. Typically stove field trials do not record HAP data with such high sampling frequency, resulting in a loss of resolution in the HAP data. Figure S2 shows a 30 minute stretch of HAP data collected during the present field trial. With one-minute resolution for the PM data, it is possible to observe several peaks and match them up with peaks in the CO and CO_2 data. By collecting data even more frequently at 1 Hz, it is possible to see more defined spikes in concentration. For example, between about 7:38 AM and 7:42 AM it is possible to see multiple separate peaks in the CO data while only one peak can be seen in the PM data. This clearly shows the benefit of collecting data more frequently.

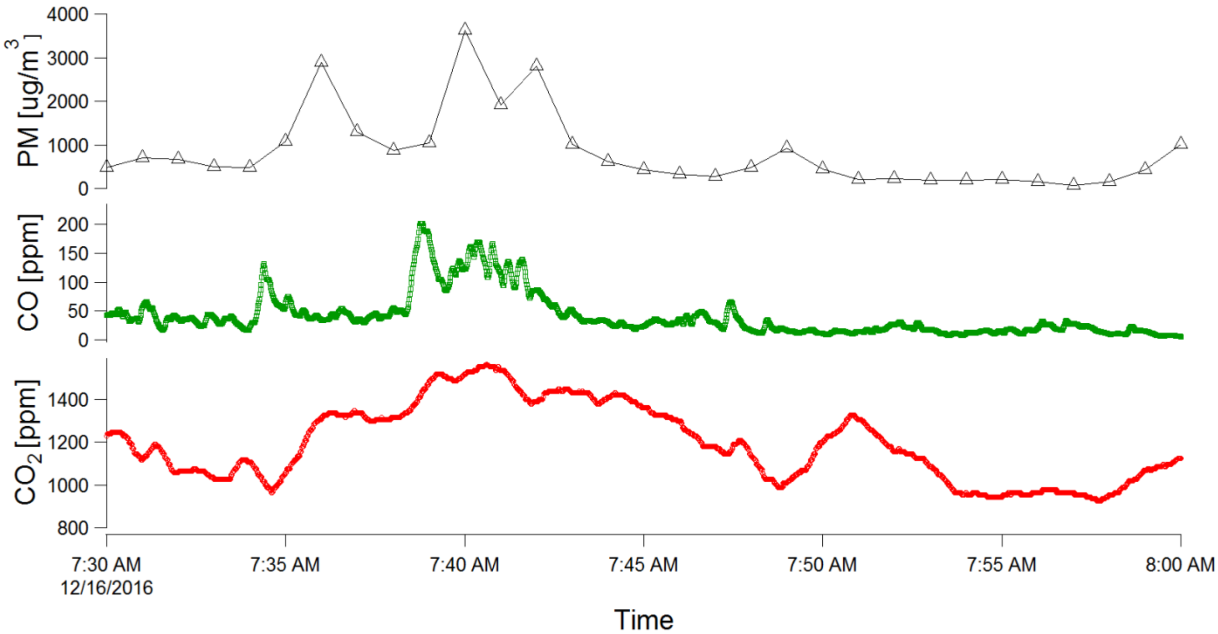

Figure S2. Resolution of HAP data. PM concentration was recorded once per minute while CO and CO_2 concentrations were recorded once per second.

The data collected from the HAP meters was used to calculate the emission factor (EF) during cooking events for both CO and PM emissions. The emission factors were calculated based on the average CO, CO, PM, and CO_2 concentrations generated during a cooking event. Equations and specified variables were taken from the water boil test (WBT) 4.2.2 protocol.[1] Equation 1 was used to calculate the total exhaust carbon concentration (CC_C) based on CO_2, CO, and PM measurements. The CO and PM baseline were determined to be zero. The units of CC_C are ppm_v, but PM was measured as a mass concentration, so the Ideal Gas law was used to convert to a volume concentration [ppm_v], with T being the average temperature measured in a user's home. The CO emission factor (EF_{CO}) was calculated using Equation 2 where CO_{avg} is the average CO concentration (ppm) during a cooking event, CC_C is taken from Equation 2, MW_{CO} is the molecular weight of CO, MW_C is the molecular weight of carbon, *fuelFracC* is the mass fraction (taken to be 0.5) of the fuel assumed to be carbon, and 1000 is a unit conversion from grams of fuel to kilograms of fuel.

$$CC_C = \left(CO_{2,avg} - CO_{2,base}\right) + \left(CO_{avg} - CO_{base}\right) + \frac{(PM_{avg} - PM_{base}) \cdot 0.008314 \cdot (T + 273.15)}{15 \cdot P_{atm}} \quad \text{Equation 1}$$

$$EF_{CO} = \frac{(CO_{avg} - CO_{base})}{CC_C} \frac{MW_{CO}}{MW_C} \cdot fuelFracC \cdot 1000 \quad \text{Equation 2}$$

To determine EF_{PM}, we need to convert CC_C to a mass concentration using the ideal gas law, as shown in Equation 3. Here 12 is the molecular weight of carbon, and 10^{-6} is a unit conversion. The PM emission factor (EF_{PM}) was calculated using Equation 4 where PM_{avg} is the average PM concentration (μg/m^3) during a cooking event, 1,000,000 is a conversion from micrograms to grams, and 1,000 is a conversion from grams of carbon to kilograms of fuel. More detail regarding derivations can be found in the WBT 4.2.2 protocol.[1]

$$C_C = \frac{CC_C \cdot 12 \cdot P_{atm} \cdot 10^{-6}}{0.00831 \cdot (T+273.15)} \qquad \text{Equation 3}$$

$$EF_{PM} = \frac{(PM_{avg} - PM_{base}) \cdot fuelFracC \cdot 1{,}000}{C_C \cdot 1{,}000{,}000} \qquad \text{Equation 4}$$

Catalyst Effect on Household Emissions Data. Twenty one cooking events were measured using the prototype catalytic stove; however, only four stoves had an intact or partially intact catalytic monolith during the emissions testing, which occurred after the stoves had been used in the homes for ~3 weeks. To examine the effect of the catalyst, we compared the average emissions and fuel consumed per standard adult (SA) meal between experiments with and without a catalyst present; Table S1 is a summary of the results. None of the data were found to be statistically different. This was caused by the small sample size (only four partially catalytic stoves) and the inherent error associated with controlled cooking tests. Therefore, the current field trial results cannot be used to confirm the laboratory results, which showed improvement when adding the catalyst to a rocket stove. In order to confirm that the catalyst reduces emissions in real-world conditions, a larger field study and a more robust monolith would be required.

Table S1. Emissions and fuel usage data for the prototype stove with and without the catalyst present.

	With Catalyst		**No Catalyst**		
	Mean	**St. Dev.**	**Mean**	**St. Dev.**	***p*-value‡**
CO_2 [g/SA meal]	307.2	166.3	446.1	230.6	0.27
CO [g/SA meal]	19.6	14.3	13.4	8.5	0.26
PM [g/SA meal]	1.11	0.67	1.13	0.80	0.97
Fuel [MJ/SA meal]	3.84	1.98	5.02	2.24	0.35
Fuel [g/SA meal]	203.9	106.8	264.0	131.2	0.41

‡*p*-value based on two-tailed, unpaired Student's *t*-test.

Customer Demand and Willingness-to-Pay. Study participants expressed high levels of interest in adopting the stove but not necessarily in purchasing the stove; "*If we get it as a gift, we will use it, but if we have to use our own money to buy it, we won't buy it.*" Although the stove was acknowledged to provide many benefits, users felt they were too poor and could not afford the luxury of the catalytic stove. When asked what they would do when they no longer had the stove, users said they would return to using traditional open fires. Some said they would be disappointed but had no choice. This specific market, rural with high poverty levels, is unable to justify the investment in the stove. However, the positive reception of the stove suggests that a subsidy or donation program would be effective. Urban markets could possibly yield higher demand, especially among small families where women work, have less time to devote to a large kitchen, and fuel wood is purchased. Women that work have greater expenditure discretion and have weaker incentives to continue spending on firewood.[2] Despite reluctance to purchase the catalytic stove, users enthusiastically adopted the stove and even changed their cooking habits to do so, demonstrating the potential for catalytic stove adoption via donation programs.

User Suggested Design Improvements. Users perceived the stove as non-durable. This perception was strongly enforced by the breakdown of the ceramic catalyst monolith in the stove. High temperatures in the stove embrittled the ceramic monolith, which when combined constant use in the home led to the monolith breaking after a few weeks of use. Users also noted stove appearance deteriorated over time and a few noticed deformations of the combustion chamber. Replacing the ceramic monolith with a metal monolith is expected to significantly improve longevity. Metal monoliths are unlikely to break from shocks to the stove and already exist as an option for some automotive catalytic converters. When asked, users estimated the lifespan of the stove at 2–4 months, despite using the stove 1.5 months. Extended demonstrations in the field lasting several months to several years are needed to demonstrate durability.

Size of the stove was the most desired design change. A larger stove would be able to accommodate large pots and tortilla cooking. Similar to the overall size, some participants suggested a stove with two burners was desirable. A double burner would allow for simultaneous cooking and could promote adoption in areas where people are less willing to adopt a sequential cooking method. Both the size of the stove and the desire for a second burner could be ameliorated by changing the cooking surface or introducing an attachment that locks onto the stove and directs hot gases to separate pot supports, allowing simultaneous cooking. An attachment could also widen the useable surface area of the stove to fit large pots or *comales*.

A summary of additional concerns expressed during these interviews is outlined in Table S2. Only the negative feedback is included in this table. In addition, Table S2 outlines our response to these concerns and how best to address them. Durability and size were the most common concerns. Durability can be addressed via minor design changes. However, size concerns would require significant design changes or the development of new stove attachments.

Table S2. Summary of user concerns regarding the catalytic cookstove.

	User Concerns	**Potential Design Changes to Address Concerns**
Durability	The monolith broke	Replacing the ceramic monolith with a more durable material less prone to embrittlement and fracturing

	Appearance deteriorated	This was primarily due to soot dirtying the stove or the paint fading where exposed to high temperatures. A hardened powder coat would make the stove easier to clean and less likely to discolor.
	The combustion chamber was deformed	Deformation was not detrimental to performance. Thicker steel parts would mitigate deformation, but is seen as unnecessary
	Rattling was heard within the stove	Two parallel 0.125-in. rods were used to suspend the monolith. When the monolith broke the rods could move slightly and cause rattling. Therefore a monolith that does not break will prevent any rattling.
	Stove lifetime was perceived as 2-4 months	[Addressed through longer term durability trials.]
Size	The stove was too small to accommodate large pots	An attachment that flares out the cooking surface could help the stove hold larger cookware
	The stove was seen as insufficient to cook tortillas due to size and uneven heating of the *comal*	Demonstrations of tortilla cooking or an oversized drip pan could help. However, tortilla cooking may remain the one food people do not cook with this stove.
	A second burner was desired to cook multiple dishes at once	An attachment could be used to direct hot gases through two separate pot supports.
Price	Users considered the stove a luxury item and therefore unaffordable	The stove may require subsidies or donations in poor, rural regions. Urban regions where the cook works outside the home, and fuel is purchased may provide a suitable market.
Monolith	The monolith was considered non-essential and a detriment to stove power	[Addressed through user education and training.]
Burns	Users were surprised the stove was hot despite not radiating much heat	Explicit training upon stove introduction and/or placing warning symbols on the stove could reduce burn potential
Potskirt	The potskirt did not fit all pots and was too hot to remove during cooking	A tiered potskirt could be built to accommodate different pot sizes

References

1. *The Water Boiling Test Version 4.2.3*; Partnership for Clean Indoor Air: Washington DC, http://cleancookstoves.org/technology-and-fuels/testing/protocols.html (accessed Jan 2, 2019).
2. Lascurain, J. *Market Segmentation: Improved Cookstoves and Clean Fuels in Guatemala*; Technical Report for the Global Alliance for Clean Cookstoves; Fast Track Carbon, March 2016.