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EMISSIONS AND EFFICIENCY OF IMPROVED WOODBURNING COOKSTOVES IN HIGHLAND GUATEMALA

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A comparison was made of the thermal efficiency and emissions of the traditional three-stone fire and the "Plancha" improved stove-burning wood. Simultaneous measurements of efficiency and emissions of suspended particles and carbon monoxide were taken in order to incorporate both of these factors into a single standard of performance - emissions per standard task. These factors were measured during both a Water Boiling Test (WBT) and a Standardized Cooking Test (SCT). No statistical difference in efficiency between the Plancha and traditional stove was found. The Plancha required more time to perform both of the tests, and this difference was statistically significant (p=0.048) for the WBT. The Plancha emitted 87% less suspended particles less than 2.5 μm in diameter (PM2.5) and 91% less CO per kJ of useful heat delivered compared to the open fire during the WBT. The relative environmental performance of the Plancha improved during the SCT, resulting in a 99% reduction of total suspended particulate matter (TSP) emissions and a 96% reduction of CO emissions per standardized cooking task. A strong correlation ($r^2 = 0.87$) was found between the average kitchen concentrations of CO and PM2.5 during the WBTs, indicating the usefulness of CO measurements as an inexpensive and accurate way of estimating PM2.5 concentrations. ©1998 Elsevier Science Ltd

INTRODUCTION

As in most countries in the developing world, the majority of Guatemalan families depend on biomass as their primary source of household fuel. A survey from 1985 estimated that 72% of Guatemalan households use wood fires for cooking, heating, and lighting their homes (Caceres and Caceres 1987). Of these, 83% were homes with traditional three-stone fires, which are known to lead to high emissions of health-damaging air pollutants and result in inefficient use of scarce fuel-wood supplies.

A number of epidemiological studies have estimated the risk of severe, acute respiratory infection (ARI) to be significantly elevated (2-6x) among children living in homes where unvented biomass stoves are used (McCracken and Smith 1997). ARI is the leading cause of mortality among the world's children under 5 y of age, killing 4.3 million annually, 95% of whom live in developing countries (Smith 1996). In 1990, ARI accounted .for 20% of all registered deaths for children under 5 y in Guatemala. The following study was carried out in the rural area of San Juan Ostuncalco, where respiratory infections accounted for 35% of

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general mortality and 48.1% of infant morbidity in 1990 (Hostnig 1991).

In addition to the health costs to a family cooking over an open fire within an enclosed area, there are also the economic costs of buying or gathering fuel-wood. As fuel-wood supplies become scarce, the costs increase due to the increased market price of fuel-wood or the increased distance one must travel from the home to the forest. Guatemala is a country with both a large population dependent upon fuel-wood and an increasing amount of local fuel-wood shortages. A recent report entitled "*La Deforestación en Guatemala*" (Deforestation in Guatemala) noted that the area of Guatemala that is forested has dropped from 51 to 31% between 1980 and 1996, mostly due to the advancing agricultural frontier (Pilon 1996). Improved stove programs in Guatemala have been primarily motivated by the goal of easing the pressure on the forests and the families who depend upon them for fuel (Mendez and Pineda 1991).

Tinker documented that for women in Guatemala using the *Lorena* improved stove, however, faster cooking was often even more important than fuel-saving to the burdened subsistence household manager (Tinker 1987). This makes the time it takes to cook a meal an important variable in stove evaluations.

Thus, this study was designed to test the performance of the "*Plancha mejorada*", an improved stove that is presently being promoted by development organizations in Guatemala through the Guatemalan agency *Fondos de Inversión Social* with regard to these three critical parameters: emissions, efficiency, and time. The *Plancha mejorada* (here called the Plancha) was compared with the traditional three-stone fire by testing simultaneously the emissions of air pollutants inside the kitchen area and overall stove thermal efficiency. Initial studies comparing the Plancha-improved stove with the traditional open fire found clear, though variable, reductions in indoor air pollution (Naeher et al. 1996a; 1996c), but the results of efficiency tests have been inconclusive (Gallego and Hernández 1995). The Plancha and an improved version with baffles are also being studied for possible use in a controlled intervention study that will measure the impact of reduced exposure to indoor pollutants on respiratory health of children under 5 y.

EXPERIMENTAL DETAILS

The Guatemalan Plancha was named for its ability to grill (*planchar*) tortillas on the flat, iron surface above the firebox. The body of the stove is made up of cinder blocks and red bricks. The firebox has a length and width of 98 cm and 45 cm, respectively, and a height ranging from 19 cm in the front half the firebox to 7 cm in the back due to a baffle at the midpoint. The iron surface may have three or four concentric rings that can be removed for placement of pots. A metal tube chimney allows for removal of most of the smoke from the kitchen.

The methodology of this study combined the chamber method for measuring emissions from biomass-burning stoves, developed by Ahuja et al. (1991), with the VITA Water Boiling Test (WBT) and a Standardized Cooking Test (SCT) to determine fuel efficiency (Baldwin 1986). As shown by Dutt and Ravindranath (1991), efficiency results from the WBT alone should be interpreted with caution because there is only a weak relationship between decreased specific fuel consumption and increased efficiency results from this short test.

Ten WBTs took place in Varsovia and Monrovia, two of the hamlets of San Juan Ostuncalco, Quetzaltenango. The WBT consisted of heating 4 pots of water, one of which was brought to boiling temperature (94 C) and boiled for 15 min. This comprises a high-power phase test for efficiency. Flat-bottomed, aluminum pots without lids were placed on each of the potholes of the Plancha. A similar procedure was performed with the open fire by placing the main pot, used to boil water, in the center and the other pots between each of the stones of the traditional, three-stone fire. The extra pots of water were utilized to compare the ability of the Plancha and open fire to cook or heat several items simultaneously, which may decrease overall cooking time and, thereby, increase efficiency and decrease exposure to indoor air pollutants.

The low-power efficiencies of the open fire and Plancha were assessed through 11 applications of the longer SCT. These tests were performed in Telená and Tochulup, two hamlets of Concepción Chiquirichapa. The SCT was developed using input from community members as to what is the most common cooking task and how it is carried out. The efficiencies resulting from the SCT allowed comparisons with WBT efficiencies to determine if the WBT is relevant to local practices.

The SCT involved cooking both black beans and tortillas at the same time. First, 1 lb (450 g) of black beans, which had been soaked for 15 h, were brought to a boil with onions, red peppers, garlic, and salt.

When the beans were well on their way to being cooked (~1.5 h), the pot was moved to the second pothole of the Plancha or between two stones of the open fire and the cook began to cook tortillas on an iron surface where the pot of beans had been. When 1 lb 2 oz (510 g) of dry corn flour was made into approximately 25 cooked tortillas, the pot of black beans was returned to its original location until the beans were cooked. The determination of when the beans were cooked was made by the same woman cook during all SCTs. This was based on a constant texture of samples of several beans eaten near the end of each test.

There were further differences between the ways in which the WBT and the SCT were performed in this study. Concentrations of total suspended particulate matter (TSP) were measured during the cooking of beans and tortillas, whereas concentrations of suspended particulate matter smaller than 2.5 μm in diameter (PM2.5) was measured during the boiling of water. In addition, the WBTs were performed on four-pothole Planchas, whereas the SCTs were performed on the three-pothole Planchas that were more common to the hamlets of Concepción Chiquirichapa.

During both types of tests, water temperature was measured every 5 min, particulate matter concentrations every 10 s, and carbon monoxide concentrations every 30 s. The volume of the house was measured for the emissions calculations, and the weight of fuel-wood before and the weight of fuel-wood and charcoal remaining at the end of the test were also measured for efficiency calculations. The amount of time to bring water to a boil or total cooking time was also noted.

The CO was measured using the Databear (Langen 1992), as validated by Lee et al. (1992) and gas chromatography (Ott 1995). TSP and PM2.5 were measured using the Miniram Personal Particulate Monitor (GCA, now TSI Inc.) connected to an extra data-logging channel of the Databear. The Miniram was calibrated daily by setting the reading to zero while in a room free of air pollution and inserting a dark calibration glass that is designed to produce a reading equivalent to a concentration of 43.5 mg/m^3.

Average concentrations of particles and CO and their decay rates after removal of the fire from the house were calculated. Air exchange rates (S = exchanges/h) were estimated using the slope of the least squares fit to the natural logarithm of the decay in concentrations of both CO and suspended particles with time after the fire had been removed from the house, using the following equation:

$$S(h^{-1}) = (\ln C_0 - \ln C_i)/t_i \qquad (1)$$

The air exchange rates were used along with the concentrations at equilibrium (C_e), the kitchen volume (V), and the burn rates (F) to calculate emissions (E) according to the following relation:

$$E(g/kg) = C_e SV/F \qquad (2)$$

An average concentration was used in this study to substitute for the equilibrium concentration. This was deemed acceptable because the averages are calculated excluding the period of decay in concentrations after removing the fire. The rises at the beginning were steep curves, making any disparity between equilibrium and average concentrations negligible.

The method used also differed from the recommendations for the chamber method in that the fire was maintained at a fairly constant rate throughout most of the test, rather than adding one stock of wood at the beginning. This was done because it more closely approximates local practices, resulting in a more appropriate efficiency test, and also because it proved difficult to start a fire in the Plancha with the amount of wood required to use only a single stock. In addition, according to recent findings about the accuracy of the chamber method for estimating emissions from biomass-burning stoves, more uniform refueling may reduce estimation errors due to decreasing the variability of emission rates (Ballard-Tremeer 1997). Constant emission rate is a fundamental assumption in deriving the above algebraic equation from a first order derivative. Since these errors were not found to be directional, they should also be decreased by taking the average of a group of tests. The advantages of low cost and ability to do measurements in place balance the imprecision due to the assumption of constant emissions. The advantages of low cost and ability to do measurements directly in place at households would seem to counterbalance the disadvantage of the imprecision due to the assumption of constant emissions. A study of the emissions from Guatemalan kerosene lamps used this same technique in a simulated village house (Schare and Smith 1995).

The fuel-wood for these experiments was taken from a single lot of wood and maintained at relatively constant humidity by protection from sun and rain. The local name for the tree from which the wood came is "*cushín*", which grows in the coastal area and gives an edible fruit found in most markets. Local fuel-wood

Table 1. Concentrations (average ± SD) and correlation between particles and CO.

	Water boiling test		Standardized cooking test	
	Open fire (n=5)	Plancha (n=5)	Open fire (n=5)	Plancha (n=6)
PM2.5 (µg/m^3)	14 800 ± 4100	1170 ± 810	27 200 ± 13 600	450 ± 550
CO (µg/m^3)	86 400 ± 23 500	2040 ± 2160	118 000 ± 31 200	14 900 ± 22 700
Ratios (CO/PM2.5)	5.9 ± 1.0*	7.1 ± 5.4**	6.9 ± 4.4**	23.7 ± 7.8
Correlation (r^2)	0.87		0.66	

T-tests performed to compare ratios of CO to TSP during the SCTs using the Plancha with the other test conditions. * $p < 0.0001$, ** $p < 0.005$. Correlations refer to the relationship between average CO and PM???.5 levels during the WBTs and SCTs.

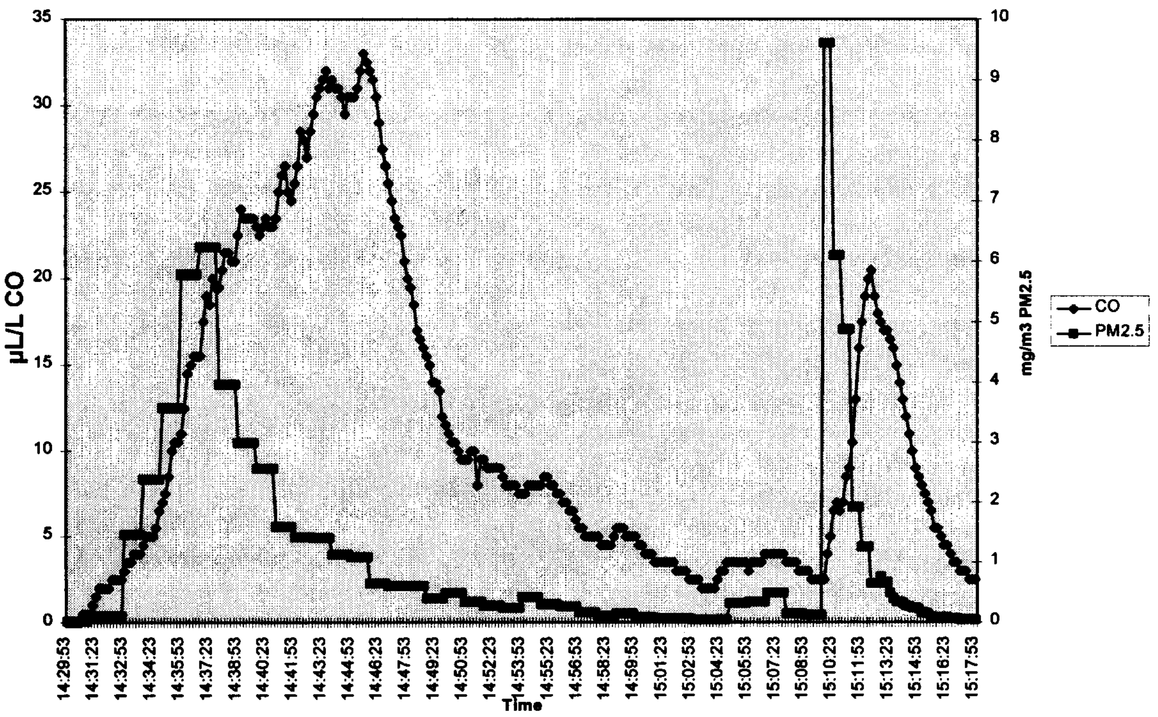

Fig. 1. Concentration vs. time during a WBT with a Plancha.

scarcity, local laws prohibiting the felling of trees, and the advent of the rainy season in the highlands are all reasons given for why firewood is often transported from the coast. Many people who gather, rather than purchase wood, continue to consume local forest products.

Calorimetric and humidity measurements were performed in the laboratory at the Institute of Nutrition of Central America and Panama (INCAP). Samples of charcoal and sawdust cut from the wood were taken at the beginning and end of the study. The moisture contents of the wood and charcoal were calculated by weighing the samples, storing them in an oven overnight, and weighing them the next day. The difference in the two weights is the moisture content, which is expressed as a percentage of the weight of the sample. The energy content of the dry samples was measured using a bomb calorimeter.

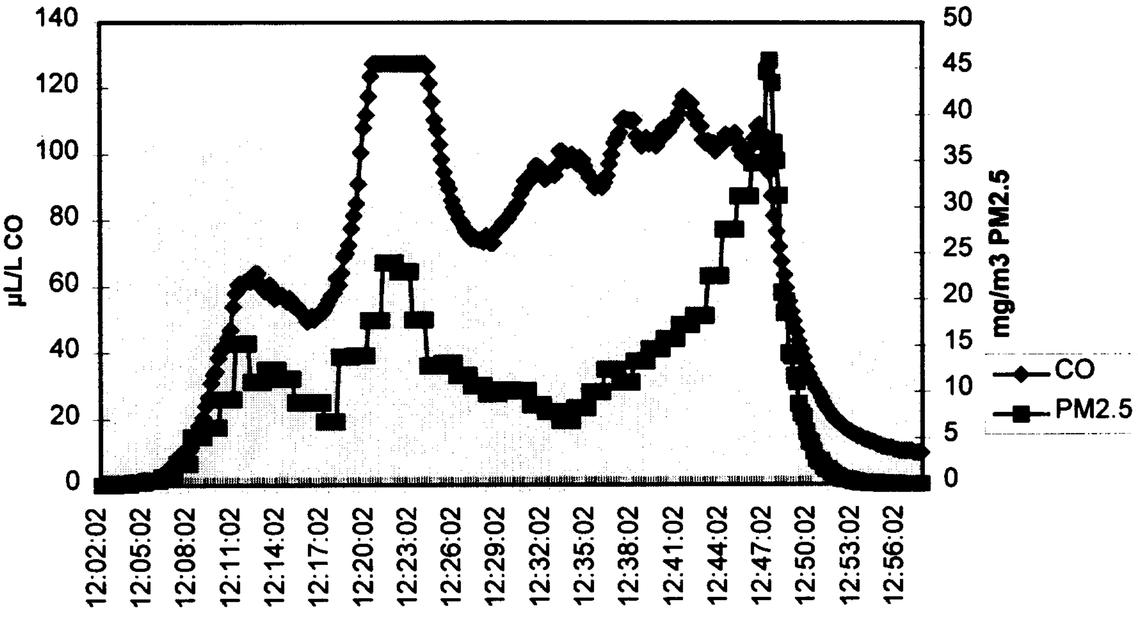

Fig. 2. Concentration vs. time during a WBT with an open fire.

RESULTS

The calorimetric values were 18.2 MJ/kg wet weight for wood and 27.9 MJ/kg wet weight for charcoal. The moisture contents for the wood and charcoal measured at 14.6% and 4.2%, respectively. These values are averages of the measurements made at the beginning and end of the study, which varied by less than 10%.

Table 1 provides the average pollutant concentrations from the WBT and SCT, along with the ratios and correlations between CO and suspended particles. The values presented for PM2.5 during the SCT were derived from TSP measurements and the ratios of PM2.5 to TSP found by Naeher et al. (1996b). These ratios were calculated using the data from the same type of stoves. PM2.5/TSP = 0.63 for the open fire and PM2.5/TSP = 0.35 for the Plancha. See Table 4 for the TSP concentrations during the SCT.

Figures 1 through 4 give an idea of how the concentrations of CO and suspended particles vary with time during a representative WBT and SCT. Elevated emissions were found at the start of cooking with the Plancha because it was necessary that the potholes and door be open for starting the fire. This temporary situation had a greater effect on the average concentration during the WBT than the longer SCT. See Figs. 1 and 3 for examples of this initial elevation in concentration during the WBT and SCT, respectively.

Tables 2 and 3 below provide the emissions and efficiency estimates from the WBT and SCT, respectively. The average emissions per kg of fuel were much less for the Plancha during the SCT (0.1 ± 0.1 g PM2.5/kg fuel) than the WBT (0.6 ± 0.6 g PM2.5/kg fuel). Compared to the open fire, the Plancha emitted 87% less PM2.5 per kJ heat delivered to the water during the WBT. The reductions of PM2.5 per standardized cooking task (derived from TSP measurements) were estimated at 99% during the SCT.

The typical time spent in the kitchen by women and children in this highland region, approximately 5 h per d, suggests that the greater improvements found during the longer tests may be more relevant (Engle et al. 1997). A valuable observational study would be to look at the amount of time the Plancha potholes and door are left open during normal cooking cycles. This could have a significant effect on the levels of exposure that would not be predicted by the results presented here.

The time required to boil water was significantly ($p=0.048$) shorter (21% less) for the open fire. Cooking beans and tortillas with the Plancha took considerably longer, although skimming above the 0.05 level of statistical significance with this small sample size.

None of the results for efficiency showed a statistically significant difference, although the open fire averages were slightly higher for both the WBT and SCT.

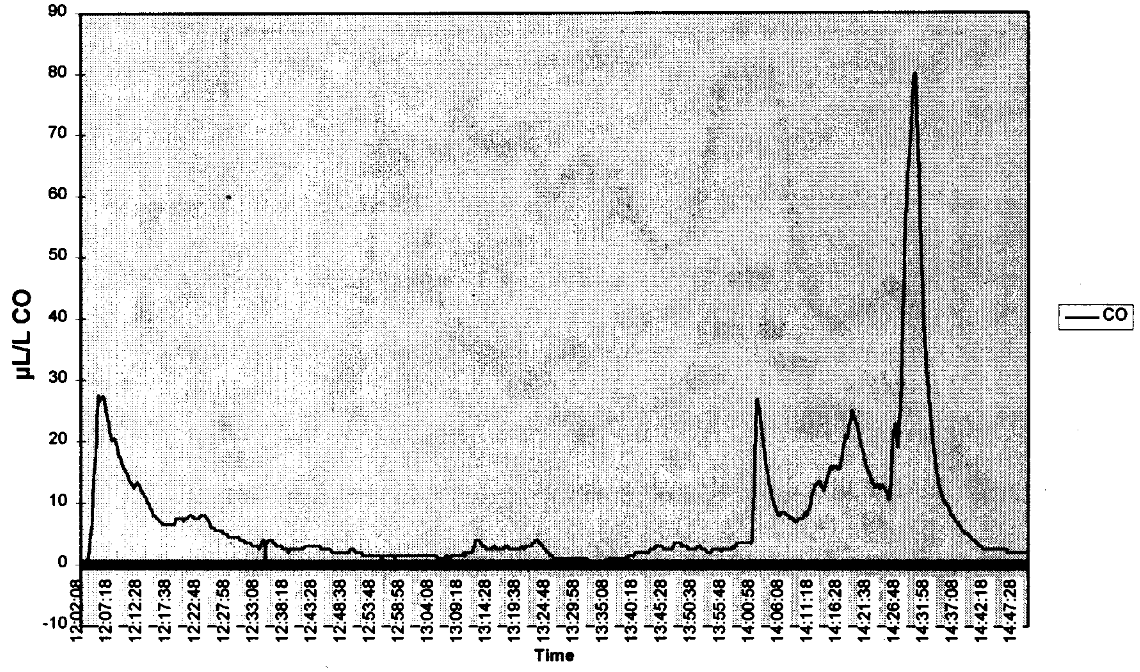

Fig. 3. Concentration vs. time during a SCT with a Plancha.

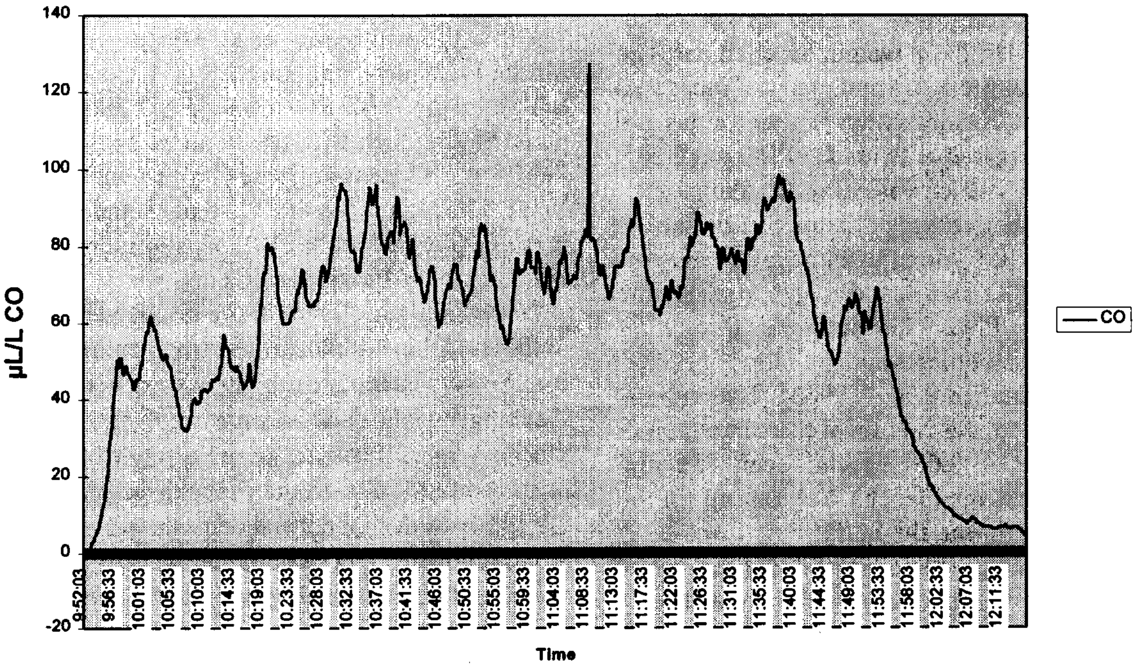

Fig. 4. Concentration vs. time during a SCT with an open fire.

Table 2. Results of WBTs (average ± SD).

Stove type	Time till boiling (min)	Efficiency (%)	Emissions per unit heat delivered (mg CO/kJ)	Emissions per unit heat delivered (mg PM2.5/kJ)
Open fire	25.4 ± 4.0	14.8 ± 1.8	10.1 ± 5.6	1.86 ± 0.95
Plancha	32.2 ± 5.1	13.7 ± 0.7	0.91 ± 0.67	0.24 ± 0.25
T-test (n.s.)	p = 0.048	(p = 0.189)	p = 0.016	p = 0.007

All of the raw data used in the above calculations are presented in Table 4.

Table 3. Results of SCTs (average ± SD).

Stove type	Time to cook beans and tortillas (min)	Wood consumed per task (kg)	Emissions (g CO/task)	Emissions (g PM2.5/task)
Open fire	122 ± 3	3.84 ± 0.16	320 ± 136	50.0 ± 29.0
Plancha	164 ± 45	4.09 ± 0.63	13 ± 18	0.14 ± 0.15
T-test (n.s.)	(p = 0.065)	(p = 0.414)	p = 0.0005	p = 0.002

All of the raw data used in the above calculations are presented in Table 4.

DISCUSSION

These disappointing results for Plancha efficiency are in agreement with reports of the Plancha and the Improved Plancha with baffles (Gallego and Hernández 1995) incorporating a WBT with both high-power and low-power phases. This strengthens the evidence against the Plancha as an intervention to reduce the household burden of fuel-wood scarcity, which is one of the primary reasons for the promotion of and the community's desire for the Plancha. In addition, the increased time required for cooking tasks may be an important weakness of the Plancha.

Anecdotal reports by people who perceive that they are saving fuel by using the Plancha contradict the results of both the WBT and SCT. Fuel savings may be achieved by factors other than thermal efficiency during cooking, such as the improved space heating capacity of the Plancha during cold evenings in the highlands. Further investigations must be carried out to determine the validity of these tests for estimating fuel savings during everyday cooking practices. One way of estimating the actual fuel savings due to the *Plancha mejorada* would be to conduct fuel consumption surveys to estimate the actual rate of fuel consumed per person-week using the Plancha and open fire. The similar efficiency estimates between the high-power WBT and the longer, low-power SCT suggest that the WBT may be a useful and easy method for evaluating the thermal efficiency of improved stoves in the Western Highlands of Guatemala.

The correlation between average kitchen concentrations of CO and suspended particles during the WBT ($r^2 = 0.87$) and SCT ($r^2 = 0.66$) were relatively high and similar to the findings of Naeher et al. (1996b). The correlations were also lower during less-polluted conditions, such as during the SCT. These relatively strong correlations allow the estimation of PM2.5 from CO measurements using a constant ratio. Table 1 indicates that this ratio of CO to PM2.5 was much greater during the SCT with the Plancha. These ratios may only be accurate for the respective test or stove from which they are derived, which would make them considerably less useful. In addition, Naeher et al. (1996b) showed that CO and particulate matter ratios are correlated over the entire wood-burn cycle, but that there are significant variations at different times during the burn.

In terms of emissions, the Plancha shows great potential for reducing exposure to health-damaging, indoor air pollutants. Therefore, the Plancha would serve well as a tool for assessing the burden of ARI in children that is attributable to high levels of air pollution in the kitchen environment. Observation of practices related to starting a fire in the Plancha would be valuable to estimate the importance of the elevation in emissions due to opening the potholes and the firebox door, which is often done to increase air flow and access to the firebox. One Plancha was removed from the analysis of the SCT because the concentrations were extremely high (TSP = 10.6 mg/m^3) due to the opening to the chimney being blocked by ash. Two

Table 4. Water boiling and standardized cooking tests.

Water boiling tests						
Air exchange (/h)	Burn rate (kg/h)	PM2.5 (µg/m³)	CO (µg/m³)	Heat delivered (MJ)	Fuel used (kg)	Efficiency (%)
46.44	2.55	11 380	83 210	4.898	1.701	16.9
52.9	2.35	12 490	69 280	4.179	1.843	12.8
45	3.02	20 550	120 520	4.519	1.814	16
28.59	2.72	35 740	--	4.009	0.814	13.1
33.22	2.47	14 640	72 580	4.245	1.644	15.3
8.99	2.21	120	--	4.108	1.956	12.4
16.81	2.27	1920	7000	4.649	1.701	13.9
9.55	2.66	170	1740	4.739	1.799	13.9
46.14	2.89	860	12 950	4.73	1.928	14.6
52.82	2.92	1720	4040	5.468	2.339	13.5
36.68	2.99	10 570	46 600	4.691	2.41	13.5

Standardized cooking tests				
Air exchange (/h)	Burn rate (kg/h)	TSP (µg/m³)	CO (µg/m³)	Fuel used (kg)
15.24	1.958	42 540	130 620	3.965
11.35	2	73 500	131 100	4.068
19.57	1.871	31 800	76 800	3.742
25.58	1.986	17 570	131 510	4.153
15.16	1.974	85 690	--	3.898
10.13	1.562	1390	11 570	4.479
18.96	1.642	310	1550	4.323
6.38	1.741	790	6630	4.352
17.63	2.1	590	6810	5.075
13.87	1.658	4410	60 570	3.813
17.52	1.538	260	2040	3.24

other Planchas had relatively high emissions due to holes in the metal chimneys, which were frequently reported to last no longer than 2 or 3 y. These construction and maintenance issues should be addressed in future testing, design, and dissemination efforts.

CONCLUSIONS

The method tested for simultaneously evaluating the emissions and thermal performance in order to estimate the emissions per standard task proved reasonably reliable.

The results suggest that CO may only be a good proxy measure for particles when the fuel, stove, and cooking cycle are the ones from which the ratios are derived. The quantitative relationship should be explored further in a broader range of circumstances, however.

Further studies are also needed to explore the relationship between the efficiencies estimated above and the actual rate of household fuel consumption. It seems, however, that the design of the *Plancha mejorada* must be improved before it can be promoted as a reliable fuel-saving intervention.

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