Fuel efficiency of an improved wood-burning stove in rural Guatemala: implications for health, environment and development

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Around two-thirds of the populations of developing countries are still primarily dependent on biofuels for domestic use, and it is now well documented that this results in high levels of indoor air pollution. The fuel efficiency and pollution emitted from biofuel stoves therefore have important implications for a number of important, interrelated aspects of development, including health promotion, protection of the environment, and the household economy. This study reports on the fuel efficiency of a popular wood-burning stove (the* plancha*) in western Guatemala, in comparison with the traditional open fire. This stove has been shown previously to substantially reduce levels of indoor air pollution. In standard water boiling and cooking tests, the* plancha *consumed more fuel and took longer than the open fire. Modification of the* plancha *combustion chamber by inclusion of a baffle resulted in a 12% improvement in overall thermal efficiency, bringing it up to the value for the open fire. In five-day tests of routine cooking, the modified* plancha *(with the baffle) was found to use 39% less fuel wood than the open fire. In selecting* plancha *stoves for the study, a high proportion were excluded due to cracks and other faults, and this highlights the pressing need for more attention to be paid to the longer-term sustainability of improved stoves. Nevertheless, the potential that stoves such as the* plancha *may have for substantially reducing fuel use as well as household pollution has important implications for poor populations in many parts of Latin America and other developing countries.

1. Introduction

It is estimated that around two-thirds of the populations of developing countries rely on biomass fuel (wood, dung and fibre residues) for cooking and heating, involving around three billion people [WRI, 1998]. Studies from many countries have demonstrated that this leads to very high levels of indoor air pollution (IAP) [Smith, 1987; Smith, 1993; WHO, 1997], and there is growing concern about the health effects of this exposure, particularly among women and children. Health problems associated with indoor air pollution include acute lower respiratory infection (ALRI) among children, currently the leading cause of mortality in children under 5 years [Anon, 1992; Kirkwood et al., 1995; McCracken and Smith, 1997; Bruce et al., 1998, Bruce, 1999], chronic obstructive lung disease (COLD) among adults [Pandey, 1984; Pandey et al., 1985; Norboo et al., 1990; Dennis, 1996], possibly low birth weight [Boy et al., in preparation], still-births [Mavalankar et al., 1991] and an increased risk of tuberculosis [Mishra et al., 1999]. In addition to concern about health are the demands that wood fuel places on the natural environment, and the opportunity cost for women who often have to spend many hours each day collecting wood [WHO, 1992].

Although work on improving biofuel stoves has been going on for many years, much of the effort has been directed at reducing fuel consumption primarily for economic and environmental reasons, rather than at reducing exposure levels within the home for health reasons. With some important exceptions, e.g., Kenya [WHO, 1992] and China [Smith et al., 1993], this approach has met with limited success, with stoves often falling into disrepair or being abandoned. In recent years, greater emphasis has been laid on the health consequences, so that an approach that integrates disease prevention, environmental sustainability, economic factors and cultural requirements is

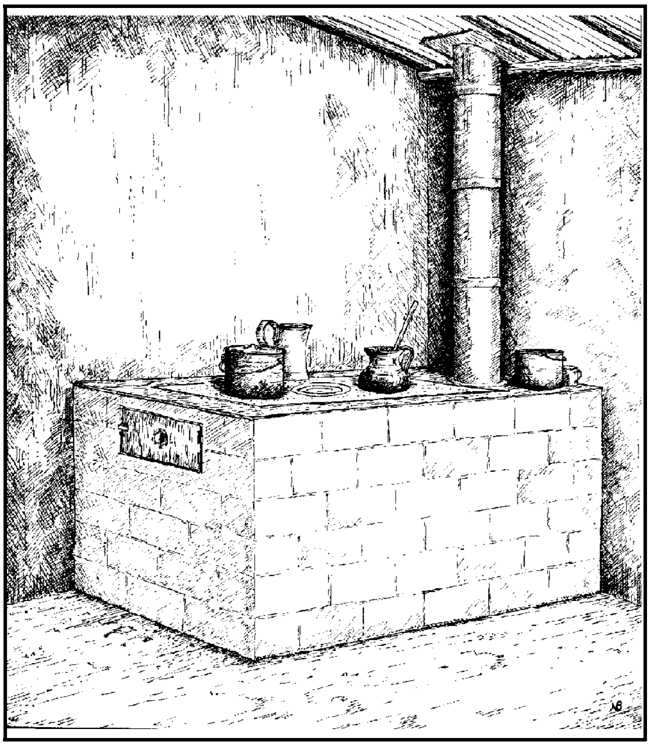

Figure 1. A typical *plancha* stove in western Guatemala, showing the metal plate with three pot-holes, the door which opens into the combustion chamber, and a flue rising through the roof (which is usually of corrugated iron or pantiles)

regarded as being appropriate and most likely to meet with success [WHO, 1992]. Consequently, there remains a need for good information about stoves with the following key attributes:

- ability to carry out the cooking tasks required by the household and, depending on the setting, also provide space heating;
- combining construction that is durable with a cost that is not beyond the capacity of most households (although the potential of low-interest community finance initiatives should be included as a factor);
- ready acceptability to or, preferably, active desirability by the household;
- reduction of indoor air pollution to levels that will substantially improve the health of women and young children. Ideally this should be to WHO guidelines levels, but in practice this may not be achievable in the short or medium term [Bruce, 1999]; and
- fuel utilisation efficiency greater than that of the traditional stove or open fire.

The *plancha* is an indigenously designed and constructed wood burning chimney stove used in Guatemala (Figure 1), a country whose rural population – like many in the region – is mainly dependent on increasingly stressed sources of wood fuel [FNUAP, 1995].

Evolved over the last 20 years, the *plancha* is a popular stove and if well made and installed can be relatively durable. Its central feature is a thick mild steel plate through which pot-holes are cut. The metal discs removed are then cut into a number of concentric rings, which allow the pot-holes to fit a range of pot sizes. When the pot-holes are covered with the complete set of rings, the stove top becomes a flat plate *(plancha)* which is used in the manner of the traditional flat earthen pan *(comal)* for cooking tortillas. The steel plate itself must be manufactured industrially in Guatemala City from imported metal, but cutting of the pot-holes and rings, and all other aspects of manufacture and installation, are carried out locally. The cost of the stove, including installation, is between US$ 100 and 150 depending on the design, materials and contribution of labour by the household. Because of the cost, *planchas* are not easily afforded by poor rural people. Most *planchas* in the villages have been paid for by NGOs or since 1994 by the Social Investment Fund (FIS). A minority of these stoves have been purchased directly by households. So far as we are aware, community financing projects and low-cost loans have not been tried in this area as a means of achieving wider dissemination.

The *plancha* has been identified as suitable for a controlled intervention study being developed by World Health Organization (WHO) in order to establish the effects of a measured reduction in indoor air pollution exposure on the incidence of ALRI in children and COLD in adults [Bruce et al., 1998]. Feasibility studies carried out as part of this research programme comparing the *plancha* with the open fire have demonstrated that the *plancha* can reduce indoor particulate air pollution (measured as particles less than 2.5 microns in diameter – $PM_{2.5}$) levels from a mean of 520 $\mu g/m^3$ found in homes with open fires to around 90 $\mu g/m^3$ [Naeher et al., 1996]. A second study of stoves that had been in use for some time showed a higher mean $PM_{2.5}$ of 152 $\mu g/m^3$, although this was still very substantially lower than the value of 868 $\mu g/m^3$ $PM_{2.5}$ for the comparison group of homes using open fires [Naeher et al., 1996]. Although local women report that the *plancha* uses less wood than the open fire, indeed this being one of a number of features that they like about the stove, there has only been one published assessment to date of the stove's fuel efficiency using standard methods applied to in-situ stoves in typical homes. This showed that the *plancha* was no more efficient than the open fire in carrying out two standard tests, the water boiling test (WBT) and the standardized cooking test (SCT), and indeed required significantly more time (27%: $p = 0.048$) to complete the WBT [McCracken and Smith, 1998].

One other (unpublished) study of designs similar to the *plancha* did show that some types were more efficient than the open fire, but these tests were carried out in a laboratory setting in Guatemala City [Lou Ma, 1981]. We carried out the present study to confirm the earlier findings of poor efficiency in standard tests, and to investigate whether the anecdotal reports by women that the *plancha* might be more fuel-efficient than the open fire in everyday use could be verified.

2. Energy supply in rural Guatemala: the importance of wood

The situation regarding the use, supply and future development of wood fuel in Guatemala serves as a useful case-study, and a context in which to assess the wider importance of this evaluation of the *plancha* stove. Over the years 1980-91, 65-68% of the total energy consumption in Guatemala has been derived from firewood [Urizar and Pineda, 1991]. Between 1960 and 1990 deforestation from commercial exploitation of forests and expansion of agricultural land use have diminished the forest areas from 77% to 23% of the national territory [FNUAP, 1995]. The main determinants of this trend and the resulting deforestation are rapid population growth, dense rural populations, subsistence agriculture, economic deterioration of the poorer groups in society, and traditional felling of trees without reforestation. These factors are common to Central and South America.

Forest resources have the potential to make a major contribution to development by meeting basic needs in energy as well as other forest products, by contributing to food security, by sustaining industries which provide employment and income, and by maintaining environmental stability. But if this potential is to be fully realised, uncontrolled exploitation must be replaced by appropriate management of the entire forest production chain, from the establishment through to the maintenance and harvesting of forest crops to processing, marketing and fuel use in the home and elsewhere. The domestic stove, as a key element of the end-use of forest products, plays an important part in this process.

Guatemala has only recently made substantial efforts to attain relative domestic energy autonomy from fossil fuels, as is the case for other countries in Central America. The Guatemalan Ministry of Energy and Mines (MEM) was established in 1983, and among its roles is the coordination of development of alternative energy sources. Until the change of government in 1995, key policy goals were: (1) to reduce demand for firewood by using improved firewood-saving stoves, and (2) to increase supply by encouraging energy forests [Urizar and Pineda, 1991]. Since the mid-1990s, there has been a quite extensive programme of installing improved stoves in western Guatemala (mainly *planchas)* through the FIS, but progress with expansion of energy forests has been insignificant due to lack of governmental and private resources.

Against this background, the fuel efficiency of a stove that is locally made, relatively durable, meets household needs, and has been shown to substantially reduce indoor air pollution is of considerable interest. This experience is important for Guatemala, but also for the many other rural populations throughout the world to whom these health, energy, economic and ecological issues matter.

3. Study aim

The aim of this study was to assess the efficiency of the *plancha* wood-burning stove in comparison with the open fire in the typical domestic setting of rural Guatemala, by determining:

- the thermal efficiency and wood consumption when carrying out standardised tests;
- the wood consumption for standard cooking tests when modifications were made to the combustion chamber to improve heat transfer; and
- the wood consumption when carrying out normal household cooking over a period of five days.

4. Study area and methods

The study area is San Juan Ostuncalco, a rural district of the western highlands of Guatemala, with a population of 32,000. The area is mountainous, lying at an altitude of between 2,000 and 2,300 metres. Night temperatures fall to just below freezing during the coldest months of the year (November to February), so there is a need for space heating. *Planchas* are manufactured locally in workshops in a number of villages in the adjacent district. The evaluation of the *plancha* stoves consisted of three component studies.

1. Measurement of the thermal efficiency (TE) of the *plancha* compared with that of the open fire (OF), in performing standardized tests (typical domestic cooking tasks).
2. Measurement of the TE of the *plancha* before and after temporary improvement of the internal structure of the combustion chamber (addition of a baffle) to increase heat transfer between the hot gases inside the chamber and the cooking surface.
3. Measurement of the wood consumption of typical households by direct daily weighing of wood consumed during alternating 5-day periods when the improved *plancha* (with baffle) or the open fire was used exclusively for all cooking tasks.

4.1. Study 1: Thermal efficiency of traditional plancha stoves and open fires

4.1.1. Field study procedures

Three Mam (the local indigenous Indian ethnic group) women with a high school education were recruited, and trained by Ruben Hernandez (RH) at the MEM laboratories in Guatemala City in all field methods. Training continued during the first week of data collection in San Juan, and was conducted in collaboration with MEM technicians. Initial training was reinforced and operational errors were corrected during this phase and throughout data collection. Supervision of fieldwork was carried out by MEM personnel and Erick Boy (EB).

For Study 1, sample size was calculated for 0.05 significance levels (2-sided), 0.9 power, 25 gm standard deviation for wood consumption (per test), and a minimum difference of 25 gm wood consumption (per test) to be detected between *planchas* and open fires. This yielded a sample size of 21 per group.

Each field assistant visited homes in her neighborhood and registered the type of stove within each house as well as the availability of the female head of the household to participate in a 3-day trial. Lists of eligible households with open fires (OFs) or *plancha* stoves (PSs) were drawn up for 3 of the 4 segments of the township of San Juan and the nearby village of Varsovia. Sixty-seven out of 100 PSs initially identified were excluded due to structural defects (cracks in the fire box, absence of a door to cover the wood-feeding aperture, malfunctioning/clogged chimneys) and twelve because of basic design differences (4 pot-holes on the metal plate, or different material such as cast iron used). A total of 20 OFs and 21 PSs were included in the study. Two of the initially selected stoves had to be substituted because the fire boxes were considerably larger than any other stove included in this evaluation. The inclusion criteria for the PSs were as follows.

- *Cooking surface*: metal plate with 3 in-line pot holes covered by removable concentric rings to adapt to the size of the cooking pots. The acceptable dimensions for the plate were: 85-90 cm long × 40-45 cm wide × 0.4-0.5 cm thick.
- *Fire box*: construction from brick or adobe blocks. Presence of a functioning sliding or hinged door at the fuel-feeding end. Internally, the vertical distance from the metal plate to the bottom of the fire box at the center of each pot-hole should be 18-21 cm, and should remain constant through the length of the stove.
- *Use*: Continuous use and maintenance of the PS should be not less than one year.
- *Chimney*: No leaks or visible cracks should be observed. Sweeping of the chimney should have been carried out within the last 3 months. Internal visual and manual inspection of the chimney intake should reveal no obstruction to the flow of air.

In addition, for a household to be included, the main cook needed to have one or more years of experience using the PS or the OF and be willing to participate in managing the wood-fuel, preparing the tortillas and watching over the beans under the direct guidance of a field assistant. The tests on the stoves were carried out by two field workers, each working with half of the homes.

4.1.2. Standardized tests

Three different tasks were carried out in order to assess the efficiency of the *plancha* stove in comparison with the open fire.

1. *Thermal efficiency (TE) test:* TE is defined as the ratio between the heat utilized by the system composed of the cooking utensils and their contents plus the heat used to vaporize water and the amount of heat that is actually generated by the burning wood (lower heat content). The formula for TE is given in Appendix 1. TE was measured in a two-phase water boiling task, following the methodology used by the MEM. The high power phase (HPP) comprises taking a fixed amount of water from ambient temperature to boiling temperature (b.t.) and keeping it at b.t. for 15 minutes. The low power phase (LPP) consists of maintaining the b.t. constant (± 1-2ºC) for another 60 minutes. For the OF, 6.5 kg of water was used in a single pot. For the PS, the amounts of water used were 6.5 kg on the front pot-hole directly over the burning wood, 2.4 kg on the second pot-hole, and 1.6 kg on the rear pot-hole towards the chimney. Note that the formula for TE allows for the difference in total amount of water heated by the two types of stove. Temperature was recorded from the pots every 5 minutes.
2. *Cooking task A:* Field workers measured wood consumption and time elapsed while cooking 450 gm of black beans which had been left to soak in plain water overnight and spiced with salt and onions immediately before cooking. The weights of the soaked and drained beans (795 gm), the spices (86 gm) and the water (5.2 kg) were standardized. Each cook determined when the beans were sufficiently cooked according to personal preference.
3. *Cooking task B:* Field workers measured wood consumption and time elapsed while cooking 1.35 kg of lime-treated corn dough *(masa).* After lighting the *plancha,* the pot-holes were covered with the concentric metal rings and the whole surface of the cooking plate was brushed with a layer of lime dissolved in water to prevent the tortillas from sticking. Tortillas were cooked on the open fire in the traditional way with a *comal,* a metal plate placed over the fire. Timing began when the fire was started and ended when the last tortilla was removed from the cooking plate. Wood consumption was measured by difference between initial and final weights of the wood set aside for the task.

Each field assistant completed 2 tests daily, one per house. At any given time of day (a.m. or p.m.), all field assistants would perform the same task (i.e., tortillas), switching to a different task in the afternoon (i.e., beans). This was done to control for changes in climatic conditions. For all the tasks, the field assistants followed standard procedures for weighing the fuel and pots before each test or phase of the test, and then weighing the pots, residual wood and coal after each test was completed. Since wood was provided free, all households were asked to use no more wood than normal, and not to give it away to friends and neighbors. Field assistants reviewed completed data collection forms once a week as a quality control measure. One pooled sample of sawdust from 12 pieces of the wood bought for the tests was taken on the first day of testing. Direct bomb calorimetry of the sample and humidity were determined by the food chemistry laboratories at the Institute of Nutrition of Central America and Panama (INCAP). The wood provided was of the same type and condition as wood available commercially to residents of the study area: this was brought from the Pacific coastal plains due to shortage of fuel wood in the highlands.

4.2. Study 2: TE of plancha stoves before and after improvement of the combustion chamber

A convenience sample of ten PS households that had participated in the previous study was selected, and TE tests carried out using the same methods. Baseline TE was measured again since the wood purchased for this study was of a different variety from that used in Study 1. On completion of this baseline test, the temporary modification of the chamber was carried out for all the stoves using dry bricks and sand only. The inclined plane built into the chamber was recommended by the MEM in the light of the TE results obtained from Study 1. This structure was intended to direct the hot gases towards the metal cooking surface and allow for an increase in the heat transfer to the part of the metal plate more distant from the burning wood. (See Figure 2.) The inclined plane structure built

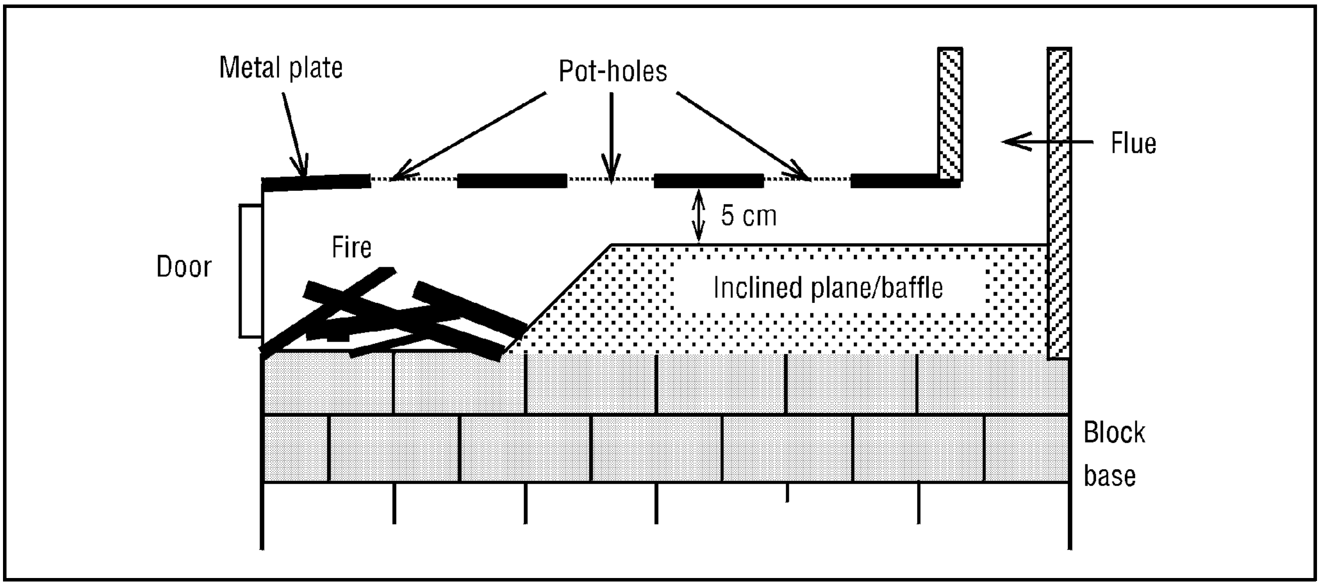

Figure 2. Cross-sectional view of the *plancha,* showing the position of the inclined plane and baffle fitted for the tests in Study 2.

into the combustion chamber was made of one layer of bricks covering a mound of pumice-stone sand. This inclined plane was installed on the chamber's floor starting directly below a point midway between the first and second pot-holes and reaching its maximum height 8cm farther back towards the chimney. From this point it formed a plateau running 5cm below the cooking plate from the proximal third of the second pot-hole all the way back to the chimney hole.

4.3. Study 3: Usual wood consumption for cooking during one working week using either the PS or an OF

The sample for Study 2 agreed to participate in this final study which entailed using the improved PS exclusively during 5 consecutive days (Monday-Friday) to perform all cooking tasks for the household and then revert to the exclusive use of an OF during the following Monday-Friday for the same purpose. All fuel wood was provided at no cost, and women were asked not to change their cooking habits in changing from one stove type to the other. Five women were asked to use wood as they normally would if there was no shortage of fuel, while the other five were asked to use the fuel as they would in time of fuel shortage when prices are very high. None of the participating households ever used wood for commercial activities. Weekends were excluded to avoid the potential for confounding the results by religious celebrations and visiting families/friends.

Every morning before preparation of lunch began, the household's allocation of ready-to-use pieces of dry wood (5-7 kg, about 12-18 pieces) was replenished in excess of daily needs and the amount used during the preceding 24-hour period measured. During each morning visit, the field workers recorded the number, sex and ages of people who ate at the table during each meal. Subjects were also questioned regarding other uses of the wood provided for the study. Field workers discreetly inspected for evidence to confirm the information given to them. For instance, during the OF week, field workers would touch the PS to see if it was warm. At the end of each 5-day period, women were asked about their experience with the cooking system used.

4.4. Analysis

Data was analyzed using Epi-Info software [Dean et al., 1994]. Mean TE and wood consumption values were compared by independent sample t-test. Wood use for OF and PS in each of the ten houses was expressed as the specific daily fuel consumption (SDFC), calculated as the wood consumed per ''adult male equivalent'' (AME) cooked for [Baldwin, 1986]. Essentially, this method involves taking the adult male food consumption as a reference, and assuming that other family members (women, children, elderly persons) consume lesser amounts which are calculated according to specified ratios. Mean values were compared using a single-tailed t-statistic for matched pairs and 9 degrees of freedom (critical $t_{I=0.01}$ = 3.250, $t_{I=0.05}$ = 2.262). For comparison of SDFCs according to mode of wood use (thrifty vs. frugal), 4 degrees of freedom were used ($t_{I=0.01}$ = 4.604, $t_{I=0.05}$ = 2.776).

Table 1 summarises the three studies, and the tests which were carried out in each.

5. Results

5.1. Study 1: TE, time and fuel consumption for standard tasks

Tables 2-4 compare the fuel efficiency of the PS and OF, controlling (in formula for TE) for the different humidity contents of the batches of firewood used at the township (13.2%) and the village (10.8%). Table 2 shows that the OF had a significantly (p = 0.006) higher TE than the PS in the high power phase (HPP), that is, it was more efficient in raising a fixed volume of water to boiling point. There was no evidence of a difference in TE for the low power phase (LPP), however. The combined efficiency, which includes both the HPP and LPP, showed that the OF was significantly more efficient than the PS (21%; p = 0.002).

Similar, but non-significant, results were found for the time taken for the bean and tortilla cooking tasks (Table 3).

Table 1. Summary of the three studies and the tests carried out in each

Study	Stoves being compared	Tasks	Measurement
1	• Open fire • Plancha (as found in homes)	• Bringing water to boil and maintaining for 15 mins (high power phase) • Maintaining water at boiling temperature for 60 minutes (low power phase)	Thermal efficiency (TE) See text and Appendix A for description.
		• Cooking beans	Time taken and wood consumed
		• Cooking tortillas	Time taken and wood consumed
2	• Plancha • Improved plancha	• Bringing water to boil and maintaining for 15 mins (high power phase) • Maintaining water at boiling temperature for 60 minutes (low power phase)	Thermal efficiency (TE) See text and Appendix A for description.
3	• Open fire • Improved plancha	• Usual household cooking and stove use, Monday to Friday	Wood consumed (expressed per adult male equivalents cooked for)

Table 2. Thermal efficiency (±SD) for water heating test: high power, low power, and combined efficiencies

Stove type	n	High power phase (%)	Low power phase (%)	Combined efficiency (%)
Open fire	20	11.08 ± 1.78	16.05 ± 4.96	12.54 ± 2.20
Plancha	21	9.33 ± 2.04	15.94 ± 10.18	10.35 ± 2.02
Comparison	t	8.560	0.002	11.095
	p	0.0058	0.9632	0.0022

Table 3. Average time (±SD) spent by the open fire and plancha stove for boiling beans and cooking tortillas (min/100 g)

Stove	n	Average time (mins) taken to cook 0.45 kg of black beans	Average time (min) taken to cook 1.35 kg of corn dough into tortillas
Open fire	20	132.6 ± 27.3	17.1 ± 11.7
Plancha	21	142.9 ± 40.0	25.8 ± 14.9
Comparison	t	0.948	1.79
	p	0.647	0.08

The OF required less time for both tasks, with the result for tortillas approaching significance (50%; p = 0.08). The results for wood consumption, and residual charcoal, also show that the OF used significantly less fuel for these two tasks than the PS (Table 4). As two field workers (observers) were involved, it was important that there was no evidence of any observer differences in recorded time taken or wood consumed, independent of fire/stove type.

5.2. Study 2: Effect on TE of combustion chamber modification

The effect of the modification of the combustion chamber's internal structure on the TE of the PS is shown in Table 5. The modification significantly *increased* the efficiency of the stove during the HPP by 40% ($p<0.01$) but significantly decreased the efficiency during the LPP of the test by 32% ($p<0.05$). There was a marked reduction in the standard deviation during the LPP after the modification, perhaps because of the reduction of the space available to place the fuel inside the combustion chamber and a more controlled flow of gases towards the chimney. Overall thermal efficiency increased by 12% as a result of the modification ($p<0.05$), bringing it up to the level of the OF (Table 2).

5.3. Study 3: wood consumption of improved PS (IPS) and OF in everyday use

The total number of adult male equivalents served over the 5-day periods was comparable for the two types of fire, which was as hoped given that these were the same households asked to carry on with their lives as normally as possible (Table 6). The weight of wood consumed by the IPS was substantially less than that by the OF, with the SDFC for the PS being 61.4% of that for the OF ($p<0.01$). The absolute difference in SDFC during the IPS weeks was 0.82 ± 0.59 kg/AME per week.

Analysis of the households according to the requests made to women about the usage of fuel (normal vs. frugal)

Table 4. Wood consumed (kg) and left-over charcoal (kg) for cooking tasks (±SDs)

Stove	n	Firewood consumed (kg) for beans task (0.45 kg)	Firewood consumed (kg) for tortilla task (1.35 kg)	Left-over charcoal from beans task (kg)	Left-over charcoal from tortilla task (kg)
Open fire	20	3.88 ± 0.86	0.97 ± 0.51	0.217 ± 0.073	0.121 ± 0.046
Plancha	21	4.73 ± 0.82	1.24 ± 0.020	0.235 ± 0.090	0.159 ± 0.066
Comparison	t	3.181	2.00	0.667	2.087
	p	0.003	0.05	0.516	0.04

Table 5. Thermal efficiency (±SD) of plancha stoves for water heating test before and after their modification: high power, low power, and combined efficiencies

Moment of evaluation	n	High power phase (%)	Low power phase (%)	Combined efficiency (%)
Before modification	10	10.03 ± 1.24	15.78 ± 5.97	11.10 ± 1.75
After modification		14.02 ± 2.07	10.73 ± 1.15	12.43 ± 0.56
Comparison	$t_{df=9}$	4.466	2.895	2.289
	p	< 0.01	< 0.05	< 0.05

Table 6. Adult male equivalents (AMEs) cooked for, total wood consumed, and specific daily fuel consumption (±SDs) in everyday use, by stove type

Stove used	n	Adult male equivalents served (AME)	Weight of wood consumed (kg)	Specific daily fuel consumption (kg/AME)
Plancha stove	10	58.5 ± 21.4	69 ± 18.6	1.18 ± 0.505
Open fire	10	57.7 ± 20.7	111 ± 31.8	1.93 ± 0.818
Comparison	$t_{df=9}$			5.098
	p			< 0.01

shows that the SDFC increased in both groups during the open fire periods. The fuel savings during the IPS period in the frugal fuel use group of 0.95 ± 0.77 kg/AME were significant, but the savings in the normal fuel use group of 0.68 ± 0.33 kg/AME were not significant. The numbers are very small (n = 5 pairs), so this non-significant result is quite likely to be due to lack of statistical power. It may however indicate that the IPS allows better management of fuel use and cooking tasks when this is required on account of fuel shortages.

6. Discussion

The *plancha* was chosen for this fuel use study because of its other attributes, namely the marked reductions in indoor air pollution [Naeher et al., 1996], the fact that it meets all domestic cooking and heating needs, and is relatively durable when well built and maintained. It is an appliance that women living in this poor rural area of Guatemala want for their homes.

There has been concern that solidly constructed chimney stoves such as the *plancha* may often be no more fuel-efficient than the open fire, in spite of having an enclosed combustion chamber, because of heat losses to the stove body and increased natural draft due to the chimney [VITA, 1985; Baldwin, 1986]. This study has shown that the *plancha* currently in use does not seem to save time or fuel compared with the open fire in simulated cooking situations, providing evidence to support these earlier concerns and findings. This is true even though cracked or otherwise visually defective stoves were eliminated from the sample.

On the other hand, when modified into an improved *plancha in situ* by construction of a combustion chamber baffle, it achieved statistically significantly higher efficiency in simulated cooking tests than the unimproved version. Furthermore, during a five-day test of normal cooking, this improved *plancha* yielded savings in wood consumption of around 40% when compared with the open fire, which is likely to be more representative of actual household use over time than the simulated tests. Although during frugal use of wood the *plancha* appeared to have some comparative advantage, the numbers involved do not allow any firm conclusions to be drawn about the potential that careful use of fuel has for improving efficiency of this stove.

There are a number of possible reasons why the *plancha,* as tested, should be so much more fuel-efficient in everyday use, apart from the inclusion of a baffle. This important issue requires further study, but may in part be explained by the way in which women are able to manage various cooking tasks on a stove with three pot-holes and use of the metal plate for tasks such as cooking tortillas. Since the 5-day tests were conducted using the modified *planchas,* they are not directly comparable with the initial set of results (Study 1). Nevertheless, the modified *planchas* had an overall thermal efficiency (TE) only 12% greater than the unmodified stoves, and similar to the TE of the open fire. Although these TE results are based only on water boiling and boiling temperature maintenance tasks, the low power phase (maintaining boiling) is probably more representative of general cooking, and the TE for this test was actually worse in the modified *plancha.* It therefore seems unlikely that the considerable savings in fuel achieved by the *plancha* in everyday use are simply due to the combustion chamber modification.

Given that Study 3 alternated stove use in the same homes, it is important to consider whether the higher fuel consumption during the open fire periods was due to increased demands for cooking, or other influences. The assessment of demand is provided by the AMEs served, and this was virtually identical for the open fire and *plancha* periods. These were families that had become used to relying on the *plancha,* but there would have been no particular reason or incentive for being less careful with the wood during the open fire period. Wood was supplied free throughout the period of the tests. Checks on the *plancha* to see if it was warm did not suggest that any of the women used the wood stove during the open fire week. The fact that wood consumption was less in both the frugal and normal wood use groups, although significantly so in only the frugal group, provides some additional evidence of consistency of effect.

6.1. Condition of stoves

It has been noted in this study that a high proportion of *plancha* stoves (67%) had to be excluded from the initial sample because of structural defects and poor maintenance. Indeed, two other studies of stoves in the area have confirmed this observation. One of these, which included pollution monitoring of *planchas* and some other types (e.g., *lorena* and *ceramica),* showed that ambient PM_{10} levels were between 300 and 600 $\mu g/m^3$, which compares unfavourably with the much lower values achieved by the stoves in good condition [Naeher et al., 1996], although still somewhat lower than the PM_{10} levels of around 1000 $\mu g/m^3$ for open fires. Another study in the district noted that in some cases the pot rings had been removed and pots placed directly on the hot embers, so the stove was in effect little different from an open fire [Bruce et al., 1998].

6.2. Conclusions

In isolation, these findings on fuel use might be of limited interest as there are other improved wood stoves throughout the world capable of reducing fuel consumption. What makes this important is that the *plancha* is also capable of markedly reducing indoor air pollution and meeting all domestic cooking and heating needs, and is relatively durable when well built and maintained. The study carried out by McCracken and Smith [1998] in which the particulate and CO levels were calculated per kJ of useful heat provided, or per standardised cooking task completed, emphasised that even with a lower test efficiency the *plancha* should result in substantially reduced health risks from indoor air pollution. These new findings of much reduced wood consumption in everyday use suggest that this stove could offer an even more impressive combination of economic, health and environmental benefits.

The evaluation of the modified combustion chamber yielded rather inconsistent changes in performance, and further technical development and field testing are required. This experience emphasises that stove improvement is a technically complex matter, and underscores the necessity for this expertise to be available in the countries where need is greatest [Reddy et al., 1997]. Further studies are also required of the performance of the *plancha* over a longer period of time, including both fuel efficiency and indoor air pollution levels in wet and dry seasons. The reasons for lower fuel use should be explored further with women, in particular whether they do indeed manage cooking tasks more efficiently on this type of stove.

The condition of many of the *planchas in situ* is a source of considerable concern. Large numbers of these stoves have been installed in recent years by the Guatemalan FIS (Social Investment Fund) and NGOs, but with little or no evaluation of maintenance procedures or later condition of the stove. Anecdotally, there are many accounts from individual households reporting that *planchas* installed over 20 years earlier are in good working order, but so far as we are aware there has been no systematic evaluation of the longer-term durability and performance of these stoves – whether purchased by households or installed by the FIS or through the activities of NGOs. Further assessment of this is now a priority, in Guatemala and many other settings, together with an evaluation of how best to ensure that households do carry out chimney cleaning and essential repairs. From experience in other areas, e.g., Kenya [WHO, 1992], it is recognised that successful implementation requires that stoves and other interventions must meet household needs, and be developed with the involvement of the community, producers and others (such as NGOs, government) concerned. However, stoves in East Africa have not so far included chimney stoves, and case evaluation studies of inclusive, community-based stove programmes such as this are lacking.

As has been emphasised, the use of wood and other biofuels, and the resulting health consequences – in particular from indoor air pollution – are issues that concern the majority of those living in developing countries. While the *plancha* itself may not be directly transferable to other countries, much of what can be learned about design, performance, stove development and maintenance offers lessons for other situations. The costs of installing, using and maintaining the *plancha* should be assessed, and compared with the open fire and other options such as gas. Overall cost-benefit analysis, taking into account health and environmental benefits, should also be carried out. From the evidence available to date, a stove such as the *plancha* may prove to be a very worthwhile investment when all these factors are considered, despite the relatively high initial cost of around US$ 100-150. ■

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Appendix A

Formula for thermal efficiency

TE = (Sum of Q_u for all pots)/Q_a

where:

$Q_a = W \times C$, where Q_a is the heat generated by the wood (dry weight),

W = weight of the wood burnt during the trial,

C = the calorific content of the wood estimated as 17.39 kJ/g.

$Q_u = (W_i - W_f) \times C_v + (T_f - T_i) \times W_f \times C_e$, where

Q_u = heat utilized (kJ),

W_i = initial weight of water (g),

W_f = final weight of water (g),

C_v = water vaporization heat (2.253 kJ/g),

T_i = initial water temperature (degrees Celsius),

T_f = final water temperature (degrees Celsius),

C_e = water specific heat (0.00418 kJ/g/degree Celsius).