Assessing Cook Stove Performance: Field and Lab Studies of Three Rocket Stoves Comparing the Open Fire and Traditional Stoves in Tamil Nadu, India on Measures of Time to Cook, Fuel Use, Total Emissions, and Indoor Air Pollution

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Overview

The following is an initial report of the performance of three types of Rocket stoves: a single pot stove, a double pot stove, and a double pot stove with chimney, compared to both the open fire and traditional stoves commonly used in Tamil Nadu, India. The stoves were tested using the Controlled Cooking Test to measure fuel use, carbon monoxide and particulate matter emissions made while local cooks prepare commonly made foods. Portable emissions measurement equipment created by Aprovecho Research Center was used to measure emissions made in both the lab and field.

The in-field use of Rocket stoves (without pot skirts) resulted in approximately 18% to 35% fuel savings as compared to the traditional stoves and reduced fuel used from 39% to 47% compared to the Three Stone Fire. Emissions savings for the non-chimney stoves were about 45% when compared with the traditional stoves and about 50-55% in comparison to the three stone fire. When emissions released into the room were compared for the chimney stove, a 40% improvement was seen over the traditional chimney stove, while an 84% improvement was seen in IAP as compared to the three-stone fire.

	One-Pot	Two-Pot	Chimney
To Traditional			
Fuel Reduction	18%	35%	28%
CO Reduction	41%	45%	41%
PM Reduction	46%	44%	37%
To Three-Stone Fire			
Fuel Reduction	41%	47%	39%
CO Reduction	46%	60%	86%
PM Reduction	56%	57%	78%

The performance of the traditional stoves might be slightly reduced in homes, as they are frequently fully submerged in the earth and surrounded by mud, lowering both heat transfer and combustion efficiency.

This data also showed that the same meal cooked on a kerosene stove would cost 3.5 Rupees for the fuel at the current subsidized price of 9 Rupees per Liter. The Rocket stoves used an average of about 1.5 kilos of firewood to cook the standard meal, while the traditional stoves used an average of 2.2 kilos. The cost of cooking with wood is dependant on the source of the fuel.

The three Rocket stoves and the Three Stone fire had been previously tested using the UCB revised Water Boiling Test in the Aprovecho laboratory. Relative reductions as compared to the three-stone fire in the laboratory studies were analyzed. Emissions reductions from the laboratory and field testing agreed within 18% or less, while fuel savings agreed within 12% except for the chimney stove. Time savings agreed within about 30% or better.

Introduction

A month long series of Controlled Cooking Tests (CCT) were conducted in Tamil Nadu, India comparing three Rocket type biomass burning stoves for sale in India with the open fire and traditional stoves. The Rocket stoves had been previously tested using the Water Boiling Test in the Aprovecho laboratory.

The purpose of this study was:
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1. To try to determine real-world fuel and time savings.
2. To identify likely reductions in IAP levels due to switching to the Rocket stoves.
3. To gather data on the total emission reduction and the resulting reduction in emissions contributing to climate change and the “brown cloud” of pollution over India.
4. To examine the user acceptance and usability of the stoves
5. To see if there was a correlation between lab and field studies done by Aprovecho Research Center staff.
6. To investigate the performance of the in-field emissions equipment developed by Aprovecho.

Details

The details of the testing series are as follows:

1. Testing Protocol –

The CCT is the second test recommended in both the VITA International Testing Standards (1987) and the revised University of California at Berkeley standard testing protocol series (2003). After stove prototypes are developed in the lab using the Water Boiling Test, the CCT is designed to measure performance when the stoves are used by local cooks preparing traditional meals. Also, the CCT provides a direct comparison between the improved and traditional stoves as used by each cook.

In these tests, a common standard meal was chosen, and a series of three female cooks per stove model were asked to prepare that meal as they normally would using the traditional and improved stoves three times each. The CCT is designed to investigate stove performance as used under local conditions, with local fuel, local pots, and local practice. The CCT is an essential step in validating field performance, measuring whether a stove that performs well in the lab can also perform well when used by cooks in the region where stoves are to be disseminated.

There are limitations to the CCT, however. Only one meal was prepared and only a limited number of cooks were evaluated in a controlled setting. The next step in validation of stove performance requires a population-based study of the fuel use and IAP levels under normal use conditions. This requires a much larger sample size, longer time commitment, and extensive work in the villages. The third recommended test, the Kitchen Performance Test, (KPT) provides the protocols for this type of study.

2. Stoves –

The “improved” stoves were the result of almost two years of work in the field and lab intended to create an appropriate technology meeting local needs using local materials and manufacturers. The stove prototypes were sent between lab and field six times trying to optimize the design for heat transfer and combustion efficiency while incorporating the requirements of the user. In several instances, the local cooks created innovations that resulted in improved performance and increased effectiveness.

The result of this back and forth method were three Rocket stove models with ceramic combustion chambers of .85 g/cc density. The stove bodies include carefully engineered gaps that match Indian pots. The stoves are near to the ground in response to Indian women’s preferences for height and geometry.

The Three “Improved” Rocket Stoves

The “traditional” stoves for this study were bought in the marketplace at 20 rupees for a single pot and 50 for a double pot. Typically these stoves are buried in the earth, with counter-top surfaces created around them. Generally these stoves are replaced once per year by the families. The stoves used for testing were not buried, but coated in a 1-2 cm thick layer of mud and dung by the cooks and allowed to dry. It is expected that fully submerged stove bodies will perform slightly worse for both measures of fuel use and emissions.

The Three “Traditional” Stoves

Choosing a traditional chimney stove for comparison was a challenge, as in Tamil Nadu the only chimney stoves that exist were already identified as “improved” by the various NGOs that installed them. Therefore, a fairly common stove design in India, consisting of a cement body with two pot holes and a narrow air flow path was used for comparison.

Traditional Chimney Stove

Fortunately, extra time was available due to the hard work and commitment of the cooks and testing team. As a result, the testing staff was pleased to have time to test a common pressurized kerosene stove and the three-stone fire. These stoves were also tested using a random sample of the cooks.

Three-Stone Fire

Kerosene Stove

3. Cooks –

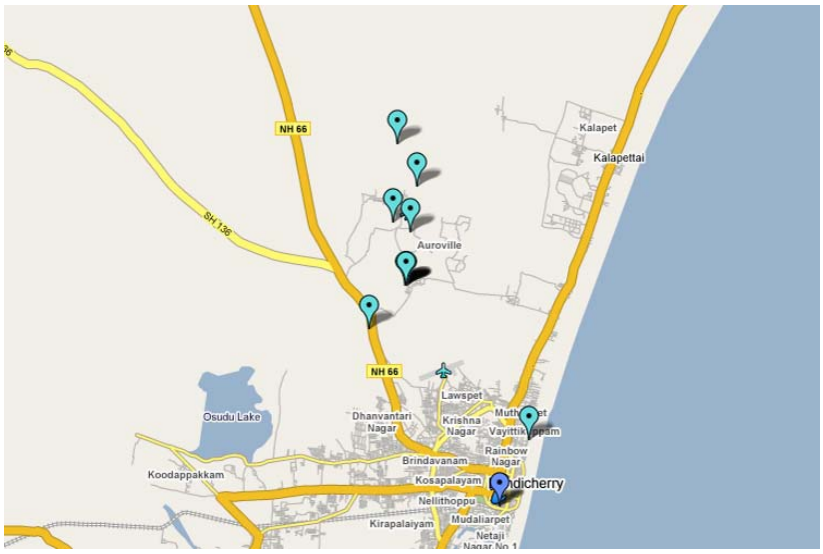
The cooks were chosen from nearby villages. Some cooks had taken part in the stove design focus groups one year earlier, while others were newly contacted participants. They were all given their stove model at least 3 weeks before the start of testing. The cooks were not trained in use of the stove, nor were they given instruction manuals as they were not available at the time. Some cooks were excited about the new stove and being able to make recommendations for improvements. Others were not very excited initially and were hesitant to switch from their traditional methods. All were verified as having used the new stoves each week prior to the testing.

During testing in a local kitchen, the cooks were not instructed how to run the stove in any way. A wonderful interpreter, Kartika, was able to make them extremely comfortable, and spent a lot of time chatting with them. This was an ideal situation because the home situation was more closely replicated, rather than the cooks feeling like they were expected to behave perfectly. The friendly translator was an immense help to this project.

The cooks were paid 50 rupees per meal cooked, and they were encouraged to take the large quantities of food home to their village. It turned out they loved this situation. People heard that they were well compensated and therefore there were no drop-outs. It was also beneficial for the cooks to bring home the food, as that encouraged them to prepare the food as they normally would (rather than more quickly), since their friends and family would be sharing in the meals.

4. Location –

Testing was conducted in several rooms of the Aprovecho Research Center in Pondicherry, near Chennai, India. Up to ten cooking tests were conducted per day with at least two cooks, sometimes their families, and assistants present. The cooks were brought to and from the office by a driver. The testing took place during December of 2007 at the end of the monsoon season with sporadic rain on about 25% of the 20 testing days.



5. Wood –

The wood was purchased locally. It was the most common wood available in the region for both purchase and collection, called Casuarina. There are many Casurarina plantations in southern India as it is used for both scaffolding and firewood. The 2-6 cm diameter sticks were split in half.The wood was seasoned as commonly done in homes to an estimated 10% moisture content. Unfortunately, the wood samples were confiscated by US Customs in case of insects so the exact moisture content is unknown.

It should be noted that contrary to some testing procedures, in this series the mass of char remaining was not subtracted from the fuel use. This is because the charcoal is not generally saved for later use or sale and is therefore wasted and should be considered as burned fuel.

6. Food –

The meal chosen was a typical dish consisting of Lady Finger Sambar and Rice. This dish was prepared a total of 120 times in a quantity suited to about four to six people. The vegetables were cleaned and cut up before distribution to the cooks in equal quantities. “Doneness” was determined by the feel of the rice and the lady fingers in the sambar.

Quantity (g)	Ingredient	Cooking Instructions
Dahl		
200	Dahl	Wash Dahl, boil water, add dahl, cook, then mash. Then add to sambar when ready.
1340	Water	
Sambar		
200	Lady Finger	Fry about half the vegetables and spices in the oil. Add water and cooked dahl. Boil, stirring frequently. Add remaining vegetables and lady finger, simmering until lady fingers are cooked.
200	Onion	
200	Tomato	
20	Chili Pepper	
13	Herbs	
30	Garlic	
20	Ginger	
30	Turmeric	
100	Oil	
1700	Water	
Rice		
1000	Rice	Wash rice. Add to water. Bring to boil, stir frequently until rice is done to touch. Drain.
5020	Water	

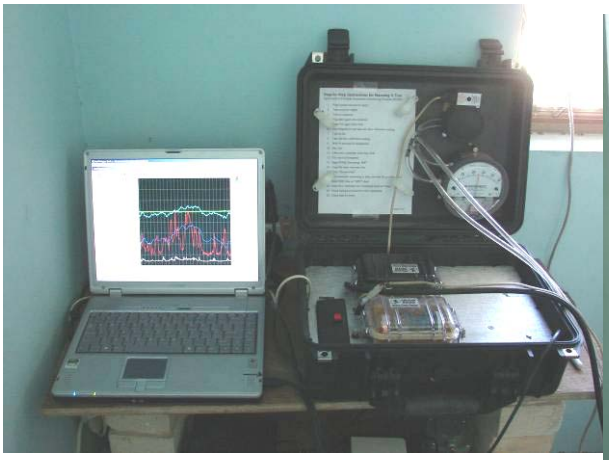
It should also be noted that the mass of cooked food was measured after the rice was drained. This is because the women would habitually drain it immediately, making it difficult to coordinate timely measurements. Therefore the amount of "cooked" food appears lower than it would if the extra ~3 Liters of boiling water had been included. In cases where the food must be drained, it is a judgment call whether to weigh before or after. Either method is considered acceptable, as long as the same protocol is used throughout a test series.

7. Pots –

The pots were typical 6-Liter aluminum Indian pots, available for purchase in many shops. It was noted that the lids, equipped with holes for steam escape and later draining of rice, were used about 50% of the time. Additional smaller pots were used for frying the vegetables and boiling the dahl.


8. Emissions Collection Equipment--

To investigate the total emissions released during a cooking task, the emissions must be collected, analyzed, and then removed from the room. The Portable Emission Monitoring System, or PEMS, was developed by Aprovecho Research Center for laboratory and in-field emissions collection and measurement. The PEMS consists of a hood structure, blower and flow measurement system, and sampling system for the emissions. The emissions monitoring system is designed for quantification of the total emissions released during a cooking task. The PEMS used in India was equipped to measure CO, CO2, and PM in real-time. Additional equipment was added for gas and particle sample collection.




9. Indoor Air Pollution Equipment

To investigate the possible reduction in room concentration of pollutants, a separate series of the same experiments was conducted. These experiments were done in a room with relatively constant ventilation using an Aprovecho IAP meter that measures concentrations of CO and PM every 10 seconds. The average concentration of both CO

and PM were compared between stoves as meals were being prepared, allowing for 1.) Estimation of the exposure to the cook, as well as 2.) Estimating the relationship between total emissions (measured in the hood by the PEMS) to dispersed emissions (measured in room concentrations by the IAP monitor).

The room dimensions were 4.4 m by 3.4 m by 3.0 m tall, for a total volume of 45 m^3. To ensure adequate ventilation for the safety of the cook, there were three open windows, each with dimensions of 1.2m X 0.4 m. The 2.1 m X 0.8 m door was also open with a ceiling fan running about 2 m from the door. The IAP meter was placed 1.5 m to the side and 1.5 m up from the center of each stove.

The room was tested two times for ventilation levels using a tracer gas decay method which resulted in an average of a **nominal air exchange rate of approximately 30 air exchanges per hour**.

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10. Experiment Construction

The following matrix of tests was conducted in both settings: total emissions measured in one room and room concentrations measured in the other room.

Cooks	**Single Pot**	**Double Pot**	**Chimney**	**Kerosene**	**Three-Stone Fire**
Cook A Cook B Cook C	3 Meals Each Improved, 3 Meals Each Traditional			3 Meals, Various Cooks	3 Meals, Various Cooks
Cook D Cook E Cook F		3 Meals Each Improved, 3 Meals Each Traditional			
Cook G Cook H Cook I			3 Meals Each Improved, 3 Meals Each Traditional		

The outcome was extensive data on 60 tests, in each of two emission measurement settings (PEMS and IAP monitor), for a total of 120 meals analyzed.

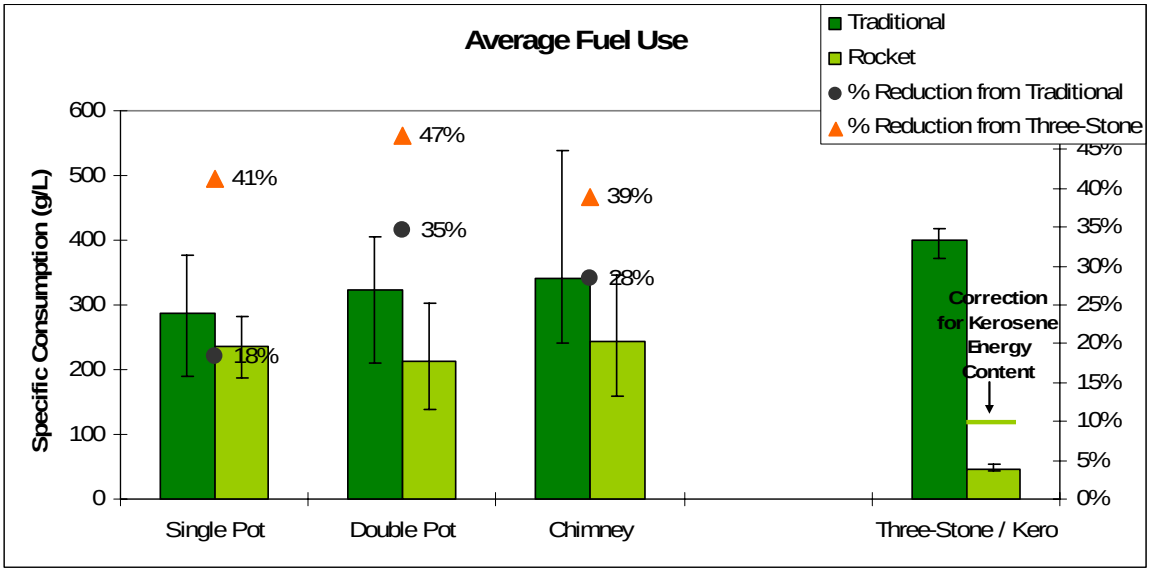
Results

The following presents the results based on the average of three cooks per stove model. It should be noted that the variability between cooks was quite high, suggesting the cook can be as important a variable as the stove.

1. Fuel and Time Savings

The fuel use data represents the average fuel use from both the PEMS and IAP test series. Each bar represents the average of 18 tests. However, kerosene and the three stone fire were tested only 6 times each. Error bars show maximum and minimum data point seen from of all three cooks in both the PEMS and IAP test series.

Please note that data is presented as specific fuel consumption rather than the total mass of fuel used for the cooking task. Specific fuel consumption is the grams of dry fuel used per Liter of cooked food produced. Specific consumption is generally preferred for reporting as it has been corrected for the moisture content in the fuel and the amount of water boiled off during cooking.

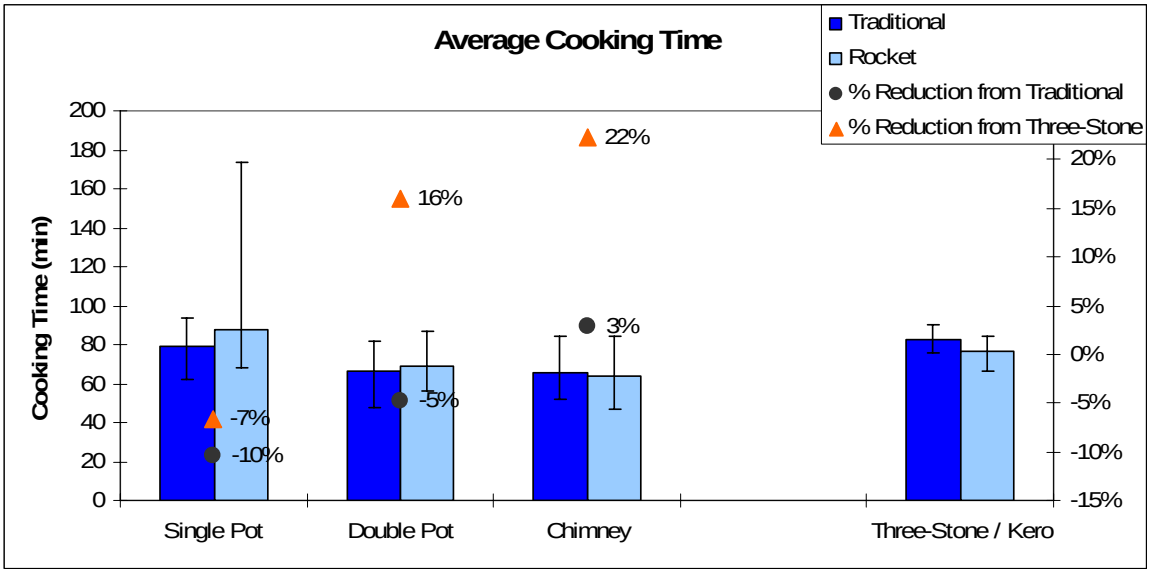


The single pot Rocket stove (without pot skirt) used 18% less fuel compared to the traditional stove. It saved 41% of the fuel compared to the open fire. The two pot used 35% less fuel compared to the traditional stove and saved 47% compared to the open fire. The chimney stove followed the same pattern by reducing fuel use by 28% compared to the traditional stove and 39% compared to the open fire.

The traditional stoves create a shield around the fire and create gaps under the pot that force the flames closer to the bottom and sides of the pot. The Indian traditional stoves were also shown to be improvements over the open fire. The difference in fuel savings between cooks was large. Cooks who made careful traditional fires saw almost no improvement when switching to the Rocket stove. How cooks operate the stoves is a powerful determining variable.

The fuel use of kerosene to cook the standard meal was approximately 315 grams, or 390 mL, per meal. At the subsidized cost of kerosene (9 Rupees per Liter) the cost of cooking this meal with kerosene is 3.5 Rupees. Black market kerosene (30 rupees per Liter) would cost about 12 Rupees per meal. The same meal cooked on the improved stoves required about 1.5 kilos of firewood, while the traditional stoves used about 2.2 kilos. The cost of this would depend on the source of the firewood.

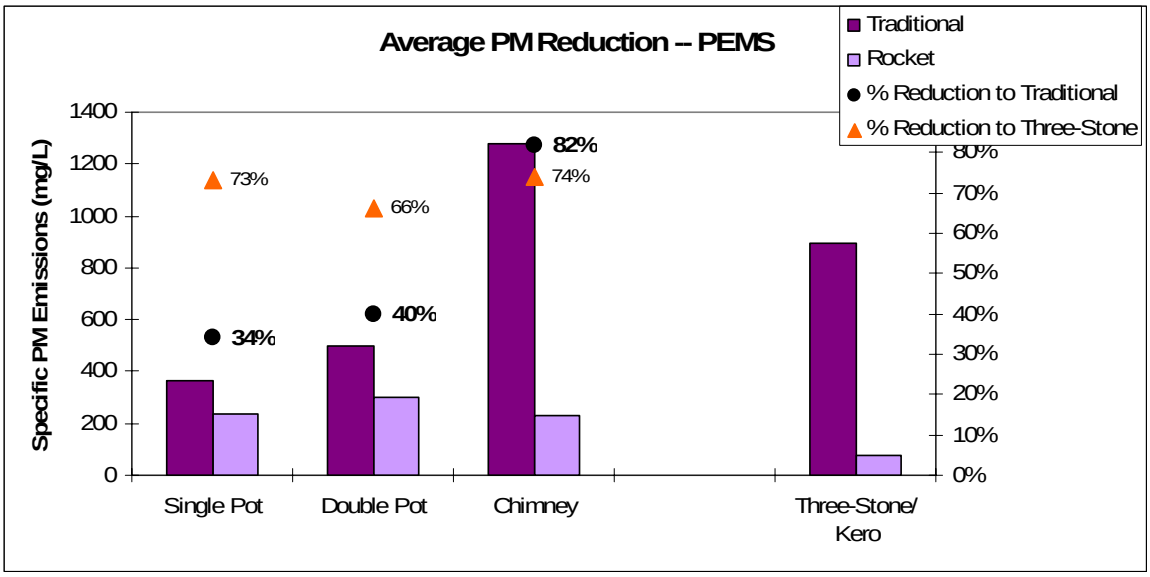
2. Average Cooking Time



Differences in cooking times between the Rocket stoves and the traditional stoves were generally negligible. The double-pot stoves saved about 20% of the time as compared to the single pots (including three-stone and kerosene). The chimney stove required the same average amount of time as the non-chimney double pot to cook the meal. The single pot Rocket stove was slightly slower to cook compared to the open fire but the two pot stoves were 16% and 22% faster.

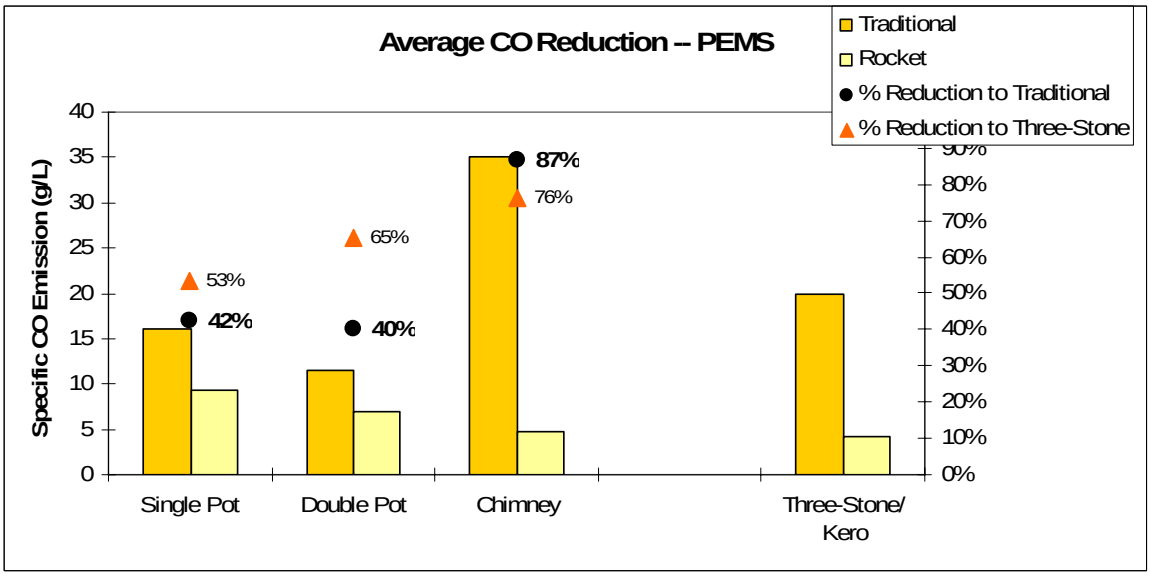
3. Total Emissions Savings

Total Emissions as measured by the PEMS system are an indication of the in-field combustion efficiency of the stoves. In the next two charts, the total emissions from the chimney of the chimney stove are reported as opposed to emissions escaping the stove body.



The three Rocket stoves reduced Particulate Matter emissions by 73%, 66%, 82% compared to the open fire. These stoves reduced PM by 34%, 40% and 74% in comparison to the traditional stoves. The Rocket chimney stove most successfully reduced PM which may be due to higher draft in the stove or increased dwell time throughout the stove body. The Rocket chimney stove was cleaner burning, with most of the emissions occurring at start-up. The clean combustion of the chimney stove results in less emissions being released into the outside air.

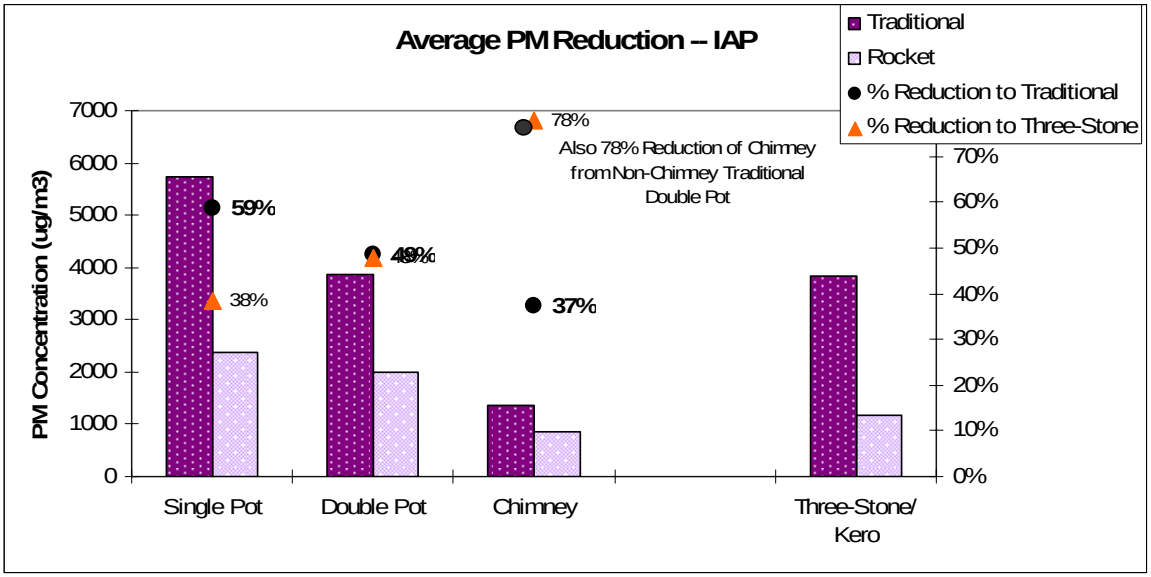
It can be seen that kerosene did create some PM. When lighting the stove, considerable smoke is visible. Also, the pressurized stove requires frequent cleaning of the nozzles as it becomes clogged and low-powered at least once per cooking test. To remedy this, the cook must insert a pin into the nozzles to force out the clog. When this is happening, a great deal of toxic smoke is produced. Frequently cleaning puts the fire out, so the stove must be re-lit, releasing an additional quantity of smoke.

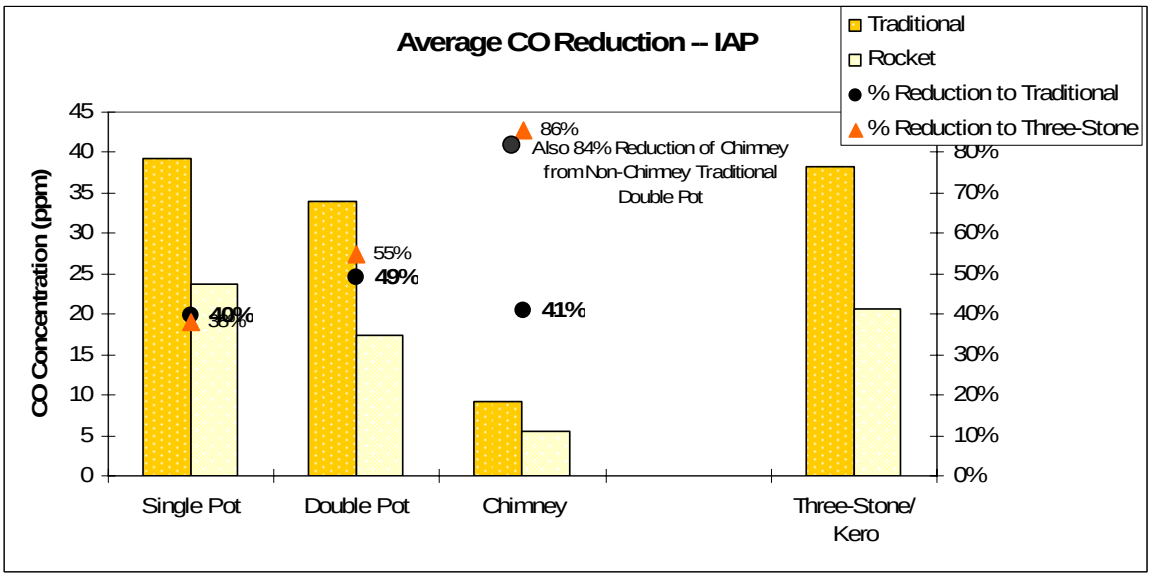


The reduction in carbon monoxide of the stoves is of a similar magnitude to the PM reduction. Again, Kerosene did emit fairly high levels of CO. The CO emissions seemed to be more of a steady-state artifact of kerosene combustion rather than due to start-up and cleaning of the stove.

4. IAP Comparison—

As explained previously, the PEMS series investigated total emissions while the IAP study measured the average concentration of emissions dispersed within the room during the cooking task. The room concentration study revealed the following:



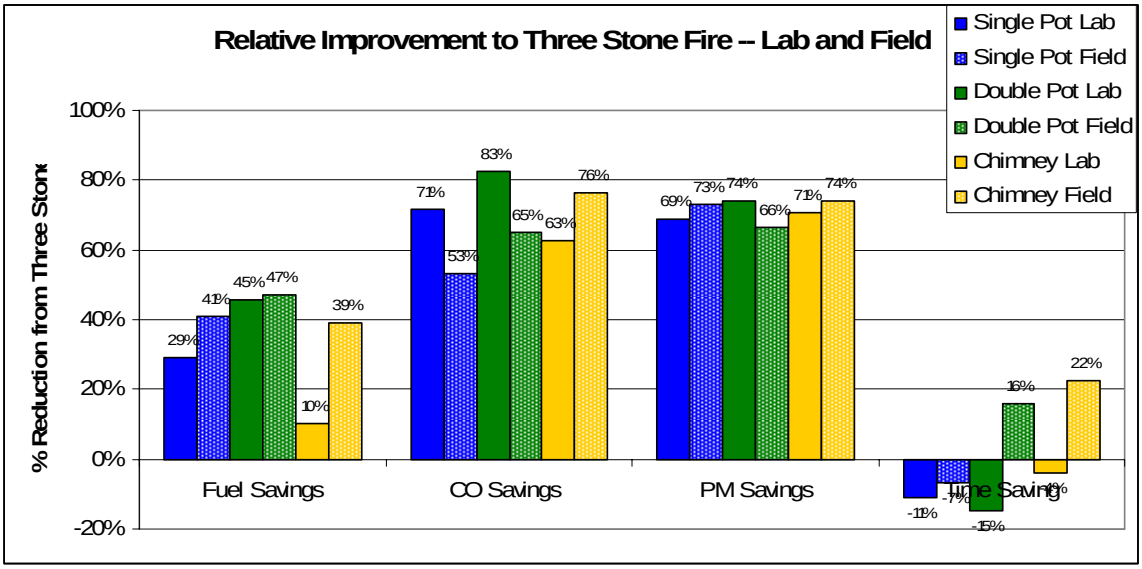


The Rocket stove single pot and double pot stoves without chimneys both exhibited improvement over the traditional method on measured levels of Indoor Air Pollution exposure to the cook. This improvement in IAP was approximately 50% on all measures.

The Rocket stove chimney removed most of the pollution from the room. The reduction was about 40% as compared to the traditional chimney stove, but more than 80% when compared to the non-chimney traditional stove or open fire. Some smoke did remain in the room, however. This seemed to be predominantly due to the habit of the women to start the stove with the pots off. The majority of emissions occur at startup, and these are released into the room and then linger until replaced by the ventilation with fresh air. Nevertheless, when the chimney stove is compared to the non-chimney stove, an 82% reduction in IAP is seen.

5. *Comparison between Lab (WBT) and Field (CCT) Studies –*

One of the intentions of this study was to examine how well the Aprovecho lab studies of stoves relate to the field performance tests. The following chart shows the performance of each of the three Rocket stoves performances as compared to the three-stone fire in the four major areas of concern:



Generally there was a good agreement when comparing the total emissions from the stoves to the three stone as measured in both the lab and field. Fuel savings was greater in the field, anywhere from 2% in the two-pot to 29% with the chimney stove. Reduction in CO was less than expected in the field from the non-chimney stoves with an 18% difference. There was a13% improvement from the chimney stove in the field.

PM savings were remarkably close, with all three stoves agreeing within a relative 8%. Time savings were well predicted for the single pot, but the double pots saved more time than expected in the field. This may be due to the actual cooking process making best use

of the two pots as opposed to the standard WBT which remains focused on the first pot only. Overall the link between WBT and CCT seen here seems to be quite strong.

Observations

The cooks were carefully observed during the cooking processes. They were also interviewed regarding their impressions upon completion of the testing. The major observations and comments were as follows:

- Women who have scarce firewood available tend to build careful, clean fires, while those with an abundant scrap wood supply seemed to make larger fires in all stove types. Variation between cooks was high on most measures, suggesting the cook is an equally important variable as the stove.
- The women comment that pots stay cleaner on the Rocket stoves than they do on the traditional stoves. In the traditional stoves, the slow sooty flames wrap around to the top of the pot.
- The women liked to start the stoves with the pots off. This is unfortunate practice for the chimney stove, since much of the emissions occur when the fire is first lit.
- One of the women was a part of the focus group one year ago. She loved the stove and was helping to teach the other women in her village how to use the stoves properly.
- Some of the women felt the single-pot pot supports are too thin. If they were thicker they would last longer and the pots would be "more comfortable."
- When the sticks are almost fully burned, the remaining ends can hit a tipping point and fall through the fuel shelf, creating an unsafe situation. An extra bar added near the inward end of the fuel shelf would prevent this.
- One cook felt there was not enough space for the ash to collect under the fuel shelf when cooking large meals at home.
- When the women asked about the price of the stove, they all compared that price to what they would pay for LPG. Some women had an LPG cylinder which they paid 300-500 rupees for and made it last for 1 year. Some women thought 400-1000 Rupees might be affordable for the improved stoves, as they thoughtfully considered the amount of materials in the stove. The issue of price was not approached with most women as the interviewers did not want questioning to interfere with the test series.

Summary

The Controlled Cooking Test series conducted on the pilot stoves in India was a positive experience. Results showed fuel and emissions savings to be substantial, and generally in-line with what was expected from the laboratory design. The portable emission equipment functioned well and was easy to use and unobtrusive to the cooking process. Observation of the cooking practice was informative, and spending time with the women

who will actually use the stove was invaluable. It is hoped that the results of this study can be shared in order to encourage other stove groups to take the time and direct resources needed to conduct field testing in a careful and scientific manner.

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