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Partnership for Clean Indoor Air Biannual Conference
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Trying to find out how to make improved stoves has been my personal pursuit now since 1989 when I met Larry Winiarski under a shady tree at Aprovecho. Every year I feel that we make progress and as I grow older I appreciate how much work it takes to move towards success. My goal today is to share what we have studied at Aprovecho since the last PCIA meeting. It has turned out to be an extended list. The list became long enough that I wrote down what I feel are the most important learnings and hopefully each of you has a copy in your hands. I wanted to write it down so that you can see graphs and drawings and maybe even re-read parts that you find interesting.

Perhaps we could all agree that an improved stove needs to please the cook because if it doesn't it may well not be used. I think that an improved stove should make cooking: easier, cleaner and more pleasant. At the same time, it's important for the stove to: save fuel, remove or reduce harmful emissions from the kitchen, and hopefully help to reduce the emissions adding to climate change. Is it a lot to ask? Maybe this defines good engineering?

Aprovecho uses two tests to create prototypes to create stoves: A Water Boiling Test and a Controlled Cooking Test. The WBT uses the same wood, same pot, the same way of making the fire to try to isolate the performance of the stove. Promising prototypes then go to groups of local cooks, almost always women, who use their own wood, their pots and their ways of making fires to see if the stoves are useful. This is the CCT. We go back and forth between lab (WBT) and field testing (CCT) until stoves evolve that use less wood, make less pollution and are liked by cooks. The process can take months and months, as you can imagine. A lot of times cooks end up wanting more than one kind of wood burning stove!

One method to determine if stoves are "improved" has been to compare them to the Three Stone Fire. How the fire is operated has a large effect on performance. The Three Stone Fire can be very smoky and use lots of wood to cook or if operated carefully can be moderately efficient. This difference has made comparing fires much more difficult. How stoves are used changes all measures of performance. I think that how the fire is made is the most powerful variable, more important than wood moisture, wood type, etc.

In the Aprovecho laboratory we tested 18 stoves nine times each using a Water Boiling Test in which every stove was operated carefully trying to optimize using fuel to boil and then simmer 5 liters of water in a 7 liter pot. The stoves were tested under an emissions hood that measured how much carbon monoxide, carbon dioxide, hydrocarbons and particulate matter less than 2.5 microns was emitted during the boiling and simmering. Because the amount of air flowing through the hood is known, the parts per million of pollutants can be refigured into weighed amounts. CO is reported in grams and PM (which is a lot lighter) is reported in milligrams.

The same stoves were also tested in a Test Kitchen where water was boiled and simmered with all the windows and doors closed. The CO and PM were measured using HOBO data loggers for the CO and A.P. Buck and Airmetrics pump and filter particulate meters. It was interesting that the tests done under the hood and in the Test Kitchen resulted in similar findings. More on that later…

We tested stoves that used wood, charcoal, propane, alcohol, kerosene and solar energy. The same dry wood, same pot, same method of feeding the fire was used in each test. The Water Boiling Test attempts to isolate the stove as the experimental variable. Comparing the 18 stoves has shed some light on how to define an improved stove which I will try to share in this talk.

Does boiling and simmering water carefully in a laboratory predict how the stoves will perform in houses? With stoves like propane, alcohol and kerosene where operator influence is minimized it may. However, cooks have a big influence on wood burning stoves and therefore testing in houses will more accurately predict local results.

The Three Stone Fire was thought to be very inefficient in the 1970's when the first large scale stove movement began. Early studies characterized the open fire as between 5-10% efficient: saying that only that small percent of the heat from the fire entered the pot on average. Several years ago Dr. Tami Bond got the highest thermal efficiency that I have witnessed when operating a Three Stone Fire: (32%).

Dr. Kirk Smith and Dr. Grant Ballard Tremeer created a lot of controversy a decade or more ago when they separately wrote that tests of "improved" stoves had shown that some stoves were dirtier burning than a Three Stone Fire. Kirk has continued to remind stove makers that moving the pot closer to the fire can decrease fuel used but creates so much more carbon monoxide and particulate matter that the end result is more pollution made per meal even when less fuel is consumed. Many stovers now feel that an improved stove should save wood and make less pollution at the same time.

The Three Stone Fire was a bit cleaner than some stoves in our tests…

Three Stone Fire

Fuel Use	1126 g
CO	56 g
PM	2363 mg

Ghana Wood Stove

Fuel Use	875 g
CO	50 g
PM	4287 mg

The Ghana Wood Stove saved wood but as Kirk and Grant predicted made a lot more smoke (PM) compared to the Three Stone Fire. Surrounding a fire with walls can reduce fuel used, and keeps the wind from the fire, but by itself does not make a fire less smoky.

VITA

Fuel Use	668 g
CO	43 g
PM	2150 mg

Dr. Sam Baldwin is one of my great heroes, as some of you know. I have a lot of other stove heroes many of whom are here in this room. Sam studied fire for many years and in West Africa worked with villagers to create an inexpensive stove that was designed to save fuel. Back in the 70's smoke and CO were not really a big part of the design criteria. He found that using a sheet metal skirt with a tiny gap all around the sides of the pot really helped to get more of the heat into the pot. Getting more of the heat into the pot decreased the amount of wood need to boil and simmer water.

The size of the gap is very important. The gap has to get bigger when the fire is larger because a larger fire needs more air. If the gap is too small the draft of air into the fire is reduced. Then the fire starts to smolder and cannot make bigger, cleaner flames. But, if the gap is too big then the heat is not forced to scrape against the sides of the pot. Instead the hot gases flow up the middle of the gap and less heat gets into the pot.

I really like the VITA stove because it is simple to make, very portable and is the result of careful development. How to make the VITA stove is described in Baldwin's book, "Biomass Stoves: Engineering Design, Development and Dissemination" which is on the REPP stove site.
http://www.bioenergylists.org/stovesdoc/apro/VITA/vitastove.pdf
Also we have a video showing how to make the stove at: Aprovecho.org.

Four techniques that make water boil faster:

1.) Create a large enough fire in the combustion chamber.

2.) Force the hot gases to scrape against the bottom and sides of the pot in narrow channels.

3.) Make sure the hot gases are as hot as possible.

4.) Increase the speed of the hot gases flowing over the surface of the pot.

Mud/Sawdust

Fuel Use	793 g
CO	48 g
PM	2352 mg

A VITA stove can also be made from sand and clay. If sawdust or ground up grasses or leaves or rice hulls or any burnable material is added to the earthen mixture the walls will be more insulative which helps to decrease heat mis-directed into the stove body and helps to keep temperatures in the combustion chamber higher. Usually, a hotter fire is a cleaner fire. Although the stove is not as fuel efficient as the sheet metal version, nor as clean burning, it can be built with found materials. I like this stove and think that it is one of the best earthen stove designs.

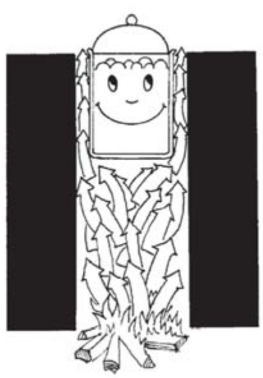
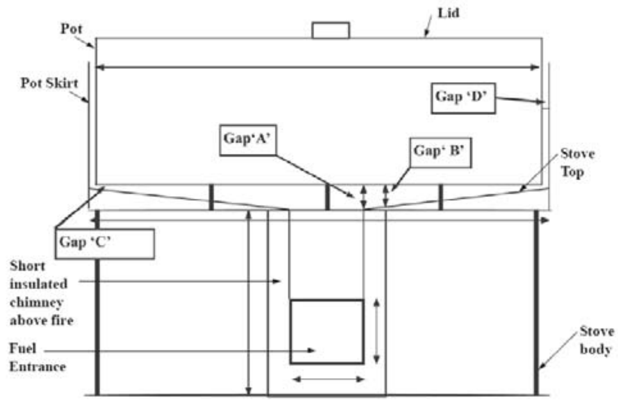


Figure 17 - A proper sized gap optimizes heat transfer to the pot

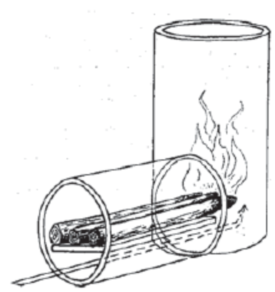
Figure 18 - Too large a gap will reduce heat transfer to the pot

The Right Sized Gap Under the Pot Helps, Too…

Hot flue gases can be forced to scrape against the bottom of the pot as well as against the pot's sides. If the space below the bottom of the pot has an improved shape more of the heat will enter through the bottom. This shape can be permanently made into the top of the stove. This simple adjustment saves a considerable amount of fuel.



The Rocket Stove



When Dr. Larry Winiarski invented the family of Rocket stoves in 1982 he also used the skirt technique to force the hot flue gases to scrape against the sides of the pot. But, under the pot and skirt he used an insulated short chimney right above the fire. The insulated chimney created more draft that assisted the air, smoke and flame to mix together. Mixing the air, flame and smoke together burns up some of the carbon monoxide and particulate matter so that less pollution is made per amount of fuel burned. The cleaner hot flue gases then go through the gap made by the skirt and a larger percentage of the heat gets into the pot. Improving Combustion Efficiency and Heat Transfer Efficiency together is the goal of the Rocket family of stoves.

The three T's

Carbon monoxide (CO) and particulate matter (PM) are always formed when fuel and air are not completely mixed, and complete mixing does not usually occur in stoves with natural draft. The orange color of flames comes from the radiation of PM (soot) within the flame. The blue color of flame results from the reaction of CO to produce CO2. So, colored flames indicate that PM and CO are being produced.

Emissions of these harmful pollutants can be reduced by burning them before the exhaust cools down. Wood stove designers know that this burnout requires the three T's: **"Time, Temperature, and Turbulence."** Time means that the longer the exhaust gas stays hot, the longer pollutants have to burn. Temperature means that the gas needs to stay as hot as possible; the reactions stop when the gas gets too cool. Turbulence is an engineering word describing rough flow. If the air is turbulent, pollutants have a greater chance of coming into contact with oxygen so they can burn out.

A stove can be designed to optimize both heat transfer efficiency and combustion efficiency at the same time:

Heat Transfer Efficiency

In continuous feed stoves, Heat Transfer Efficiency (HTE) into the pot is determined by:

- *Temperature* difference between the flue gases and the outer surface of the pot
  - The flue gases should be kept as hot as possible
- *Proximity* of the flue gases to the pot
  - The gases should be forced to pass close to the bottom and sides of the pot. Heat transfer is slowed by the boundary layer of still air around the pot.
- *Velocity* of the flue gases
  - Hot flue gases more effectively heat the pot when velocity is increased. Faster flue gases get closer to the pot.

Increasing HTE decreases fuel use.

Combustion Efficiency

To improve Combustion Efficiency (CE):

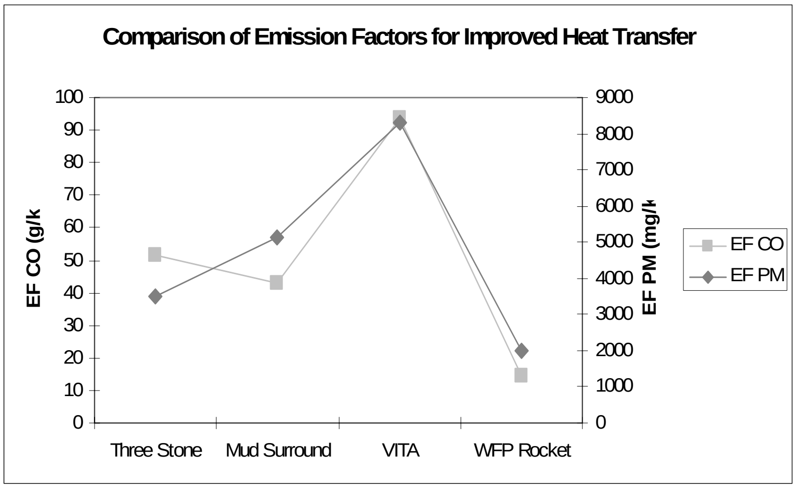
- Keep the combustion area as hot as possible to burn up pollution.
- Incoming air should be directed into the fire and coals. High velocity, low volume jets of air clean combustion. Too much air can cool the combustion zone.
- Burn small amounts of fuel. Heating wood makes gas. All the gas should become flame. Too much fuel makes too much gas for the flame to burn and emissions rise.
- Shape the combustion chamber to encourage mixing of gases, air, and flame. This is the most important factor in clean combustion.

Increasing CE decreases harmful emissions.

Dr. Larry Winiarski, the inventor of the Rocket stove, approached designing stoves by separating functions. His hope was that if wood was burnt in an improved combustion chamber that cleaner hot gases could be forced to scrape against the pot without making more smoke.

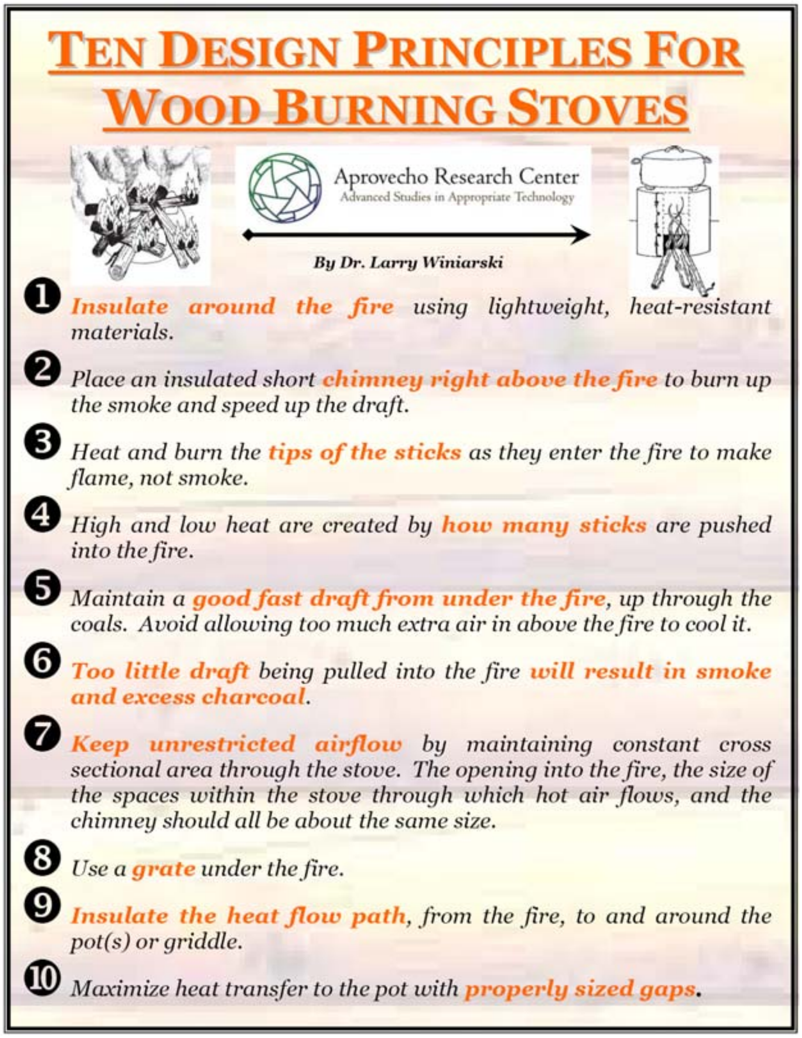
The following chart shows examples where increasing HTE can decrease CE. Emission factors, which report the mass of pollution per mass of wood burned, are used to compare CE. As can be seen, the Mud/Sawdust stove and especially the VITA stove sacrifice clean burning for reduced fuel use and quicker time to boil. However, neither of these stoves has a combustion chamber.

In these stoves the CE is unimproved. HTE is increased by using small channels that force the hot gases to scrape against the bottom and sides of the pot. The condensing of dirty gases on the cool surface of the pot can make more pollution per meal compared to the open fire (3 Stone Fire).



	Three Stone	Mud Surround	VITA	Rocket
Time to Boil (min)	27	16	14	22
Fuel to Cook (g)	1118	793	689	733
CO to Cook (g)	56	49	43	15
PM to Cook (g)	2363	2352	2150	1289
Emission Factor CO (g/kg)	51	43	93	14
Emission Factor PM (mg/kg)	3520	5124	8328	1976

Using an insulated combustion chamber can clean the gases before contact with the pot. This technique improves Combustion Efficiency and Heat Transfer Efficiency simultaneously. Well engineered combustion chambers in cooking stoves create cleaner gases that can be forced to more effectively get heat into the pot.



VIDEO

Stoves with Chimneys

Uganda Two-Pot

Fuel Use	720 g
CO	22 g
PM	678 mg

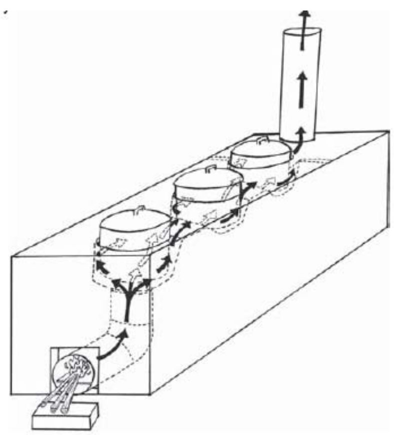
Ecostove

Fuel Use	2014 g
CO	48 g
PM	5102 mg

Several of the chimney stoves that we tested were not designed primarily for boiling water. An example is the EcoStove designed by Rogerio de Miranda and manufactured in Brazil by the NGO Prolena. The EcoStove has a very nice heavy cast iron griddle that is used for grilling. A large flat griddle (or 'plancha' in Spanish) is needed for making flat breads like tortillas.

Heat has to pass through the griddle to the pot. And wherever the pot is not touching the surface heat is unused for heating the water. A Water Boiling Test therefore does not adequately test the utility of this type of cooking stove. For this reason, fuel use was elevated. But cooks love grilling on the EcoStove. It should be noted that the griddle not the chimney is responsible for the higher fuel use.

When a chimney stove is designed to boil water fuel use can be as low as other improved stoves. The Uganda Two Pot stove is an example of a fuel efficient stove with a chimney.



A Rocket type combustion chamber made from clay/sawdust fired bricks sends hot flue gases directly at the bottom of the first pot. The pot is partially submerged under the top of the stove. Because the pot(s) fit tightly into sheet metal enclosures, the hot flue gases are captured and flow past the bottom and sides of both pots in correctly sized gaps. The Uganda Two Pot boils water about as quickly and uses about the same amount of fuel as stoves without chimneys. Submerging the pots is a very effective way to create a fuel efficient stove with chimney. In China, most stoves use this technique.

Using a chimney can remove essentially all the pollution from the living space. When the chimney stoves were run in a Test Kitchen the results were dramatic. In 1997, approximately 30 million homes in the United States were heated by burning wood. Chimneys protected the inhabitants from the dangerous levels of pollution made by stoves that frequently operate for months at a time. A functional chimney can remove all the emissions made inside the stove if there are no leaks in the stove or chimney.

Chimneys protect the well to do from smoke on planet Earth and they could do the same for everyone. Submerging pots into the chimney stove improves heat transfer so that food is cooked without additional wood use or extending time to boil. The functional chimney has evolved to be the primary low cost solution to indoor air pollution. If there are no leaks, pollution is removed from the house and diluted in the outside air.

Figure 16 - Chimney Stoves: Fuel to cook and time to boil

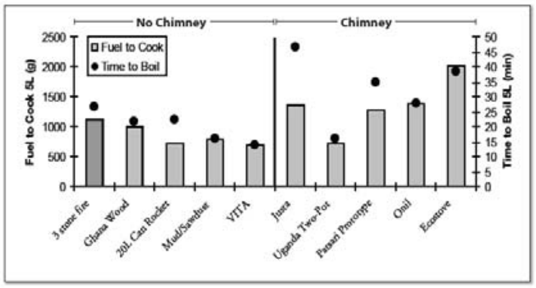
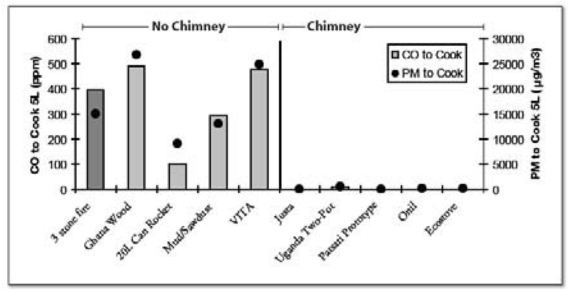
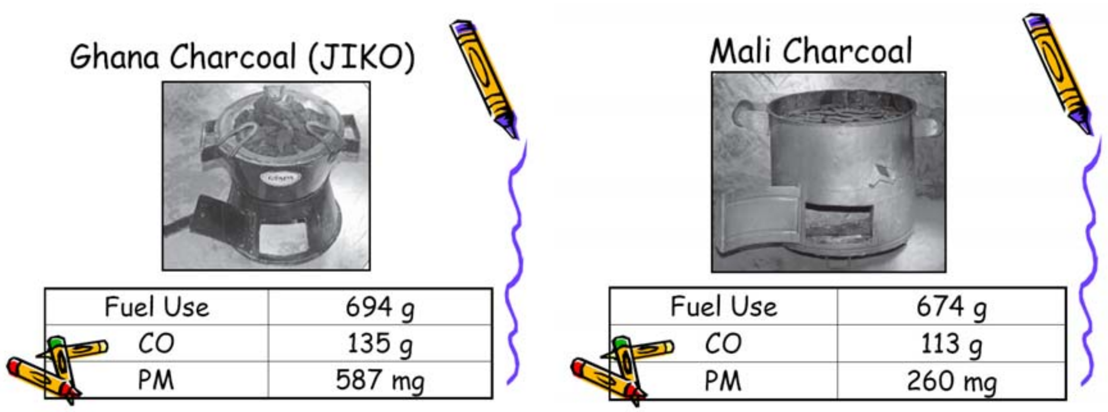


Figure 17 - Chimney Stoves: Kitchen emissions to cook 5L



Charcoal Stoves

We used mesquite charcoal made from trees and branches in Mexico in these tests. Two stoves were tested, one from Ghana and the other from Mali. These stoves had outperformed more traditional stoves in previous experiments.

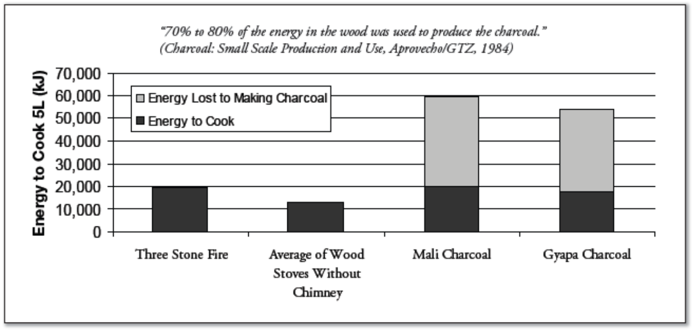


Charcoal is made by heating wood or other biomass inside a relatively airtight enclosure, like an earth covered pit in the ground. The smoke escapes through holes in the covering and causes air pollution. The wasted smoke is fuel that could have been used to cook food. “70% to 80% of the energy in the wood was used to produce the charcoal.” (Charcoal: Small Scale Production and Use, Aprovecho/GTZ, 1984).

“The charcoal thus produced retains the same shape of the original wood but is typically just one fifth the weight, one half the volume, and one third the original energy content.” (Biomass Stoves, Baldwin 1986)

The following graph compares the energy in charcoal and wood fires. Since so much energy is lost when making charcoal, wood stoves were found to be much more energy efficient. Almost three times as much total energy was used to cook food with the charcoal in these tests.

Figure 30 - Charcoal comparison - Energy used to cook 5L



The two charcoal stoves boiled water slower than the Three Stone Fire and the average single pot wood burning stove. Charcoal has a great advantage that it keeps going almost like propane with little tending. It seems especially well suited to simmering food. Reducing the air entering the fire prolongs the useful cooking time and provides a gentle heat.

Figure 31 - Charcoal comparison: Time to boil 5L

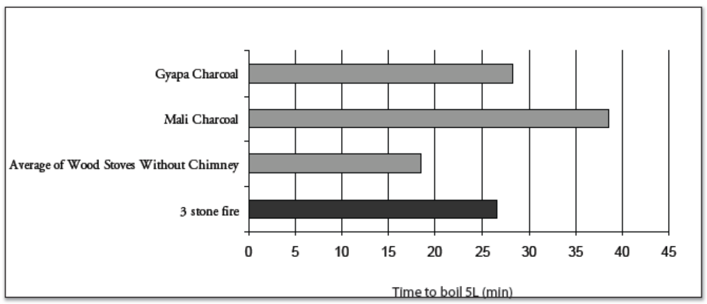
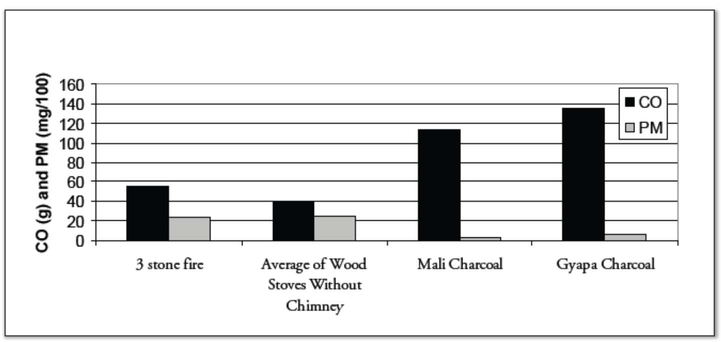


Figure 32 - Charcoal comparison: CO and PM emissions to cook 5L



Charcoal is well known for making a lot of carbon monoxide. In these tests this was certainly true. The amount of CO was at least twice as high as any of the wood burning stoves. On the other hand, particulate matter emissions are quite low, especially during simmering. The real reduction in PM is a positive benefit of using charcoal.

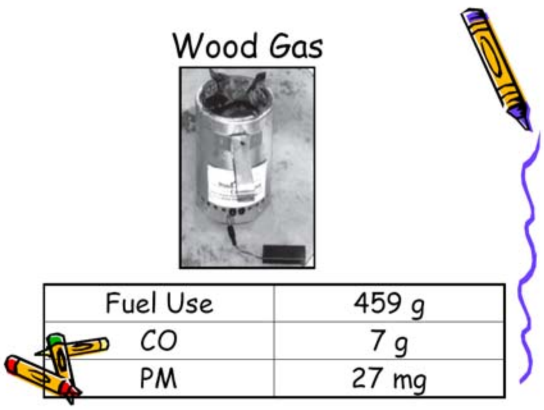
Burning Charcoal in a Vertical Combustion Chamber

Charcoal is usually burned directly under the pot. Air comes through a door under the charcoal up through holes in a grate and enters the combustion zone. The pot sits very close to the bed of charcoal in a shallow bowl shaped combustion chamber. Recent experiments at Aprovecho have shown that burning charcoal chunks in an insulated vertical combustion chamber can reduce fuel used and emissions.

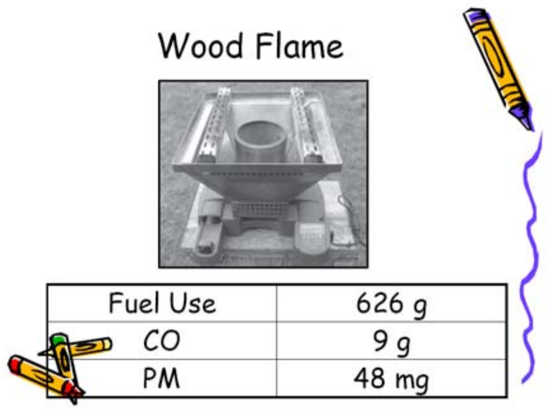
The emission performance of charcoal is largely dependent on the configuration of the charcoal. When small pieces of charcoal block the air, charcoal smolders and does not burn as cleanly. In this way, it is the same as the combustion of wood. Wood and charcoal burning is greatly influenced by the arrangement of the fuel. Large chunks of mesquite charcoal allow air to flow up through the pile which results in cleaner combustion. Burning the charcoal in an insulated cylinder provides some of the same benefits as when burning wood. The CO is given more time to combust and temperatures rise higher which improves heat transfer decreasing fuel used to cook.

SHOW VIDEO

Forced Air Stoves



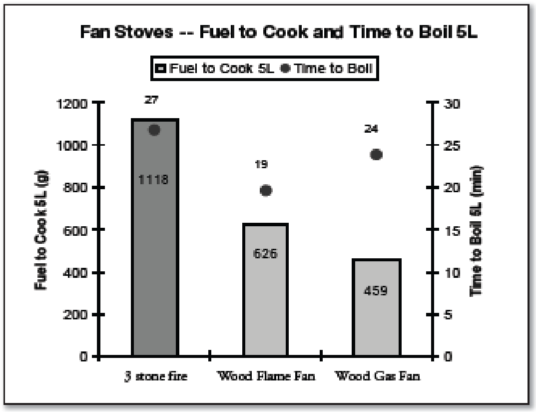
Fuel Use	459 g
CO	7 g
PM	27 mg

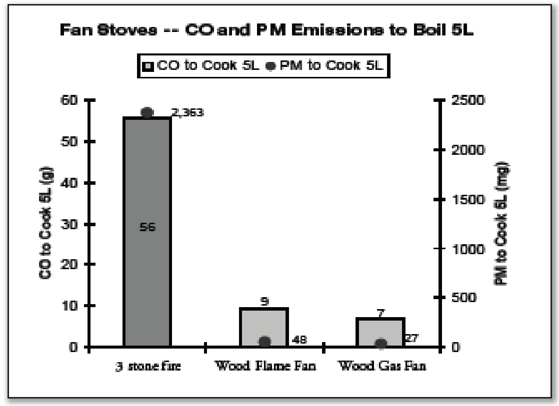


Fuel Use	626 g
CO	9 g
PM	48 mg

We tested two stoves that used electricity to run a fan. This fan created jets of air that shoot into the fire. The jets of air help to burn wood in many ways. In natural draft stoves the flame air and smoke are not forced to mix very well. Smoke goes one way and flame another way. However, if all the smoke is forced to contact flame it combusts. When jets of air create very good mixing emissions are dramatically reduced.

In the Wood Gas stove, designed by Dr. Tom Reed, jets of air are blown into and above the fire. The Wood Flame stove only blows air up into the bottom of the fire. Both techniques work very well. These fan stoves used an average of 540 grams of wood to boil and simmer the water. The average stove without a fan used 870 grams to do the same task. The fan increased both the temperature and velocity of the hot gases touching the pot. Heat transfer is increased which lowers fuel used.





These stoves are remarkably clean burning! The Rocket stove is cleaner than some other stoves but fan stoves are a lot cleaner burning. Adding a fan to a stove or adding a chimney are two really good ways to reduce Indoor Air Pollution.

It is quite possible to make low cost stoves with fans. It has been estimated that 40% of the people who use biomass for cooking also have electricity in their homes. Small fans are not expensive and making high velocity jets can be accomplished by drilling very small holes that blow the air into the fire. I am sure that many people in this room could design and make fan stoves that cost between five and ten dollars.

The Wood Gas and Wood Flame stoves are handicapped because they require small bits of wood fed often into a cup like combustion chamber. We have built more normal fan stoves that are side fed with long sticks of wood. The jets of air have to be aimed up the combustion chamber so that smoke is not pushed out of the fuel entrance. But, again many people in this room could design and build inexpensive side feed fan stoves. In Viet Nam, Damon Ogle, Research Director at Aprovecho, took pictures of street venders grilling meat who used hair dryers to blow air into the fire. Now that's one way to preheat air!

Haybox Cooking

When simmering food, the fire replaces the constantly lost heat from the pot. If the heat stayed in the pot then it would not need to be replaced continually and much less fuel would be needed to cook food. Placing the boiling pot of food in an airtight insulated container keeps the food hot enough that most foods can simmer to completion. Once the pot is in the box, cooks can do other work. The Haybox saves time, effort and fuel, freeing the cook from long hours feeding the fire.

50% of time and fuel can be saved.

Figure 33 - Time savings through the use of a haybox

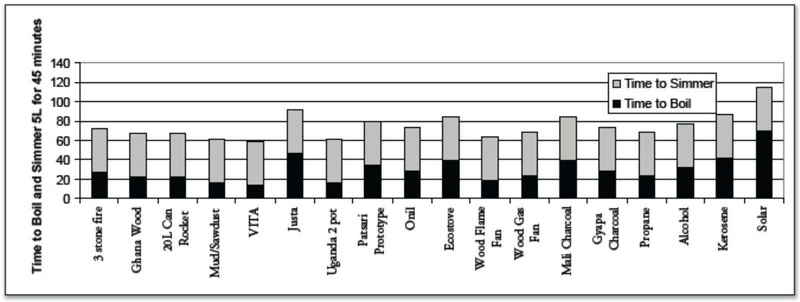
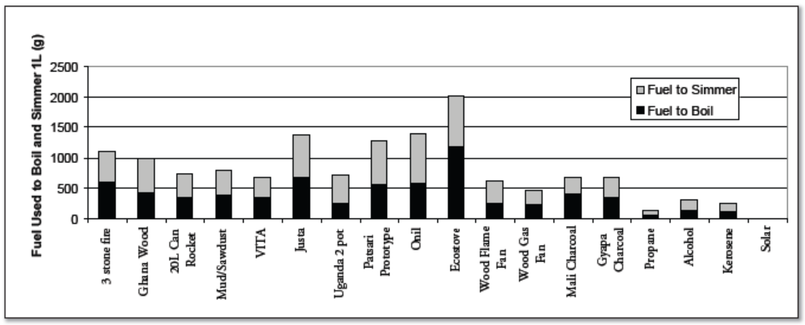


Figure 34 - Potential fuel savings through the use of a haybox



Because the fire is used only for bringing the pot to boil, the Haybox also decreases harmful pollution. The Haybox resulted in a 56% savings in CO and a 37% saving in PM emissions. (Less PM and more CO is made during simmering.) Charcoal makes CO, flame makes PM.

Figure 35 - Potential PM emission savings through the use of a haybox

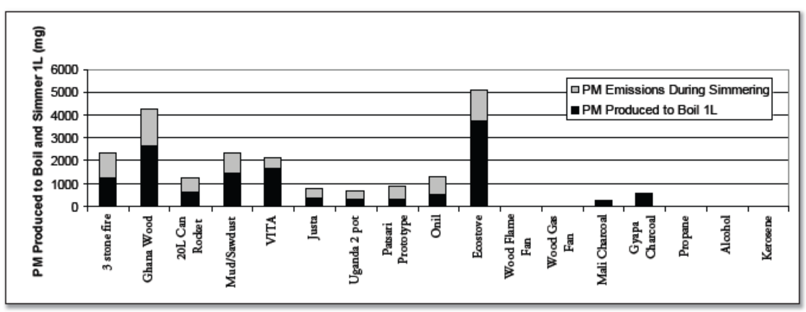
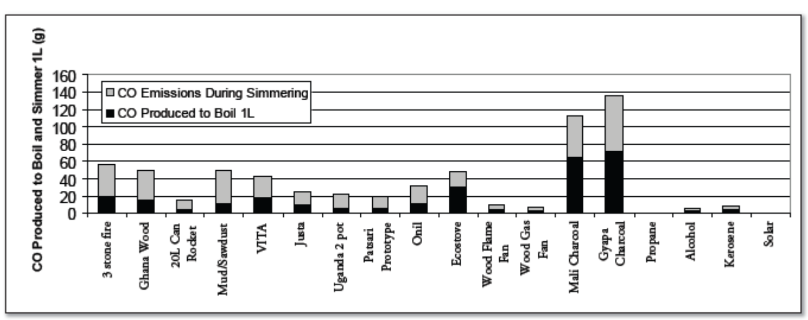


Figure 36 - Potential CO emission savings through the use of a haybox



Design Principles for a Retained Heat Cooker

1.) Air exchanges are more important than insulation
    A.) Make the enclosure as air tight as possible
    B.) Use R-7 insulation at a minimum

2.) The mass of the insulation and any mass within the envelope of insulation will rob heat from the pot of food unless the mass is above simmering temperatures.
    A.) Keep insulation and inner walls of the retained heat cooker as light as possible.
    B.) To work well insulation should not be less than R-2 per inch of thickness.
    C.) Full pots of near boiling temperature food retain more heat and cook food more effectively.

3.) Conduction looses more heat than convection. Convection looses more heat than radiation.
    A.) Lift the pot up off the floor of the box using a non-conductive material. Leave an air gap of .5 inch.
    B.) The walls and ceiling of the box optimally should be .5 inch bigger than the pot.

4.) Insulation looses its ability to slow the passage of heat when slightly moist.
    A.) Do not allow moisture to contact the insulation.
    B.) Use a moisture proof barrier between the pot and the insulation.
    C.) Use a closed cell insulation.

5.) The inner box will grow mold.
    A.) The inner surface should be easy to clean.
    B.) Cloth will become unsanitary if unprotected.

6.) To cook pinto beans
    A.) They need to be pre-soaked
    B.) The retained heat cooker needs to be able to keep 5 liters of water above 90C for 90 minutes.

Increasing Heat Transfer Efficiency

The next three graphs show different approaches to getting and holding more heat in the pot. As just discussed, the Haybox captures the heat and replaces simmering which reduces fuel used to cook and emissions produced.

Increasing Heat Transfer Efficiency

- Using a Haybox

Rocket Stove	Without Haybox	With Haybox
Fuel Use	689	360
CO	12	4
PM	1289	645

Changing the shape of the pot and floating oil on the surface of the water can act like a Haybox. The pot in the graph below has two tablespoons of cooking oil floating on the water. The oil completely stops the water from evaporating during simmering when bubbles do not rise rapidly so heat stays in the pot. (Most heat leaves the pot when the hot water evaporates and makes steam.) Reducing the surface area of the water also reduces evaporation. An improved pot has a large bottom to encourage heat to enter the pot and a small top so that less heat leaves by evaporation.

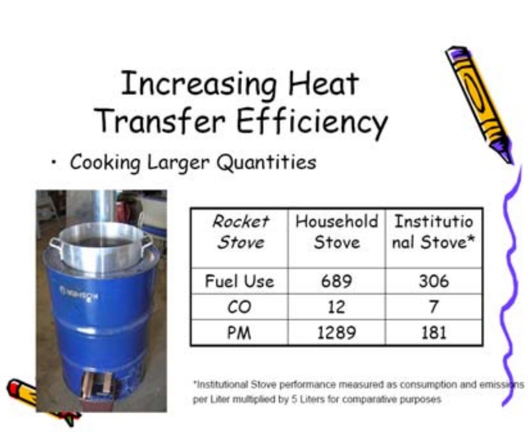
When this kind of pot with floating oil is used much less heat escapes. The remaining 40 grams of charcoal, made as wood was burned to boil the water, has enough energy in it to keep the pot at simmering temperatures (4 degrees less than full boil) for 45 minutes. A door closes off the fuel entrance allowing only a small amount of air to keep the charcoal burning.

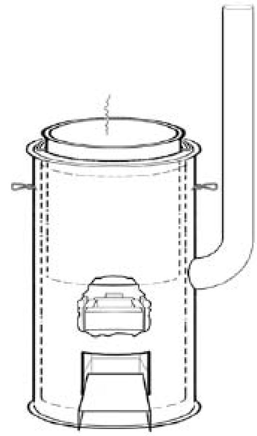
Increasing Heat Transfer Efficiency

- Reducing Evaporation and Simmering with Leftover Charcoal

Rocket Stove	Without Conser-vation	With Conser-vation
Fuel Use	884	383
CO	19	11
PM	712	441

Cooking larger quantities of food in a really big pot also increases heat transfer efficiency. The big pot has a lot more surface area and gets hot using less fuel per pound of food cooked. The institutional stove in the photo below is made from a 200 liter drum. The hot flue gases scrape against the bottom and sides of the big pot. As can be seen, both less fuel is used and fewer emissions are produced.



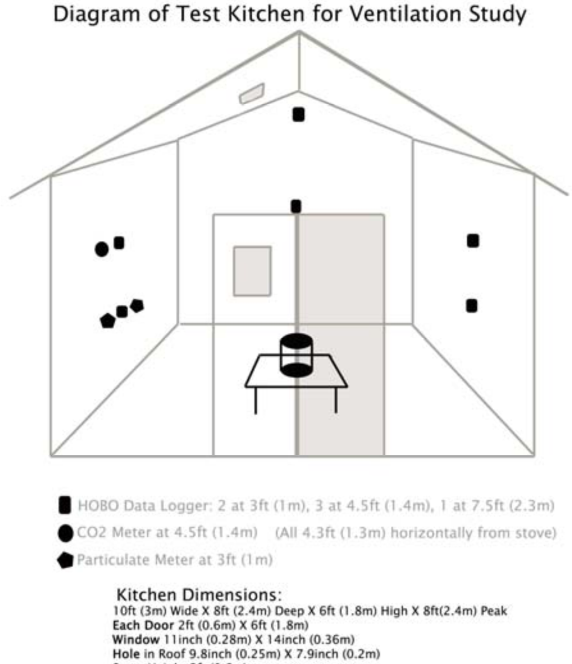


The Effect of Ventilation in the Aprovecho Test Kitchen

What happens in a kitchen to levels of pollution when a hole is cut in the roof, or if the door or window is opened? The stoves that were tested under the emissions hood were also tested in the Aprovecho Test Kitchen. The testing was done with windows and doors closed. The tester had to wear a forced air hood to be safe from the really high levels of pollution in the room. (We all know that many people especially in cold climates cook like this every day without protection.)

After the tests were done we wondered how much ventilation it would take to make the Test Kitchen a healthier place.

Diagram of Test Kitchen for Ventilation Study



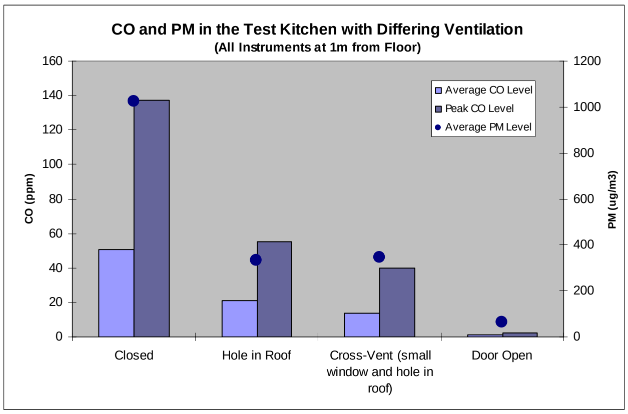
We burned charcoal in this study because we wanted to have similar findings and charcoal can be burned with predictable results.

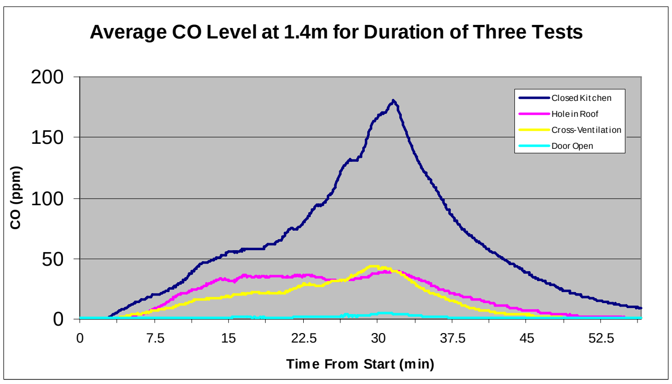
Three tests were performed with:

1.) All windows and doors closed.
2.) One 0.6m by 1.8m door open.
3.) Opening a 20 cm by 25 cm hole in the roof.
4.) Opening a small 28 cm by 36 cm window along with the 20 cm by 25 cm hole in the roof.

The charcoal was left to burn vigorously for 30 minutes. It was then quickly removed through a small opening in the door, which was then closed. The test continued for another 30 minutes as levels of carbon monoxide and particulate matter declined, for a total of one hour of measurement.

The following graph shows the peak concentration of carbon monoxide after a half-hour of burning, the average level throughout the test, and the average concentration of particulate matter during the four levels of ventilation. It was found that increasing amounts of ventilation dramatically lowered levels of both types of emissions. The second graph shows the average CO level at the height of 1.4m above the floor for the duration of each test:





The next chart summarizes the variability and potential reduction in IAP resulting from making a small hole in the roof, opening the door and window and only opening the door:

CO and Average PM Level Reduction by Ventilation		Average	Variation of Three Tests	% Reduction from Closed Kitchen	IAP Reduction for This Ventilation
Closed Kitchen	CO Average (ppm)	54	19%		
	CO Peak (ppm)	160	38%		
	PM Average (ug/m3)	1025	47%		
Hole in Roof	CO Average (ppm)	18	61%	67%	
	CO Peak (ppm)	41	75%	75%	
	PM Average (ug/m3)	334	69%	67%	**70%**
Cross-Ventilation	CO Average (ppm)	14	48%	75%	
	CO Peak (ppm)	44	65%	73%	
	PM Average (ug/m3)	345	62%	66%	**71%**
Door Open	CO Average (ppm)	1	40%	97%	
	CO Peak (ppm)	6	37%	96%	
	PM Average (ug/m3)	66	23%	94%	**96%**

The levels of both CO and PM with all the doors and windows closed were pretty high. A concentration level of 160ppm of CO makes people sick with nausea and headaches which gets worse with longer exposure. Opening the door and cutting a small hole in the roof successfully reduced these levels.

Three additional tests were run to study the stratification of pollutants in the closed kitchen using 6 HOBO CO data loggers and 6 MiniVol PM monitors at three different heights on opposite sides of the room. The HOBOS and MiniVols were located across from each other at 1 meter, 1.4 meters, and 1.8 meters in height. It was apparent that both the CO and PM tended to collect in higher concentrations near the ceiling and to taper off to lower levels near the floor. Levels were lowest near the floor suggesting that exposure could also be reduced by remaining seated or by squatting while cooking.

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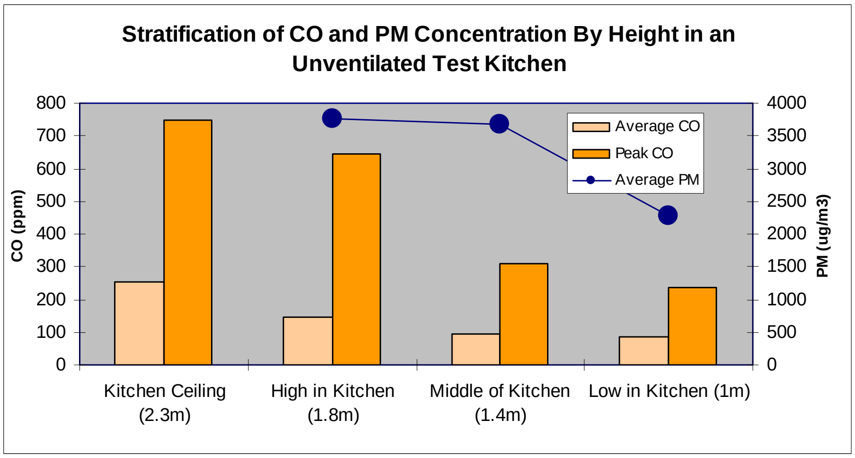


Levels were lowest near the floor suggesting that exposure could also be reduced by remaining seated while cooking.

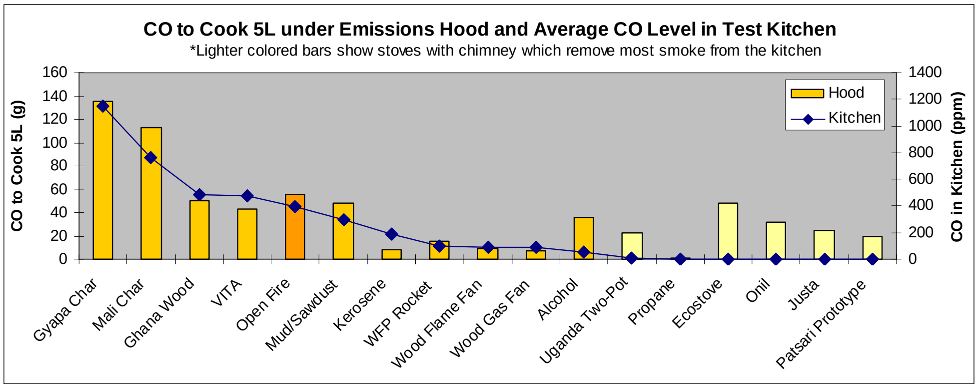
Using a Test Kitchen to Test Stoves

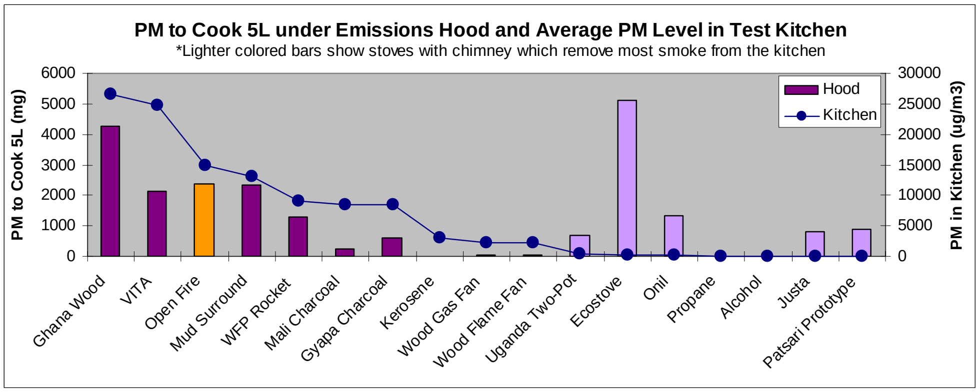
I like the Test Kitchen method for testing stoves. It is simpler and cheaper compared to using an emissions hood. It's not as accurate but as the graph shows below many of the non-chimney stoves performed about the same when tested under the hood and in the kitchen.

Aprovecho is working to develop a standard method for testing in a Test Kitchen. If stovers used a same size kitchen with the same number of air exchanges per hour and the same equipment to measure CO and PM we might all develop a method for doing Water Boiling Tests and Controlled Cooking Tests that measure emissions as well.

A Controlled Cooking Test involves local cooks using their own pots, wood, cooking methods, etc. Local cooks make the same food using traditional stoves and improved stoves. If say, ten local women made food using both stoves in a Test Kitchen then fuel savings and emissions could be compared. Because there are so many variables like different pots and different wood, results cannot be compared from different countries However, it is one way to establish if the new stove is a real improvement. Seeing if the new stove saves one third of the fuel and cuts PM by one half (requirements in the current PCIA grants) could be done accurately in a Test Kitchen by NGO's and in a fairly short amount of time.

Nordica MacCarty, Aprovecho Lab Manager, has developed low cost instruments that can be used to measure CO and PM under a hood and in a Test Kitchen. We plan to manufacture this emission equipment this year and make it available to all PCIA members.


CO to Cook 5L under Emissions Hood and Average CO Level in Test Kitchen
*Lighter colored bars show stoves with chimney which remove most smoke from the kitchen
CO to Cook 5L (g)
CO in Kitchen (ppm)
Hood
Kitchen
Gyapa Char
Mali Char
Ghana Wood
VITA
Open Fire
Mud/Sawdust
Kerosene
WFP Rocket
Wood Flame Fan
Wood Gas Fan
Alcohol
Uganda Two-Pot
Propane
Ecostove
Onil
Justa
Patsari Prototype


PM to Cook 5L under Emissions Hood and Average PM Level in Test Kitchen
*Lighter colored bars show stoves with chimney which remove most smoke from the kitchen
PM to Cook 5L (mg)
PM in Kitchen (ug/m3)
Hood
Kitchen
Ghana Wood
VITA
Open Fire
Mud Surround
WFP Rocket
Mali Charcoal
Gyapa Charcoal
Kerosene
Wood Gas Fan
Wood Flame Fan
Uganda Two-Pot
Ecostove
Onil
Propane
Alcohol
Justa
Patsari Prototype

How can wood burning stoves be improved?

The success of some of the groups of stoves in this study point out a few simple techniques that help to improve performance.

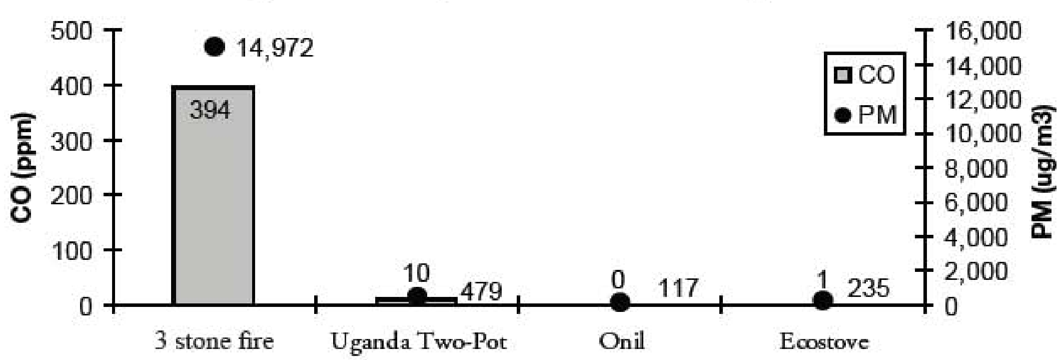
Functional chimneys can successfully address the problem of indoor air pollution. The Onil stove, the Ecostove and the Uganda 2-pot stove (Figure 54) have chimneys that removed most emissions from the test kitchen. Chimneys are the practical solution that evolved in all affluent countries to remove harmful pollution from the indoor environment.

The test kitchen is a 15 cubic meter building in which a door and a window are closed to simulate the worst conditions when fire is used inside in a cold climate. Even in this mostly unventilated structure the stoves with chimneys removed most of the pollution. It is important to use a cooking stove with good draft, however. If smoke can flow backwards out of the fuel entrance, or leak in other ways into the room, harmful emission levels will rise.

Chimney stoves dramatically reduced the emissions of PM and CO as can be seen in Figure 55. The use of chimneys is probably the most cost effective technique to address the problem of indoor air pollution.

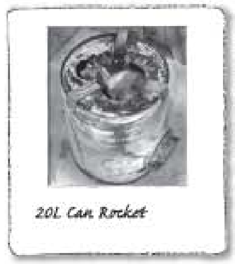
Figure 54 - Chimney Stoves

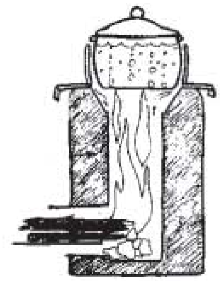
Figure 55- **Concentration of CO and PM in the test kitchen generated by stoves with chimneys**



Insulating the combustion chamber provides a space around and above the fire to create better mixing of gases, flame and air, which helps to boil water faster, reduces fuel use, and decreases carbon monoxide and particulate matter. The 20L Can Rocket, the Uganda 2 Pot, Justa, and the Patsari Prototype stove have insulated combustion chambers (Figure 56). The higher temperatures in an insulated combustion chamber and improved mixing above the fire help to burn wood more completely (Figure 57).

Figure 56 - Five stoves with Rocket-style combustion chambers





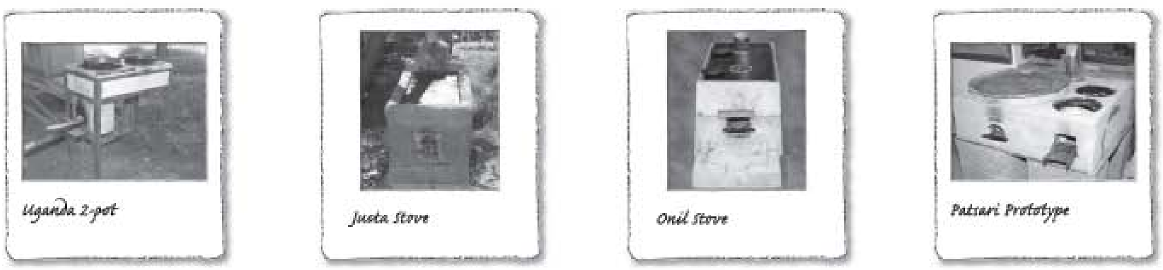
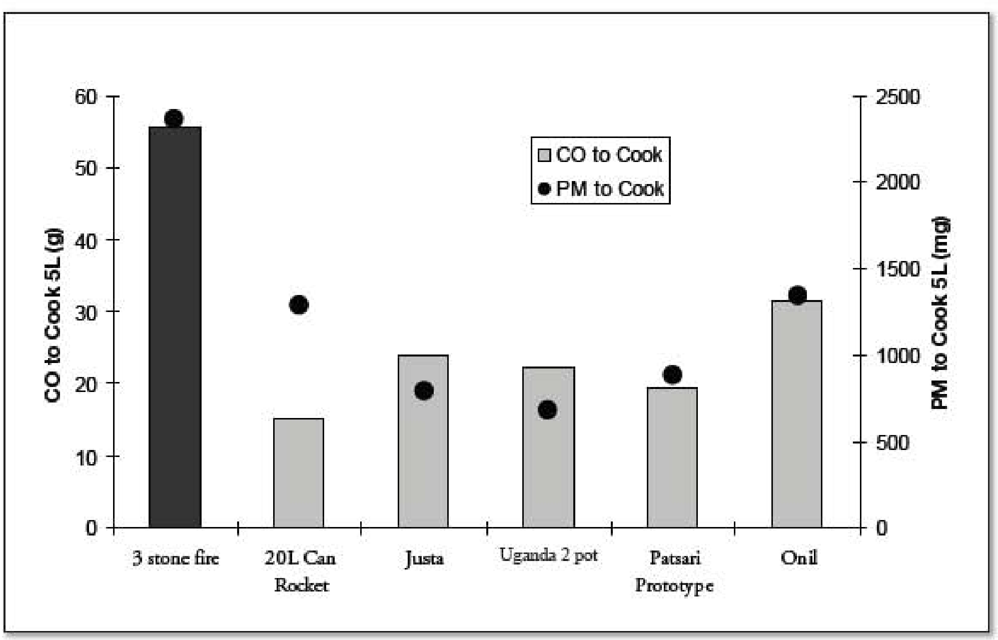


Figure 57- Insulated combustion chamber CO and PM emissions to cook 5L



Forcing the hot gases to scrape against as much of the pot or griddle as possible improves heat transfer. This is an effective method to reduce the fuel needed for cooking. The 20L Can Stove, the VITA stove, the Uganda 2 Pot stove and the Mud/Sawdust stove use small channels that direct the hot gases to contact the sides and bottom of the cooking pot. Baldwin and Winiarski have shown that improving heat transfer significantly decreases fuel use.

The VITA (Figure 60) and Mud/Sawdust (Figure 59) stoves are cylinders surrounding the pot creating a small gap between the pot and stove body. This simple technique dramatically reduces fuel use (Figure 58). In outdoor cooking situations where fuel efficiency, not reduction of emissions is most important, this approach provides a low cost method for decreased fuel consumption.

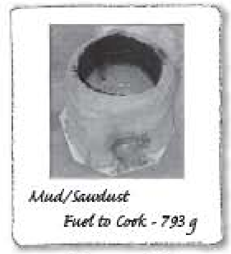


Figure 59

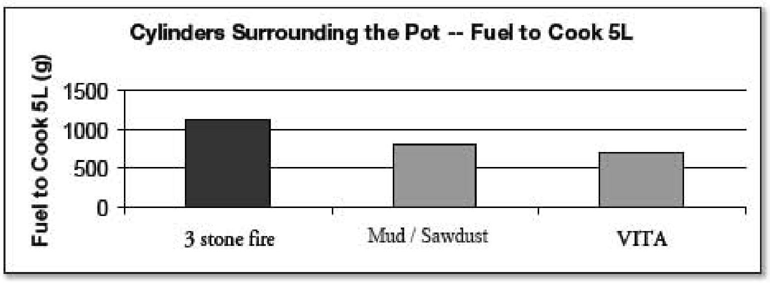


Figure 58

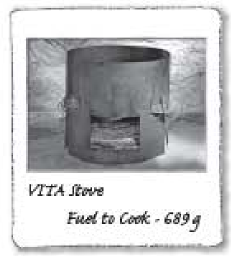


Figure 60

Adding an inexpensive fan to a wood burning stove can create high-velocity, low-volume jets of air that mix fuel, air, and flame. This mixing is mostly missing in stoves without fans. Mixing dramatically reduces pollution (Figure 62). The Wood Flame and Wood Gas stoves burn wood much more cleanly. Adding low cost fans to stoves could provide another low cost solution to cleaner, more efficient cooking with biomass (Figure 61 & 62).

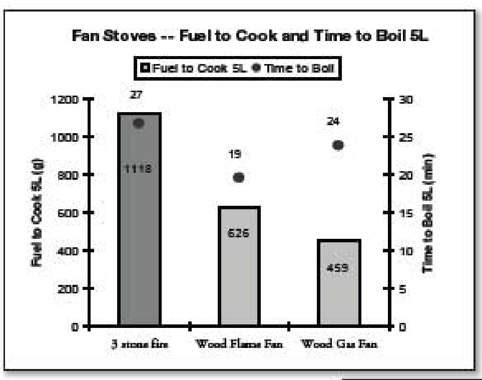


Figure 61

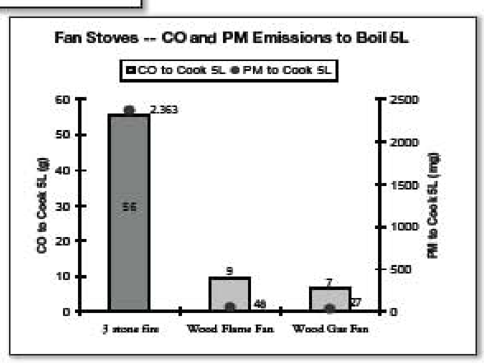


Figure 62