

Capturing Heat Two

*Fuel Efficient Cooking Stoves with Chimneys,
A Pizza Oven, and Simple Water Heaters:
How to Design and Build them*



*Praise for the
Capturing Heat series:
"An excellent book...
illustrated, easy to follow...
useful for any community."
-Where Women Have No Doctor*

*By Dean Still, Mike Hatfield, Peter Scott
Aprovecho Research Center*

The Capturing Heat Series is dedicated to my supportive and wonderful family. And thanks especially to Kim, my wife, for making it all work. -D.S.

The Capturing Heat Series:

Capturing Heat

Five Earth Friendly Cooking Technologies
and How to Build Them

Capturing Heat Two

Fuel Efficient Cooking Stoves with Chimneys,
A Pizza Oven, and Simple Water Heaters:
How to Design and Build them

Coming Soon:

Capturing Heat Three

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By Dean Still, Mike Hatfield, Peter Scott

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Additional copies of this book are available for \$8 postpaid from Aprovecho. Copies are available for the cost of postage to those working to benefit the poor.

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Aprovecho: An Introduction

Aprovecho Research Center has been around since 1981, when a bunch of road-weary (and itchy) consultants to foreign aid agencies, including the Peace Corps, USAID, GTZ, etc., bought 40 acres of land near Eugene, Oregon and began to study seriously what they had once taken for granted as understood. Five years previously, in Guatemala, these appropriate technologists had helped to invent a sand and clay stove called the Lorena which had become "famous." Until returning to the cool hills of Oregon, the consultants had been teaching people all around the poorer and hotter parts of the world (visiting 60 countries) about this neat stove. They had been telling everyone that the stove saved a lot of firewood. In fact, they very much liked their lovely invention and were proud of it.

It turned out that the Lorena, while likable in many respects, did not really save fuel. In fact, scientists who examined Aprovecho's trail of work around the globe frequently found that indoor open fires could be more fuel-efficient than the pretty Lorena. Reading the bad reviews flowing down from academia forced a re-examination of the assumptions that had gone into the design of the Lorena. The researchers at Aprovecho, now a non-profit land trust, spent a lot of time trying to figure out what had gone wrong in this popular design.

Living with a very public mistake helped to dedicate staff to finding out what does work, and then to try to teach about facts, not fads. This formative experience exposed staff to the negative repercussions of bragging about how great an invention performs. It made the new generation of Aprovecho researchers a more cautious bunch, aware of inventor's pride.



The "thinking chair" in the shop was frequently occupied by puzzled looking eco-scientists.

After years of investigation, and consultations with a mechanical engineer who specializes in combustion (Dr. Larry Winiarski), Aprovecho staff began to know a bit more about fires and cooking. Larry's new design, the Rocket stove, coupled with an insulated cooker made from hay or straw, could cook food using one half to one quarter the wood compared to cooking in the traditional way—a fire made between three stones that held up the pot. The road had been long and somewhat rocky. But eventually, experimentation and study did manage to provide a more accurate picture of fire, heat, and how to design stoves. Our new designs use less firewood and produce less smoke.

The *Capturing Heat* series of booklets attempts to summarize what we have learned about Appropriate Technology in the last 19 years. *Capturing Heat One* shares a cooking system that uses both direct and stored solar energy (biomass). Larry has led our investigations into this field. Most of the true "inventions" explained in *Capturing Heat One* are his and the same continues to be true in this second booklet.

Dr. Winiarski is a rare and gifted person. He is a born teacher and hands-on tinkerer, who has gained a feeling for how things work. Aprovecho's investigations into simply-made wood stoves and his explanations of thermodynamics unexpectedly taught our team about a whole range of unexpected applications: from wood stoves to solar cookers and then all the way to solar houses. The role of mass and insulation in stoves and houses became a great concern of the Appropriate Technology staff as we realized that the concepts were frequently misunderstood. Studying how things get hot also seems to have uncovered a few oversimplifications made by some noted solar architects.

Modern instruments, such as pyranometers (that measure sunlight) and data loggers,

made it possible for us to measure how well various apparatus worked. We could accurately measure, for instance, what percentage of the energy from sunlight made it into the pots in a solar cooker. Data loggers could track temperatures and relative humidity inside both straw bale and cob walls. Repeated and careful experiments on wood stoves were necessary to determine the success and failure of cherished designs. Our best experiments often resulted in findings that were completely unexpected.

Again and again our expectations were confounded by evidence from experiments. But it was only because of experimenting that designs eventually performed more efficiently. The whole first generation of Aprovecho designs were replaced as evidence pointed out primary errors in design. What became obvious was often in direct opposition to generally accepted beliefs. More than once, our results slammed us against commonly accepted paradigms and it took a while (sometimes a year or two) for us to recognize the implications of the evidence right in front of our eyes.

You are invited to join Aprovecho in an intellectual adventure, one whose goal is the lessening of suffering. The trail of investigation begins with stoves but it continues to solar houses. *Capturing Heat Three* and *Capturing Heat Four* visit heat exchangers, heating stoves, and simpler geodesics, natural houses made from cob and straw and the like. We hope to share some simple math and a bit of thermodynamics so that anyone can analyze and determine what is a fact and what is only a fad. Hyped-up fads concentrate optimism and attention but all too often do not successfully move optimistic people on to viable alternatives.

Given the choice, Aprovecho instructors would much rather teach someone how to be a designer instead of promoting particular

designs. The intention is to give you the necessary facts to, in this case, successfully design wood stoves for baking and cooking and teach you the rudiments of water heating. All of the designs are meant to be "appropriate," which, simply put, means that you should be able to both make and repair the device from locally available, inexpensive materials.

The "best" A.T. design would be the one that can be replicated in most any town around the world, built on site for use locally, and made from vernacular materials. It's preferable if the device is designed on site with local input. A goal of the Appropriate Technology movement is to involve people in the technologies they use. In industrialized countries many people are psychologically removed from the technologies that support them. This distance and lack of understanding can easily result in a feeling of alienation. An important part of the philosophy behind A.T. is to encourage a fondness for and familiarity with designing and living using culturally compatible tools.

Residents at Aprovecho share a common belief in voluntary simplicity. In my case a preference for simplicity stems from mostly selfish reasons. Living with less allows a great deal more personal time to pursue one's own fascinations. It's more fun to accomplish more by needing less. Trying to build things that work, out of vernacular materials available to poor people in various countries, results in very inexpensive experiments. Therefore, lack of money doesn't slow down our progress very much. The "mud-tech" science of helping isn't dependent on grants or tied to direction from funding agencies. We can follow our own crooked-enough noses.



The Research Center

Aprovecho Research Center is located on a 40-acre farm and woodland. There is a beautiful acre-and-a-half garden that provides almost all of our fresh produce. The woods are managed to supply both lumber and firewood for heating and cooking while steadily becoming both healthier and more productive.

Aprovecho classes and research are divided into four main areas: Organic Gardening, Sustainable Forestry, Indigenous Skills, and Appropriate Technology. Our school teaches these four subjects to mostly college-aged or older interns. This book concentrates on A.T., but it is only one fourth, and certainly not the most important quarter, of our investigations into how to live sustainably. (Carl Jung, in a famous rebuttal to Freud's insistence on the preeminence of infantile sexuality, agreed with farmers worldwide when he pointed out that sustenance surely leads the hierarchy of needs.)

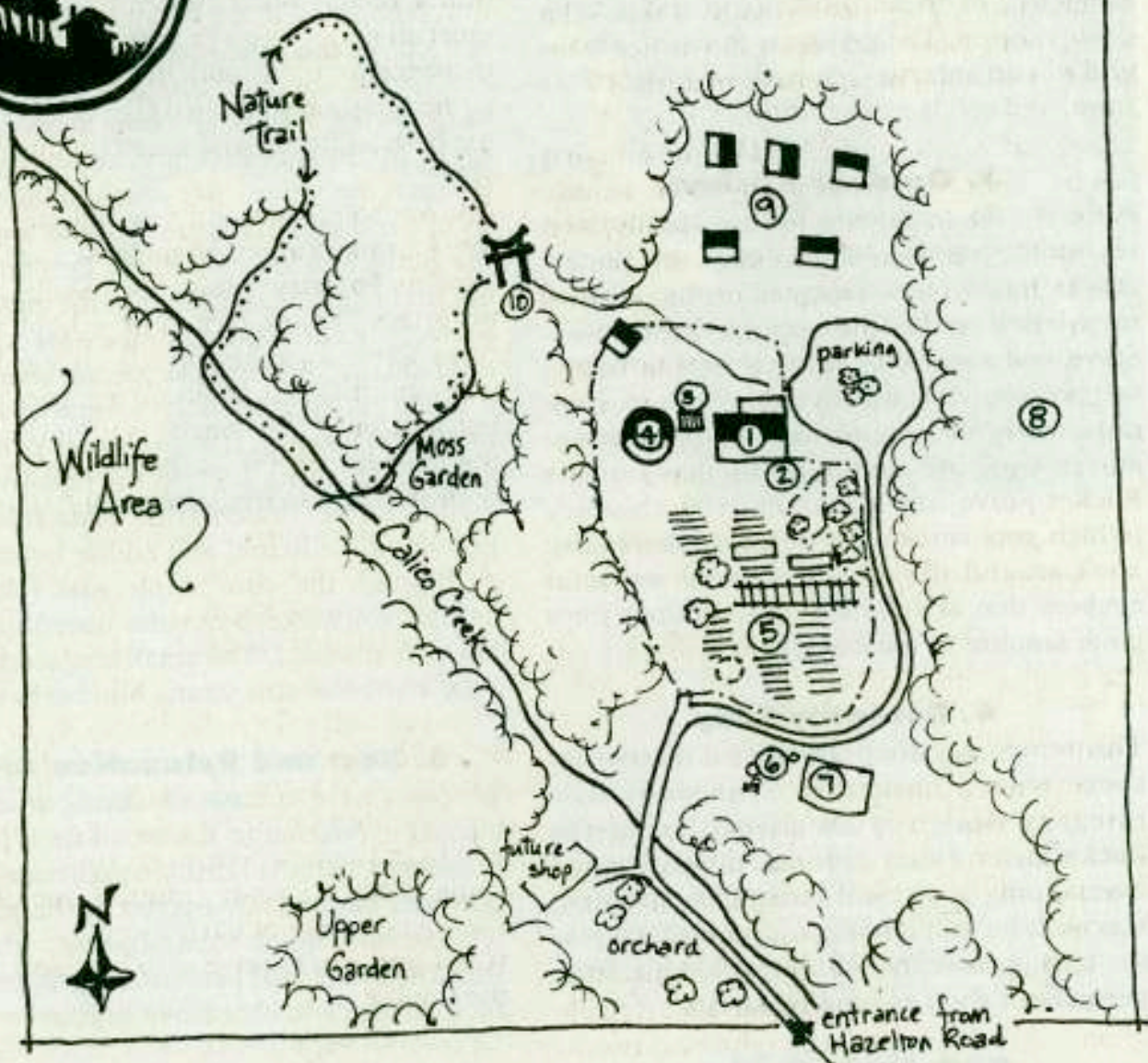
The self-guided tour described here introduces you to some of the major features of the Research Center. Please visit whenever you're in the neighborhood! You're also welcome to come for our monthly Open House, the first Sunday of each month at 2:00 pm, when you can receive a full guided tour of the Center.

Self-Guided Tour

1. Straw Bale Dormitory

This experimental and demonstration building was constructed in 1996-7 with funding from the Oregon Department of Agriculture, the Woodard Family Foundation, the Rose Tucker Charitable Trust, and many generous members of Aprovecho. The post-and-beam framing, built mainly with wood from

Aprovecho Research Center



Aprovecho's forest, supports the structure, while straw bales provide the infill and insulation for the passive solar building. Sensors embedded in the straw monitor relative humidity of the bales in order to determine whether the straw can last in this damp climate. This building is the first of the new campus we are developing in order to become fully up-to-code and accessible as a public facility. The new campus will consist of this

experimental straw bale dormitory, a community meeting hall, a shop, and six staff cabins. The goal of the campus is to create housing and teaching facilities that exemplify energy-efficient, solar-assisted, ecologically-friendly building techniques.

2. Photovoltaic Modules Create Electricity

A 1.6 kilowatt photovoltaic system donated

by Enron is mounted on the roof of the dorm with a few modules on the ground for visitors to look at more closely. We're working with Enron as well as the two local utility companies, EPUD and EWEB, to determine the efficiency of these modules in this mostly cloudy region. The system is connected to the grid via an intertie. We both buy electricity from, and sell it to, the utility.

3. Outdoor Kitchen

Here we do outdoor cooking, appropriate-technology style. Often you'll see Rocket Stoves made out of recycled cans, a bread oven based on the same design as the Rocket Stove, and some of our most recent stove prototypes resulting from recent work in Honduras and other countries. The most recent stoves combine the high efficiency of the Rocket Stove and the beneficial chimney (which gets smoke out of indoor kitchens). Look around the area and you'll see solar cookers that are used in the summer for a great amount of our cooking.

4. Rotegrity Shop

This temporary shop provides a mostly dry space with a minimum of expense. The rotegrity design is an adaptation of the Buckminster Fuller geodesic dome, but has overlapping structural bars. This structure was built for just a few hundred dollars, plus the tarp. Aprovecho will be building a more permanent shop as funding allows.

5. Organic Garden

Our garden provides almost all of the fresh food used to feed the approximately twenty people who reside at the Research Center. All of the work done in the garden is performed with human power and without the use of chemicals. Resident interns, under the direction of gardening instructors, prepare the beds, raise starts, and care for their vegetables until harvesting. They incorporate techniques including raised beds, crop rotation, compan-

ion planting, edible weeds, vermiculture, composting, and much more. Many of the trees located throughout the garden are volunteer plum trees, and a stroll through the grape arbor in late summer is an experience not to be missed. The ducks patrol the eastern side of the garden in search of our greatest enemy—the slug. Two greenhouses extend our growing season, allowing for melons and more in the summer and fresh greens all through the winter. We also start the majority of our plants in the greenhouse, away from the hungry mouths of slugs. Two fenced areas in the northeast corner of the garden also act as young orchards and space for our chickens to roam. Water for the garden comes from a spring via a gravity-fed system with no moving parts. Head to the southwest part of the garden to sit for a spell in the contemplative garden circle, noticing the beds filled with perennial medicinal and edible herbs. Then go through the vine maple gate (closing it behind you to keep out the deer!) and turn left onto the road. The small enclosed area to your right contains young blueberry bushes.

6. Rest and Relaxation Area

We come here to unwind, sitting around the campfire, floating in the wood-fired hot tub, or taking a "cannibal bath" in the Rocket Stove-powered bathtub. Or maybe in the summer it'll just be a quick solar shower with water from the batch solar heater. Closer to the creek there is also a Rocket Stove sauna.

7. Goat Pen

Goats (Nestle and Lulu) provide the community with a supply of fresh milk and friendly hoofed companionship.

8. Pole Forest

As you continue up the road, off to your right you can see part of the twenty (out of our thirty-five) forested acres that serve as the production zone. This land was clear-cut approximately forty-five years ago and naturally re-

generated, leading to dense growth. Our forester thins out trees, using the wood for building, firewood, and sometimes for sale. Cut logs are pulled out by a team of draft horses and sawed with a portable sawmill. We are working towards creating a managed old-

growth forest, leaving important biomass on the forest floor in order to continue building layers of humus. Snags are left standing to attract birds. You'll often hear the loud cry of the Pileated woodpecker echo through the woods. Wild mushrooms, such as chanterelles, thrive in this type of forest and you might find some during the fall season. Behind the small green structure in the parking lot, you can also see some of our cultivated mushroom operations. Fifteen acres on the northwest part of the property are a designated Wildlife Area where no cutting occurs. In this area especially, watch out for the three shiny leaves that indicate poison oak.

9. Staff Cabins

Continuing up to the parking lot, you'll be able to see up the hill where six staff cabins will eventually be located (two are already there). This co-housing area will allow up to twelve staff to live on-site, providing private sleeping quarters, with communal activities continuing to happen in other buildings.



Aprovecho Interns

Grants from the Meyer-Memorial Trust, the Collins Foundation, and the Jackson Foundation, as well as generous member donations, are allowing for this construction. We are using environmentally-friendly building techniques as much as we can, while pointing out that the size of a structure is crucial in terms of resource consumption. Here specifically, wood is the most bioregional building material available. We stress local and appropriate building materials, encouraging houses that are well-insulated and passive solar in design.

10. Nature Trail

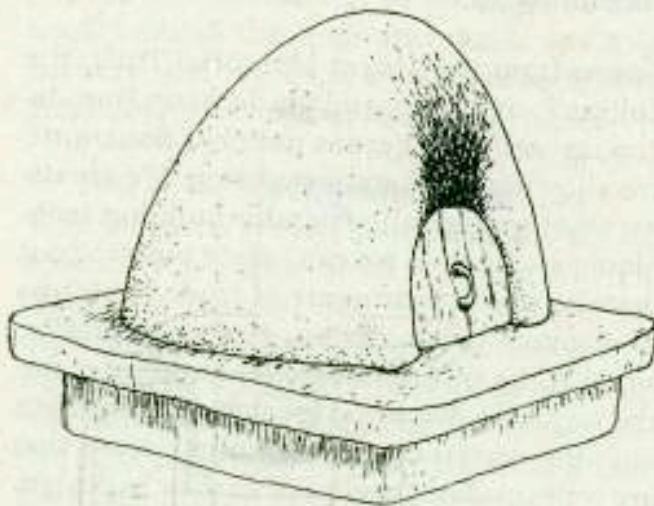
This short 1/3-mile trail leads you through our designated Wildlife Area and back out into the production zone of our forest. Follow the trail north of the dorm that goes through a wide gate and west into the forest. Look for the beautiful wooden Torii gate that marks the start of the trail. The walk goes through the Moss Garden and other pristine quiet spots that are a source of inspiration and rejuvenation for our community. Enjoy!

The Pizza Oven

(Analysis of Retained-Heat Baking)

Traditional High-Mass Bread Ovens

Both plain and fancy bread ovens can use retained heat for cooking. Fire heats up rocks or bricks or earth or the cement walls of an oven. When the mass is hot enough the food is placed inside the oven to be cooked. High-mass brick pizza ovens made the gourmet pizza I loved to sample in San Francisco. The English traditional bread oven and the Navajo beehive earthen oven are also based on first heating mass and then using the stored heat to cook food.



Navajo Beehive-Style Oven

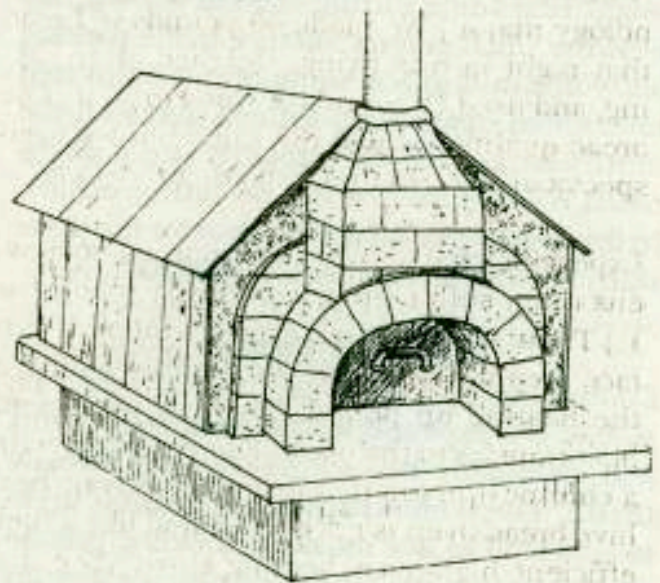
Experimentation shows, however, that heating air, which then directly heats food, is usually a more fuel-efficient way for a family to bake food.

The trick to making a good low-mass hot-air oven is to put the heat where you want it without a.) losing the heat into the body of the stove or b.) letting the heat escape up the chimney. We

want the heated air to cook food!

Trying to optimize a retained-heat oven is a bit more difficult. It needs the right amount of mass to store the right amount of heat. Also, without insulation on the outside of the thermal mass, heat easily dissipates, so that retained heat is lost before it can be efficiently used.

Earthen stoves can use so much wood, to bake so little bread! At the very least, earthen stoves can be covered by insulation (wood ash, rock wool, fiberglass, etc.) so that the heat isn't as easily lost. But to be truly efficient the interior surface of the oven also needs to be optimized to absorb most of the heat from the fire and reduce exit temperatures out of the chimney. An earthen oven usually requires split logs fed into it for long periods of time to reach cooking temperatures. When people learn that it is possible to use a little fire to directly heat bread, it is amazing how much fuel can be saved.



The English Bread Oven

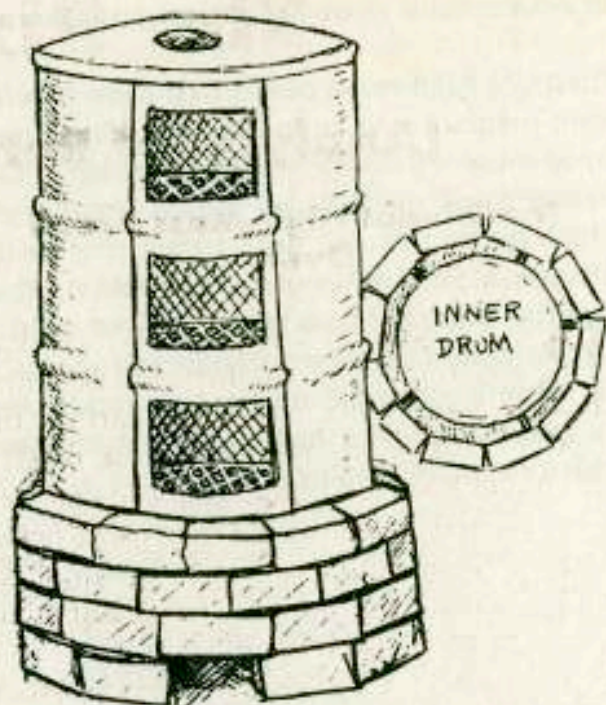
More than ten years ago Alan Scott (*The Bread Builders*, 1999) visited Aprovecho and built an early version of his retained-heat English bread oven. People had a great time cooking in it for a whole day after it was brought up to temperature. I remember all of us getting stuffed with bread, cakes, pastry, etc. It was a wonderful time. Alan was experimenting with high-mass retained-heat bread ovens for commercial applications. He figured that Aprovecho might be able to use an oven meant for constant use since we baked food almost every day.

The Rocket Low-Mass Bread Oven

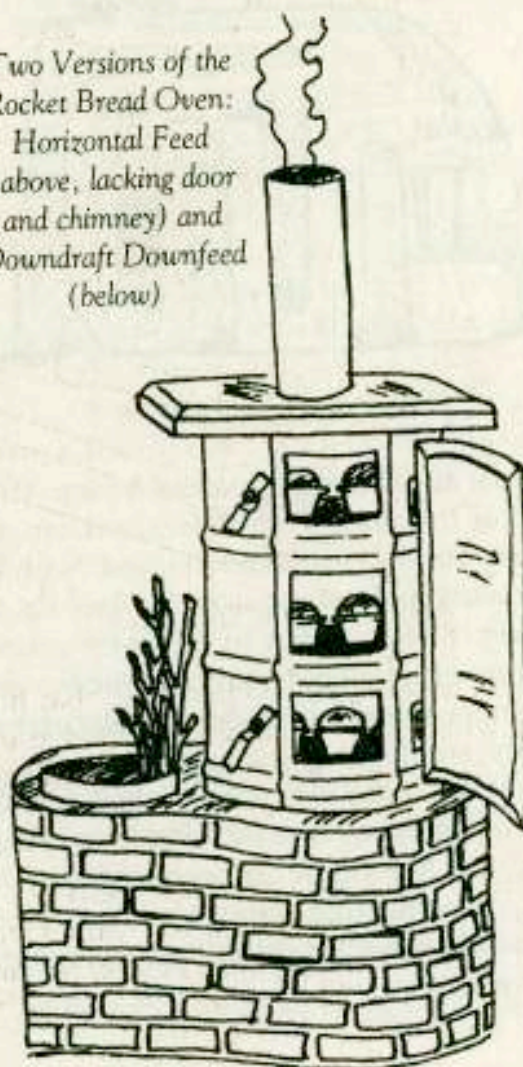
Over the years, we used both Alan's English Bread oven and an earthen oven for baking bread. No one questioned the wood use because we had nothing to compare it to. Then Larry built a low-mass hot-air bread oven right in between the two high-mass models.

We tested Larry's Rocket oven one night before a visit from thirty, usually hungry, Humboldt State students. (Humboldt State College in California, like Appalachia State in North Carolina, offers an Appropriate Technology major.) We made 66 pounds of bread that night in one firing, weighed after baking, and used 11 pounds of wood to do it. The bread quality seemed the same but we used spectacularly less fuel to feed our visitors.

Experience has shown that retained-heat ovens often suffer from two classic problems: 1.) There's not enough exposed internal surface area to lower exit temperatures during the heating up period. There is inefficient heat transfer to the oven. The little cave with a chimney on top that forms the Navajo beehive bread oven is not convoluted like a fuel-efficient high-mass heating stove. (See diagram.) Too much of the heat just shoots up the chimney, in this case. A better heat trans-

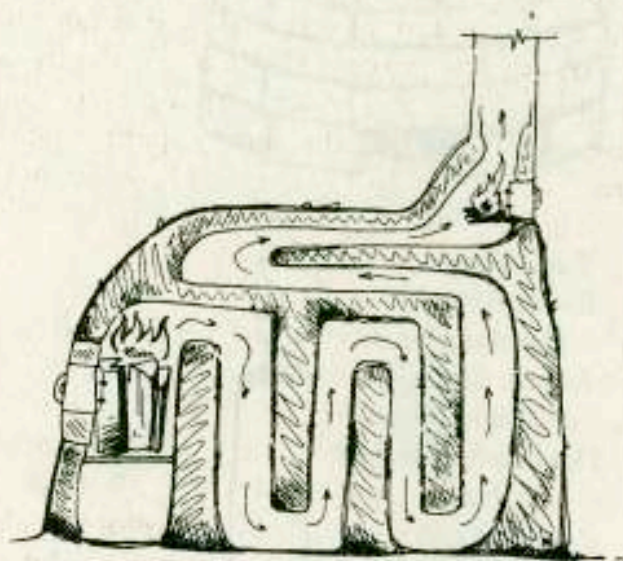


Two Versions of the Rocket Bread Oven:
Horizontal Feed
(above, lacking door
and chimney) and
Downdraft Downfeed
(below)



fer necessitates more optimized surface area.

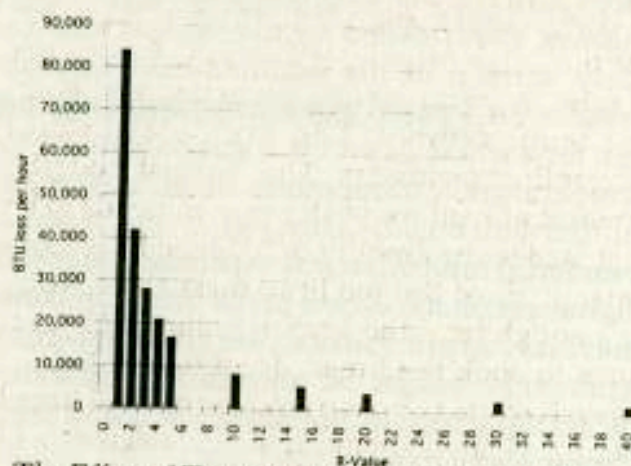
Then, 2.) high-mass ovens can have insufficient insulation to keep the heat doing work for as long as possible. A few years ago, Alan changed his design and added insulation, which helps a lot. We would want perfect insulation around the mass if possible. In that way the captured heat would be put to best use. Any amount of insulation will increase the benefit gained from heat retention, but it's great if an oven has an insulative cover with a rating of R-10 or better.



High-Mass Heating Stove

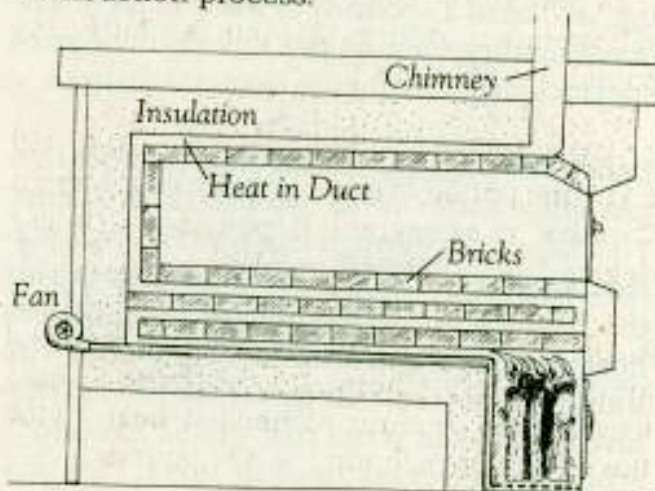
The great advantage of retained heat ovens is that after the mass is sufficiently warm, the chimney can be completely closed. With the door closed as well, heat is not lost up the chimney. Keeping heat in the oven can improve the efficiency. In practice, however, it is first necessary to remove all coals and potentially smoldering material since smoke will ruin the bread and possibly leak into the room. Sweeping out the burning fragments is a messy job. But it should be remembered that completely shutting down the draft while continuing to cook is possible only in retained heat ovens.

Heat Loss at 30 Degree F Temperature Difference



The Effect of Temperature on the Passage of Heat through Insulation

The spring '99 class at Aprovecho designed a "best case" retained-heat oven and started building the prototype. It has 72 square feet of surface area where heat rubs against the mass to lower exit temperatures out of the chimney. As a rule of thumb, it takes at least 75 square feet of exposed mass surface area to adequately absorb the heat from a fire, i.e., to lower temperatures from around 2,300 degrees Fahrenheit (the temperature of yellow flame) down to minimum exit temperatures of around 250 degrees Fahrenheit. The student's oven is insulated to R-40 so that the heat isn't lost very quickly. Air is preheated as it is pushed by a small fan to aid in the combustion process.



Summer '99 Best Case High-Mass Bread Oven

In a fuel-efficient retained-heat oven we have to design in the right amount of mass. If we use too much mass we will have to waste Btu's to raise more mass than necessary up to baking temperatures. The oven stays warm longer than necessary. The thermal load (the amount of food we wish to cook) needs to be matched to the amount of retained heat. Conversely, if we use too little mass there won't be enough retained heat at baking temperatures to cook the bread. Heat below 350 degrees F. starts to be too cold for normal bread baking. Heat at greater than 450 degrees will usually start to burn bread.

As a rule of thumb, most materials used for mass in stoves will hold *about .2 Btu's of heat for each degree of temperature rise (Fahrenheit)*. Our tests show that it takes something like *350 Btu's per pound to bake bread*. Aprovecho has an average of 25 daily mouths, firmly attached to souls clamoring for knowledge, who also lust for bread.

Using these formulas, let's practice together and design a bread oven that will retain enough heat (at a temperature between 350 and 450 degrees F.) to bake 12 loaves of bread. Only the heat at the correct temperature helps in baking bread. Each loaf weighs two pounds.

1. 24 pounds of bread will require 8400 Btu's of heat energy to bake. (24 pounds x 350 Btu's/pound = 8400 Btu's.)
2. A 100-degree temperature rise (350 to 450 F.) in one pound of earth or brick stores about 20 Btu's. (100 degrees F./pound x .2 Btu's/degree F. = 20 Btu's/pound.)
3. Dividing 8400 by 20, we find that we need approximately 420 pounds of thermal mass to store the amount of needed heat. (8400 Btu's ÷ 20 Btu's/pound = 420 pounds.)

In other words, the heat needed (8400 Btu's)

to bake 24 pounds of bread will be released when 420 pounds of thermal mass drops in temperature from 450 degrees to 350 degrees F.

This heat must be well insulated so that it is forced into the bread instead of lost while heating cooler exterior air. The efficiency of heat transfer to the mass will, in large part, determine how much fuel is burned to bring the oven up to temperature. But even in an insulated convoluted retained-heat oven, the Btu's required to raise temperatures up to the point where baking commences are wasted! Typically, at 350 degrees F. and below, the oven's large store of retained heat is not put to any useful purpose. Unless the family is well-organized and ready with a project that uses a slow oven, all the energy spent in heating the mass up to 350 degrees F., while necessary to allow baking to begin, is ultimately lost when the oven cools down.

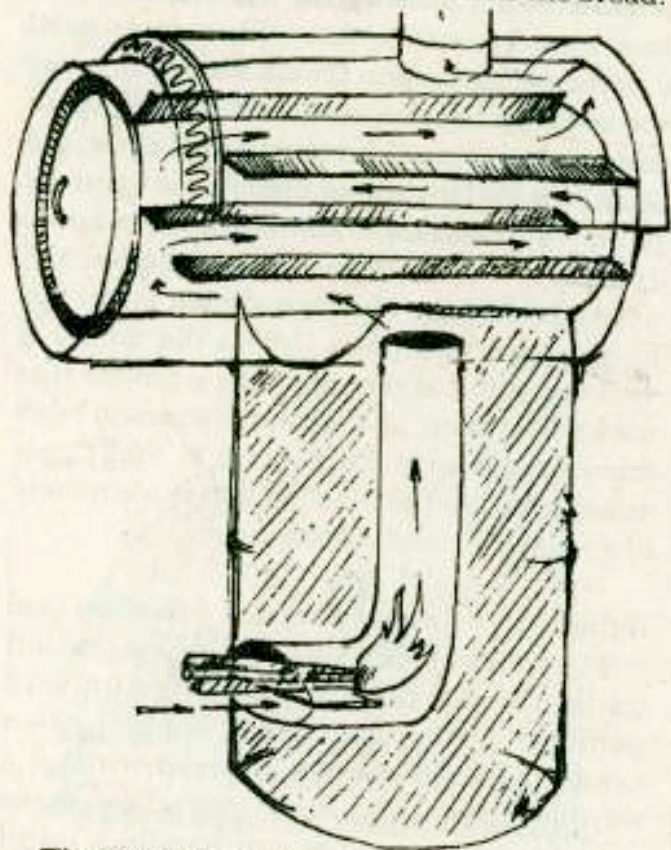
If the oven is designed to cook a thermal load of 24 pounds of bread, a lot of heat is also left unused when the chef prepares only 12 pounds. On the other hand, such an oven cannot bake 48 pounds of bread without a refiring. Designers usually, therefore, make very heavy ovens that can handle a lot of bread. Obviously, if the retained heat and thermal load are not sized in relation to each other, fuel efficiency suffers.

In the same manner, we can imagine that the amount of thermal mass added into a solar house probably needs to be sized to the input of sunlight-generated Btu's, if we want unassisted sunlight to heat the house.

Let's leave mass behind for a moment and consider the low-mass oven in which hot air directly cooks food.

The air is forced to rub against the inner drum that forms the oven. Hot air moves in a maze over the oven, so that, at the end of this cir-

cuitous route, exit temperatures are relatively cool. The annulus is created by splitting another 55-gallon drum lengthwise and sliding it over the first, leaving a 3/4" gap between the two drums. The heat passes through this gap and rubs against the bottom, sides, and top of the inner barrel that contains the bread.



The Rocket-Style Pizza Oven with Big Door

The maze is made up of sausage-like sections of fiberglass bat insulation covered by three layers of aluminum foil. The Pizza oven is also well insulated, both around the combustion chamber and the oven itself. This oven is essentially the same as the vertical bread oven featured in *Capturing Heat One*. Laying the oven drum on its side allows us the use of the reclosable lid as a door, so that a large tray of pizza can enter. The fire is also closer to the oven than in the vertical Rocket Bread Oven.

This low-mass oven gets up to 400 degrees F. twenty minutes after the fire is started. Temperatures are controlled by the amount of

sticks inserted into the combustion chamber. Combustion continues only as long as the food is cooking, and then the fire is extinguished.

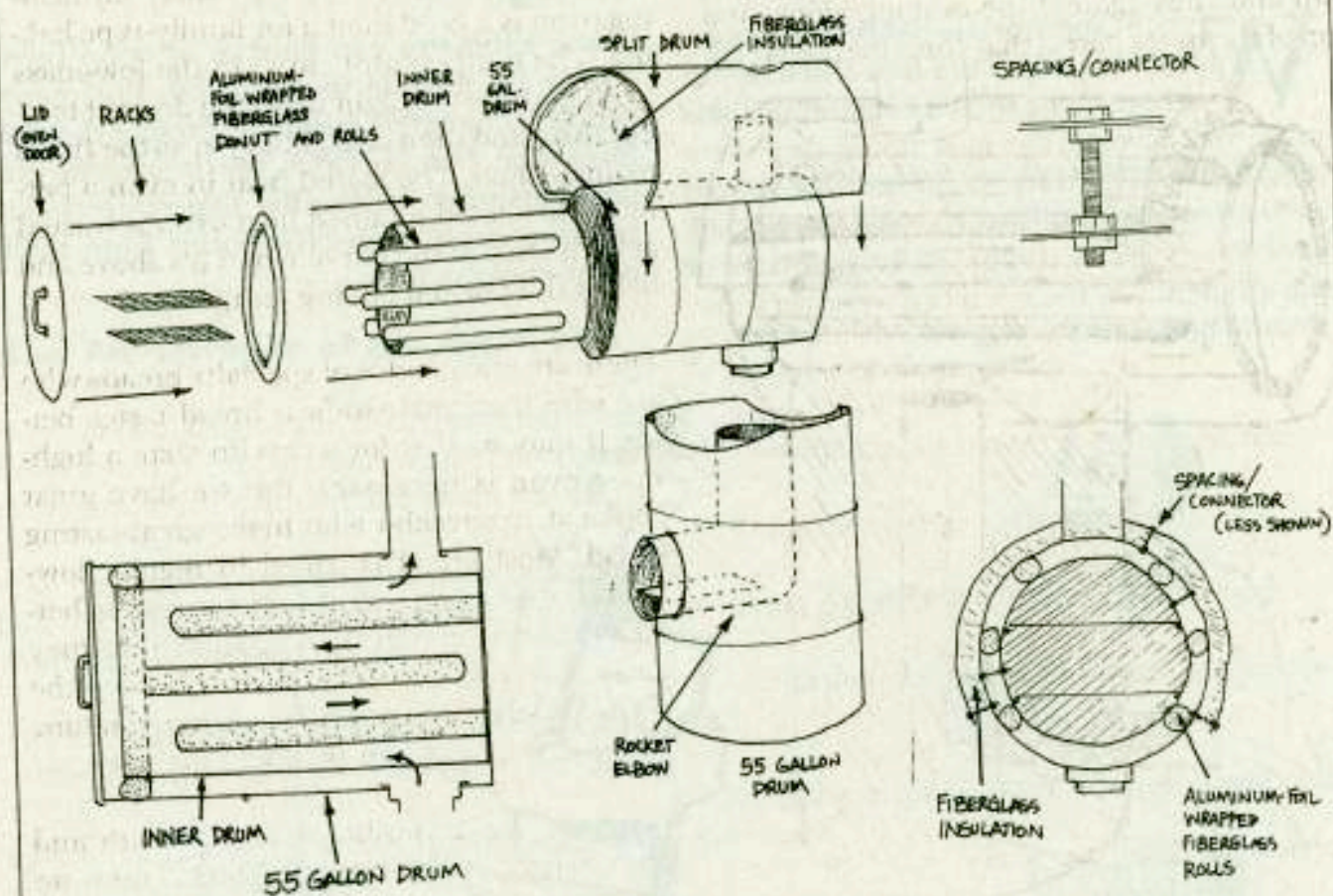
Experience shows that a low-mass air-heating oven is a good match for family-type baking. The temperature curve in the low-mass oven is almost straight up to the desired temperature and then straight down as the fire is extinguished. The stored heat in even a perfectly insulated retained heat oven is wasted at both ends of the curve when it's above and below the desired baking temperature.

There are aficionados of specialty breads who are sure that retained-heat bread tastes better. It may be that for a certain taste a high-mass oven is necessary. But we have great cooks at Aprovecho who make great-tasting bread. Most bread is baked in regular low-mass hot-air ovens. Massive ovens seem better suited to commercial situations where they are in constant use. The mass will keep the commercial oven at a very steady temperature, which is important for product reliability.

However, most families can cope with and ignore slight imperfections. (Heck, I grew up in a family!) Because they save fuel, and are easy to build and fun to use, we can wholeheartedly recommend low-mass ovens that heat air that then cooks food. The vertical oven (*Capturing Heat One*) and the horizontal oven presented here are variations on a theme.

It's nice to have a ready-made big door as in the Pizza Oven. But the original vertical oven is a great introduction to the wonders of fuel-efficient wood-fired ovens, as well. The Pizza Oven is slightly more fuel-efficient because the fire is closer to the bread. The hot flue gases also follow a more circuitous route around the inner oven. But for this reason, a higher chimney is required to reinforce the draft. Of the two, the Pizza Oven is a bit easier to build. Give it a try!

How to Build the Pizza Oven



A handle is attached to the removable lid of the 55-gallon drum.

Two shelves are inserted into the 33-gallon drum. We used chicken wire stretched tight and bolted into the sides of the 33-gallon drum.

A donut made from three layers of aluminum foil wrapped around fiberglass insulation seals the gap between the 33- and 55-gallon drums.

Long sausages made from three layers of aluminum foil wrapped around fiberglass insulation form the maze through which heat is forced to travel.

A 55-gallon drum split longitudinally covers the top of the oven, protecting the fiberglass insulation that lays on top of the oven.

The rocket elbow can be made from 8"-in-diameter stove pipe or elbow.

Cooking Stoves with Chimneys

When appropriate technologists began to look at the fuel efficiency of three-stone fires, an assumption was made that favored the new stoves they were introducing. The three-stone fire was viewed as "very wasteful of fuel." (*Wood Conserving Cook Stoves*, VITA, 1980). Early estimates of the efficiency of the open fire were very low, usually between 3% and 7%.

These estimates can be true of open fires, which are outside in the wind. But many people either cook inside or protect the fire from wind. In these cases, the three-stone fire performs more efficiently. Expert users can get reasonably high efficiencies from their home cooking fires.



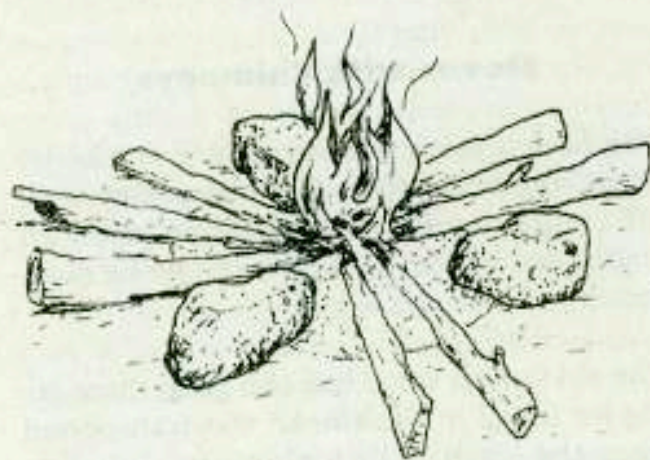
"Looks to me like a preference for an open fire has a lot more going for it than just the conservative nature of tribal societies!"

Our latest Spring 1999 experiments with the three-stone fire resulted in an average fuel efficiency of 11.2%. (11.2% of the heat made it into the pot.) The testers were amateur US College students who were trying to do their best. Trained fire operators can usually do better. Even the amateurs sometimes scored much higher than their average. The range of scores in ten tests was from 7.6% to 17.8%. Experts would obviously tend to score in the higher ranges of efficiency.

The Advantages of the Open Fire

How can we design a stove that beats the open fire? First, let's list the advantages of the three-stone fire when compared to some stoves:

- No heat is absorbed into the mass of a stove body. High-mass stoves can absorb heat that could have gone into the pot.
- Fire hits the bottom and sometimes the sides of the pot, exposing a lot of the pot to the heat.
- Sticks can be fed in at the appropriate rate, assisting complete combustion.



The Amazing Three-Stone Fire

How to Achieve More Complete Combustion

Every stove suffers because it has some mass. But a stove can achieve better combustion than an open fire. The good stove helps to make hotter and more efficient fires by doing the following things:

- Insulates around the fire. A hot fire burns up more of the combustible gases and produces less smoke.
- Limits the cool air that lowers temperatures in the area of combustion.
- Pre-heats the air before it enters the fire.
- Forces the user to meter the fuel.
- Forms a grate out of the sticks of wood.
- A chimney creates draft, assisting combustion.
- Escaping smoke passes through flame and combusts.

How to Get More of the Heat Into the Pot

Although flames sometimes touch the pot pretty efficiently in an open fire, the stove can improve upon the efficiency of heat transfer in the following ways:

- Force the heat to contact as much of the pot as possible. Increase the maximum surface area exposed to hot flue gases. Make heat rub against the pot's surface.
- Insulate around the fire everywhere except where it touches the pot(s).
- Make the heat contact the pot(s) for as long

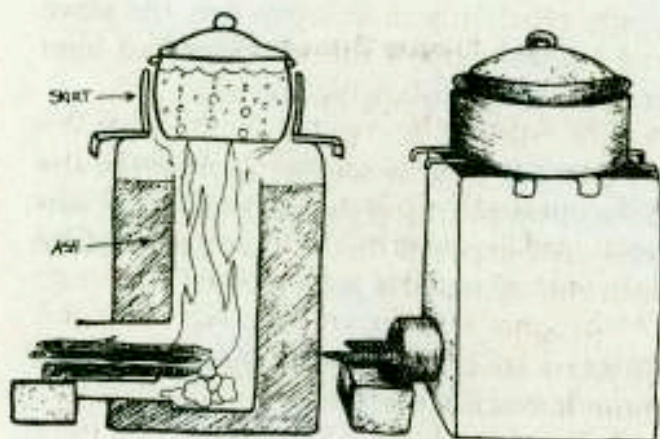
a time as possible. Prolong the dwell time. (See the Pizza oven.)

- A greater percentage of the heat enters the pot if there is as large a difference in temperature as possible between the pot and the heat source.
- It helps if the pot is as conductive as possible.
- Increase speed of flue gases so they hit the pot harder.

The Rocket Stove

The Rocket Stove is designed to do all of the preceding things to both a.) achieve more complete combustion and b.) force as much heat into the pot as possible. The Rocket stove attempts to burn up as much smoke as possible and then uses a skirt to force the hot flue gases to rub against both the sides and the bottom of the pot. The Rocket stove is also made with low-mass materials if available and is well insulated, if possible.

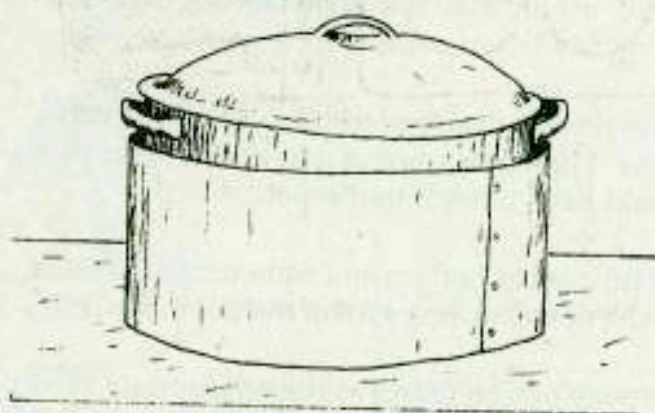
Forcing the hot flue gases to rub against the pot is very important when trying to save fuel. The Rocket stove, by itself, cleans up a lot of the smoke from a fire but it is only about as



The Rocket Stove

fuel-efficient as a well-run open fire. In amateur tests conducted in the spring of 1999, the Rocket stove without a skirt averaged 12.5% efficiency. (Again, experts can score higher.)

But, when a skirt was added (a simple cylinder of metal around the pot, under the handles) the average amateur efficiency rose to 23.6%. The skirt is very important for fuel efficiency. The heat passes through a very small gap, usually 1/8" to 1/4", between the skirt and the pot and is forced to scrape against the pot, increasing heat transfer. In fact, fuel efficiency in a stove is usually much more affected by heat transfer to the pot than it is by improving combustion efficiency.



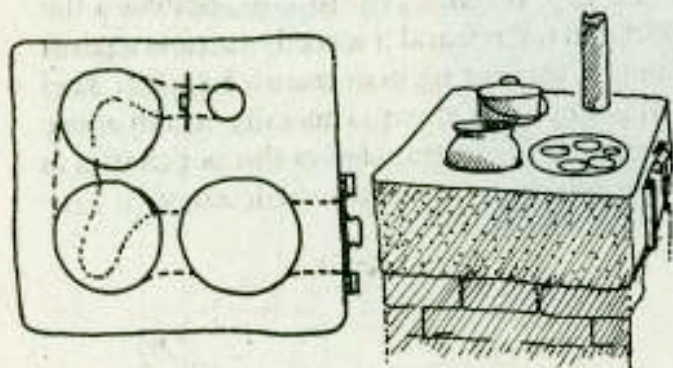
A Skirt Greatly Improves Heat Transfer to the Pot

Stoves with Chimneys

The Rocket stove tries to reduce smoke by improving combustion. But if people are well-off enough to afford a chimney, then all smoke can be removed from the living quarters.

The old Lorena stove had one great thing going for it. All of the smoke was transported from the kitchen in a chimney. Inhaling smoke is very bad for one's health, so even though the Lorena wasn't very fuel-efficient, smoke removal was a great contribution in and of itself.

In fact, there are many NGO's including the World Health Organization who might conclude that removal of smoke is more important than fuel efficiency. Recent studies confirm what has been obvious for decades. Inhalation of smoke does cause a host of medical problems including very serious respiratory illnesses. Breathing wood smoke is dangerous. It is very important to reduce exposure to smoke, especially for children!



The Mud and Sand Lorena Stove

Problems with the Lorena Stove

The Lorena stove was originally designed by a group of volunteers in Guatemala including consultants from Aprovecho. Ianto Evans, a founder of Aprovecho, wrote the book *Lorena: Owner-Built Stoves* published by Volunteers in Asia in 1979. The Lorena continues to attract friends but there are several problems in the Lorena design that have been corrected in later Aprovecho stoves with chimneys. These problems are:

- The fire directly contacts the very heavy mass of the stove body, which absorbs heat, robbing it from the pot.
- The combustion chamber is uninsulated. The cold walls cool the fire, causing smoke.
- The fire flow path does not intimately touch the pots. It flows horizontally past the pot,

resulting in poor heat transfer. The walls of the fire tunnels are uninsulated.

Earth Is Not Good Insulation

Before experimentation proved us wrong, Aprovecho stove designers thought that earth was insulation. We did not fully understand the difference between mass and insulation. Good insulation is made up of little pockets of air separated from other tiny pockets of air by a lightweight, relatively non-conductive material.

Earth, especially rammed Lorena, doesn't contain many pockets of air. Good insulation resists the passage of heat; thermal mass does the opposite, absorbing heat. Instead of using sand and clay near the fire now, Aprovecho designers use natural insulation, like wood ash. And instead of rushing the fire past the pots, the new designs force the hot flue gases to rub against the metal surface, which greatly increases heat transfer.

The retained heat in the stove body does not assist in cooking since the pot is hotter than most of the surrounding mass. Once the stove absorbs heat, it is mostly diverted and lost. For fuel efficiency, it is important to insulate the entire heat flow path.

The Dona Justa Stove

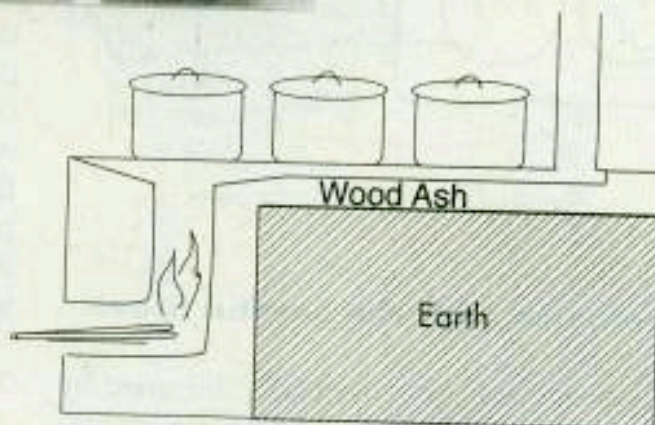
In 1999, Aprovecho was invited to assist two non-governmental organizations in Honduras to design and help build a stove that has a metal griddle covering the stove's top. This plate of steel is called a "plancha" in Spanish. The original Honduran plancha stove was designed in 1995, with help from Rogerio Miranda and PROLENA. Stoves like the Dona Justa have been built in various places around the world; this type of design is not new.



Left: A Honduran family enjoys its new stove.

Tests show that this stove is about 19% efficient. The plancha griddle is good at transmitting heat to the pots. The thin metal is a great conductor of heat. But, for the same reason wherever the plancha is open to air, where it isn't

The Aprovecho version of the plancha stove includes a Rocket-type insulated firebox and chimney. Hot flue gases are also forced to pass directly underneath the metal griddle. The following diagram points out the design features of this type of improved plancha stove named after Dona Justa. (Mrs. Justa helped to design, build, and test this stove in Honduras.)



The Dona Justa Stove



Mike Hatfield (far right) and women of Nueva Esperanza, a co-op in Honduras which makes durable stove parts

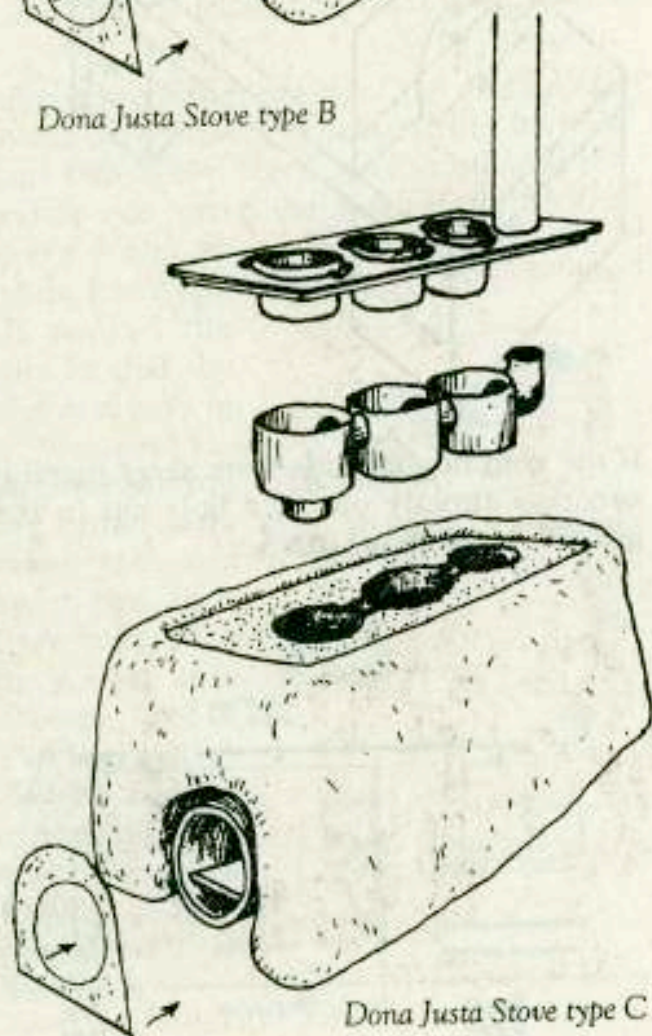
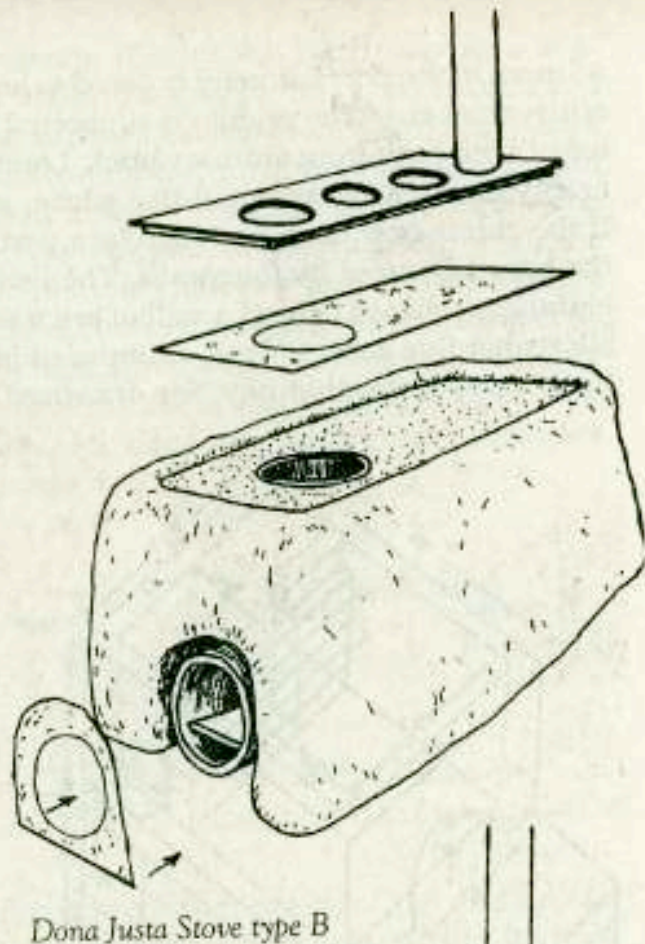
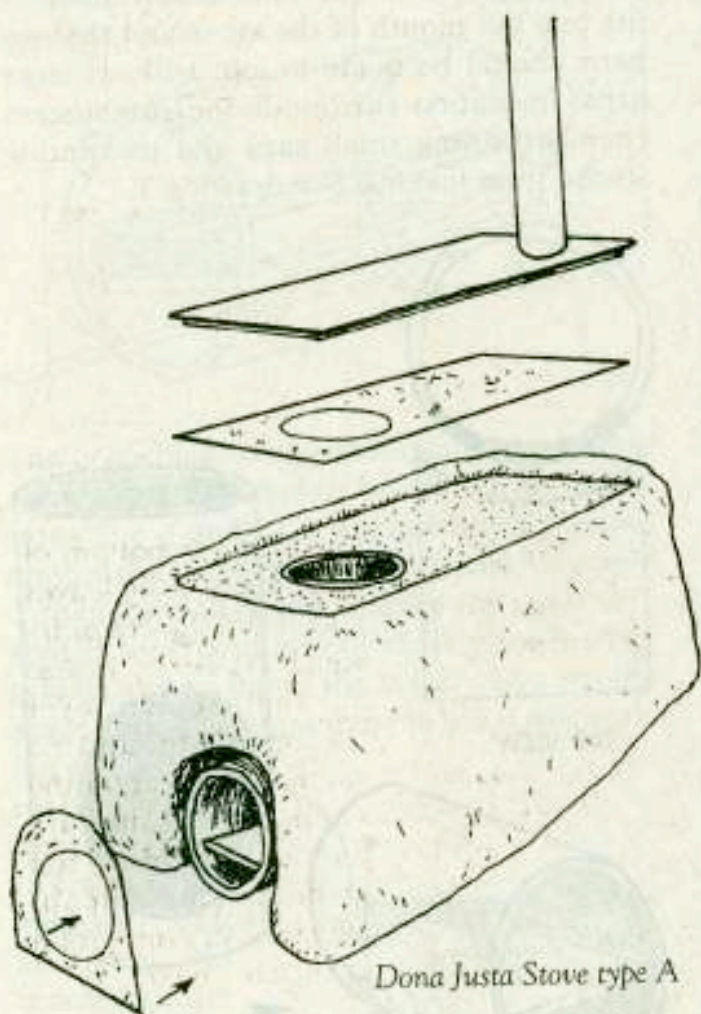
touching the bottom of a pot, heat easily leaves and heats the room instead. However, 19% is an improvement over the open fire, and no smoke should enter the kitchen. Pots that are heated on top of the griddle stay clean, which is very important to certain cooks.

The Justa stove does many of the same things that the beautiful

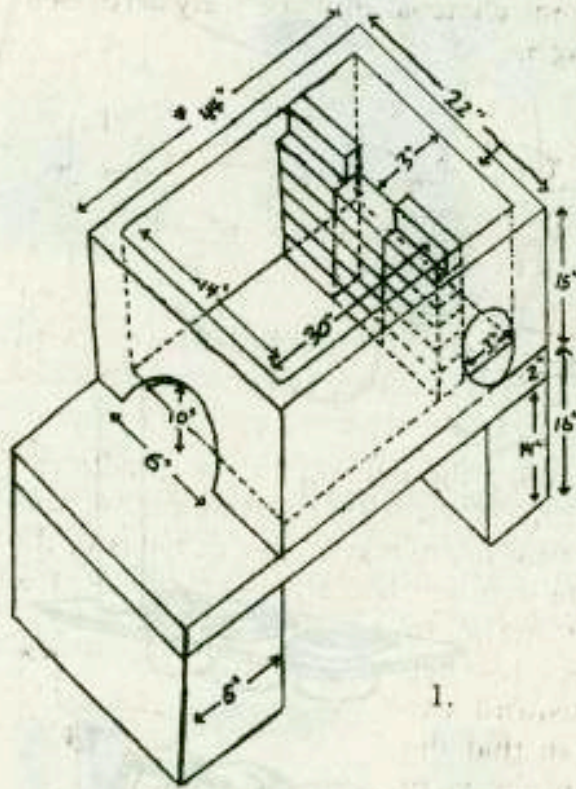
old cast-iron cooking stoves did. These older-type stoves now cost more than a thousand dollars in the US. But a Justa stove can cost less than 20 dollars to make. We plan to install this stove and one quite like it in the kitchens at Aprovecho, reducing our use of propane.

How to Build Three Variations of the Dona Justa Stove

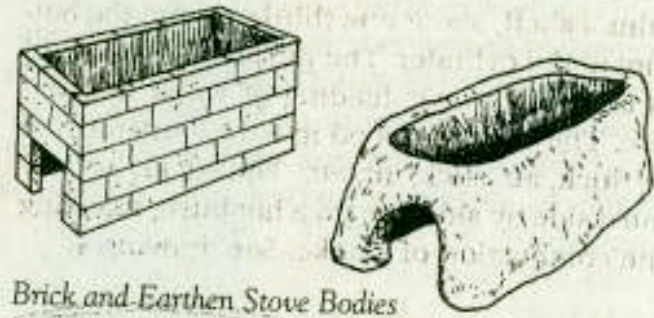
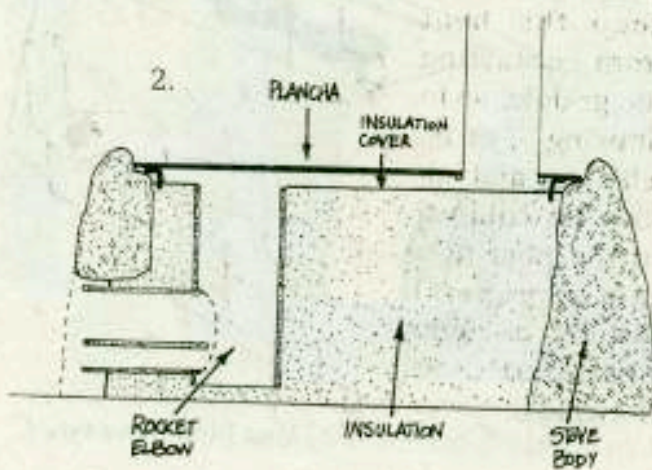
The pots can sit on top of the griddle (A), be placed over holes cut in the griddle (B), or be partially submerged into the griddle (C).



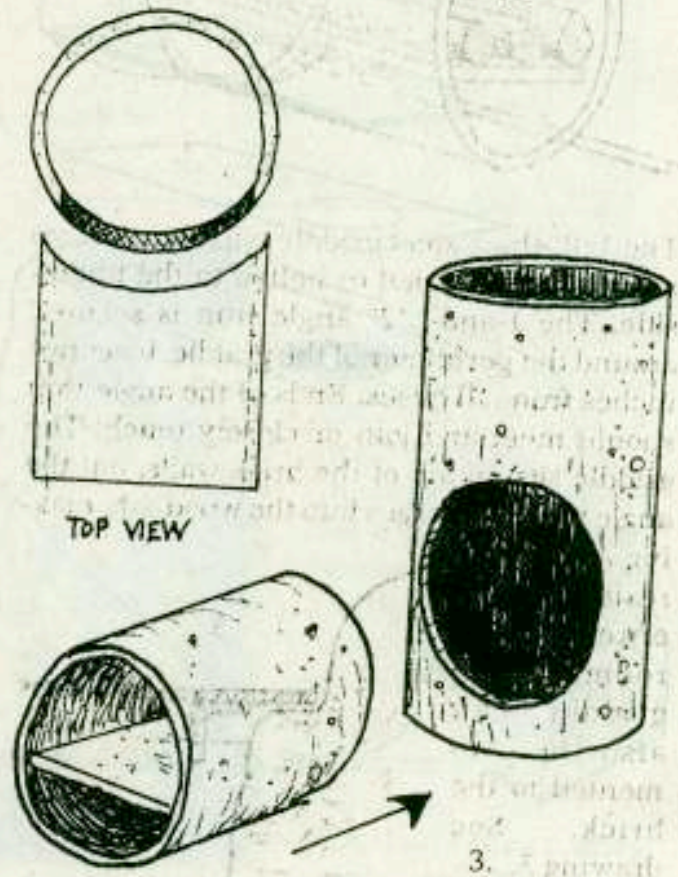
As more of the pot is directly exposed to heat, efficiencies rise. The griddle is supported on top of a box built from ordinary brick, Lorena, or any inexpensive material like adobe, etc. If the chimney is cement, it can be a part of the box, supported by four walls. The heavy chimney is placed behind a wall of brick that allows hot flue gases to flow unimpeded into the bottom of the chimney. See drawing 1.



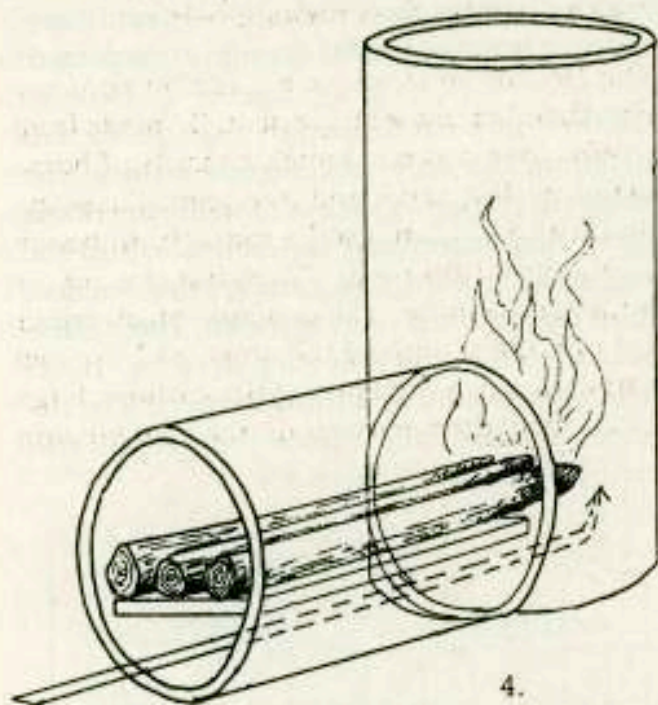
If the chimney is made from sheet metal it can rise directly out of a hole cut in the griddle. See drawing 2.



The Honduran stoves use a Rocket combustion chamber in the shape of an "L" made from a refractory ceramic which consists of horse manure, clay, sand, and tree gum. These cylindrical parts can also be made from heavy steel, black iron pipe, 430 stainless steel, or refractory cement. The combustion chamber fits into the mouth of the stove and the two parts should be made to join without large gaps. Insulation surrounds the combustion chamber, filling small gaps and preventing smoke from leaking. See drawing 3.

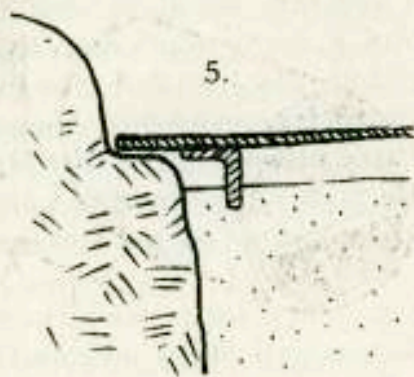


The mouth of the combustion chamber contains a shelf, about one third up from the bottom of the cylinder. The purpose of this shelf is to assist proper feeding of wood into the fire. The sticks of wood make a grate formed by stick, air, stick, air, etc. The sticks, as they burn side by side, create a hot burn, assisting the combustion of smoke. See drawing 4.



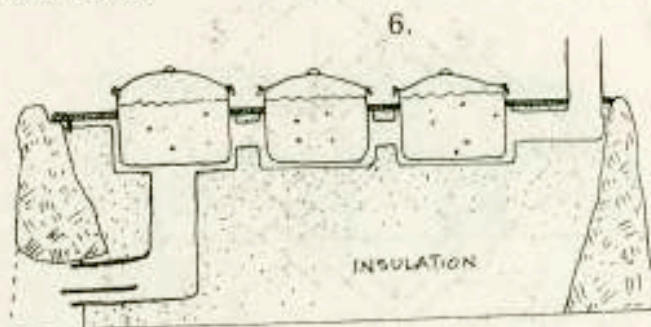
4.

The 1/8"-thick steel griddle will warp unless angle iron is welded or bolted to the underside. The 1-and-1/2" angle iron is secured around the perimeter of the griddle, inset two inches from all edges. Ends of the angle iron should meet and join or closely touch. The griddle sits on top of the brick walls, but the angle iron submerges into the wood ash, making a seal that resists smoke entering the room. The griddle can also be cemented to the brick. See drawing 5.



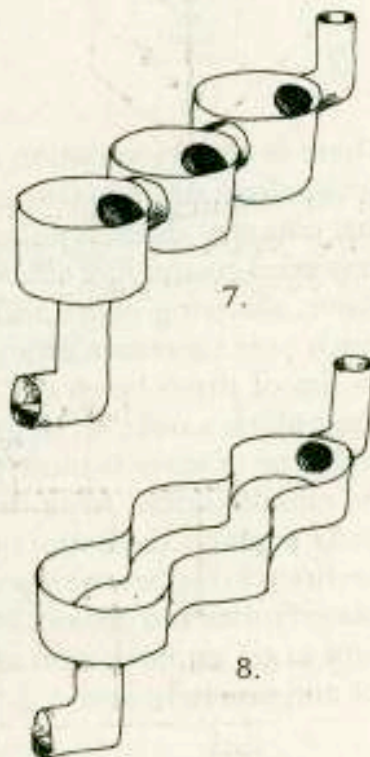
5.

Insulation fills up the stove, leaving a 3/4" gap under the griddle. The most natural and least expensive insulation is probably wood ash. If a sufficient quantity of wood ash is hard to find, a poorer insulator can fill most of the stove as long as 6" of wood ash surrounds the combustion chamber and lies under the griddle. Poorer insulators (which can also fill the entire stove, with less optimal results) include perlite, vermiculite, light pumice rock, dead coral, charcoal, and dry fluffy earth. See drawing 6.

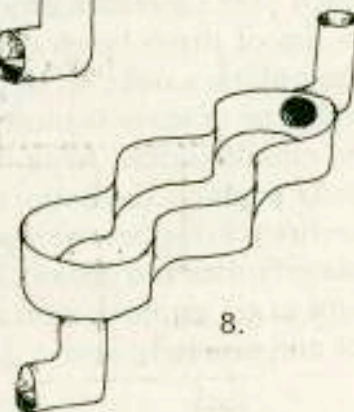


6.

Submerging the pots under the griddle can double the efficiency of heat transfer. We have done this in two ways. A.) Cut holes in the griddle into which the pots exactly fit. Use sheet metal to create a 1/4" gap all around the pots so that the heat is always in an insulated environment. You can either do a great job and keep the heat from contacting the griddle, as in drawing 7, or be a bit lazy and follow the contour of the pots in a more general fashion, as demonstrated in drawing 8.

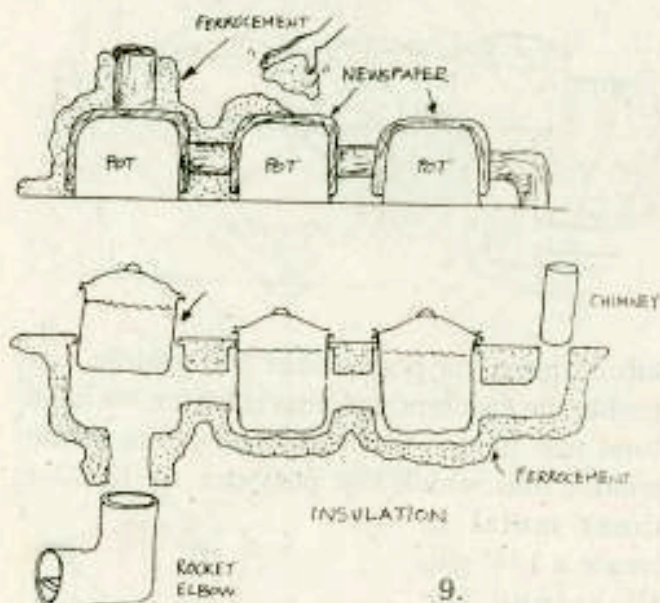


7.



8.

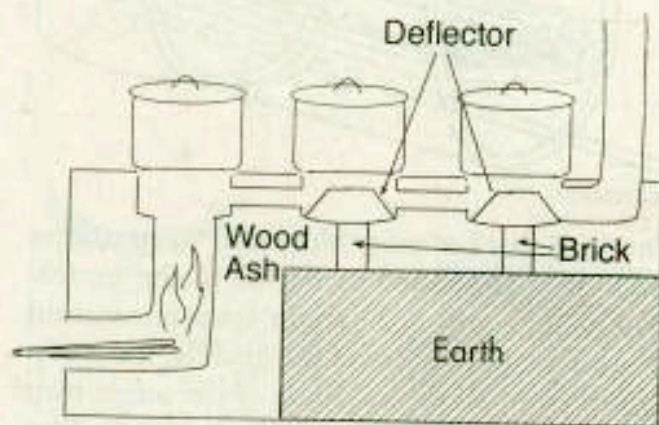
Method B. uses refractory cement. The cement is formed around the actual pots to be used. Wrap the bottom half of the pots in newspaper or other material. A gap of 1/4" will be created when cement is pressed around the male mold. Let cement directly touch the oiled pot so that a smoke-tight fitting is created near the top of the pot or just under the handles. Adding the mass to the stove does cut back on efficiency, but the refractory cement will greatly outlast the sheet metal used in the low-mass model. See drawing 9.



There is always variation in an Appropriate Technology design. One village may insist that pots stay clean. A village fifty miles away may need greater fuel efficiency. As explained above, allowing heat (and soot) to directly touch pots increases efficiency. Pots can sit on top of three holes cut into the plancha. They block smoke from entering the room. This type of stove is more fuel-efficient than the closed-griddle Justa because the fire directly contacts the bottom of the pots. When the fire travels between pots it can be in insulated tubes and doesn't lose much heat. We want to get as much heat as possible into the pot and nowhere else!

The open-hole variation of the Dona Justa stove can be up to 30% efficient. The efficiency rises a little more when a fourth pot is exposed to the heat. A four-pot stove absorbs a bit more of the heat before it is wasted out of the chimney. But the little amount of remaining heat makes for a very low-powered fourth burner. The fourth burner is really only good for heating dish water, etc. In our experience, it is not powerful enough to cook food.

Another important design feature of this variation, the deflector, directs heat at the bottom of the pot. A piece of metal or ceramic sits in the burner and forces heat up to the pot, making sure that, unlike the Lorena, there is improved heat transfer. The deflector is shown in the following drawing. It sits inside the second and third burners. The deflector substantially raises the overall efficiency of the stove about 6%.



A More Efficient Dona Justa Variation

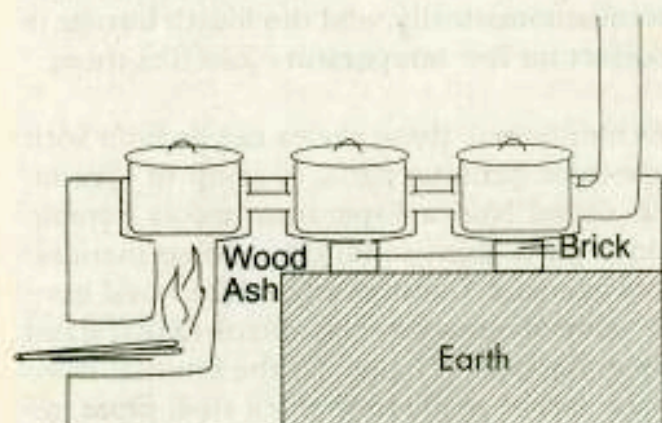
A 40%-efficient stove with chimney results from partially submerging the pots below the griddle. The heat from the fire is directed at each pot through a skirt around the pot's sides. Three pots are tightly fitted into holes cut in the plancha. If the holes are cut properly, smoke cannot escape into the kitchen.

A cement plancha can be formed around the pots, as well. Skirts surround the bottom and

sides of the pots, under the stovetop, forcing the heat to contact more of the pot. If the gap is optimal (in this case about 1/4") and the same cross-sectional area is maintained (to assure steady draft) as heat travels past the sides and bottoms of all three pots, this stove can reach efficiencies of 40%.

The efficiency of this stove is highest because the greatest amount of heat is striking the most surface area of the pots.

As in the previous stove, both combustion chamber and fire flow path are insulated with wood ash, perlite, vermiculite, or fluffy earth. The plancha is also thermally isolated from the heat by insulation.



The Most Efficient Dona Justa-Type Stove

These stoves, the Rocket and the Dona Justa, demonstrate more or less efficient ways to help create a reduced-smoke or smoke-free kitchen. The Rocket stove can be a useful option if, for economic or other reasons, a chimney is not going to be used. The stove with chimney removes the smoke and for that reason is always preferable. Although the griddle-type stove, and variations including sunken pots, have been built and used in the past, Larry has introduced several features that are novel and important:

1.) The Rocket elbow assists cleaner and more

complete combustion.

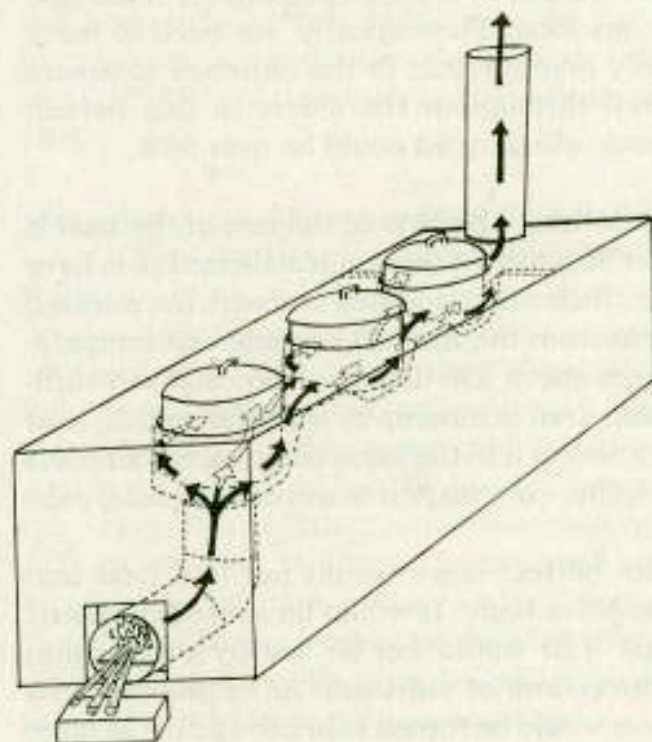
2.) The gap between the pot and skirt is smaller, forcing heat to rub against the pot.

3.) The entire heat flow path is insulated, lessening heat absorption into the stove body.

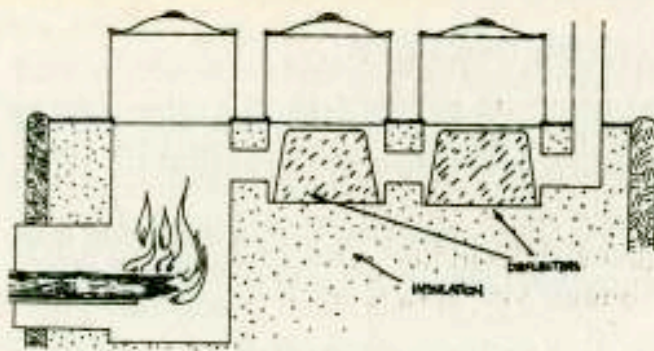
4.) A smaller, well-insulated combustion chamber allows the use of fewer sticks, since the fire does not tend to die out as easily.

Fuel Efficiency in Stoves

The draft created by the internal Rocket and external chimney makes it possible to force the heat through a narrow opening beneath the second and third pots, increasing the success of efforts aimed at heat transfer. Tall chimneys are a big help when sucking heat through a circuitous maze of heat exchangers inside a stove. For example, the deflector in the burners aims the heat at the pot. It can be used only when there is sufficient draft.



Air Flow in the Most Efficient Dona Justa-Type Stove



Deflectors Force Heat at the Pots

Forcing heat to contact the sides as well as the bottoms of the pots dramatically increases fuel efficiency. Increasing contact to the pot in the Dona Justa stove increases efficiency up to around 40%. It makes sense that to get a large percentage of the heat into the pots it is necessary to expose the maximum pot surface area to hot flue gases.

For better fuel efficiency, insulating the fire flow path is also essential. Imagine if the fire flow path were perfectly insulated so that no heat was lost or absorbed. By exposing sufficient pot surface area to hot flue gases we can be sure that a very high percentage of the heat cooks food. Theoretically, we need to leave only enough heat in the chimney to assure draft throughout the stove. In this perfect stove, efficiencies could be over 50%.

Something like 50% of the rest of the heat is lost because 1.) three normal-sized pots have insufficient surface area to absorb the released heat from the fire; 2.) keeping exit temperatures above 250 degrees F. to establish sufficient draft is inherently wasteful; and 3.) heat is also lost into the stove body, excess air cools the fire, combustion is never complete, etc.

The perfect stove would not lose heat into the stove body. It would be so well insulated that heat would not be lost by conduction, convection, or radiation. All of this captured heat would be forced to brush against as large a percentage as possible of the surface area

of the pots, efficiently heating them up, until the exit temperatures from the chimney were very low. Almost all the heat would be in the pots, leaving only enough to continue the draft.

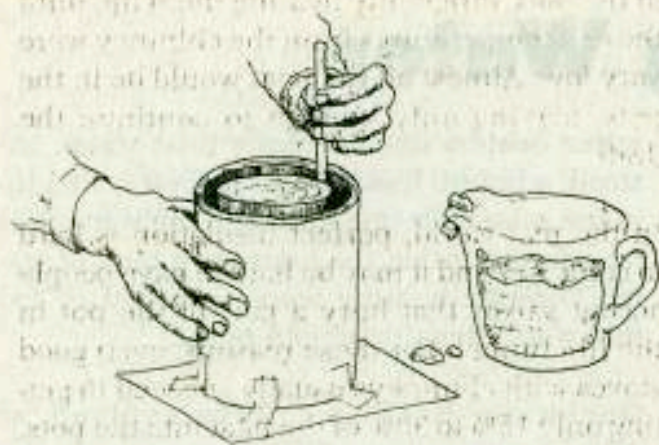
In the real world, perfect insulation is hard to come by. And it may be hard to have people accept stoves that bury a part of the pot in the fire tunnel. For these reasons, even good stoves with chimneys usually succeed in getting only 15% to 30% of the heat into the pots.

Using more pots to pull heat from the fire increases efficiencies. However, as mentioned above, more than three pots are hard to heat. The fourth pot will warm but it's not likely to boil. Of course, it's nice to heat wash water semi-automatically, and the fourth burner is perfect for low temperature jobs like these.

As mentioned, these stoves can be built with low-mass ceramic parts. A co-op in Honduras called Nueva Esperanza makes durable stove parts from sand, clay, horse manure and tree gum. Cultures around the world have developed refractory clay mixtures that stand up to the heat of flame. Or the internal stove parts can be made from thick steel pipes, replaceable thinner steel, tin cans, 430 stainless steel (which holds up in stove use), etc.

There are also pourable refractory cements that do not degrade at normal stove temperatures. We find that parts made from this material are relatively cheap (20 dollars for a 50-pound sack), are easy to work with, and have a long life. We don't recommend reducing wall thickness to less than 1/2".

(Refractory cements are available from North American Refractories Company, 500 Halle Building, 1228 Euclid Ave., Cleveland, Ohio 44115. Phone: (216) 621-5200.)



Tamping Refractory Cement into the Mold

It is quite easy to make molds out of cardboard. Or you can use big pop bottles or found objects to act as molds. The refractory cement pours easily, but it's best to use a stick to make sure there are no air bubbles in the casting. Be careful not to breathe the dry mixture, as it contains silica. We find that the wet mixture is easier on the hands than regular cement, although it is still advisable to wear gloves.

The internal stove parts are surrounded by insulation, which can be wood ash, pumice rock, perlite, vermiculite, fluffy soil, etc. This combination makes for a highly insulated stove. The outer, durable box can be made from brick, Lorena, cement block, etc. The mass of the stove body is thermally isolated from the heat of the fire by the insulation.

If the internal parts are made from heavy amounts of Lorena mix, concrete, or simply mud and clay, then the overall efficiency of the stove will drop considerably due to absorption of heat into the mass. Even high-mass stoves, however, will benefit from many of the design patterns suggested in this chapter. The low-mass three-burner *Justa* made from tin cans averaged 33% efficiency. When we surrounded it with more than 75 pounds of concrete, the average efficiency dropped to 24%. Tin cans, however, do not last.

It is a good idea to design a stove to achieve as complete combustion as possible. Even though chimneys carry smoke out of the room, that is not a great solution if the smoke enters the neighbor's house through the open doors and windows. Designing for "complete combustion" always seems preferable.

To accomplish better combustion Larry insulates around the combustion chamber, uses a shelf in the fuel magazine, and includes a Rocket-style chimney above the combustion chamber. A hot, fierce fire is a clean fire.

Larry also does not include dampers in the chimney. If a decrease in air is needed it is better to regulate excess air through the opening into the combustion chamber. Using a damper is something like regulating air flow into the car's carburetor by partially blocking the tailpipe with a potato! It's far better to allow the proper amount of air into the carburetor initially. We want a small amount of hot air contacting the fire at high velocity. A small opening that aims air at the base of the fire will keep the fire burning fiercely. Partially blocking the chimney slows down the airflow, and is therefore detrimental to clean combustion.

The options and suggestions put forth in this booklet summarize a couple of decades of stove designing and testing. The general understanding of how stoves work has matured a lot since the early days of the 1970s. Hopefully these design patterns will come in handy if you need a wood-burning cooking stove! Any of the *Justa* models are easy to make and can serve as a primary source for cooking. Add an oven by building an insulated box around the chimney, on top of the plancha. For a hotter oven, change the chimney shape from cylindrical to rectangular and include as much chimney in the box as possible.