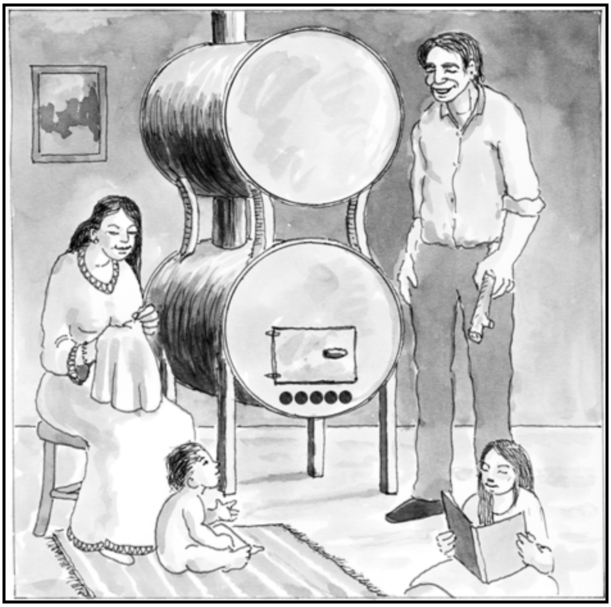
Designing
Improved Wood Burning
Heating Stoves



Dr. Mark Bryden, Dean Still,
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Aprovecho Research Center
Advanced Studies in Appropriate Technology

Shell Foundation

To: Kim, Victor, Max, Hanna, and Doug
who keep Dean warm

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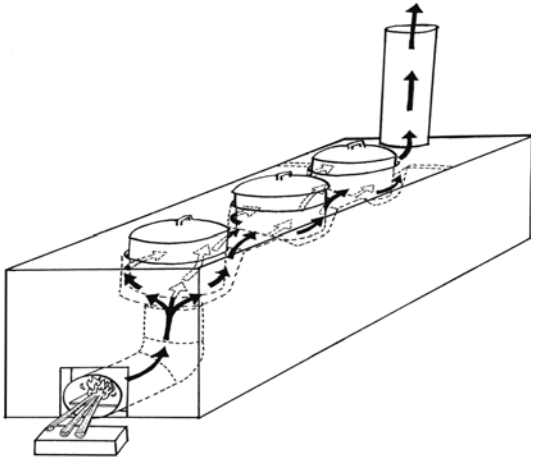
Chapter 1- Learning from Cooking Stoves

Aprovecho Research Center has been investigating how to burn wood and biomass since 1976. Most of this work has been with cooking stoves. However, a lot of the lessons that were learned experimenting with cooking stoves are applicable to heating stoves as well. After years of investigation, it became clear that ***heat transfer to the pot largely determines the fuel efficiency of a cooking stove***, especially since high combustion efficiency (transforming a large part of the wood into heat) is relatively easy to achieve.

The Technical Director at Aprovecho is Dr. Larry Winiarski, Mechanical Engineer. Larry is a gifted teacher who has led our investigations at the research center. The cooking and heating stoves which Aprovecho helps indigenous groups develop around the world are his inventions. Larry's understanding of stove thermodynamics has resulted in a set of design principles that can be used to create many types of stoves.



An improved cook stove

One of Dr. Winiarski's key observations is that that the combustion chamber (where the fire burns) is only one part of the successful heating stove. The heat exchanger assists heat transfer to the room, largely determining how much wood is used.

The first job of an improved stove is to achieve nearly complete combustion of fuel (turning almost 100% of the wood into heat) and to not allow smoke, which is un-combusted fuel, to escape. Enough air needs to rush into an insulated chamber to create a hot fierce fire that burns cleanly. The second job of the good heating stove is to get close to 100% of the heat into the room.

Chimney Pipes are Poor Heat Exchangers

A cylindrical chimney pipe allows a lot of the heat to escape instead of forcing the heat into the room where it can be of use. The chimney pipe is an inefficient ***heat exchanger***. Hot flue gases rush up the middle of the pipe, avoiding the friction of the sides. So, a large portion of the heat created by burning wood is wasted as it escapes up the chimney and out into the cold air beyond the windows and walls. Testing at Aprovecho has shown that capturing the lost heat dramatically reduces fuel consumption. Using a good heat exchanger gets families warmer more quickly using less fuel!

Clean Burning First

A good combustion chamber changes wood or other biomass into heat without creating much smoke or creosote (condensed wood tars). Complete combustion of wood results in two byproducts: carbon dioxide and water vapor. In contrast, incomplete combustion creates unburned particles that cause pollution and creosote that fills chimneys and can cause chimney fires if it ignites.

Complete combustion is the goal of the combustion chamber. But a slow burning heating stove cannot burn wood very cleanly. Nearly complete combustion in a wood burning stove can be achieved by doing the following things:

1.) Metering the fuel– Cutting wood up into smaller pieces and feeding them at a proper rate into the fire as they are consumed.

2.) Making a hot fire- Creating a combustion zone where fuel, flame and air are mixed by ***turbulence***, at a high enough ***temperature***, for a long enough ***time*** to completely combust. Combustion temperatures must be hot enough to assist burning all escaping gases released from the wood.

Remember that wood itself does not burn. Wood gets hot and then releases constituent gases that hopefully all burst into flame. The remaining solid residue, char, is then combusted to form carbon dioxide. A hot fire is a clean fire. A lazy fire pollutes the air which humans need to breathe.

3.) Insulating the combustion chamber– Insulation helps to keep temperatures high.

4.) Igniting escaping smoke– Passing smoke, which is un-combusted fuel, through a flame.

5.) Providing sufficient oxygen– Starving the fire slows it, cools it down, and produces smoke.

Ignition Temperature (Fahrenheit in Air) of Wood Gases

Hydrogen	750º
Carbon Monoxide	1125º
Methane	1000º

Combustion Engineering, Borman & Ragland, 1998

6.) Warming and increasing the velocity of the cold air entering the fire– Air is warmed as it passes through a small opening into the combustion chamber. ***For systems without a fan, make enough small holes under the door into the combustion chamber so the holes have as much cross-sectional area as the chimney exiting the stove.*** Position the holes so that primary air is sucked into the coals and up into the combusting wood***. Do not allow the user to block the holes reducing primary air. Blocking the necessary amount of air will create pollution***. The rate of burn in a heating stove should be determined by the amount of fuel in the combustion chamber, not by shutting off air to the fire.

7.) Forming a grate out of the firewood– Sticks burning close together heat each other and keep the temperatures high. The pattern should be stick, air, stick, air, with even spaces between the sticks.

8.) Creating sufficient draft– Use a tall enough chimney or better yet a small fan. An insulated chimney creates a lot more draft than an un-insulated chimney. High velocity, low volume jets of hot air entering under the fire, up though the coals, create mixing which reduces emissions. ***Do not use a damper in the chimney. Design the stove to run efficiently with enough air entering and leaving the stove to burn fuel cleanly.***

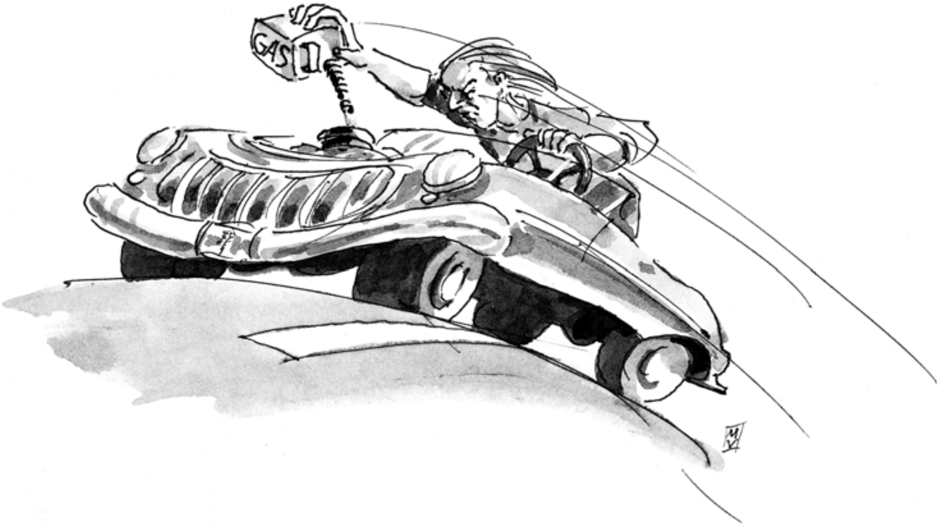
Complete combustion cannot occur when starting a stove because the combustion chamber is too cold. An insulated combustion chamber will heat up more quickly and then, when burning metered amounts of biomass, make less smoke. Throwing a big log on the fire, however, always makes smoke. The log cools the fire and releases more pyrolysis gasses that overwhelm the available air and are too cold to be combusted.

Without enough air, wood cannot burn cleanly. The size of the air inlets into the fire should add up to be about as large as the chimney exiting the stove. The power level of the stove should be set by the wood loading rate, not the air flow. When users try to control the power of the stove by shutting off air to the fire they can send horrible plumes of smoke out of the chimney. A stove must have enough air to function efficiently.

Metering the Fuel

Throwing a big log on the fire is like dumping a gallon of gas down the carburetor of a car all at once. The car may keep running, if it doesn't stall completely. However, smoke will certainly pour out of the exhaust as the car struggles to burn too much fuel.

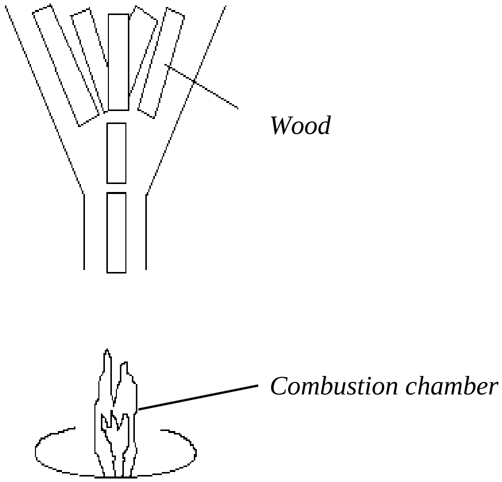
Fuel needs to be metered to achieve efficient combustion. That's why cars have carburetors that precisely mix just the right amount of air, fuel, and spark. The improved heating stove does the same thing, burning up the gases and not letting them escape without combusting.



Pellet Stoves

Many pellet stoves don't smoke because just the right amount of fuel is delivered as it is burned up. A fan makes it possible to preheat the air coming into the fire and assures good mixing of gases, air and flame. Lots of air is needed for hot clean burning. The amount of heat is regulated by adjusting how much fuel enters per minute into the fire. In a pellet stove, fuel drops down into a small crucible, replacing the burning fuel at the same rate it is consumed. This small amount of fuel combusts completely. Little smoke and few emissions exit out the chimney.

Metering fuel makes clean burning easy. In a regular wood burning stove, the same thing can be accomplished by burning small pieces of dry wood and watching to make sure that a fierce flame is present. A little observation teaches the operator quickly how to maintain clean burning. Unfortunately, adding fuel at regular intervals is much more demanding and time consuming than just throwing a log onto the fire and then ignoring the smoke polluting the environment.

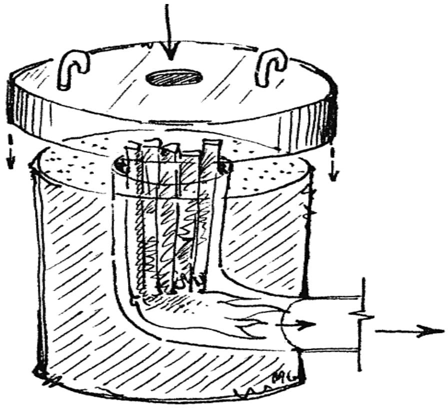


Pellet Stove

Chapter 2- Patterns for Combustion Chambers

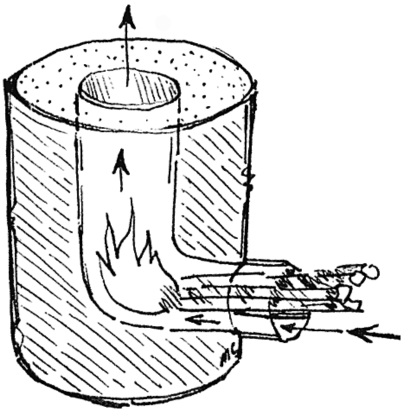
If smoke passes through flame, it ignites. Which one of the following patterns has the greatest potential for clean burning?

The illustrations on pages 10 & 11 show different clean-burning patterns of feeding wood into a combustion chamber.



1.) Downdraft /downfeed

1.) The pattern that Dr. Winiarski favors is downdraft/down feed. The wood is burned at the bottom of a vertical stick that falls down as it is consumed. Air is pulled down alongside the sticks and into the fire. The coals fall in front of the flame path and help to create a second environment that ignites smoke. A wall of flame is pulled horizontally into an insulated space. Smoke escaping the initial burn will usually ignite in the flame. The down feed/downdraft stove is clean burning like the pellet stove because of the metering of fuel into the fire.



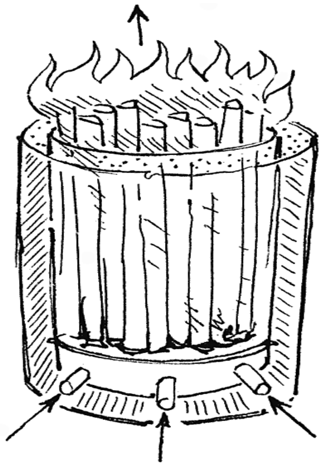
2.) Side feed

2.) Side feed/side draft is how most people feed a fire. The sticks are pushed into the fire as they burn. In this pattern, the fire creates coals that lie underneath the flame which is less helpful for assisting secondary combustion. With care however, side feed can be an effective option.

3.) The third pattern is to pack the wood into the combustion chamber. This is called batch loading. The sticks are vertical and hold each other up.

If you wanted to minimize smoke would you light the fire at the top or bottom of the stack?

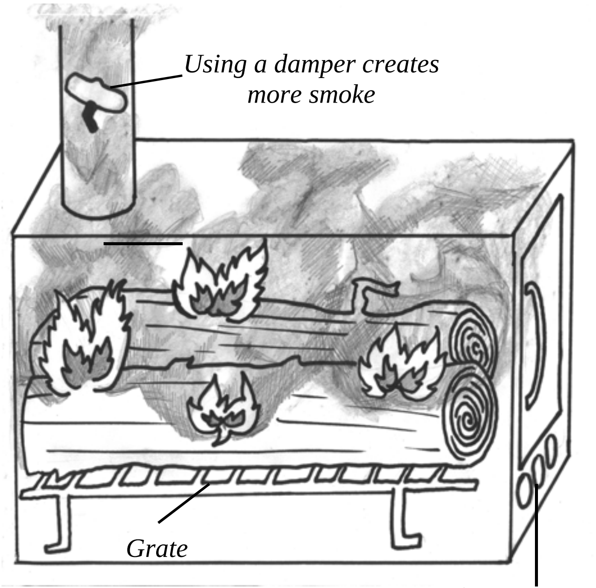
If the batch of wood is lit at the bottom any escaping combustion gasses rise up and away from the flame. Lighting the stack at the top, on the other hand, can result in clean burning because smoke is more likely to pass through flame. Masonry heating stoves often use this top burning technique.



3. Top burning

4.) There is, of course, a fourth pattern for a combustion chamber. Logs of wood are in an enclosure and held up off the floor by a grate . The large pieces are started burning using kindling. Air is supplied through holes which create high velocity jets that pass up through the charcoal to the burning wood.

Do not allow the user to block the holes reducing primary air* or to reduce airflow in the chimney by using a damper. Cutting down the primary air makes smoke, creating pollution and wasting fuel.



Given plenty of air, the logs will burn without tending for a couple of hours, making the stove easy to use. Providing enough primary air and insulating around the fire will not alter the nature of this arrangement. This is an inevitably smoky pattern. On the other hand, this pattern is so pleasant to use that even though it can be environmentally unfriendly it has to be included as an option.

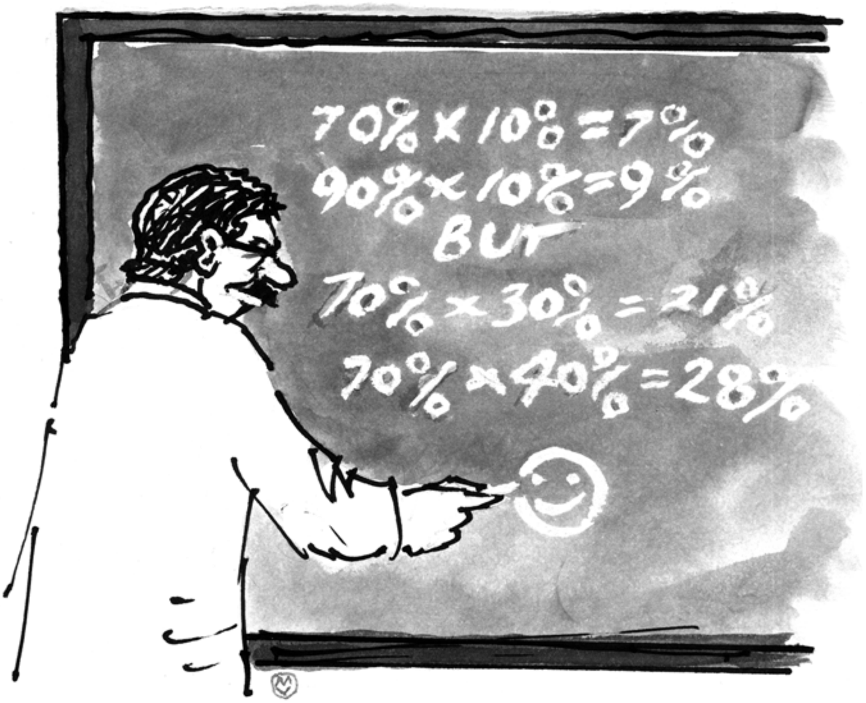
*Primary air directly enters into the fire, secondary air enters above the fire to assist the mixing of fuel air and fire and to provide oxygen if needed for combustion of gases. Secondary air must be used very carefully in stove design to ensure that is does not cool the flame too much.

Chapter 3- Heat Exchangers

There are three types of heat exchangers generally used to capture the heat produced in the combustion chamber. The hot flue gases can: A.) Heat **mass,** like heavy stone or masonry B.) Heat **water** which then warms the house or C.) The easiest and least expensive route is to make the hot stove gases efficiently heat the **air** inside the room.

Heat exchangers increase heat transfer to the room by making sure that the hot flue gases leaving through the chimney are as cool as possible. Even a smoldering fire turns at least 70% of the wood used into heat. Heat transfer efficiency (heat delivered to the room) can be less than 20% in poorly designed systems. As the cartoon shows below, a little improvement in heat transfer equals impressive increases in fuel efficiency.

When analyzing a system, try to improve the least efficient part first. This has the greatest beneficial effect on overall system efficiency!



Choosing Between Air to Air and Air to Mass Heat Exchangers

High mass heat exchangers were created in the days of drafty houses when heating air was a losing proposition. Old houses had air exchange rates of more than 10 exchanges per hour. All the air in the house was replaced ten times or more every hour! It didn't make sense to heat air that would quickly be outdoors.

Storing heat in a large thermal mass inside the house does two things: **1.)** Allows big hot clean burns that store the excess heat instead of over heating the interior of the house, and **2.)** even when full of stored heat, the surface of the heat exchanger remains at a relatively low temperature so that radiant heat is released at a slower rate per hour into the living space. The big warm rock in the living room heats occupants by radiation even when the room air is cold. High mass stoves are perfectly suited to the cold drafty environments for which they were designed.

Drafty Houses Constantly Lose Heat

Today many houses are not so drafty. Modern houses can have one-half an air exchange per hour. Heating air becomes an acceptable option. The hot air has time to warm occupants and interiors. Sealing the cracks that allow air into the house is the most important first step to holding heat in a house. Insulating the house is the second most effective step in using

A lot of people still live in drafty houses with a lot of air exchanges per hour. An air-to-mass stove evolved to heat just such a house. It is less necessary to use a massive heat exchanger in tighter, better insulated houses.

Heat the inside, not the outside

Pluses and Minuses:
Massive Heat Exchanger

Positive

1. The mass stores heat that can keep the house warm overnight.
2. Gentle radiant heat feels good.
3. Burning time can be reduced.
4. The fire can be huge and hot resulting in clean burning. Since the heat is stored at a lower temperature to be released more slowly, the room doesn’t tend to overheat.

Negative

1. Stored heat is there if you need it or not. If the day suddenly gets warmer, the room can overheat.
2. The mass takes up room. To store sufficient heat, the heat exchanger must weigh thousands of pounds.
3. The cold mass will take a long time to heat up and warm the room. Coming home and lighting the stove for warmth will not work with a high-mass, slow-response heating stove. The stove needs to be kept warm.
4. Creating the ductwork in stone, brick, or adobe frequently requires experience.

Air to Air Heat Exchanger

Positive

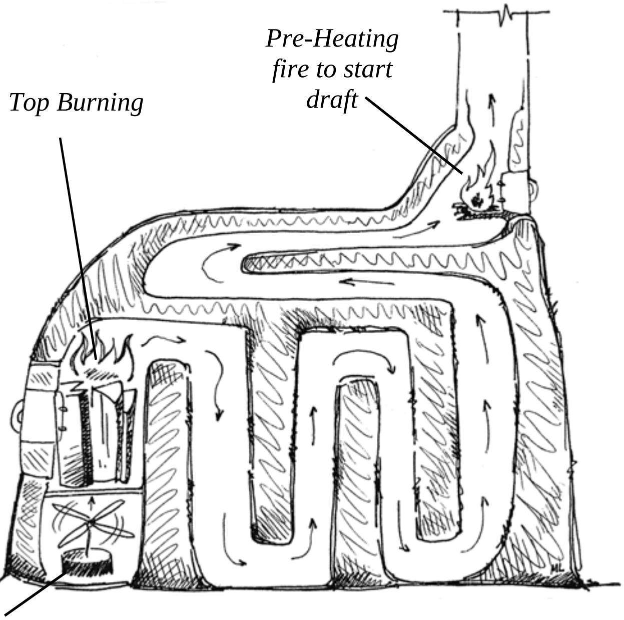
1. It is inexpensive and easy to make.
2. It doesn’t weigh very much.
3. It takes up less space.
4. It heats the room quickly.
5. If the weather suddenly warms, the heat can be adjusted.

Negative

1. It doesn’t retain heat and is cold after the fire goes out.
2. It discourages big, hot, clean-burning fires (which overheat the room) and can encourage small fires that pollute.
3. It is better suited to less drafty houses.

Massive Heat Exchangers Encourage Clean Burning

The great thing about air-to-mass heat exchangers and air-to-water systems is that the stove can be fired very hot for a long time without overheating the room. The heat goes into the cool stone or water, instead of immediately into the room air. Big fires are very hot and for that reason can produce less harmful emissions. The harmful gasses burn up in the hot fire.



Pre-Heating fire to start draft

Top Burning

Optional fan decreases heat loss by pushing hot flue gasses through longer passageways

High mass heat exchanger

When using mass to capture heat after an intense burn, the fire can be allowed to go out. An airtight damper and door on the stove stops air from moving up the chimney. The stored heat in the mass radiates into the room, replacing heat lost to the outside. Room temperatures stay relatively constant even though the fire is extinguished for prolonged periods of time.

Shutting the flue (sealing off the chimney) after a burn also helps to decrease the number of air exchanges in the room. As long as air is rising up the chimney, it is replaced by cold air that is pulled into the house through cracks in the doors and window frames. Starting a stove increases the number of air exchanges in a room or house. Using a wood stove that is constantly burning can have this negative side effect. Shutting the flue after a three to four hour burn solves this problem.

Air-to-air heating stoves can also reduce or eliminate increased air exchanges by feeding the fire with air supplied from outside the house through a tube in the wall or floor into the stove. In this manner, air is supplied directly to the fire and is not sucked in through the cracks.

An external supply of air into the combustion chamber is very helpful as it eliminates increased air exchange into the house. Even a hole through the wall or floor near the stove helps, if most of the air entering the room is drawn into the fire.

Air-to-Water Heat Exchangers

Heating water requires care because of the potential pressure rise as water nears boiling. Pipes full of water can corrode or fill with mineral deposits. Except for these problems, water is a great storage medium for heat. Per pound water stores 5 times more heat than rock (the density of rock offsets this difference to some degree). One BTU will raise the temperature of one pound of water one degree F. To raise the temperature of rock or adobe requires only 1/5th of a BTU.

For this reason, heating water can be a very efficient way to capture the heat of a fire before it slips away into the sky. The efficiency of heat transfer into large containers of water can be very good. Water stores and holds heat for a long time.

Unfortunately, even the most carefully built wood fired-showers at the research center occasionally leaked or even exploded! Air-to-water heat exchangers for house heating seem so full of potential problems that we have never installed one at Aprovecho. Imagine trying to repair lots of leaking pipes buried in your floor. So far, potential difficulties and cost have steered us back to simpler solutions. Heating water is theoretically a great idea but can be complicated.

Storing Heat In Water

Advantages	*Disadvantages*
1. Can provide very efficient heat transfer 2. Retains more heat than other thermal mass 3. Allows for control of the amount of heat by opening or closing radiators	1. Usually requires a thermostat 2. Needs safety release valves 3. Water can leak 4. Minerals in water can reduce internal pipe diameter, leading to reduced water flow, greater temperature rise and increased pressure loss in the system

Environmental Building News (Volume 11, Number 1, January 2002) concludes that radiant water heating isn’t necessary in insulated, tight houses. Controlled air exchange into the house (say, better than one air exchange per hour) and enough insulation (for example: R-38 in the roof and R-21 in the walls) works so well that a heating system can be smaller, simpler, and inexpensive. Insulation and air tightness make heating simple and easy.

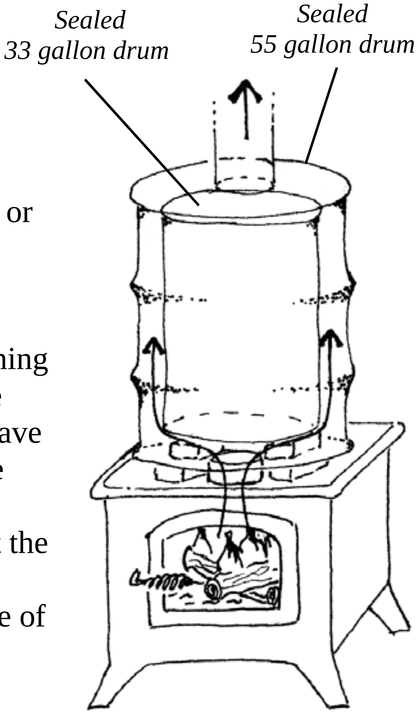
The Air-to-Air Heat Exchanger Is Hotter and Cheaper

A stove using a high-mass heat exchanger can get away with short hot burns. An air-to-air heating stove has a harder task to accomplish: to create an equally hot, smaller fire that matches the heating demand of the space. The air-to-air type of stove is more dependent on doing things right to reduce emissions since it’s not creating one huge hot fire. The factor favoring air-to-air solutions is that they can be built inexpensively and quickly.

Stoves with Air-to-Air Heat Exchangers

After making sure that the combustion chamber will burn cleanly, Dr. Winiarski adds two basic types of air-to-air heat exchangers to the stove: either downdraft or updraft.

The heat exchangers must do at least two things to work efficiently. While maintaining about the same cross-sectional area as the original chimney, the hot gasses should have contact with a much greater metal surface area. The hot flue gases travel in reduced channels that force the heat to rub against the metal. Hot flue gasses warm the inside surface of the metal. The hot outer surface of the metal then warms the room air.



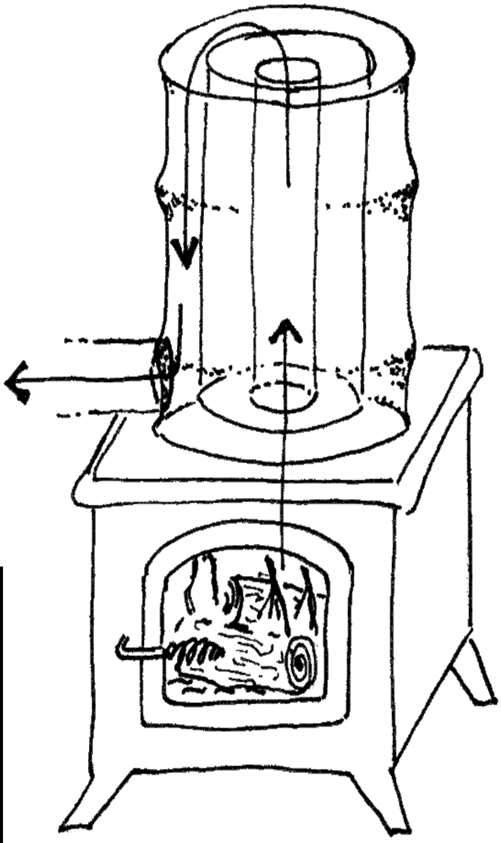
Updraft Heat Exchanger

Good air-to-air heat exchangers have the following characteristics:

1. A large surface area.
2. A great difference between temperatures. A really hot surface loses a greater percentage of heat to a room than a cooler surface. The surface of the heat exchanger should be as hot as possible.
3. They force as much hot air through the system as possible.
4. The walls of the heat exchanger should have high conductivity (metal rather than ceramic, for example).

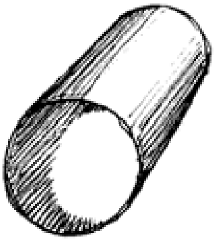
On the following pages are three examples of air-to-air heat exchangers that can be quickly built and added to existing heating stoves. They are all made out of 33- and 55-gallon drums. Each has been used and tested at Aprovecho.

55-gal Drum sealed on top

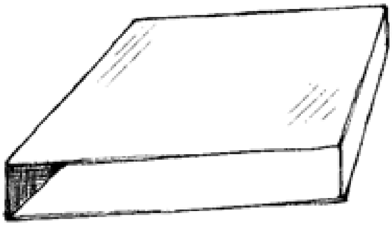


Downdraft Heat Exchanger

Cylinder

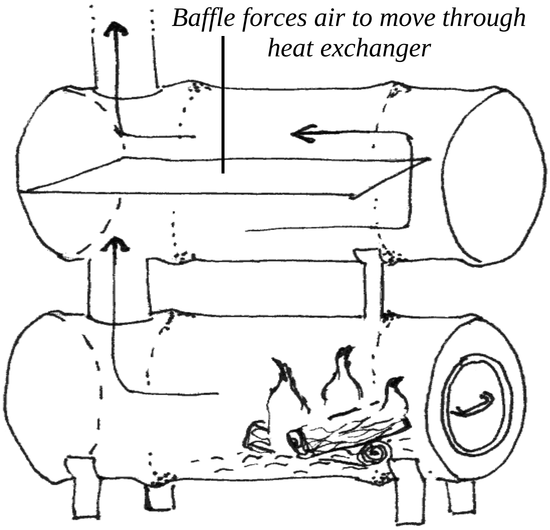


Rectangle



Same cross-sectional area, but greatly increased surface area in the rectangle.

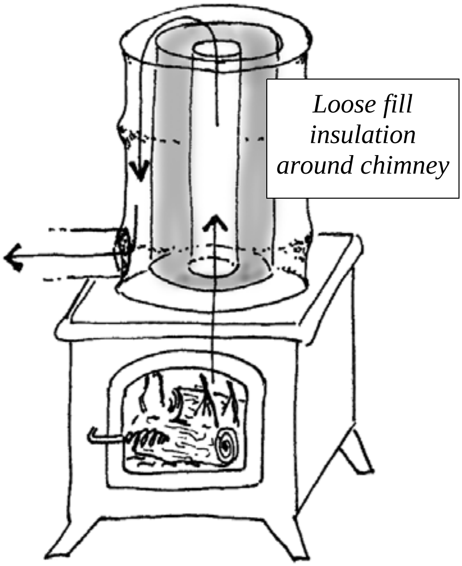
1.) Two Barrel Stove



The barrel stove is great in many ways. It is easy to make and is reasonably fuel-efficient. Firebrick protects the thin walls of the combustion chamber, which then can last for years. The upper chamber captures the heat and helps to reduce exit temperatures keeping more heat in the room.

2.) 33-Gallon Drum within a 55-Gallon Drum

The drawing illustrates a Winiarski heat exchanger in which a 33-gallon drum filled with insulation surrounds the chimney pipe. The hot air then passes down a gap between the 33- and 55-gallon drums before exiting. The insulated chimney creates a powerful draft that forces the heat down the circular gap between the 33- and 55- gallon drums.



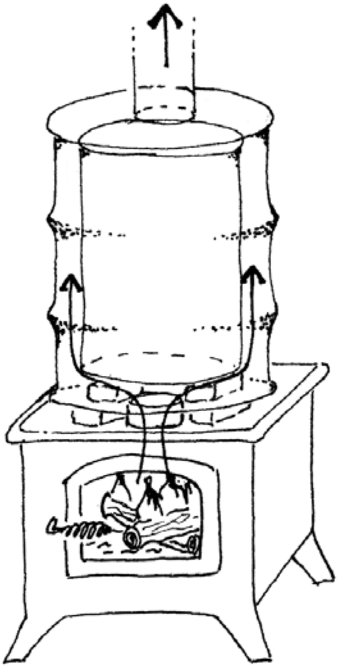
Stove Insulation:
-Pumice rock
-Wood ash
-Perlite
-Vermiculite
-Aerated autoclaved cement
-Fire brick
-Lightweight refractory cement

DESIGN HINT: Insulating the interior chimney in the heat exchanger helps downdraft designs to function by increasing the draft.

3.) The Updraft Version

You can't beat a thin walled, low mass metal combustion chamber for effective radiant heating. The waves of radiant heat from a really hot metal surface can warm up a cold body quickly. The outer surfaces on a high mass stoves, on the other hand, may not get hot enough to send much radiant heat to a shivering body. The warming effect of a high mass stove/heat exchanger is more subtle.

Adding insulating bricks to a metal walled combustion chamber in an effort to raise temperatures (and protect steel from degrading) has this one drawback. The insulating bricks lower the temperature of the metal walls and reduces radiant heating.



The amount of heat emitted per square foot is dependent on the temperature of the radiating body. Because surface temperatures are lower, massive heat exchangers need a lot of surface area to radiate heat into a room.	TEMPERATURE OF SURFACE (° F)	TOTAL ENERGY TRANSFERRED BTU / Hour - ft^2
	80°	15
	100°	51
	150°	168
	200°	315
	400°	1230
	600°	2850
	800°	5430
	1200°	9370

Chart from The Woodburner's Encyclopedia, 1976

Even a relatively small heat exchanger that’s hot can quickly deliver a lot of soothing radiant heat to a room. A tight insulated home can require something like 20,000 Btu’s per hour to replace lost heat. If the surface of the heat exchanger is 100 º F, it is necessary to provide 400 square feet of surface area to keep up with the house’s heat loss. A hotter surface temperature of 400 º F allows the heat exchanger surface area to shrink down to 16 square feet!

Before adding a heat exchanger to the chimney, check the exit temperatures.

First, insert a thermometer in the chimney pipe near the ceiling where it exits the house. We want exit temperatures to be around 250 º F. The flue gases need to be at this temperature so that there is sufficient draft. Adding a heat exchanger may reduce exit temperatures by about 400 º F. If the heat exchanger diverts so much heat into the room that your exit temperatures drop below 250 º F, you may have to make a smaller or less efficient heat exchanger.

Lowering exit temperatures works well if wood is burned cleanly. If wood is burned at a low temperature without enough air entering the fire, lowering exit temperatures can result in creosote deposits which can clog heat exchangers.

Creosote in the Heat Exchanger

Creosote is caused by the condensation of potential pollutants that were not initially burned up in the fire. If there is efficient combustion, there should be little or no creosote. Cool burning heating stoves do not create efficient combustion. The tars and other substances that fly up in the smoke condense on colder surfaces, build up, and can eventually catch fire inside the chimney.

The solution to creosote is to build hotter, cleaner fires, and to regularly check and clean the inside of your chimney and heat exchanger. The particles that make up creosote burn at relatively low temperatures. A good neighbor burns wood hot and clean.

The three heat exchangers shown previously have been used for many seasons at Aprovecho. In each design flue gases contact very hot surfaces directly after leaving the combustion chamber. Most of the unburned gases and tar droplets may be ignited at that point.

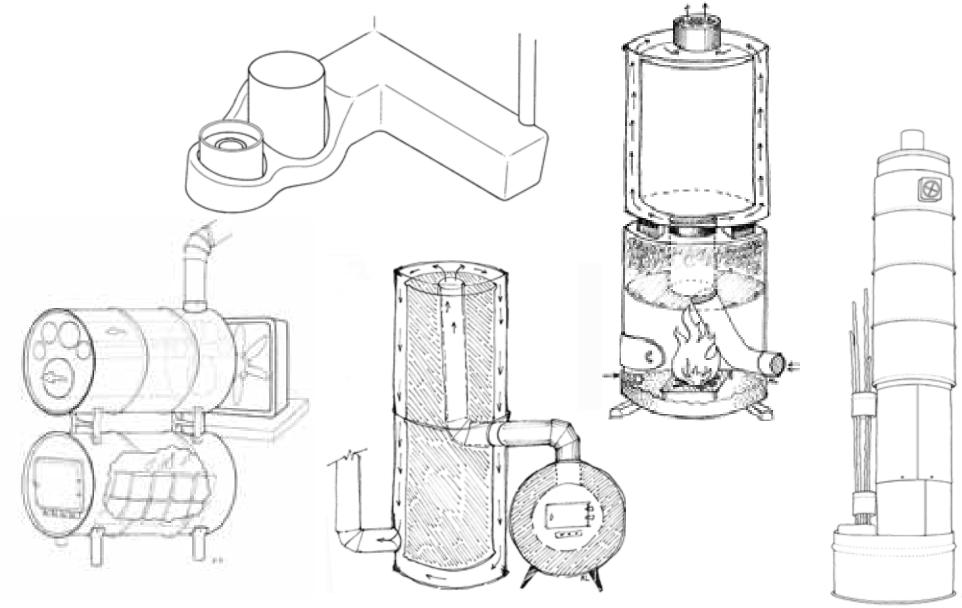
Any heat exchanger and chimney should be opened regularly and if dirty, should be cleaned. The removable lids on the 55- gallon drums make great inspection ports.

Chapter 4- Examples: Heating Stoves

The following heating stoves have been built and used at Aprovecho. We learned from them and loved some more than others:

- A down-feed stove in which heat warms an earthen bench.
- A batch-fed insulated stove with tower downdraft heat exchanger.
- A tower stove including preheated air for secondary combustion.
- An improved two-drum heating stove that it easy to make.
- A down-draft pole burning stove.
- Stoves that make use of fans for improved efficiency.

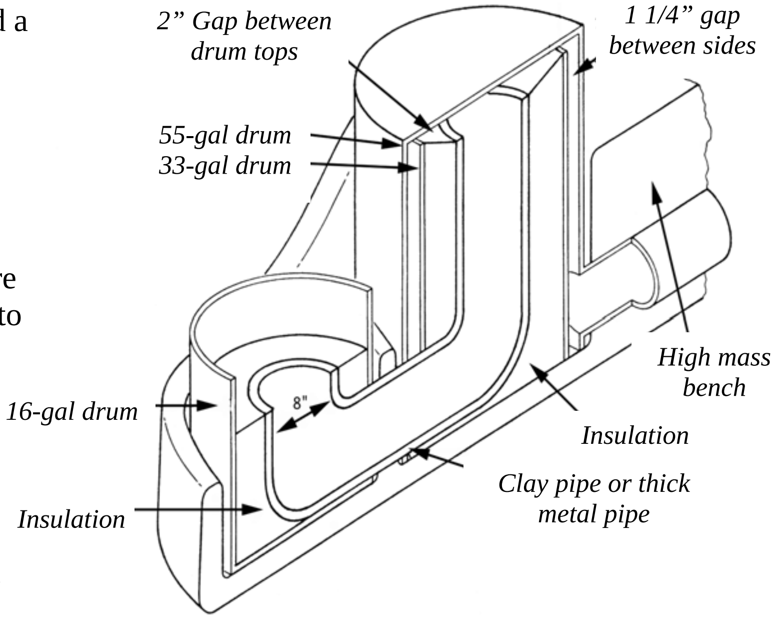
Your stove will probably be a little different from these ideas. You’ll find different parts available, and come up with personal variations. The second stove may be better than the first and, if you’re like us, the third one might be good enough to give to your mother or father.



Down-Feed Heating Stove With High Mass Bench

This stove taught us a lot about heat transfer into mass. Studying the effectiveness of a buried chimney pipe in a bench made of sand, clay, mud, and straw called *cob* began one of those wonderful intellectual adventures that can make life so interesting!

In the early 90s, the occupants of the Cob House at Aprovecho asked Dr. Winiarski to design and build a heating stove based on the downfeed combustion chamber and downdraft heat exchanger. There is a novel extra to this stove: after the heat exits the metal heat exchanger, it travels 8’ horizontally through a bench made of cob.



The combustion chamber is made from a 16-gallon drum. A clay cylinder (Mexican rain gutter) eight inches in diameter, creates the burn chamber and three foot high chimney within the heat exchanger.

Wood ash is used as insulation and fills the space between the clay tile cylinder and the inside of the 16-gallon drum. Sticks of wood are fed vertically into the fire. They are supported by a brick behind the sticks. Air is sucked down toward the fire and is appreciably warmed, which assists clean combustion.

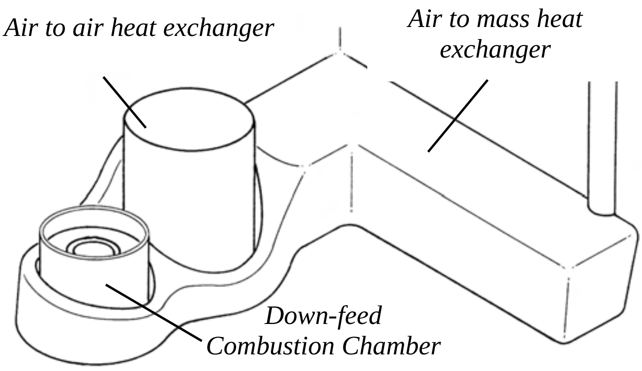
In the self-feeding downdraft pattern only the tips of the wood burn. Flame and smoke are pulled horizontally over a hot bed of glowing coals. This helps to burn all of the gases. Unfortunately, a downdraft/down feed combustion chamber can be hard to light; pulling the air down requires a lot of draft. Because of this, you can’t have small leaks in the stove. The side feed pattern is usually more natural and friendly, but it is not self-feeding.

The air-to-air heat exchanger is made from two barrels: the outer barrel is bigger (55 gallons) and closes over a smaller 33- gallon barrel. Wood ash fills the space between the clay cylinder and the inside of the 33- gallon drum. Perlite, vermiculite, or light weight pumice can be used in place of ash.

The insulation surrounding the fire increases the draft, since the flue gases stay very hot. The increased draft is sufficient to then force the gases *down* the gap between the 33- and 55- gallon drums.

The hot flue gases exit at the bottom of the 55- gallon drum and, in this case, travel 8’ horizontally in a 6” diameter stove pipe before turning upwards and eventually exiting the room.

As mentioned, lighting a downdraft stove can be difficult. Practice helps. I like this method: put a piece of paper into the combustion chamber. Make a vertical grate out of, say, ten skinny sticks, making sure that there is a space between each stick. Put a lightly crumbled piece of paper under the vertical interior chimney. Using a long match, light the piece of paper in the vertical interior chimney, starting the draft. Once the draft is established, light the paper behind the sticks in the combustion chamber and watch as the fire is sucked horizontally through the grate of sticks. More paper can be lit behind the sticks until the fire is established.



Here are a few important construction tips:

1. Always make sure that the 8” in diameter fuel magazine is not too tall. Six inches is a nice height, just enough to support the sticks. If the downdraft fuel magazine is too high, it becomes a chimney and can backdraft making the air go the wrong way. Also, having a tall fuel magazine makes the wood hard to light.

2. Make sure that the gap between the 55- and 33- gallon drums is equal. It’s good practice to bolt the two drums together to ensure that they stay in the correct position.

3. We bed the heat exchanger, the 55- gallon drum, in sand, which works well, sealing the bottom of the drum so no smoke escapes.

Learning from the bench heat exchanger

In 1995, we measured the efficiency of this stove. To my surprise, there was only a 100 degree F. drop in temperature due to the 8’ horizontal run through the cob bench. Not much heat was captured by the bench. In fact, after a two hour burn in the stove, which heated air temperatures into the 90’s in the cabin, the middle of the bench wasn’t noticeably warmer to the touch.

Exit temperatures in the chimney pipe leaving the room were still very high, around 500 º F. We had overestimated the ability of the cylindrical stove pipe going through the bench to transfer heat to the earthen bench.

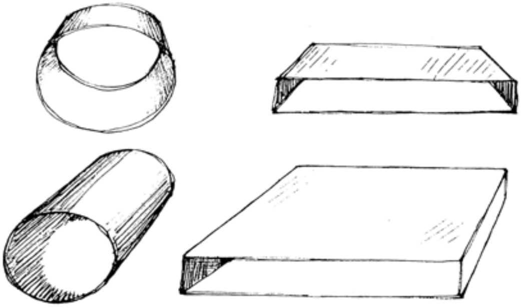
Getting Heat Into Things Is Difficult

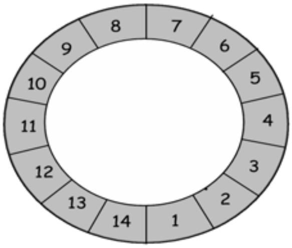
After years of thinking about and experimenting with heat exchangers, Larry and I have realized that getting heat into materials is hard, not easy.

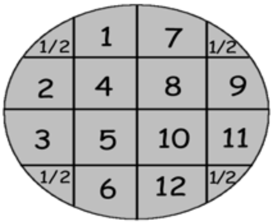
It is difficult to get a large percentage of heat into substances like rock, water, cement, or air. To optimize heat absorption, flame and hot flue gases must be forced to intimately contact the surface of the mass, *to rub against it*. Heat in a flue pipe mostly shoots up the middle of the pipe, not much heat is transferred through the wall of the cylinder. The chimney pipe is designed for longevity, not for heat transfer.

Use a Different Shape

To optimize heat transfer it’s better to make a chimney with a different shape, not cylindrical, but with the same cross sectional area. The shape should be wide, shallow, and rectangular. Even though the same amount of hot gases pass through the inside, a great deal more surface area on the outside is in contact with the substance you want to heat.







As a rule of thumb, it takes about five square feet of optimized surface area, in a heat exchanger, to lower exit temperatures from the stove about 250 º F.

Temperatures in the combustion chamber are above 2,000 º F when yellow flame is present. We want exit temperatures to be about 250 º F. In an optimized design, approximately 40 square feet of surface area is needed to transmit this much heat into the room.

To summarize: even in an optimized design, a heat exchanger requires a lot of surface area. Just piling mass near a stove will result in poor heat transfer to the mass. Only a small percentage of the heat will end up in the mass. Hot flue gasses need to be forced to scrape against surfaces over long distances for efficient heat transfer to occur.

One pound of stone or cement stores approximately 0.2 BTUs per degree of temperature rise. An insulated house might require something like 20,000 BTUs per hour to stay warm on a cold day. 1,000 pounds of cement or stone warmed up to 200 º F stores 40,000 BTUs which is enough to warm the house for two hours. Five tons of cement or stone, warmed up to 200 º F, can release enough stored heat to replace the lost BTUs for about ten hours.

The optimized design criteria that we've covered in this discussion are met in a good masonry stove: proper heat transfer, sufficient weight of material for one-half day of storage, and sufficient area to radiate heat into the room. The high mass stove also encourages hot, fast, clean burns that do not over heat the room, all of which makes this type of stove very impressive. A great book on the subject is: *The Book of Masonry Stoves* by David Lyle published by Brick House Publishing Co., Andover, Massachusetts.

It's easy to overlook how difficult it is to get heat into mass. It is natural to hope that a small amount of mass will hold an appreciable amount of heat. Our advice would be to consider the masonry stove as a system that works because all parts are tuned to function together. To design a high mass stove, make sure that all parts are correctly proportioned and interconnected.

Hot Cob

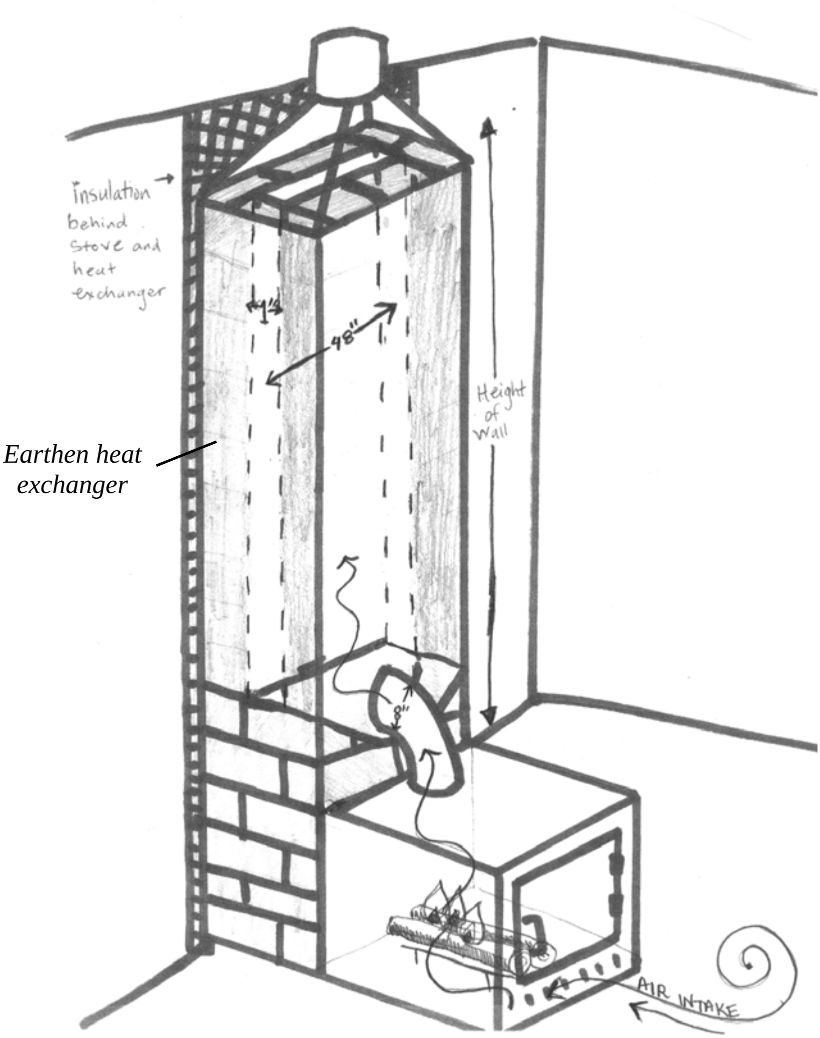
Let’s think about the bench that we wanted to use for heat transfer and storage. How can we design an easily built earthen enclosure that would significantly lower exit temperatures?

Design Opportunity

Why not take a few minutes and play around with the idea of wide rectangular chimneys in earthen enclosures. Try making a few sketches and practice designing appropriate technology.

Remember that hot air wants to travel up. Sideways travel in an optimized high drag passageway is limited to about 8 feet at the maximum, probably less, even if you have a really tall chimney outside. Downflow severely reduces flow because of added friction.

For this reason, we like to limit our first musings and sketches to designs in which the flow is always upwards…these heat exchangers tend to function beautifully. Going sideways or down usually requires testing of prototypes. On the next page you’ll find one example of an earthen addition to a stove. We’re sure your invention will be better.



Earthen heat exchanger

An example of an earthen heat exchanger

Testing Challenges Presumptions

Testing inventions is how they improve. It’s unlikely that a first attempt will be the best solution. Getting a baseline measure of performance is very important. If you know how something performs, changes to the prototype can be evaluated.

Finding the efficiency of a prototype heating stove is not difficult. In the 1820s, Marcus Bull built a special room in which he could burn a measured amount of wood in a particular stove and see the effect. In a way, any house owner is in the same position. A better stove will heat the room using less fuel.

Another useful measure is to determine exit temperatures out of the chimney. A good heating stove should be pumping heat into the room, not outside the house up the chimney. Inserting a thermometer in the chimney pipe near the ceiling quickly gives us a lot of good information. Another easy way to get a feel for heat loss in your house is to use an electric heater or other heat source which delivers heat at a known rate. See how much heat is needed to keep temperatures stable during a time of day when outside temperatures are not fluctuating. Start the experiment after the house is thoroughly warm.

Since there are about 8,600 BTU’s in a pound of dry wood, we can figure that at 100% efficiency the house losing 20,000 BTU's per hour requires only about 3 pounds of wood per hour to maintain a comfortable interior temperature. At 50% efficiency, it should take approximately 6 pounds of wood per hour.

Figuring on 50% heat transfer efficiency for heating stoves is another rule of thumb that, being close enough to reality, allows estimates to roughly predict performance. Stove companies tend to use higher numbers, but they are usually referring to combustion efficiency. In optimized designs we have probably done a bit better than 50% heat transfer to the room and large heat exchangers using a fan can get close to 100% since exit temperatures can get as low as room temperature.

Inventor’s Pride

Inventor’s pride has steered the wagon on more than one occasion here at the research center. Inventor’s pride is amazingly powerful and difficult to guard against. That’s why we like to have other people test our inventions. An inventor may be unable to keep from influencing the testing process. Getting impartial testers to critique a stove is exceptionally helpful and creates a more appropriate technology.

“Almost Perfect!”

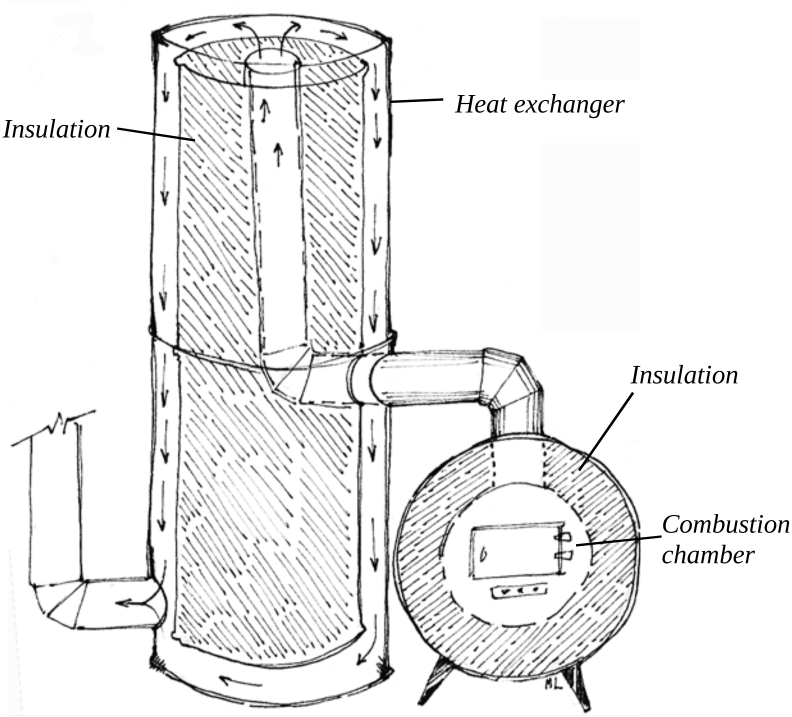
The Library Stove

Our old library was an awful place. The building was un-insulated and terribly cold. It was the worst place imaginable for studying. In 1992, we got tired of suffering and built a stove that captured enough heat to keep readers comfortable. This stove was a great representation of a design pattern that we have come to respect, which is:

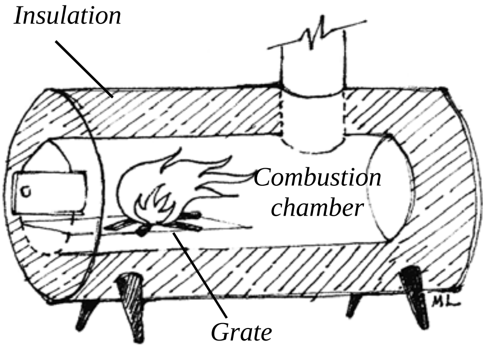
Separate Functions for Efficiency

Students are always ready to try to make a design perform many functions at once. In our experience, it is usually better to do one thing well. For example, attempting to make the combustion chamber serve as the heat exchanger, as in most modern stoves, makes for a nice small box but the tradeoff is reduced efficiency. The highly efficient heating stove that artfully combines functions is the high mass ceramic stove. It incorporates the heat exchanger and combustion chamber in one box. However, that box can weigh five tons or more.

The library stove separates combustion and heat transfer, and then attempts to optimize them both.



We even put the two functions in separate containers. The inner drum in the combustion chamber was made from a 16” in diameter thick iron pipe. We cut a hole in its top for inserting the 6” chimney pipe and enclosed the ends with welded steel plates, leaving an opening for a door and air holes.



A grate was used to help separate the wood. Without a grate the logs would roll together at the bottom of the cylinder which impedes air flow. Air enters beneath the grate into the combustion chamber through six 1” holes cut under the door. The six 1” holes approximately equal the cross-sectional area of the 6” chimney

Thick insulation surrounds the combustion chamber. We also put a piece of tin foil around the outside of the insulation to slow down the passage of infrared heat. Shiny tin foil emits radiant heat slowly. Old style cooking stoves were chromed on the outside so warm metal walls would emit less radiant heat, keeping the cook cooler. The combustion chamber in the library stove was so well insulated (with wood ash) that it took about one-half hour after starting the fire for the outside to become warm.

One result of this super insulation was that even large split logs would continue burning, leaving behind a line of fine gray ash. The insulation kept the fire hot and reduced smoke. Obviously, the optimized super insulated combustion chamber didn’t help to warm the library very much.

It was the big tower heat exchanger that heated the room. A 6” chimney pipe rose up inside a cylinder made from three 33- gallon drums stacked vertically. The bottoms and tops were removed so the drums fit together. Insulation (vermiculite) filled the space between the stove pipe and the inside of the vertical cylinder formed from the three 33- gallon drums.

The insulated 6” chimney produced enough draft to successfully push the hot air all the way up and then down the outside of the stack. Two 55-gallon drums created the outside of the heat exchanger. The space between the 33- and 55- gallon drums was about equal in cross section area to the 6” chimney pipe.

Remember, if the spaces within the stove become larger, air flow slows. If the cross-sectional area narrows, the air flow (draft) slows again. Think of a river rushing into a pond. The water slows as the river banks widen. If a river enters a narrow canyon, the opposite happens. The speed of the water increases as the river narrows, but the total volume passing through the narrows decreases. The water rises behind the narrows.

While cross-sectional area is about the same as the 6” chimney pipe in the heat exchanger the surface area of the original 6” flue is now greatly increased. Hot metal is in contact with a lot more room air. The air in the room is heated much more effectively, which lowers temperatures inside the chimney and decreases fuel use.

This stove was on the right track. The library was warm. The only problem was that people hated the stove!

The very tall downdraft heat exchanger reduced the initial draft so that unless a small intense fire was first created underneath the chimney leading to the heat exchanger, smoke could easily back draft into the room. The stove was also difficult to start.

Usually, a primary goal of appropriate technology is to conserve resources. Stoves and other tools offered for sale in developed countries like the United States are often designed for simplicity of use. That’s one reason why designing appropriate technology is so much fun: it isn’t easy to make something that is both simple to use and that is much more efficient. It takes a bit of experimentation to learn how to create something great that can last a long time, please users, conserve resources, and guard health.

Even though vertical rise heat exchangers are a bit less exotic, vertical rise does not depend on first establishing a lot of draft in the stove to work well. Folks tend to appreciate it’s simple functionality.

The Picasso Stove

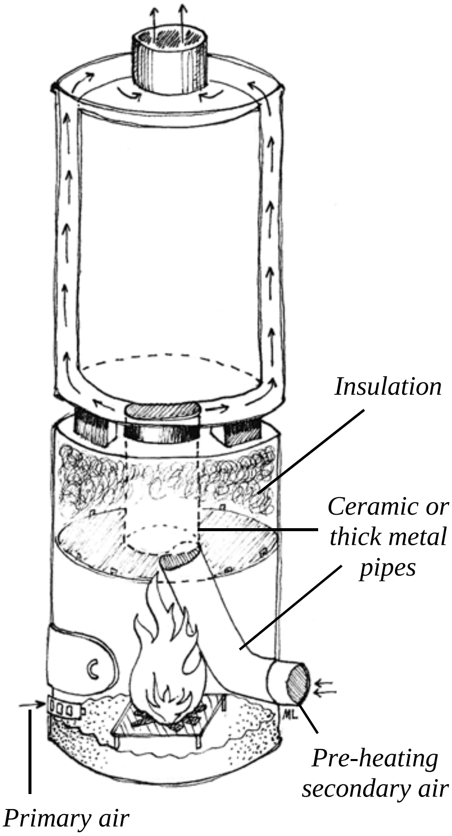
In 1996 the students and I started a series of experiments designed to see if it's possible to preheat primary air coming into a stove. The idea of preheating the air feeding a fire is tantalizing: if the air entering the combustion chamber is above 1,200 º F, more complete combustion should be occurring.

So far, all of our attempts to substantially preheat the air entering the fire (*primary air*) have proven to be unworkable. Hot air wants to rise, not fall. Friction in a pipe easily defeats the slight draft created by a fire. Preheating air for primary combustion is difficult. However, heating air to assist secondary combustion (combustion that takes place after the initial burn) is a lot easier.

The Picasso stove, named after a famous photo of Picasso sitting in front of a gorgeous heat exchanger in 1939, features preheated secondary air.

Secondary combustion occurs where escaping smoke ignites. As you see, the tricks used in the Picasso stove are the same as those in the library stove, but we varied things a little. In fact, this is a very good stove.

The stove is made from a 55- gallon drum set up on concrete blocks. A thick bed of ash insulates the combustion chamber from the floor. Fire brick was placed around the combustion chamber inside the drum. A grate lifts the wood above the floor so air can circulate through the combusting pile of wood. Primary air is sucked through six one-inch openings below the door.



Flames lick up into the entrance of the secondary combustion chamber, made from a six-inch pipe, and a false floor, made from the lid from a 55- gallon drum that holds insulation (vermiculite) around the stove pipe. Hot air flows into the mouth of this secondary combustion chamber through a 4” stove pipe that is exposed directly to flame. *We are trying to make sure that air, fuel, spark, and sufficiently high temperatures are present in one place to burn up escaping smoke*.

The heat exchanger is made from a sealed 33- gallon drum suspended in a 55- gallon drum by bolts that hold the two barrels in place. The path of heated air is only upwards through the gap between the two barrels. Good draft and ease of starting are assured.

We like this stove and would recommend it. It’s simple to build, requires no welding, and does seem to reduce the smoke associated with using large chunks of wood. There is a significant amount of secondary combustion. Air temperatures in the 4” tube can be over 1,200 º F.

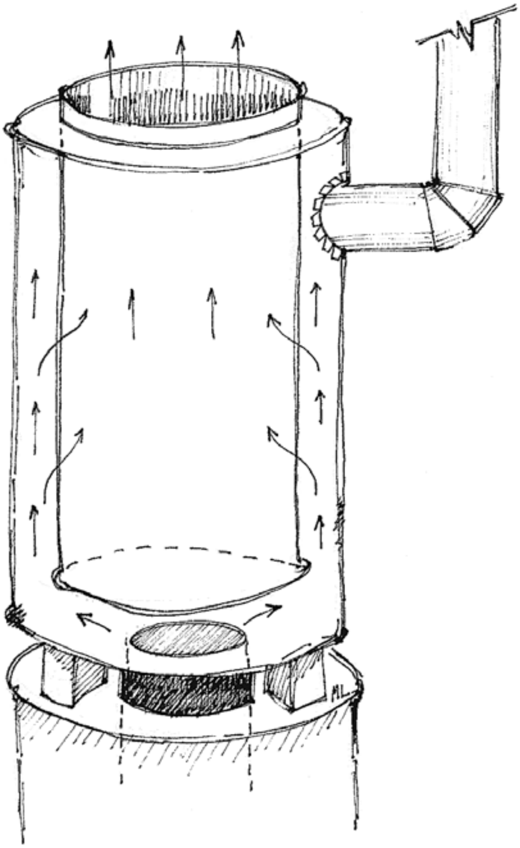
A Quiz

The students were having fun building the Picasso stove when Larry happened to enter the shop. Larry checked out the heat exchanger and then posed a question to the gathered staff and students: “Using exactly the same materials how could we nearly double the surface area of this heat exchanger?”.

A couple of students figured it out that night.

Here’s a chance for you to think about a design, trying to improve it. Can you see what was obvious to Larry?
(answer on next page)

Answer



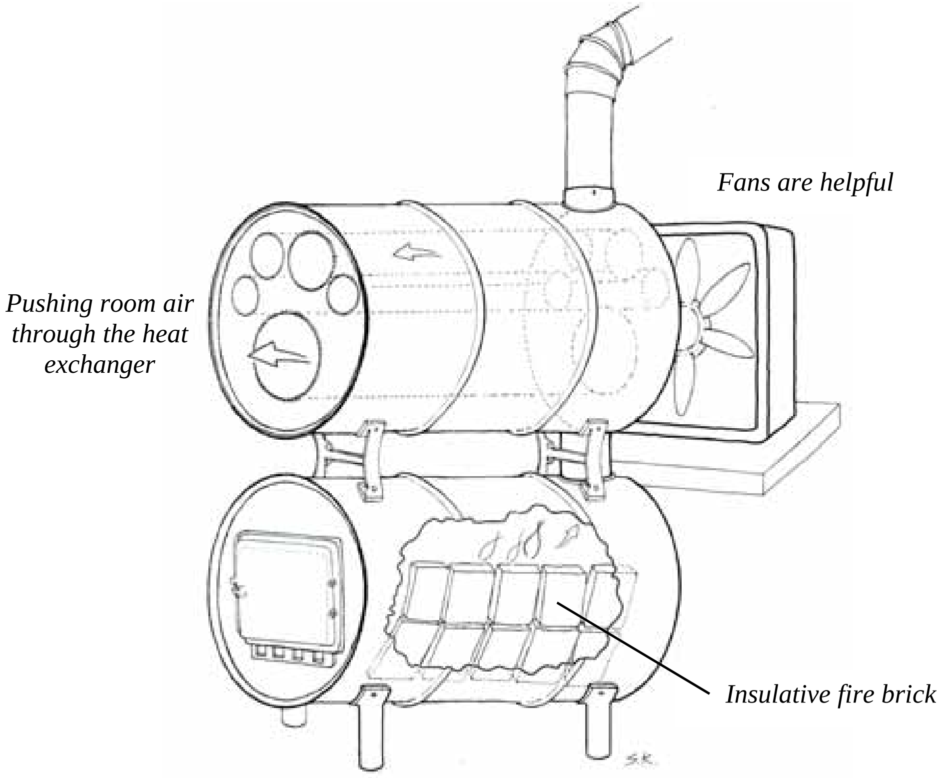
By removing the top of the 33- gallon drum, Dr. Winiarski exposed the entire *inside* of the 33- gallon drum to the room air, therefore allowing a lot more hot metal surface area to be in contact with the room air. This design is used in institutional stoves now being built by the World Food Program in Africa in which almost all of a huge pot full of food is directly exposed to the fire and subsequent hot gasses.

This solution seems both simple and elegant to us.

The Improved Two Drum Stove

In the United States, kits are available to change two 55- gallon drums into a popular and inexpensive heating stove. The students at Aprovecho revised this stove and created quite a powerful and efficient heater for the 900-square-foot shop building. Insulative firebrick was placed inside the bottom barrel, protecting the steel from degrading, and making for hotter, cleaner-burning fires.

The upper barrel had large-diameter pipes installed lengthwise through the entire barrel so that air could be blown through the pipes into the room (see illustration). These pipes were sealed using two dollars worth of stove cement and have lasted for three years so far. A box fan blows cold room air into the tubes that leaves at about 140 ° F. In 30 minutes the large volume of hot air has circulated through the shop and raised the temperature by about 20 ° F. Without a fan assisting heat transfer, the room stays cold for hours.



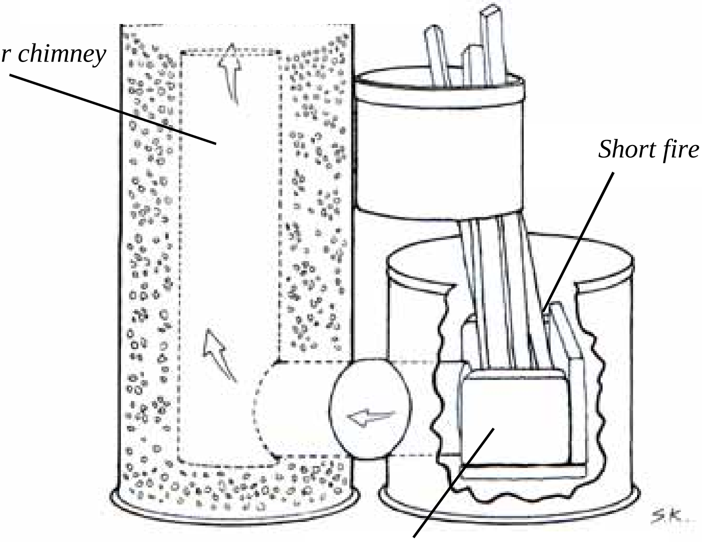
A Down Draft Pole Burning Stove

This is a 8’ high stove design in which 2” poles or branches enter vertically into the combustion chamber. The downfeed pattern is clean-burning because, like the pellet stove, the wood is metered by gravity into the combustion zone. Only the tips of the poles are burning. As the wood is consumed, the charcoal breaks off and fresh wood catches fire.

The fire is encouraged not to burn up the stick because a strong draft pulls the flame horizontally into a 3’ tall interior chimney. The chimney, made from insulated fire brick inside a sheet metal cylinder, shoots the hot flue gases into a larger opening about 12” high (see illustration on next page). Entering this large opening slows down the flue gases.

Question: Why is it necessary to slow down the hot flue gases?

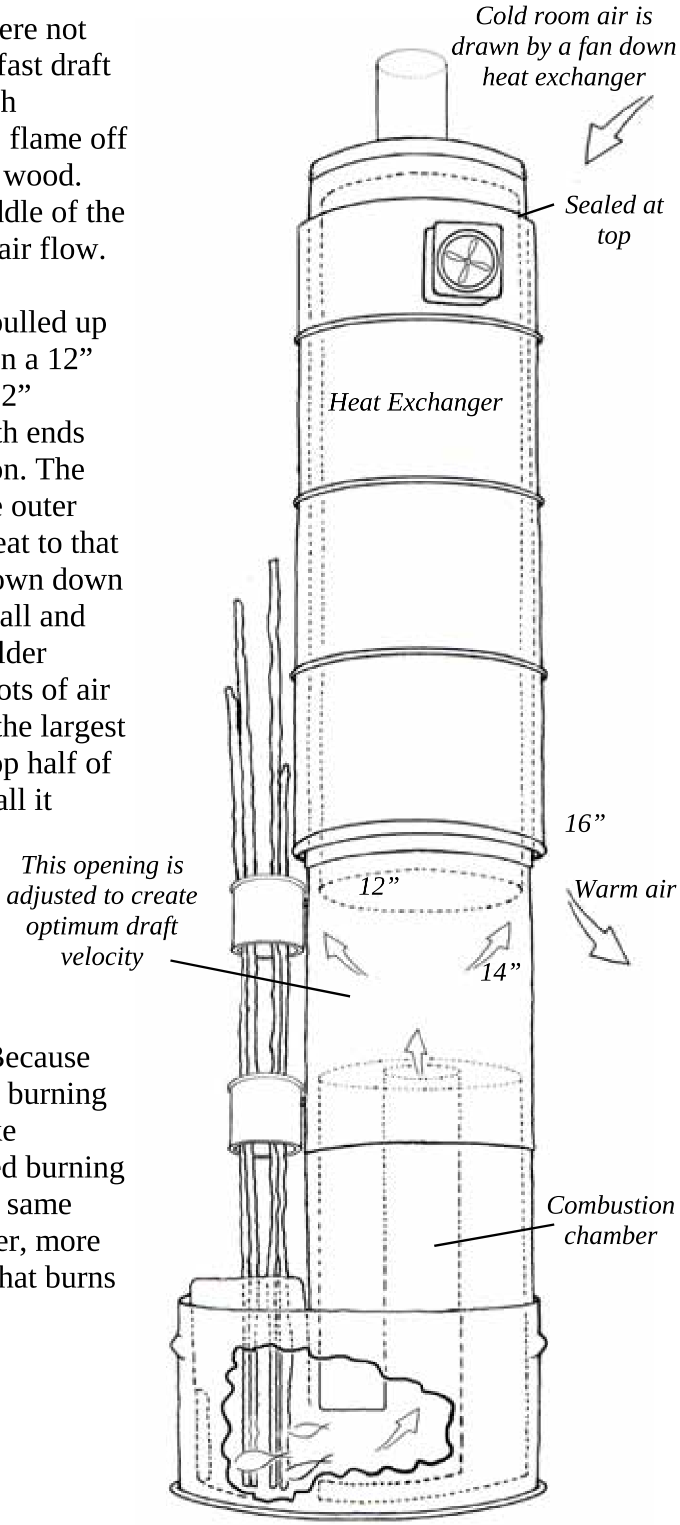
Downdraft / Downfeed Combustion Chamber



Answer: If the gases were not slowed down, the very fast draft developed by the 8’ high chimney would pull the flame off of the burning sticks of wood. This opening in the middle of the cylinder moderates the air flow.

The hot flue gases are pulled up into a small gap between a 12” and 14” cylinder. The 12” cylinder is closed at both ends and filled with insulation. The gases scrape against the outer cylinder, transferring heat to that surface. Room air is blown down the outside of the hot wall and enters the room at shoulder height. The fan forces lots of air down the gap between the largest cylinder covering the top half of the stove and the hot wall it surrounds.

The stove is very tall because the bottom half is the combustion chamber. The top half is the heat exchanger. Because the tips of the wood are burning there is almost no smoke produced. The downfeed burning pattern has many of the same advantages as the fancier, more expensive pellet stove that burns prepared uniform fuel.

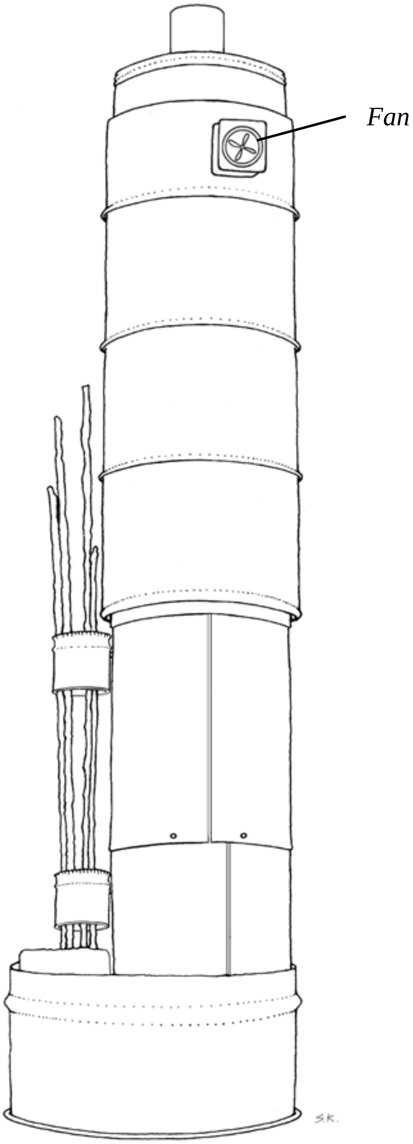


Fans Increase Both Combustion and Heat Transfer Efficiency

The push created by hot rising air is very gentle. Even flame itself doesn't travel at much more than three miles per hour. Natural convection produces a lazy draft that cannot be asked to do too much.

Can you picture in your mind's eye how fast cigarette smoke rises? Smoke rising is slow and languid, not fast and powerful. The draft produced by a hot fire can easily be defeated by friction inside of a chimney pipe if there are many twists or downturns.

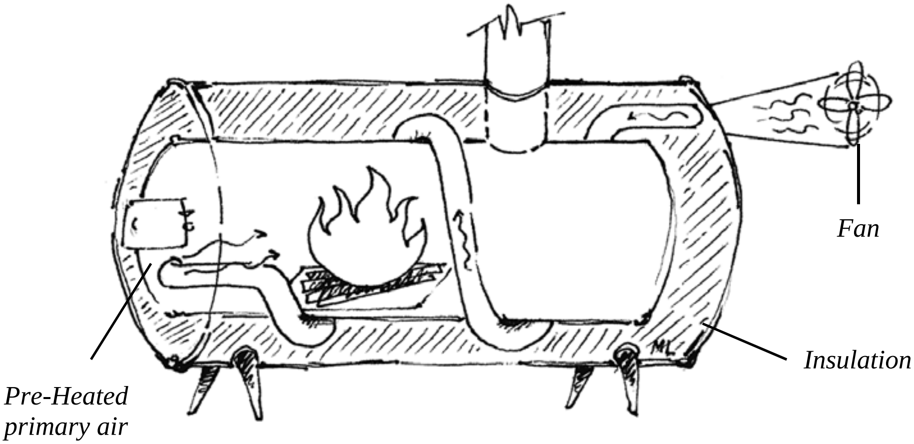
Many amateur designers hope that natural draft will overcome impressive obstacles such as long runs with little rise. Unfortunately, it just isn't so! The gentle river of hot flue gases is easily slowed by turns and twists and can also widen into a stagnant lake if spaces inside the stove suddenly increase.

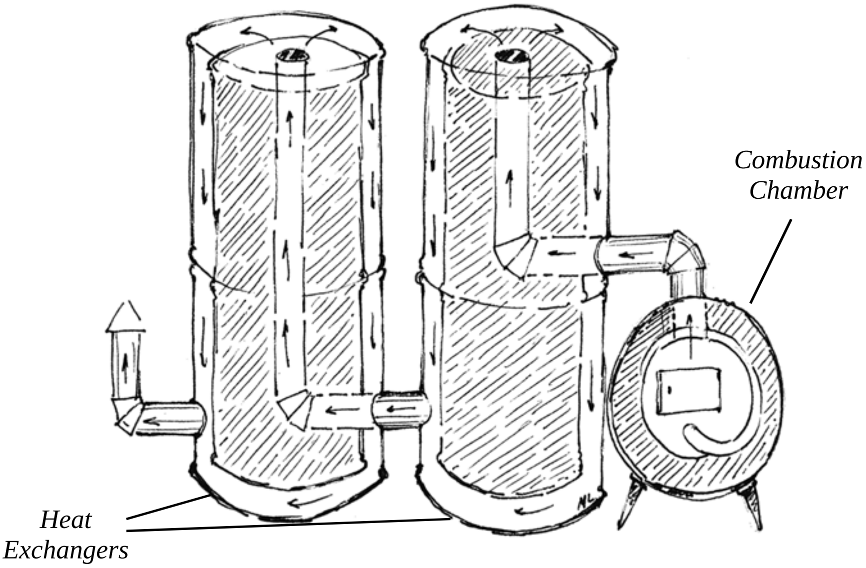


Two Heating Designs Using Fans

Fans are great because **primary** air (the air entering the fire) can be preheated, which greatly improves combustion. Forced air helps the coals to burn down completely, leaving only a bit of ash. The rush of low-volume high- velocity jets of hot air do a great job mixing fuel, air, and fire which clean up combustion. A fan can also push air through such a long length of heat exchangers that close to 100% of the heat stays in the room. Doubling heat transfer efficiency can double fuel efficiency. Fans make everything easy.

Here are a couple examples that have been successfully tried:





The fan is pushing air through a one-inch-in-diameter pipe that is in contact with the very hot outer surface of the combustion chamber. Insulation around the combustion chamber and pipe keep both very hot! The air enters the combustion chamber at temperatures of around 800 º F, depending on the heat of the fire. It is amazing to see the effect of a fan on a fire, especially with preheated air.

The logs burn very brightly. The fire is easy to light and combustion is more complete. The combustion chamber is usually glowing red hot. (Only combustion chambers made from refractory cement or firebrick can withstand this kind of heat.) This is the cleanest-burning stove that we’ve used at Aprovecho even though it is burning stacked split logs.

Due to the draft created by the fan, the heat is driven through lengths of heat exchangers that would obviously stall a stove dependent on natural draft. It’s possible to add heat exchanger surface area until exit temperatures are equal to room temperature air.

Adding a fan to a stove makes it easy to achieve clean combustion and very good heat transfer to the room. Air is pushed through pipes in contact with the fire until the swirling air entering the combustion chamber is very hot. The fan then pushes the hot flue gases through a big enough heat exchanger so that most all of the heat stays in the room.

Why aren’t fans used more often in wood burning stoves? One reason is that if air is preheated and blown into the combustion chamber temperatures can rise to the point where steel begins to melt**.** Blowing preheated air into a big fire creates a blast furnace. Also, being dependent on a fan means that stoves may not work correctly when most needed, like during a winter storm when the electricity fails. Some people dislike the whirring of fans, preferring the silence of natural draft. However, when fuel efficiency is the highest priority, the amount of electricity used by the fan is very small when compared to the benefit received.

A Blast Furnace Heating Stove

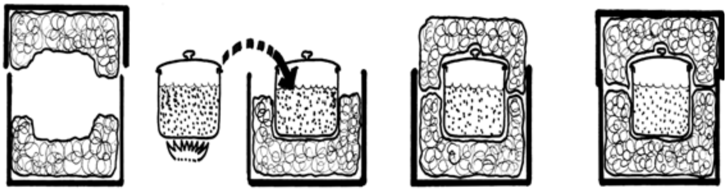
If preheated air is used, the combustion chamber needs to be made from stone or high-temperature ceramic, refractory bricks, or refractory cement.

Refractory cement is absolutely great stuff. It looks a lot like regular cement and it's mixed up with water in the normal way. The wet mixture can be poured into a mold made from any stiff material, like cardboard, eighth-inch-thick plywood, door skins, etc. Wall thickness can be as little as one inch, but in a heating stove two-inch thick walls are recommended for added safety.

In Central America, a fired red clay ceramic ceiling tile called a "baldosa" forms the combustion chamber in Aprovecho-designed cooking stoves. Fired clay brick can also withstand high temperatures. Test your local supply by heating it until red hot and then plunge it into cold water. If it doesn't crack, it will probably last for years in your stove. (See the following section on "Options for Insulating Combustion Chambers" for recipes of home made refractory bricks.)

The House as "The Best" Heat exchanger

We cook food at Aprovecho in an unusual way using a "haybox". The pot of food is boiled for ten minutes on a stove and then the pot is placed in a well-insulated, airtight box. The beans inside the pot get soft and palatable because the retained heat is sufficient to finish cooking them. We end up using a great deal less fuel because the haybox has improved the heat transfer into the pot. (It's also a much easier cooking method!)



A Haybox

Hot House

The reason that beans are simmered over a fire for two hours is because the pot constantly loses heat to room air. The reduced flame underneath the pot replaces the lost heat. A furnace or a wood stove in the same way replaces the heat in our houses because the house allows the same amount of heat to constantly leak away! The house loses heat and the burning wood replaces it.

If the house loses a lot of heat, we use a lot of wood per season. If the house loses only a little heat per hour, we can save forests of trees and are better stewards of this precious resource. If the house looses very little heat, the stove is frequently not even lit because energy in sunlight and interior sources of heat now are equal to the heating demand.

To reduce energy use in a house:

It is most important to reduce uncontrolled air exchanges by filling cracks in the walls, around windows and doors and secondarily to insulate the house. A house that is relatively airtight and insulated like a thermos bottle or a box full of hay does not require constantly burning wood in a stove to maintain interior temperatures.

The “haybox house” helps to reduce fuel consumption just like the heat exchangers that can be added to a heating stove. Capturing the heat more effectively diminishes the need for burning wood all the time to keep warm.

Over the last ten years, we have replaced the old leaky houses at Aprovecho with new tight houses that don’t require constant inputs of energy to heat occupants. It’s great to enter the straw bale dormitory on a chilly day and realize while taking off shoes and jackets that the wood stove isn’t even lit. The heat from the cooking stove has warmed the entire 2,000- square-feet of the dormitory. Today, some new houses in cold climates require no additional heating besides what is done daily when cooking, heating water, lighting, indoor work, etc.

The most fuel efficient heating stove is one that is never used!

People live in houses that exist. It costs money and takes time to insulate and reduce air exchanges in older houses. At the same time, however, it doesn’t make sense to spend the time and effort to build and make the world’s most efficient heating stove and then use it in a building that could also be made less dependent on constant burning to just stay warm. Which part of your heating system is the least efficient? Is it the house or the stove?

Your Stove

Hopefully these stove design ideas will help to create better performing, simple, homemade stoves that are useful to you. Just as Dr. Winiarski’s cooking stoves vary tremendously from place to place, these heating stove examples follow a set of principles that allow for flexibility and adaptation to local or individual circumstances. Learning how to design a stove is the intention, not to teach specific designs. Your perfect stove may be an amalgam of several of these ideas. It may be completely unique.

To be perfect, the stove only needs to fit your needs. It may be true that, like personal requirements and preferences, a great stove matures and evolves over time. Maybe developing good technology will become a satisfying hobby, an expression of your genius.

Best of luck!

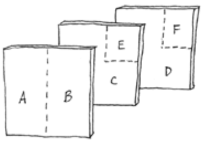
Appendix A: Options for Insulating Combustion Chambers

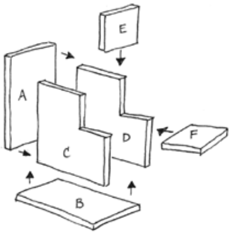
Cleaner-burning stoves can produce such high temperatures in the combustion chamber (where the fire burns) that metal, even stainless steel, can be destroyed pretty quickly. Cast iron combustion chambers, though longer- lasting, can be expensive.

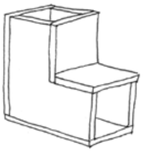
Stove makers have been using ceramic parts in cooking stoves for many years. The Thai Bucket stove uses a ceramic combustion chamber. The Kenyan Jiko stove also uses a ceramic liner to protect the sheet metal stove body. Books have been written describing how to make clay combustion chambers that will last for several years. A good book on the subject is *The Kenya Ceramic Jiko: A Manual for Stovemakers* (Hugh Allen, 1991). Nueva Esperansa, a women's co-operative in Honduras, makes long-lasting refractory ceramic stove parts from a mixture of clay, sand, horse manure, and tree gum. These combustion chambers are used in the Doña Justa and Eco-Stoves now popular in Central America.

Option #1: Floor Tiles

Don O'Neal (HELPS International) and Dr. Winiarski located an alternative material in Guatemala, an inexpensive ceramic floor tile called a *baldosa.* The *baldosa* is about an inch thick and can be cut or molded into appropriate shapes to make a combustion chamber. Loose insulation fills in between the combustion chamber and the inside of the stove body. Wood ash, pumice rock, vermiculite, and perlite are all good natural heat-resistant sources of loose insulation. The *baldosa* is inexpensive and has lasted four years in the insulated HELPS and Trees, Water and People cooking stoves built in Central America.







Baldosa are usually made with red clay and are fired in a kiln at around 900º - 1000º Celsius. They are somewhat porous and ring when struck with a knuckle. Using *baldosa* in a combustion chamber surrounded by loose insulation adds one more material option for the stove designer.

Option #2: Insulative Ceramics

The following recipes create insulative ceramics which are used in combustion chambers to make hotter, cleaner fires. Each of these materials incorporates clay, which acts as a binder. The clay forms a matrix around a filler, which provides insulation. The filler can be a lightweight fireproof material (such as pumice, perlite, or vermiculite), or an organic material (charcoal or sawdust). The organic material burns away, leaving insulative air spaces in the clay matrix. In all cases, the clay and filler are mixed with a predetermined amount of water and pressed into forms (molds) to create bricks. The damp bricks are allowed to dry, which may take several weeks, and then fired at relatively low temperatures in a kiln.

Our test samples were made using clay obtained from a local potters' supply store. In other countries, the best source of clay would be the kind used by local potters or brick makers. Almost everywhere, people have discovered clay mixes and firing techniques that create sturdy ceramics.

Insulative ceramics need to be lightweight (low-density) to provide insulation and low thermal mass. At the same time, they need to be physically durable to resist breakage and abrasion due to wood being forced into the back of the stove. These two requirements are in opposition; adding more filler to the mix will make the brick lighter and more insulative, but will also make it weaker. Adding clay will usually increase strength but makes the brick heavier. A good compromise is achieved in a brick having a density between 0.8 gm/cc and 0.4 gm / cc.

The recipes in Table 1 (next page) indicate the proportions, by weight, of various materials. These recipes are a starting point for making insulative ceramics. Variations in locally available clays and fillers will probably require adjusting these proportions to obtain the most desirable results.

Table 1; Insulative Ceramics

Type	Filler Wt. (g)	Clay (damp) Wt. (g)	Water Wt. (g)	Fired at (ºC)	Density (gr/cm^3)
Sawdust	490	900	1300	1050	0.426
Charcoal	500	900	800	1050	0.671
Vermiculite	300	900	740	1050	0.732
Perlite Mix	807	900	1833	1050	0.612
Pumice Mix	1013	480	750	950	0.770

Insulative ceramics used in stoves undergo repeated heating and cooling (thermal cycling), which may eventually produce tiny cracks that cause the material to crumble or break. All of these recipes seem to hold up well to thermal cycling. The only true test, however, is to install them in a stove and use them for a long period of time under actual cooking conditions. If you can afford it, buying commercial fire brick is certainly an easy and workable option.

Sawdust/Clay:

In this formulation, fine sawdust was obtained by running coarse sawdust (from a construction site) through a #8 (2.36-mm) screen. Clay was added to the water and mixed by hand to form thick mud. Sawdust was then added, and the resulting material was pressed into rectangular molds. Excellent insulative ceramics can be made using sawdust or other fine organic materials such as ground coconut husks or horse manure. The problem with this method is obtaining large volumes of suitable material for a commercial operation. Crop residues can be very difficult to break down into particles small enough to use in brick making.

This method would be a good approach in locations where there are sawmills or woodworking shops that produce large amounts of waste sawdust.

Charcoal/Clay:

In this formulation, raw charcoal (not briquettes) was reduced to a fine powder using a hammer and grinder. The resulting powder was passed through a #8 screen. Clay was hand-mixed into water and the charcoal was added last. A rather runny slurry was poured into molds and allowed to dry. It was necessary to wait several days before the material dried enough that the mold could be removed. Dried bricks were fired at 1050º Celsius.

Charcoal can be found virtually everywhere, and can be used when and where other filler materials are not available. Charcoal is much easier to reduce in size than other organic materials. Most of the charcoal will burn out of the matrix of the brick. Any charcoal that remains is both lightweight and insulative.

Charcoal/clay bricks tend to shrink more than other materials during both drying and firing. The final product seems to be lightweight and fairly durable, although full tests have not yet been run on this material.

Vermiculite/Clay:

In this formulation, commercial vermiculite (a soil additive), which can pass easily through a #8 (2.36 mm) screen, is mixed directly with water and clay and pressed into molds. Material is dried and fired at 1050º C.

Vermiculite is a lightweight, cheap, fireproof material produced from natural mineral deposits in many parts of the world. It can be made into strong, lightweight insulative ceramics with very little effort. The flat, plate-like structure of vermiculite particles makes them both strong and very resistant to heat.

Vermiculite appears to be one of the best possible choices for making insulative ceramics.

Perlite Mix/Clay:

For best results, perlite must be made into a graded mix before it can be combined with clay to form a brick. To prepare this mix, first separate the raw perlite into three component sizes: 3/8” to #4 (9.5 mm to 4.75 mm), #4 to #8 (4.75 mm to 2.36 mm), and #8 (2.36 mm) and finer. Recombine (by volume) two parts of the largest size, one part of the midsize, and seven parts of the smallest size to form the perlite mix. This mix can now be combined with clay and water and formed into a brick, which is dried and fired.

Perlite is the mineral obsidian, which has been heated up until it expands and becomes light. It is used as a soil additive and insulating material. Perlite mineral deposits occur in many countries of the world, but the expanded product is only available in countries that have commercial “expanding” plants. Where it is available, it is both inexpensive and plentiful.

Perlite/clay bricks are some of the lightest usable ceramic materials we have produced so far.

Pumice Mix/Clay:

Pumice, like perlite, produces the best results when it is made into a graded mix. Care should be taken to obtain the lightest possible pumice for the mix. Naturally occurring volcanic sand, which is often found with pumice, may be quite heavy and unsuitable for use in insulative ceramics. It may be necessary to crush down larger pieces of pumice to obtain the necessary small sizes. The mix is prepared by separating pumice into three sizes: ½” to #4 (12.5 mm to 4.75 mm), #4 to #8 (4.75 mm to 2.36 mm), and #8 (2.36 mm) and smaller. In this case, the components are recombined (by volume) in the proportion of two parts of the largest size, one part of the midsize, and four parts of the smallest size. Clay is added to water and mixed to form thin mud. The pumice mix is then added and the material is pressed into molds. Considerable tamping or pressing may be necessary to work out the air and form a solid brick. The mold can be removed immediately and the brick allowed to dry for several days before firing.

Pumice is widely available in many parts of the world and is cheap and abundant. Close attention to quality control is required, and this could be a problem in many locations. It is very easy to turn a lightweight insulative brick into a heavy non-insulating one through inattention to detail. Pumice (and perlite as well) is sensitive to high heat (above 1100° C). Over-firing will cause the pumice particles to shrink and turn red, resulting in an inferior product. Despite these concerns, pumice provides a great opportunity to supply large numbers of very inexpensive insulative ceramics in many areas of the world.

There are many viable recipes to make lightweight refractory ceramic combustion chambers. It is necessary to create high temperatures in a combustion chamber in order to clean up dangerous emissions. Unfortunately, these high temperatures quickly degrade metals, including stainless steel. Refractory ceramics are a great alternative.

Aprovecho is a center for research, experimentation and education on alternative technologies that are ecologically sustainable and culturally responsive. The Advanced Studies in Appropriate Technology Lab works to develop energy-efficient, nonpolluting, renewable technologies that reflect current research which are designed to be made in most any country.

Aprovecho Research Center offers intensive ten week internships in sustainable living skills. Daily classes focus on three major areas: Sustainable Forestry, Organic Gardening, and Appropriate Technology. Classes combine lecture and discussion with practical hands-on activities. We encourage a holistic understanding of each subject area that is grounded in specific experience and enhanced by the broader intellectual perspectives available in our diverse learning environment.

The center is located on a beautiful 40-acre land trust near Eugene, Oregon.

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