Aprovecho Research Center

Design Principles
Biomass Cook Stoves, 2026

Dean Still

Sam Bentson

What is a design principle?

- Dr. Winiarski created Rocket design principles to help work with villagers when evolving improved stoves.
- Cooks are experts in making food. Many types of stoves are needed. We learn a lot from them! For instance, cooks in China need high powered stoves that often do not simmer. In southern India, cooks require low power and may not bring water to a full boil.
- ARC engineers are experts in heat transfer and combustion efficiency but we don’t know the cooking functions. Cooks learn from us.
- Design principles are teaching tools that summarize subjects as information is exchanged and better stoves are evolved by the team.
- Hopefully, as time passes, design principles become more accurate.
- Teaching and listening go hand in hand as learning occurs.

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Improving traditional stoves

Including:
Open fires
Shielded fires
High mass rockets
Plancha stoves

Improving these stoves helps to maximize impact

>80% of rural global poor (2.3 billion people) use traditional biomass stoves to cook food (WHO, 2022)

Many dedicated people, like Peter Scott, are trying to improve stoves

Improvement Goals

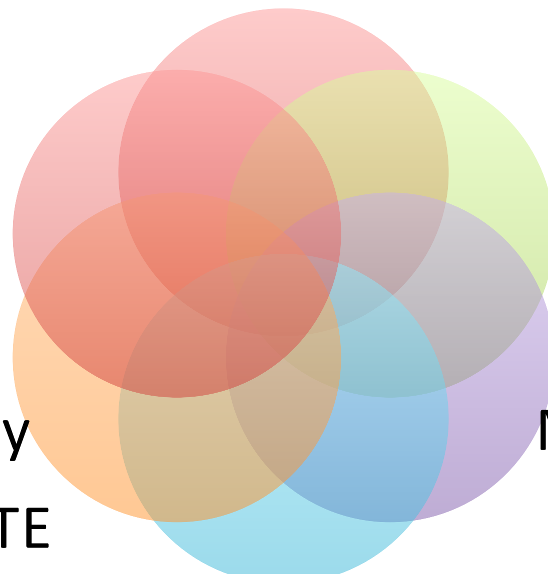
Usability:

Cook's happy!

Safety

Maximize impact:

Sold for market prices



Thermal Efficiency

Carbon based on TE

Manufacturability:

Changes a lot!

Protect health and climate

Trying for Impact

PERFORMANCE * ADOPTION * SCALE

- *If a stove is not widely used, it will not generate impact.*
- More impact if millions of good stoves, not fewer best stoves, are making food
- **Effectiveness:** It’s not just having a great stove - it also has to be used well.
- **Stove Stacking:** Many households use traditional stoves alongside new ones.
- **Design with Users:** Respect cultural significance and function.

(Johnson, Chiang, 2015)

Open Fire

Can achieve ~30% thermal efficiency (!) when:

- Carefully tended
- Small flames touch the bottom of the pot
- Fire is close to the pot
- No wind

HOWEVER:

Can be ~5% efficient if:

- Not carefully tended
- Big flames
- In the wind

Not carefully tended

Always makes a LOT of PM2.5 (smoke)

Winiarski Open Fire Design Principles

- Only burn ends of sticks (8cm)
- Do not cross sticks
- Use dry wood
- Fire is close to pot (~6”)
- Use a grate
- Burn made charcoal for less smoke
- Cook out of the wind!
- Larger diameter pots expose more surface area to the fire

Shielded Fire

A mud or sheet metal wall surrounds the open fire.

The sides of the pot can also be heated by the fire resulting in ~45% Thermal Efficiency.

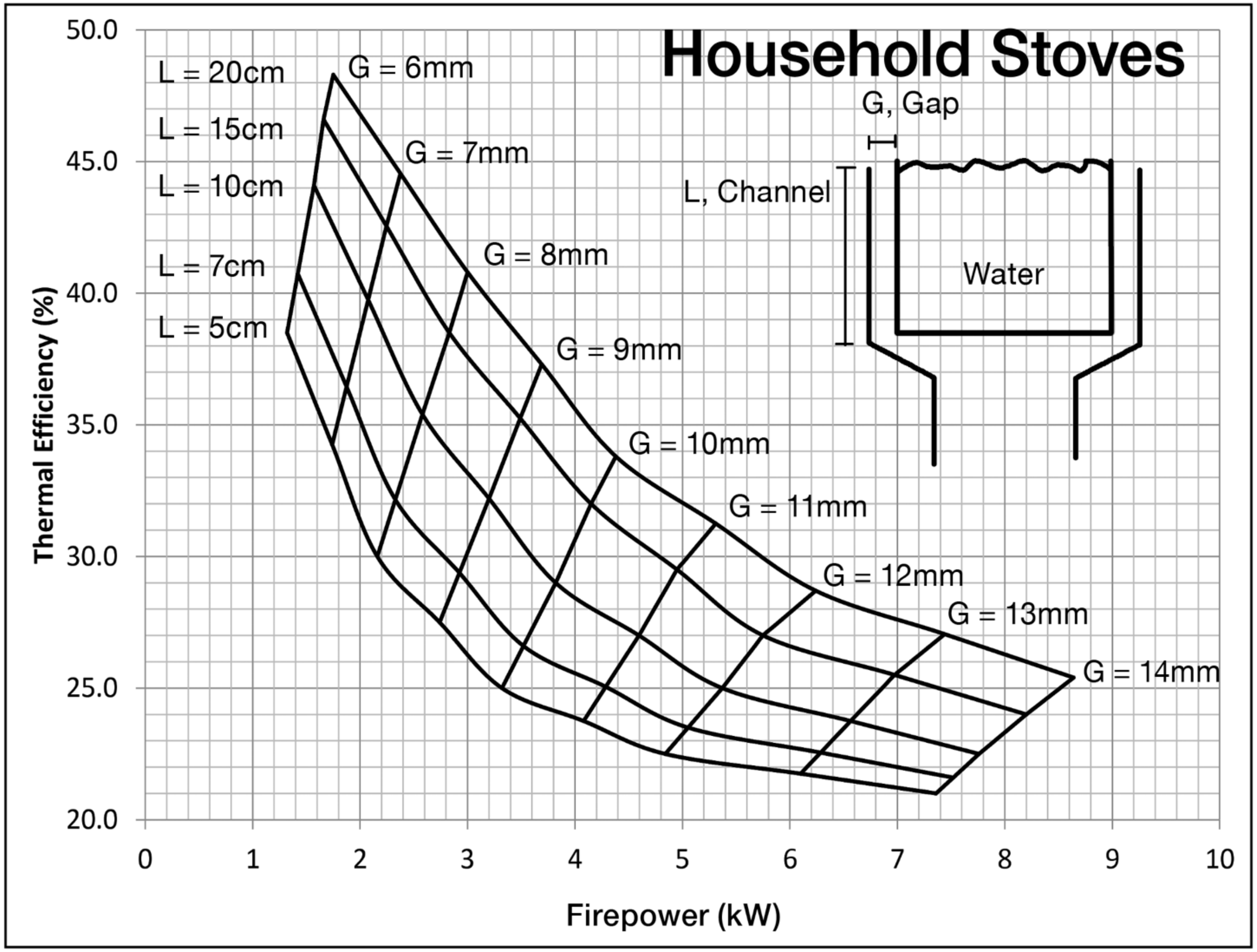
The pot skirt can be adjustable so various pots can be used.

We recommend a 6mm channel gap for stoves under 4kW firepower.

A wall creates a narrow channel next to the sides of the pot increasing exposed surface area

Pot slides down into opening

Channel gaps make a big difference!



Sam Baldwin, Engineering Design, Development, Dissemination, 1987 VITA

Winiarski Shielded Fire Design Principles

- Make the stove body as light as possible!
- Mix lightweight materials into earthen mixtures: wood ash, pumice, saw dust, cut up straw, etc.
- Sheet metal is better!
- Use a grate
- Add a chimney to protect health!

Damon Ogle and 41% TE shielded fire

$6 ISO Tier 4/5/5

High Mass Rocket Stoves

Summary Evaluation Report of Fuel Efficient Stoves in IDP Camps, USAID, 2007

Table 2: Results of Water Boiling Tests: Average Stove Efficiencies

Stove type	No. of tests conducted	Thermal Efficiency			
		Cold start	Hot start	Simmering	*Average*
6-brick stove (NGO D)	8 tests, 4 stoves	13.6%	14.3%	15.4%	*14.4%*
Open fire	6 tests, 2 fires	13.7%	12.5%	15.5%	*13.9%*
Traditional mud stove	7 tests, 3 stoves	10.9%	9.3%	15.8%	*12.0%*
Trench stove	8 tests, 2 stoves	8.5%	10.1%	17.4%	*12.0%*
Lorena 2-pot (NGO B)	6 tests, 2 stoves	8.8%	7.5%	10.8%	*9.0%*
Lorena 2-pot (NGO A)	6 tests, 2 stoves	4.8%	4.5%	10.3%	*6.5%*

Note: Stoves are ranked by average efficiency over the three test phases.

- Heavy Rocket stove bodies or combustion chambers dramatically reduce heat transfer efficiency.
- The Lorena stove, invented by ARC, used much more fuel to cook compared to the open fire. We should have tested it more carefully!
- Mass and insulation are two different things. Earth is not insulation.

Winiarski Rocket Stove Design Principles

- Minimally, combustion chamber floats on water.
- Lighter is much better! WHY?
- Gases get hotter increasing heat transfer and combustion efficiency.
- Heat Transfer Efficiency: Force as hot as possible gases as close to the pot(s) as possible without reducing velocity.
- Combustion Efficiency: ‘Complete combustion” requires 850C, molecular mixing, >0.2 seconds of a metered amount of wood gas/air/flame. (Still, 2015)

Has to be lightweight!

Evolution in the Field

Short is better

During the Shell Foundation project, in 2004, ARC worked with 18 villages in southern India evolving Rocket stoves with cooks, distributors, funders and retailers.

The cooks lowered the stove so it would use less wood and boil water faster.

To our surprise, emissions were reduced, as well.

The resulting short, insulated Rocket stove design is now manufactured globally (~4 million/year).

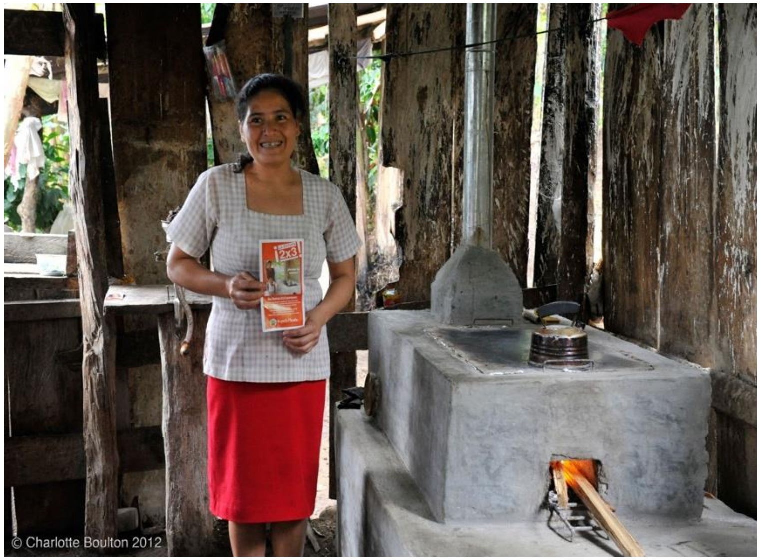
Modern Rocket stoves are usually about 12” high.

Shengzhou Stove Manufacturer, BURN, Envirofit, Ener-G-Africa and other factories sell short Rocket stoves

Plancha Stove w/Chimney

- Locally made, thin refractory ceramic tiles make long lasting combustion chambers, surrounded by ash.
- More than 1 million plancha stoves have been installed in homes.
- All smoke can be transported outside when chimney and stove are fully functional (Tier 5 for CO and PM2.5)
- A plancha (griddle) is used to make tortillas.
- However, the griddle reduces heat transfer efficiency to the pots to ~21% (Tier 2). (Chica, 2019)

Since 1998, ARC has been working with plancha stove projects in Central America

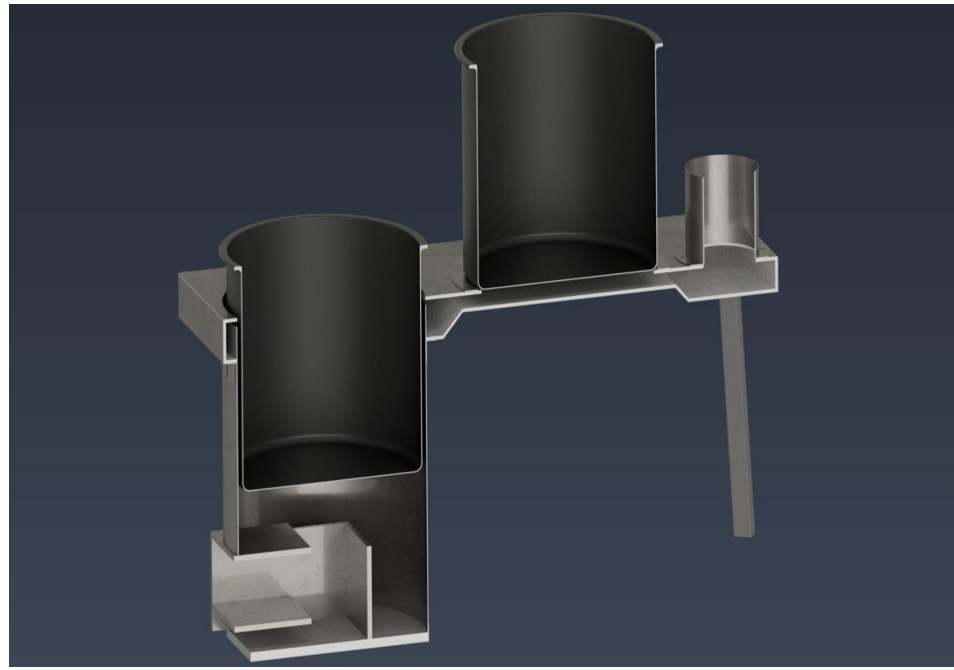


Proyecto Mirador

Dos Por Tres stove

Improved Plancha Stove?

- Increase thermal efficiency by increasing pot surface area contacted by hot gases
- Force as hot as possible gases as close to the pots without decreasing velocity
- Insulate everywhere else
- Maintain constant cross sectional area including chimney



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Chimneys to protect health and solar electricity in Africa

RESTORE, Tanzania 2026

Improving Heat Transfer Efficiency

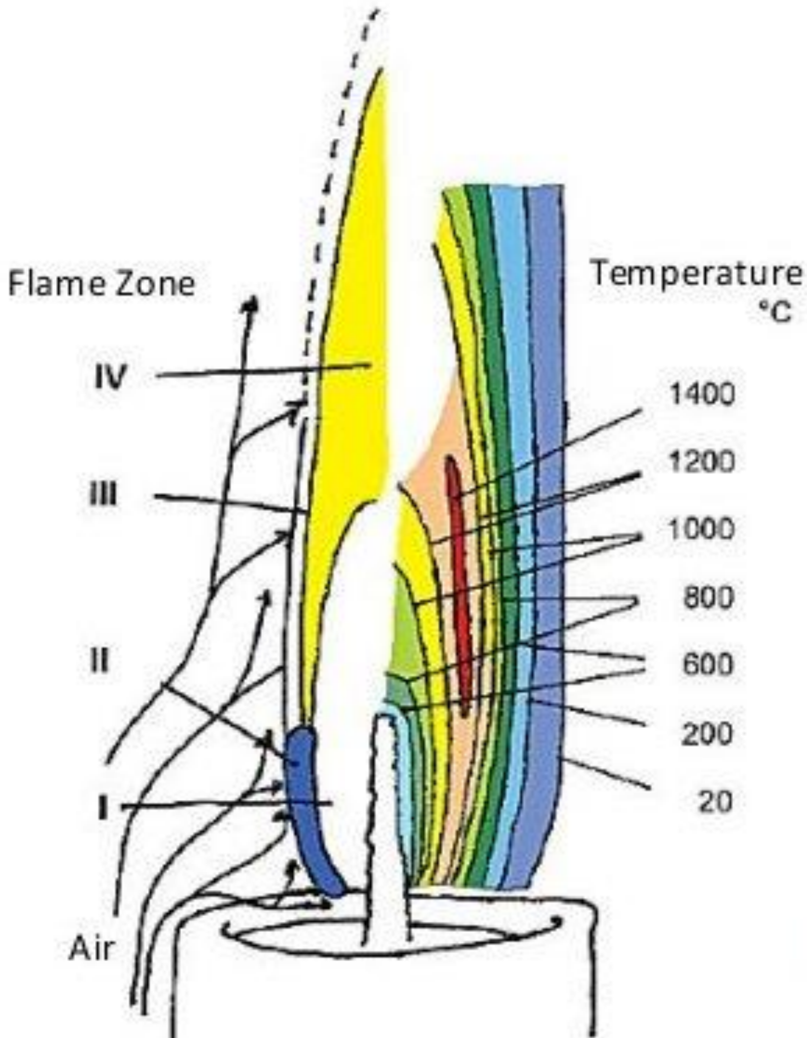
Temperature, Area, Radiation, Proximity, Velocity, Evaporation: “TARP-VE”

Temperature

- Make the hot gases that pass by the surface to be heated as hot as possible.
- Create the biggest difference between the hot and cold sides in the heat exchanger (pot).
- Insulate the combustion chamber.
- Try for temperatures above 850C
- 1100C possible. (Flame is hot!)

Incoming air is a lot colder

Flame: Hot on the Inside!



Area

- Expose as much of the surface to be heated as possible to the as-hot-as-possible gases.
- Create most efficient heat exchanger with:

Highest temperature gases, at fastest velocity, in tightest channel gap without reducing speed.

EASY TO MEMORIZE?

Increased Area

Hot gases touch sides as well as bottom of the pot

Radiation

- Encourage radiative heat transfer as much as possible.
- Have the as-hot-as-possible fire as close to the surface to be heated without making smoke
- ~1/3 of heating can be from radiation.

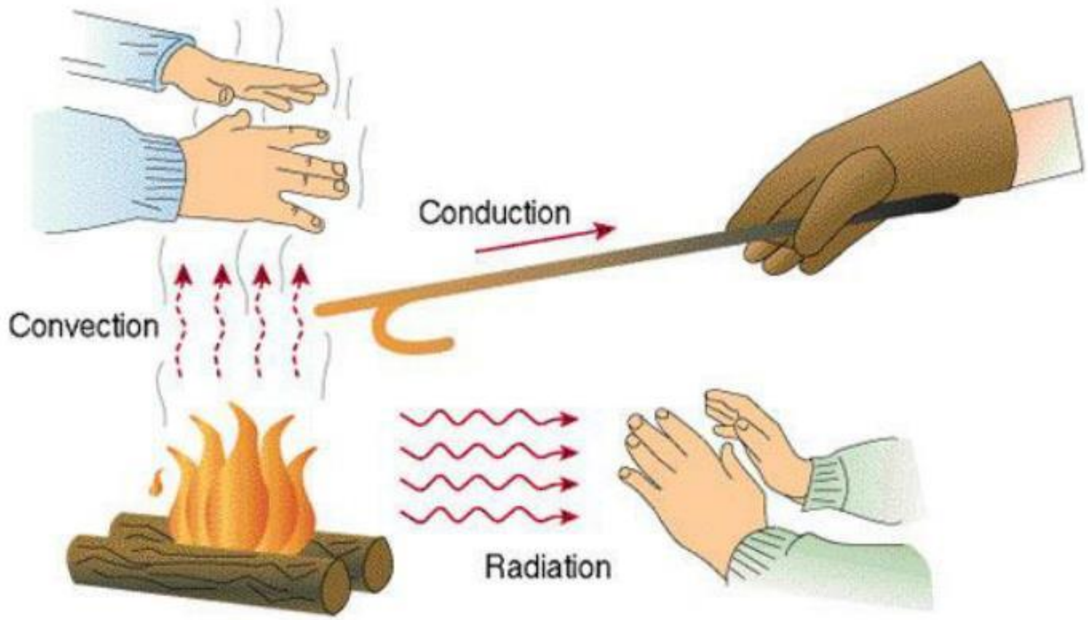
Primary air into charcoal creates hot temperatures and more radiation into pot

Don't forget radiation!

How is Heat Transferred?

There are THREE ways heat can move.

- Conduction
- Convection
- Radiation

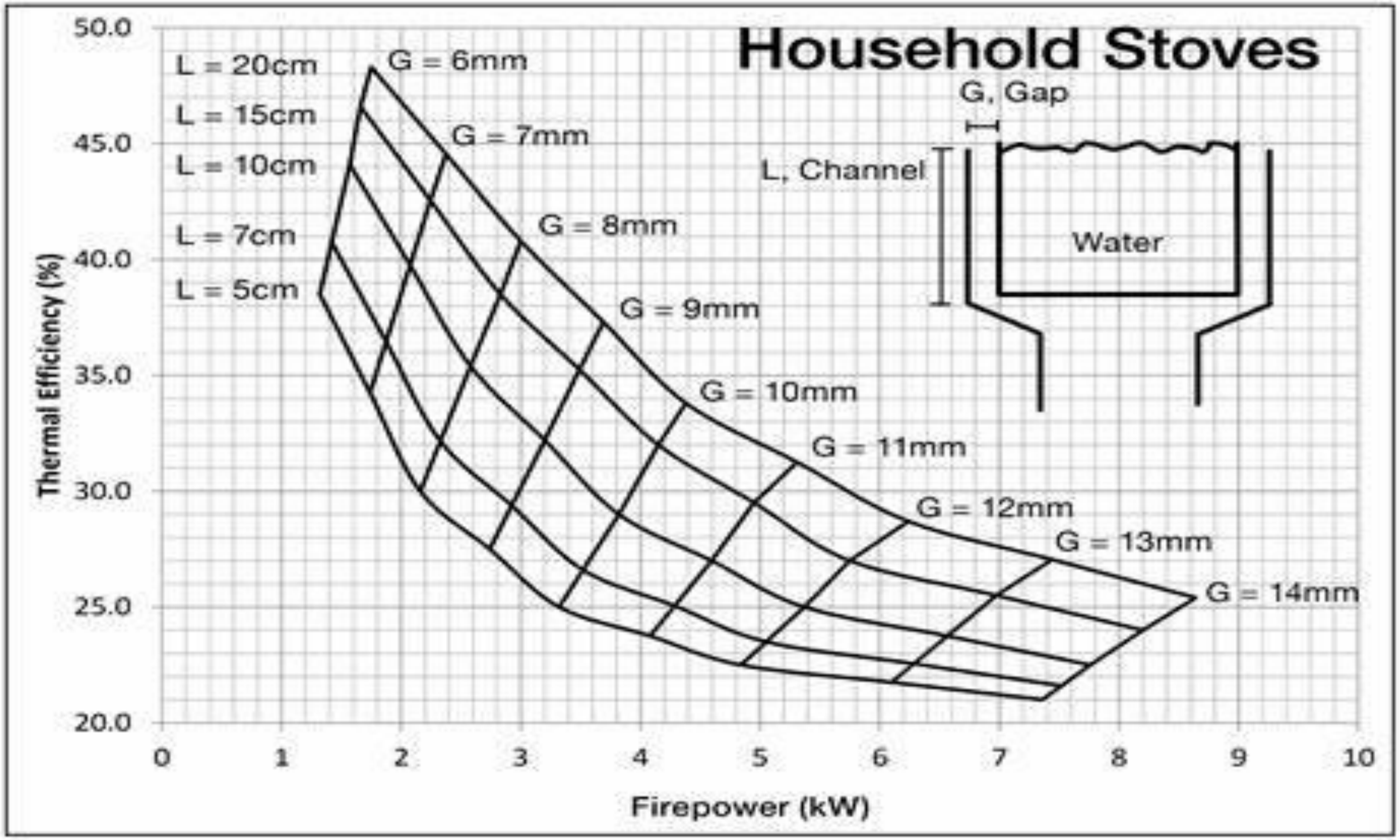


Proximity

- Make the as-hot-as-possible gases flow as close to the surface to be heated without decreasing velocity
- Double velocity = double heat transfer!
- Try 6mm channel gaps in pot skirts
- Test gaps under the emissions hood in a prototype

Maintain beneficial velocity
or everything crashes!

Baldwin: Heat Transfer Graph, again



With tight channel gaps, hot gases, sufficient surface area most stoves achieve ~50% Thermal Efficiency:

Unless they are too heavy

Adjustable pot skirt!

- Most cost effective technique ($1 to $2) to increase thermal efficiency
- 24% average increase
- Use 10cm high with 6mm channel gap for up to 4kW stoves
- Use 8mm channel gap for up to 6kW (ARC, 2024)

Adjustable pot skirt on $4 Timor Leste SSM refractory ceramic combustion chamber Rocket stove with cement body

Velocity

- Increase the velocity of the hot gases as much as possible without decreasing temperature
- Doubling **V**elocity ~doubles heat transfer efficiency
- AND, GUESS WHAT?

Doubling **A**rea ~doubles heat transfer efficiency

&

Doubling **T**emperature ~doubles heat transfer efficiency

IMPROVING HEAT TRANSFER EFFICIENCY IS EASY TO UNDERSTAND!!

Natural Draft: Slow Velocity

~One meter per second average

Improving Combustion Efficiency

TIME, TEMPERATURE, TURBULENCE

&

MIXING, METERING, MOISTURE, AIR

Mixing

- Make sure that turbulence mixes all the gases, flames, and air together
- Create lots of flame
- Meter all woodgas into flame
- Burn it up!
- Escaping woodgas is smoke, CO, etc.
- Primary and/or secondary forced draft air jets are needed to achieve ‘complete’ combustion
- Too much injected air can lower temperatures
- Try to maintain 850C!

Air Jets Are Generally Needed

Primary air:
Controls rate of reactions: How fast wood becomes woodgas

Secondary air:
Mixes metered amount of air, woodgas, flame

Create Flame!

- Add primary air below the fuel/flame
- Not too much (maintain 850C)
- The size of fuel influences the amount of flame
- Small sticks make more flame but make more smoke
- Big sticks make less flame and less smoke
- Force the gases and smoke to vigorously mix with the flameand air
- Charcoal makes much less flame than wood
- Hard to burn up escaping CO with charcoal

Charcoal doesn't make enough flame to burn up the carbon monoxide but,

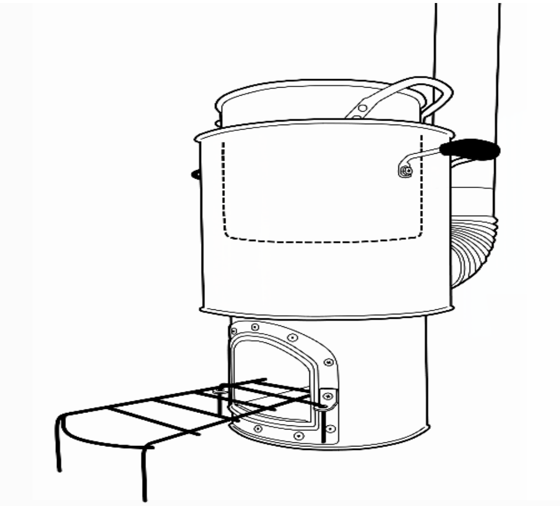
Charcoal makes ~ 90% less smoke than wood (Jelonic, 2020)

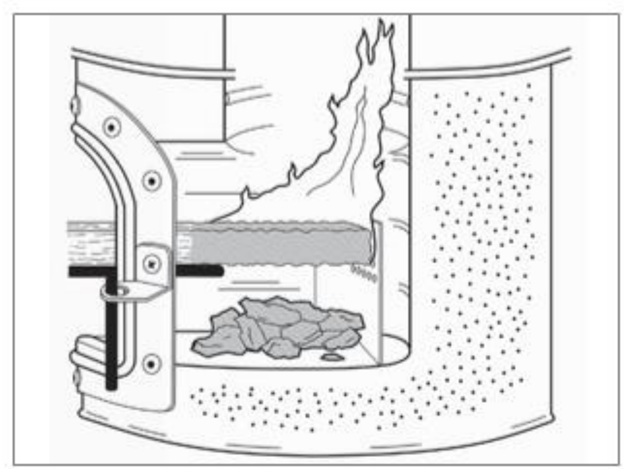
Metering

- Only make the amount of wood gas that will enter the well mixed flame and combust
- Unfortunately, the beneficial effects of sufficient mixing at above 850C, w/0.2 seconds residence time, @>1.5 air/fuel ratio can easily be overcome by too much wood gas entering the combustion zone
- Metering may be the most important component of clean combustion
- Determine how much woodgas can be made and then combusted by testing a prototype
- It’s not hard! Make one change a day and test

Reduce the amount of wood gas entering the fire until smoke disappears

Metering Sticks in Rocket





SUNKEN POT LOWER EMISSION ROCKET STOVE

- A **fence** in the back of the super-insulated Rocket combustion chamber allows **8cm** of the tips of the wood sticks to burn.

Stove type/model		Sunken Pot Rocket		
Location		Average	COV	Average Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	49.7%	4%	4
Low Power Specific Consumption	MJ/min/L	0.020	19%	3
High Power CO	g/MJ_d	2.22	38%	4
Low Power CO	g/min/L	0.05	42%	4
High Power PM	mg/MJ_d	152.2	53%	3
Low Power PM	mg/min/L	1.73	58%	3
Indoor Emissions CO	g/min	0.25	41%	4
Indoor Emissions PM	mg/min	11.8	46%	2

Determine the clean burning rate of reactions

How much woodgas can be cleanly burned in your stove?

Kirk Harris has spent fun weeks tuning his clean burning TLUDs at the ARC lab. We make good coffee!

Moisture Content

- Very dry wood can suddenly burst into flame releasing too much gas and smoke, and woodgas escapes uncombusted
- Wetter wood (15% moisture content) burns more slowly which can improve metering

- Greater than 30% moisture content wood will probably not make sufficient flame.

Moderately dry wood can burn more cleanly in traditional stoves (Yuntenwi, 2008)

Wood can be moderately dry

15% to 20% % moisture content seems to work well

Air

- Inject sufficient primary air to encourage the needed amount of flame above the fuel into which gases and smoke enter and are combusted
- There is a beneficial compromise between lots of air which makes a lot of flame and too much air cooling the fire
- A colder fire chamber decreases both combustion and heat transfer efficiency.

AIR AND TEMPERATURE ARE RELATED

CURRENT SUGGESTION:

850C for > 0.2 seconds with > 1.5 air/fuel ratio (Only clean burning with not too much woodgas)

Not too little or too much air

Dr. Winiarsky: More secondary air only cools combustion chambers in Rocket stoves. Enough air comes in through the big open door.   "Don't add secondary air."

Thanks very much!
Please visit us when you can!

Dr. Winiarski, who invented the Rocket Design Principles, wins a Lifetime Achievement Award from the Partnership for Clean Indoor Air (2009)