

**Welcome to Aprovecho Research Center's Spring Webinar Series!**

# Stove Design

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*Aprovecho  
Research Center*

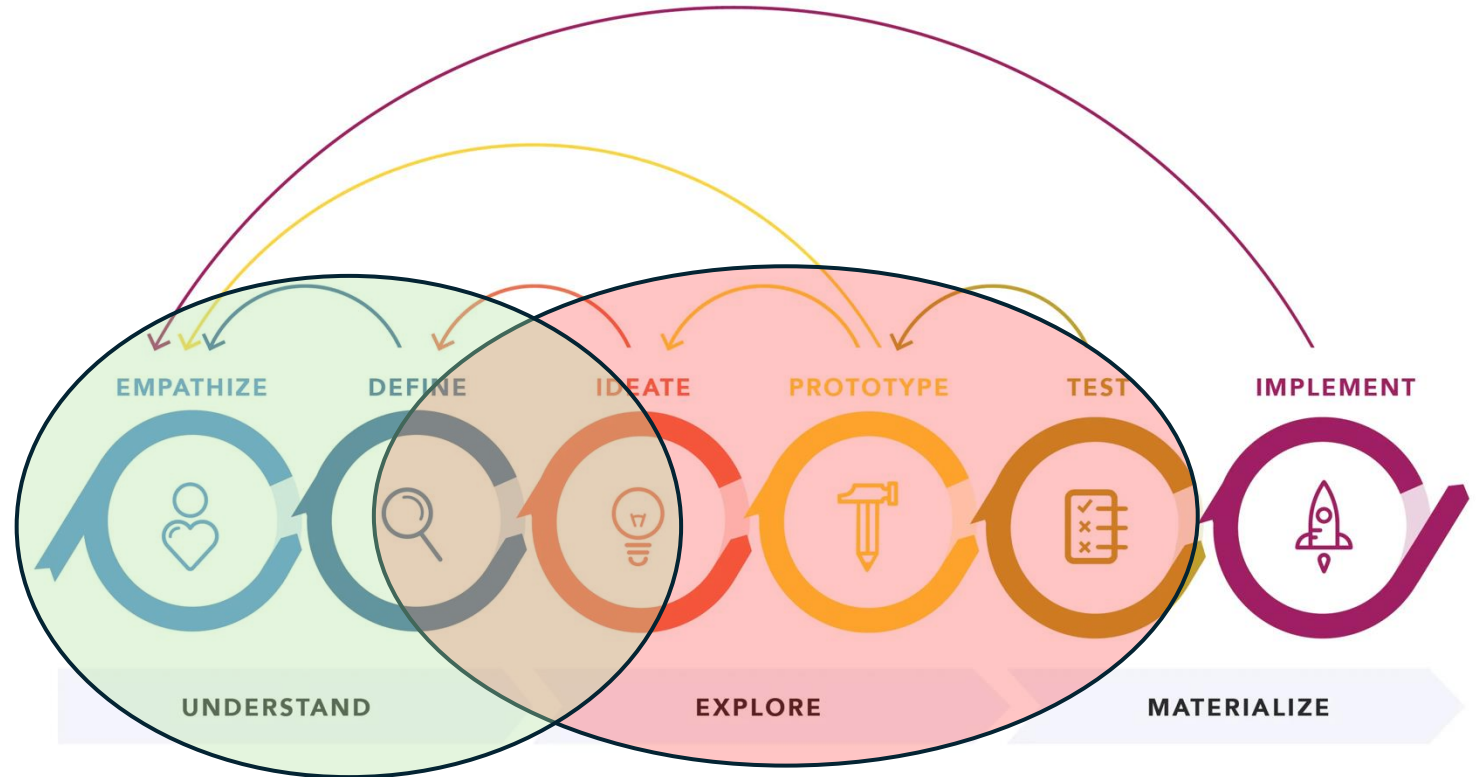


# Agenda

- The designer's and cook's roles in cookstove design
- Understanding three stone fire
- Rocket Stove
- Forced Draft rocket stove
- Pellet stoves
- Charcoal stoves
- Method of iterative development

# Roles in cookstove design

While the designer has a role in the entire design process, the designer must work with the cook to define the problem and ideate/iterate the solution.



Primarily Cook Input

Primarily Designer input

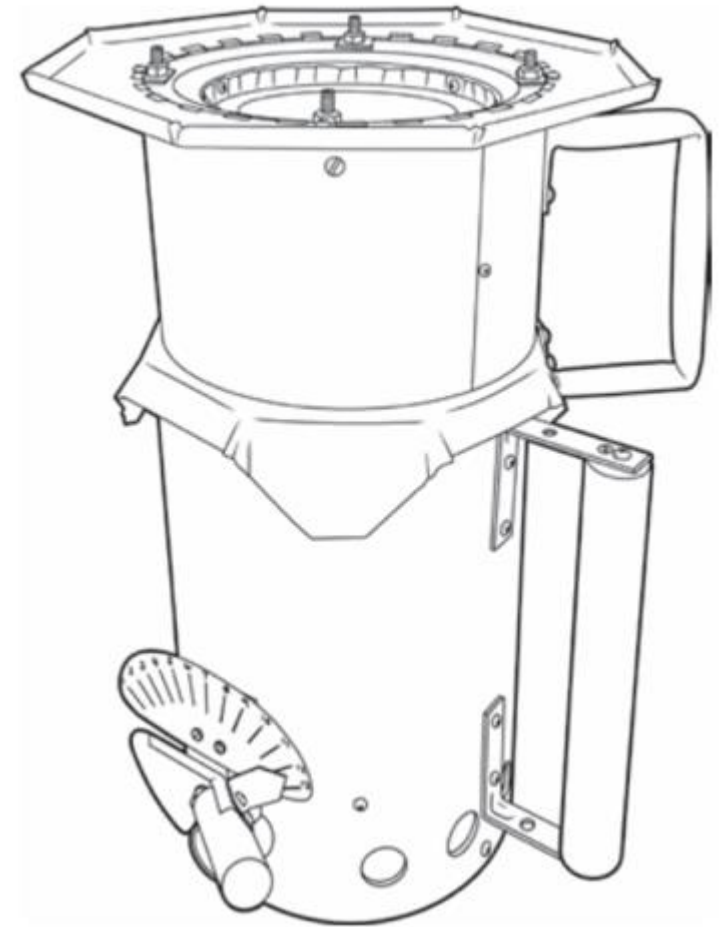
Manufacturing and distribution

# What info to observe from users

- Maximum, minimum firepower
- Pot size and shape
- Quantity of water and desired time to boil
- Firepower curve
- Fuel size and moisture content
- Startup time and method
- Fuel tending time
- Structural stability, impact resistance
- Cost and lifespan

# What happens when the Designer works alone?

- The stove will contain innovative features and score well during lab testing
- The features will probably be desirable
- But the job doesn't get done
  - technology can become difficult to use
  - Difficult to manufacture
  - Not durable



# Understanding the Three-Stone Fire

- The open fire (out of the wind) has many advantages that must be overcome:
  - Low mass, heats up quickly
  - Short stones with fire close to pot is more efficient
  - Careful tending equals good heat transfer efficiency
    - 20 to 30% possible in lab, but 11.3% was average of 254 recent field tests<sup>1</sup>
  - Three large stones make a stable cooking surface suitable for vigorous stirring
  - Variable firepower
  - Variable size pots, flat or round bottomed
  - **Free**, traditional, durable, and portable!



1. "Quantifying the Efficiency and Fuel Consumption of Cooking with Traditional Wood and Charcoal Stoves in Malawi, Ghana, and Kenya", Urban et. al. *Environmental Science & Technology* 2025 59 (32), 16913-16922

# Rocket Stoves

# 10 Rocket stove design principles

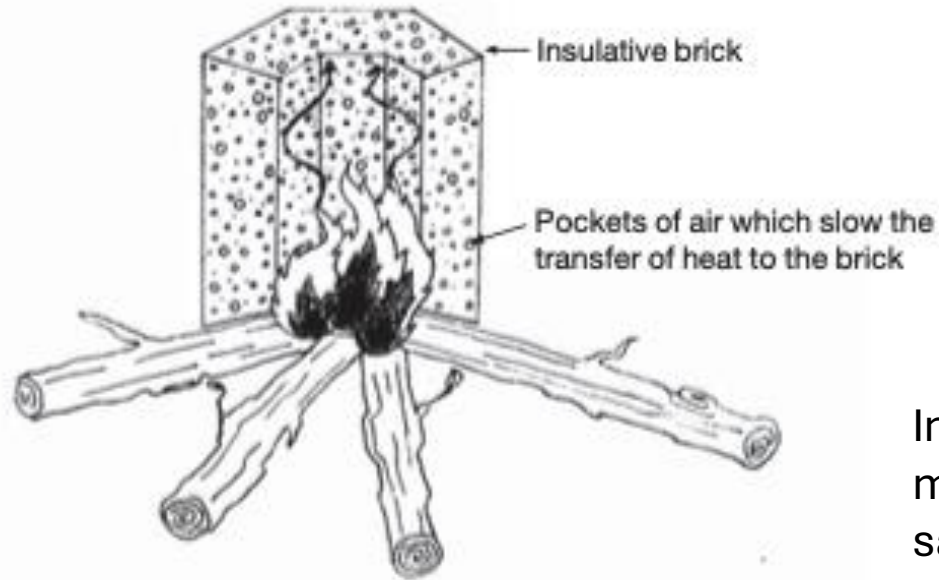
- General guidance to design improved wood burning cookstoves
- Solutions must be iterated to become market ready
- Photos from ARC/EPA/Shell Foundation publication
  - EPA-402-K-05-004 *Design Principles for Wood Burning Cook Stoves*

## Design Principles for Wood Burning Cook Stoves



Aprovecho Research Center  
Shell Foundation  
Partnership for Clean Indoor Air

# Insulate around the fire



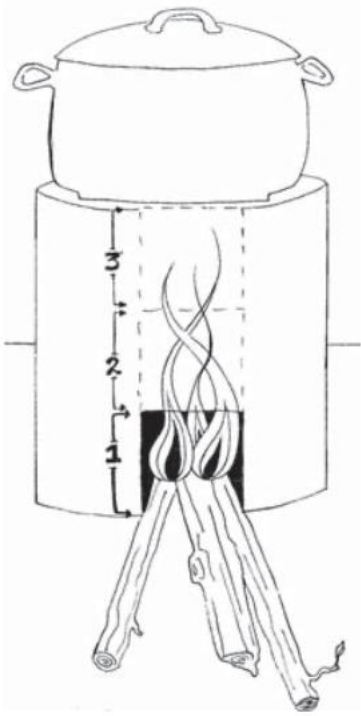
**Figure 7** - Insulation around the fire

Insulative brick is made by including sawdust or charcoal in the clay/sand mixture which is burned away during production to create airgaps.

## Insulation:

- Multiple layers of shiny metal with air in between
- Ceramic fiber
- Pumice
- Vermiculite
- Wood ash
- Low density ceramic (floats on water)

# Insulated chimney above the fire

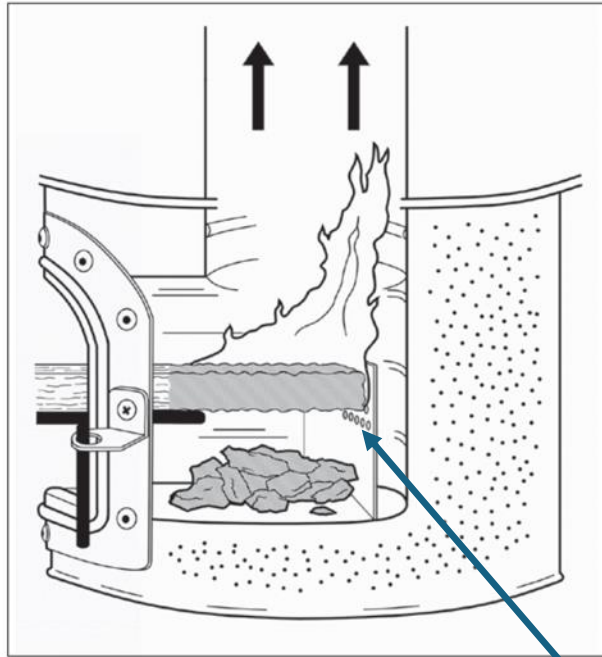


**Figure 8** - An insulated short chimney above the fire

A hot space above the fire (riser) allows emissions to burn before they hit the bottom of the pot. Flames hitting bottom of pot make PM2.5 and CO.

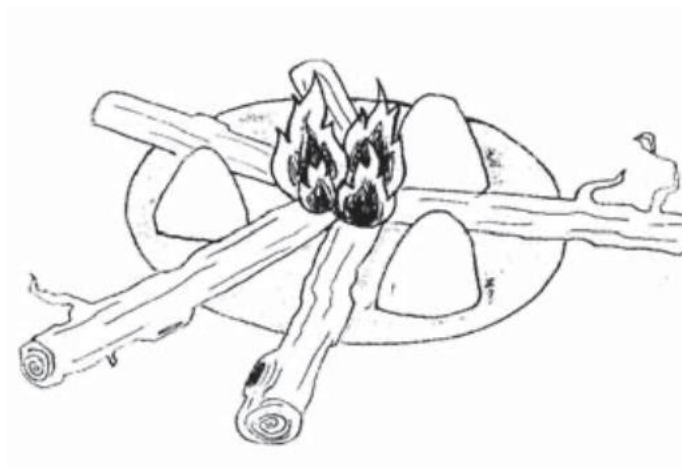
If the riser is too tall (more than two to three times the width of the combustion chamber opening) thermal efficiency will decrease.

# Burn the tips of the sticks

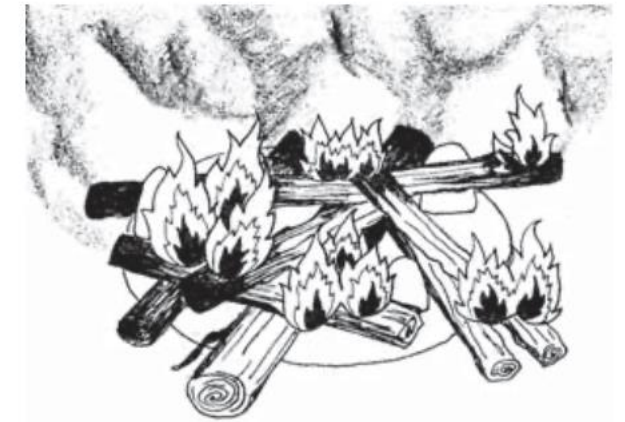


1  
1  
1

Best way to reduce emissions!



**Figure 9 - Cleaner Burning**

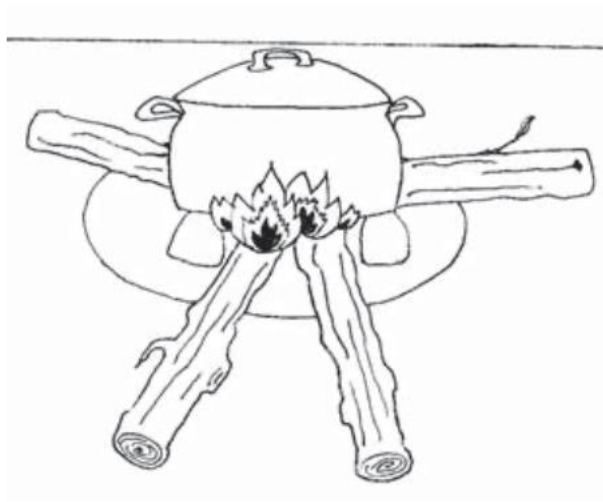


**Figure 10 - Smoldering Wood Makes Smoke**

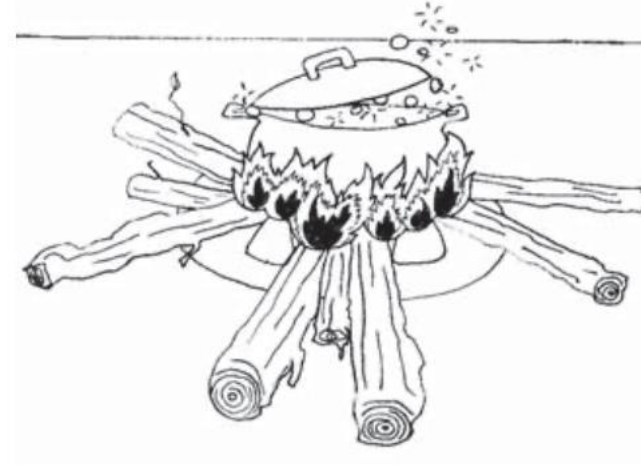
*Clean Burning Biomass Cookstoves (2021)*

Fence allows only 8 cm of stick to burn. Too much wood in the combustion chamber creates long flames that quench on the pot and make black carbon

# Number of sticks controls firepower



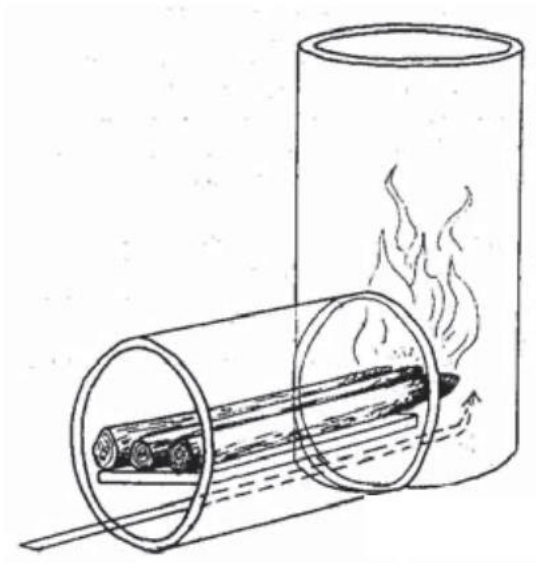
**Figure 11 - Low Heat**



**Figure 12 - High Heat**

The length of the stick burning also determines firepower – more fire in combustion chamber makes more heat

# Maintain strong airflow through stove



**Figure 13** - Maintaining a Good Draft

The riser section and adequately sized channel gaps will allow air to easily move through the fuel and mix with the wood gas to promote complete combustion and high temperatures

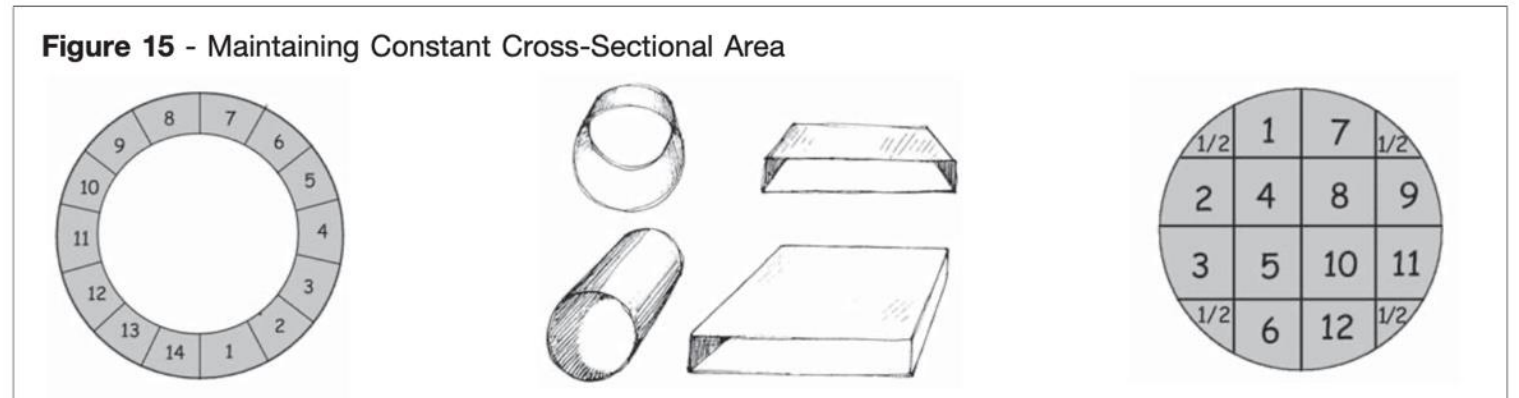
Too little airflow will create excess charcoal. Short stoves will have less airflow, as well as stoves with tight channel gaps or convoluted flow paths. (Principle 6)

# Maintain constant cross sectional area

An airflow path with constant cross sectional area and minimal directional changes will allow more air to pass through the stove and at a higher speed.

High speed air generates more heat by striking the charcoal and by encouraging mixing with the woodgas

High speed air more easily reaches the pot and leads to higher thermal efficiency

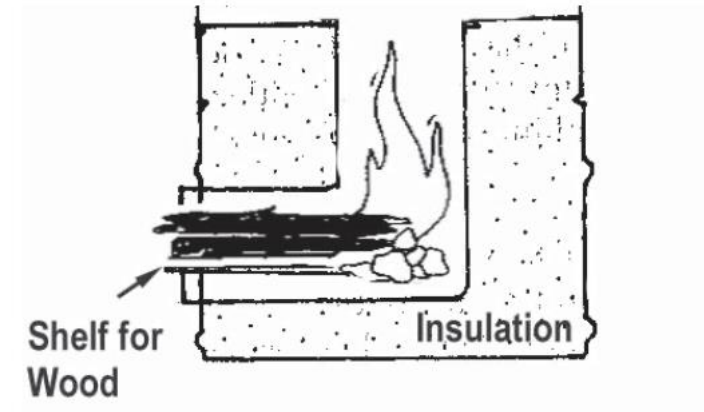


The area of the donut (left) and the area of the circle (right) are almost the same.

# Place a grate under fire/charcoal

The grate under the charcoal prevents excess charcoal buildup.

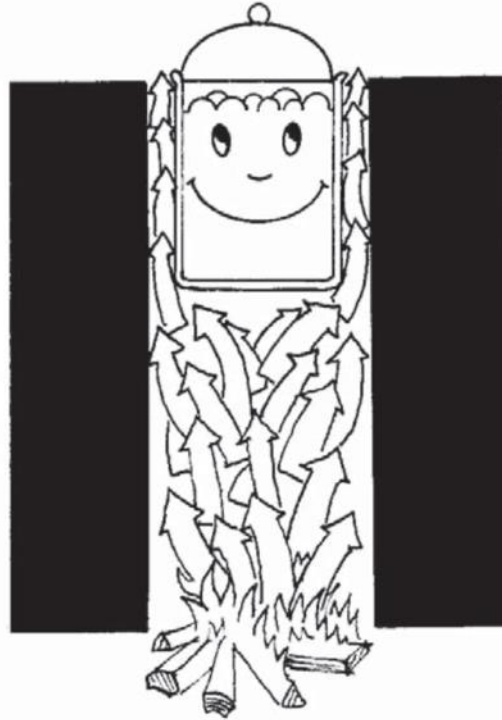
A shelf can be used if ceramic or cast iron cannot be formed into a grate.



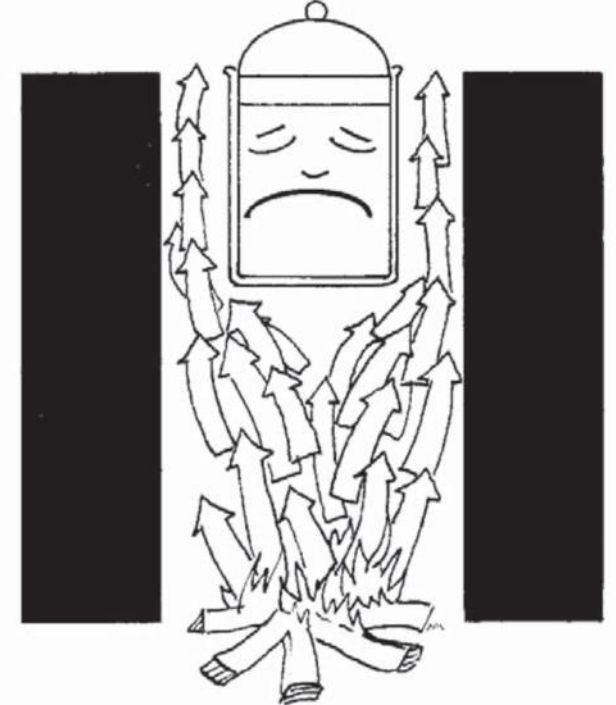
**Figure 16** - Use of a Grate Under the Fire

# Use small channel gaps

Narrow channel gaps, 6 mm for household stoves, maximize heat transfer efficiency



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



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

# Rocket stove design principles applied

- Data review of three rocket stoves and a pot skirt stove

# High mass rocket stove with wind blocking pot skirt

This wide pot skirt blocks the wind, but efficiency would be higher with a narrower channel gap

The high mass mud combustion chamber can be made by users and does not degrade with heat. It blocks the wind.



A stick shelf helps to burn the charcoal because it keeps the sticks off of the floor of the combustion chamber.



If the firepower is too high the charcoal will build up under the sticks and block the airflow underneath the sticks



**ISO Performance Metrics  
(High)**

	units	
Thermal Efficiency Without Char	%	12.3
Average Cooking Power	W	1093

**ISO Performance Metrics  
(High)**

	TIER
Thermal Efficiency Without Char	1.2

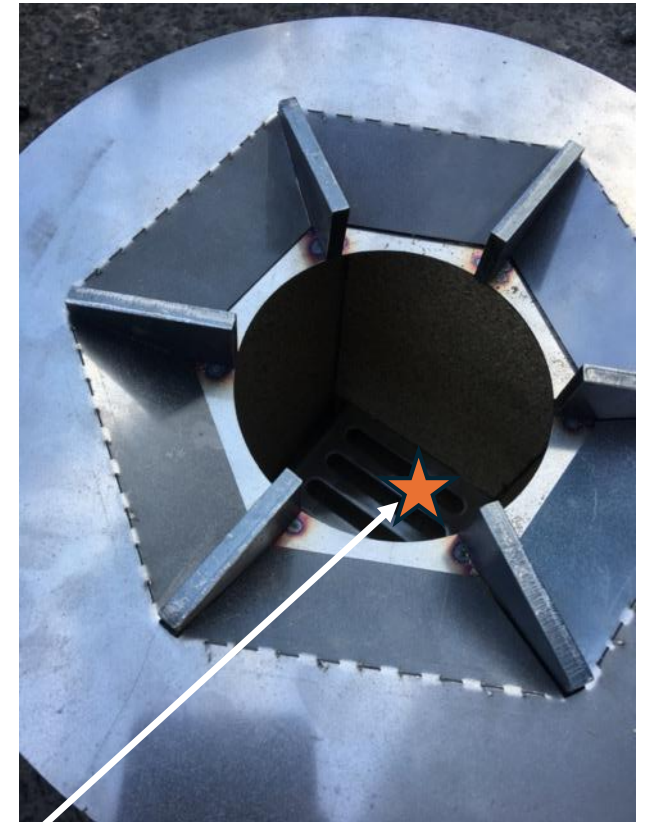
High mass, large channel gap, and relatively small pot made low thermal efficiency

# Low mass single wall rocket with large pot



The stove top had narrow channel gaps to increase convective heat transfer from the exhaust gasses

The walls of the combustion chamber were low mass and prevented heat from escaping from the combustion chamber



The grate held the sticks and charcoal off of the combustion chamber floor so that air could pass through the charcoal and allow it to burn



**ISO Performance Metrics (High)**

	units	
Thermal Efficiency Without Char	%	31.3
Average Cooking Power	W	1299

**ISO Performance Metrics (High)**

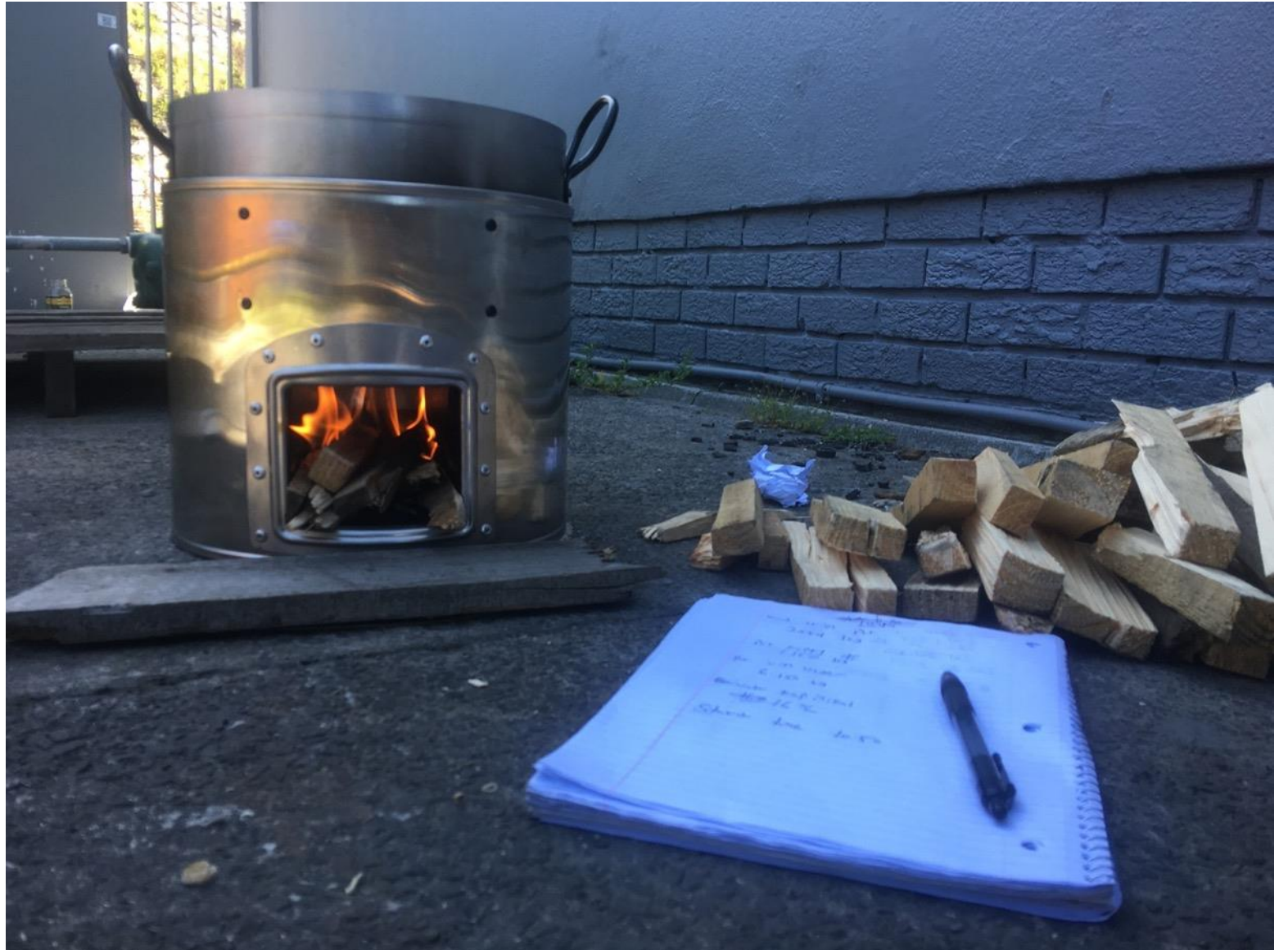
	TIER
Thermal Efficiency Without Char	3.1

The smaller channel gaps and better insulation increased the thermal efficiency relative to the high mass stove.

No pot skirt was used, but thermal efficiency is still dependent on the shape and size of the pot

# Low mass, single wall bucket stove with large sunken pot

The pot is sunken down inside of the stove so that a greater surface area of the pot is exposed to the hot exhaust gasses. The stove is essentially a pot skirt.



# Low mass, single wall bucket stove with sunken pot



The combustion chamber is very wide. It effectively only blocks the wind and forces the hot gasses up towards the pot and into the pot skirt channel gap. The combustion chamber stays cool enough to prevent metal degradation.



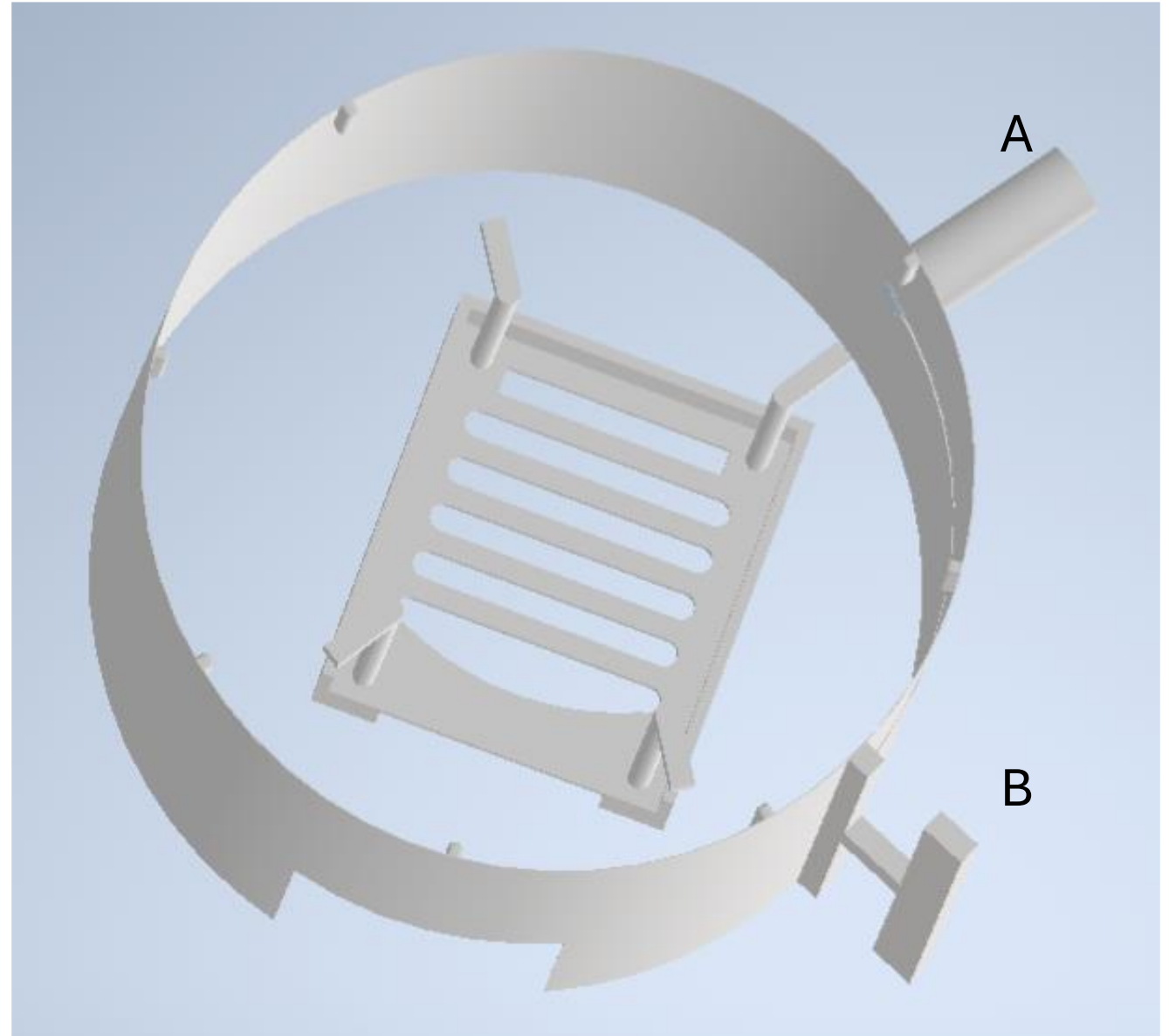
A grate keeps air flowing through the charcoal. Short walls on the grate keep the sticks over the grate.



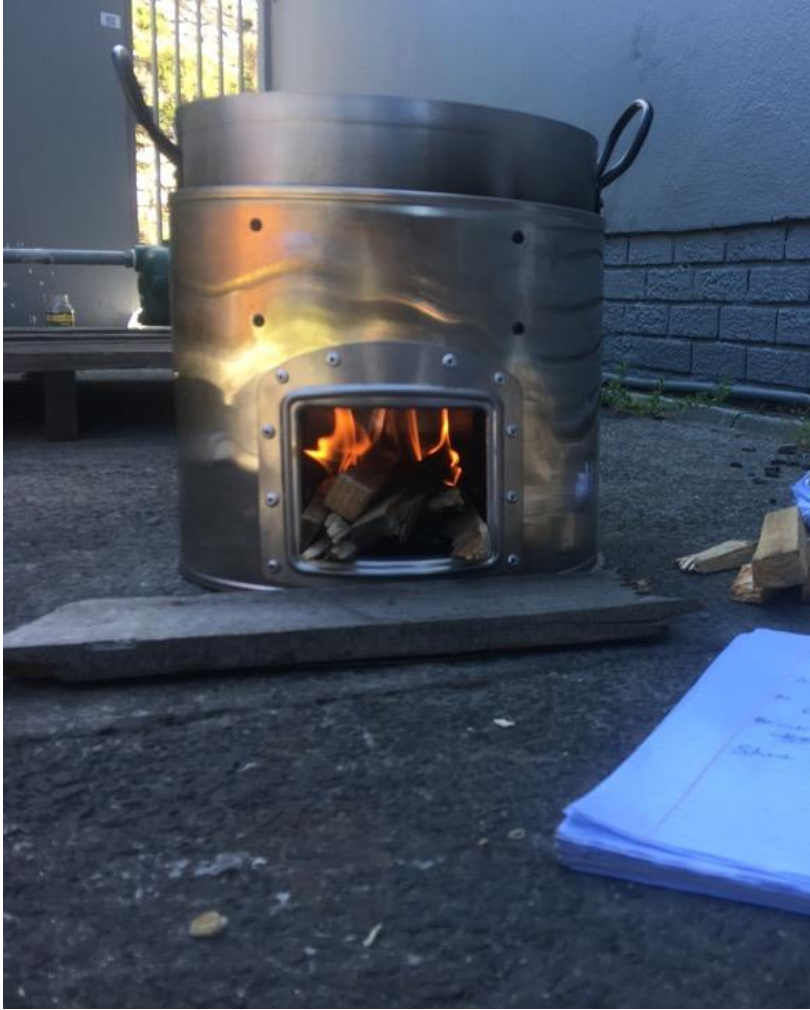
The combustion chamber is cool enough to prevent metal degradation of the grate.

# Adjustable pot skirt detail

- Twist handle A to loosen nut
- Pull handles A and B together to tighten skirt against pot
- Twist handle A closed to tighten nut



April 2022 original prototype drawing



### ISO Performance Metrics (High)

	units	
Thermal Efficiency Without Char	%	37.1
Average Cooking Power	W	1699

### ISO Performance Metrics (High)

	TIER
Thermal Efficiency Without Char	3.7

The highest thermal efficiency was achieved with the most durable and easy to build stove because of the narrow channel gaps and large surface area of the pot exposed to the heat of the fire.

To achieve this thermal efficiency users must always use this pot

# Forced Draft Rocket Stoves

# Jet-Flame combustion accessory

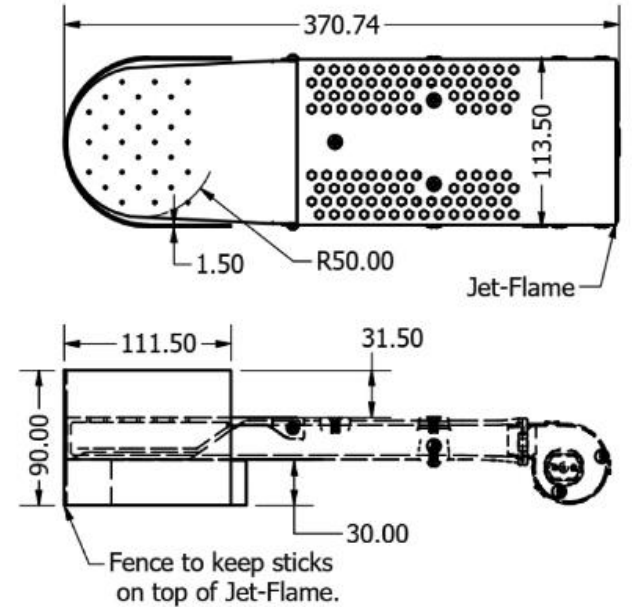
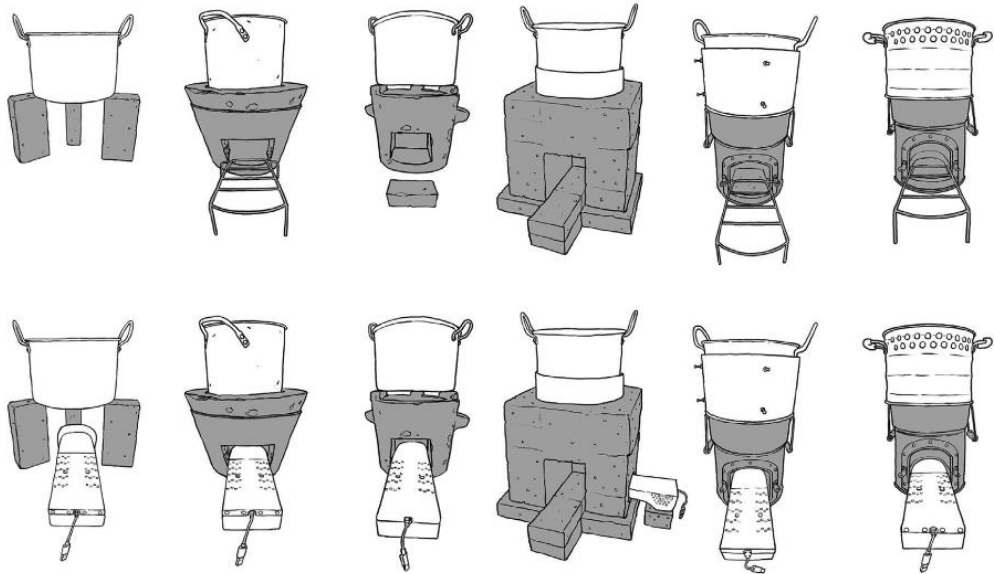


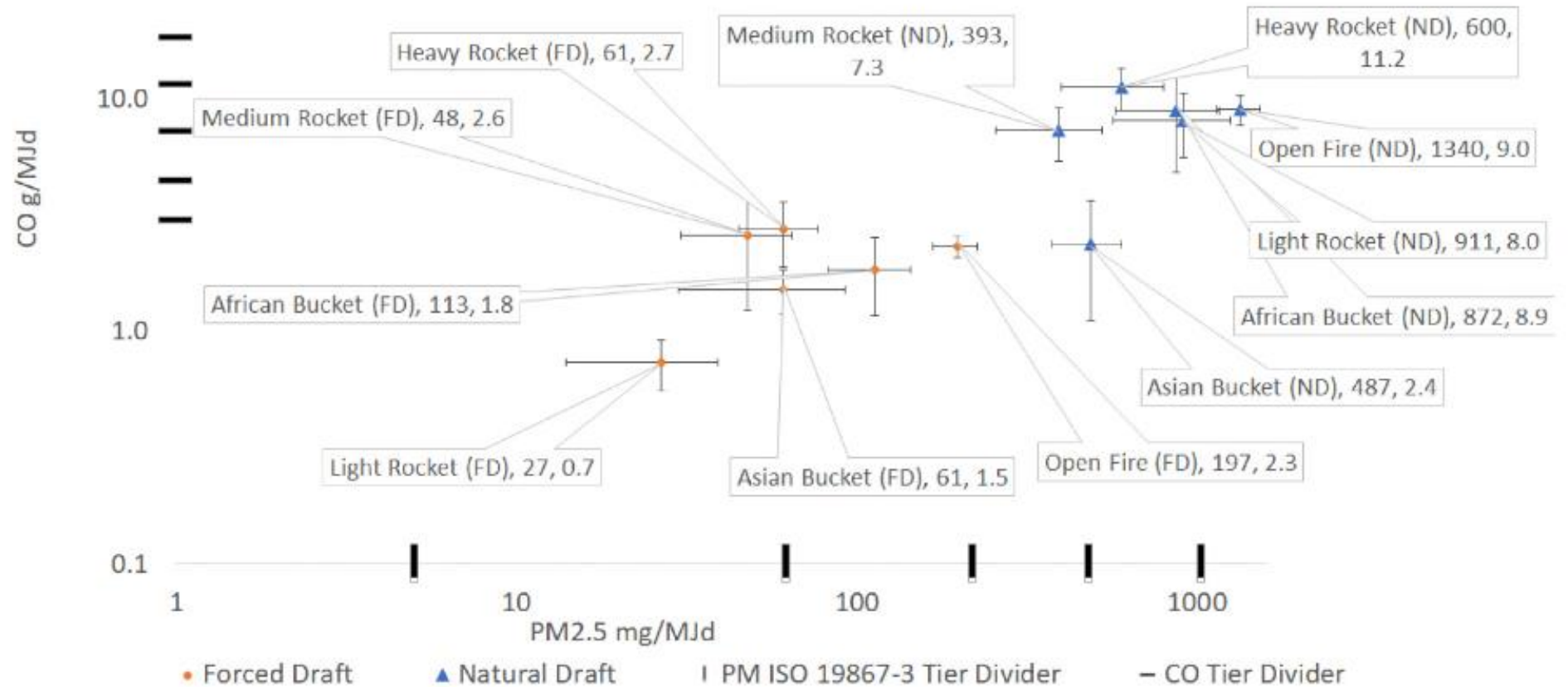
Fig. 1. Jet-Flame A) product and B) CAD drawings.

The Jet-Flame is a forced draft combustion accessory that makes rocket stoves cleaner and more efficiency using 2-5 W of electricity (USB power).

“Retrofitting stoves with forced jets of primary air improves speed, emissions, and efficiency: Evidence from six types of biomass cookstoves”, Bentson et al, Energy for Sustainable Development 71 (2022) 104–117

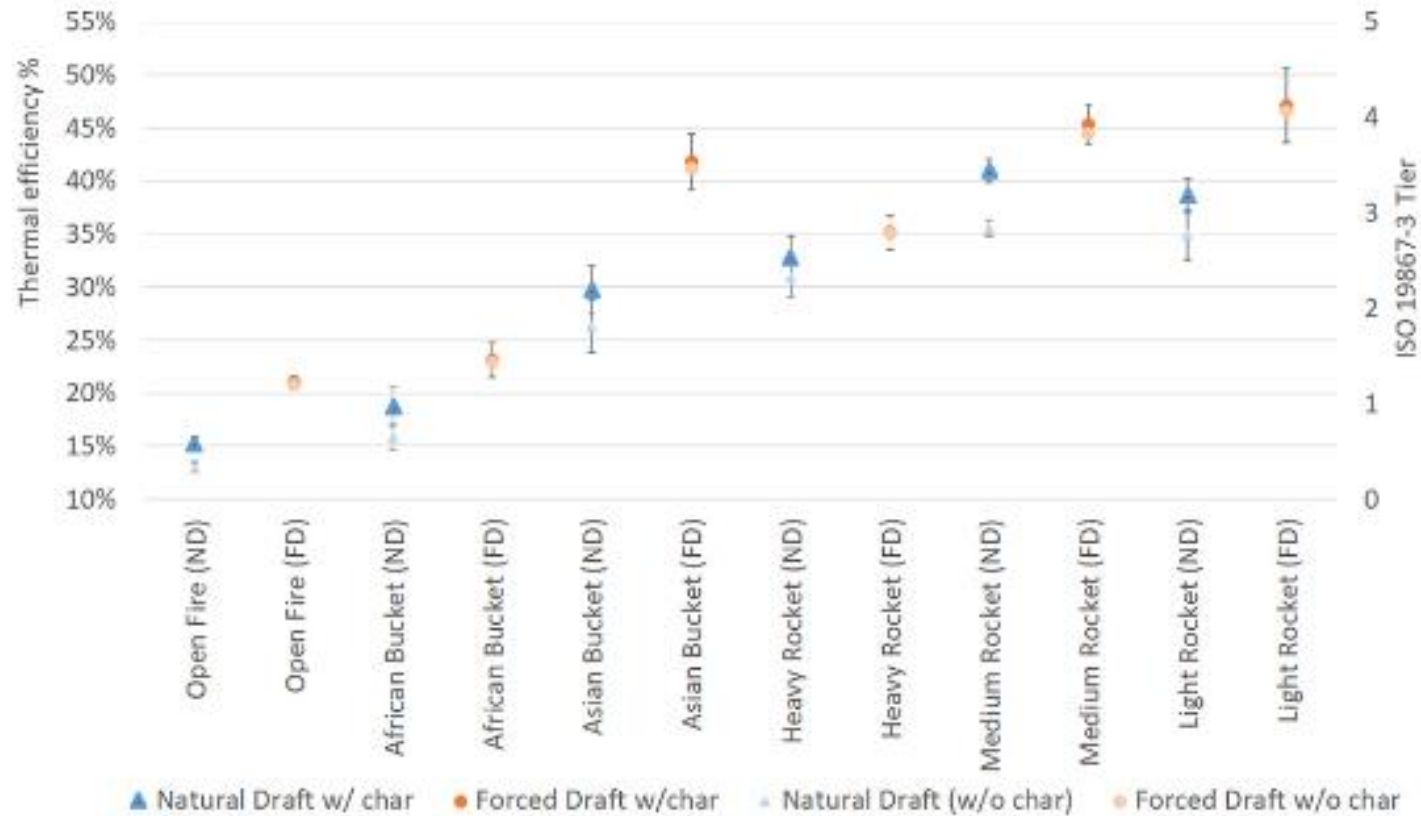
“Saving time and reducing smoke: A sensor-based performance assessment of a forced-draft ‘Jet-Flame’ cooking system in Malawi”, MacCarty et al, Energy for Sustainable Development 80 (2024) 101–469

# Jet-Flame makes stoves cleaner



**Fig. 6.** ISO Tier Mapping for CO and PM<sub>2.5</sub> per MJ<sub>delivered</sub> for the natural (blue triangle) and forced draft (orange dot) cases. Note the log scale on both axes.

# Jet-Flame makes stoves more efficient



**Fig. 5.** Thermal efficiency with and without char for forced and natural draft conditions. Error bars show 90 % confidence interval.

# Pellet Stoves

Also known as semi-gasifier or TLUD (Top Lit Up Draft)

# TLUD - top lit updraft semi-gasifier

Clean burning with pellets

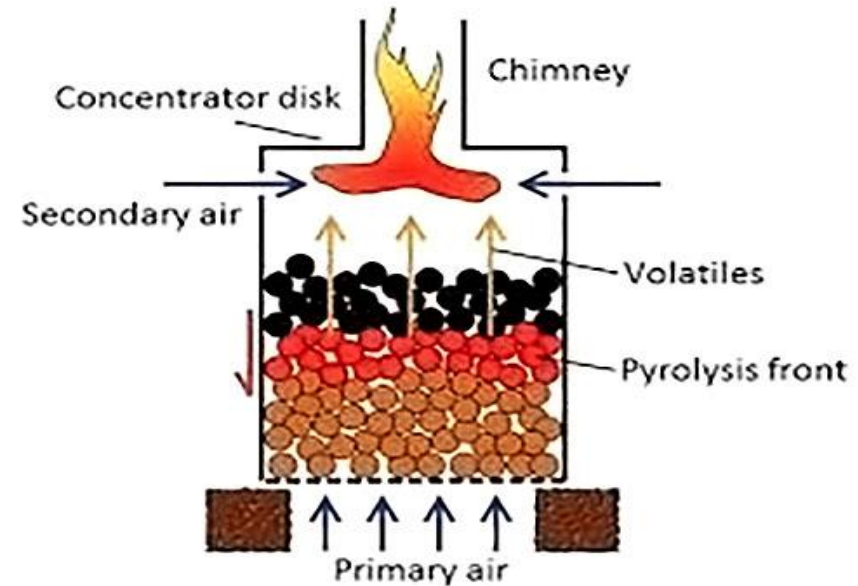
Primary air controls how fast solid wood becomes gas that burns (woodgas).

Woodgas passes up through burning charcoal.

Secondary air provides the oxygen that maintains the flames above the fuel bed.

Primary air is decreased and secondary air is increased until smoke disappears.

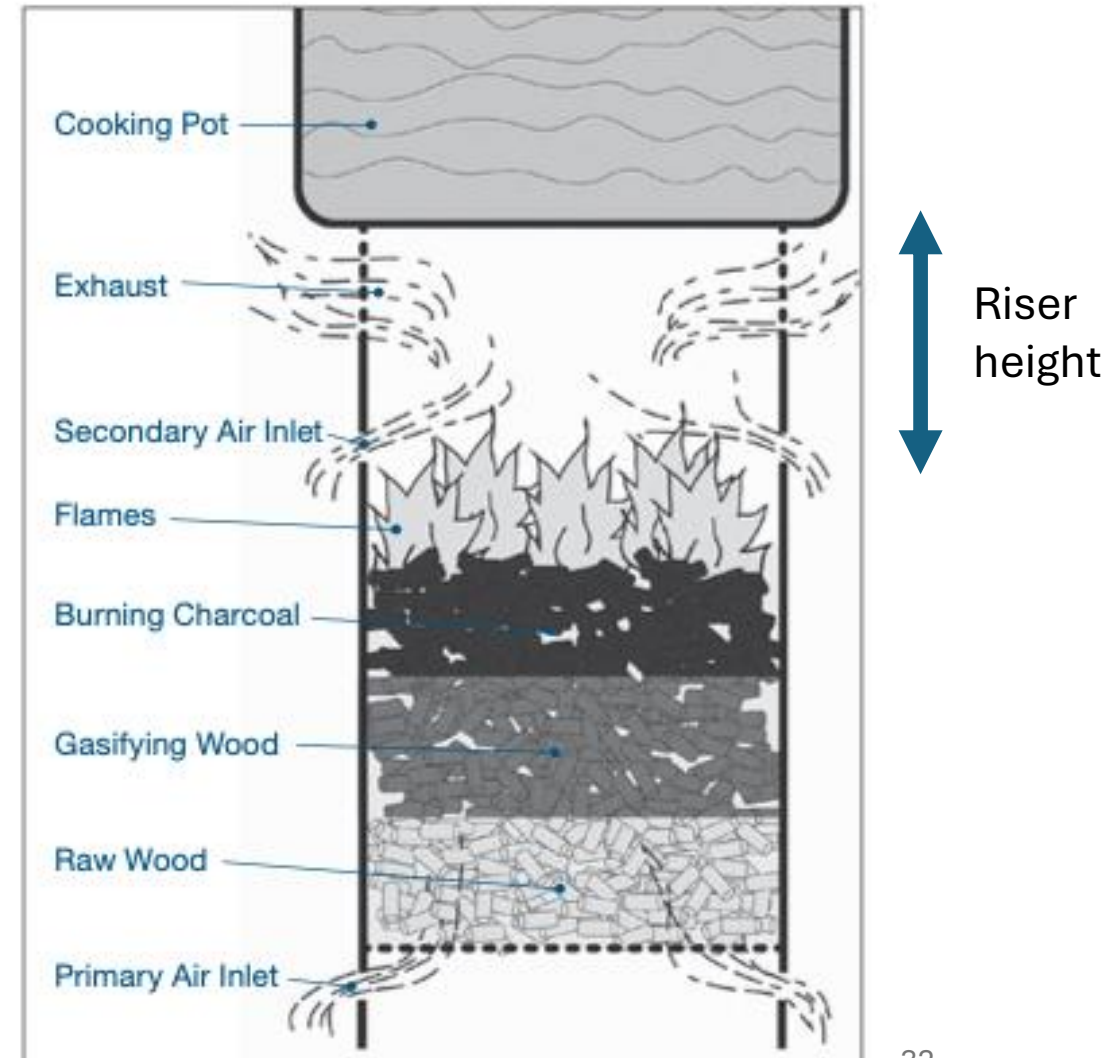
Invented by Dr. Reed and Wendelbo



Batch fed like charcoal.  
Cannot be fully reloaded  
without smoking.

# Natural draft vs forced draft TLUD

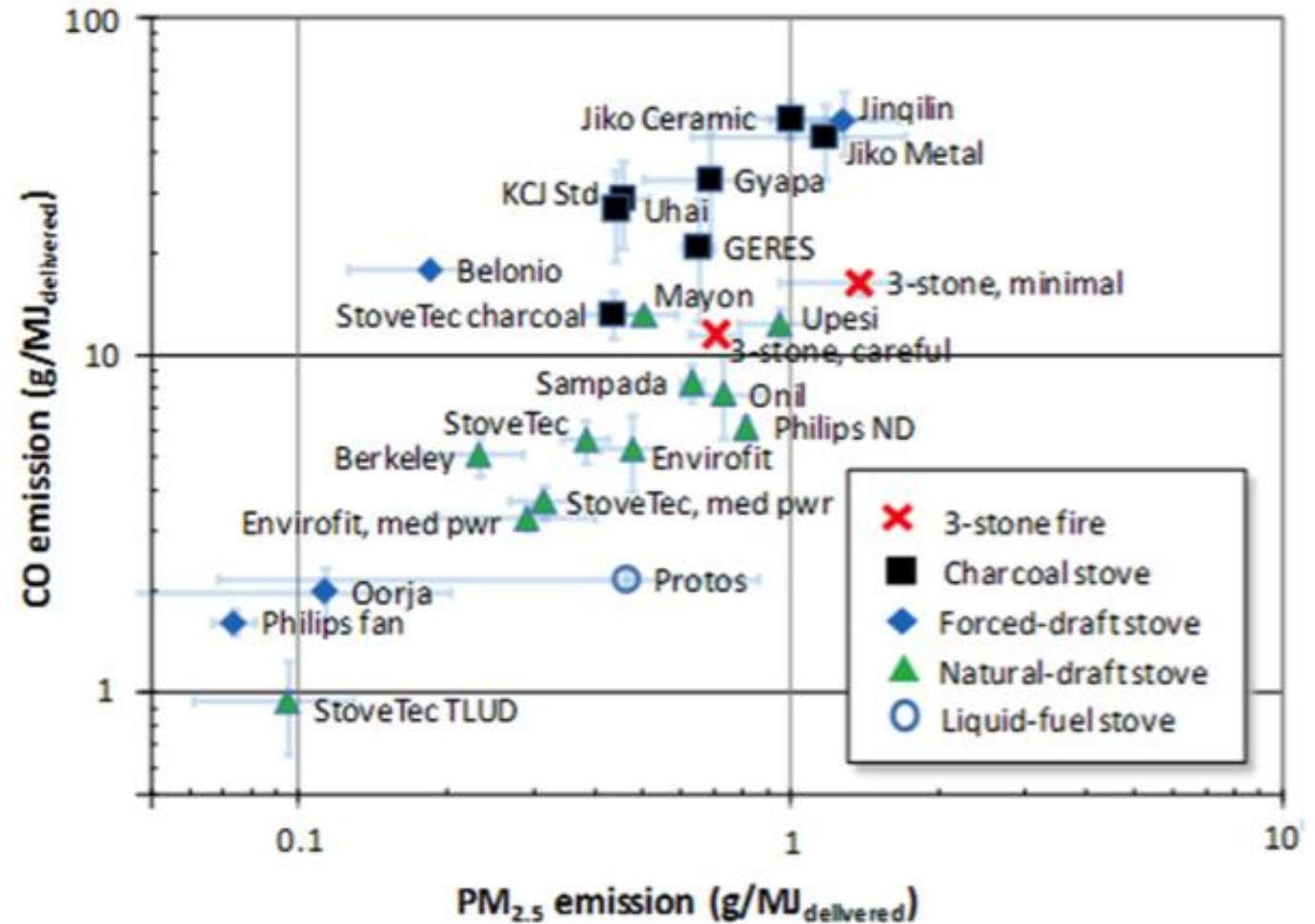
- Forced draft TLUDs have more burning charcoal at the top of the fuel pile because the secondary air jets collide and hit the charcoal.
- The riser height can be shorter on forced draft TLUD because the secondary air jets are faster than in the natural draft stove and create adequate mixing with less residence time
- Two fans can be used and computer controlled to independently control the amount of primary and secondary air which is especially useful during the transition to charcoal burning



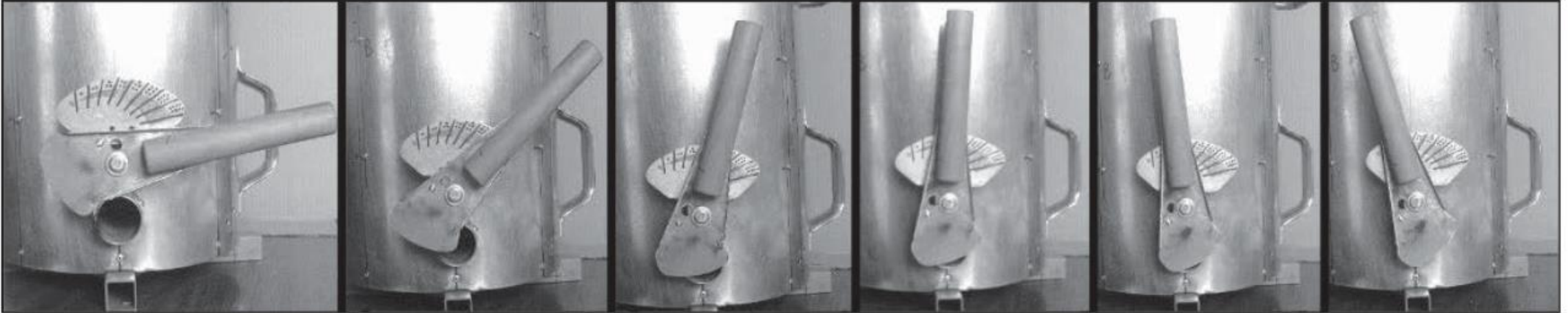
# Phillips was forced draft, Stovetec was natural draft – cleanest burning out of many



Phillips was short with a fan (F),  
 Stovetec was tall with no fan (T).  
 Both fueled with Douglas Fir pellets



# Importance of controlling TLUD primary air

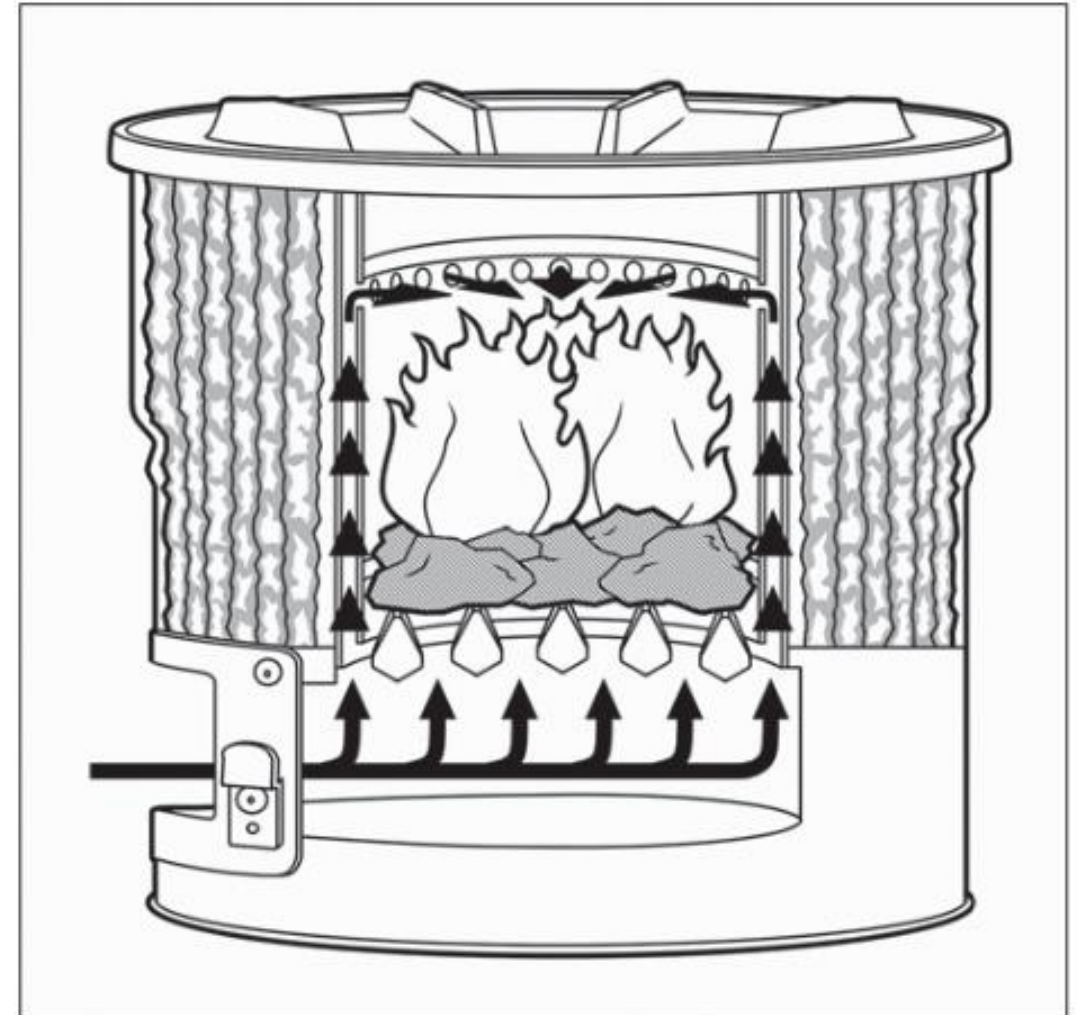


- The area of the opening controls the amount of primary air that enters through the bottom of the stove and into the pyrolysis zone
- Small changes in primary air lead to large changes in rate of woodgas generation/firepower/flame height
- Tall flames hitting the bottom of the pot will produce smoke
- Inadequate secondary air or mixing, especially in natural draft TLUDs, will make smoke

# Charcoal Stoves

# Charcoal stove design

- The charcoal needs to get hot quickly to burn the CO
  - Using reflective insulation and/or carefully lighting the stove from the top gets the charcoal hot fastest
  - Low mass materials and parts heat up faster
- Secondary air will help burn the CO if the combustion chamber is hot enough – a blue flame will be visible
- Small channel gaps and pot skirts work for charcoal just like wood
- Charcoal can burn with very little air – a tight sealing primary air door will give excellent turn down ratio
- The fuel burns as a batch – too much fuel in the combustion chamber will result in wasted firepower and lower thermal efficiency



# Importance of pot skirt for charcoal stove

ARC improved a high mass charcoal stove in 2022

- Pot supports were sized so that a 330 g fuel load left a distance of 12 mm between the top of the fuel and the bottom of the pot
- 12 cm tall, 6mm channel gap pot skirt
- Flat top so that combustion gasses did not escape between pot and stove
- High power TE went from 25.4% to 33.6% (N=5)



*Figure 12 Final stove configuration, detail of 22 mm pot supports*



*Figure 13 Final stove configuration*

# Iterative development – test hypothesis

Does secondary air lower CO g/min?

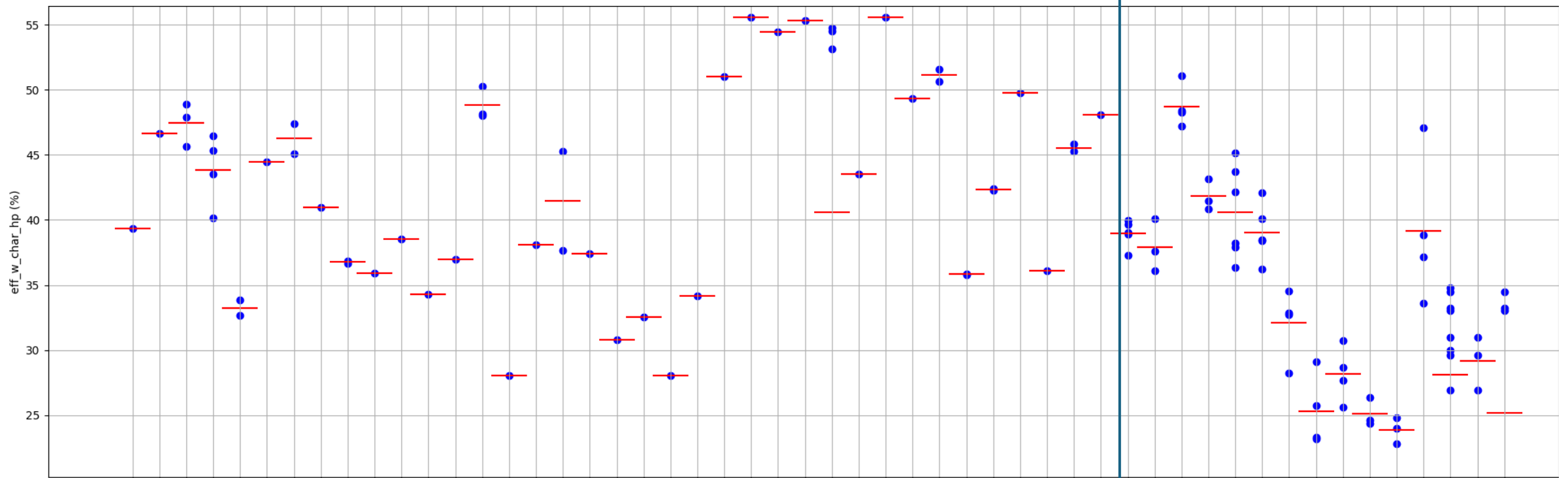
Secondary Air



Primary Air

Yes, in ARC tests from 2016 emissions factor was halved (34 to 17 g/MJd )

# Iterative development – learn from many tests



Blue dots are individual tests. Red lines are average of the same test configuration. Can compare results to decide which feature is best.

Most of these tests were performed at EGA in South Africa in less than three weeks starting at 7AM each day.

These were reference data from Aprovecho

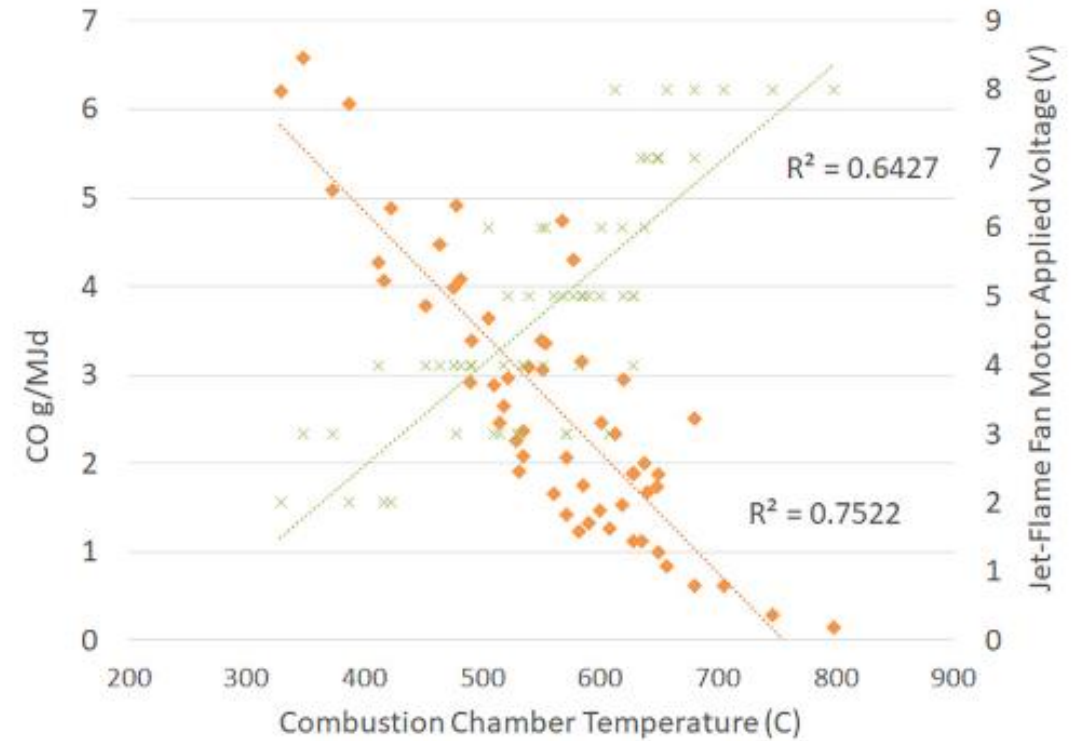
# Summary

- Rocket stoves are an evolution of the three stone fire and is an example of how spending money on technology and materials makes life better
- The three stone fire is flexible and available
- TLUD pellet fueled stoves can be clean burning but depend on availability of fuel and tuned airflow
- Charcoal stoves can be made to save fuel when advanced materials and manufacturing are available
- Making good cookstoves takes iterative testing in the lab and field
- Please join us for Travis's webinar on Emissions Testing in the Lab
  - **Thursday, July 2nd, 8am-9am PST:** Lab Testing, Travis Volpe-- This webinar provides an overview of the ISO 19867 stove test protocol and the Aprovecho LEMS and data processing software.

# Questions?

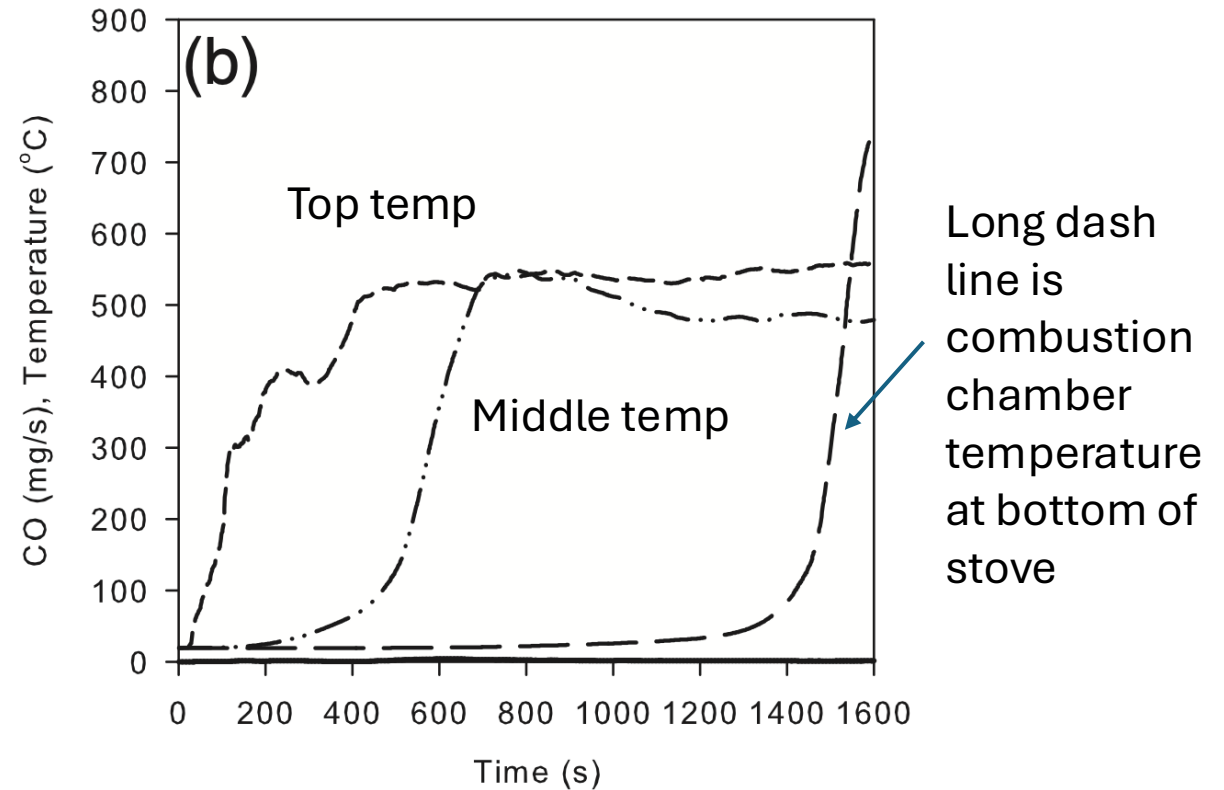
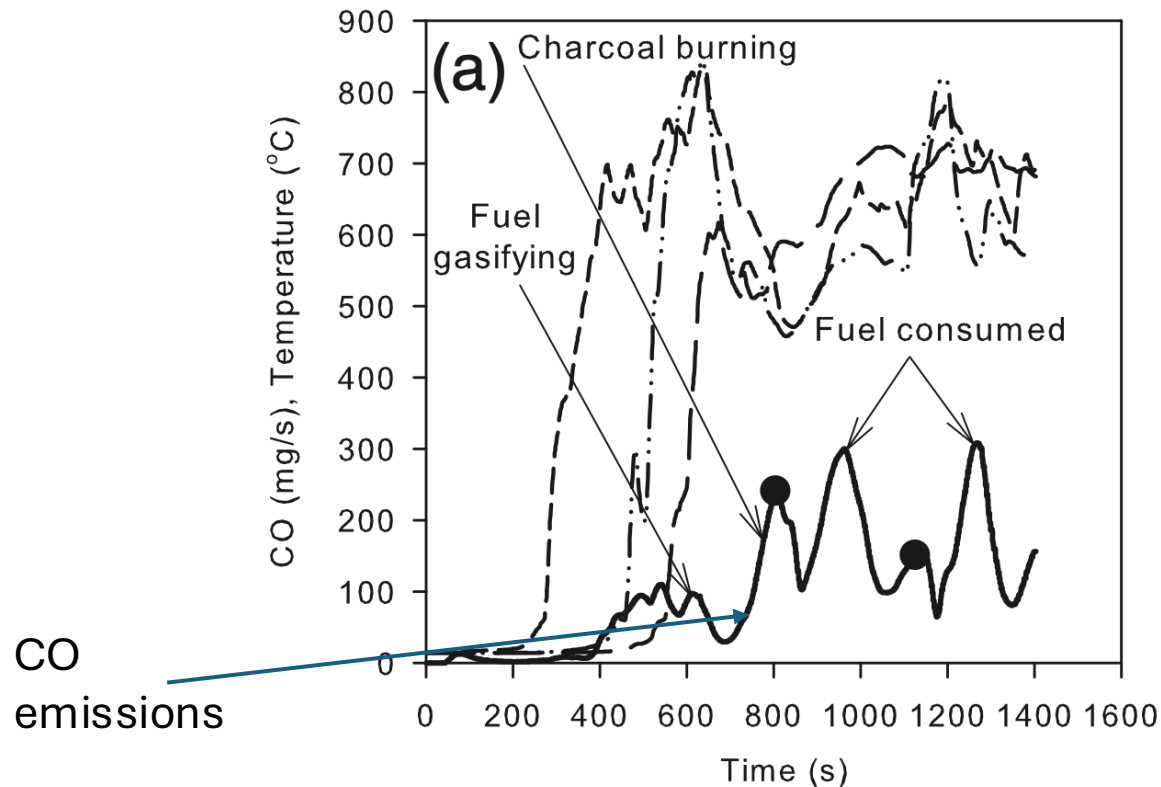
- Thank you!
- And thanks to the Osprey Foundation for supporting this webinar series
- Feel free to reach out: [sbentson@aprovecho.org](mailto:sbentson@aprovecho.org)

# CO temperature dependency during Jet-Flame tests



There was a strong correlation between combustion chamber temperature and CO (orange dots) during testing of the Jet-Flame in the high mass rocket stove. CO temperature dependency is probably why lighter charcoal stoves make less CO.

# Why is it difficult to refuel TLUD stoves?



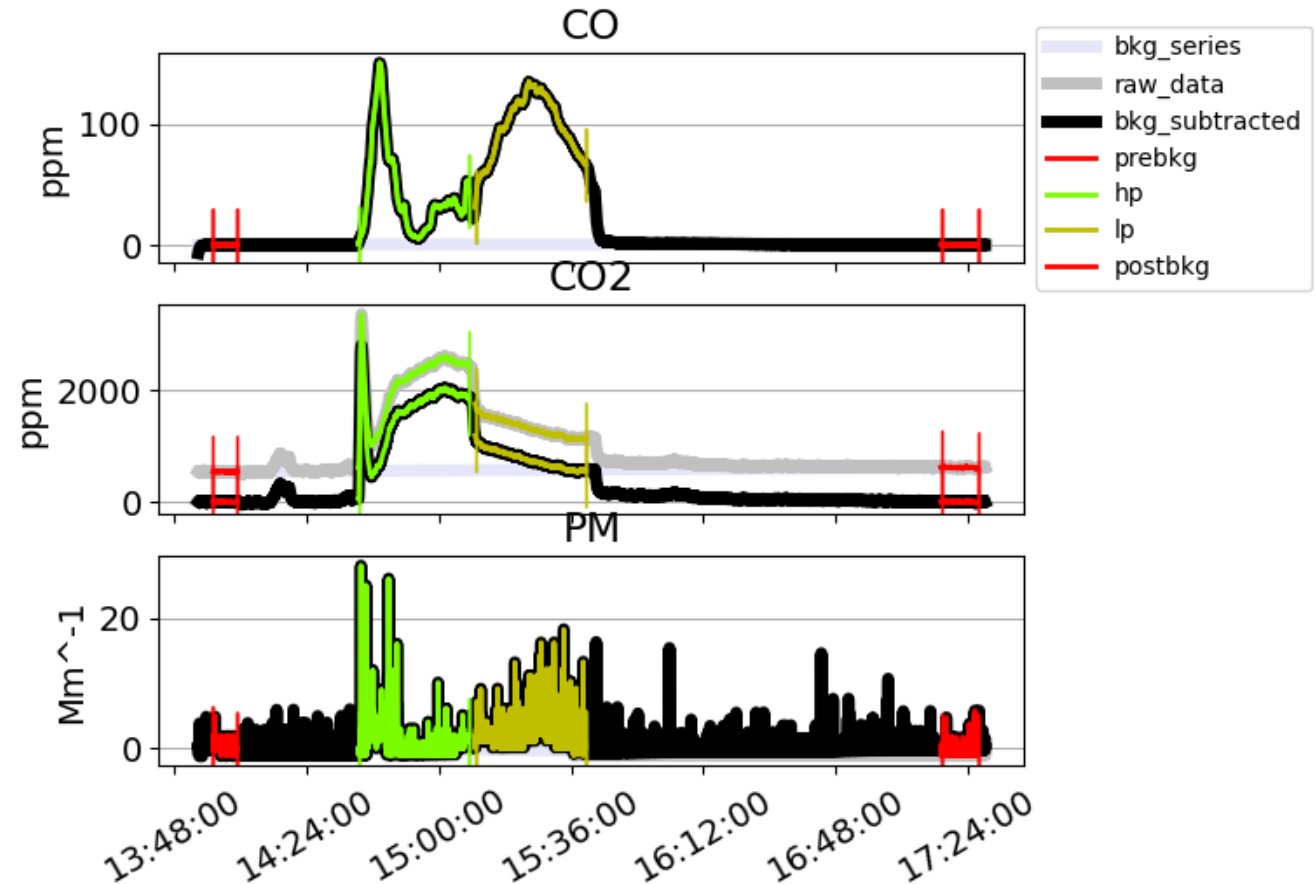
When stove was filled with low density fuel (a) fuel burned too fast and combustion chamber temperatures were elevated resulting in too much woodgas and higher CO emissions. Reloaded fuel (dots) burned even faster.

Same stove with pellets didn't get too hot (b)

# Typical CO curve from charcoal stove – ceramic with secondary air

The CO starts out high during ignition, then gets low as the stove heats up (CO<sub>2</sub> increasing). CO starts coming up as the firepower starts to decrease.

Stove started with top layer of charcoal soaked in alcohol. Initial spike of CO<sub>2</sub> is alcohol burning.



# Typical CO curve from charcoal stove – layers of metal with secondary air

The CO starts out high during ignition, then gets low as the stove heats up (CO<sub>2</sub> increasing). CO starts coming up as the firepower starts to decrease.

Stove started with kerosene drizzled on top of fuel load. Initial spike is kerosene burning. Increasing CO<sub>2</sub> to maximum is from fanning for 4 minutes.

