Welcome to Aprovecho Research Center's Summer Webinar Series!

Charcoal Stove Design

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September 3rd, 2026

Aprovecho Research Center

OSPREY FOUNDATION

Evolving Charcoal Design Principles

1.) Size the combustion chamber for the required task. Charcoal will be burned at a rate proportional to the amount of air made available to it.

2.) Charcoal stoves can have a high turn-down ratio (2026: 4 to 1). If the air supply is reduced close to zero, the fuel will keep burning. When the primary air is increased, the firepower will increase.

3.) Use secondary air jets to burn up the CO. Traditional charcoal stoves have primary air coming in from the bottom of the batch of fuel. The needed oxygen can be consumed as it passes up through the burning charcoal. When air is added above the charcoal, it is available to combust the CO. Try to keep the bottom of the batch of charcoal as cold as possible to regulate the amount of gas into flame.

4.) Create 0.3 seconds of residence time at 772C to combust CO.

Evolving Design Principles

5.) Compared to bowl shaped combustion chambers, cylindrical combustion chambers seem to provide beneficial draft, increased residence time, and reduce the need for fanning when lighting the fuel.

6.) Insulate the combustion chamber until a temperature of 772˚C or higher is achieved above the burning fuel five minutes or less after lighting. Insulation is lightweight and traps still air.

7.) A skirt with 6mm channel gap around the pot increases heat transfer efficiency. Both convection and radiation are important in a charcoal stove.

8.) Radiative heating is highly temperature dependent, and higher view factor is more efficient.

9.) Make the air-tight primary air door large enough to boil the water quickly. The door can be almost airtight to reduce firepower and CO for simmering.

10.) Top lighting seems to reduce CO.

Charcoal background: How charcoal is made

Charcoal is made by burning wood underground with limited air. The wood gas (smoke) escapes and well-made charcoal is the left-over carbon that essentially does not smoke when cooking food. Once lit, charcoal keeps burning, requiring less tending compared to wood. Rural workers make a living selling an improved prepared fuel to urban cooks.

Unfortunately, ~twelve pounds of wood makes only one pound of charcoal! (Urban, et al, 2025)

Charcoal: Lots of wasted fuel

Charcoal is banned or controlled in: Chad, Somalia, Kenya, Uganda, Zambia, Rwanda

- Burning wood instead has the potential to save a lot of biomass.
- For >40 years, efforts have been made to limit charcoal use for cooking in Sub-Saharan Africa.
- Despite these efforts, charcoal remains the dominant urban fuel across the continent, supporting an estimated **195 million primary users** and a massive economy. Gituku, et al, (2021), Njenga, et al, (2016), Sundberg, et al (2020)
- LPG and electricity continue to be too expensive for the majority of households and smokier wood burning stoves are not preferred. Van der Kroon, et al, (2013), IEA, (2024), FAO, (2017)

Should charcoal stoves be illegal?

BURN Manufacturing promotes selling charcoal stoves as a harm-reduction tool during a proposed transition to clean energy. (BURN.com)

While some global campaigns push to eliminate biomass entirely, BURN argues that ignoring current consumer behavior is counterproductive.

Over 1.7 billion people in Africa are estimated to continue to cook with biomass over the next few decades. Gituku, (2021)

Studies also show that even modern charcoal stoves **emit dangerous levels of carbon monoxide (CO)**. Bruce, N., Perez-Padilla, R., & Albalak, R. (WHO Bulletin, 2000)

What policy best serves humanity?

ARC and charcoal: Studying how to improve

- Aprovecho has historically opposed the use of charcoal because cleanly burned wood could theoretically save so much energy.
- At the same time, investigating how to improve cook stoves has included learning about charcoal.
- Let's look at a **literature review**:

What is known about charcoal stoves?

How can they be improved?

Increase thermal efficiency?

Reduce CO?

Reducing Carbon Monoxide: Temperature and Residence Time

- **Thermal Gas-Phase Oxidation (CO to CO_2)**
- In standard combustion chambers the requirements to achieve **>99.5% destruction** of carbon monoxide have been defined:
- **Optimal Temperature: (772°C to 827°C)**. Below 527°C, the post-flame gases become chemically unreactive and combustion of CO ceases.
- **Residence Time: 0.3 to 0.4 seconds** under well-mixed, oxygen-rich conditions.
- **Industrial Incinerators:** Typically operate at **980°C to 1200°C** with an extended residence time of **1.0 to 2.0 seconds**.
- **Fluidized bed combustion:** Keep the temperature at or above **950°C**

U.S. EPA. *Control Techniques for Hazardous Air Pollutant Emissions*. EPA-450/3-91-012.emissions.

Firepower requirements for cooking?

- Masekameni et al. (2016) tested three African charcoal stoves (Zambian, Kenyan Jiko, Madagascar) and measured firepower of 3.1–7.3 kW.
- South Africa has a firepower acceptability threshold of 3–5 kW average.
- Jetter et al. (2012): Charcoal stoves tested were 2kW to 4kW.
- Berger, (2025): Studies in Ghana, Malawi, Kenya found an average of 2.7 +- 1.5 kW firepower.

Must determine firepower before manufacturing stove!

How much can charcoal stoves cost?

1.) "Adoption success depends critically on matching stove technology to local contexts and overcoming cost barriers." Lewis, J. J., & Pattanayak, S. K. (2012). Who adopts improved fuels and cookstoves? A systematic review. *Environmental Health Perspectives*, 120(5), 637–645.

2.) Despite generating fuel savings of $237 over two years, households are only willing to pay $12 for the BURN charcoal stove. (BURN, com.)

3.) In Bangladesh willingness-to-pay for improved biomass cookstoves drops sharply when prices approach $10. Mobarak, A. M., Dwivedi, P., Bailis, R., Hildemann, L., & Miller, G. (2012).

4.) $5–$10 represents the practical limit of out-of-pocket liquidity for traditional stove replacement in low-income rural and peri-urban markets. Jeuland, M. A., & Pattanayak, S. K. (2012).

Baseline Thermal Efficiency?

- Clay-based improved charcoal stoves achieve 25-30% efficiency Ekouedjen, et al (2021)
- Manafa et al. (2025), review of 52 studies (1994–2025): traditional charcoal stoves 11–16% efficiency
- Using Water Boiling Test (IWA) protocols: traditional open-metal charcoal stoves15–20% thermal efficiency. Improved charcoal stoves (ICS) 23–34% and coalpot 23.3% efficiency, Gyapa 30.0% (Obeng, et al., 2017).
- MacCarty et al. (2008) & Jetter et al. (2012) conducted extensive laboratory testing. Basic improved charcoal models 23–35% thermal efficiency range depending on pot materials and thermal insulation.
- Urban et al. (2025) *Environmental Science & Technology* measured 360 charcoal stove tests in Malawi, Ghana, and Kenya: mean 22.1 ± 9.8% for traditional charcoal stoves.

Conduct in field tests to determine fuel savings in project area before manufacturing!

Baseline CO

- Gituku et al. (2021, preprint) compared two insulated Kenyan charcoal stoves with a pellet gasifier: CO EF 20.8–24.4 g/MJd
- Kyuvi, Nyangaya & Aganda (2023, *J Energy Research & Reviews*) Optimised ceramic insulation in Kenyan stoves: CO 21 g/MJd
- MacCarty, N., Still, D., & Ogle, D. (2008) Traditional stoves exhibited high CO emissions at 69.7 g/MJ

Improved and traditional charcoal stoves

ISO Tier 0 CO > 18.3 g/MJ

ISO Tier 1 CO < 18.3 g/MJ

ISO Tier 2 CO < 11.5 g/MJ

ISO Tier 3 CO < 7.2 g/MJ

ISO Tier 4 CO < 4.4 g/MJ

ISO Tier 5 CO < 3.0 g/MJ

Charcoal and PM2.5

- Bailis, Ezzati & Kammen (2003, *Env Sci & Tech*) Africa household PM with charcoal was ~88% lower than open wood fires.
- Kituyi et al. (2004) Kenya: 44–65% fewer ALRI cases than wood users over two years.
- Abera et al. (2019) Africa charcoal 3.3 g/kg vs 37 g/kg for wood.
- Koala, et al., (2023) Traditional charcoal stoves ranged from 1.0 to 3.5 g PM2.5 / kg fuel, compared to 4.0 to 8.0+ g PM2.5 / kg fuel for wood three-stone fires.
- Eriksson et al. (2022, *Indoor Air*) Charcoal was lowest among solid fuels.
- Obeng et al. (2017) Coalpot and Gyapa charcoal stoves emitted PM2.5 four times lower than wood stoves .
- Masekameni et al (2016) PM emission factors of 5.2–7.5 mg/MJ for three improved charcoal stoves, Tier 4.
- Wandara, et al., (2021) Gasifier stoves (PM2.5 52.35-61.50 mg/MJd) and charcoal stoves (40.81-41.13 mg/MJd).

Insulation increases thermal efficiency

- Kyuvi, et al. (2023) Insulation increased efficiency by 28% (from 25.8% to 33%).
- Obeng, et al. (2017) Uninsulated stove 23.3%, insulated charcoal stove 30.1%.
- Bhattacharya, S. C., Albina, D. O., & Salam, P. A. (2002). Useful heat transfer increases significantly with insulating materials.
- L'Orange, C., DeFoort, M., & Willson, B. (2012). Insulation around charcoal fireboxes yields a major gain in thermal efficiency.

Pots and thermal efficiency

Assandé, A., et al. (2025/2026) Pot diameter directly governs thermal efficiency and specific fuel consumption.

•**MacCarty, N., Ogle, D., Still, D., & Bond, T. (2010)** Pot skirts reduce fuel consumption by optimizing channel gaps for convective gas flow.

Bailis, R., Ogle, D., MacCarty, N., & Still, D. (2007). Pot diameter, weight and material effect thermal efficiency in biomass and charcoal stoves.

•**Kshirsagar, M. P., & Kalamkar, V. R. (2014)** Pot dimensions and clearance gaps are dominant factors governing heat transfer efficiency.

Summary of Literature Review

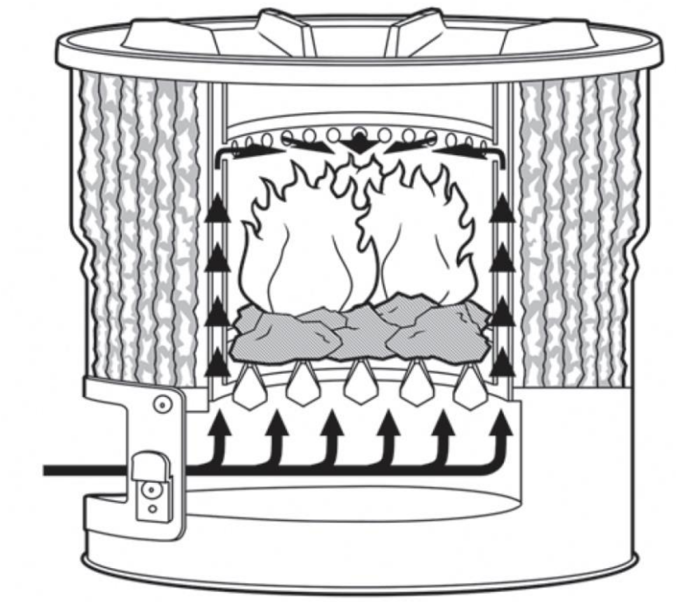
- Is it OK to promote charcoal stoves when ~twelve pounds of wood make one pound of charcoal?
- Yes: Using less charcoal is good. No: Should be illegal now. ARC: Learn to improve stoves, supply decision makers with facts.
- Time and Temperature to combust CO: Minimum of 772C for 0.3 seconds.
- Firepower: South African law is 3–5 kW. Field tests report higher and lower firepowers. FIELD TEST PROTOTYPES LOCALLY BEFORE MANUFACTURING
- Acceptable market cost: Around $12 USD or less. MARKET TEST LOCALLY BEFORE MANUFACTURING
- Thermal Efficiency: traditional 11% to 16%, improved 23–34%. ESTABLISH LOCALLY…
- CO: improved, ~20.8–24.4 g/MJd, traditional ~69.7 g/MJd ISO Tier 0: 18.3g/MJ
- PM2.5: Charcoal stoves emit a lot less PM2.5 than wood stoves.
- Insulation: Increases thermal efficiency ~25% to 30%?
- Pot Size: Bigger pots increase thermal efficiency. Pot skirts help, too.

Can charcoal stoves be improved?

2014 ARC Design Principles

ARC researchers spent four years (2011-2014) experimenting with charcoal stoves and tested many under the emissions hood.

Sam Bentson and Ryan Thompson evolved a Tier 4 (IWA) prototype currently being manufactured.



Prototype Charcoal Stove

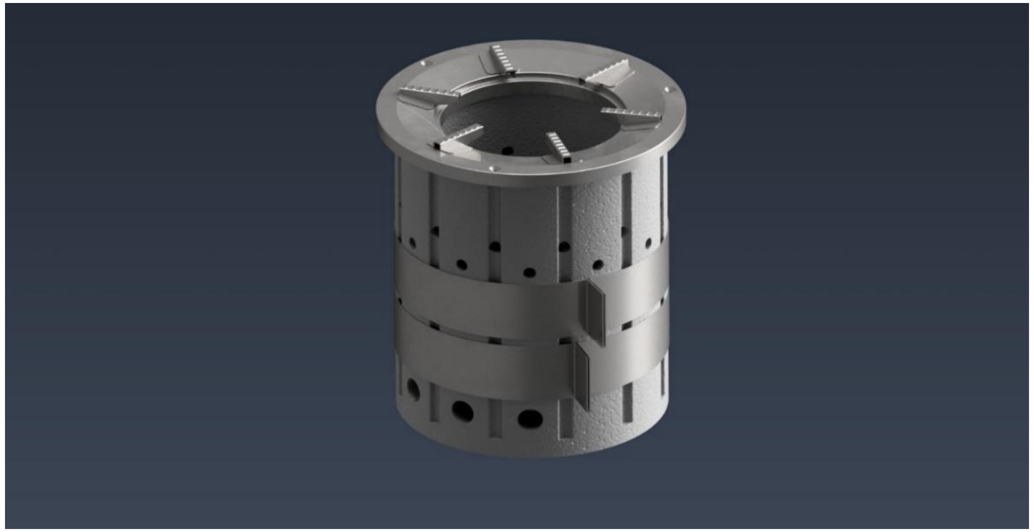
Test Results

Stove type/model Location **IWA Performance Metrics**	**units**	**Charcoal** Average	COV	Average Tier
High Power Thermal Efficiency	%	47.0%	4%	4
Low Power Specific Consumption	MJ/min/L	0.002	10%	4
High Power CO	g/MJ_d	6.35	19%	4
Low Power CO	g/min/L	0.01	11%	4
High Power PM	mg/MJ_d	28.2	54%	4
Low Power PM	mg/min/L	0.01	6%	4
Indoor Emissions CO	g/min	0.41	25%	4
Indoor Emissions PM	mg/min	1.8	58%	4

The 2014 ARC charcoal stove: 1.) Air-tight door controls primary air 2.) Combustion chamber is cylindrical 3.) Pre-heated Secondary air creates a hot zone of mixing above the fuel 4.) Stove is very well insulated which raises temperatures

ARC 2026 Charcoal Stove

$6 SSM Refractory Ceramic Charcoal Stove



1.) Three 1" in diameter primary air holes under a grate = ~4kW. 2.) Combustion chamber: 800C to 900C. 3.) Primary and secondary air holes were closed for lowest power4.) Top Lit like a TLUD.

Number of ISO Test Replicates:	5	Test Sequence Phase				Tier Rating
		High	Medium	Low	Average	
Thermal Efficiency w/o char	%					
Thermal Efficiency w char	%	37.85		77.87	57.86	Tier 5
Fire Power	kW	3.97		1.01	1.03	n/a
PM2.5 per useful energy	mg/ MJ	33.88		13.93	23.90	Tier 4
PM2.5 mass per time	mg/ min	3.06		0.45	1.75	n/a
CO per useful energy	g/M J	2.63		6.16	4.40	Tier 4
CO mass per time	g/mi n	0.24		0.20	0.22	n/a
Time to boil	min	24.3				n/a

2014 and 2026 charcoal stove test results

High power	2026	2014
Thermal Efficiency (%)	37.8	47.0
PM (mg/MJd)	33.9	28.2
CO (g/MJd)	2.63	6.35
Fire power (kW)	4.0	2.3
Time to boil 5L (min)	24.3	30.0
Combustion chamber diameter (cm)	15	12
Combustion chamber height (cm)	19	14
Stove weight (kg)	4.4 as tested (5.3 with body)	5.5

Similar Results

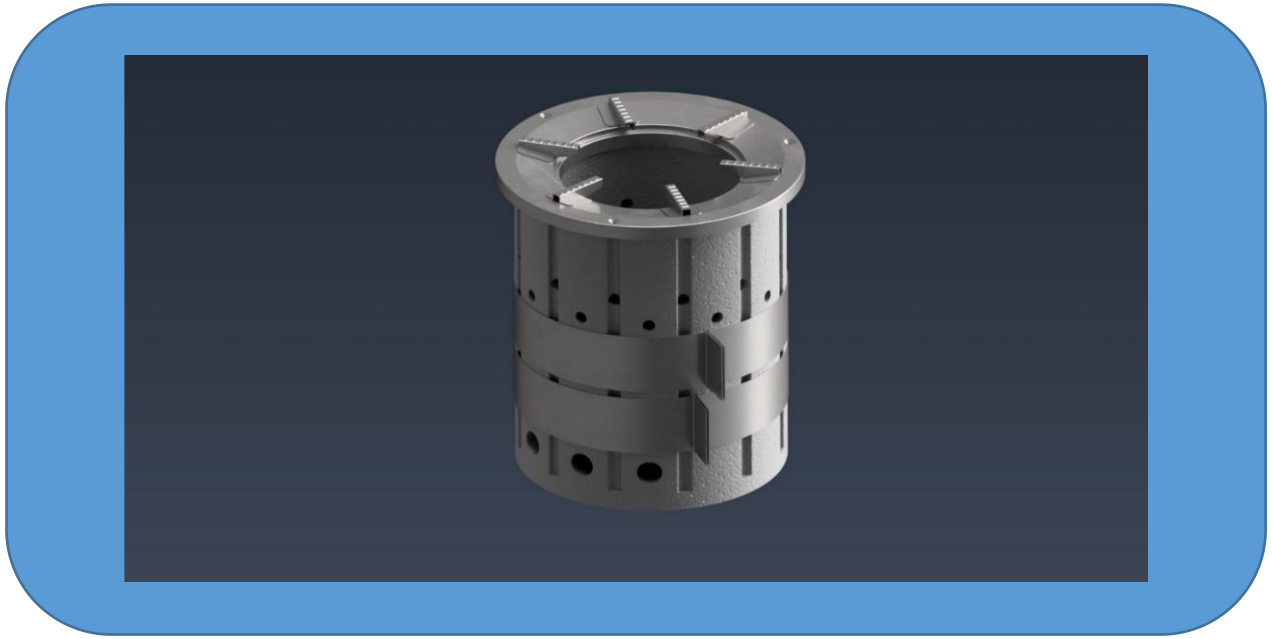
2026 stove tested with ISO 19867-1, 2014 stove tested with IWA 4.2.2, same high power basis

FIELD TESTING BEFORE MANUFACTURING!

- To be useful, a stove needs to meet regional cooking requirements, which vary a lot.
- The high and low firepower and the duration of each phase determines the depth and diameter of the combustion chamber.
- Charcoal is not necessarily the same. Try to demand well-made, Low PM2.5 (no remaining wood) charcoal.
- LMIC market viable stove prices are ~ $12 or lower.
- Before manufacturing, ARC also recommends measuring emissions, Thermal Efficiency, Air Change Hour using prototypes.
- ISO 19867-3 calculates protecting health (Tier 4) by combining emissions rates and Air Change Hour as measured in real life.
- For example, a stove emitting 120mg/mg PM2.5 (Tier 3), in real-life tests, achieves Tier 4 (<62mg/MJ) when Air Change Hour doubles.

Video of 2026 Charcoal Stove

Osprey Foundation has supported development of refractory ceramic stoves (Rocket, charcoal, ND-TLUD) starting with the $2.43 SSM 0.7g/cc (floats on water) combustion chamber.



https://www.youtube.com/watch?v=KdnZjrRbykQ

Questions?

- Thank you!
- And thanks to the Osprey Foundation for supporting this webinar series
- Feel free to reach out: dean@aprovecho.org or sbentson@aprovecho.org