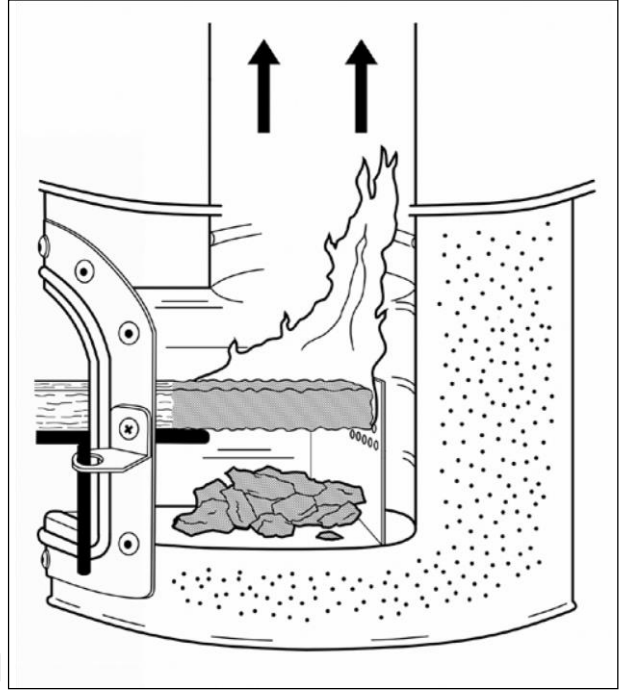
2018 ETHOS:
Clean Biomass Combustion

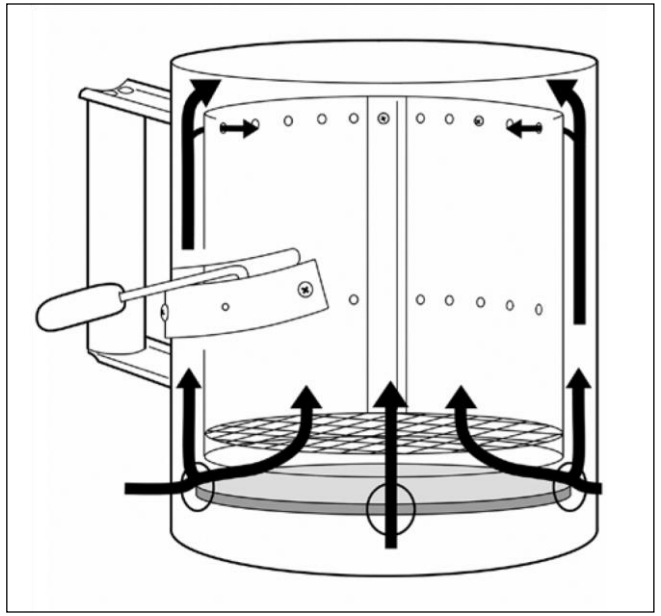
Clean Burning Stoves

1.) Increase heat transfer efficiency to 45% or above: See aprovecho.org
2.) Burn the tips of the wood (8cm)
3.) Increase mixing of gases, fire, smoke
4.) Decrease primary air to control rate of reaction
5.) As little mass as possible and super insulation



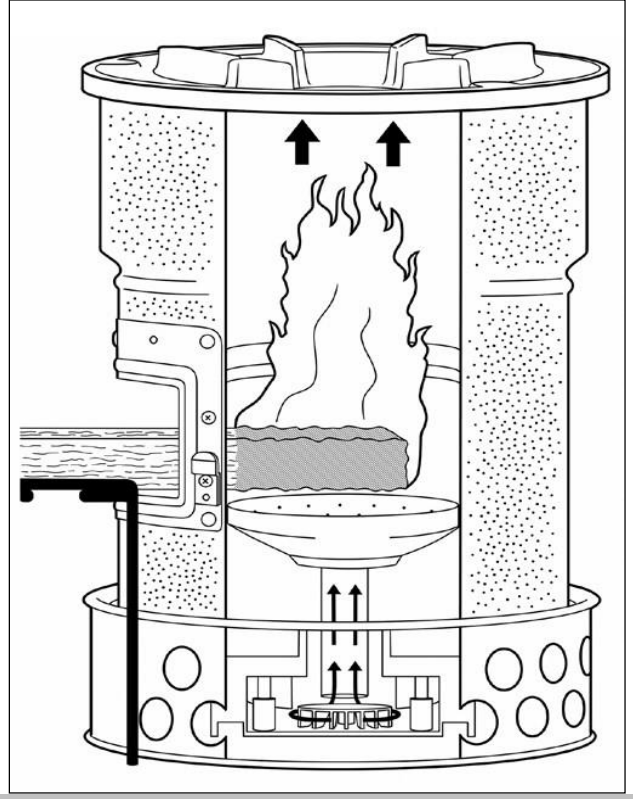
Stove type/model		sunkenpot1		
Location		Average	COV	Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	49.7%	4%	4.0
Low Power Specific Consumption	MJ/min/L	0.020	19%	3.7
High Power CO	g/MJ_d	2.22	38%	4.7
Low Power CO	g/min/L	0.05	42%	4.3
High Power PM	mg/MJ_d	152.2	53%	3.1
Low Power PM	mg/min/L	1.73	58%	3.2
Indoor Emissions CO	g/min	0.25	41%	4.4
Indoor Emissions PM	mg/min	11.8	46%	2.5

If a TLUD smokes reduce the primary air
Charcoal is on top of fresh fuel
Add lots of mixing and swirl
5” in diameter combustion chamber



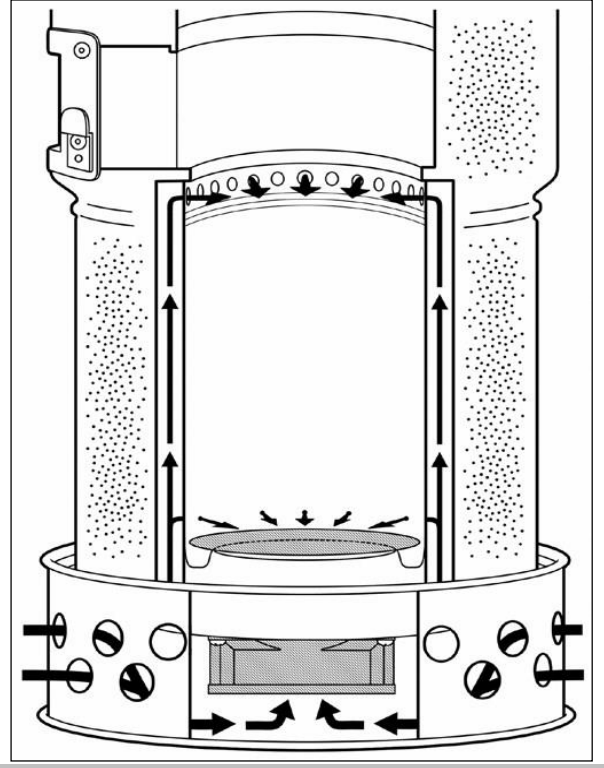
Stove type/model		Wonder Werk Strata		
Location		Average	COV	Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	43.8%	5%	3.8
Low Power Specific Consumption	MJ/min/L	0.018	12%	3.9
High Power CO	g/MJ_d	0.15	34%	4.9
Low Power CO	g/min/L	0.01	37%	4.9
High Power PM	mg/MJ_d	26.4	16%	4.3
Low Power PM	mg/min/L	0.28	57%	4.7
Indoor Emissions CO	g/min	0.05	37%	4.8
Indoor Emissions PM	mg/min	3.6	5%	3.7

1.) Jets from underneath the burning sticks work as well as on top
2.) Burn 8cm of the tips
3.) Adjust the velocity and volume of the jets under the emission hood



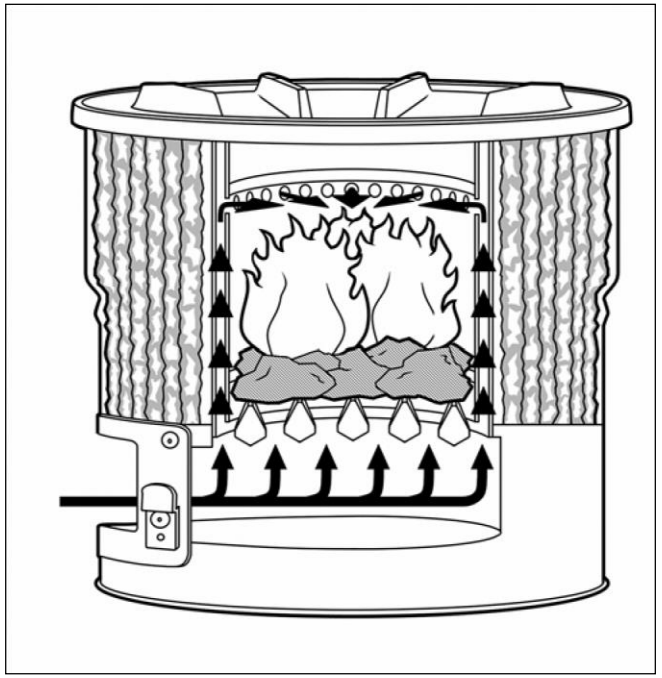
Stove type/model		Side Feed Fan Stove		
Location		Average	COV	Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	47.1%	4%	4.0
Low Power Specific Consumption	MJ/min/L	0.010	8%	4.3
High Power CO	g/MJd	1.76	30%	4.7
Low Power CO	g/min/L	0.01	24%	4.8
High Power PM	mg/MJd	47.2	53%	3.9
Low Power PM	mg/min/L	0.47	48%	4.5
Indoor Emissions CO	g/min	0.16	22%	4.6
Indoor Emissions PM	mg/min	4.5	57%	3.5

1.) Copy Tom Reed's WoodGas stove for size of top and bottom air jets
2.) A fuel door can be added below the stove top
3.) Super insulate the combustion chamber and add more primary air to combust added fuel



Stove type/model		Top Load Fan		
Location		Average	COV	Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	37.8%	3%	3.2
Low Power Specific Consumption	MJ/min/L	0.026	34%	3.1
High Power CO	g/MJ$_d$	0.90	14%	4.8
Low Power CO	g/min/L	0.05	10%	4.4
High Power PM	mg/MJ$_d$	24.7	26%	4.3
Low Power PM	mg/min/L	1.54	24%	3.4
Indoor Emissions CO	g/min	0.15	8%	4.6
Indoor Emissions PM	mg/min	5.0	26%	3.4

1.) Charcoal with no remaining wood doesn't make smoke
2.) Super insulated charcoal stoves with strong jets of secondary air can meet "Tier 4" for CO
3.) 609C is the auto-combustion temperature for CO
4.) Air tight door achieves 10 to 1 turn down ratio



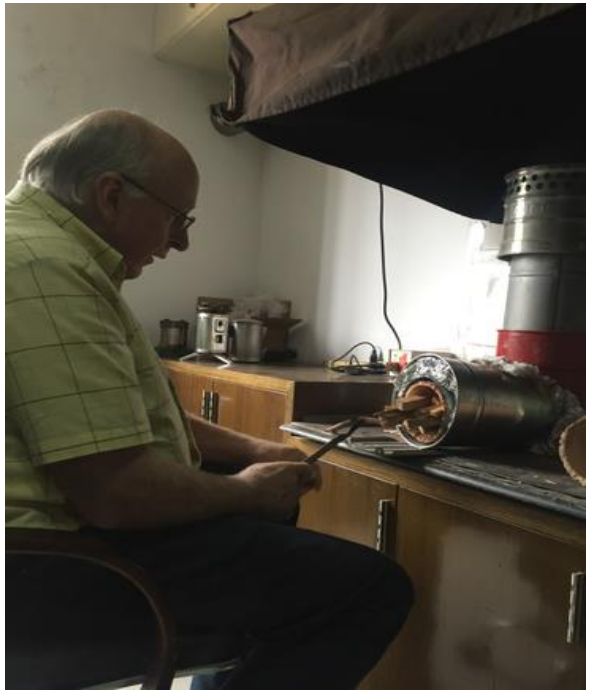
Stove type/model		finalchar1		
Location		Average	COV	Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	47.0%	4%	4.0
Low Power Specific Consumption	MJ/min/L	0.002	10%	4.8
High Power CO	g/MJ$_d$	6.35	19%	4.2
Low Power CO	g/min/L	0.01	11%	4.9
High Power PM	mg/MJ$_d$	33.2	31%	4.1
Low Power PM	mg/min/L	0.01	6%	4.9
Indoor Emissions CO	g/min	0.41	25%	4.0
Indoor Emissions PM	mg/min	2.0	39%	4.0

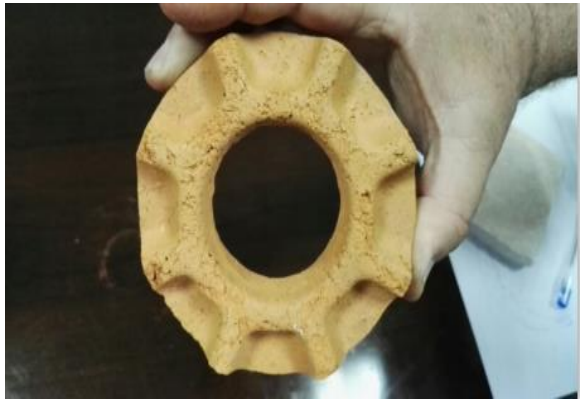
“Tier 4” isn’t all that hard to achieve

In stoves and in life

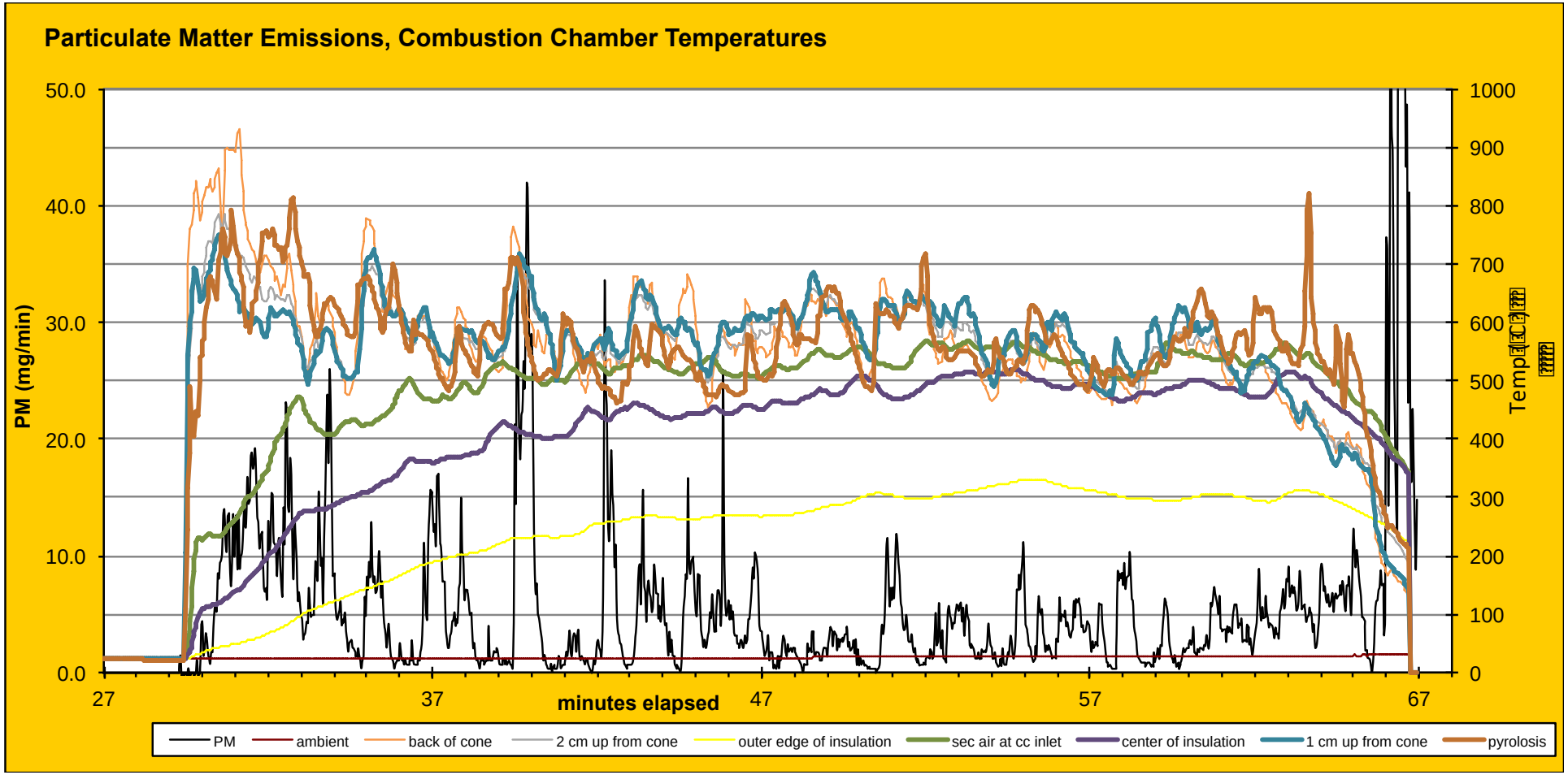
Some stove variations and conjectures

(with help from Kirk Harris and Mr. Shen)





Typical Real Time Data



PM spikes each time the stick fuel is advanced into the stove but PM is reduced when the made charcoal is burning

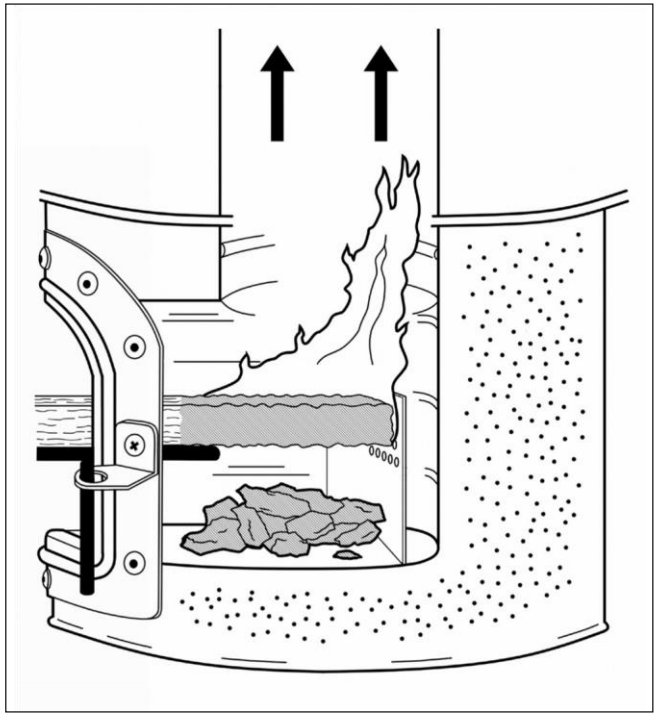
Inside the combustion chamber:

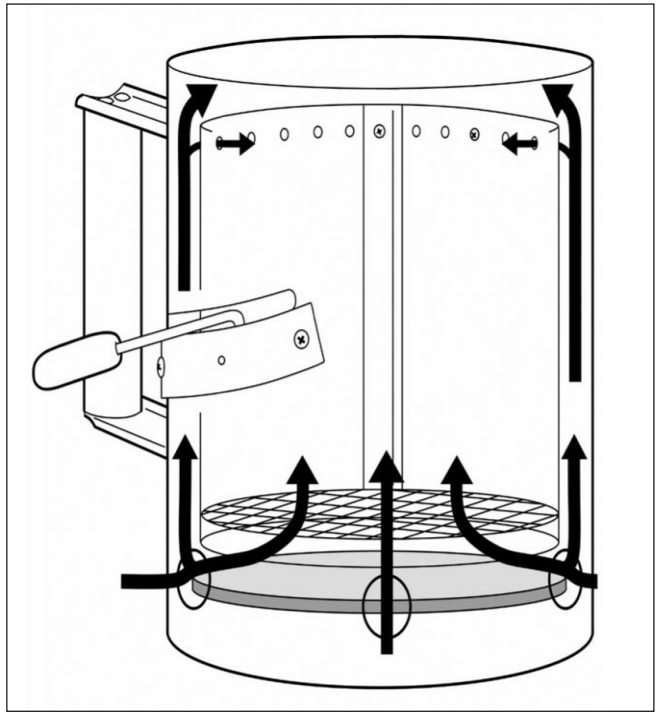
When smoke is being produced try reducing the amount of wood burning while maintaining a temperature above 609C

Control the Rate of Reaction

Reduce the Primary Air

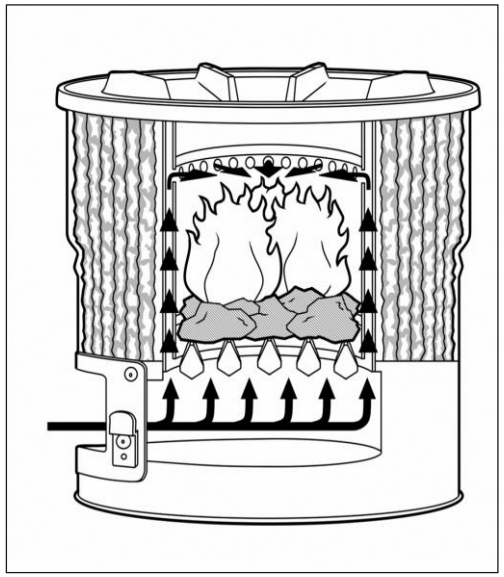
Super Insulate

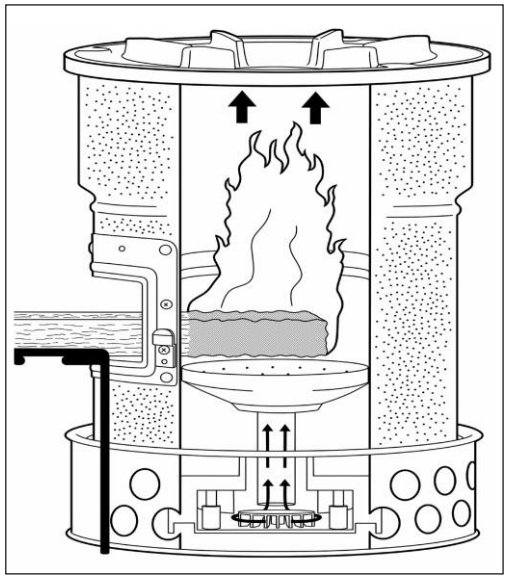


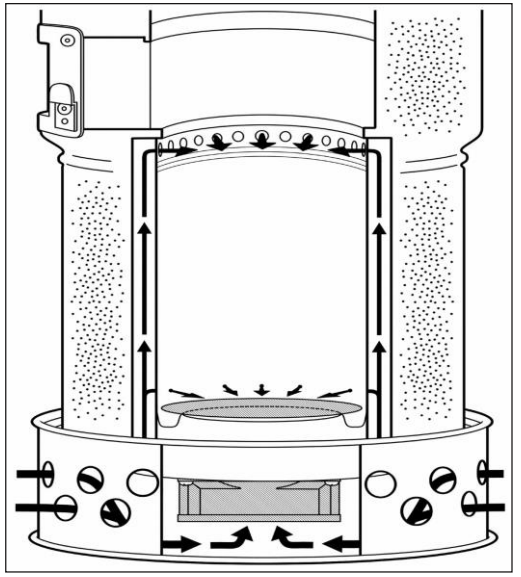


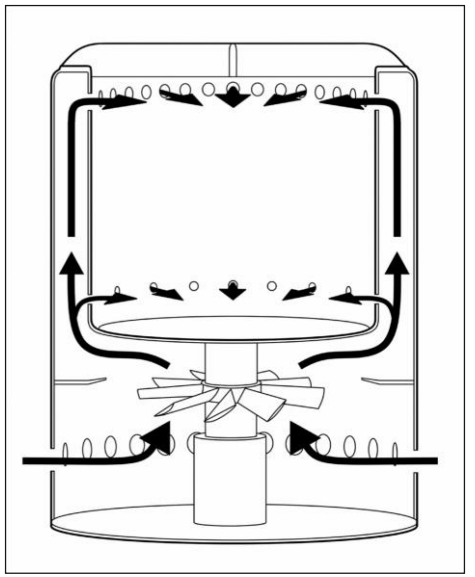
Mixing:

Better mixing of wood gas and air within the flame reduces emissions (forced air)

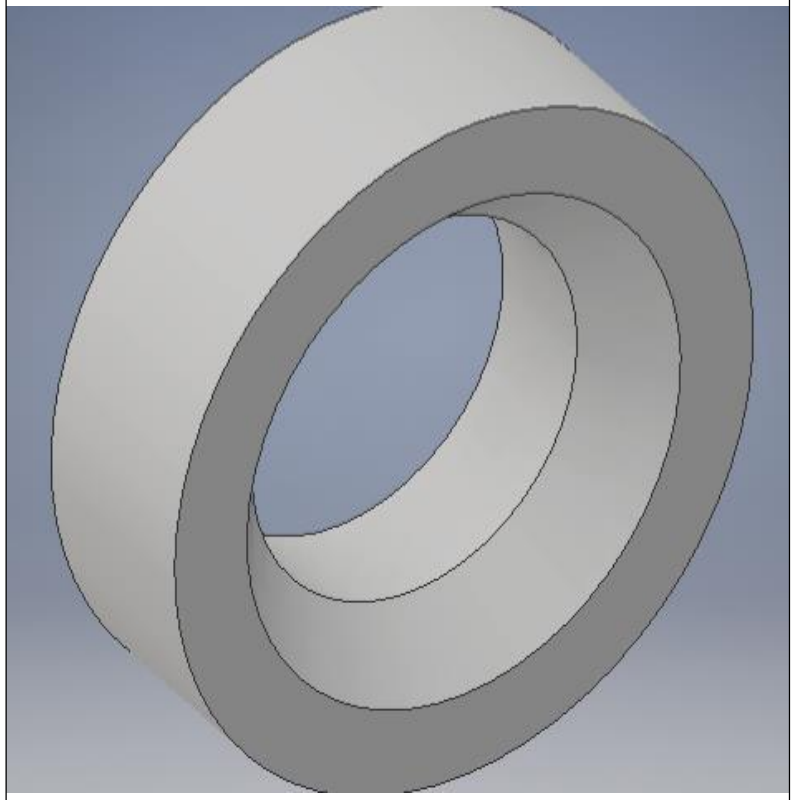




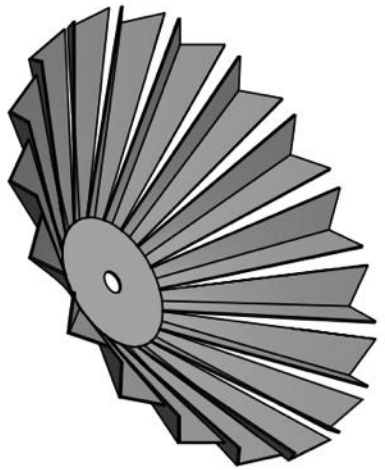




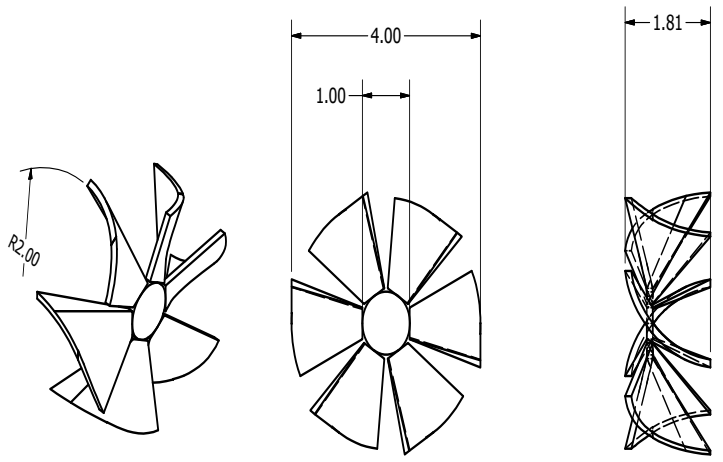
Natural Draft Mixing



2.25” ID orifice



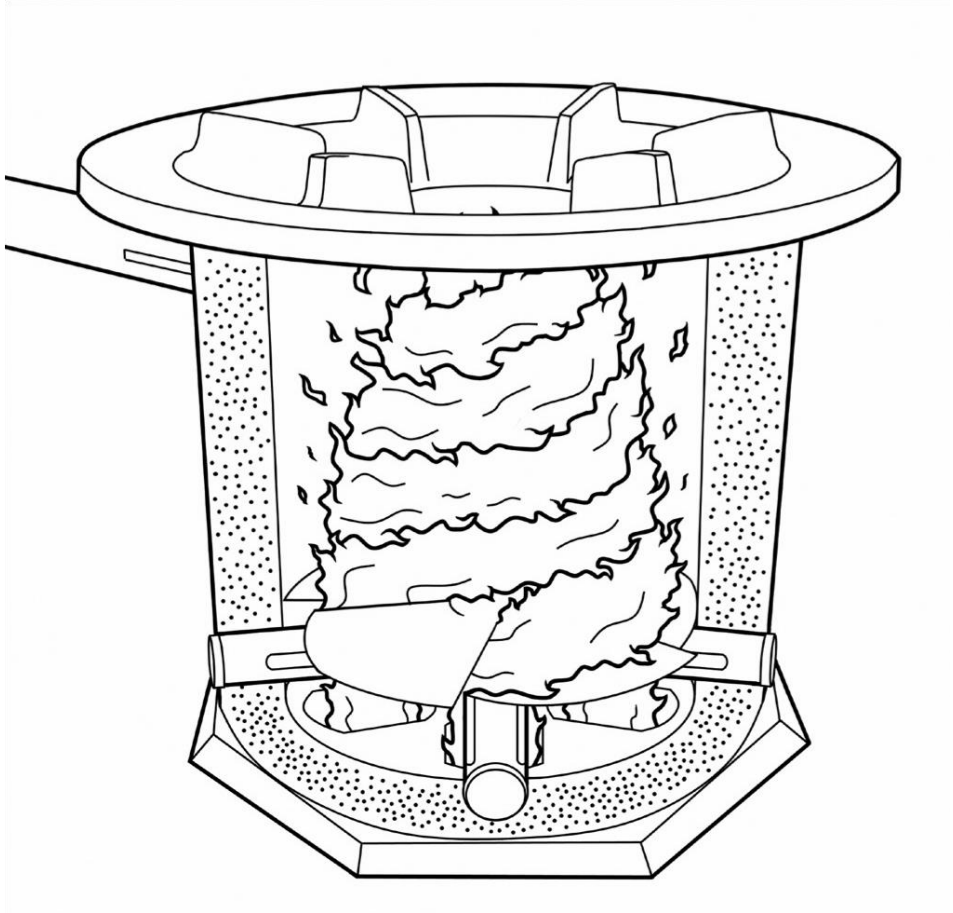
“Umbrella spokes” cut up flame



Stationary fan

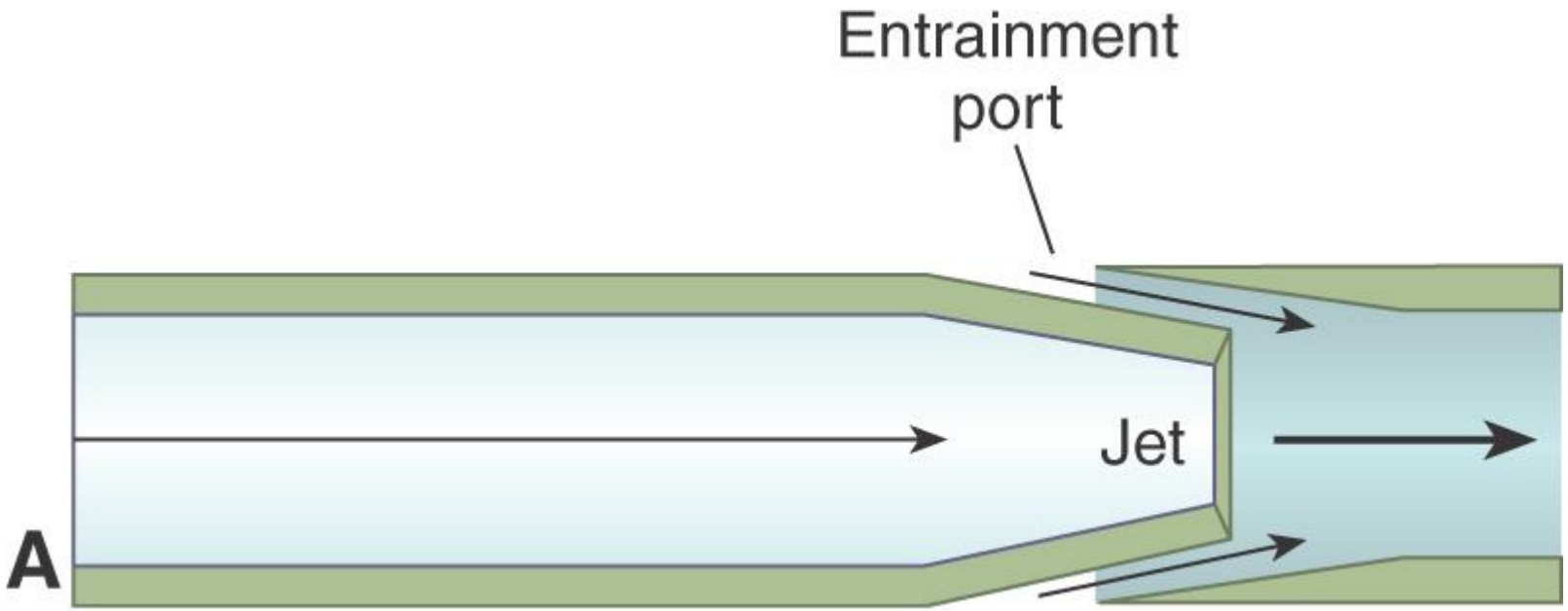
Dwell time

Providing the well mixed flame with sufficient time for more complete combustion to occur reduces emissions

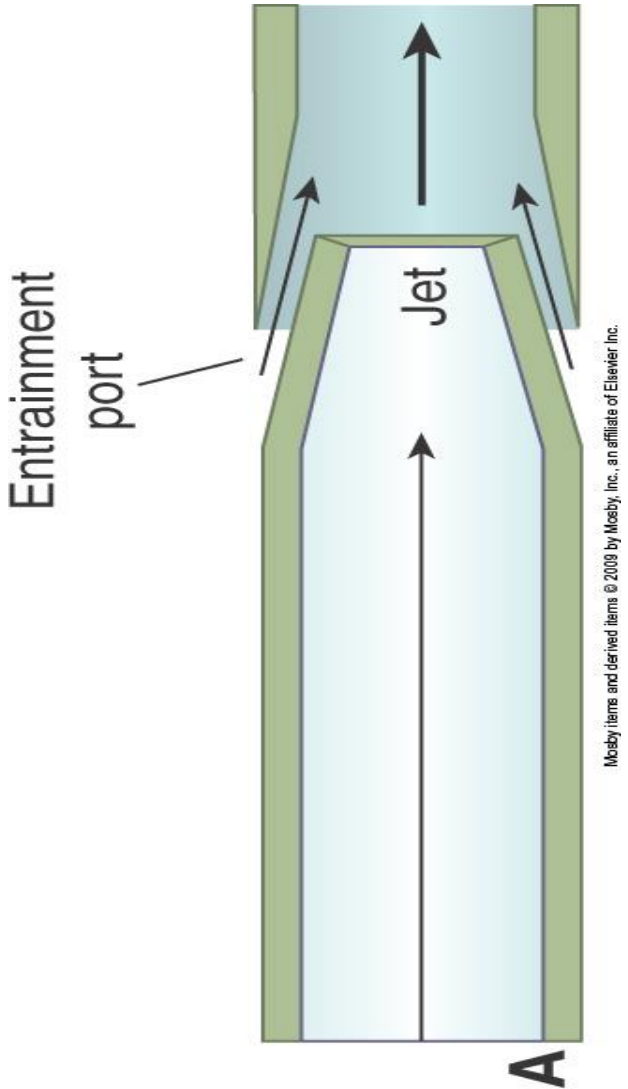


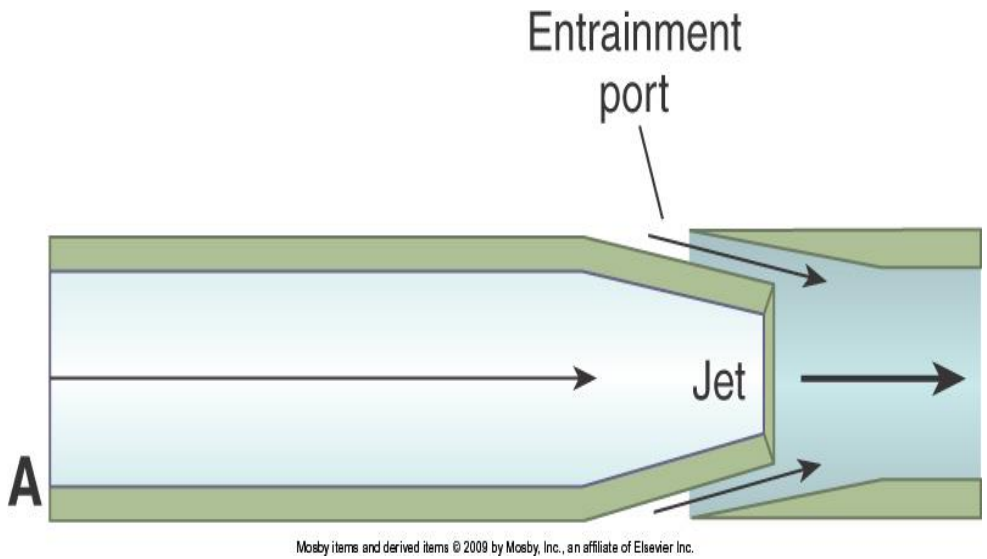
Pressure Difference

When the pressure difference between the flame and the secondary air is greatest mixing may be more effective



Vertical and horizontal “TLUD” type combustion chambers
seem to operate with some similar characteristics





Horizontal “TLUD” combustion chamber

Batch loaded sticks burn back by themselves

Rocket stove with horizontal “TLUD” combustion chamber

Mixing by fan and orifice. Secondary air is introduced downstream of the orifice.

Preliminary Horizontal “TLUD”/Rocket Results

Stove type/model		ceramic hybrid 1	ceramic hybrid 3	ceramic hybrid 4	ceramic hybrid 5
Test Conditions		Uninsulated feed tube, loose fuel pack	Insulated feed tube, tight fuel pack	Insulated feed tube, tight fuel pack	Insulated feed tube, tight fuel pack
Location		apro	apro	apro	apro
Wood species		df sticks	df sticks	df sticks	dfsticks
Date		12.14.17	12.19.17	12.20.17	12.20.17
IWA Performance Metrics	units	Value	Value	Value	Value
High Power Thermal Efficiency	%	34.2%	36.8%	36.4%	37.3%
High Power CO	g/MJ_d	2.19	1.57	4.26	0.96
High Power PM	mg/MJ_d	124.2	68.4	47.5	52.4
Indoor Emissions CO	g/min	0.20	0.15	0.46	0.11
Indoor Emissions PM	mg/min	11.4	6.6	5.1	5.8
		Tier	Tier	Tier	Tier
High Power Thermal Efficiency		2.9	3.1	3.1	3.2
High Power CO		4.7	4.8	4.4	4.8
High Power PM		3.3	3.7	3.9	3.9
Indoor Emissions CO		4.5	4.6	3.4	4.7
Indoor Emissions PM		2.6	3.2	3.4	3.3
Basic Operation					
COLD START					
Temp-Corrected Time to Boil	min	17.0	21.0	20.0	19.0
Firepower	watts	4,470	4,367	4,918	4,936

Optimizing by Testing!