DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review

Technology Innovations to Improve Biomass Cookstoves to Meet Tier 4 Standards

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Goal Statement

- The goal is to create biomass cookstoves that meet the IWA/ISO Tier 4 standards designed to use the least fuel, protect human health, and address climate change. The biomass industry is strengthened by working models that have close to optimal combustion and heat transfer efficiency.
- The relevant and tangible outcomes include methods for the clean burning of biomass, an abundant and sustainable energy source in the United states.
- USA companies benefit from export sales.

Quad Chart Overview

Timeline

- Project start date October 1, 2013
- Project end date September 30, 2015
- Percent complete 69%

Budget

	Total Costs FY 10 –FY 12	FY 13 Costs	FY 14 Costs	Total Planned Funding (FY 15-Project End Date
DOE Funded	$0.00	$74,718.00	$336,986.00	$514,593.00
Project Cost Share (Comp.)*	N/A	$0.00	$83,333.00	83,333.00

Barriers

- Barriers addressed
  - Achieving Tier 4 performance
  - Gaining consumer acceptance of new stove designs
  - Working with manufacture to produce stoves at acceptable price points

Partners

Partners

- Stovetec Inc. (20%)
- BUCT (20%)

Other interactions/collaborations:

U.S. EPA

- Colorado State University
- Lawrence Berkeley National Laboratory

Project Overview

- Three WBT surveys of 22 cleanest burning stoves were conducted under the emissions hood.
- Primary Air Stove, Tom Reed Forced Air Stove, Chinese Forced Air Stove, TLUD, Large Pot Rockets and a Charcoal Stove scored well on several IWA/ISO measures.
- Based on these clean combustion techniques, ARC developed six prototypes that achieve “Tier 4”.
- BUCT developed a “Tier 4” stove for the Chinese National Stove Project.
- ARC demonstrated five “Tier 4” prototypes to consumers in Peru, China, Senegal, Kenya, Nepal, and India. BUCT demonstrated one stove in China.
- Responding to consumer input the prototypes are being rebuilt for a 2nd round of consumer responses.
- The continued R&D includes extensive work with Shengzhou Stove Manufacturer, the largest coal cookstove manufacturer in China.
- The goal is to sell one million “Tier 4” stoves/year that are designed by ARC, manufactured by SSM, and sold in developing world markets by a USA based international retailer.
- The stoves are intended to achieve “Tier 4” when in use.

Approach (Technical)

- Three extensive surveys identified existing successful stoves. Lab based R&D resulted in improvement to “Tier 4”. Iterative development was based on experiments and modelling. Better models exist for heat transfer efficiency (MacCarty, ISU). Success was measured by achieving “Tier 4” using the WBT 4.2.3 and the IWA/ISO metrics. There were an average of over 100 iterations per stove.
- Natural Draft Rocket stove: Metered combustion.
- Natural Draft TLUD: Top lit, gases into flame.
- Forced Air Side Feed: Jets of primary air. No secondary air.
- Forced Air Top Loaded: Secondary air and complete mixing.
- Charcoal Stove: Low PM fuel and higher temperatures reduce CO.
- Chinese Stove: Only high power (12Kw).

<u>Challenges:</u>

1.) Super clean combustion requires good fuel. Does the fuel need to be supplied with the stove?

2.) New ceramic refractory materials needed to lower cost.

3.) WHO indoor air unvented guidelines are exceptionally low (PM 1.75 mg/min).

Approach (Management)

- Working closely with consumers and Shengzhou Stove Manufacturer market driven products are emerging.
- “Tier 4” technology needs to be packaged in market driven stoves: affordable (less than $20 retail), cooks better than available stoves, to be purchased in local outlets. R&D, manufacturer, distributor, retailer have to make profit and expand. (ARC, SSM, USA based international chain stores)

Challenges:

- 1.) Identify markets: ARC went to Peru, China (BUCT), Senegal, Kenya, Nepal, India.
- 2.) Lower cost: Work with manufacturer & develop new materials.
- 3.) Continuing response to market requirements

Approach:

1.) USA based international chain store sells stove(s)

2.) Mega stores provide poor with superior, more affordable products

3.) Cost reductions occur at scale (1M/year)

What is “Tier 4”? Multi Dimensional Metrics from IWA/ISO.

1 HTE 4 High Power Thermal Efficiency ≥ 45 (%)	2 LSC 4 Low Power Specific Consumption Rate ≤ 0.017 (MJ/min/L)	3 S 4 Safety ≥ 95
4 HPM 4 High Power PM ≤ 41 (mg/MJd)	5 LPM 4 Low Power PM ≤ 1 (mg/min/L)	6 IPM 4 Indoor Emissions PM ≤ 2 (mg/min)
7 HCO 4 High Power CO ≤ 8 (g/MJd)	8 LCO 4 Low Power CO ≤ 0.09 (g/min/L)	9 ICO 4 Indoor Emissions CO ≤ 0.42 (g/min)

New WHO indoor air quality guidelines: household fuel combustion (2015)

PM 2.5 EMISSIONS

The intermediate WHO PM2.5 guideline is: **1.75mg/min** for *unvented stoves*.

The intermediate WHO PM2.5 guideline is: **7.1 mg/min** for *vented stoves.*

CO EMISSIONS

The intermediate WHO CO guideline is: **0.35g/min** for *unvented stoves*.

The intermediate WHO CO guideline is: **1.45g/min** for *vented stoves*.

IWA Tier 4 standards

The Indoor Emissions of PM have to be **below 2mg/min.**
The Indoor Emissions of CO have to be **below .42 g/min.**

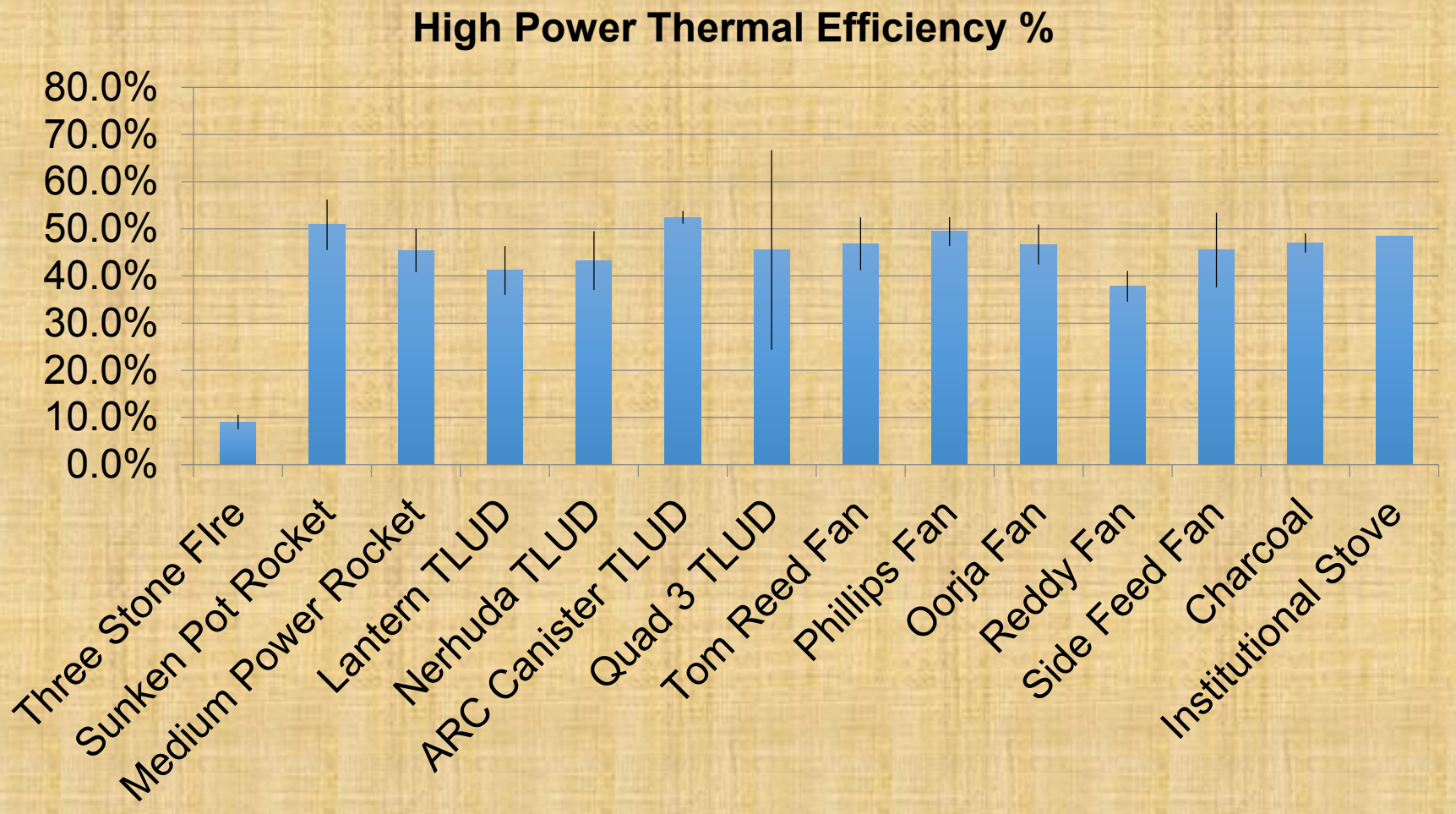
The WHO/IWA unvented PM standard is difficult **1.75mg/min** & **2mg/min**

However, vented PM is achievable (in lab) **7.1 mg/min**

The WHO/IWA guideline for even unvented CO is 'easy' **0.35g/min**

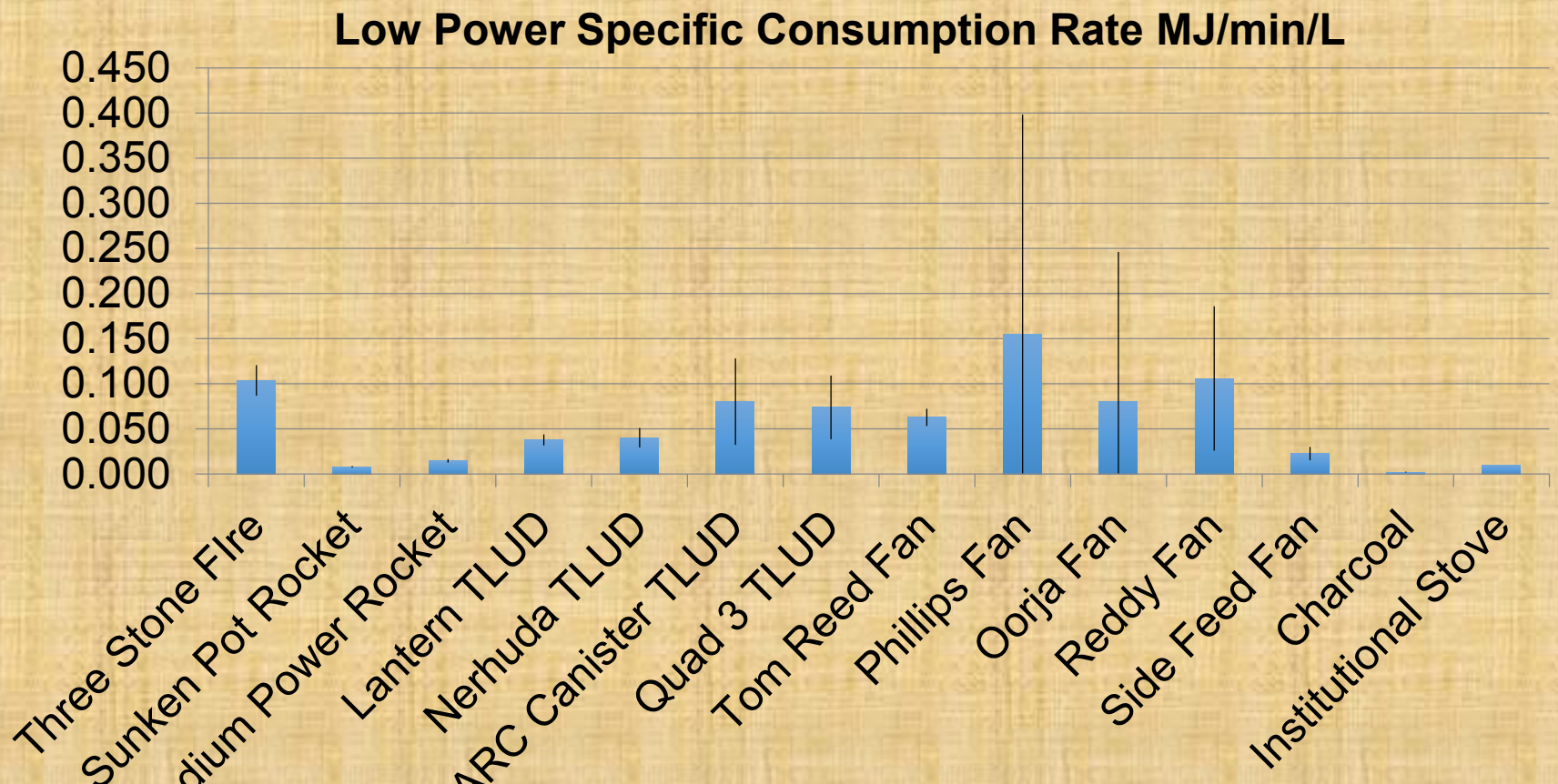
Technical Accomplishments

Stove Survey
Tier 4: over 45%



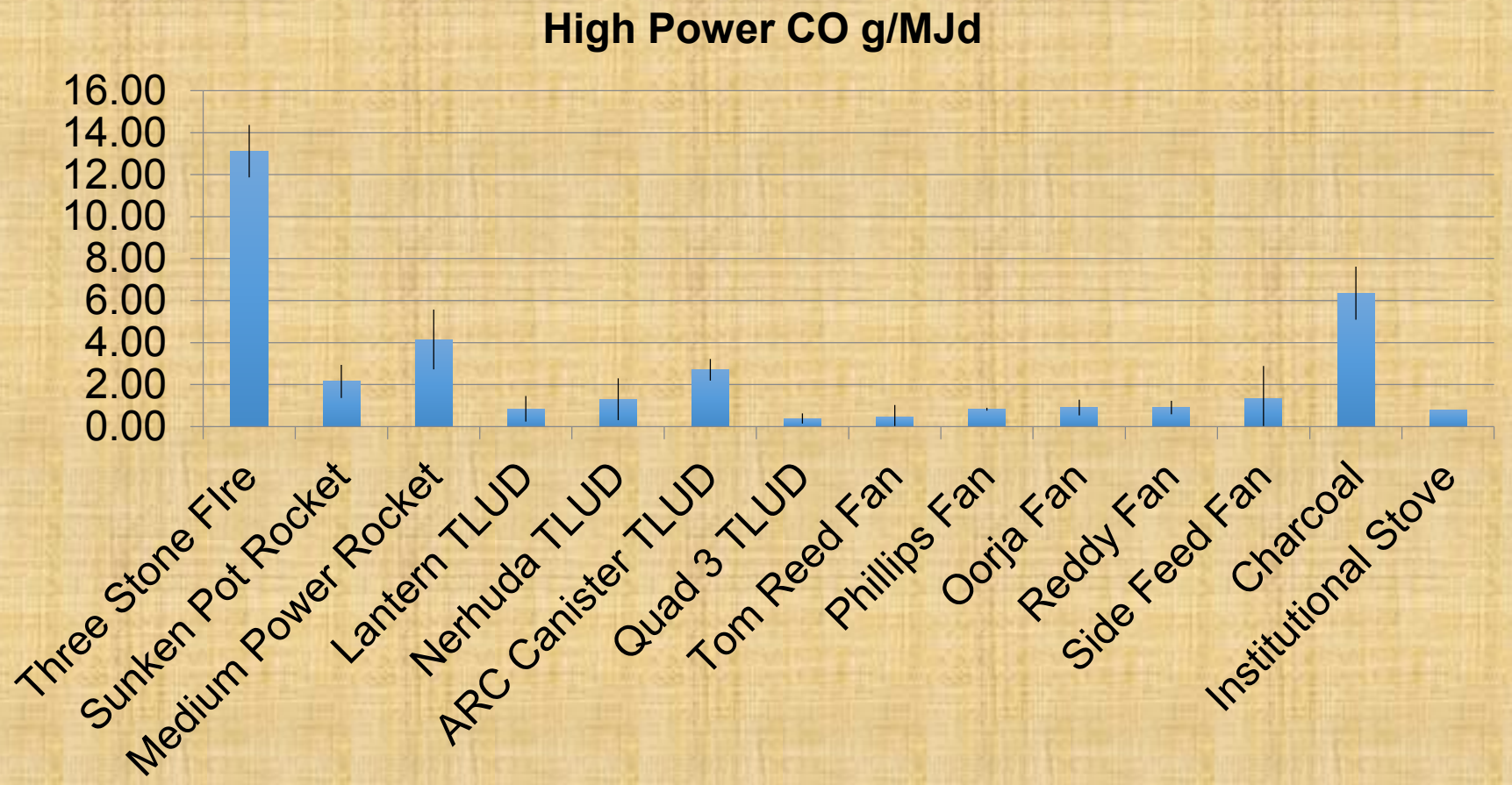
Technical Accomplishments

Stove Survey
Tier 4: less than 0.017 (MJ/min/L)



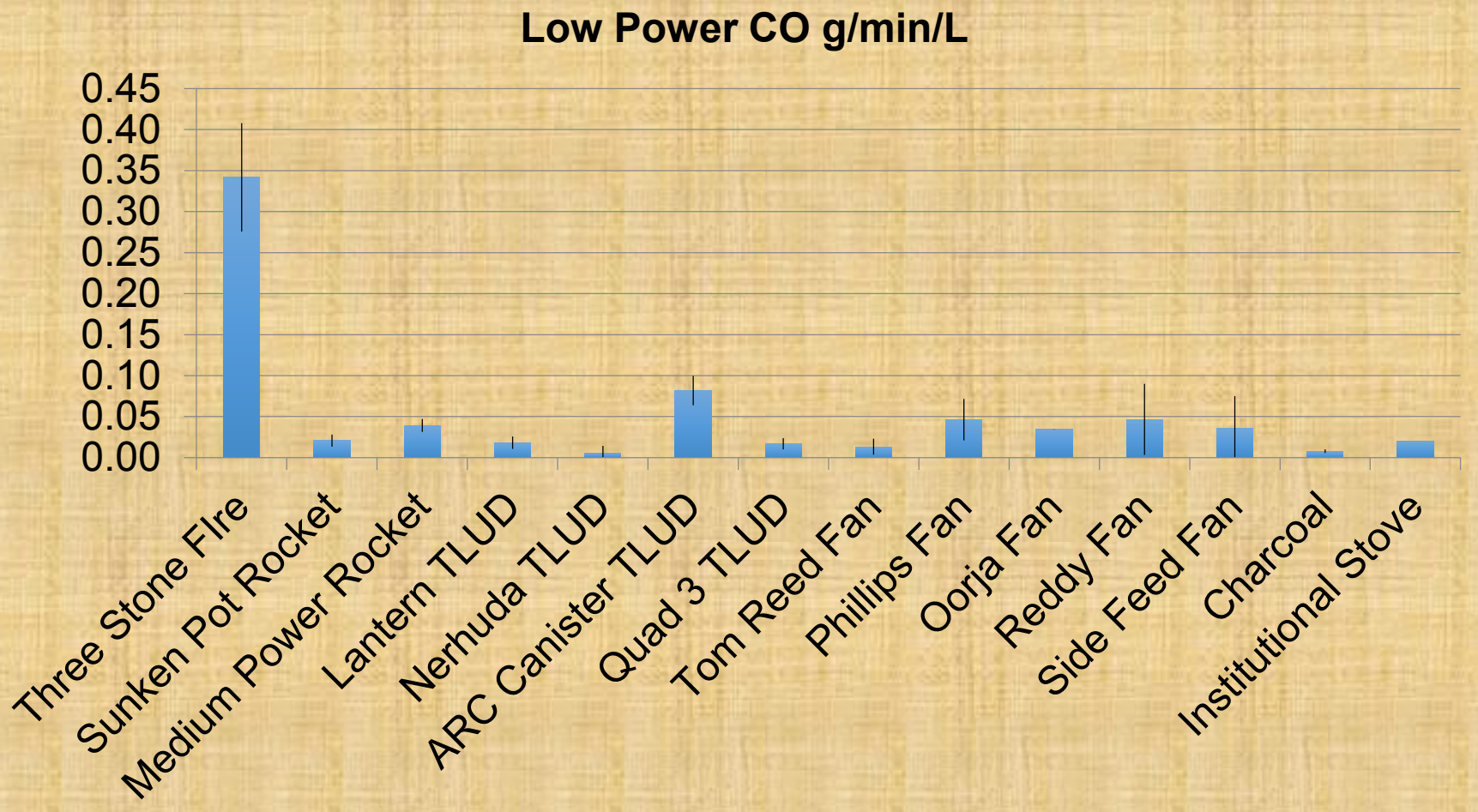
Technical Accomplishments

Stove Survey
Tier 4: less than 8 (g/MJd)



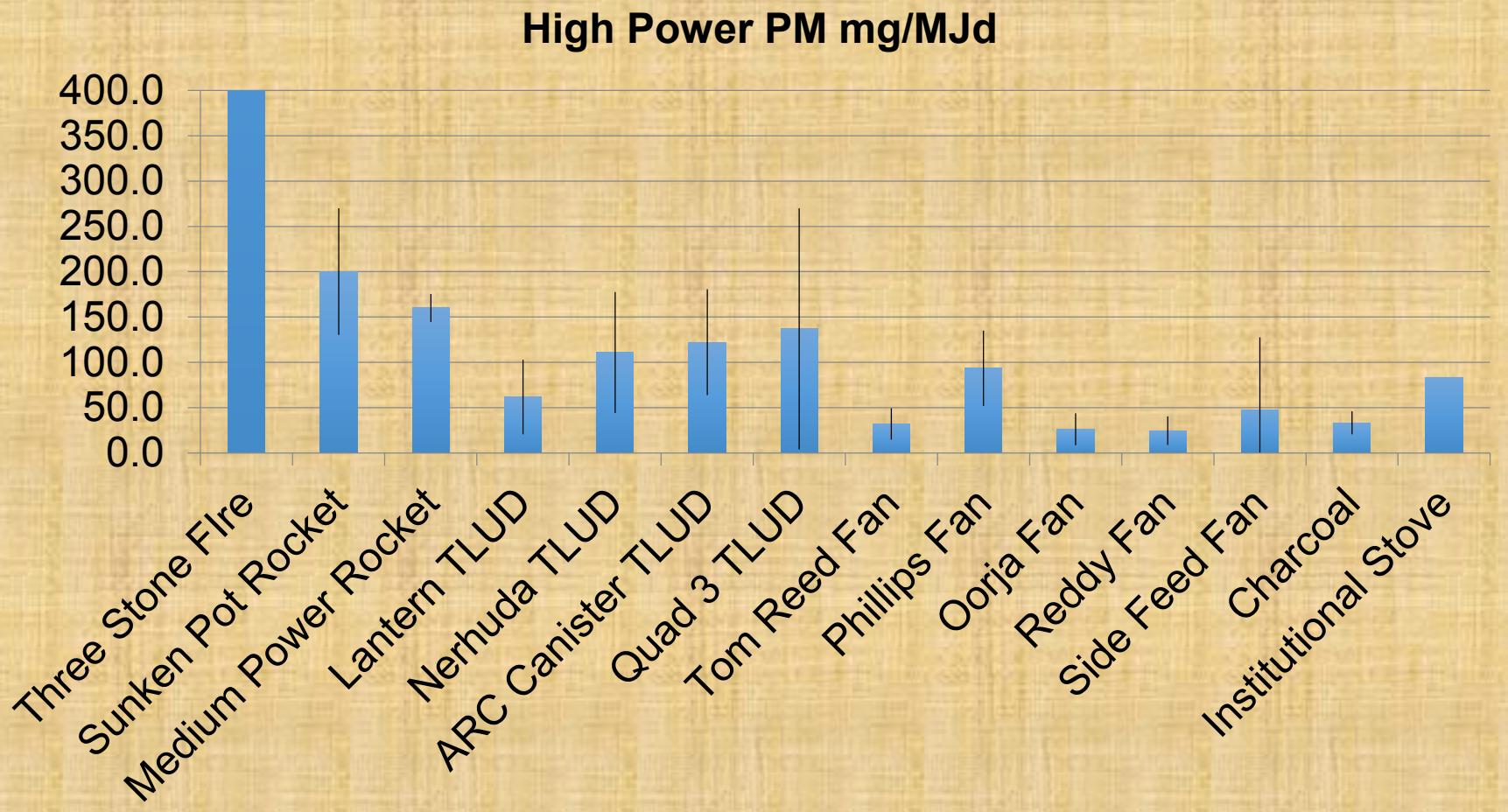
Technical Accomplishments

Stove Survey
Tier 4: less than 0.09 (g/min/L)



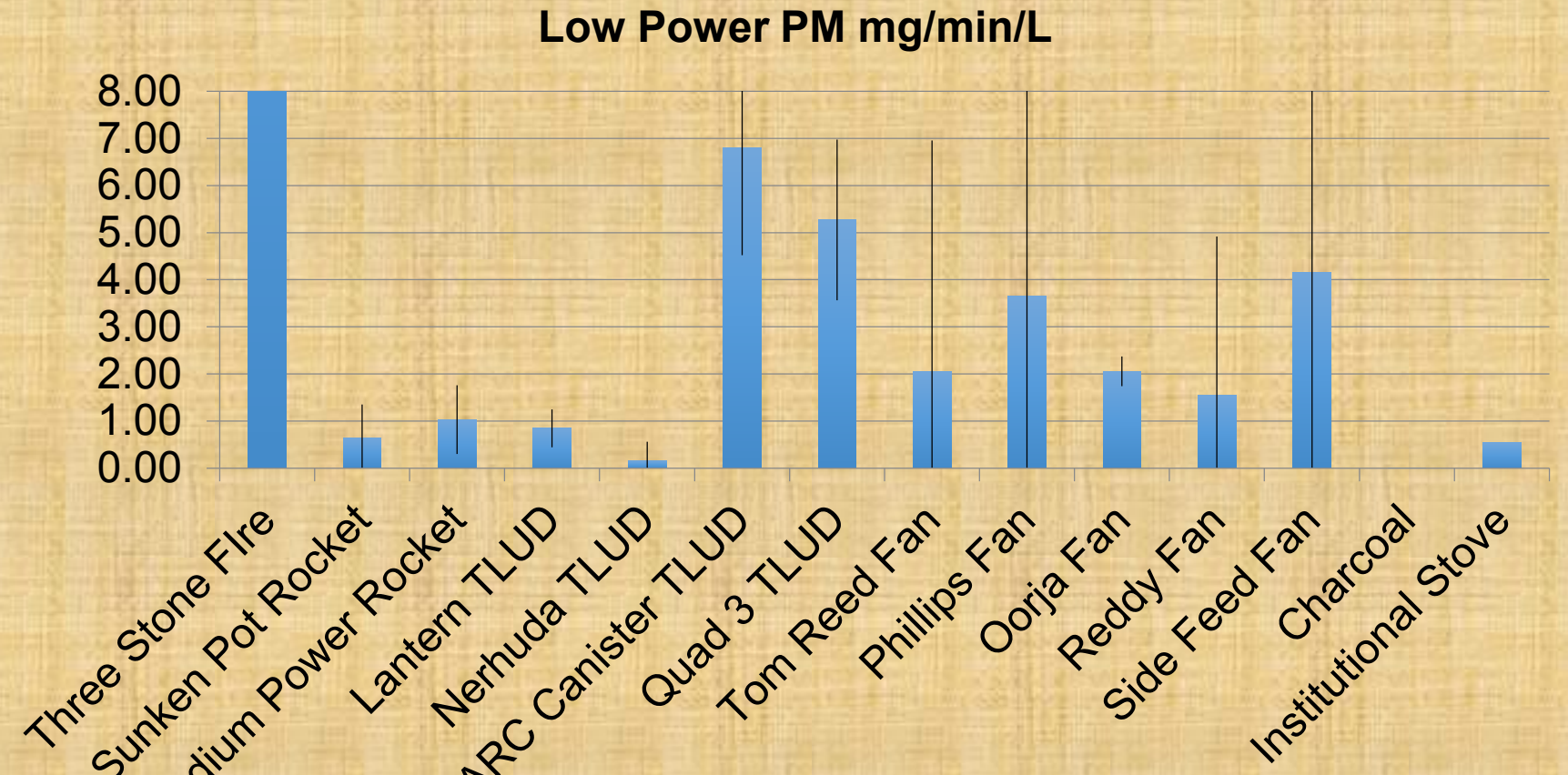
Technical Accomplishments

Stove Survey
Tier 4: less than 41 (mg/MJd)



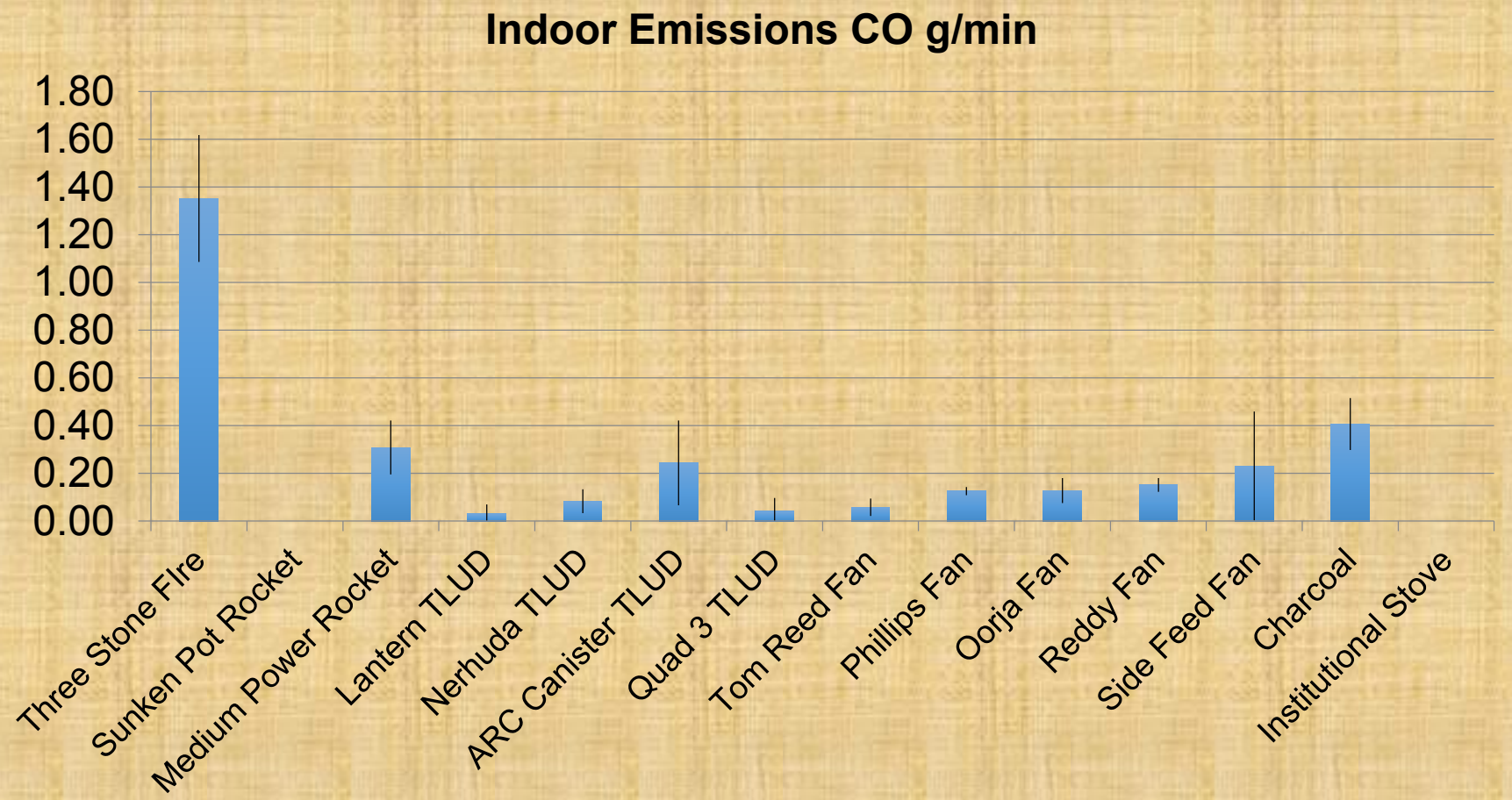
Technical Accomplishments

Stove Survey
Tier 4: less than 1 (mg/min/L)



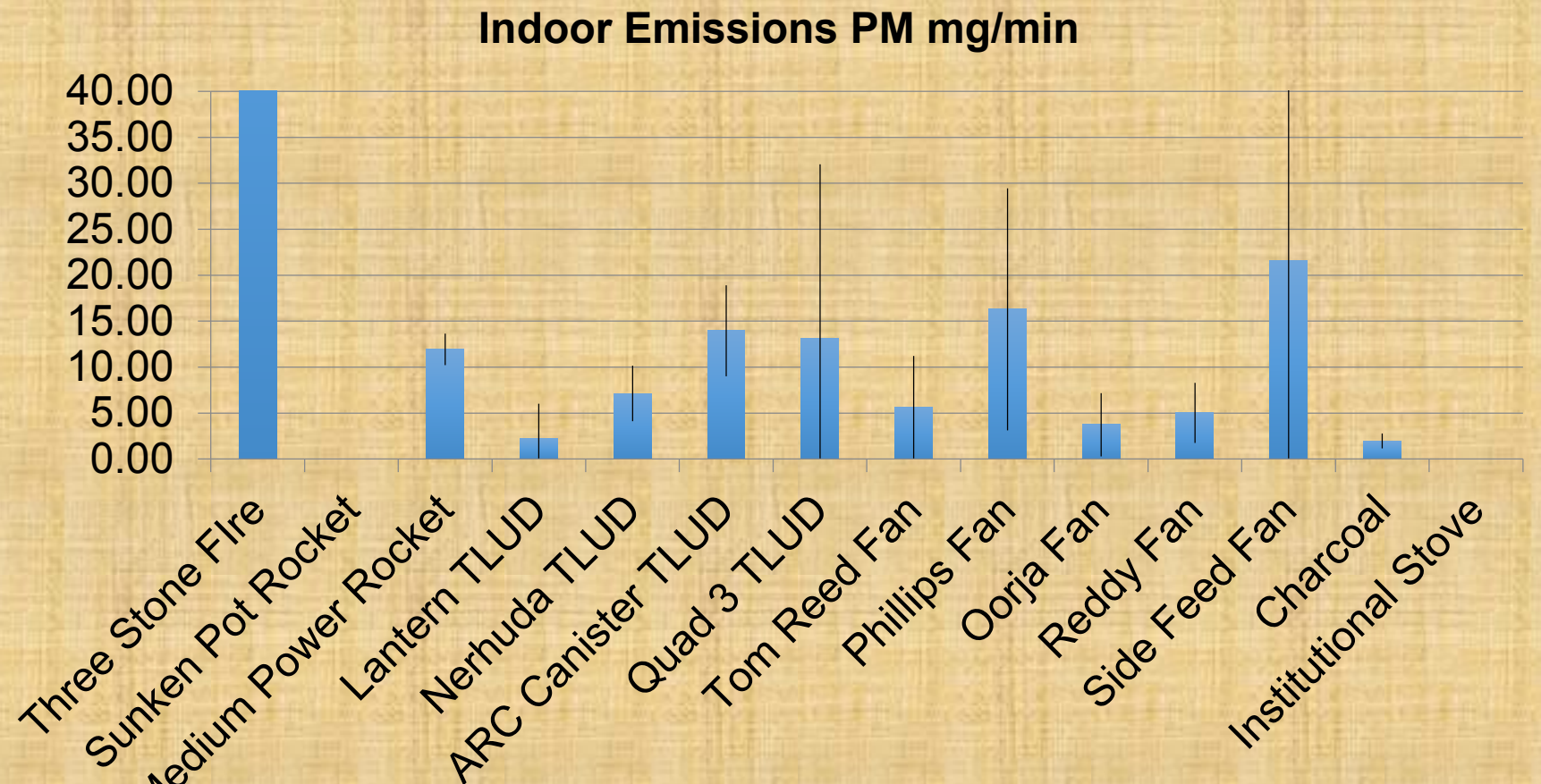
Technical Accomplishments

Stove Survey
Tier 4: less than 0.42 (g/min)



Technical Accomplishments

Stove Survey
Tier 4: less than 2 (mg/min)



Technical Accomplishments

Improved “Tier 4” Biomass Cookstoves
Move Towards Manufacturing and Sales

Aprovecho Wood Stoves that Pass WHO Intermediate Emissions Rate Targets for Air Quality Guideline IT-1				
Stove	PM2.5 Vented (7.15 mg/min)	PM2.5 Unvented (1.75 mg/min)	CO Vented (1.45 g/min)	CO Unvented (0.35 g/min)
TLUD				
Top Load Fan				
Side Feed Fan				
Natural Draft Sunken Pot Rocket				

- All stoves passed CO vented and unvented WHO standards
- No stoves passed PM2.5 unvented standards
- All but one stove passed PM2.5 vented standards

Sunken Pot Rocket

New combustion chamber.
New insulation.
Improved heat transfer.
Chimney addresses Indoor Emissions.

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

Sunken Pot Natural Draft Rocket with Chimney

- Combustion chamber has decreased depth allowing only 10cm of the tips of wood sticks to burn. *(improved combustion efficiency)*
- 2.5Kw firepower combined with 7mm channel gap and 9 liters of water results in higher IWA scores. *(Interesting to identify best combination)*
- Sunken pot technique has hot gases flowing up inside skirt and then down the outside of the skirt exiting below the pot and up the chimney*. (Better HTE)*
- Adding a tall chimney increases velocity in combustion chamber (Improves HTE) and decreases the made charcoal. *(Less clogging)*
- Sunken pot technique seals the pot sending almost 100% of smoke/gas out of the kitchen. WHO guidelines based on 75% removal.
- WHO PM indoor air vented stove guideline is 7.1 mg/min. Adding forced air to this stove lowers PM to meet the WHO vented standard in lab tests.

Top Lit Up Draft

5kW high power.
1.5Kw low power.
High velocity swirl reduces emissions.

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

Top Lit Up Draft

- The natural draft TLUD has a lever controlling primary air. High power is 5Kw and low power is 1.7Kw. *(Best TDR)*
- A plate seals the bottom of the combustion chamber or allows controlled amounts of air to enter*. (Primary air can control firepower and be clean at high and low power)*
- Flame enters a secondary chamber placed above the combustion chamber. *(Clean technique in a TLUD)*
- Stationary blades induce active swirl in the flame*. (Alternate, hotter technique)*
- The blades replace the usual metal plate with a hole in the center seen in many TLUDs. *(Creates mixing and time for combustion in flame)*
- The hole with a plate reduces firepower but the swirl inducing chamber is clean burning at 5Kw. *(A high firepower, clean TLUD)*
- The TLUD has sufficient TDR to score well on IWA measures based on Specific Consumption. *(Need good TDR to score well)*

Side Feed Forced Air

Uses sticks/ found fuel.
Very high velocity jets of primary air reduce emissions.
Regulate air for high/low power.

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/MJ_d	1.76	30%	4.7
Low Power CO	g/min/L	0.01	24%	4.8
High Power PM	mg/MJ_d	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

Side Feed Forced Air

- Side Feed uses sticks of wood like a three stone fire. *(Normal operation)*
- A fan pushes very forceful jets of air through 1/32” holes in the metal floor of the combustion chamber. *Described in ARC publication "Test Results of Cookstove Performance” (2014) EPA.*
- The flame does not tend to exit from the open door. *(Air, flame go up to pot)*
- A relatively short 8” Rocket type ‘chimney’ above the fire provides enough time for almost complete combustion. *(Determined needed length)*
- Higher velocity jets reduce emissions of CO and PM, increase HTE. *(Fast to boil)*
- The velocity should be adjusted to firepower. *(Less air for fewer sticks)*
- The fan can be placed on the side of the stove to prevent overheating when the fan is not used. *(Can operate without fan)*
- Without the fan, the stove operates as a natural draft Rocket stove.

Top Loaded Forced Air

Door under top for adding fuel.
More primary air matches metering of fuel.
Hopefully, a $10 wholesale stove.

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

Forced Air Top Loaded (FATL)

- FATL was very clean in the survey testing. *(Cleaner stoves exist)*
- Intended initially for batch loading. *(Adding fuel is needed for TDR & for longer cooking tasks)*
- FATLF used by Philips, BP, and others. *(Evidence of utility)*
- ARC placed a door under the pot. *(Facilitates adding fuel)*
- Added a Winiarski constant cross sectional stove top with 8mm vertical gap under pot at perimeter. *(Increases HTE)*
- More primary air was needed to cleanly burn added fuel. *(Better mixing?)*
- Super-insulated under floor of combustion chamber *(maintains combustion)*
- Used FeCrAl refractory metal in combustion chamber. *(Longer life)*

Charcoal Stove

Charcoal Stove:
More primary air increases firepower.
Air tight door creates good Turn Down Ratio.
Secondary air reduces CO, so does better insulation.

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

Charcoal Stove

- Charcoal (without remaining wood in it) does not tend to make smoke but emits high levels of CO.
- CO was decreased by:
- 1.) Super insulating stove body to quickly raise temperatures in combustion chamber above 700C. *(New insulation and radiation barriers)*
- 2.) Secondary air jets of pre-heated air powerfully mix CO and flame above fuel bed. *(10mm channel gap)*
- 3.) Flame is maintained by 5” by 5” shape of cylindrical combustion chamber. *(Chimney effect but wide enough for primary air to rise to top of fuel bed)*
- *4.)* CO dramatically less when at low power *(Close primary air door)*
- To increase TE:
- 1.) Use least amount of charcoal to boil and simmer! *(350g or less for ‘Tier 4’)*
- 2.) 5” combustion chamber increases radiation and velocity *(Skirt helps)*
- 3.) Increase primary air, raising firepower needed to boil, with big primary air door and large spaces in grate. *(Boil quickly, close door for 10 to 1TDR, lid on pot)*
- To increase TDR:
- 1.) Make primary air door airtight. *(Charcoal simmers with very little air, close door)*

Chinese Internal Market Stove

Charcoal Stove:
More primary air increases firepower.
Air tight door creates good Turn Down Ratio.
Secondary air reduces CO, so does better insulation.

Stove type/model		**Chinese Internal Market Stove**		
Location		Average	COV	Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	45.0%	2%	4.0
High Power CO	g/MJ_d	0.58	18%	4.9
High Power PM	mg/MJ_d	18.0	14%	4.5
Indoor Emissions CO	g/min	0.06	33%	4.8
Indoor Emissions PM	mg/min	1.9	15%	4.0

Chinese Internal Market Stove

1. A skirt was added on the top of the combustion chamber. The skirt reduces the emissions by increasing heat transfer efficiency. The exhaust gasses flow into the 7mm channel gap between the pot and skirt.
2. For wood combustion, the 0.125 cm^2 primary air hole was used to make the fire power reach 3.5kW and a 3 cm^2 secondary hole was used for clean burning.
3. For charcoal burning, a 2 cm^2 secondary air hole and a 3 cm^2 primary air hole were used.
4. A downward facing cone shaped screen was put on the bottom of the combustion chamber in order to burn all the charcoal.
5. A tube was placed between the skirt and the combustion chamber to give more space for the combustion to occur. Insulation also surrounds the tube helping to reduce the heat loss.

Technical Accomplishments

January/February 2015

- In January/February 2015 the Top Loaded Forced Air (TLFA) stove was improved.
- A chimney was added.
- The combustion temperature was raised to 840 C by reducing the excess air.
- The flame length was increased allowing more time for combustion to occur.
- The stove was operated as a T-CHAR: burning wood for boiling and the made charcoal for simmering.
- Meets WHO unvented PM 2.5 indoor air guideline.

Top Lit Forced Air Stove with Chimney

Meets WHO unvented indoor air quality guideline for PM2.5

Stove type/model		TLFA		
		Average	COV	Average Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	40.2%	3%	3.5
Low Power Specific Consumption	MJ/min/L	0.009	20%	4.4
High Power CO	g/MJ$_d$	0.13	25%	4.9
Low Power CO	g/min/L	0.04	5%	4.6
High Power PM	mg/MJ$_d$	12.0	41%	4.7
Low Power PM	mg/min/L	0.11	58%	4.8
Indoor Emissions CO	g/min	0.19	5%	4.5
Indoor Emissions PM	mg/min	1.2	44%	4.3

Relevance

- An extensive stove survey established the “State of the Art”. Results published in *EcoHealth*, an NIH journal (2014).
- Creating stoves that meet the new WHO indoor air quality guidelines for household fuel combustion positively impacts the commercial viability of the biomass industry.
- Manufacturing health protecting stoves protects consumers.
- The technology is being patented.
- A book describing the design principles for clean combustion is being written. To be published by EPA (2016).
- The intent is to manufacture and sell one million “Tier 4” stoves a year.
- The stoves will be sold by a USA based company.

Future Work

- The project ends September 30, 2015.
- The re-engineered stoves go into a 2nd round of consumer input.
- The factory continues to work with ARC to lower cost.
- A new ceramic combustion chamber could save $4 to $6.
- The lab continues to improve the technologies.
- USA based retail chain store is in 40 countries.
- BUCT publishes article describing “Tier 4” Chinese stove.
- ARC publishes *“Understanding and Building Clean Burning Biomass Cookstoves”*, EPA, 2016

Summary

Overview: Improved ‘State of the Art’ Cookstoves.

Approach: Iterative development and modeling.

Results: Six prototype ‘Tier 4’ stoves move towards market.

Relevance: Clean combustion meets new WHO guidelines. Sold by a USA company. Design principles described in a book. Patented new technology.

Future work: Evolve final products with ARC engineers, consumers, manufacturer, and distributor/retailer . Work with USA chain store to sell stoves in 40 countries. Complete new book.

Publications, Presentations, Book (in progress)

- **Still, Bentson, Li "Results of Laboratory Testing of 15 Cookstove Designs in Accordance with the ISO/IWA Tiers of Performance, EcoHealth, 2014**
- **Still "The ARC/DOE Stoves and Seven Steps to Improve Performance" ETHOS, 2015**
- **Still " ARC/DOE: Tier 4 Stoves Move Towards the Market (Keynote, ETHOS) 2015**
- **Still, MacCarty, Bentson, Bryden "Understanding and Building Clean Burning Biomass Cookstoves", (Book in progress) EPA, 2016**