DOE Bioenergy Technologies Office (BETO)
2015 Project Peer Review

Multidisciplinary Design of an Innovative Natural Draft, Forced Diffusion Cookstove for Woody and Herbaceous Biomass Fuels

March 26, 2015
Technology Area Review

Principal Investigators: Jonathan Posner and John Kramlich
University of Washington - Seattle

Goal Statement

- Develop a natural draft cookstove that performs at the Tier 4 level for particulate matter, CO, efficiency, and safety that meets the needs and desires of customers in rural Kenya.
- Relevance: Reduce the huge health risks associated with exposure to CO and especially PM
  - *Sustainable* → cost, meets users needs/desires, durable, reduce deforestation, reduce impact on environment
  - *Safely and efficient* → significantly reduce emissions and fuel usage as compared to existing solution (e.g. three-stone fire)
  - *Available fuel source* → in rural Kenya this means wood

Quad Chart Overview

Timeline

- Project start date: 9/13/2013
- Project end date: 9/16/2016
- Percent complete: 45%

Budget

	Total Costs FY 10 – FY 12	FY 13 Costs	FY 14 Costs	Total Planned Funding (FY 15-Project End Date
DOE Funded	$0	$0	$178,448	$721,552
Project Cost Share (Comp.)*			exempted	exempted

Barriers

- Barriers addressed
  - Technical: Low efficiency and high emissions
    - Poor mixing
    - Too much excess air
    - Highly variable fuel quality
  - Other barriers
    - Low cost = natural draft
    - Acceptance of features by public

Partners

- Burn Design Labs (35%)
  - Prototype construction
  - Kenya factory
  - User research in Kenya
- Berkeley Air Monitoring (15%)
  - Field evaluation of performance

1 - Project Overview

- Three-stone cooking is inefficient and produces PM that is dangerous over long-term exposure.
- Active design (e.g., forced draft) provide more tools for improvement, but costs will restrict deployment in our target market, and this will limit the overall benefit.
- Passive design (natural draft) constrains the technical design, but if successful it could have a broader integrated impact.
- Objectives: Improved performance (Tier 4 on all metrics), with low cost (~$20/unit), and acceptance of features by the user community.

2 – Approach (Technical)

Integrated and multidisciplinary design approach that includes:

- *Several natural draft stove innovations (UW, BDL)*
- *Field based user research and focus groups (BDL)*
- *Empirically verified combustion, computational fluid dynamics, and heat transfer modeling (UW)*
- *Lab testing (UW, BDL)*
- *Design for manufacturability (BDL)*
- *Field emission and efficiency verification (BA)*
- *In-home user product evaluations (BDL)*

Team

W

Jonathan Posner (PI)
John Kramlich (co-I)
Garrett Allawatt
Ben Sullivan
Anamol Pundle
Steven Diesburg
Ornwipa Thamsuwan
Devin Udesen
Todd Matsunami
Justin Brown
Jackson McFall
Emily Lore

burn
life · saving · stoves

Peter Scott
Paul Means
Boston Nyer
Nino Figliola
Constance Ambasa
Ellen Goettsch
Candace Marbury
Pauline Oudo
Siku Mathii
Janerose Kweyu
Hellen Mudia
Beula Achieng

BERKELEY AIR
MONITORING GROUP

Michael Johnson
David Pennise
Charity Garland

2 – Approach (Management)

- *Success Factors*
  - *Low emissions, high efficiency (Tier 4 metrics)*
  - *Unit cost that facilitates market penetration*
  - *Robust performance over a range of fuels, customer uses*
  - *Development of design tools and guidelines that allow domestic producers improve, upgrade and diversify their designs*

- *Challenges*
  - *Obtaining good performance with natural draft as a constraint*
  - *Robust design while holding costs down*
  - *Ensuring design is attractive to users*

- *Management Structure*
  - *Weekly meetings between UW and Burn (most face-to-face)*
  - *Milestone schedule keyed to the periodic reports to DOE*
  - *Master To-Do list maintained for the project that is addressed at each weekly meeting*

3 – Technical Accomplishments/ Progress/Results

- *User research*

User Research

User Research Objectives

- What are potential stove user's preferences for stove geometry, aesthetics, materials?
- What stove features do they value and are willing to accept?
- How much do they value the different aspects of stove performance?
- What are they willing to pay for the stove and for each individual feature?
- What are the characteristics of the fuel that will typically be used in the stove?

User Research Team

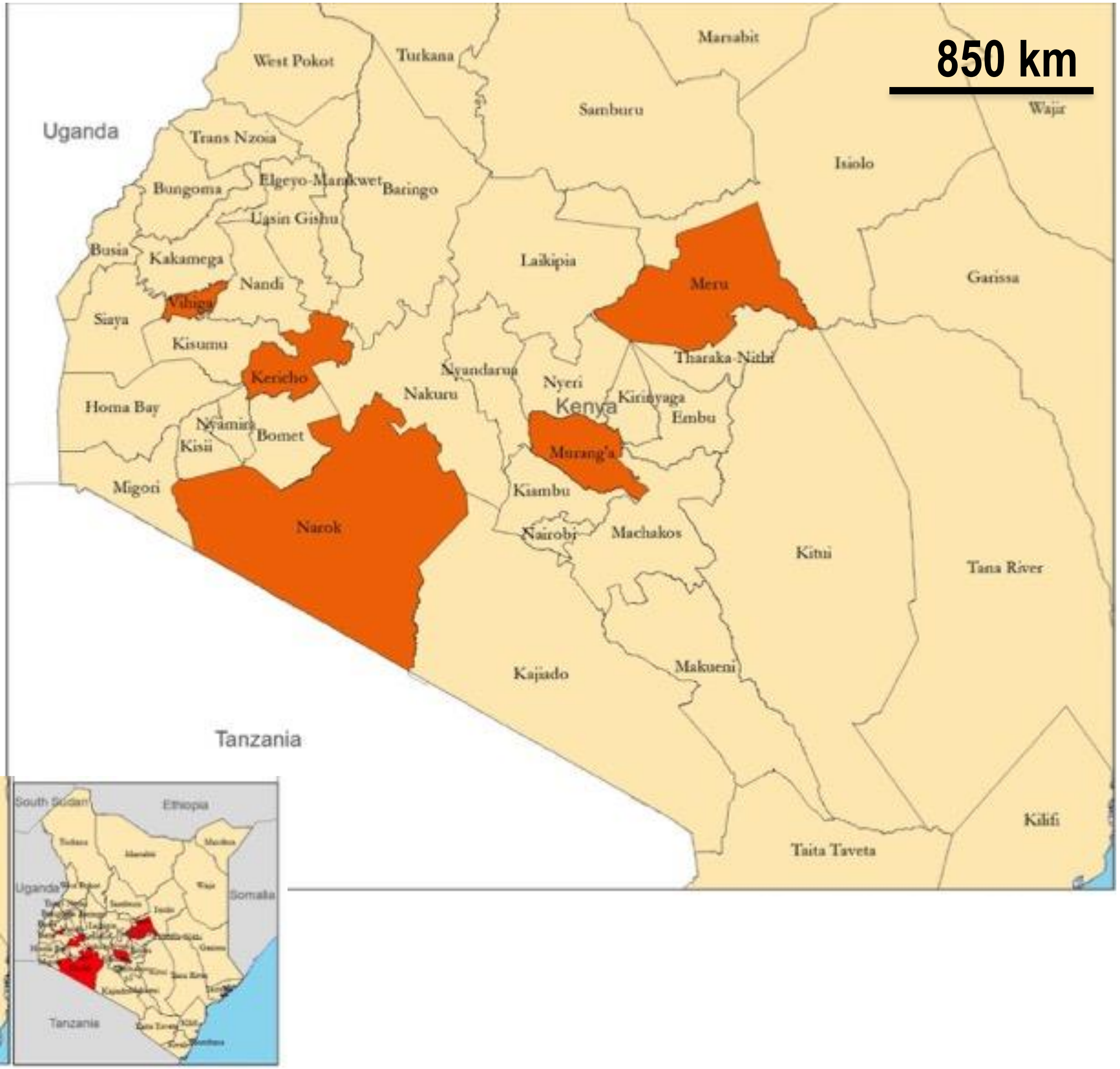
Pauline Oudo, Siku Mathii, Janerose Kweyu, Hellen Mudia, Constance Ambosa , Beula Achieng

User Research Overview

- IRB and KEMRI approved
- 6 locations in Kenya
- 4 focus groups per location
- 46 participants per location (36 cooks, 10 women leaders)
- Three target market segments with income: >$71/mo, $35-71/mo, < $35/mo.
- 250+ total cook participants
- Distributor interviews
- Manufacturer interviews
- Policy influencer interviews
- Government interviews

UW/Burn and commercially available stoves used in research

User Research Locations



6 geographic locations chosen based on their primary use of wood fuels, demographics (income), geographic variety:

- Tigania East in Meru C. ✓
- Gatanga in Muranga C. ✓
- Kericho in Kericho C. ✓
- Narok in Narok C. (Feb)
- Vihiga in Vihiga C. (Feb)
- Maragwa in Muranga C. (March)

Summary of Lessons Learned

- Most fuel is roughly twice as large and moist as used in lab: (a) increased soot and particulate emissions, (b) cooks tend their fire less often

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- Pre-cooking to post-cooking preferences changed substantially.
  - Pre-cooking stove preferences based on size, appearance, & weight.
  - Post-cooking, stove preferences based on perceived time to cook, ease of lighting, fuel required for cooking (efficiency), and particulate emissions.
  - Cooks willing to accept reduced visibility of flame for perceived improvement in performance

Summary of Lessons Learned

- Cooks indicated that they were willing to pay for some features (e.g. stove of preferred height)
- Cooks provide meaningful feedback on aspirations and desirability of the stove design (features, size, weight, feet, handles, stick tray, visibility of flame) and much of this feedback is based on performance (perceived time to boil, emissions, efficiency, stability) as opposed to pure aesthetics.
- Large variability in responses → adequate sample size and careful interpretation.

3 – Technical Accomplishments/ Progress/Results

- *User research*

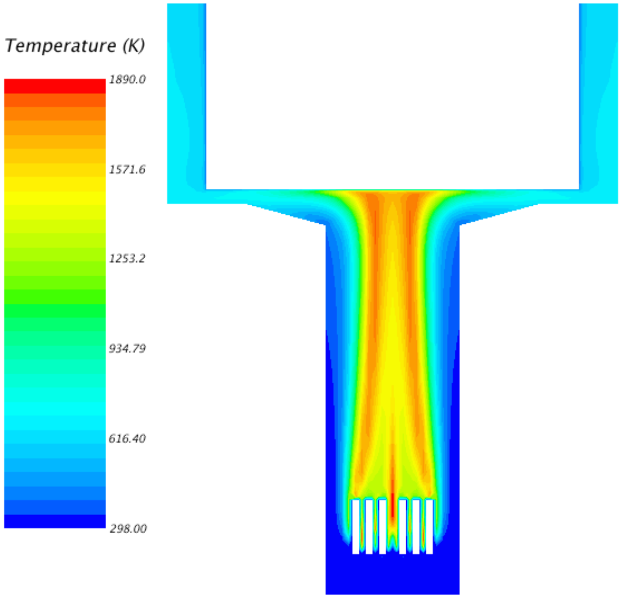
- *Flow/combustion modeling*

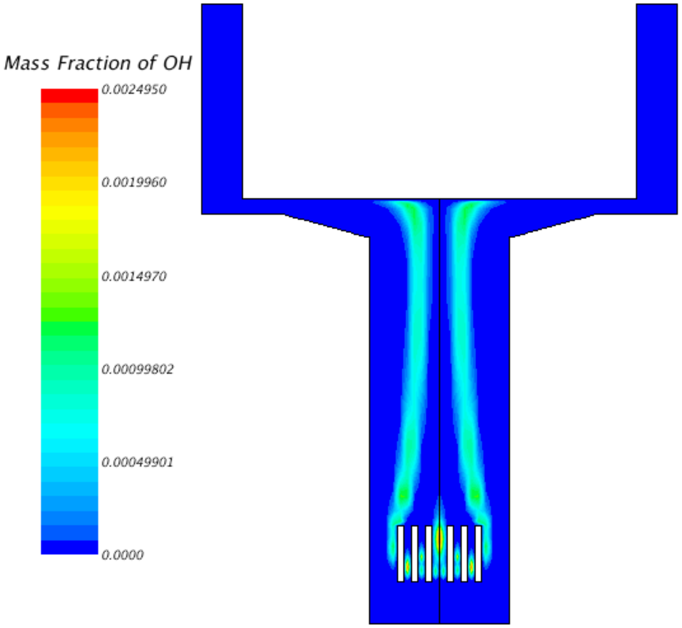
Computational Modeling

- Improve understanding of physical processes occurring inside cookstove.
- Can isolate effect of various parameters (geometry, fuel, etc.) on heat transfer, mixing and emissions.
- Efficiently inform stove design.

Computational Modeling

- Steady, 2D axisymmetric
- Fluid mechanics, conduction and convection heat transfer, combustion chemistry
- Two Layer Realizable K-ε turbulence model
- Eddy Dissipation Combustion model

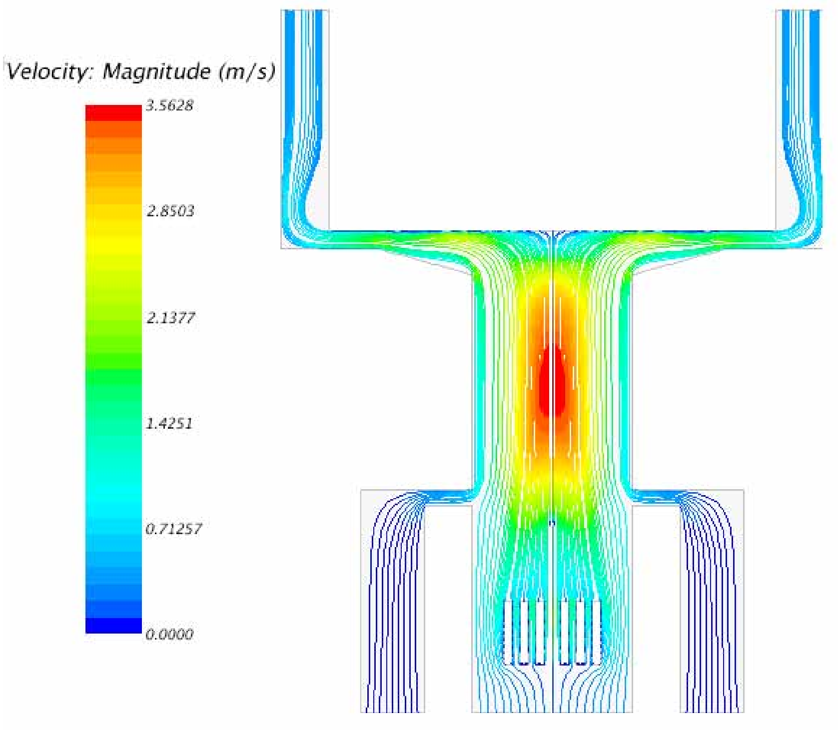




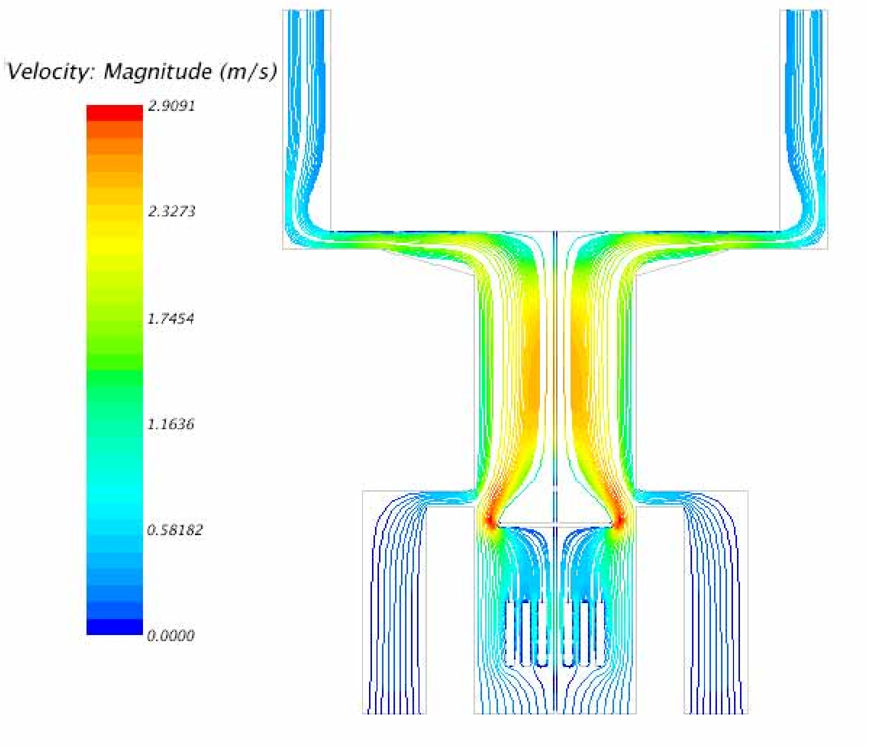
- Peak T and OH show flame sheet separating air and fuel
- Cool excess air on perimeter of combustion chamber results in lower of gas temperature, reduction in efficiency (consistent with CSU)

Velocity Fields

- Secondary air and obstructions
- Total flow rate not function of obstruction

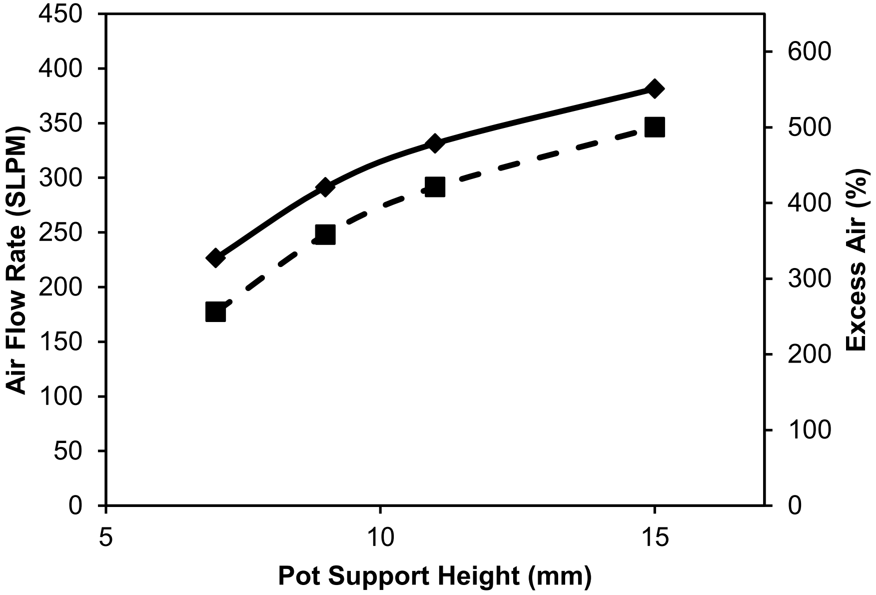


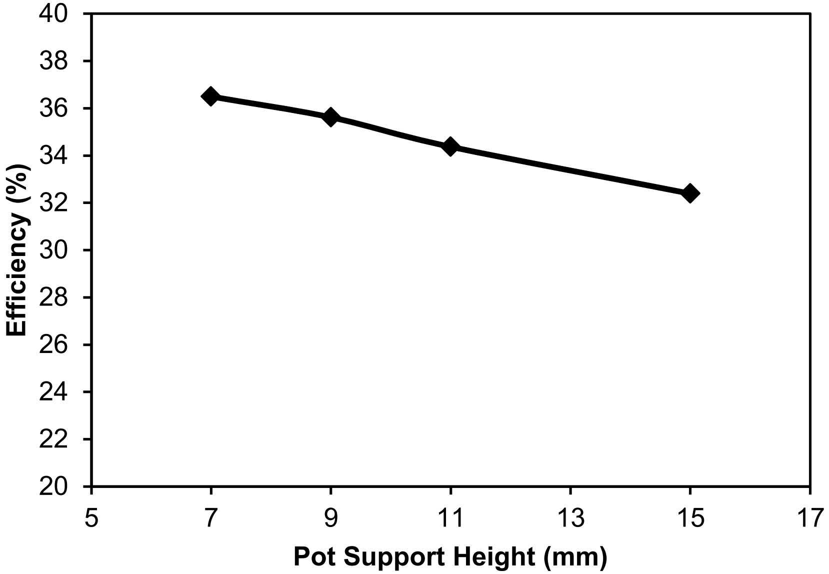
Unobstructed



Obstructed

Role of Pot Support Height





- Agreement of efficiency with experimental results
- Increasing pot support height increases flow area & excess air
- Too much excess air in our system
- High levels of excess air reduce efficiency by introducing cool air and reducing gas temperature

Computations Summary

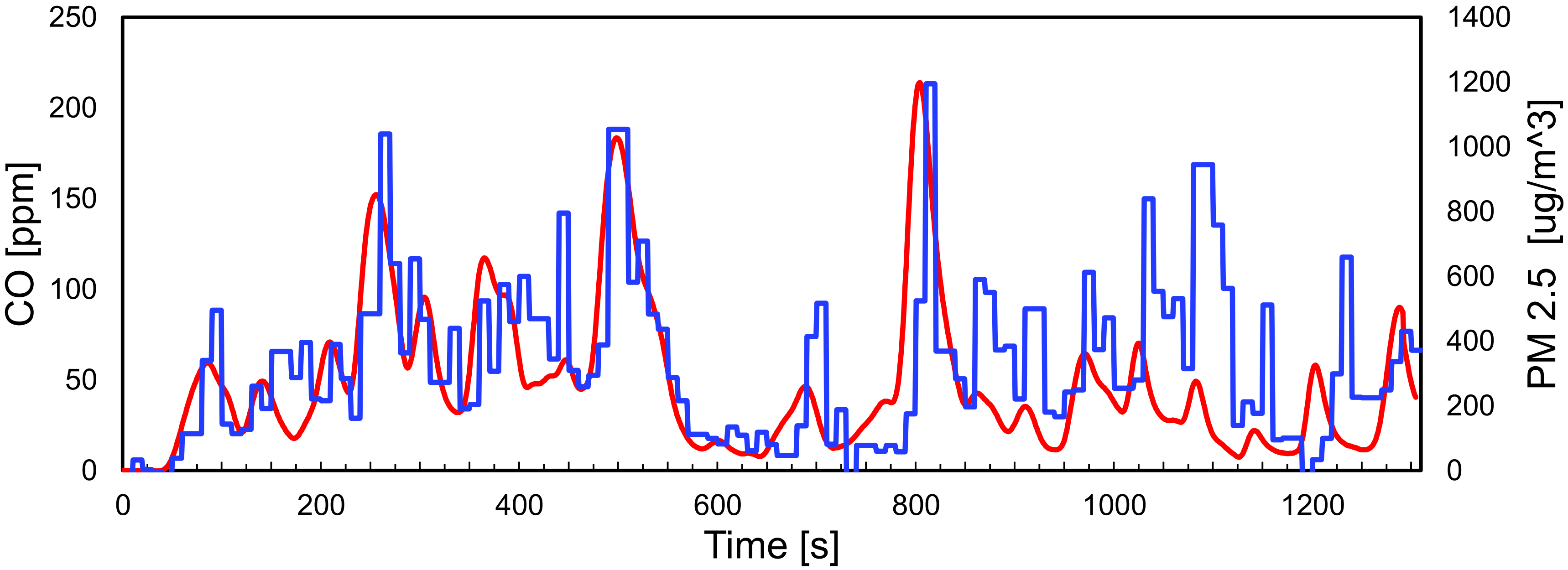
- Lessons learned:
  - Performance (efficiency & PM) impaired by poor mixing
  - Abundance of excess air impacts efficiency
  - Use model to improve mixing and control excess air to decrease PM and increase efficiency.
- Going forward:
  - Use model to reduce excess air and improve mixing to increase temperature, reduce PM, and increase efficiency
  - Two-way coupling of flame and fuel
  - Soot
  - Improve kinetics
  - 3D (complex stove configurations)
  - Open source code for design tool

3 – Technical Accomplishments/ Progress/Results

- *User research*
- *Flow/Combustion modeling*
- *Measurement innovation*

Lab Facilities

- Quantitative lab testing at UW and Burn: calibrated CO, CO_2, temperature, real time display
- UW: Real-time gravimetric PM (TEOM) *increases repeatability*, *increases testing rate*, and facilitates a deeper understanding of cookstove performance
  - Ability to link physical actions with emissions response
  - Allows for rapid stove morphology evaluation
- Real-time burning rate using gravimetric scale



3 – Technical Accomplishments/ Progress/Results

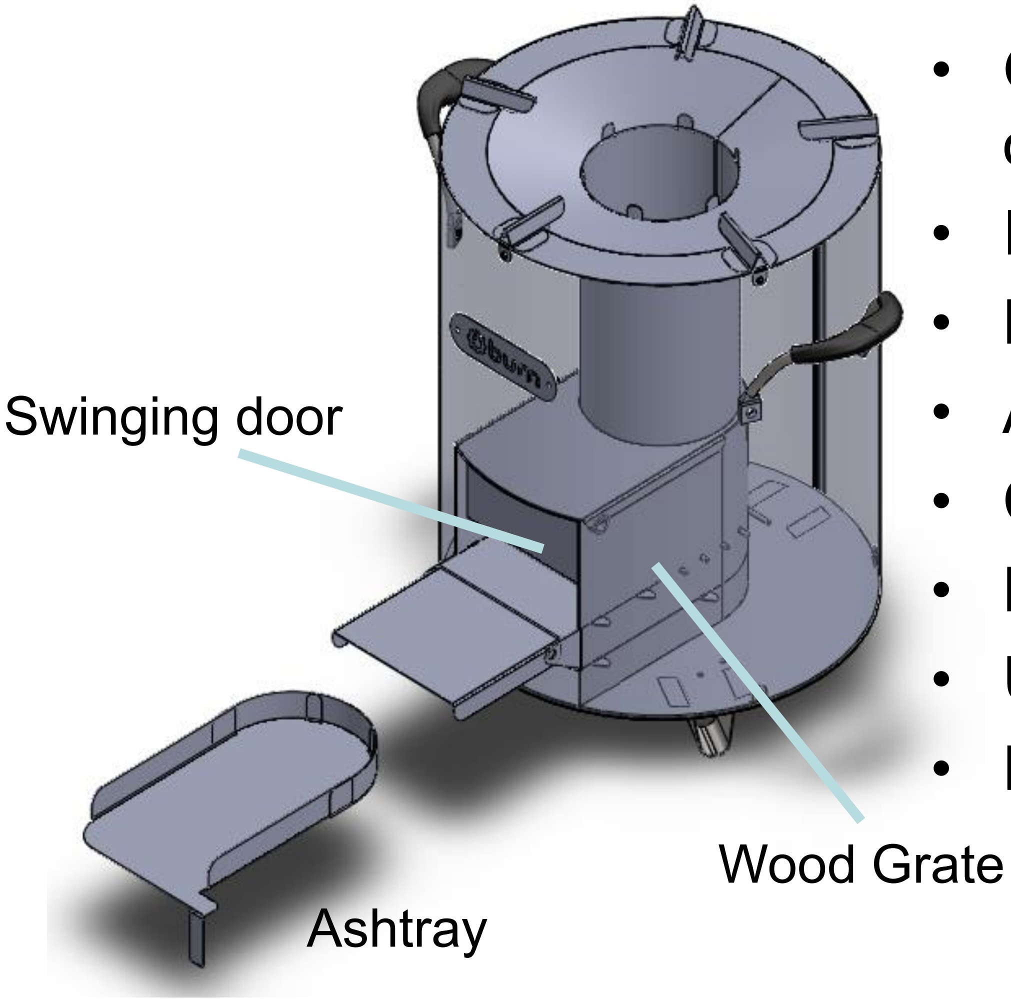
- *User research*
- *Flow/Combustion modeling*
- *Measurement innovation*
- *Stove design/innovation*

Stove Innovations and Testing

- 23 stove prototypes and 60+ configurations
- Total number of tests: ~300
- Innovations have focused on PM and user aspirations

Baseline Stove

Baseline stove is a starting point for innovative stove features



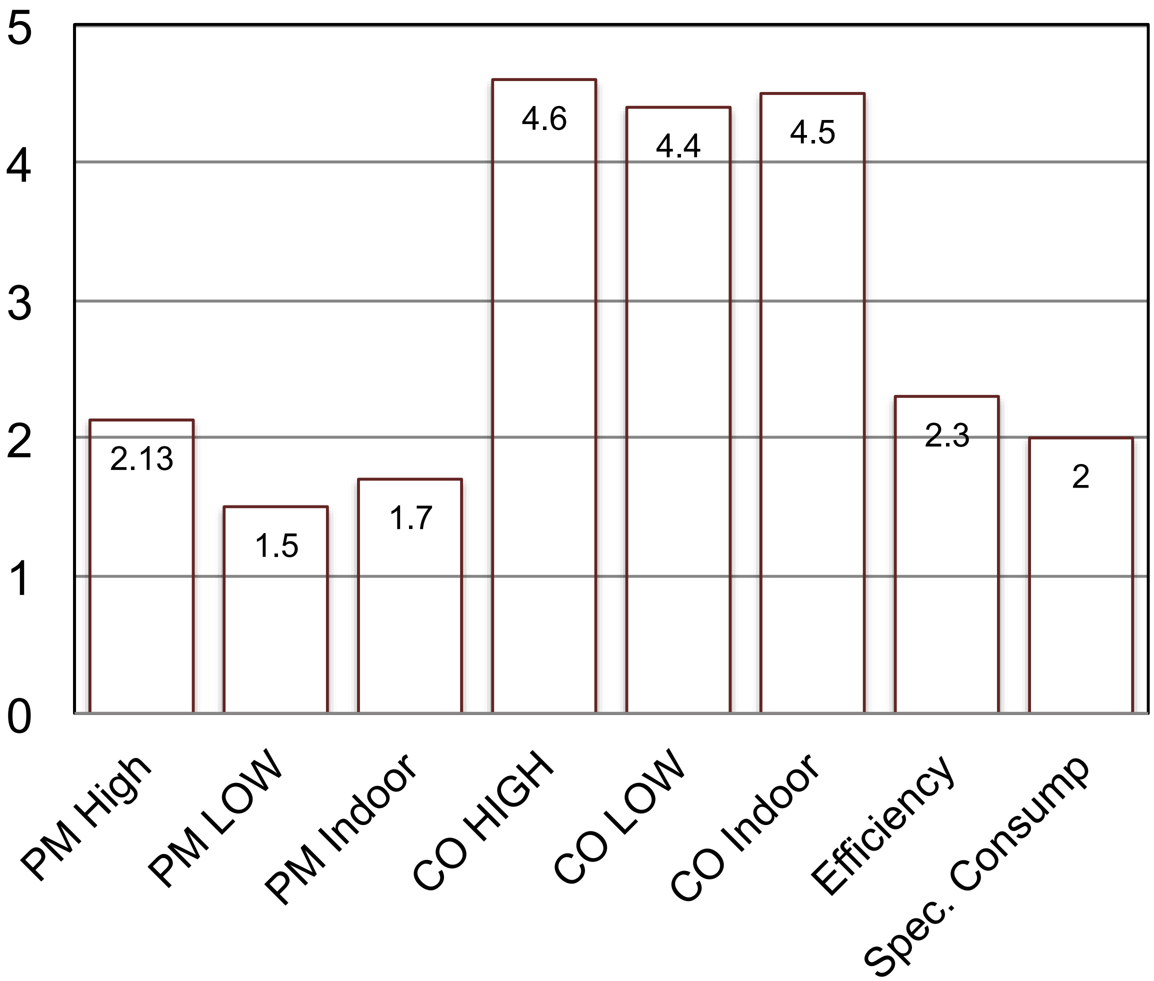
- Geometry based on averages of existing commercial stoves
- Insulated steel construction
- Primary air swinging door
- Ashtray
- Cone deck
- Pot skirt
- Under fire primary air
- Handles

Laboratory Testing: Baseline

Metric	Current Status	Current Tier	Benchmark
PM2.5 Emiss. HIGH [mg/MJ]	358	**2.13**	414
PM2.5 Emiss. LOW [mg/min/L]	6	**1.5**	3.7
PM2.5 Indoor Emiss. [mg/min]	24.7	**1.7**	36.6
CO Emiss. HIGH [g/MJ]	3	**4.6**	4.9
CO Emiss. LOW [g/min/L]	0.05	**4.4**	0.07
CO Indoor Emissions [g/min]	0.23	**4.5**	0.42
Thermal Efficiency [%]	27.7%	**2.3**	36.6%
Low Spec. Consumption [MJ/min/L]	0.04	**2**	0.028
Time to boil [min]	17.3		29.1
Burn rate [g/min)	16.3		10
Fire Power [Watts]	4850		3000

*Benchmark is the average of natural draft stoves in Jetter 2012

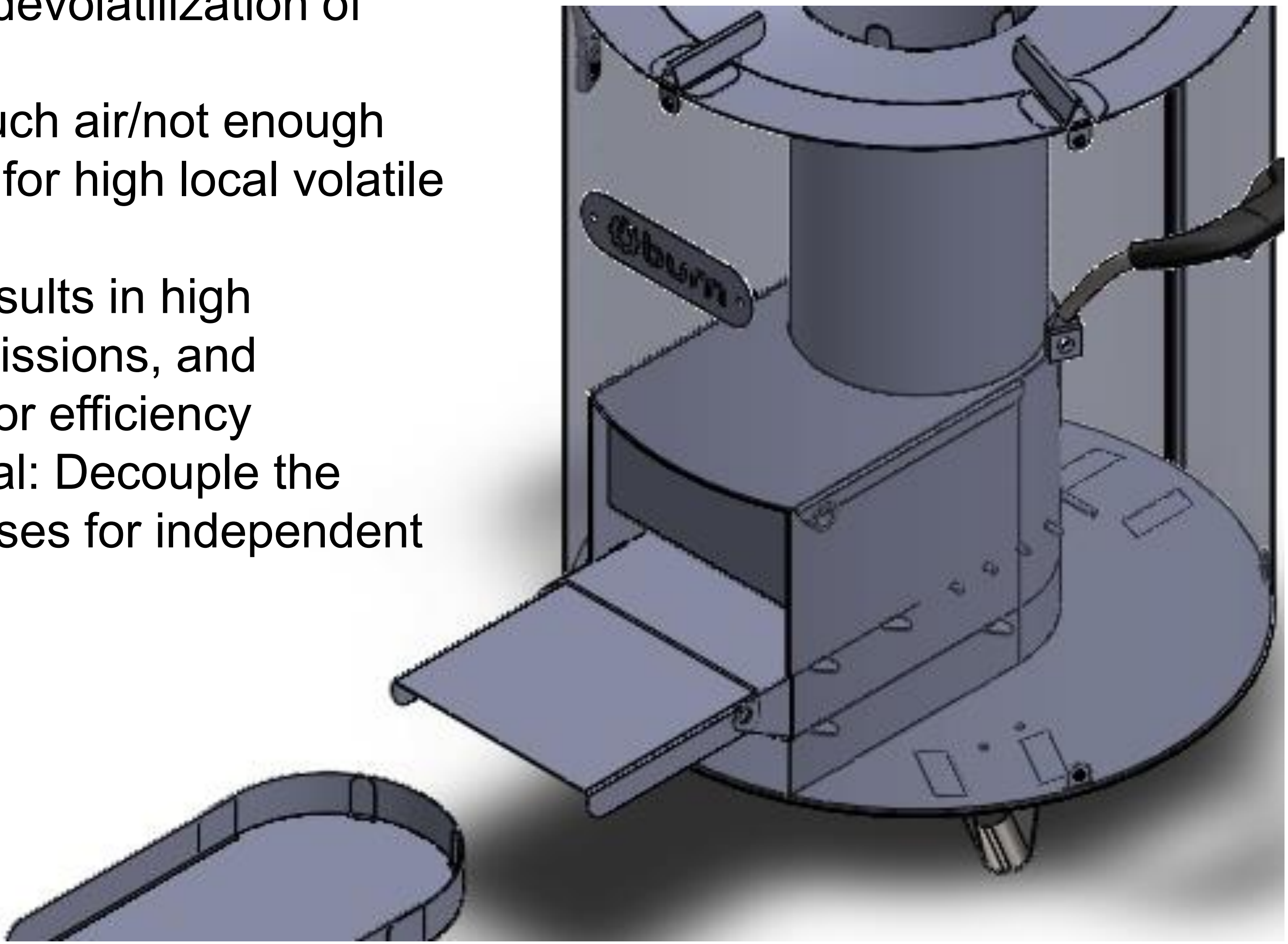
Laboratory Testing: Baseline



- CO is Tier 4
- Primary challenges are PM and efficiency
- Optimized pot standoff and skirt provide 4% increase in efficiency

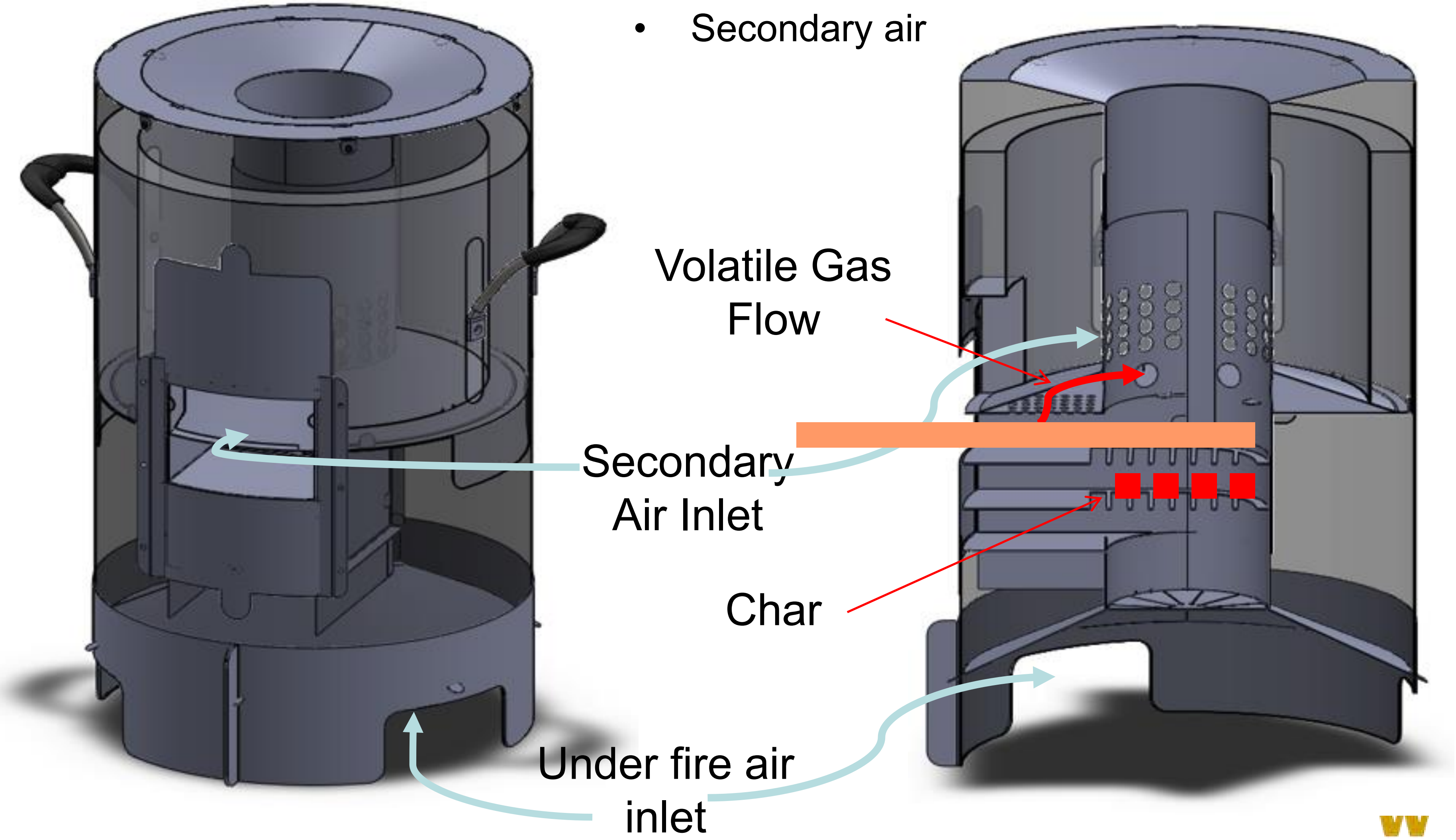
Deficiencies

- Rapid devolatilization of wood
- Too much air/not enough mixing for high local volatile flux
  - Results in high emissions, and
  - Poor efficiency
- → Goal: Decouple the processes for independent control



TallBoy Stove

- Wood and charcoal grate
- Two volatile pathways
    - Primary flame
    - Secondary flame
- Reduced char and primary air
- Secondary air



Volatile Gas Flow

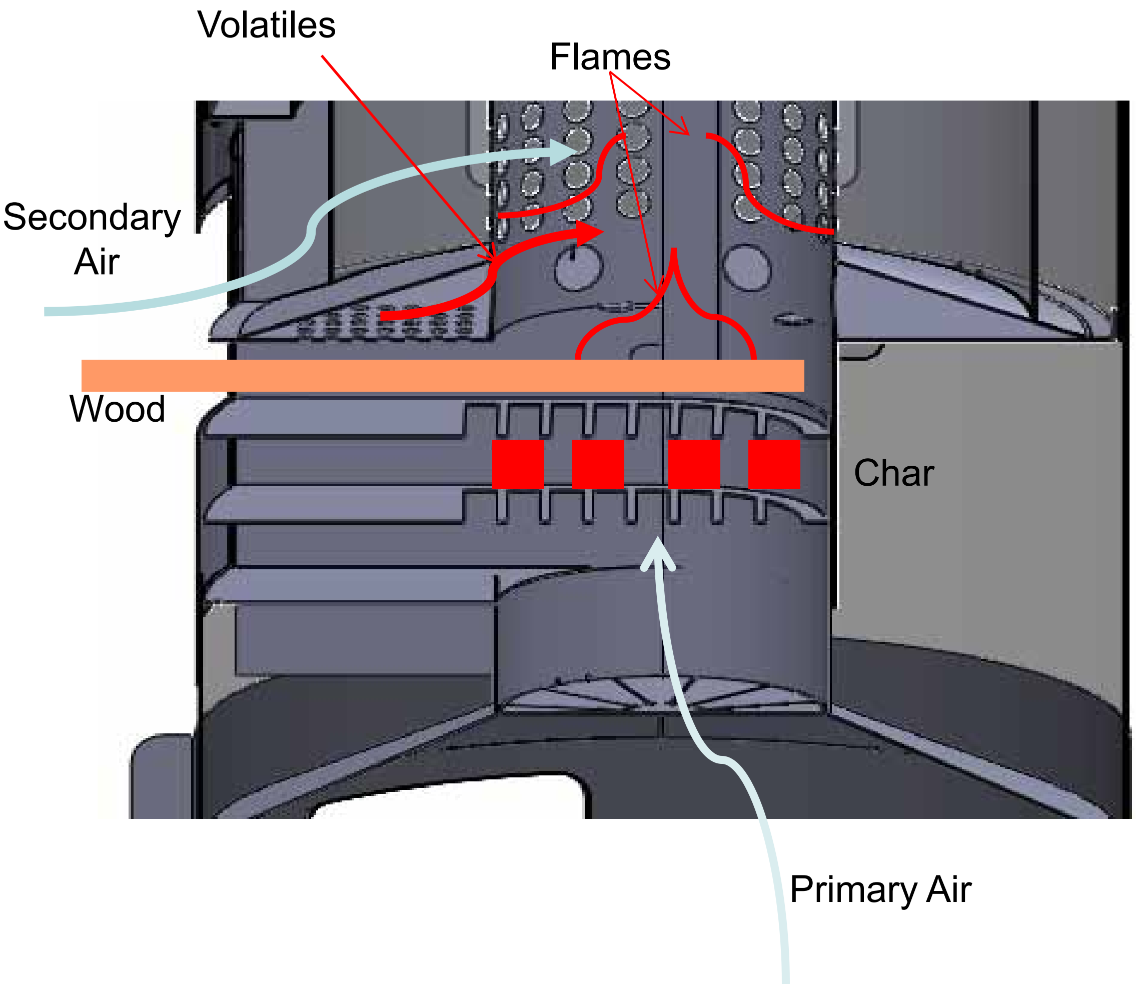
Secondary Air Inlet

Char

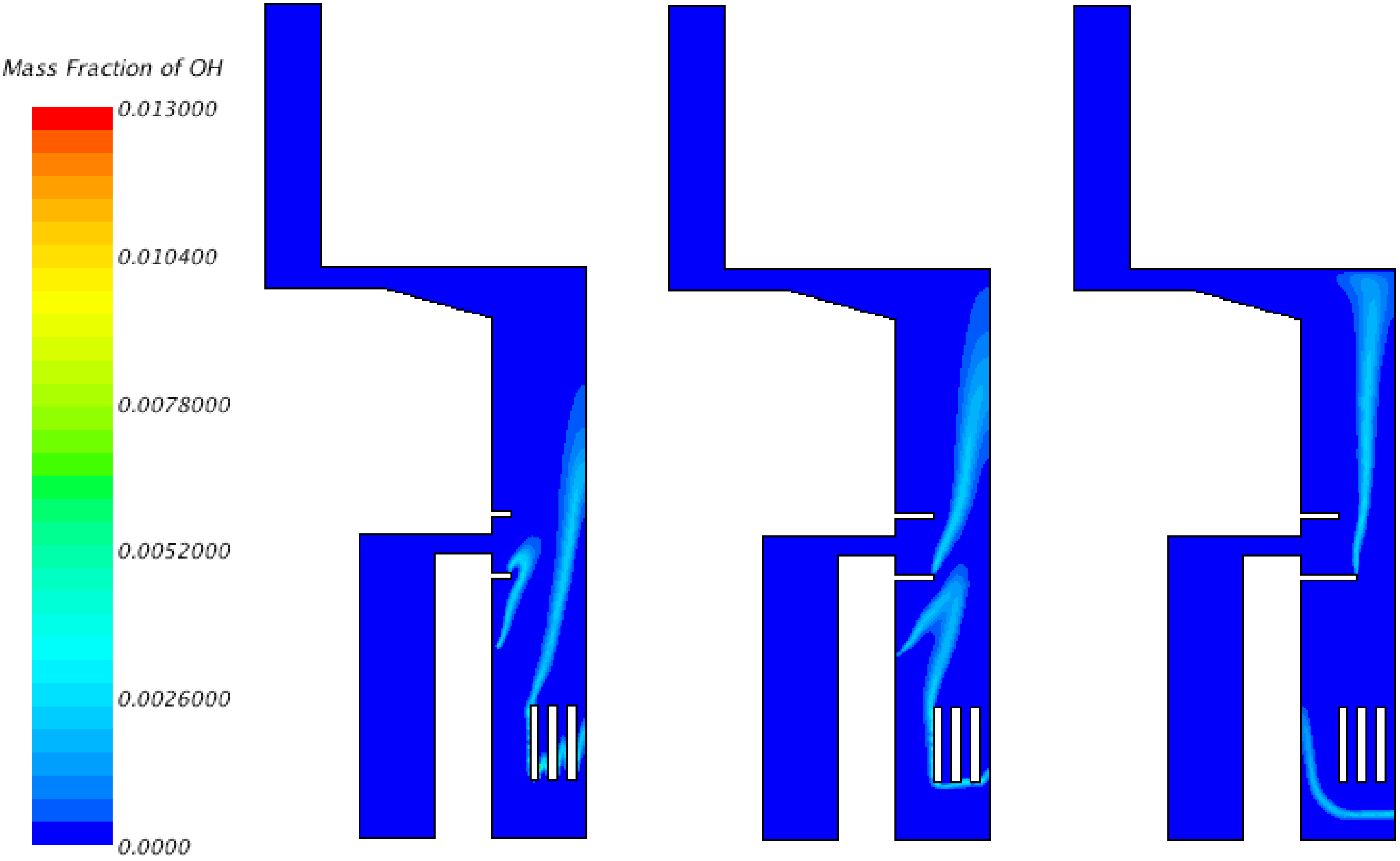
Under fire air inlet

Gasification Mechanism

- Controlled air to char and primary wood volatile flame
- Fraction of wood volatiles released away from primary flame
- These burn in a diffusion flame with secondary air
- Additional flame area results in better mixing
- Air restriction results in hotter flame and better efficiency.
- Appears complex, but totally passive system. Just redistribute the fuel and air.



OH Mass Fraction

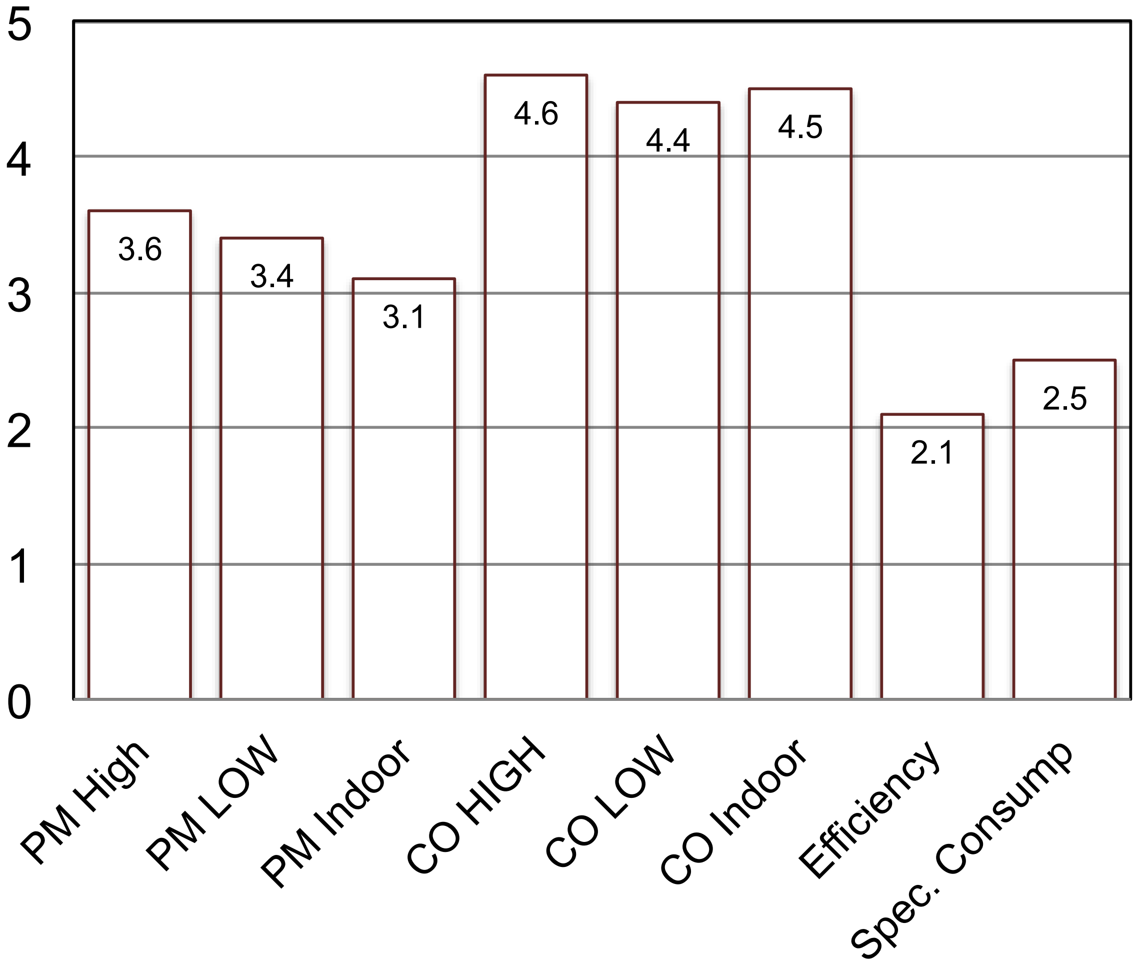


Laboratory Testing: TallBoy

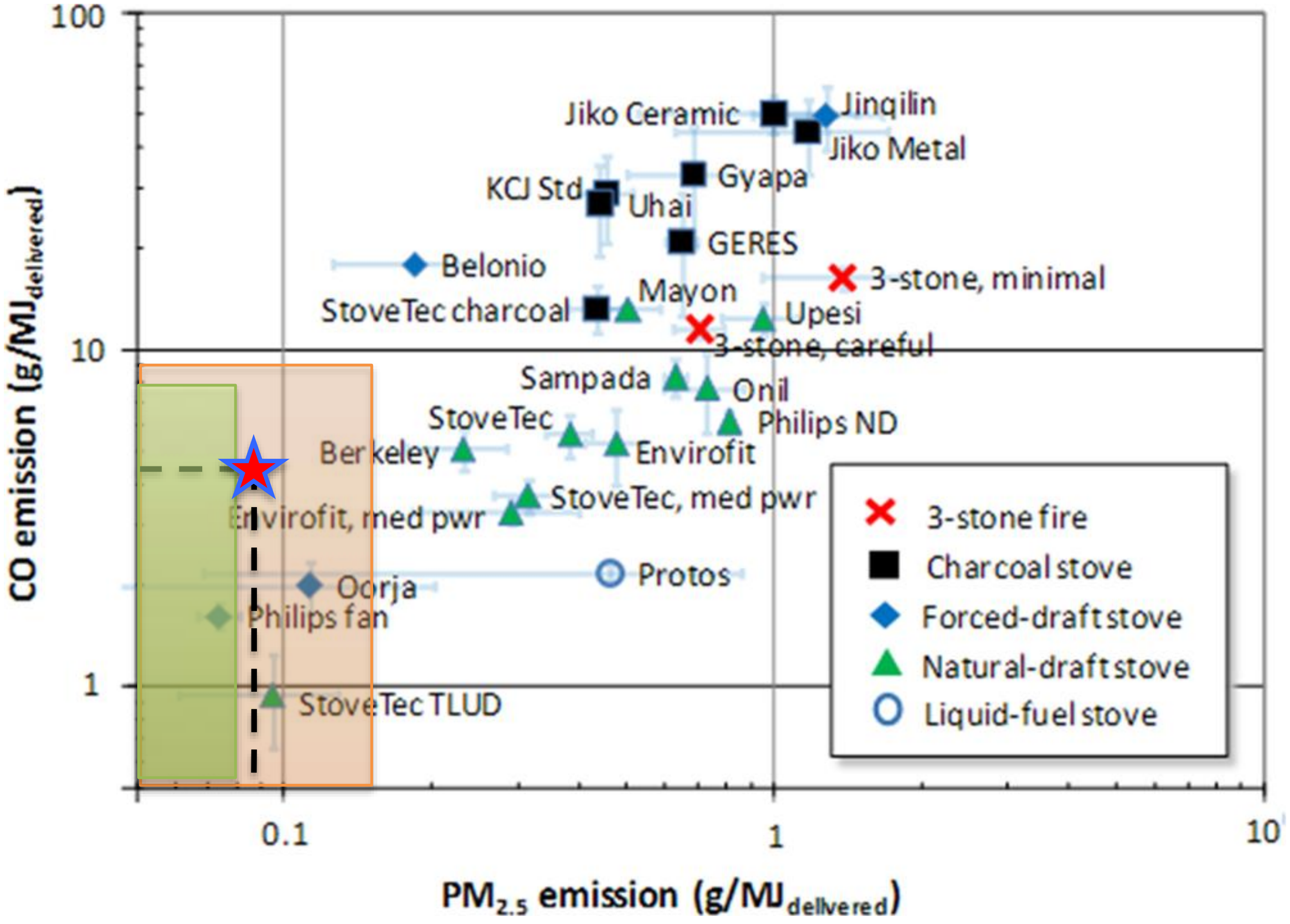
Metric	Current Status	Current Tier	Benchmark
PM2.5 Emiss. HIGH [mg/MJ]	87.3	**3.6**	414
PM2.5 Emiss. LOW [mg/min/L]	1.8	**3.4**	3.7
PM2.5 Indoor Emissions [mg/min]	7.8	**3.1**	36.6
CO Emiss. HIGH [g/MJ]	3.4	**4.6**	4.9
CO Emiss. LOW [g/min/L]	0.05	**4.4**	0.07
CO Indoor Emissions [g/min]	0.14	**4.5**	0.42
Thermal Efficiency [%]	26.3%	**2.1**	36.6%
Low Spec. Consumption [MJ/min/L]	0.03	**2.48**	0.028
Time to boil [min]	30		29.1
Burn rate [g/min)	10		10
Fire Power [Watts]	2800		3000

*Benchmark is the average of natural draft stoves in Jetter 2012

TallBoy Tiered Results



CO-PM Jetter Map

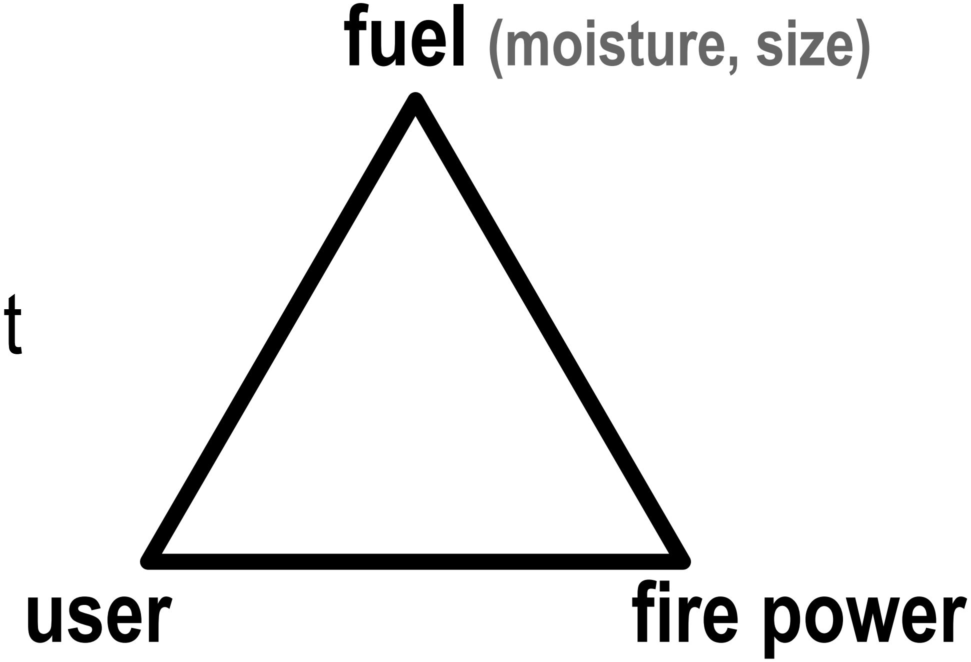


Lessons learned from lab testing

- Tier 4+ for CO, Tier 3+ for PM
- Need to further reduce PM and increase efficiency
- Secondary combustion burns out volatiles and soot
- Improved mixing alleviates segregation of fuel and air
- Stress testing: evaluate performance with varying fuel, users, firing rate.

Standardized stress test

*Acknowledge CSU efforts in this area



3 – Technical Accomplishments/ Progress/Results

- *User research*
- *Flow/Combustion modeling*
- *Measurement innovation*
- *Stove design/innovation*
- *Field testing*

Field Testing (Berkeley Air)

- **Uncontrolled Cooking Test**
  - Conducted in homes
  - CCT with uncontrolled meal and fuel
  - More variable but reflects actual use
  - Measures:
    - Fuel conditions
    - Pot size and type
    - Foods cooked
    - Lighting techniques
    - Specific fuel consumption
    - Emission factors and rates
    - Combustion efficiency
    - Firepower
    - CO, CO_2, PM, CH_4, TNMHC, BC, OC

Relevance

- Reduce the huge health risks associated with exposure to CO and especially PM
  - *Sustainable* → cost, meets users needs/desires, durable, reduce deforestation, reduce impact on environment
    - Natural draft for low cost/durability, high efficiency to reduce fuel, user survey to meet needs
  - *Safely and efficient* → significantly reduce emissions and fuel usage as compared to existing solution (e.g. three-stone fire)
    - Innovative design for emissions reduction, direct emissions measurement via novel real-time PM monitoring
    - Modeling to understand results, identify improvements, empower others to innovate.
  - *Available fuel source* → in rural Kenya this means wood

Future Work

- Continue user research in three locations and refine cooks needs and desires
- Improve model fidelity and validate
- Innovate to reduce PM, increase efficiency
- Refine and use stress test
- Field performance testing at two sites (Berkeley Air)
- Commercialize DOE V1 stove with Burn Manufacturing

BURN (BMC) Commercialization Plan

Sub-Saharan Africa's first Modern Cookstove Factory

18,000 ft2 facility currently produces and sells 8000, 100% locally made, stoves/month.

Currently employs 100+ people (>50% women) in Kenya

BURN Manufacturing Co will bring DoE **v1** Woodstove to market in 2015.

DoE **v2** (based on ongoing research) will replace V1 in 2016

USAID DIV funded **Forced Draft Stove** launched in Q1 2016

Summary

- **Overview**
  - Multi-member team focused on crossing disciplines to solve a fundamental and practical problem
- **Approach**
  - Includes design innovation, user research, involvement of a Kenya manufacturer, and development of design tools
- **Technical Accomplishments**
  - Developed a clean (near Tier 4) robust design, a set of design targets based on user research, a design tool that models the behavior in the stove
- **Relevance**
  - Directly addresses the issues of health effects (reduced CO and PM), deforestation (high efficiency), user acceptance (no success if not used), cost (no success if not purchased)
- **Future Work**
  - Complete user research, improve design's robustness, implement "stress test", evaluate design in Kenya, commercialize version 1 design at Burn's Kenya factory.

Additional Slides

Publications, Patents, Presentations, Awards, and Commercialization

- Intellectual Property: two disclosures submitted on innovative stove designs
- Publications: two conference papers at Ethos. Several archival journal publications expected: real time PM, stove design, user research, computational model.
- Synergistic Activities: BURN-UW-Engineers Without Borders mechanically powered (no electricity) forced air

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