BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

ADO Session Presentation

An Affordable Advanced Biomass Cookstove with Thermoelectric Generator (TEG)

March 4, 2019

Technology Session Area Review

Vi Rapp and Ashok Gadgil

Lawrence Berkeley National Laboratory

Goal Statement

Design, develop, and evaluate stoves that reduce PM emission by 90% per meal while maintaining user-desired features that will increase adoption

- Design novel air injection configurations for flame manipulation powered by TEG or equivalent device
- Develop rigorous aerosol and gas emissions testing protocols
- Utilize novel third-party TEG technology to affordably reduce PM2.5 emissions from wood-fueled stoves by 10 fold per meal.
- Adapt design for future auxiliary features (e.g. charging ports for cellphones and LED lights) that are highly valued and economically attractive to customers. Communicate the design to cookstove community.
- Design, develop, and implement world-class testing facility for biomass stoves: Emissions and performance testing will be asset to stoves community for training and testing.
- Disseminate results via publications, outreach, and training

Original Tasks

Revised Tasks and Key Milestones

Project Budget Table

	Original Project Cost		Project Spending and Balance		Final Project Costs
Budget Periods	**New DOE Funding**	**Project Team Funding Allocation**	**Spending during FY**	**Balance at end of FY**	**Additional funding needed to complete project**
FY 2013	$1,177K	LBNL (100%)	$0K	$1,177K	$0K
FY 2014	$1,720K	LBNL (100%)	$541K	$2,356K	$0K
FY 2015	$0K	LBNL (100%)	$356K	$2,000K	$0K
FY 2016	$0K	LBNL (100%)	$647K	$1,353K	$0K
FY 2017	$0K	LBNL (100%)	$515K	$839K	$0K
FY 2018	$0K	LBNL (94%) Potential Energy (6%)	LBNL: $475K PE: $42K	$322K	$0K
FY 2019	$0K	LBNL (100%)	$322K	$0K	$0K

Additional Leveraged Funds

Source	Total Funding	Year
NSF	$750,000	2013 - 2018
NDSEG	$250,000	2013 - 2016
Fulbright	$40,000	2014 - 2015
Harvard Global	$200,000	FY18 – FY19

Quad Chart Overview

Timeline

- Project start date 10/1/2013
- Original project end date 09/30/2018
  - Revised project end date 12/31/2019 due to delays with publications & subcontractor fieldwork
- Percent complete 100%

Barriers addressed:

- ADO-A. Process Integration
- ADO-D. Technology Uncertainty of Integration and Scaling
- At-G. Social Acceptance and Stakeholder Involvement

	FY 16 Costs	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19)
DOE Funded	$647K	$515K	$517K	$322K
Project Cost Share*	LBNL (100%)	LBNL (100%)	LBNL (94%) PE (6%)	LBNL (100%)

Partners:

Sheetak (until FY 2016) and Potential Energy (PE)

Other Collaborations:

- University of Adeliade, U.S. EPA, Colorado State University, University of Washington, Aprovecho Research Center, Centre for Research in Energy and Energy Conservation (CREEC), Centre for Integrated Research and Community Development Uganda (CIRCODU)

1 – Project Overview

Biomass smoke is the world's largest environmental-health threat: 4 million avoidable deaths per year from respiratory exposure

Half of world's population, 3 billion people, rely on biomass for cooking

US State Department, WHO, GACC, and others have identified following goals for cookstove improvement relative to traditional Three Stone Fire (TSF):

- 50% reduction in fuel consumption
- 10-fold reduction in PM2.5 emissions per meal
  - Monitor ultrafine (< 0.3 μm) particle emissions

High-Level Objectives:

- ✓ Demonstrate 90% **$PM_{2.5}$** emissions reductions in lab
- ✓ Disseminate high-efficiency low-emissions design knowledge to stoves community
- ✓ Build model testing facility for training partners
- ✓ Elevate stove testing capabilities of international researchers

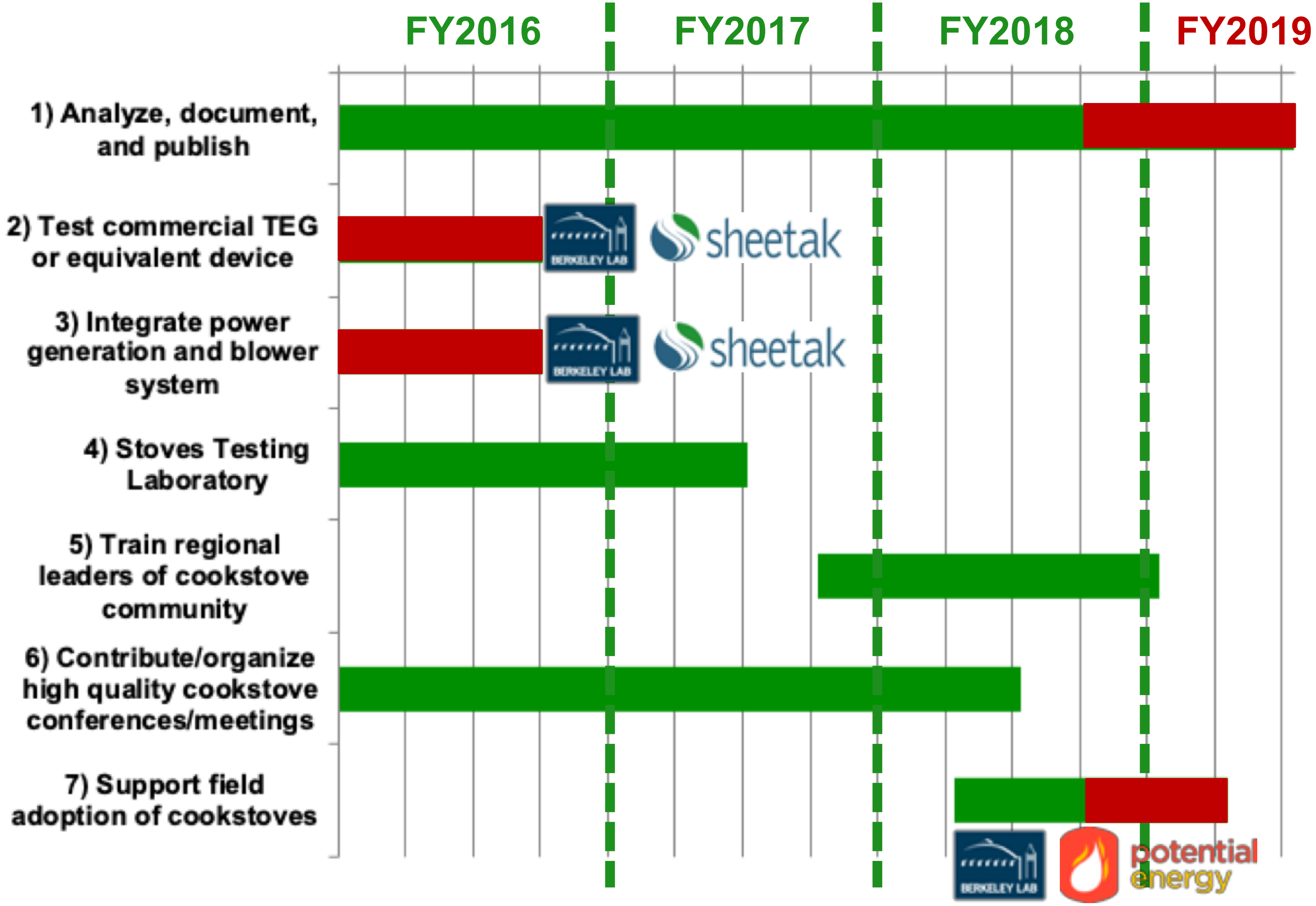
2 – Technical Approach

1. Measure what you want to manage. Measure cookstove performance & emissions accurately: Established state-of-the-art laboratory testing facility
2. Identify the design space in which air injection into the flame zone reduces PM emissions by 90% per meal
3. Identify key air injection stove parameters that most affect stove performance and emissions and advance stoves research community's knowledge
4. Evaluate performance and emissions of other DOE funded advanced stove designs (**added 2016**)
5. Understanding user behavior and adoption (**added 2016**)
6. Optimize design for lower pressure air supply (modified 2016)
7. Transfer stove testing knowledge to elevate capabilities of international researchers (**added 2016**)

2 – Management Approach (Management)

Partner Unique Capabilities
- Sheetak – high efficiency, thin-filmed thermoelectric generators (HiE TEG)
- Potential Energy - Extensive experience with stove dissemination

Partner Milestones/Deliverables
- Sheetak
  - Discontinued development of HiE TEG so partnership was ended with DOE approval
  - New DOE approved milestones established
- Potential Energy
  - Monthly project updates
  - quarterly progress reports
  - images and documentation demonstrating dissemination



3 – Technical Results

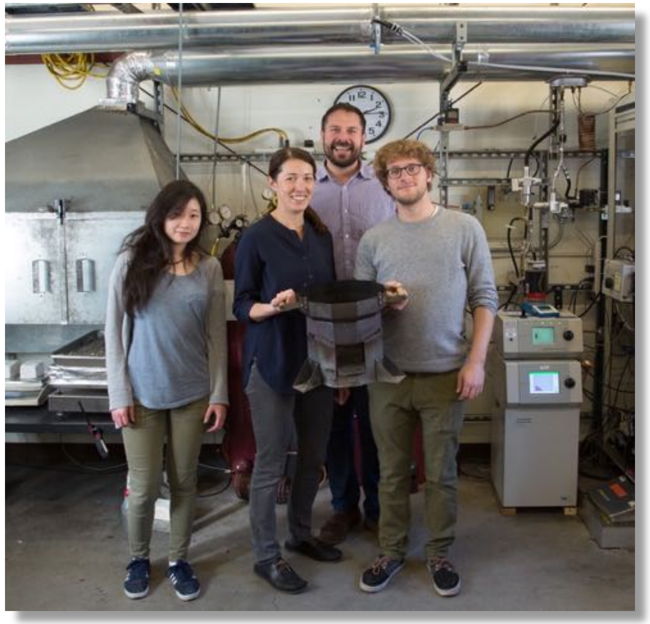
1. Measure what you want to manage. Measure cookstove performance & emissions accurately: Established state-of-the-art laboratory testing facility
2. Identify the design space in which air injection into the flame zone reduces PM emissions by 90% per meal
3. Identify key air injection stove parameters that most affect stove performance and emissions and advance stoves research community's knowledge
4. Evaluate performance and emissions of other DOE funded advanced stove designs (**added 2016**)
5. Understanding user behavior and adoption (**added 2016**)
6. Optimize design for lower pressure air supply (modified 2016)
7. Transfer stove testing knowledge to elevate capabilities of international researchers (**added 2016**)

Completed

Key Accomplishments

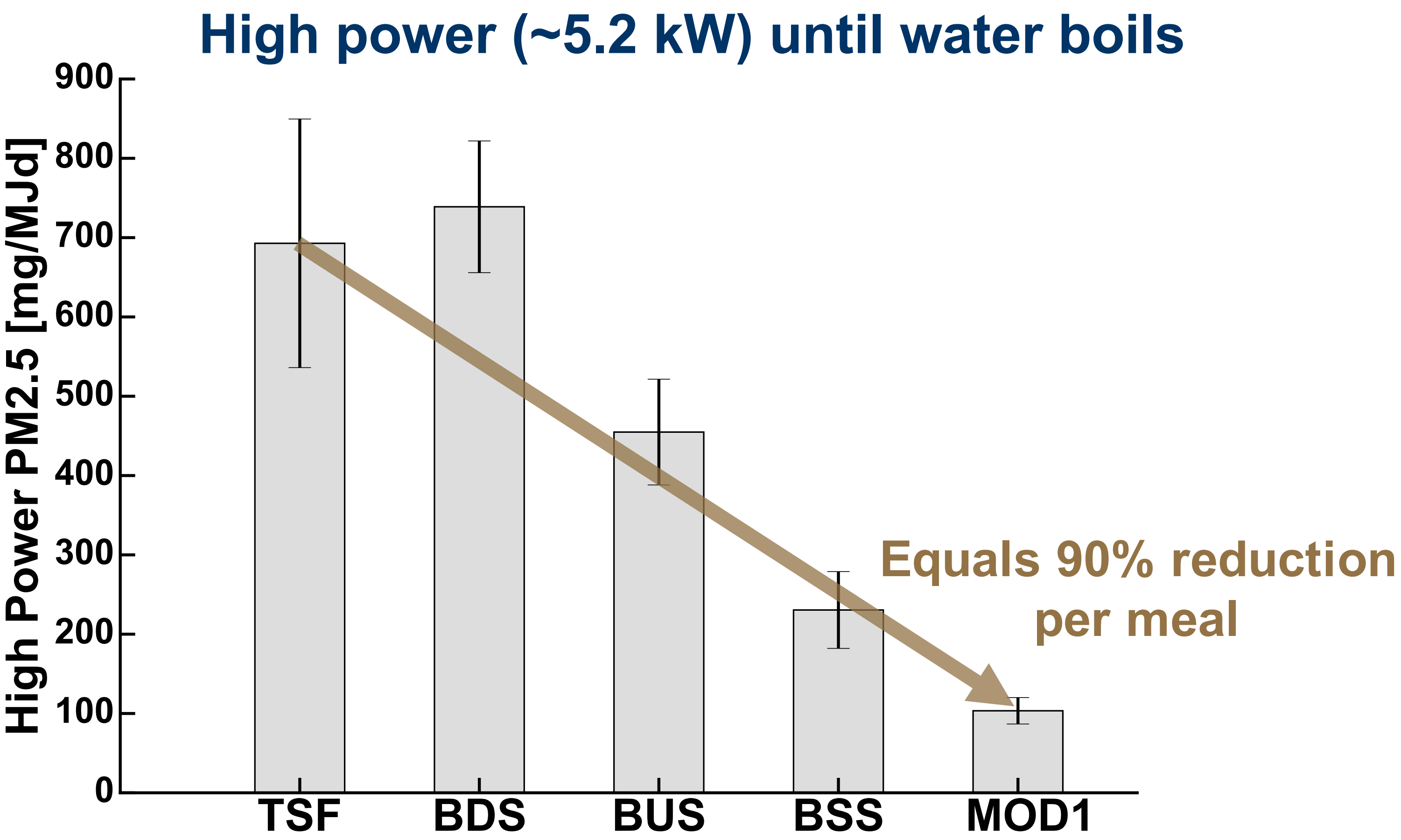
- Developed gold standard stove testing facility
- Designed, developed, and evaluated stove that reduces $PM_{2.5}$ emissions by 90% per meal and advanced scientific knowledge of the community
- Optimized stove for low pressure air supply
- Evaluated BETO funded advanced stoves
- Launched studies to understand behavior and adoption
- Elevated capabilities of international researchers

LBNL State-of-the-Art Cookstove Testing Facility



- Experienced and highly skilled cookstoves team dedicated to testing and data analysis
- Redundant measurements provide easy validation of data collected
- Developed quality assurance plan, SOP, and test protocols

Designed, developed, and evaluated stoves capable of reducing $PM_{2.5}$ emissions by 90% per meal

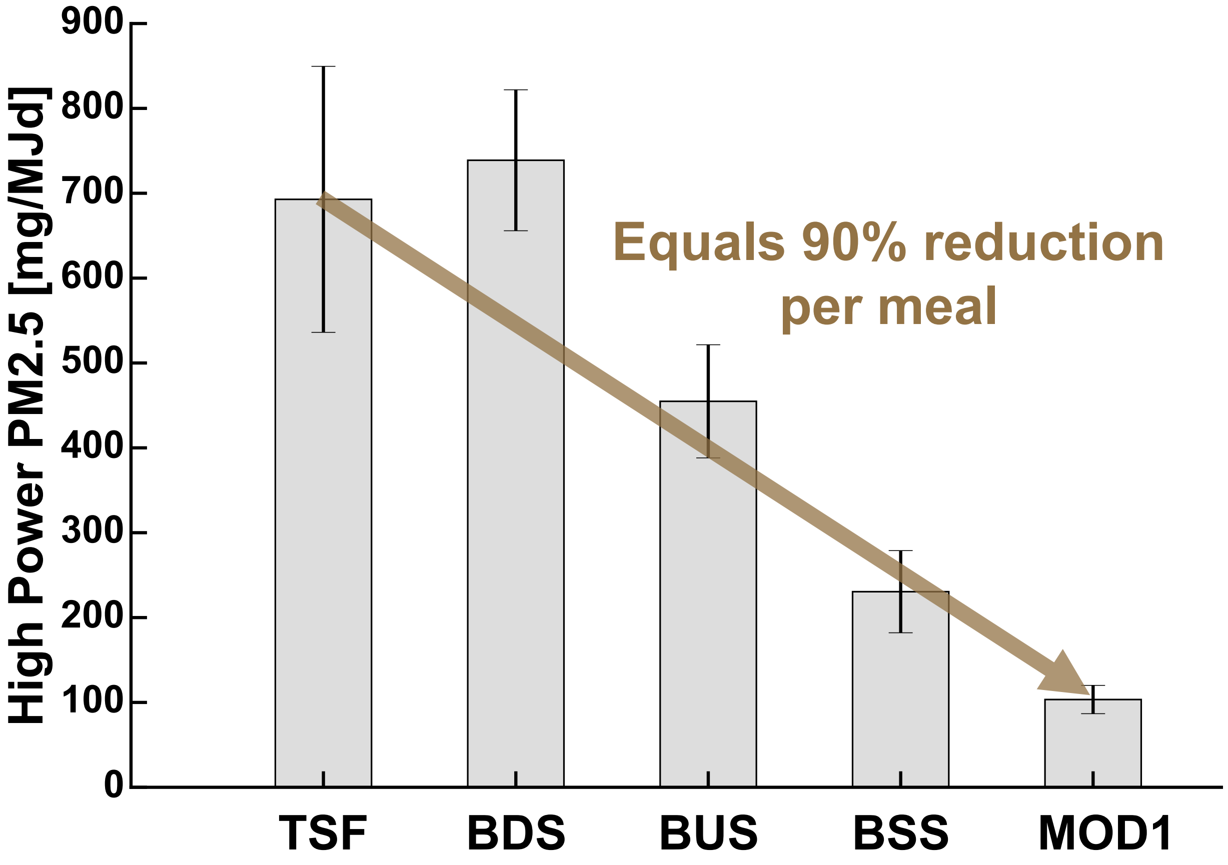


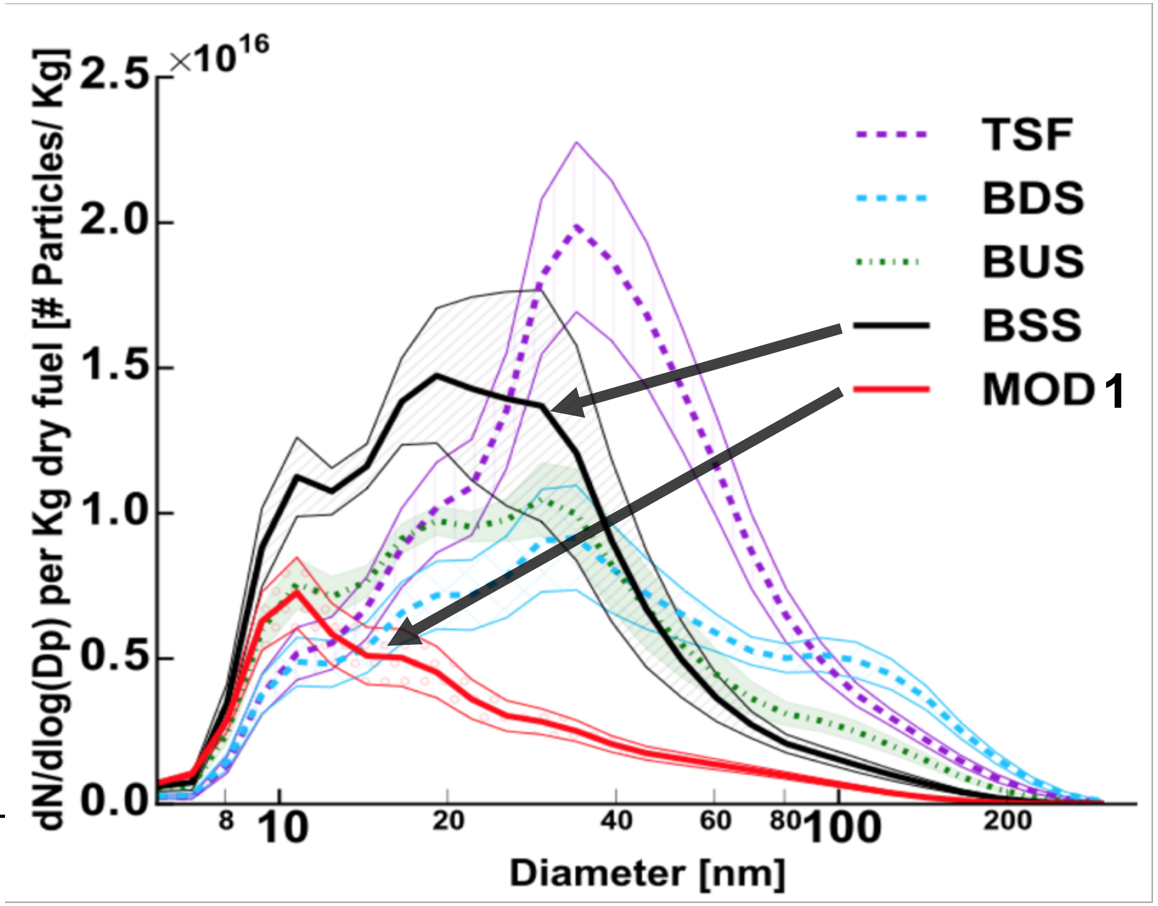
TSF = Three Stone Fire; BDS = Berkeley Darfur Stove; BUS = Berkeley Umbrella Stove
BSS = Berkeley Shower Stove; MOD1 = Berkeley Modular Stove 1

Rapp et al. *Environ. Sci. Tech.*, **2016**, 50(15), 8368-8374

Air injection affects ultrafine $PM_{2.5}$ emissions

High power (~5.2 kW) until water boils



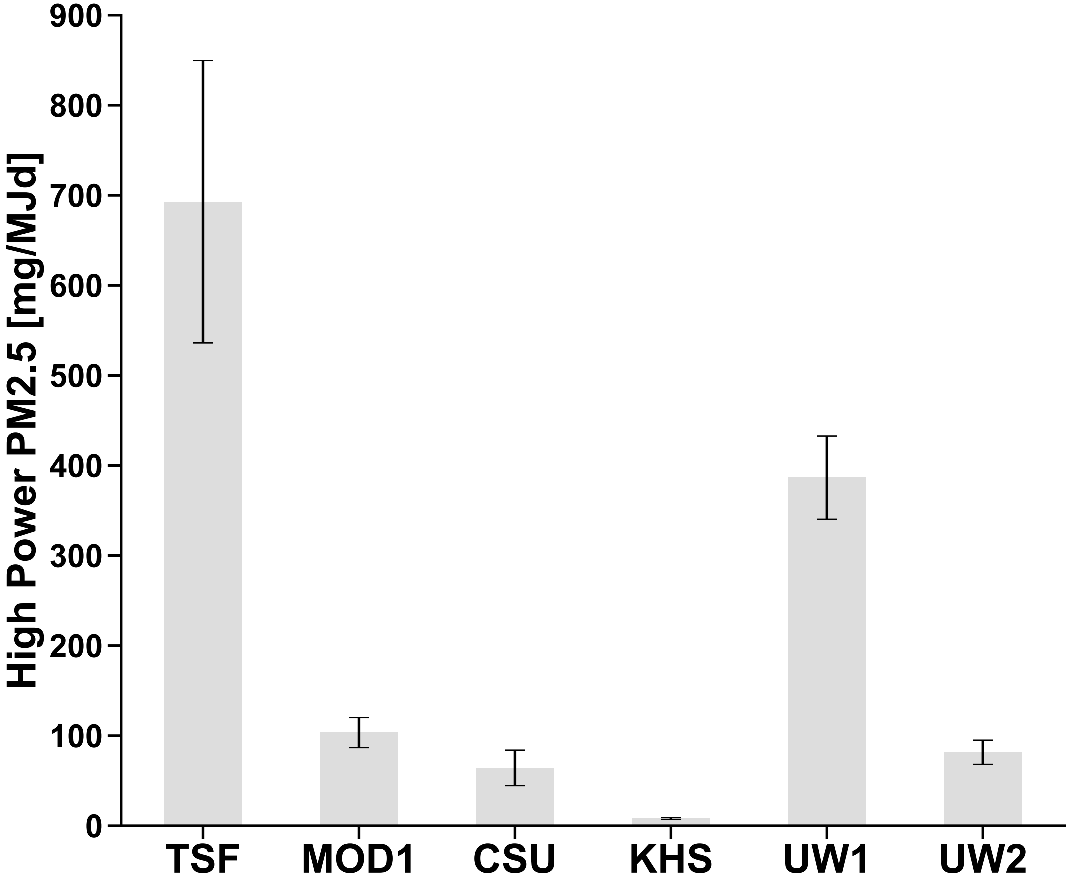


TSF = Three Stone Fire; BDS = Berkeley Darfur Stove; BUS = Berkeley Umbrella Stove
BSS = Berkeley Shower Stove; MOD1 = Berkeley Modular Stove 1

Rapp et al. *Environ. Sci. Tech.*, **2016**, 50(15), 8368-8374

Evaluated performance and emissions of other BETO funded advanced stoves

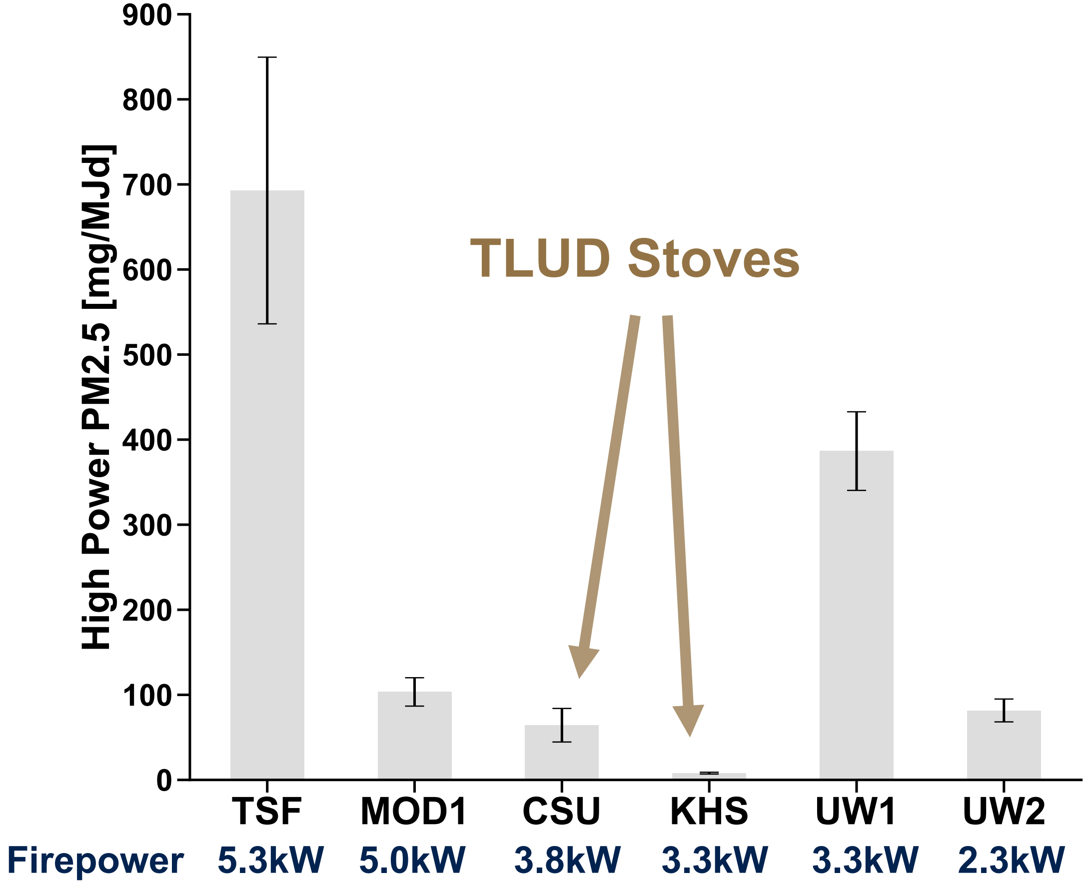
"High" (constant) power until water boils

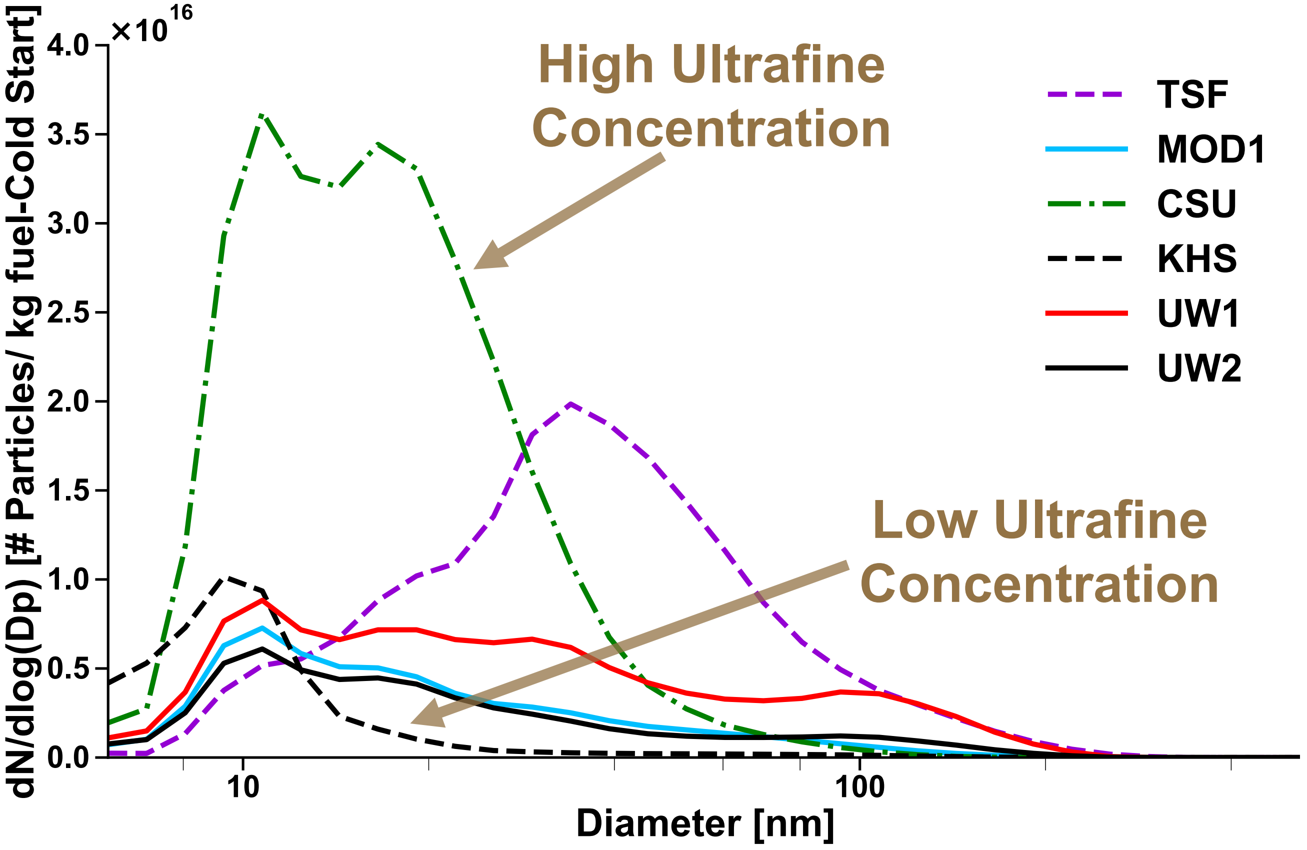


Firepower 5.3kW 5.0kW 3.8kW 3.3kW 3.3kW 2.3kW

Evaluated performance and emissions of other BETO funded advanced stoves (cont)

“High” (constant) power until water boils

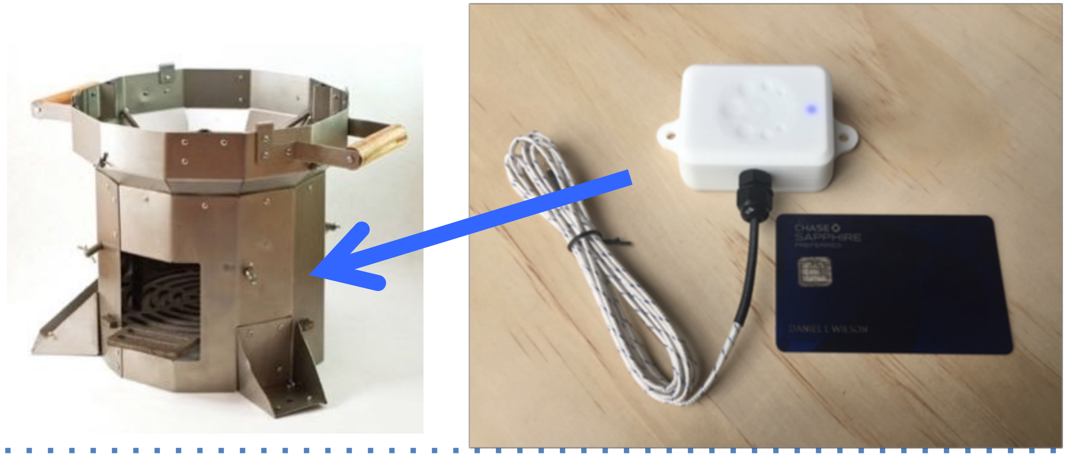




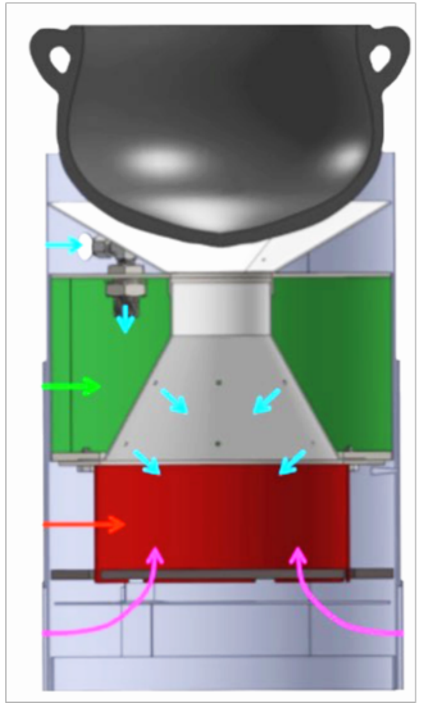
TSF = Three Stone Fire; MOD1 = Berkeley Modular Stove 1; CSU = Colorado State University;
KHS = Kirk Harris Stove; UW1 = University of Washington/Burn; UW2 = University of Washington

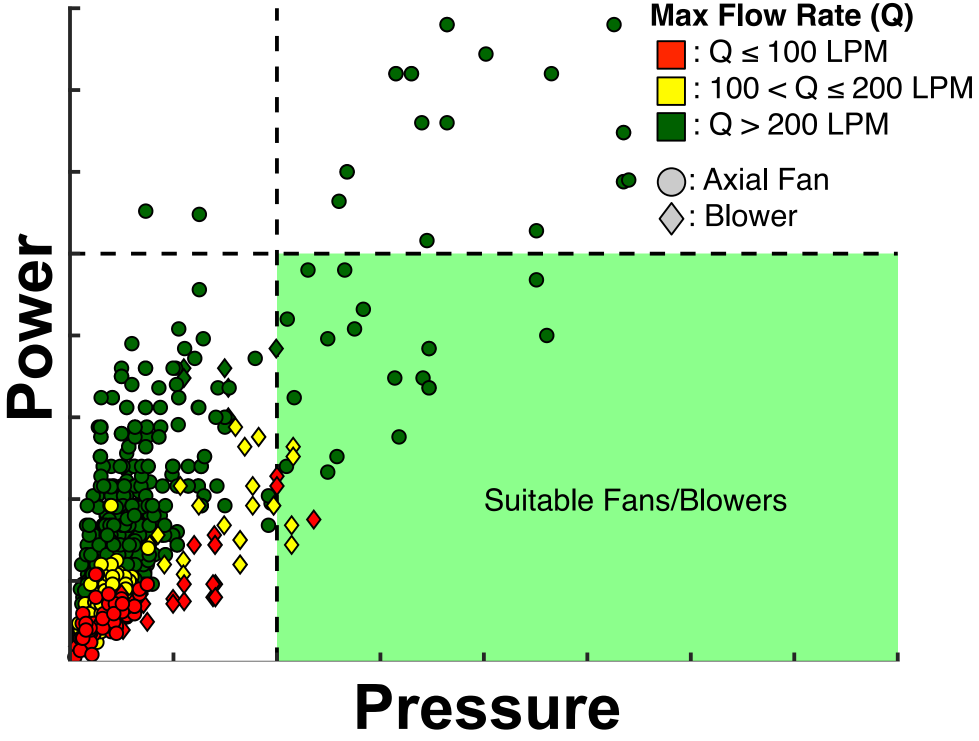
Understanding behavior and adoption

- Completed two high quality highly cited studies, one in Darfur, another in Odisha, India, on how families use advanced stoves,
- One ongoing study in Uganda
- Second study in India yet to be launched with Harvard Global, with oversight and technical support from LBNL and spinoff Geocene



Optimize for low pressure air supply (stretch milestone)

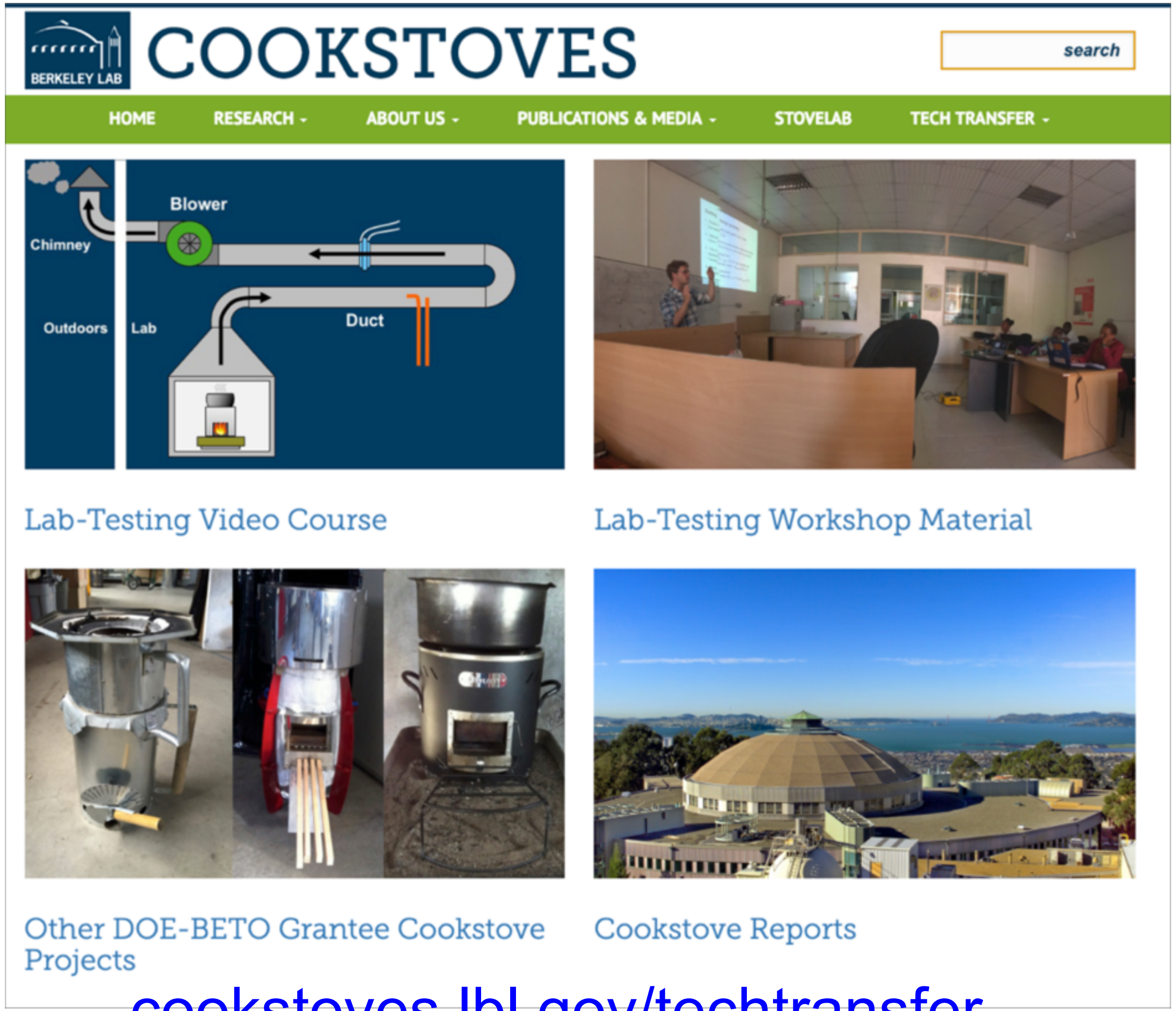




- Integrates lessons learned from MOD1 to reduce $PM_{2.5}$
- Optimized for low pressure supply air injection
- Published design requirements for low pressure fan

*Journal article under review in Environmental Science and Technology

Elevate capabilities of international researchers



cookstoves.lbl.gov/techtransfer

- Published 10 training videos
- Developed onsite training program to support development of accurate stove testing and open source data collection
- Conducted 1-week on-site training in Kampala, Uganda
- Collected feedback and evaluated success of program

Elevate capabilities of international researchers (cont)

- Onsite Training of 7 mid-career staff from CREEC and CIRCODU
- Classroom and in-lab training
- Positive feedback from participants through surveys and verbal feedback
- Validated learning through follow-up surveys and calibration data requests
- Lessons learned: Extend training to 2-weeks to accommodate learning pace

Dissemination of knowledge

- One spinoff company: Geocene, Dr. Daniel Wilson (former Ph.D. student on this project)
- Hired 3 researchers, 3 postdocs, 9 graduate students, and 5 undergraduate students, in addition to 9 visiting graduate students, for this project
- **25+ presentations** including invited presentations at MIT, Stanford Medical School, ETHOS Conference, Australian Combustion Institute, IIT Bombay, GACC Conf., and UC Berkeley.
- **13 accepted/published papers, 1 submitted manuscript** to peer reviewed journals, and 2 chapters in Technologies for Development – *not all research publications were directly funded by DOE, but the DOE funded stoves-lab was critically important for doing all reported work*
- Presentations to multiple stakeholders and potential funders (Ethiopian Stoves Delegation, Tata Trusts, Dutch PostalCode, and India's MNRE)
- Experimental collaboration (at LBNL) with MIT and other BETO-funded institutions
- Leading contributor to ISO/TC 285: Harmonized Laboratory Testing Protocols
- Elevate research capabilities of international stove researchers and designers

4 – Relevance

- Responds to DOE BETO's request for technologies and technological advances that reduce harmful emissions from biomass cookstoves (90% PM2.5 reduction) while boosting cooking performance (50% efficiency increase) compared to the baseline.
- Supports ADO Mission and Goals
  - "De-risk bioenergy production technologies through validated proof of performance at the pilot, demonstration, and pioneer scales and to conduct activities that will transform the biofuels market by reducing or removing commercialization barriers."
- Addresses Multiple BETO Barriers
  - ADO-A. Process Integration
  - ADO-D. Technology Uncertainty of Integration and Scaling
  - At-G. Social Acceptance and Stakeholder Involvement
- Supported GACC's goal of 100 million homes adopting clean and efficient stoves by 2020
- Research has lead to the design of cleaner, more efficient biomass stoves and advanced the stoves research community's understanding of wood combustion in cookstoves

5 – Future Work

Complete Tata-Harvard funded field studies in India on adoption

Use LBNL Cookstove Group’s intellectual expertise and assets to explore opportunities with:

1. Reducing particle emissions from U.S. residential wood heaters
   - Support industry to reduce particle emissions and fuel consumption from 30 million homes using wood burning heaters for primary heat and validate reductions
2. Advancing portable distributed electricity generation from woody biomass and agricultural waste
   - Advance portable gasifier electricity generation systems and/or torrefied wood systems that are emission compliant to improve rural air quality, help alleviate the threat of fire, support reduction in agricultural waste, and provide renewable base-load energy

Summary

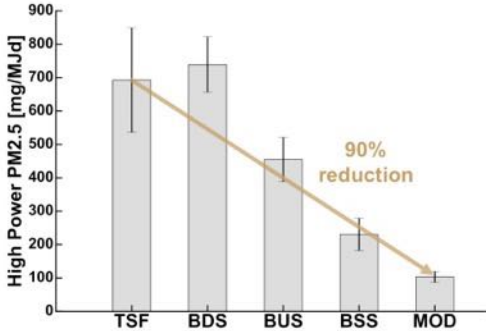
1. **Goal:** Design, develop, and evaluate stoves that reduce PM emission by 90% per meal while maintaining user desired features that will increase adoption, disseminate findings

2. **Approach:** Measure cookstove performance & emissions accurately; identify and optimize the design to reduce PM emissions by 90% per meal; evaluate performance and emissions of other DOE funded advanced stove designs; work to understand user behavior and adoption; transfer stove testing knowledge through publications and presentations

Summary (continued)

3. Accomplishments:

- Developed a gold standard test facility for testing and validating biomass technologies
- Supported development and publication of ISO/TC 285 standard for harmonized laboratory testing
- Designed and validated cookstove with 90% emissions reduction
- Published results to advance science in community
- Published research findings to elucidate cookstove users' behavior in using advanced biomass stoves
- Elevated capabilities of international researchers through videos and onsite training



Summary (continued)

4. **Relevance:** Responds to DOE BETO request for technologies and technological advances that reduce harmful emissions from biomass cookstoves (90% PM2.5 reduction) while boosting cooking performance (50% efficiency increase) compared to the baseline

5. **Future work:** Complete field work in India. Explore opportunities with advancing wood heater systems and test standards, and advancing portable distributed electricity generation from woody biomass and agricultural waste.

ADDITIONAL SLIDES

Publications

1. Daniel L. Wilson,∗,†,‡,¶ Meenakshi Monga,§ Abhinav Saksena,‖ Advait Kumar,⊥ and Ashok Gadgil†, (2018) . Effects of USB Port Access on Cookstove Adoption, Development Engineering Journal,
2. Caubel, J.J., Rapp, V.H., Chen, S.S., Gadgil, A.J., (2018) "Optimization of Secondary Air Injection in a Wood-Burning Cookstove: An Experimental Study," Environmental Science and Technology, 52 (7), pp 4449–4456
3. Lask, Kathleen, Kayje Booker, and Ashok Gadgil (2017). *Lessons learned from a comparison study of charcoal stoves for Haiti.* Sustainable Energy Technologies and Assessments. DOI: 10.1016/j.seta.2017.02.008
4. Lask, K. L., and A. J. Gadgil (2017). *Performance and Emissions Characteristics of a Lighting Cone for Charcoal Stoves*. Energy for Sustainable Development, V. 36, pp. 64-67. DOI: 10.1016/j.esd.2016.03.001.
5. Wilson, Daniel L., Jeremy Coyle, Angeli Kirk, Javier Rosa, Omnia Abbas, Mohammed Idris Adam, and Ashok J. Gadgil (2016). *Measuring and Increasing Adoption Rates of Cookstoves in a Humanitarian Crisis.* Environmental Science and Technology. V50, pp. 9393-8399. DOI: 10.1021/acs.est.6b02899
6. Rapp, V.H., Caubel, J.J., Wilson, D.W., Gadgil, A.J. (2016) "Reducing ultrafine particle emissions using air injection in wood-burning cookstoves," Environmental Science and Technology, 50 (15), pp 8368–8374
7. Wilson, Daniel L., D. R. Talacon, R. L. Winslow, X. Linares and A. J. Gadgil (2016). *Avoided emissions of a fuel-efficient biomass cookstove dwarf embodied emissions.* Development Engineering, V.1, No. 1. DOI:10.1016/j.deveng.2016.01.001
8. Lask, K.M., Medwell, P.R., Birzer, C.H., Gadgil, A.J., Soot Reduction in Cookstoves due to Turbulent Mixing. Proceedings of the Australian Combustion Symposium (2015), Melbourne, pp. 380-383. (Papers at this Symposium are treated as peer-reviewed journal papers in this field).
9. Lask, K., K. Booker, T. Han, J. Granderson, N. Yang, C. Ceballos, and A. J. Gadgil, (2015) *Performance Comparison of Charcoal Cookstoves for Haiti: Laboratory Testing with Water Boiling and Controlled Cooking Tests*, Energy for Sustainable Development, Vol. 26, pp. 79-86. DOI:10.1016/j.esd.2015.02.002
10. Wang, Y., M. D. Sohn, Y. Wang, K. Lask, T. Kirchstetter and A. Gadgil (2014). *How many replicate tests are needed to test cookstove performance and emissions? -- Three is not always adequate*. Energy for Sustainable Development **20**: 21-29. DOI:10.1016/j.esd.2014.02.002
11. Preble, C. V., O. L. Hadley, A. J. Gadgil and T. W. Kirchstetter (2014). *Emissions and Climate-Relevant Optical Properties of Pollutants Emitted from a Three-Stone Fire and the Berkeley-Darfur Stove tested under laboratory conditions*. Environmental Science and Technology **48**: 6484-6491.
12. Gadgil, A. J., A. Sosler and D. Stein (2013). *Stove Solutions: Improving Health, Safety and the Environment in Darfur with Fuel-Efficient Cookstoves*. Solutions Journal **4**(1).
13. Booker, K., A. J. Gadgil and D. Winickoff (2012). *Engineering for the Global Poor: The Role of Intellectual Property*. Science and Public Policy: 1-12.

Patent

- A design patent has been issued by the USPTO for the Berkeley-Darfur Stove. Univ. of California, the operator of LBNL, owns the patent rights. UC / LBNL has licensed the Berkeley-Darfur Stove to two entities so far.

Technology Transfer

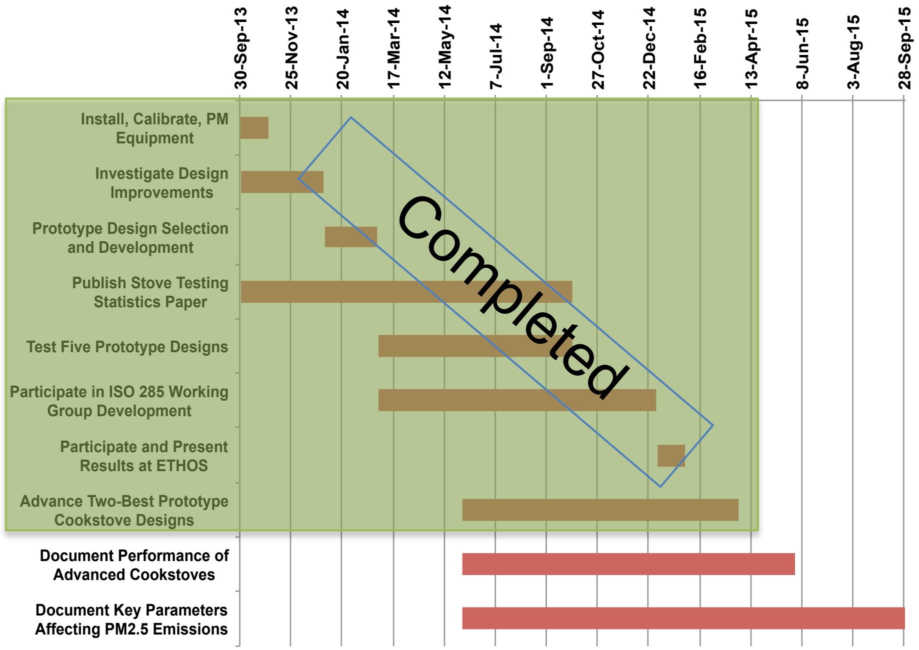
- LBNL undertook a substantial technology transfer effort in the past two years (2017-2018) to raise the standard of researchers internationally in cookstoves measurement laboratory techniques. LBNL prepared, got reviewed, and posted a set of 10 training videos that were well publicized and have been well received by the stoves research community.
- LBNL researchers visited Uganda for 10 days to deliver training at the request to two non-profit that wanted to be trained to use the stoves lab that they wanted to commission and operate correctly. Results were good.
- LBNL scientists took an international lead in **ISO/TC 285** which required long conference calls and long intense discussions with other international researchers. Our participation was gratefully appreciated by other countries.

Overview slide from mid-point review in March 2015

TIMELINE:

Project start date: Sept. 2013

Percent complete: 50% (as of 03/2015)



	Total Costs FY 10 – 12	FY 13 Costs	FY 14 Costs	Total Planned Costs FY 15
DOE Funded	$0	$0	$541,200	$450,000

Barriers / Challenges

- **Manipulate flame for 10-fold reduction in $PM_{2.5}$ emissions per meal**
- **Measure cookstove performance reliably:** Set up model lab facility
- **Translate science to affordable and desirable technology**
- **Design for Manufacturability, Cost, and User Adoption**

Partners:

- **Potential Energy (NGO):** Test tier-4 stoves in our lab
- **ISO/TC 285:** Participate in Standards development
- **CEGA (UC Berkeley):** User monitoring and evaluation
- **IIT Delhi:** Next generation SUMs
- **MIT:** Aerosol chemistry

Project Scope Change Table

Scope Changes	Date	Logic / Reasoning	Approval / Rejection Date
FY16			
Task 2 - Discontinue Test commercial TEG or equivalent device	04/15/2016	Initial FY16 – Task 2 was discontinued due to industry partner pivoting away from developing high efficiency, thin-filmed thermoelectric generators (HiE TEG). Explored other potential partners and options, but a suitable replacement was not found. Project scope was revised to reflect the change and new milestone was added to support testing of BETO advanced stoves.	Approved 04/31/2016
Task 3 - Integrate power generation and blower system with stove prototype (Discontinued in FY2016)	04/15/2016	Initial FY16 – Task 3 was discontinued due to industry partner pivoting away from developing HiE TEG. Explored other potential partners and options, but a suitable replacement was not found. Project scope was revised to reflect the change and a stretch milestone was added to design advanced stove for low pressure air supply and provide design guidelines.	Approved 04/31/2016

ADDITIONAL BACKGROUND SLIDES

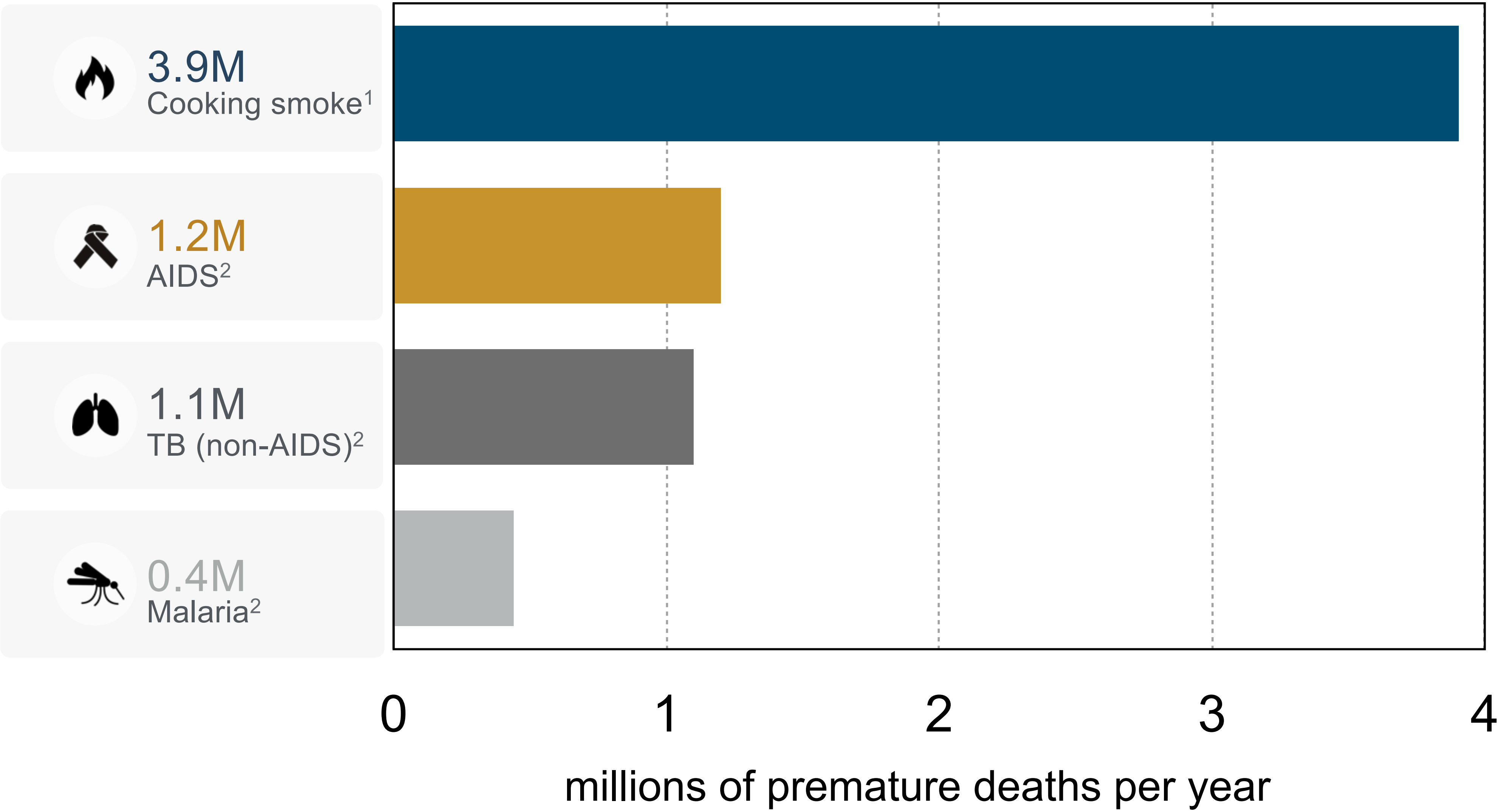
Air pollution kills

- #1 environmental risk factor for human health
- Minimal (and poorly enforced) regulations in developing countries
- > 5.5 million premature deaths per year[1]

ucsusa.org

[1]Brauer (2016), "The Global Burden of Disease from Air Pollution," Presentation at AAAS 2016 Annual Meeting

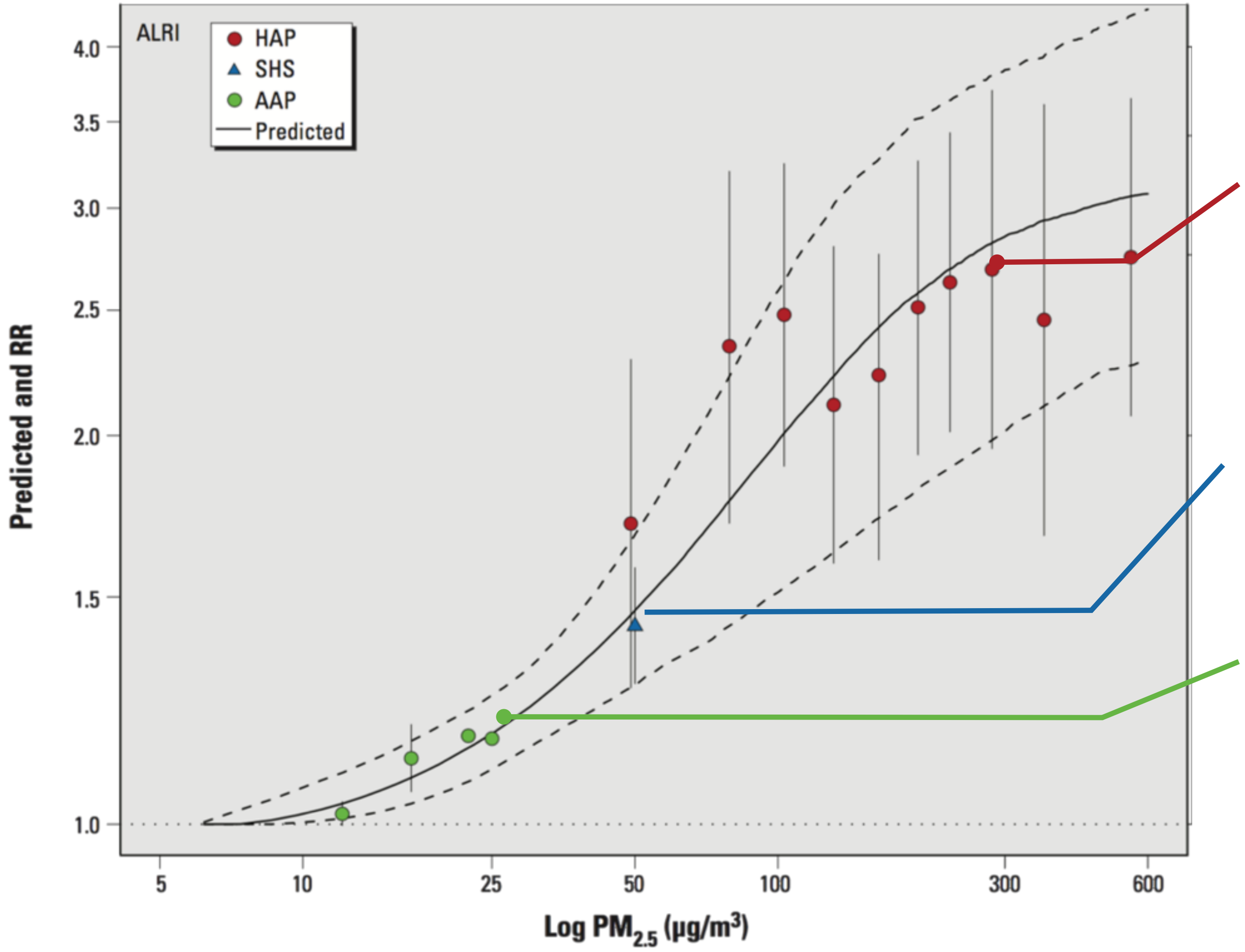
Biomass PM kills more than AIDS, malaria, and TB combined



[1] Lim, S. S. et al. *The Lancet* 380, 2224–2260 (2013)
[2] World Health, 2016

Significant risk reduction requires large reduction in $PM_{2.5}$

Relative Risk of Acute Lower Respiratory Infection in Infants, Burnett et al., (2014)



~2.5 relative risk from household air pollution from biomass cooking (HAP)

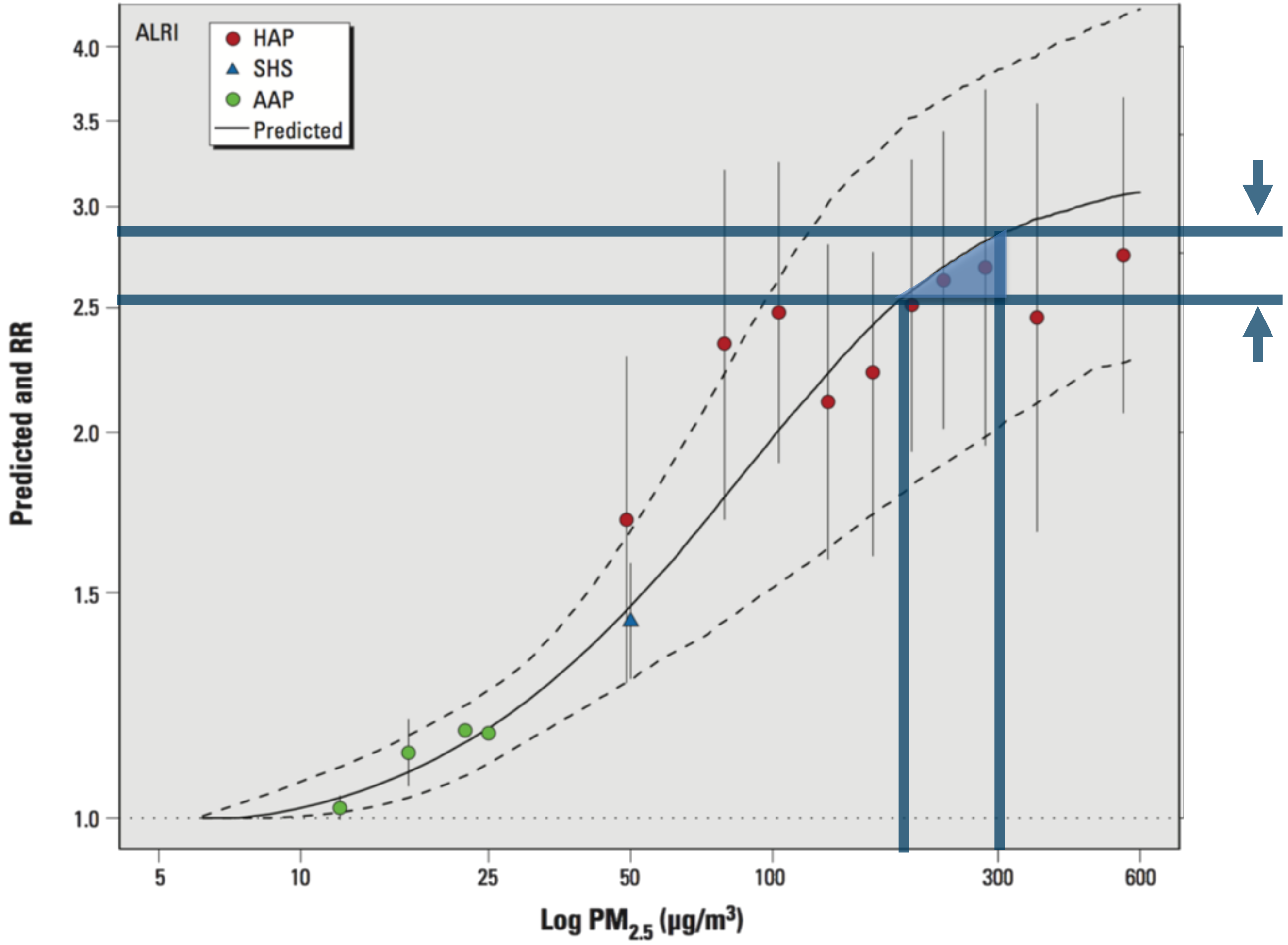
~1.4 relative risk from secondhand smoke (SHS)

~1.1 relative risk from urban air pollution (AAP)

BERKELEY LAB

Significant risk reduction requires large reduction in $PM_{2.5}$

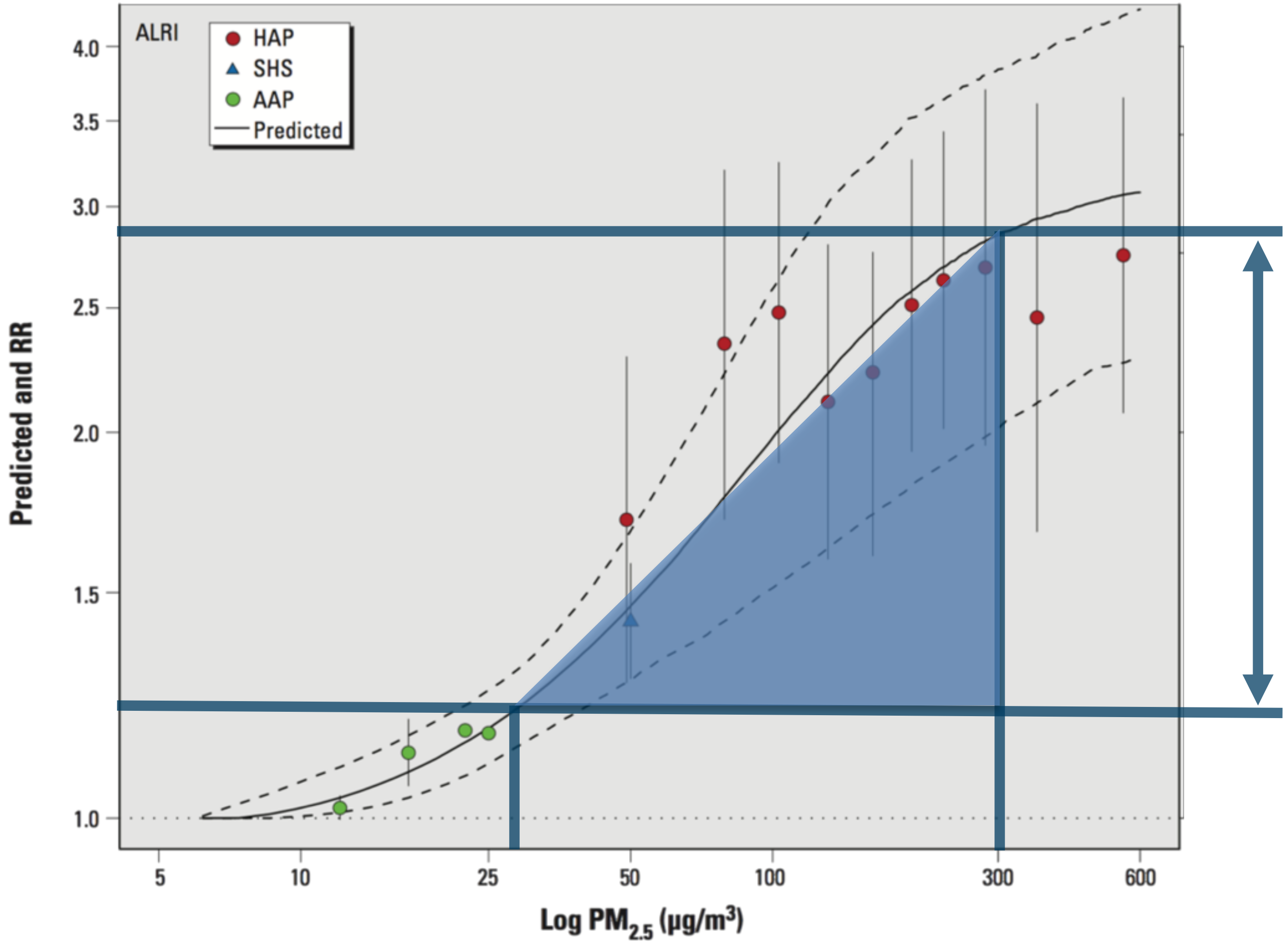
Relative Risk of Acute Lower Respiratory Infection in Infants, Burnett et al., (2014)



Risk reduced modestly with 50% reduction in $PM_{2.5}$

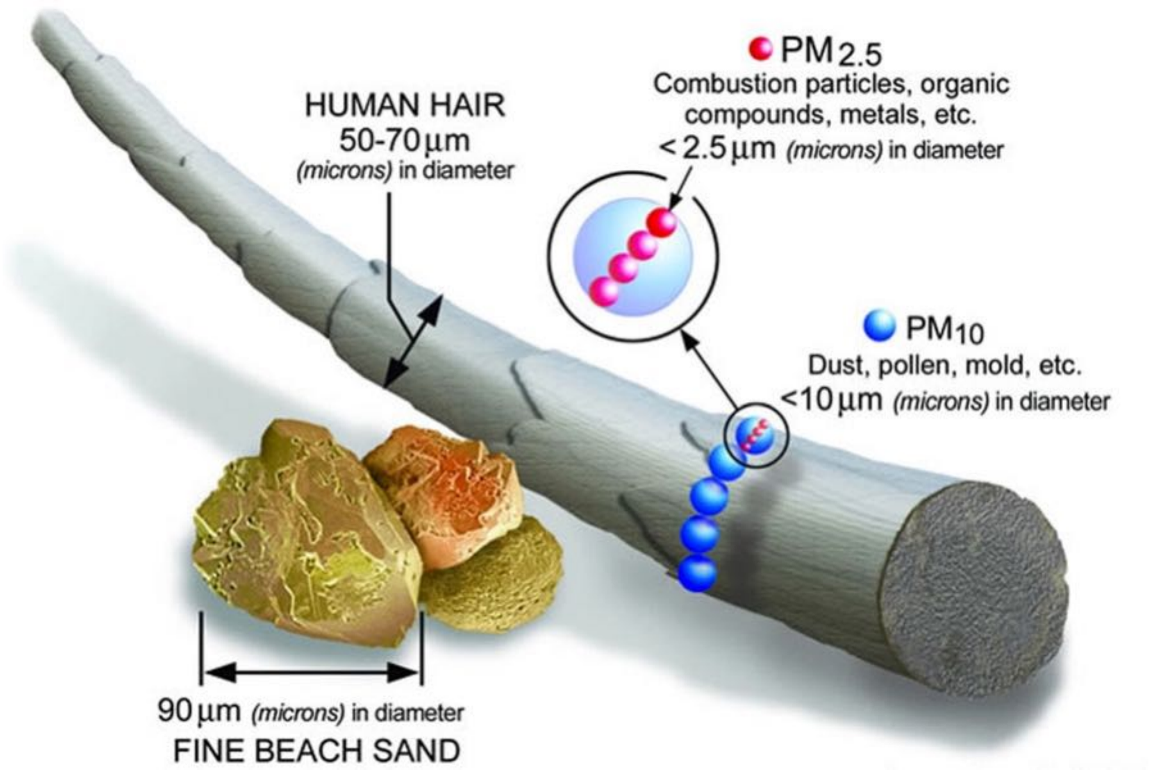
Significant risk reduction requires large reduction in $PM_{2.5}$

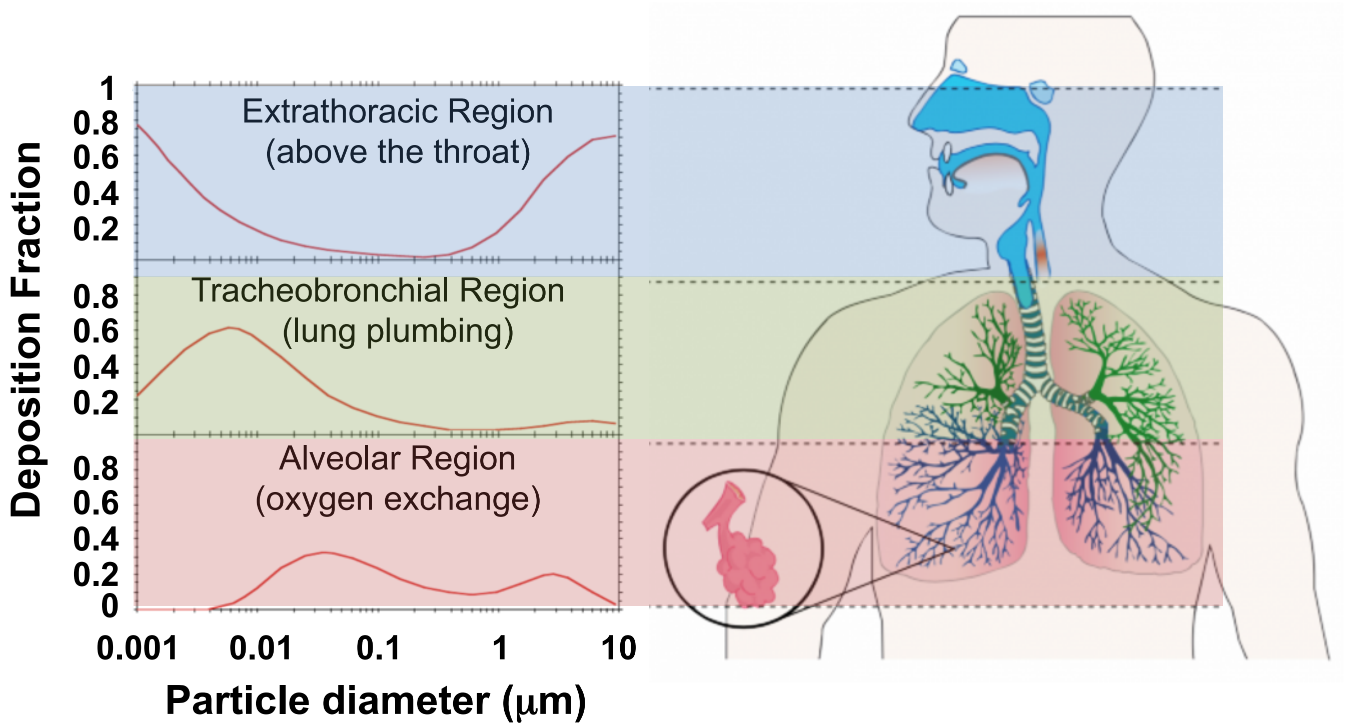
Relative Risk of Acute Lower Respiratory Infection in Infants, Burnett et al., (2014)



Risk reduced significantly with 90% reduction in $PM_{2.5}$

Health impact quantified by particles less than 2.5 μm

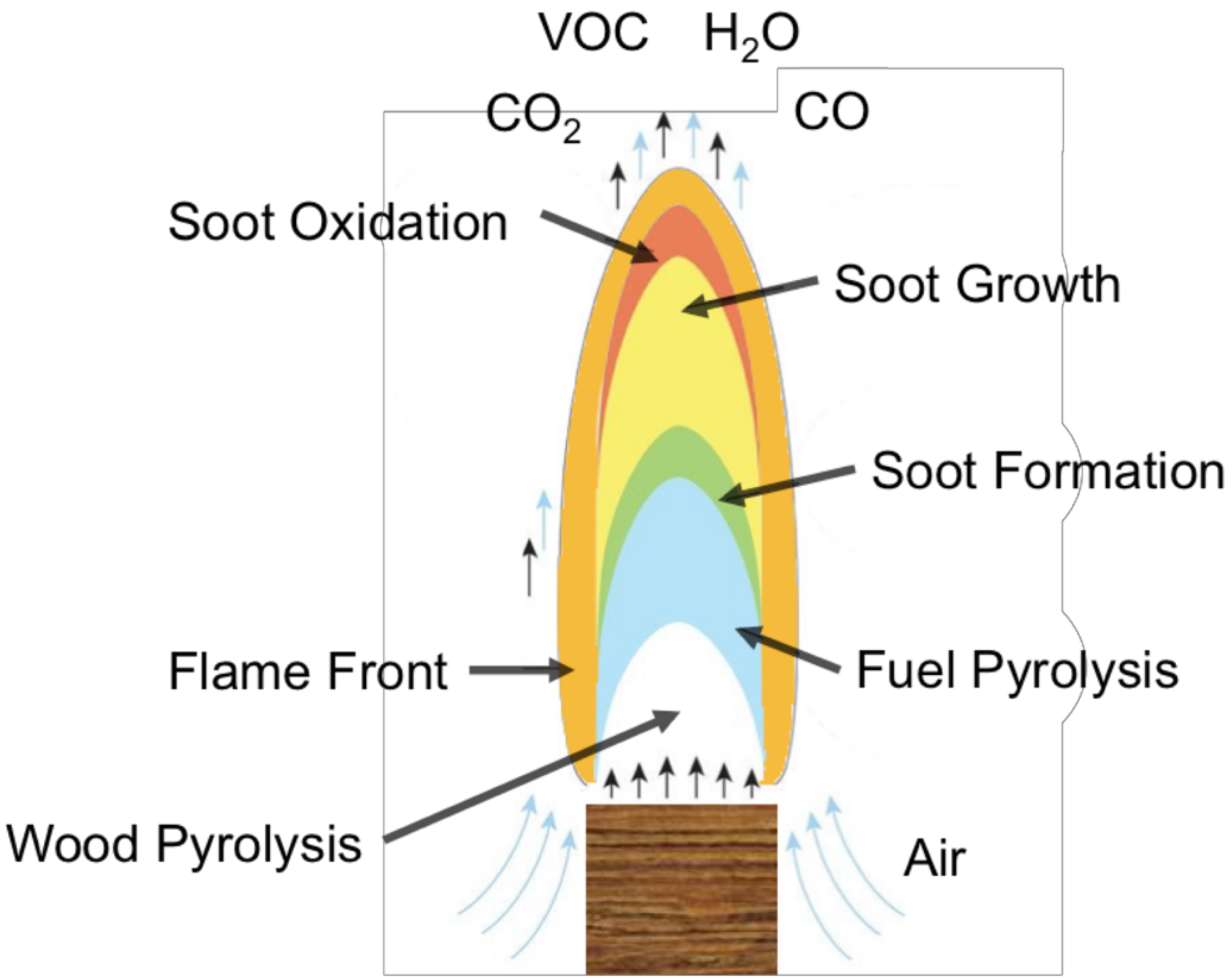




Building from previous knowledge: Berkeley-Darfur Stove

- > 45,000 disseminated in Darfur
- ~ 50% fuel savings
- Performance and emissions are well characterized
- Incorporates desirable features
  - high thermal power (~5 kW)
  - uses collected wood/fuel
  - visible flame

How air injection can significantly reduce $PM_{2.5}$



- Promote better fuel-air mixing
- Increase residence time of combustibles in the hot flame

Adopted from American Scientist Magazine

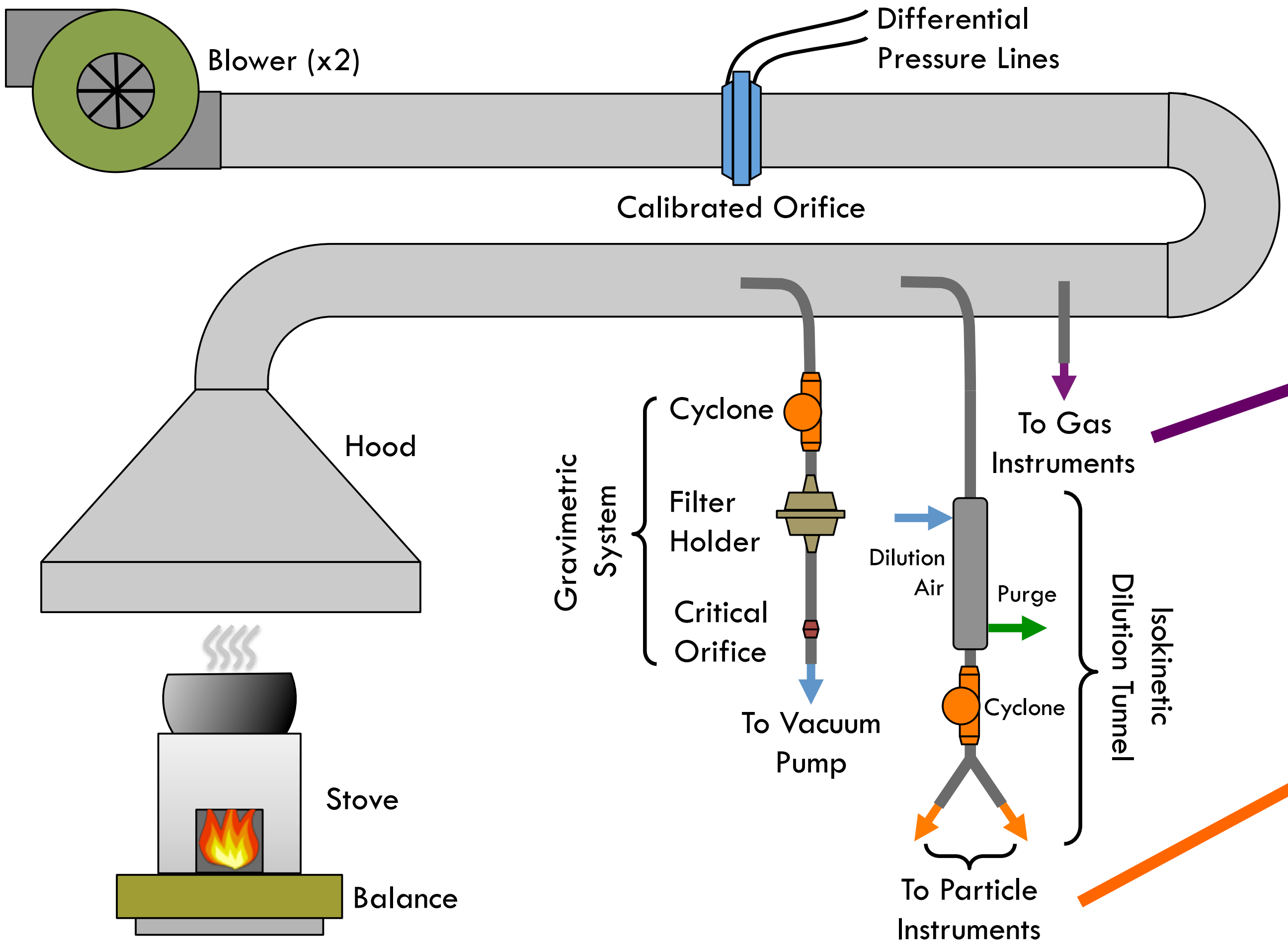
ADDITIONAL TECHNICAL PROGRESS SLIDES

Evaluating Improved Biomass Cookstoves

- Standardized (ISO) Water Boiling Test
  (5L water to boil followed by 30-minute simmer)
- Stoves tested at constant firepower
- PM and gaseous emissions collected at 1 Hz
- Results compared to baseline TSF and BDS

Three Stone Fire (TSF) | Berkeley Darfur Stove (BDS)

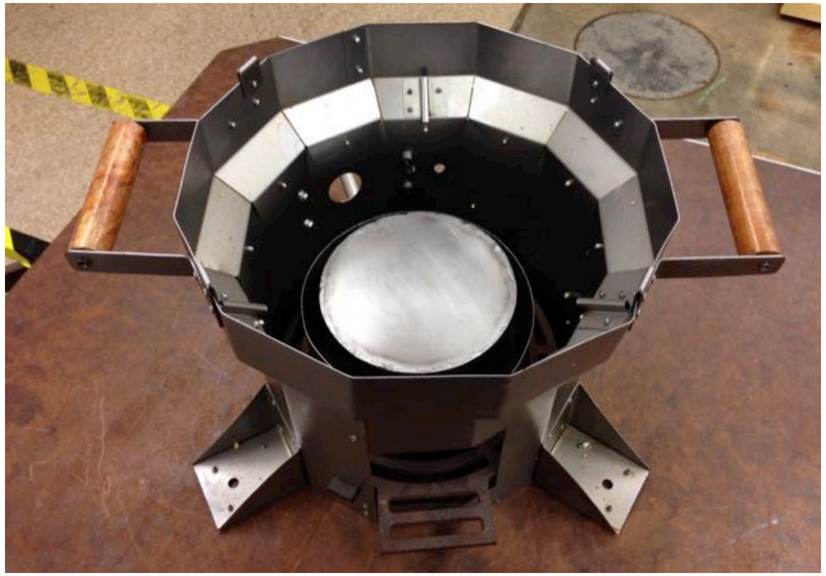
Schematic of Berkeley Lab Testing Facility and Equipment

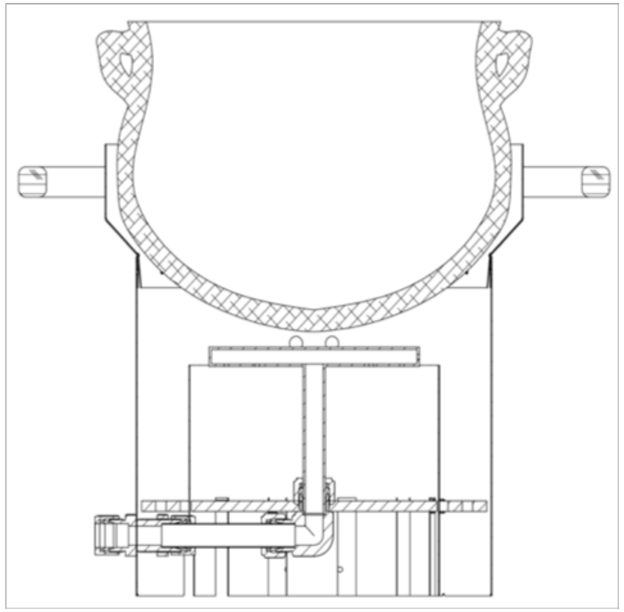


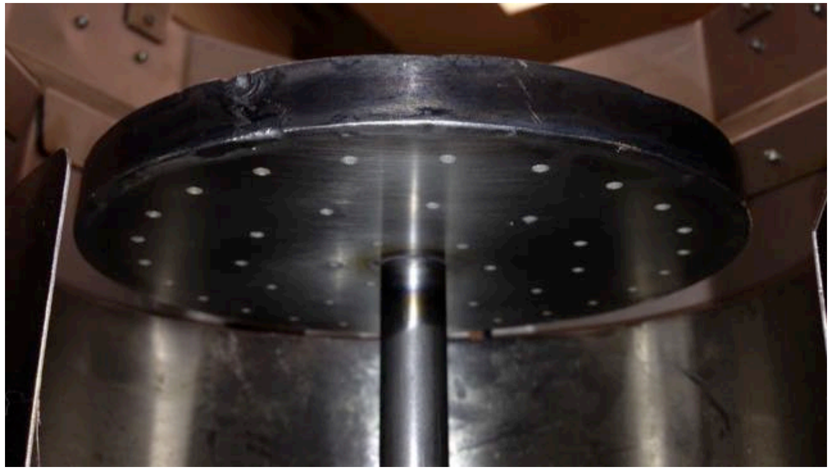
Effects of flow manipulation on $PM_{2.5}$

- Built and evaluated <u>eight</u> stove prototypes
- Explored a wide range of flow manipulation and turbulence generation techniques
- Designed two fully modular stoves for parametrically isolating key variables and operating conditions
- Explored scientific underpinning for designing a ISO-Tier 4 cookstoves

Berkeley Umbrella Stove (BUS)

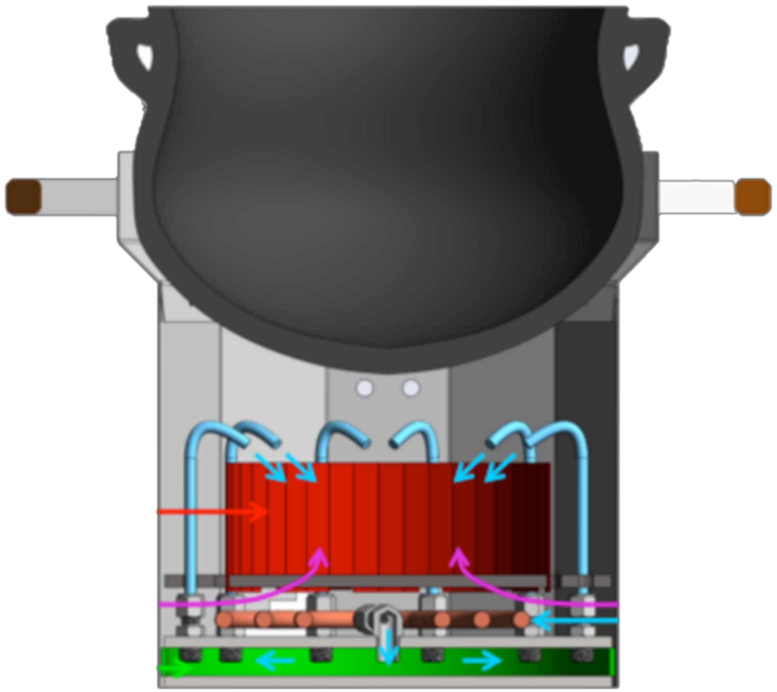


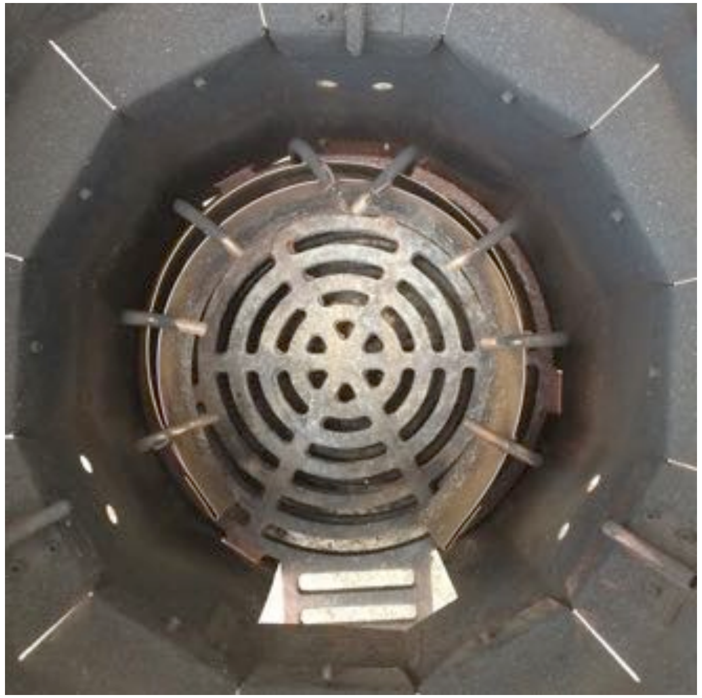




- Downward small air jets applied to combustion zone
- Air is preheated when fire is established
- Umbrella acts as radiation shield

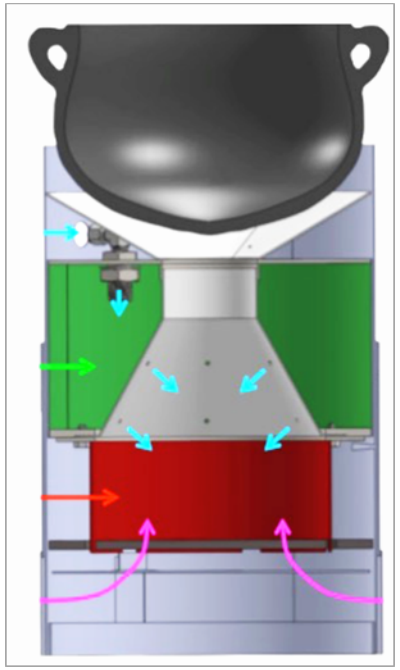
Berkeley Shower Stove (BSS)





- Concentric ring of nozzles “shower head” mounted to pancake air manifold
- Air is preheated via copper coil and manifold

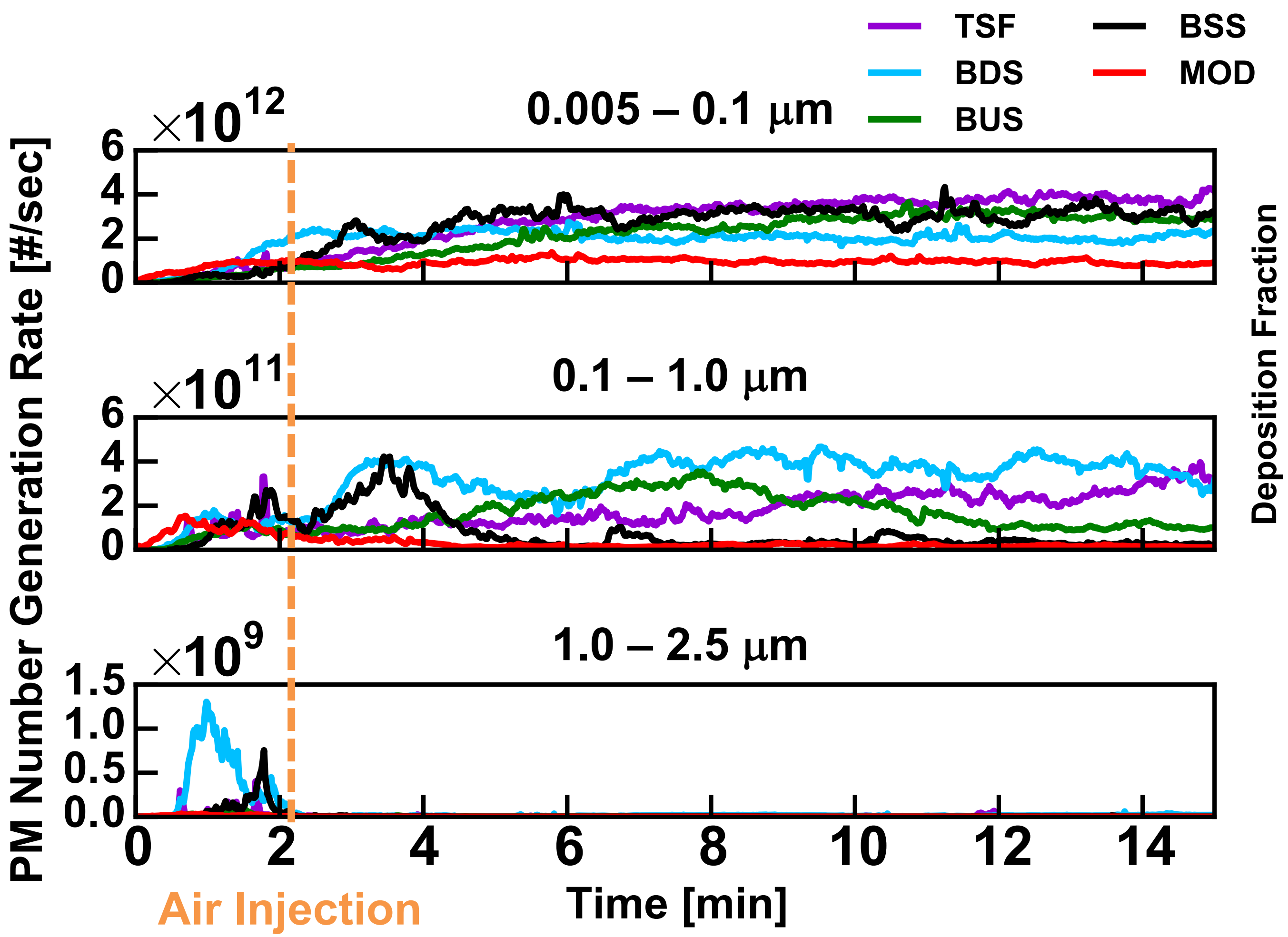
Berkeley Modular Stove 1 (MOD1)

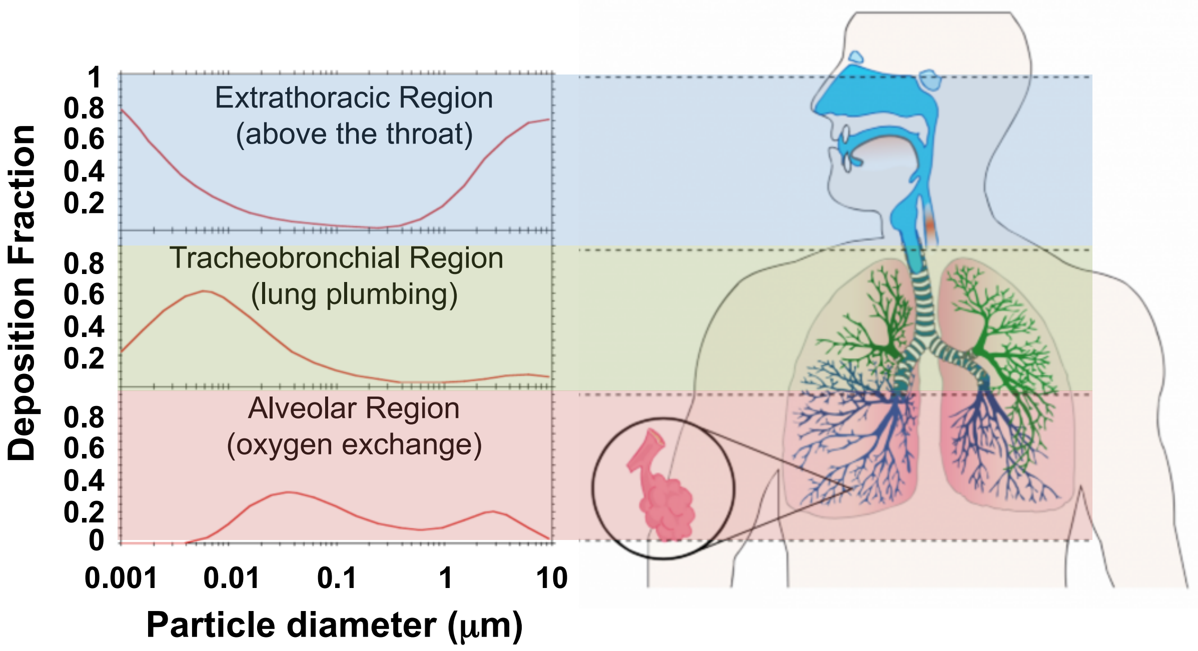


- Integrates lessons learned from BUS and BSS
- Rapid, parametric adjustment of key parameters that affect $PM_{2.5}$ emissions

Generation rate of PM varies with air injection

High Power Operation (~5.2kW)





Evaluate other BETO-funded advanced stoves

Kirk Harris Stove
(Aprovecho)
Natural draft
Top-Lit Up Draft
(KHS)

Colorado State
University
(Envirofit)
Forced-Air
Top-Lit Up Draft
(CSU)

University of
Washington (Burn)
Natural draft
Rocket Stove
(UW1)

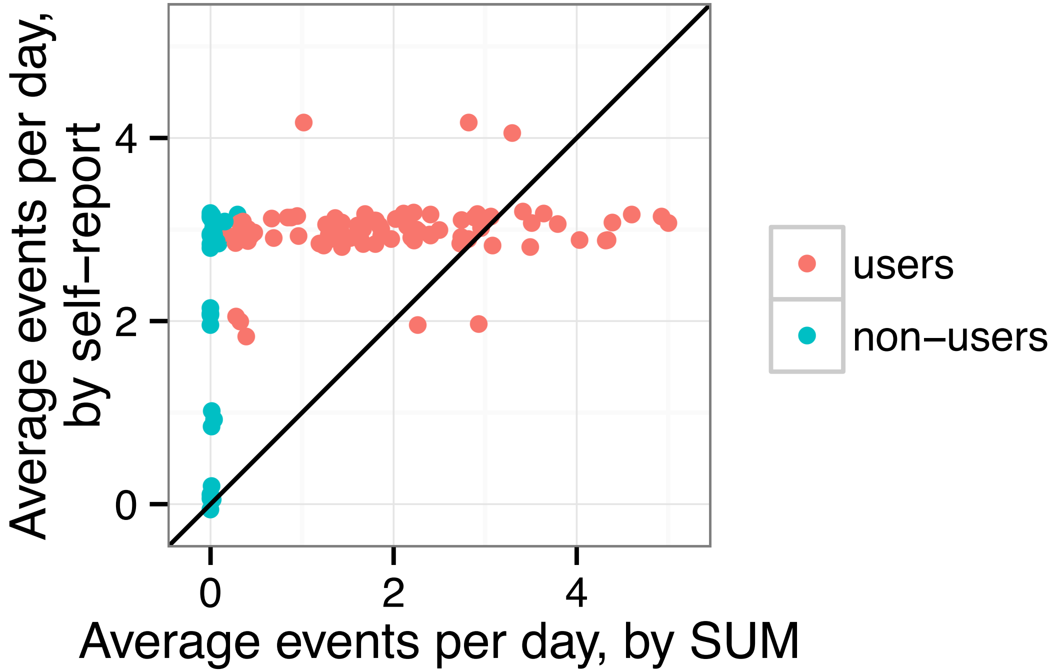
University of
Washington
“Tall Boy”
(UW2)

Understanding behavior and adoption

Affordable Advanced Stove Use Monitors (ASUMS)
~$20 for materials, commercial iButton ~$80

- Multiuse device
- 10 month continuous operation
- Temperature & analog ports

Use over-reported by 85%



Elevate capabilities of international researchers

Support development of quality assurance plan, testing checklist, and test protocols

LBNL COOKSTOVE RESEARCH FACILITY QUALITY ASSURANCE PLAN (QAP)

Lawrence Berkeley National Laboratory
Stoves Group

September 2016

EQUIPMENT START-UP

Check off boxes as you complete each step

Step 1 ☐ **Ensure that the particle sample line, SBA-5, and FMPS are disconnected**

Step 2 → **Instrument turn on checklist:**

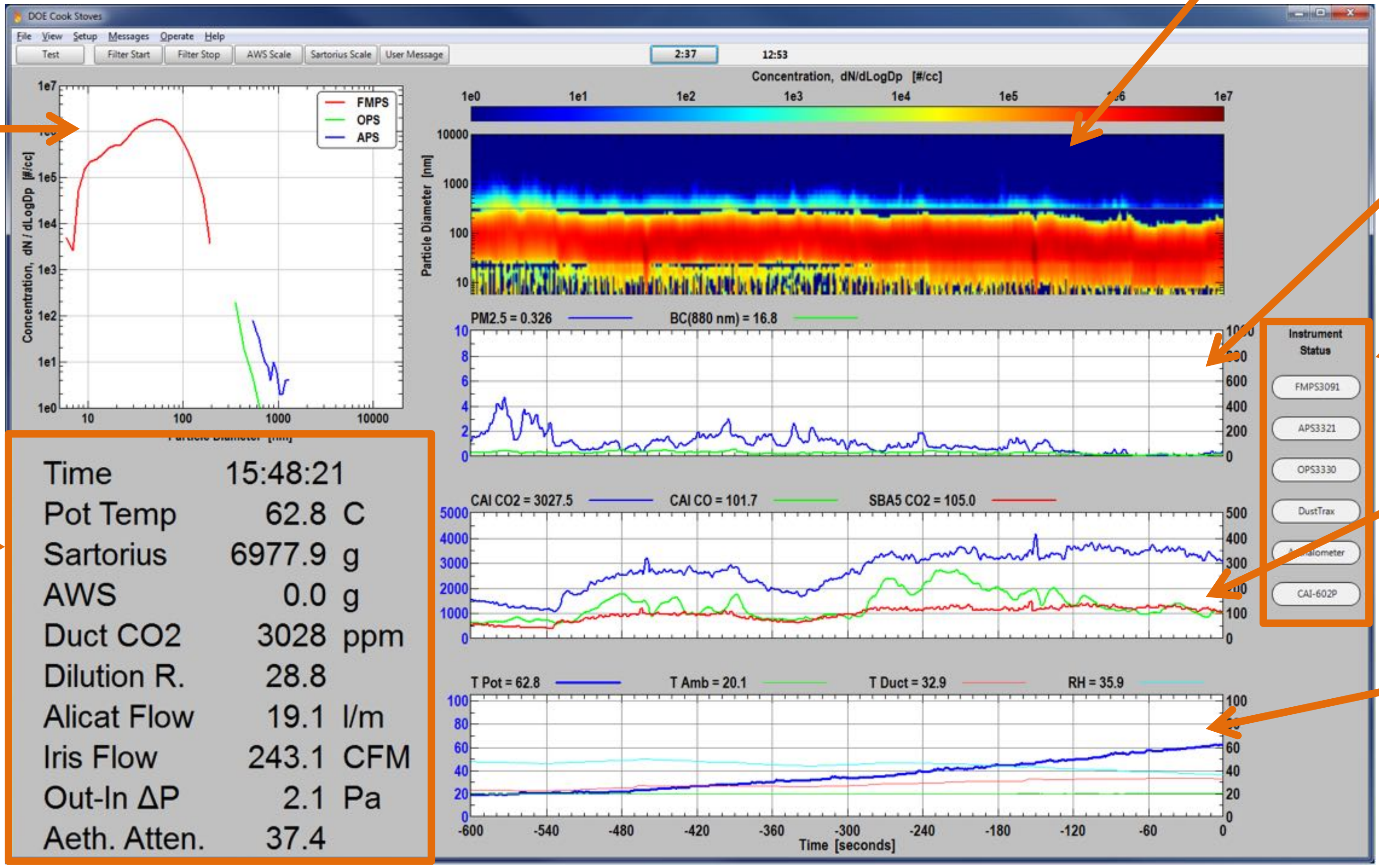
- ☐ Turn on **CAI 602P NDIR CO/CO_2 Analyzer**
  - *Press LIGHTBULB > MAIN > MEASUREMENTS [F1]*
- ☐ Turn on **Sartorius Platform Scale ("large scale")**
- ☐ Turn on **AWS KG-10 Scale ("medium scale")**
- For the **Magee-Scientific Aethalometer...**
- ☐ >>> Turn on Aethalometer
- ☐ >>> Turn on the UV channel setting:
  1. *After start-up, press ENTER > highlight OPERATE > press ENTER*
  2. *Then use UP ARROW to select UV CHANNEL ON > press ENTER*
  3. *Make sure AUTOMODE is ON > press ENTER*
- ☐ Turn on **TSI FMPS 3091**
- ☐ Turn on **TSI APS 3321**
- ☐ Turn on **TSI OPS 3330**
- ☐ Turn on **TSI DustTrak HandHeld DRX 8534...**
- ☐ Turn on **PP-Systems SB-5 CO_2 Analyzer** (button on power strip)
- ☐ Is **APT 8-channel** turned on and working?
- ☐ Is **USB-TC-AI thermocouple logger** in working condition?
- ☐ Is the **Alicat Mass Flow Controller M-Series** in working condition?
- ☐ Is the **vacuum pump** in working condition? (Cool it if it's too hot)

Development of open source data collection system

python

Ultrafine particle distribution from FMPS, OPS, and APS

Key test variables



Ultrafine particle distribution over time from FMPS & OPS

$PM_{2.5}$ and BC measurements

Instrument error indicators

Gas emissions measurements

Temperatures and RH trendlines