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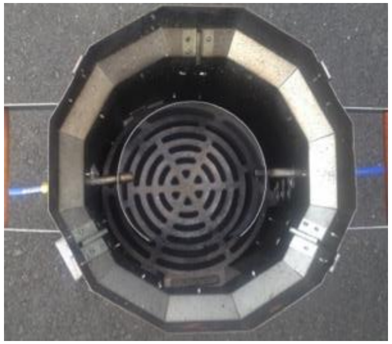
LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE Bioenergy Technologies Office

2015 Peer Review



An Affordable Advanced Biomass Cookstove with Thermoelectric Generator (TEG)

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Lawrence Berkeley National Laboratory

Biomass Cookstove Technology Review

March 26, 2015

Goal Statement

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Develop an affordable tier-4 cookstove desirable for purchase

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 $PM_{2.5}$ 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.

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Quad Chart Overview

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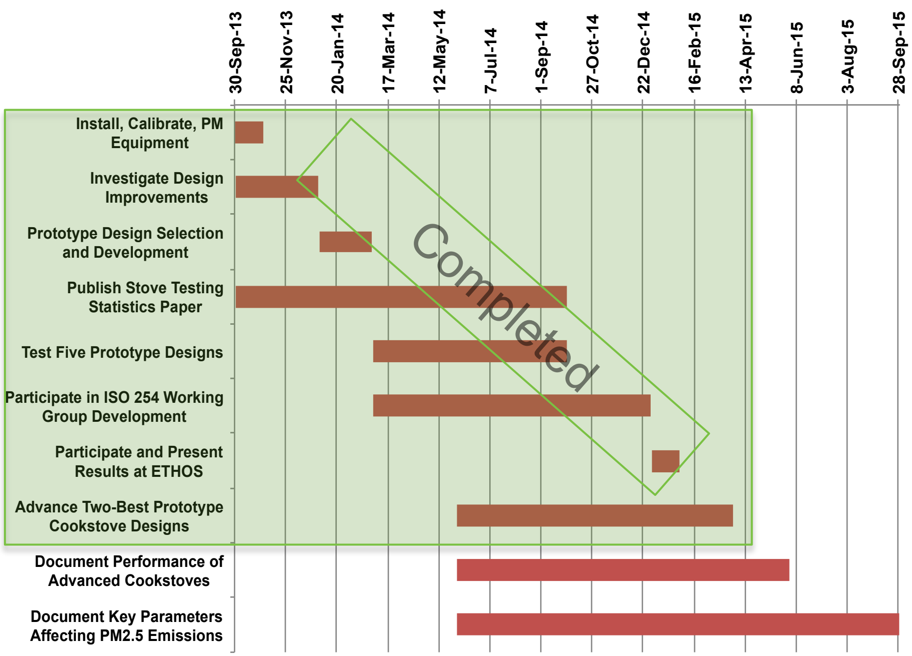
TIMELINE:

Project start date: Sept. 2013

Percent complete: 50%



	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 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 substantial $\mathbf{PM_{2.5}}$ emissions reductions in lab
- Disseminate high-efficiency low-emissions design knowledge to stoves community
- Build model testing facility for training partners
- Demonstrate manufacturable stove, working with industry partners

Approach (Technical)

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- **Emissions reduction**
  - Improve fuel/oxidizer mixing in diffusion flame, using air injection
  - Parameterize design factors (e.g., geometry, flow rate) affecting emission reductions
  - Demonstrate high concurrent thermal performance
- **Air injection powered by commercial thermoelectric device using waste heat from the stove**
  - Develop circuit for power management: charge phones, stove battery, etc.
- **Metrics of Success**
  - Reduce PM2.5 emissions by 90%
  - Maintain affordable cost (<$40) and high efficiency (>35%)
- **Challenges**
  - Design for manufacturability and scalability
  - Achieve tier-4 front-feeding wood-fueled stove
  - Design affordable electric features (e.g., USB for charging)

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2 – Approach (Management)

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Collaborative, multi-pronged approach to advance clean cookstove technology:

- **Set up and conduct world-class R&D**
- **Collaborate in R&D with others:** MIT & GACC Round Robin Tests
- **Manufacturing & Market Testing:** Shri-Hari Industries, India
- **Distribution & User Research:** Potential Energy
- **Dissemination & Standardization**: ISO/TC-285, ETHOS

Build an interdisciplinary research team with Berkeley Campus:

- **Civil & Environmental Engineering:** Prof. Tom Kirchstetter
- **Mechanical Engineering:** Prof. Alice Agogino
- **Masters in Development Practice:** College of Natural Resources
- **Applied Science & Technology:** College of Engineering

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1. Build State-of-the-Art Stove Testing Facility

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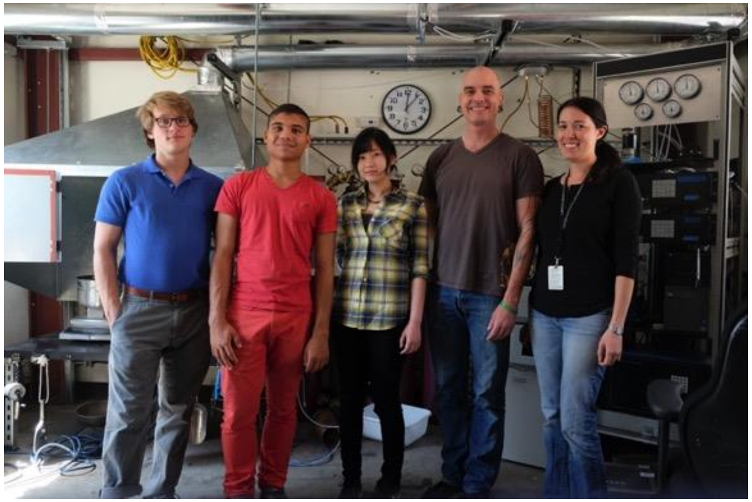

- Experienced and highly-skilled cookstoves team dedicated to testing and data analysis
- Instrumentation maintained and calibrated on a daily basis
- Redundant measurements provide easy validation of collected data

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1.1 Implement Quality Control Procedures

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Develop quality assurance plan, checklist, and test protocols

LBNL COOKSTOVE RESEARCH FACILITY QUALITY ASSURANCE PLAN (QAP)

Lawrence Berkeley National Laboratory
Stoves Group

April 2014

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)

Training slide-deck to ensure high-quality testing

Clean the pot

Clean the stove

Clean the sand

Wood chips
≈ 15.0 g

Kindling sticks
≈ 60.0 g

Wood sticks
≈ 1000.0 g

Filter

Water
≈ 5000.0 g

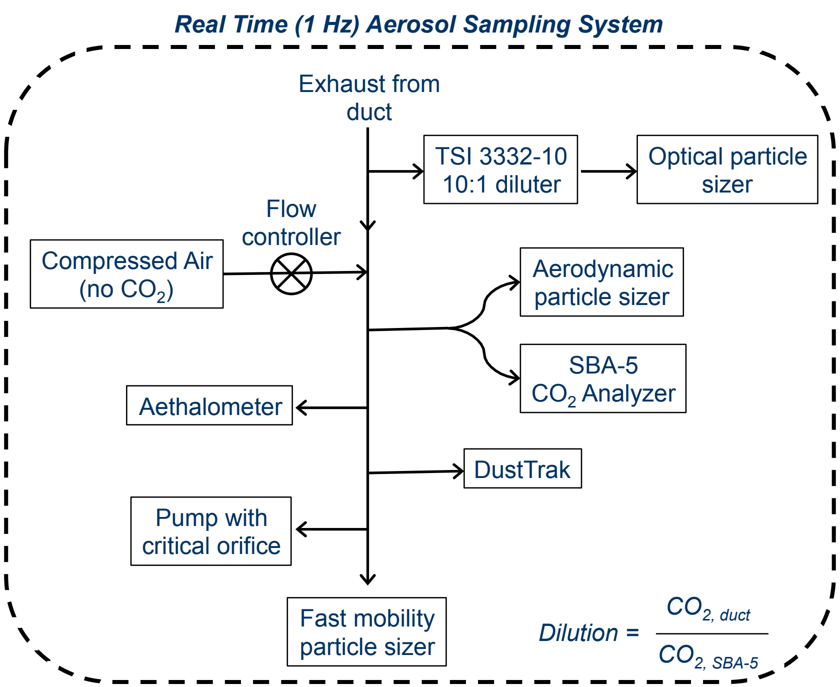
Pot

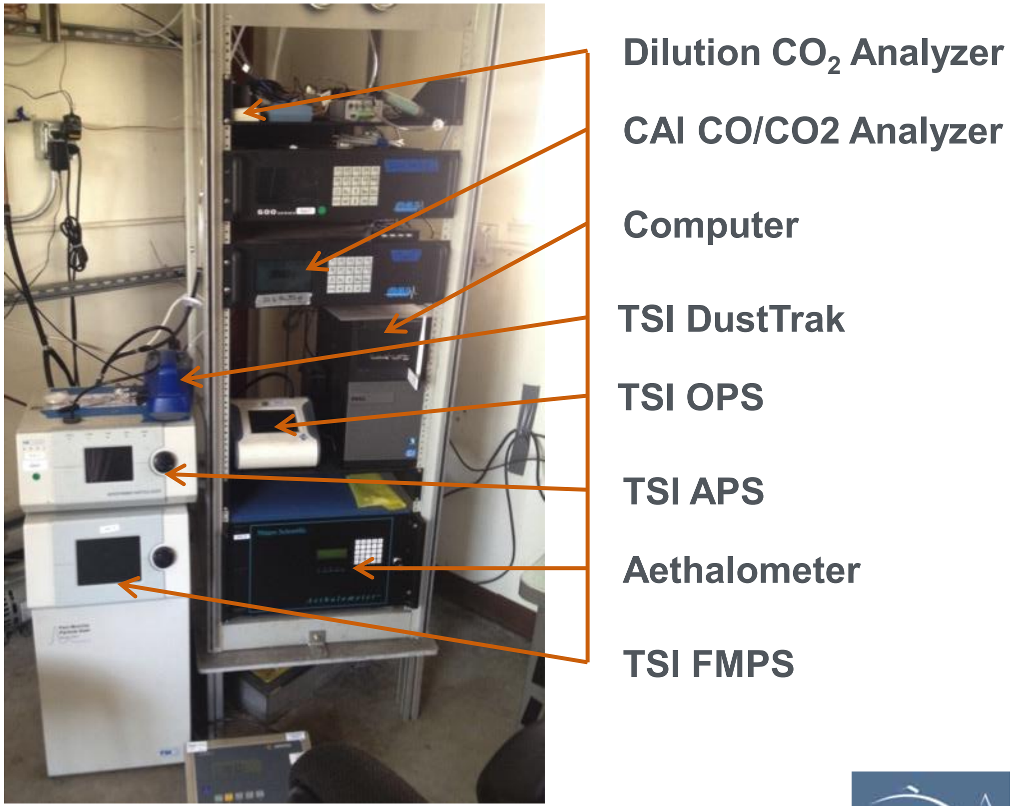
1.2 Design and Maintain Measurement System

High Quality Instrumentation:

- Redundancy in measurements ensures high confidence in data

Aerosol Sampling System





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1.3 Integrated Open Source Interface

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python™ platform screen-shot for 1 Hz data collection and analysis

Key test variables

Ultrafine particle distribution from FMPS, OPS, and APS

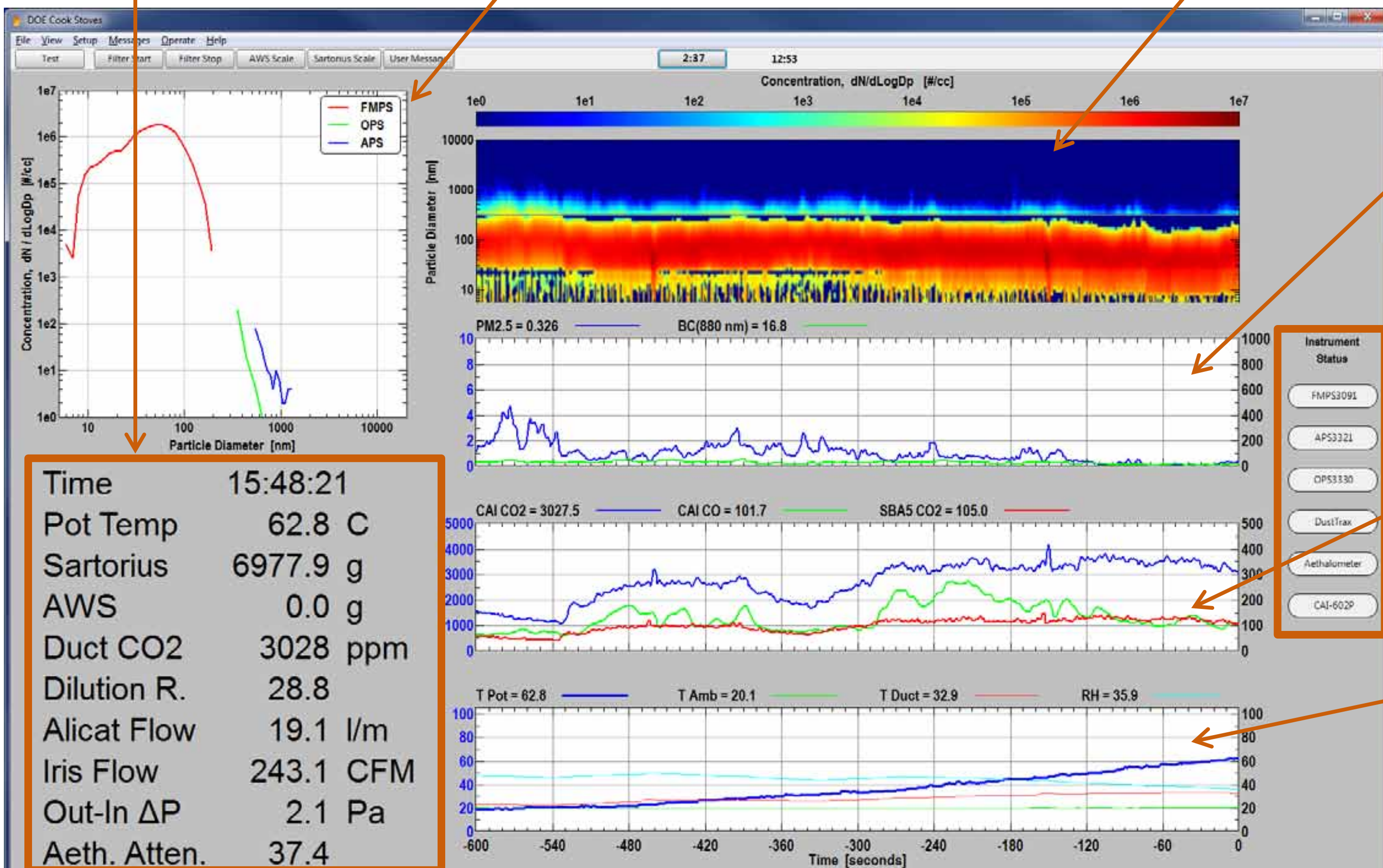
Ultrafine particle distribution over time from FMPS & OPS

$PM_{2.5}$ and BC measurements

Instrument error indicators

Gas emissions measurements

Temperatures and RH trendlines



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1.4 Comparing Stove Performance

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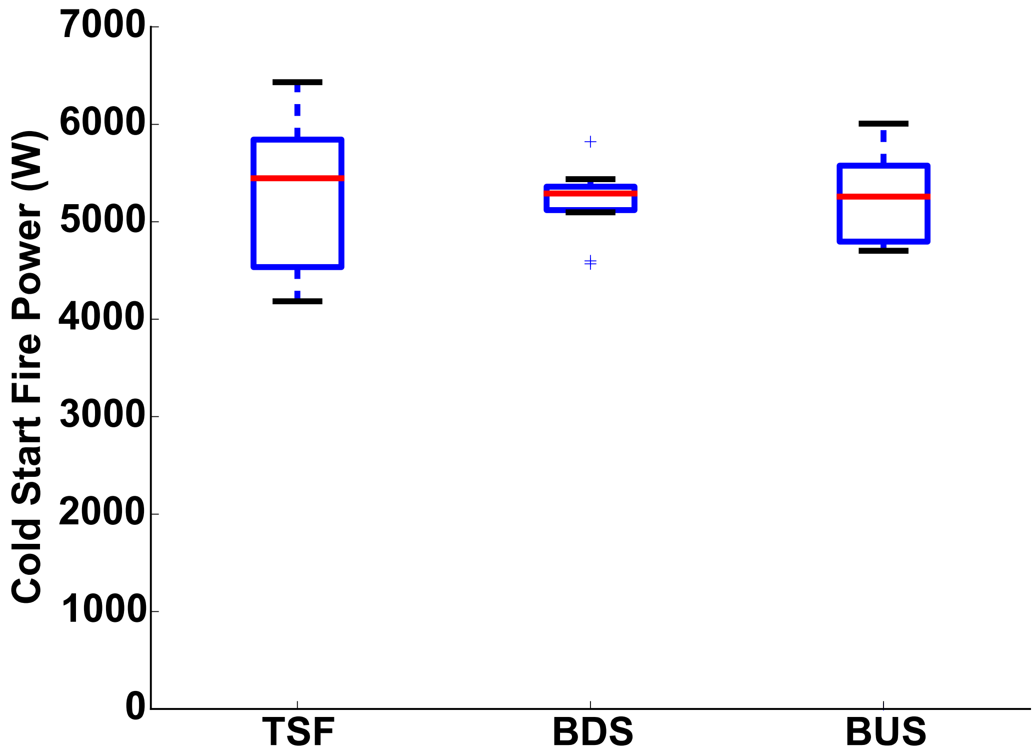
Stove performance depends on **fire power** (the rate of thermal energy release during combustion):

- Monitor CO_2 concentration in the duct during testing
- Maintain consistent CO_2 to maintain consistent firepower



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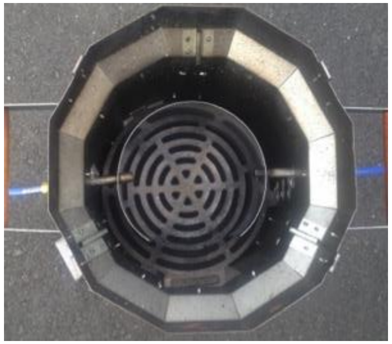
Demonstrate reduction in $PM_{2.5}$ emissions from air injection in front-loaded wood stoves



*six prototype stove designs ideated, built, and tested at LBNL

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2.1 Effects of flow manipulation on emissions and performance

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Completed to date:

- Built and tested six wood-fueled, continuously-fed stove prototypes capable of reducing $PM_{2.5}$ compared to TSF
- Stoves designed to explore a wide range of flow manipulation and turbulence generation techniques

Future Work:

- Study parametrically key variables and operating conditions to minimize $PM_{2.5}$ particulate emissions
- Disseminate scientific knowledge for designing Tier 4 wood-fueled cookstoves (“recipe for PM2.5 reduction”)
- Demonstrate manufacturability by working closely with industry (Shri Hari Industry, etc.)

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2.2 First High-Potential Air-Injection Prototype

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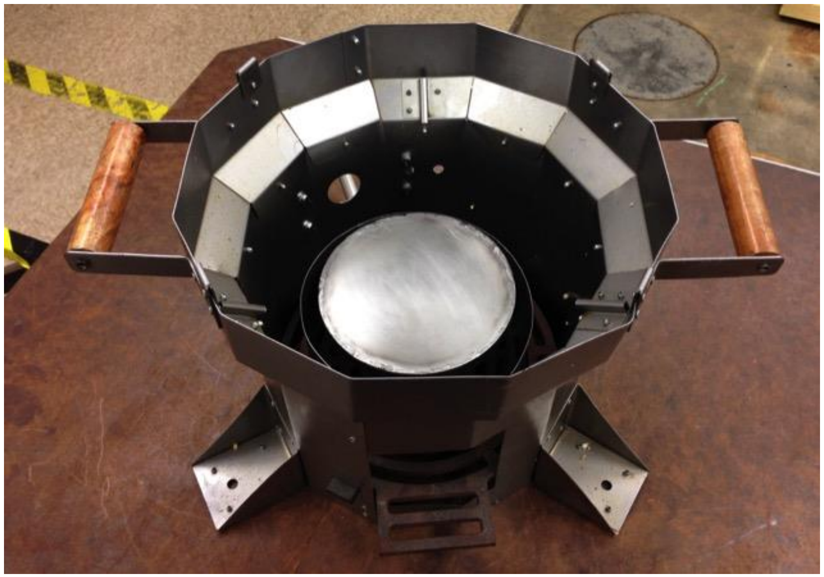
Berkeley Umbrella Stove (BUS): Design



- Umbrella-shaped air injection manifold
- Applies small air jets to flame tips
- Air preheated with fire
- Umbrella acts as radiation shield between combustion and pot

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2.3 Video of Lab Testing

2.4 Thermal efficiency and time to boil

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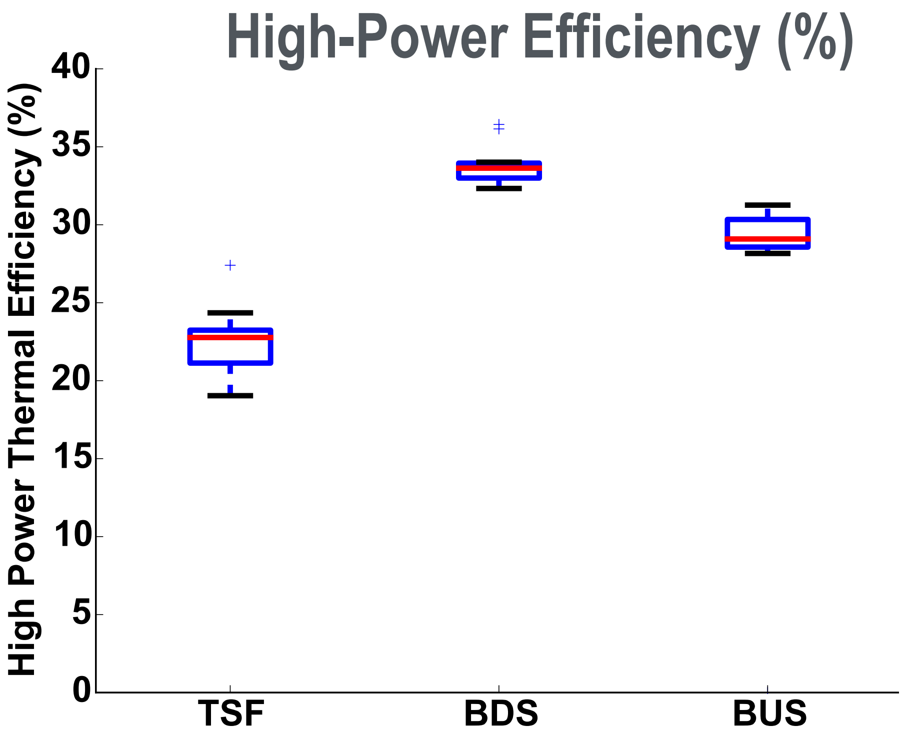
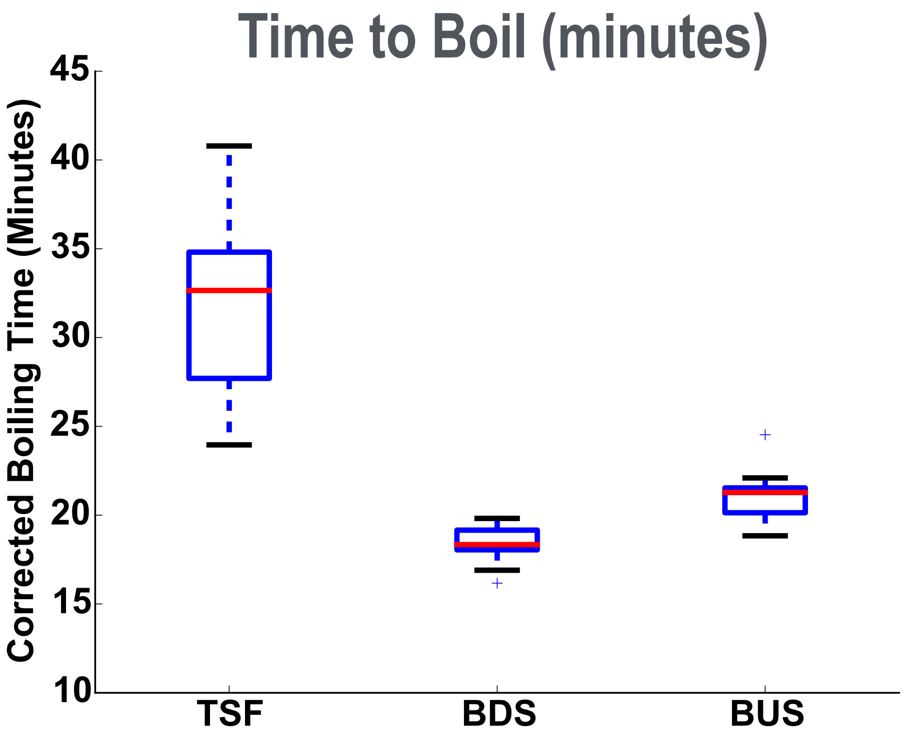
Berkeley Umbrella Stove (BUS): Performance

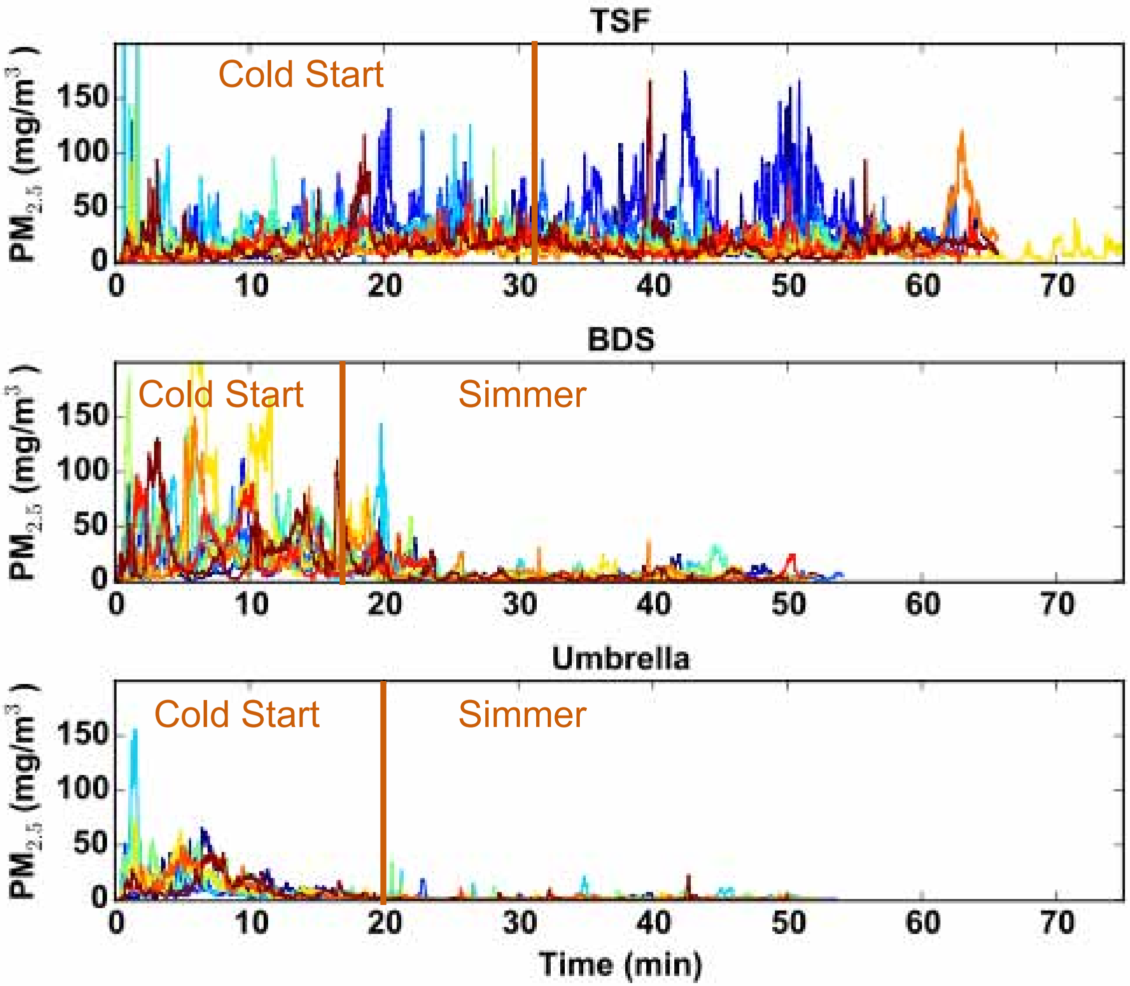
- BDS and BUS test have narrower distributions than the TSF based on ten tests each
- Multiple tests are required to have confidence in results, especially for TSF





2.5 Effects of flow manipulation on emissions and performance

Berkeley Umbrella Stove (BUS): DustTrak data corrected with filter data



- Ten tests conducted on each stove
- Each test: modified WBT; Cold Start + 30 min Simmer
- Controlled fuel feed-rate by maintaining ~3500 ppm CO_2 in duct
- 2 CFM of air added 3 minutes after start-up for BUS

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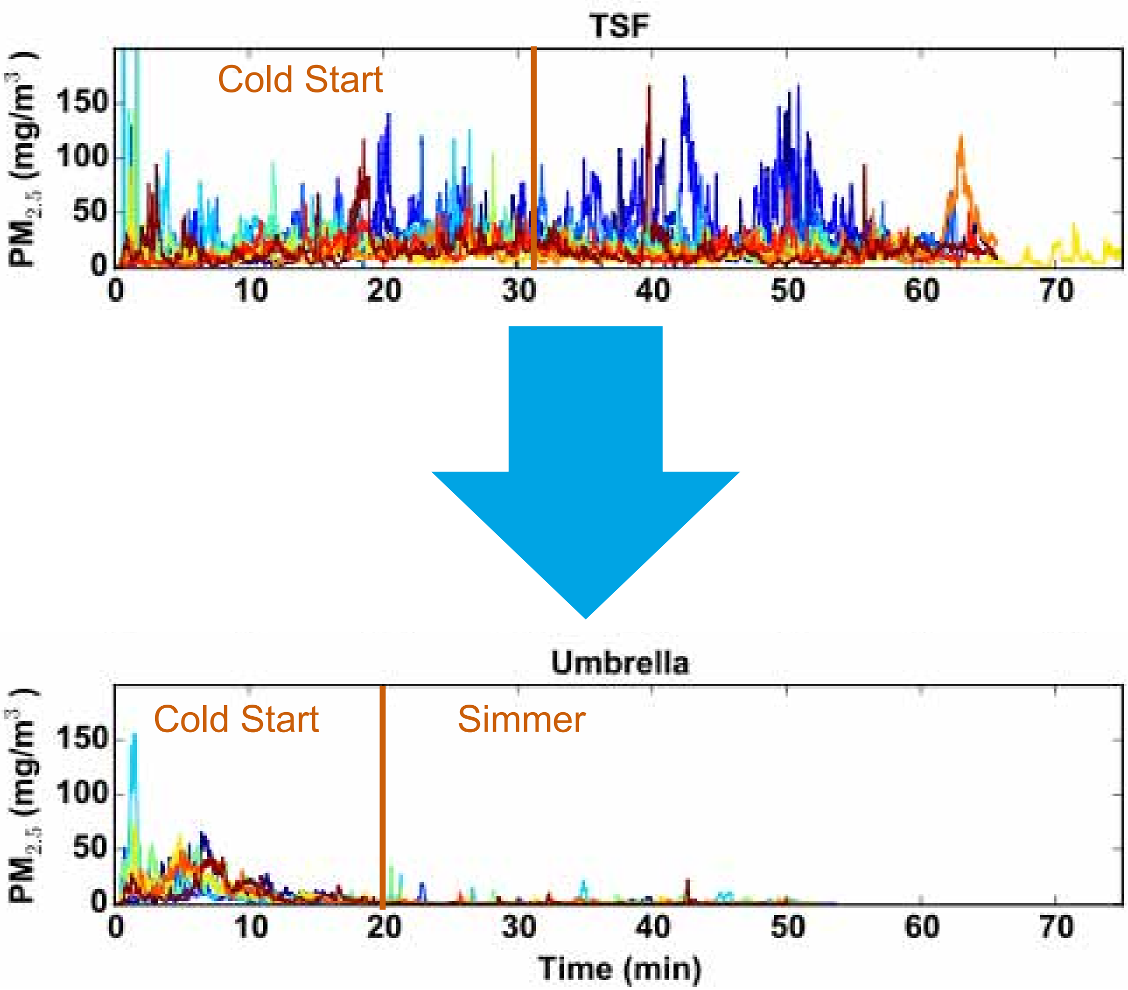
Berkeley Umbrella Stove (BUS): DustTrak data corrected with filter data



- Ten tests conducted on each stove
- Each test: modified WBT; Cold Start + 30 min Simmer
- Controlled fuel feed-rate by maintaining ~3500 ppm CO_2 in duct
- 2 CFM of air added 3 minutes after start-up for BUS

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2.7 Effects of flow manipulation on ultrafine emissions

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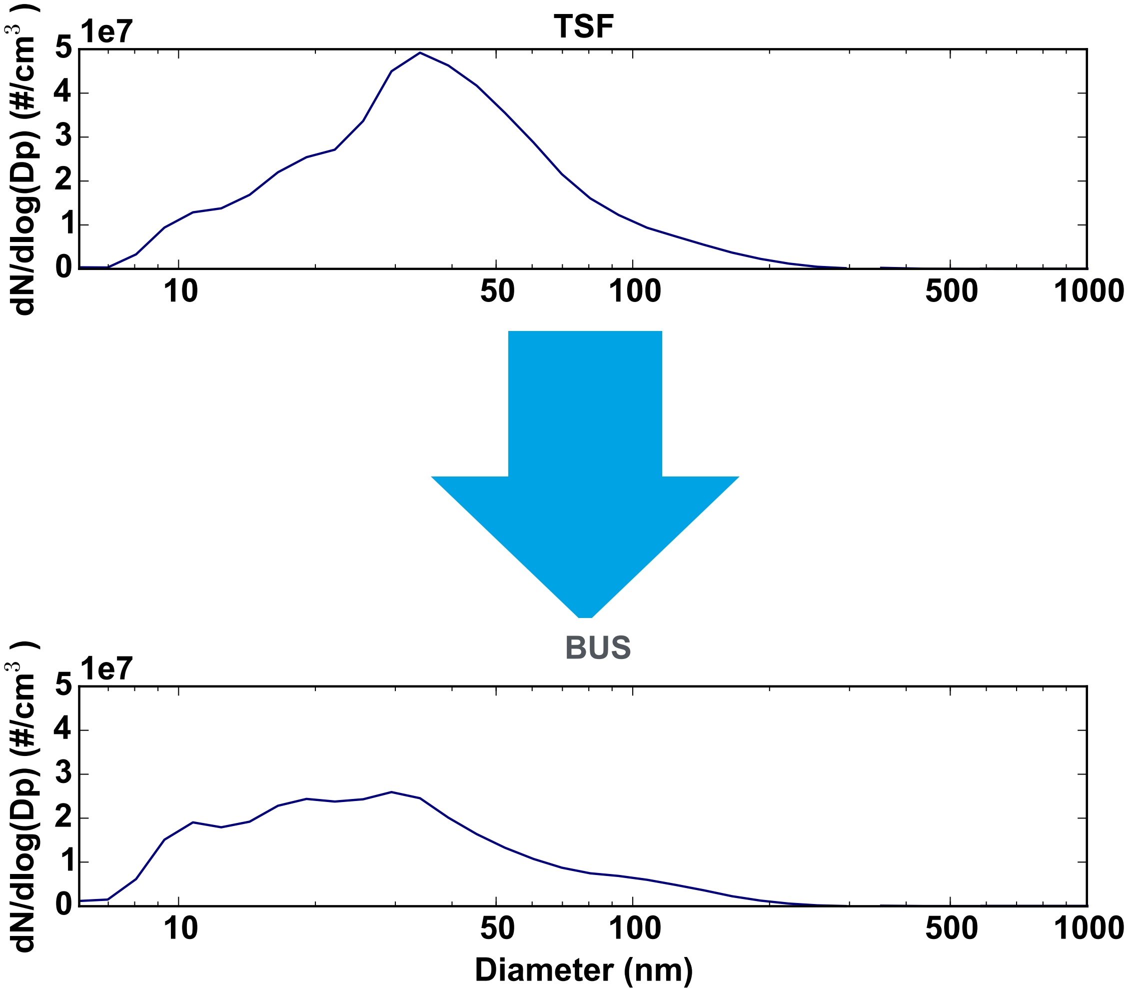
Fine Particle Emissions: Average of multiple tests



Flow manipulation

- Reduces $PM_{2.5}$
- Reduces number of particles
- Increases the number of Ultra-Fine particles

Health implications

- Less mass of particles = **good**
- More Ultra-Fines = **bad**

This points to a possible problem

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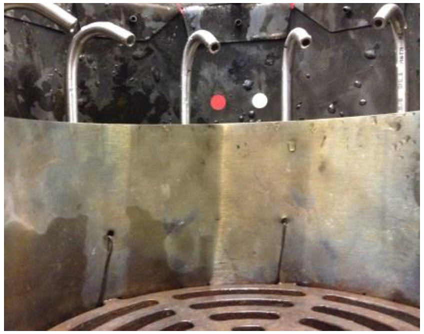
2.8 Air injection stove platform – for parametric study

Berkeley Shower Stove (BSS): Design



- Concentric ring of "shower head" jets mounted on pancake air manifold integrated into BDS stove
- Air is preheated in copper coil and manifold

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2.9 Thermal efficiency and time to boil

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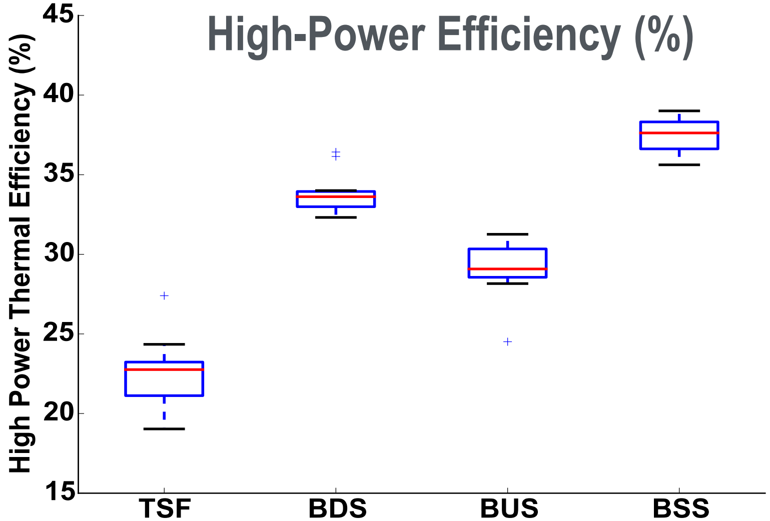
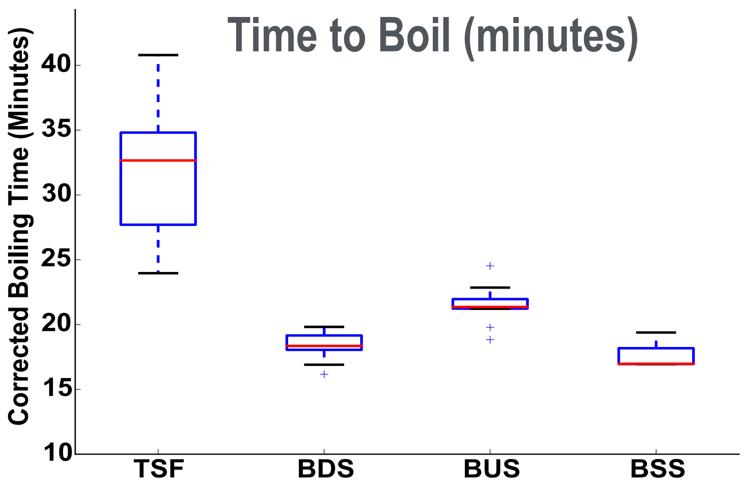
Berkeley Shower Stove (BSS): Preliminary Testing (and ongoing optimization)





Optimize flame manipulation:

- Air flow Rate: ~1-2 CFM
- Air injection geometry: Position, number, orientation of 'shower' nozzles

For quicker parametric testing, use modified-WBT: Cold start and 10-minute simmer phase

See improvement in both efficiency and time to boil

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2.10 Effects of flow manipulation on $PM_{2.5}$ and CO

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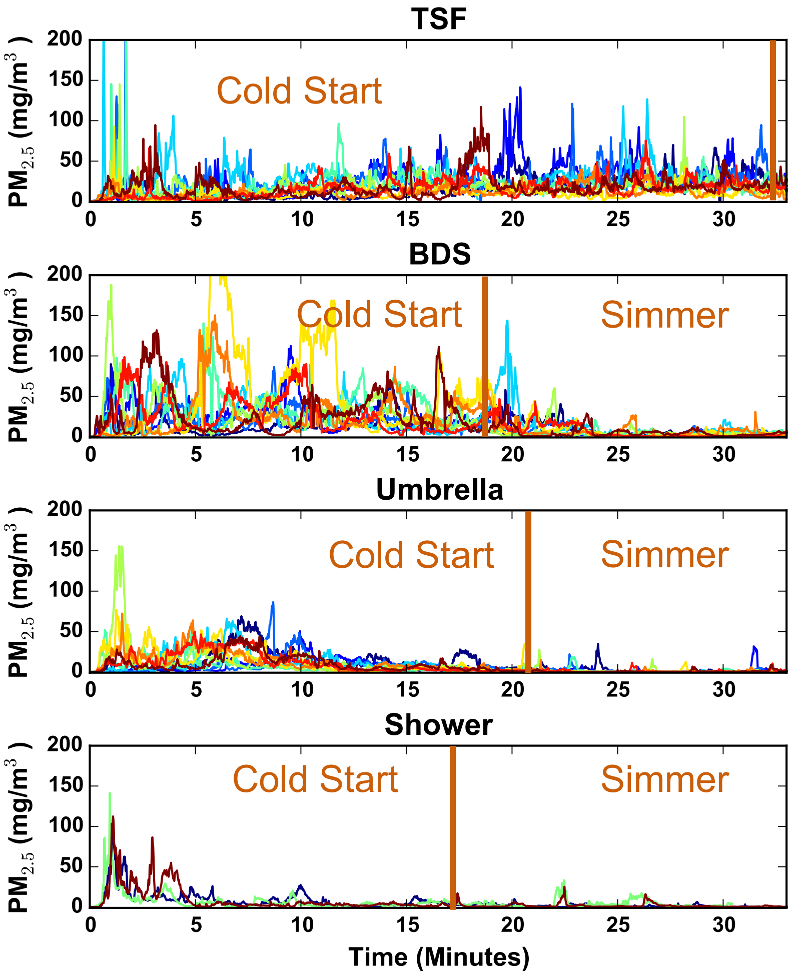
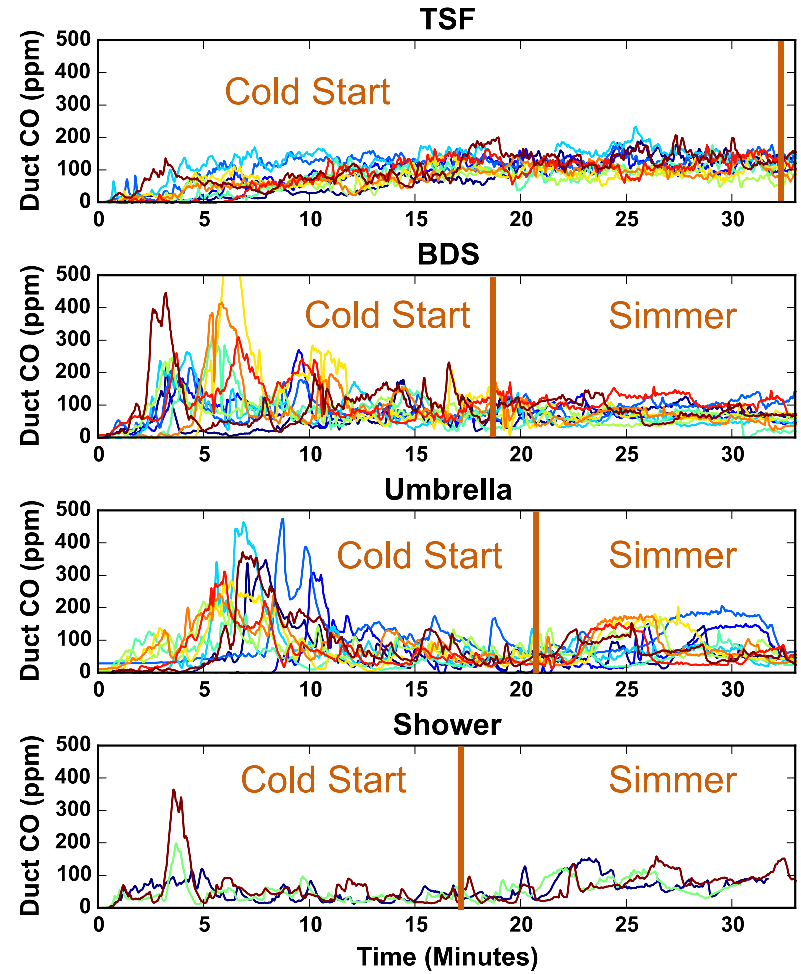
Berkeley Shower Stove (BSS): Preliminary Test Data

$PM_{2.5}$ (uncorrected for gravimetric)



CO



3. Research Collaborations

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1. **Aerosol chemistry research with MIT (Prof. Jesse Kroll)**
   - Incorporated mass spectrometer into LBNL cookstove testing facility to measure and analyze chemistry of biomass combustion emissions
     - *Size* and *speciation* of aerosol has health and climate implications
       - (e.g. silicosis and melting of glaciers)
   - Collaboration to combine equipment and expertise
   - Results to be published in a journal paper (under preparation)

2. **GACC Round Robin Testing**
   - Serving as testing facility for GACC's Round Robin program
   - Establishing our lab as standard-setting test facility to help evaluate cookstove performance for research community

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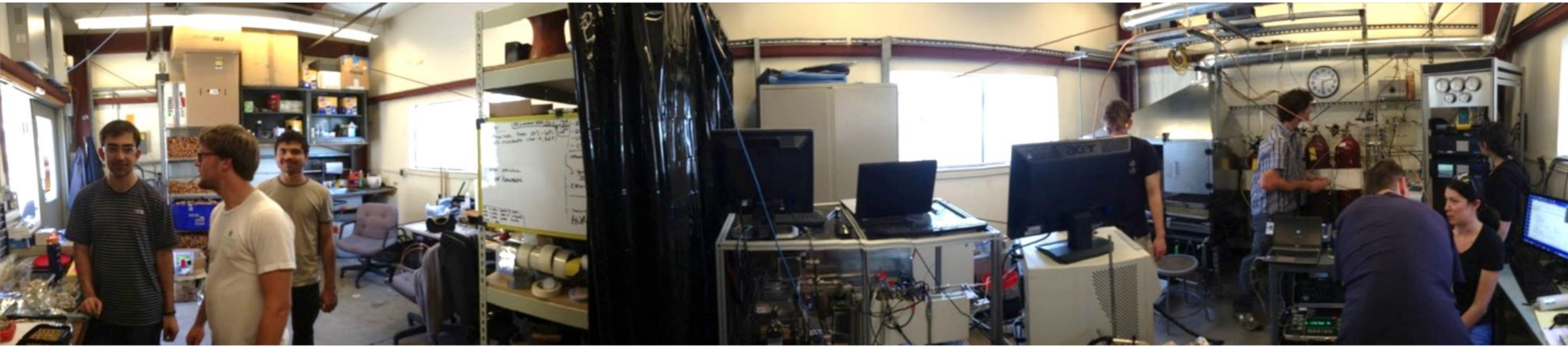
3.1 Testing campaign with MIT in June 2014



- Gain a better understanding of aerosol chemistry and particle distribution from charcoal stoves (MIT Prof. Jesse Kroll) and from LBNL wood burning stoves
- Integrated MIT Soot-Particle Aerosol Mass Spectrometer (SP-AMS) into the LBNL stoves testing facility
- **Successfully completed over 60 experiments in under two-weeks**
- Publications coming soon describing chemistry of aerosols and correlation with particle size and stove fuel: Informs effects on health and climate

3.2 GACC Round Robin Testing

- Leverage our knowledge and facilities to advance high quality performance testing among participating facilities (including us)
- Testing clean cookstoves for GACC as part of Round Robin
- One set of Round Robin tests conducted to date (Forced-Air Gasifier stove) – December, 2014

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4. Disseminate Best Practices to Cookstove Community

ETHOS Conference 2015

- Biomass cookstove conference in Kirkland, WA
- 5 presentations on laboratory testing, user adoption, instrumentation, and statistical analysis
  - Share our testing and development experience with research community

ISO/TC-285

- Develop international standards for biomass cookstove testing and implementation
  - Our group is coauthoring standards for laboratory testing (WG1) and social impact assessment (WG4)

Statistics Publication

- Publish the statistical methods required to analyze data in a way that sheds light on performance
- "How many replicate tests are needed to test cookstove performance and emissions? – Three is not always adequate". Wang et al., 2014. Energy for Sustainable Development

ETHOS
Engineers in Technical and Humanitarian Opportunities of Service

ISO

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4 - Relevance

This research is responsive to DOE's request for technologies and technological advances that reduce harmful emissions from biomass cookstoves (90% $PM_{2.5}$ reduction) while boosting cooking performance (50% efficiency increase) compared to the baseline.

Our research will lead to the design of cleaner, more efficient biomass stoves while advancing the stoves research community's understanding of wood combustion in cookstoves.

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5 – Future Work

Complete the development and dissemination of parametric design space to reduce $PM_{2.5}$ emissions:

- Conclude the development and optimization of the shower stove
- Publish generalizable results for use by others (“recipe”)

Address remaining technical barriers / challenges:

- Apply and incorporate scientific findings to diverse cookstove designs to achieve substantially reduced $PM_{2.5}$ emissions
- Adapt auxiliary design improvements to stoves so they are highly valued and economically attractive to customers
- Collaborate with stoves-manufacturing partner(s) to determine and improve / ensure manufacturability of the flame-manipulated stove
- Collaborate with field-partner(s) to feedback from limited user-testing of flame-manipulated stoves

Summary 1

Central Goal: Develop an affordable, ISO tier 4 cookstove desirable for purchase

Approach:

1. Measure cookstove performance accurately and reliably to inform design and development
2. Identify air injection parameters that significantly reduce PM emissions
3. Apply and incorporate scientific findings to cookstove designs while maintaining low cost and design features desirable to users
4. Collaborate with stakeholders with multidisciplinary expertise

Summary 2

Progress & Results

1. Built and validated a world class cookstove testing facility – Allows for uniquely fast, accurate, and reliable performance evaluation of cookstove technology. Benefits community through training, Round Robin, and serve as exemplar facility (UT Austin, All Power Labs, IIT-Delhi, Aprovecho, Tami Bond's group, MIT, and others)
2. Constructed and tested six wood-burning cookstoves designs with flow manipulation
3. Further refined two promising designs and demonstrated that flame manipulation results in substantial $PM_{2.5}$ reduction
4. Collaborated with MIT and GACC to further both combustion science and cookstove development
5. Disseminated our group's experiences and best practices to the research community through conferences and publications

Summary 3

Relevance:

- Addresses DOE's request for technologies that reduce harmful emissions from biomass cookstoves (90% $PM_{2.5}$ reduction) while boosting cooking performance (50% efficiency increase). Our research aims to meet these goals by managing turbulence in wood combustion.

Future Work:

- Continue parametric trials of shower stove design
- Understand, document, and publish the effects that result in $PM_{2.5}$ reductions
- Continue to disseminate knowledge through conferences & publications
- Continue collaborative research endeavors
- Collaborate with stoves-manufacturing partner(s) to determine and improve/ensure manufacturability of the flame-manipulated stove
- Collaborate with field-partner(s) to feedback from limited user-testing of flame-manipulated stoves

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