DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Advancing wood heater evaluation methodology for accelerating innovation

April 2023
Systems Development and Integration (SDI)

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U.S. DEPARTMENT OF ENERGY

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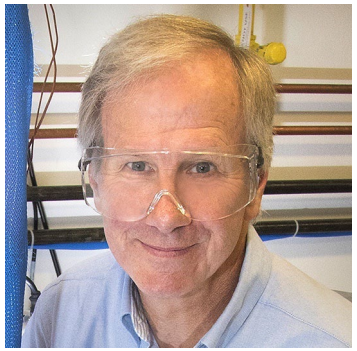
Team

BNL

Rebecca Trojanowski



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Collaborating with:
The Alliance for Green Heat

John Ackerly

ALLIANCE FOR GREEN HEAT
low carbon, renewable and local

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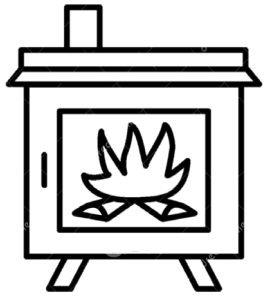
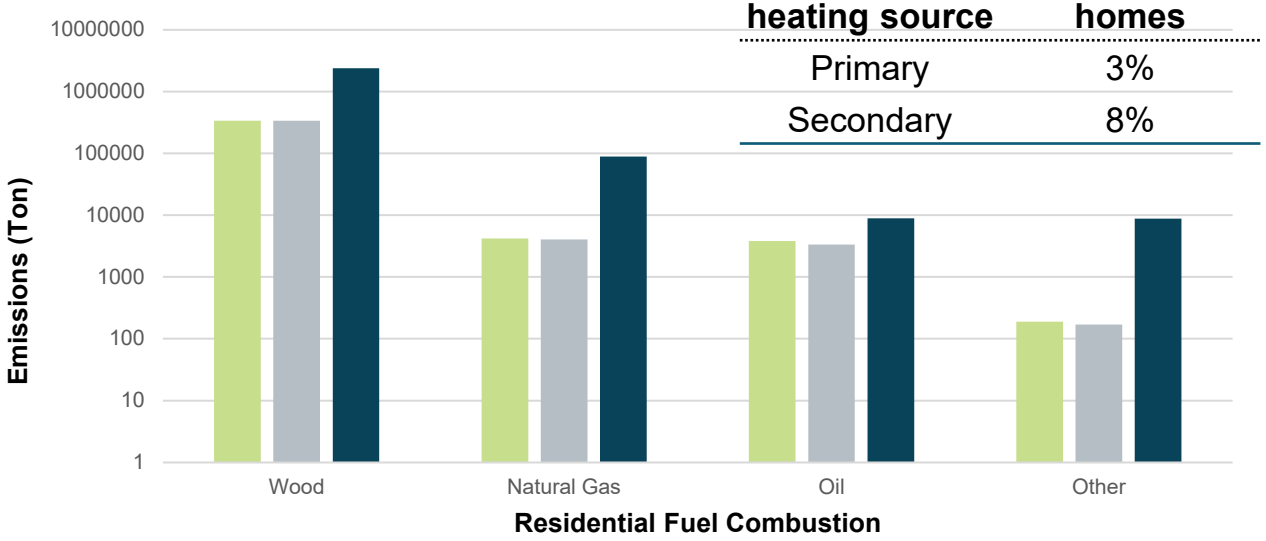
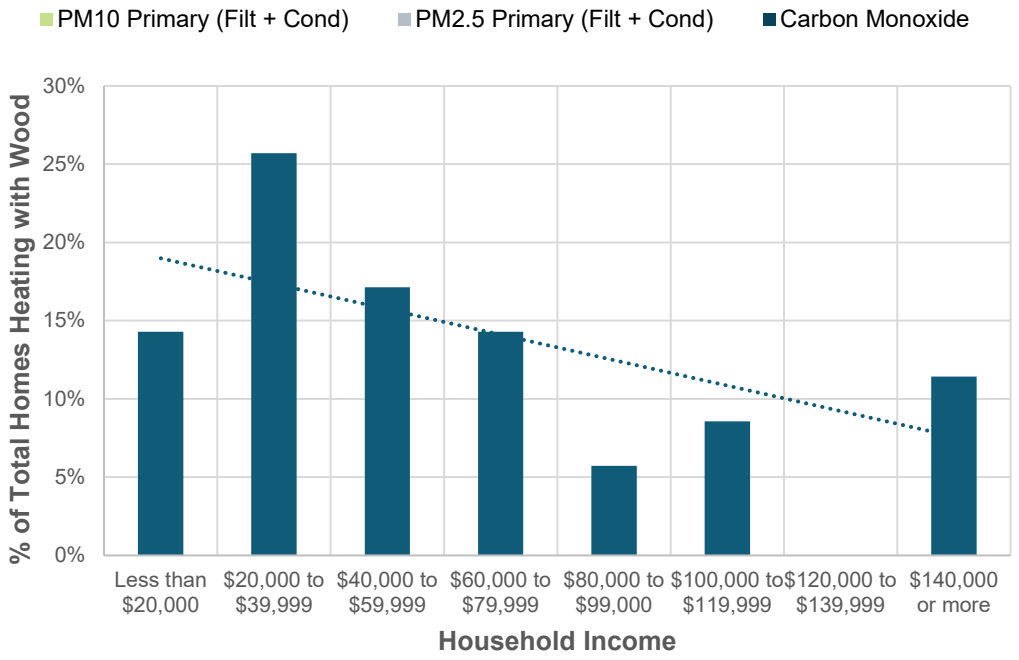
Background

- Direct combustion of biomass in homes is the most common use of woody feedstocks but is the **dominant factor in ambient air quality** in many parts of the US
  - ~6% of US total annual PM2.5 emissions are from wood heaters
  - >57% of the health-related social costs attributed to air pollution from the residential heating sector
- 2.4 million US homes use wood as primary heat source
- In 2020, largest percentage of renewable energy consumed by the residential and commercial sector was supplied by wood and waste (not including liquid fuels produced from biomass feedstocks), followed by solar at 54% and 38%
- States have recognized wood-fired appliances will play a significant role in the future of their heating sector
- For many who aren't on municipal gas lines, choosing an alternative heat source like wood, oil or propane is a necessity



Wood as a heating source	% of total US homes
Primary	3%
Secondary	8%





https://www.eia.gov/consumption/residential/data/2015/

https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data#datas

Project Overview

Goal:

Develop low-cost measurement tools, simplified test protocol(s) and analysis to reduce R&D costs and support innovation of new wood heaters

Objectives:

1. Identify major hurdles preventing innovation of wood heaters
2. Identify gaps and improvements with current test methods and opportunities to correlate with in-home performance
3. Organize Wood Heater Design Challenge and community engagement workshops

Alignment:

1. Reducing the carbon footprint of buildings
2. Workforce development and equity impacts are expected by:
   a. Supporting energy justice through innovative, ultra low polluting wood heaters that disproportionately affect marginalized and low-income communities
   b. Coordinating with wood heater manufacturers, and state and local regulatory agencies through a series of workshops to identify the best solutions for their local communities.

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Approach

Technical Approach

1. Development and verification of the new measurement methods and simpler test protocols for residential biomass heaters
   a) This will accelerate innovation and ensure our nation's competitive advantage with emerging bioenergy technologies by allowing manufacturers to quickly and affordably evaluate metrics of performance with short test times to guide and inform design decisions
1. Host the 5th Wood Heater Design Challenge
   a) Explore technology innovation, share experiences and perspectives, and reach a larger and more international community of innovators, suppliers, students, manufacturers, and other experts
   b) Drive R&D to develop the cleanest and most wood heaters

Challenges

1. Wide range in flue gas pollutant concentrations with technology and over time during operation
2. Cost of measurement methods
3. Need to be useful in climate of rapidly evolving certification test methods
4. Acceptance by community
5. Soliciting information and feedback from experts and industry stakeholders in an organized productive manner

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Progress and Outcomes

		Task	FY20									FY21												FY22												FY23												FY24		
			Jan-20	Feb-20	Mar-20	Apr-20	May-20	Jun-20	Jul-20	Aug-20	Sep-20	Oct-20	Nov-20	Dec-20	Jan-21	Feb-21	Mar-21	Apr21	May-21	Jun-21	Jul-21	Aug-21	Sep-21	Oct-21	Nov-21	Dec-21	Jan-22	Feb-22	Mar-22	Apr-22	May-22	Jun-22	Jul-22	Aug-22	Sep-22	Oct-22	Nov-22	Dec-22	Jan-23	Feb-23	Mar-23	Apr-23	May-23	Jun-23	Jul-23	Aug-23	Sep-23	Oct-23	Nov-23	Dec-23
Original Tasks	1	Report evaluating protocols																																															
	2	Wood heater workshop																																															
	3	Recommendations for technical approach																																															
	4a	Evaluate simplified protocols BNL																																															
	4b	Evaluate simplified protocols LBNL																																															
	5	Preliminary field evaulations																																															
	6	Publish simplified test protocols and results																																															
Community Engagement Workshops	7.1	Prep subcontract for AGH																																															
	7.2	Plan Agenda / Questions																																															
	7.3	Develop Invitee List																																															
	7.4	Contact Invitees																																															
	7.5	Host On-Line Meeting 1																																															
	7.6	Host On-Line Meeting 2																																															
	7.7	Host On-Line Meeting 3																																															
	7.8	Report for On-Line Meeting 1																																															
	7.9	Report for On-Line Meeting 2																																															
	7.10	Report for On-Line Meeting 3																																															
	7.11	Integrated Report / OSTI																																															
Technology SLAM	8.1	Identify / Contact Panel of Experts and Judges																																															
	8.2	Announce SLAM and Make Contacts to Develop Participants																																															
	8.3	Hold SLAM Session - U.S. Participants Only																																															
	8.4	Define Rules and Selection Criteria																																															
	8.5	Select top 5-10																																															
	8.6	Panel of Judges Review Event																																															
	8.7	Prep Highlights Video (AGH + Sub)																																															
	8.8	Select Teams for Participation Awards																																															
Stove Competition	9.1	Poster Session at HPBA #1																																															
	9.2	Define Test Methodology																																															
	9.3	Testing at BNL																																															
	9.4	Testing Report																																															
	9.5	Communication																																															
	9.6	Event after Competition at HPBA																																															

Conclusions from 2021 Peer Review

- **Working group established** to advise measurement methods and simpler test protocols for residential biomass heaters
  - Industry expressed strong need for lower cost development methods
  - Helpful for manufacturers to have data from the field on their units
  - Manufacturers want to stay ahead of their competitors
  - Manufacturers want to move towards real-time instrumentation
- Completed **review of Certification Test Methods** World-wide
  - US methods established by EPA and ASTM
    - Based on dilution tunnel and testing in fixed load categories
    - PM based on integrated filters from dilution tunnel
  - European test standard EU-wide but PM measurements vary
    - Most countries use hot in-stack filter and estimate condensables by gas-phase hydrocarbon measurement
  - Emerging test methods capturing more "realistic" events in development and using real-time instrumentation
- Completed **review of Particulate Measurement Methods** World-wide
  - Dilution is necessary to accurately capture condensables
  - Integrated filters do not provide the time resolution needed
    - The TEOM (Tapered Element Oscillating Microbalances) and TEOM type devices could be a good option but expensive
    - Optical methods are low cost but do not capture the smallest particles and correlation with filter-based methods depends on size distribution
- **Update**: **Literature review submitted** to *Renewable and Sustainable Energy Reviews Journal* and in-review discussing Certification Test Methods, Particulate Measurement Methods, and providing recommendations for simplified measurement methods

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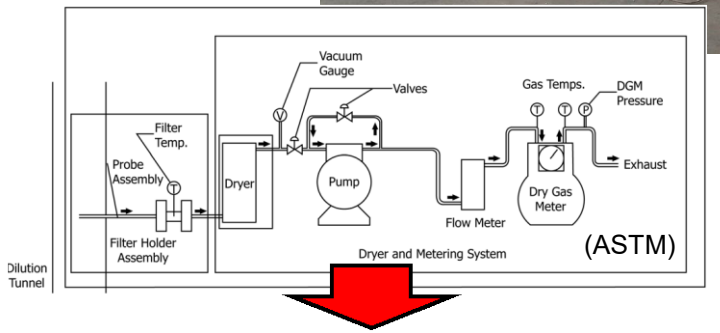
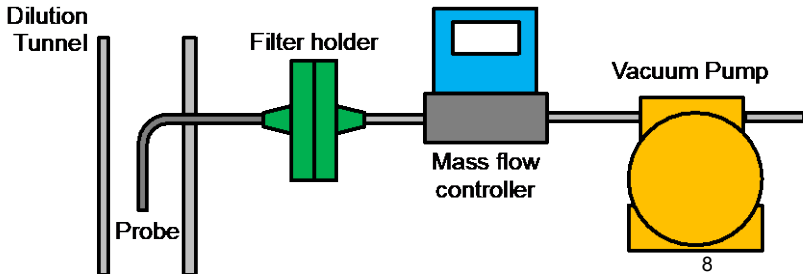
Challenges for technical approach

- Under *typical* combustion conditions, roughly half of the PM are condensables and the particulates are **carbon rich**
- Under *very clean* conditions the particulates are largely inorganic and condensables are **low**
- Gravimetric PM provides a single, test-integrated measurement that **does not capture transient emissions**
- Flue gas flowrate may be **too low to measure accurately**; calculated flowrate requires burn-rate which may not be measurable
- No official standard for field testing and **immense variability** in performance
- Any method we develop much be able to **handle all conditions** and must be:
  - More efficient and cost-effective
  - Key aspects of burn phase captured
  - Potential solution to lab and field testing





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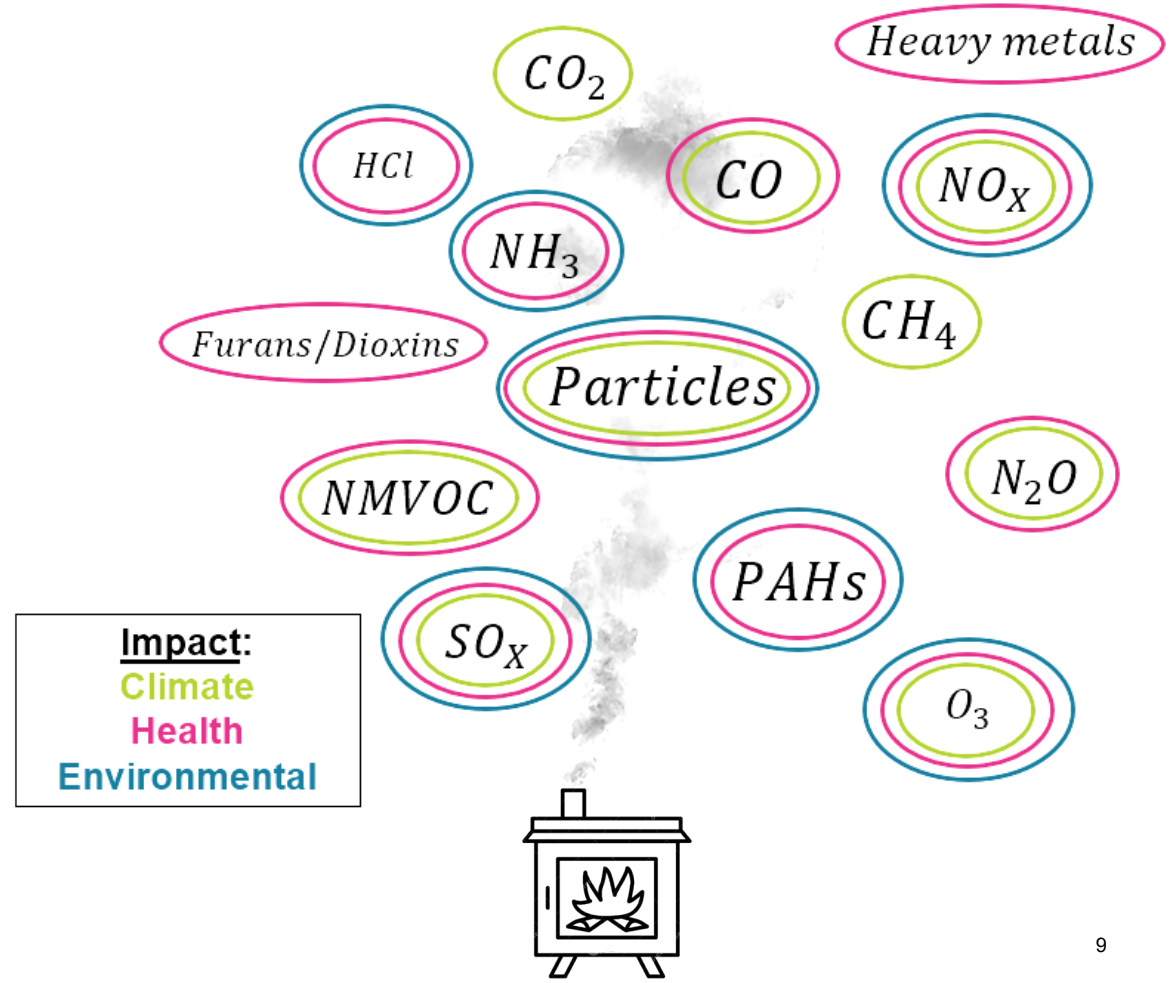
Recommendations for technical approach

These short-term measurements must be easily conducted in-house by manufacturers to guide R&D, help predict performance for compliance testing, and understand performance in the field

- Simplified instrumentation suite planned for both lab and field testing to measure:
  - Field performance
  - User operation/behavior
  - Impact on indoor/outdoor air quality
- Low cost, real-time PM measurements during specific parts of operating cycles including:
  - Cold start
  - Steady state
  - Hot restart
  - Burn-out
- Gas-phase CO_2 and CO
- Burn rate to be measured using weigh platform (in lab) or flue gas velocity with high temperature anemometer (or other)
- Efficiency determined using stack-loss measurements
- Characterizing particulate emissions (composition, size distribution, etc.)



Validate Facilities

Goal:
Confirm BNL and LBNL laboratories are in good agreement with each other

- Identical commercially available pellet stoves were purchased at each lab
- Operated pellet heater according to ASTM E2779
- The same pellet fuel was used for both sets of tests
- Testing at each laboratory done in triplicate

	Parameter	BNL	LBNL
High Burn Trim: 0	Average dilution tunnel velocity (m/s)	5.72	4.47
	Average dilution tunnel flow (ACFM)	388.0	307.2
	Dilution Ratio	17.4	26.8

Results of Triplicate Testing at Each Lab

	BNL	LBNL	COV
Knob Setting	**High**		
Trim Setting	0		
CO Stack (*ppm*)	75	110	26.4%
CO2 Stack *(%)*	9.5	9.8	2.2%
Burn Rate (*kg/hr*)	1.60	1.63	1.3%
Dilution Tunnel Temperature *(°C)*	23.8	24.4	1.6%
Stack Temperature *(°C)*	175.6	125.2	23.7%
Ambient Temperature *(°C)*	20.5	30.4	27.5%
Emission Rate *(g/hr)*	0.53	0.58	6.4%
Emission Factor *(g/kg)*	0.49	0.37	19.7%

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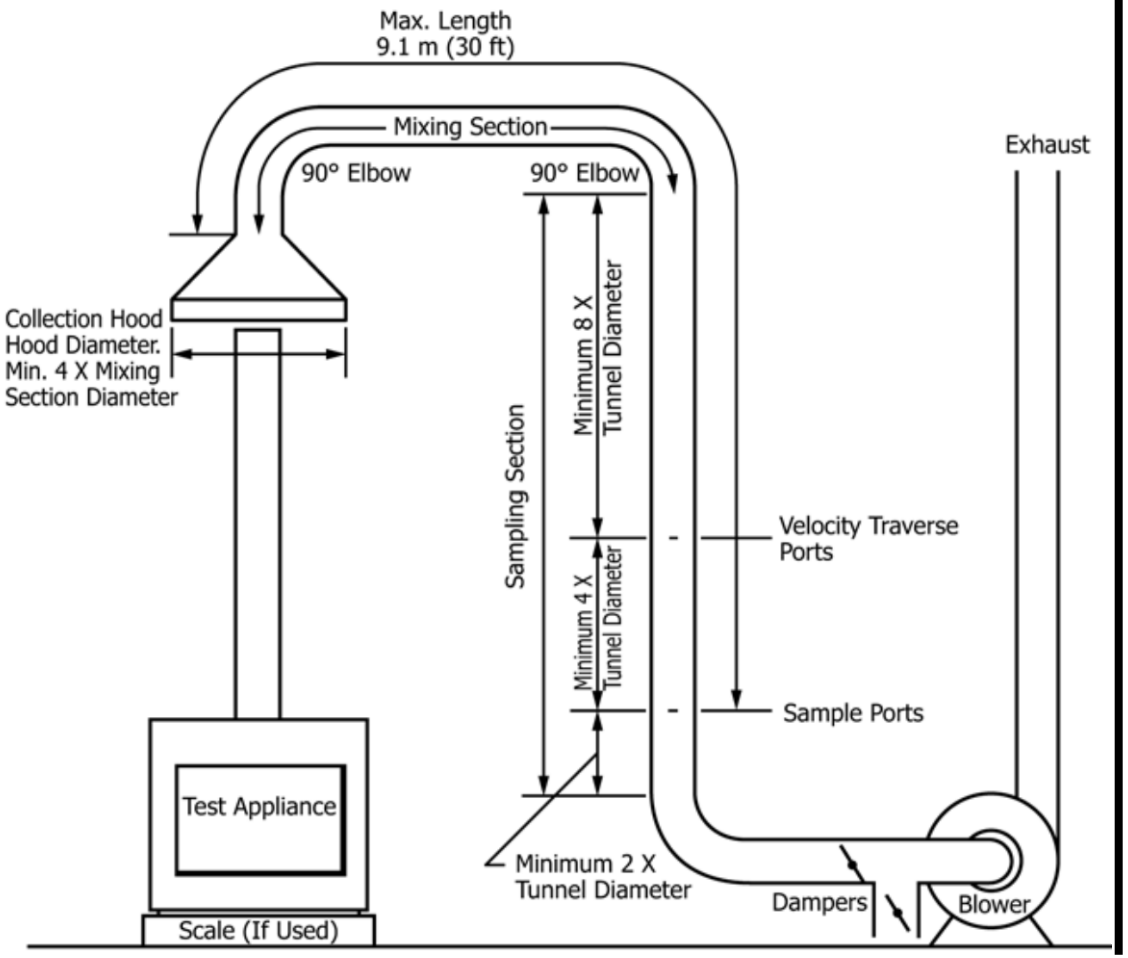
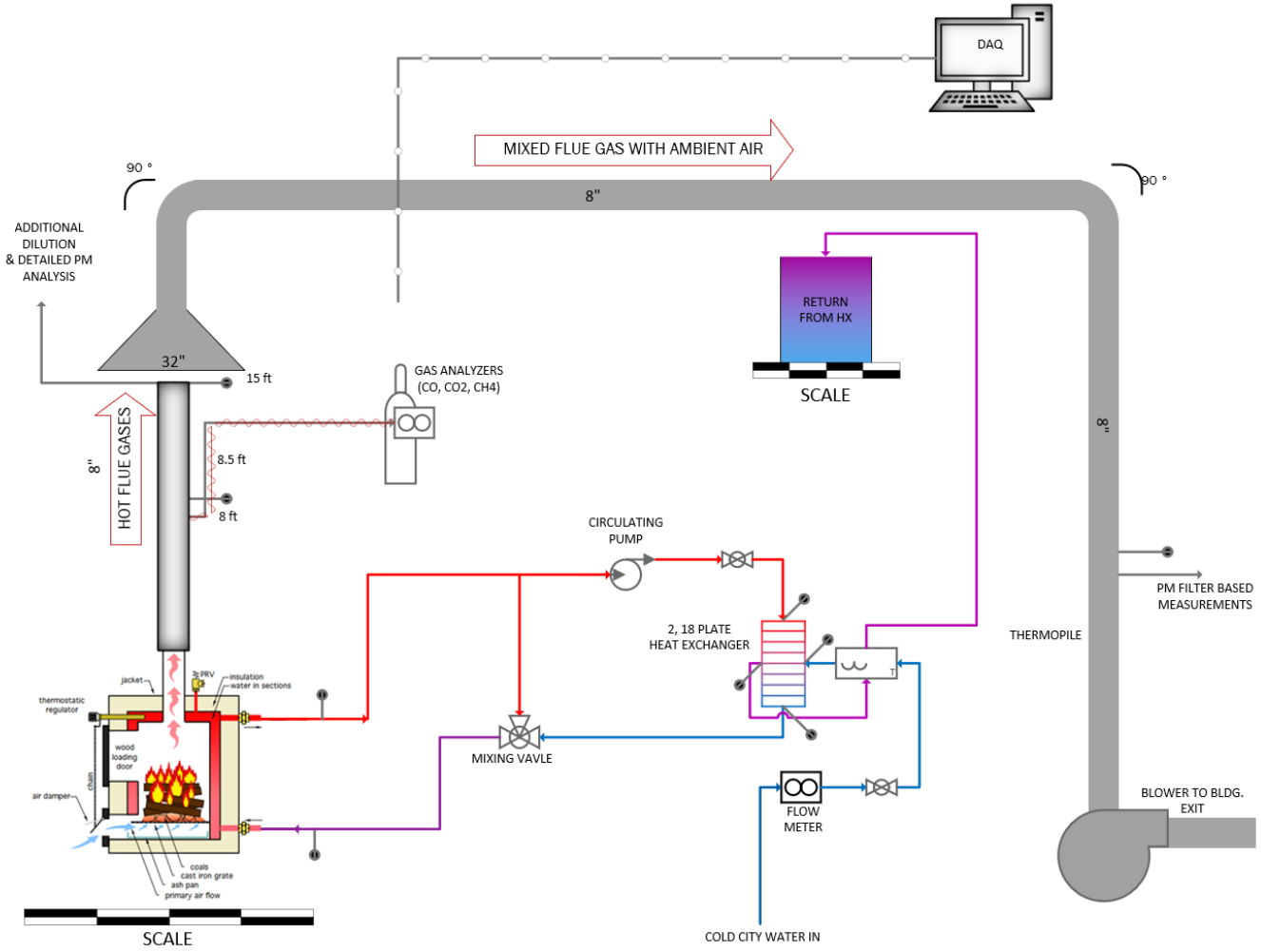
Validate Facilities

Dilution Tunnel



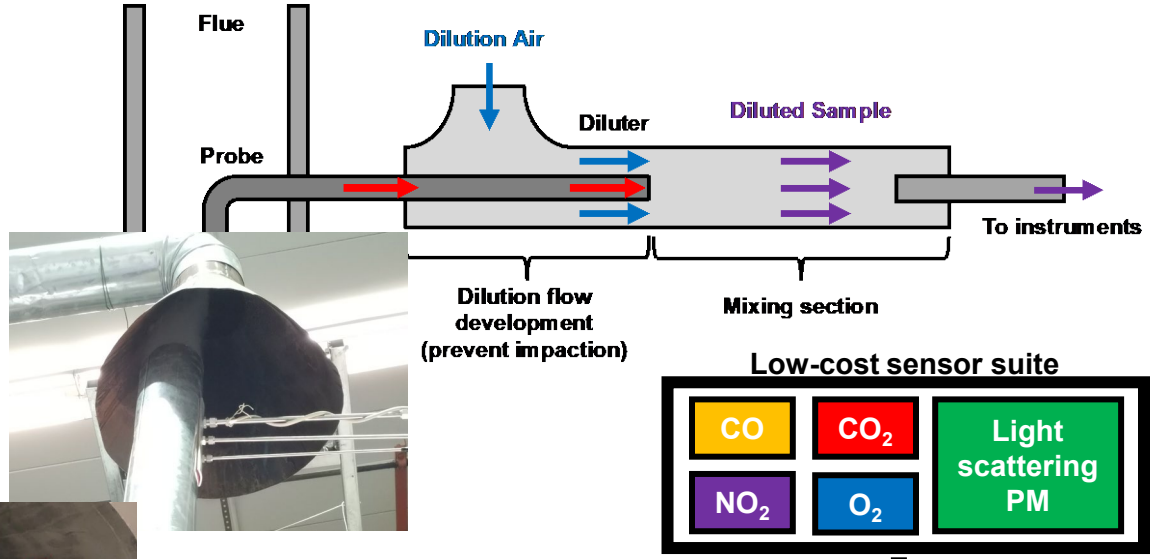
(ASTM E2515-1)

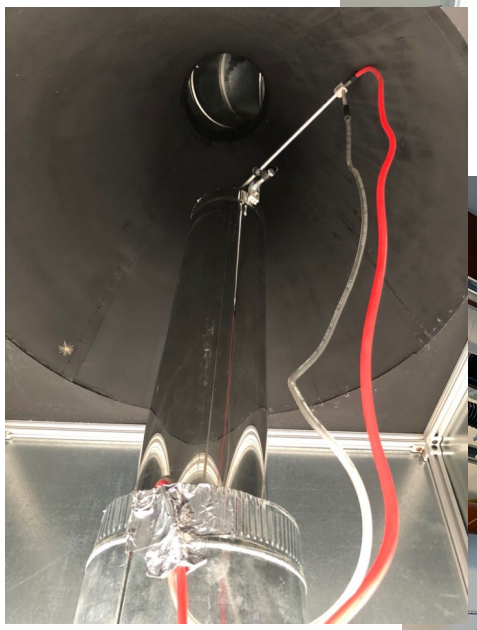


(R. Trojanowski et. al, 2022)

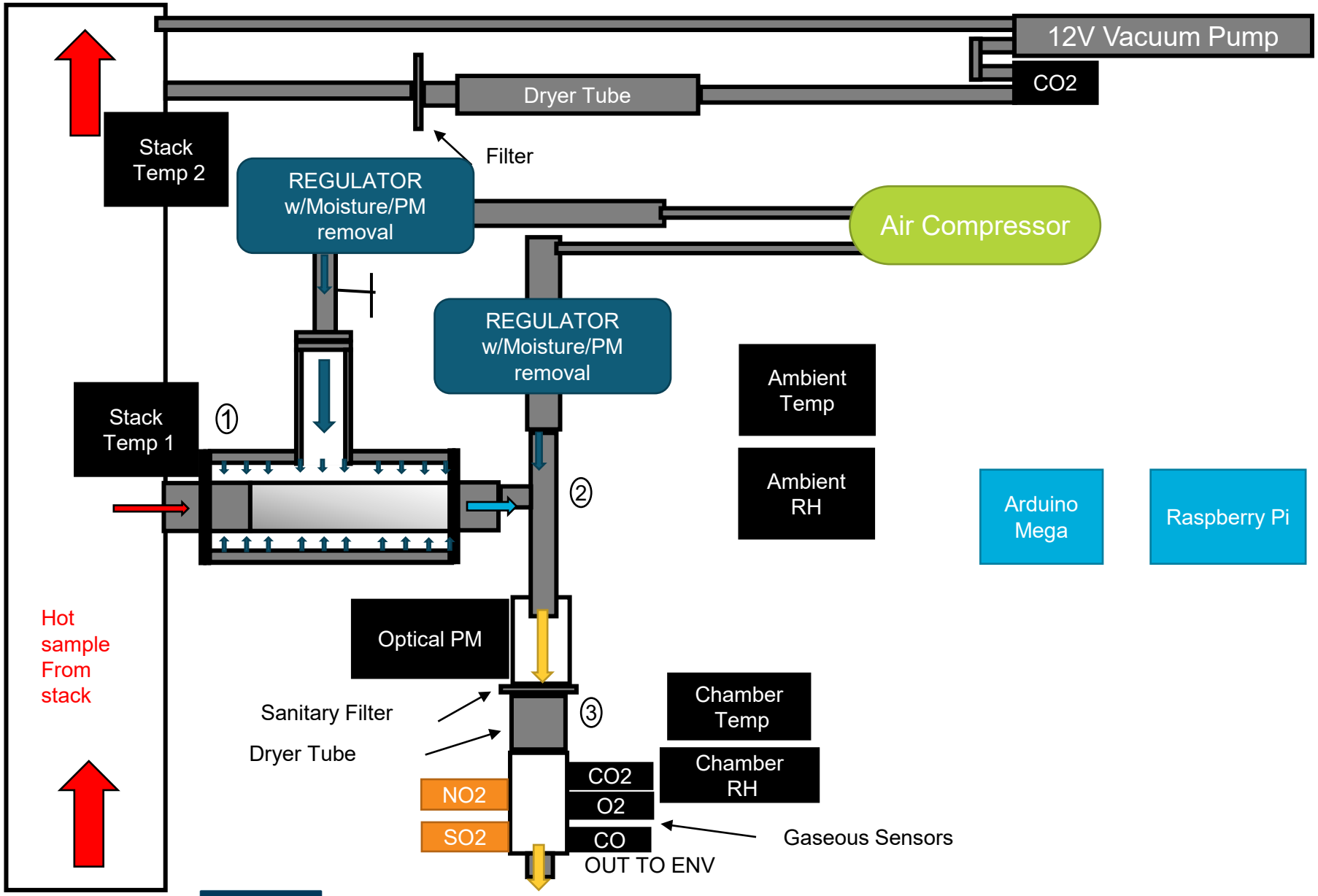
Developing simplified protocols

- Sample emissions from the flue
- Dilute sample prior to instrument measurement
- Use modern mass flow controllers to eliminate dry gas meter and flow conditioning equipment
- A hotwire anemometer may be able to measure exhaust flow rate directly in the flue if an s-type pitot tube cannot
- Harmonized test protocols and instrumentation needed to compare lab and field measurements





Progress and Outcomes: Task 5



① 1st stage dilution (Porous Tube)

② 2nd stage dilution (Ventrui Eductor)

③ Mixing Chamber with sensors + Filter

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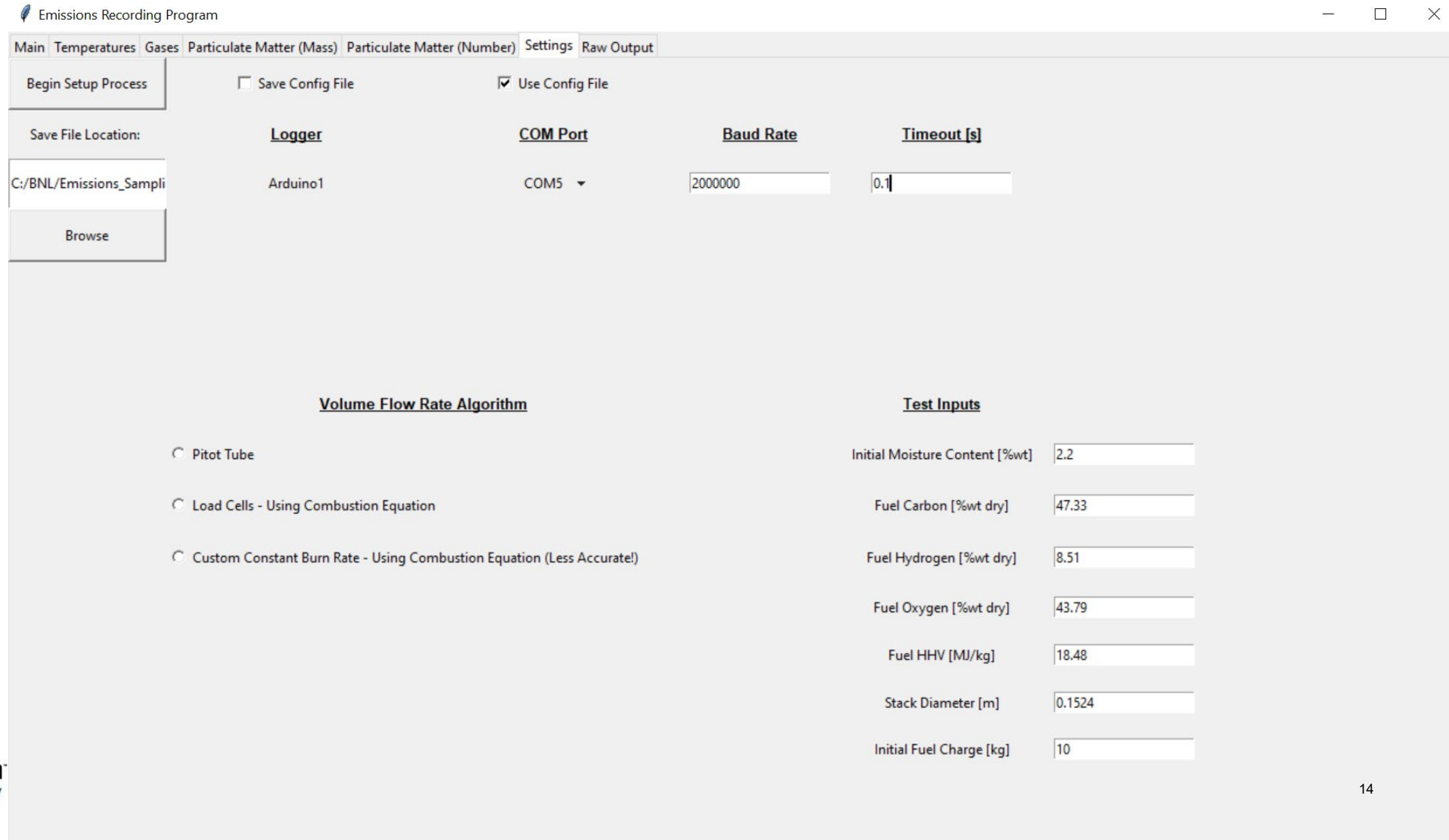
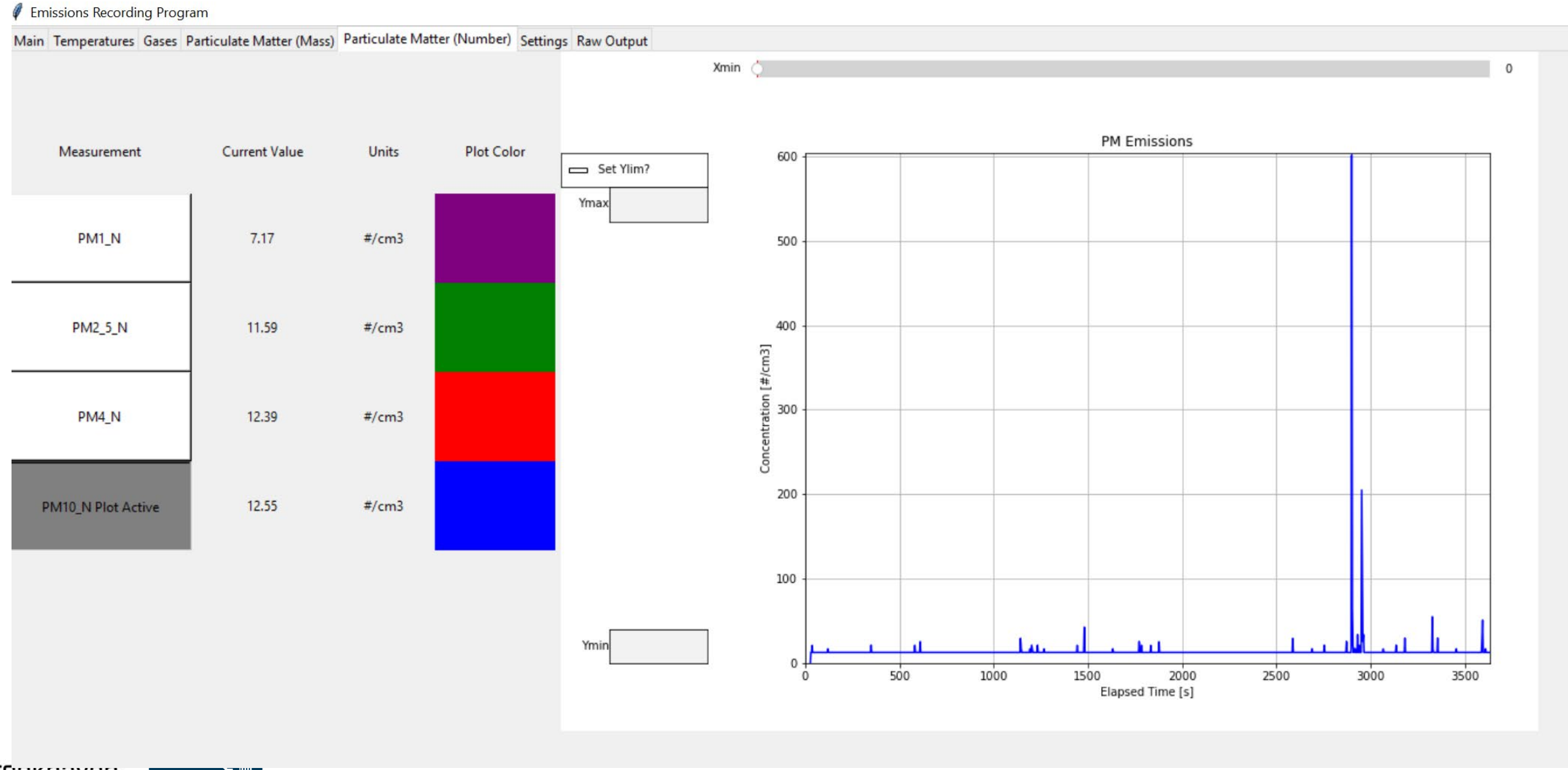
User Interface



User Interface

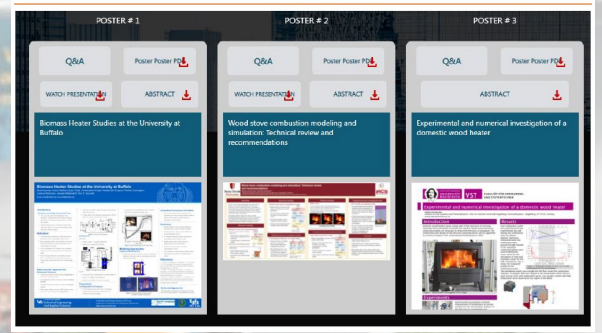


Community Engagement Workshops

- Three workshops brought together stakeholders from across the world to discuss topics related to R&D advances in wood heater research, specifically related to residential heating.
  1. Identified innovative design solutions and the key metrics that may be implemented regularly or on a larger scale to improve the performance of residential wood heaters
  2. Identified more accessible methods and instrumentation to help expedite R&D within manufacturer's facilities or the field research
  3. Determined barriers to wood heater adoption in the heating sector and how wood heaters could play a more long-term role as a renewable energy option
- More than 100 participants each workshop
- Participants indicated improved combustion technologies and emission testing protocols and regulatory policies need innovating
- Survey indicated manufacturers need help from National Laboratories for 'detailed prototype modeling and iterative support (new combustion geometries & designs)' and 'design assistance under NDA's'
- Workshop report in review

AUDITORIUM

POSTER HALL

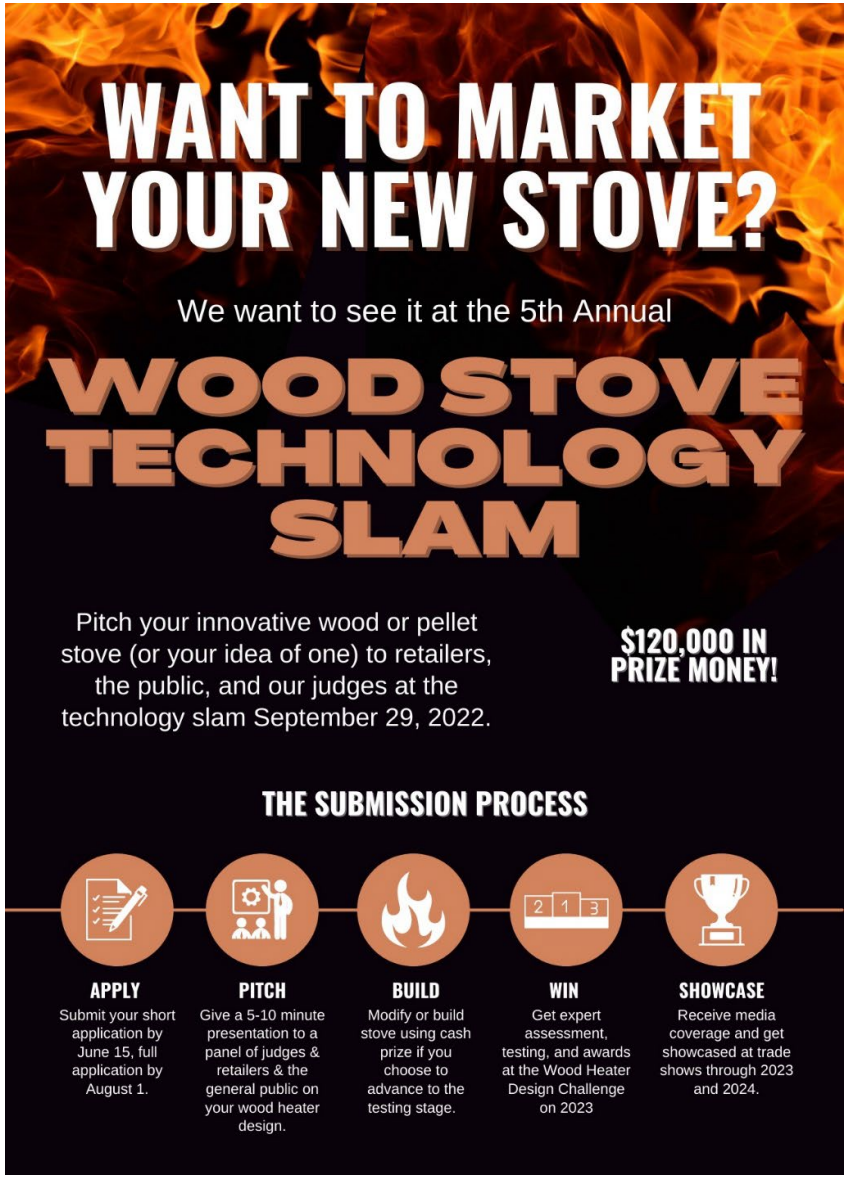


LOUNGE

Technology Slam Overview

- The Wood Heater Technology Slam provided an opportunity for teams to pitch innovative wood stove ideas to retailers, the public, and panels of expert judges
- 9 teams selected to present
  - Teams from academia, established industry, and independent/small manufacturers
- 7-minute pitch with 5 minutes of Q&A

https://www.bnl.gov/whdchallenge/events/index.php#slam



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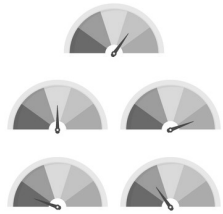
Technology Slam Scoring



1. Innovation – is the approach **innovative** and represent an **advanced concept** compared to traditional heater design.
2. Consistent performance – does the design **minimize the variability** of emissions that can occur in the hands of the average operator.
3. Commercial potential – can the unit be **affordably** produced, installed and maintained and offer features **valued by consumers**.
4. Expected performance - is the proposed technology **cleaner** and **more efficient** than what is currently on the market.

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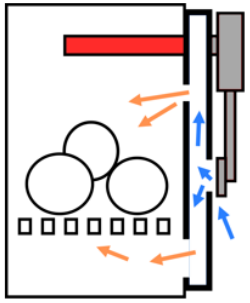
low carbon, renewable and local

U.S. Department of Energy
Wood Heater Design Challenge

Top Three Teams

- **Aprovecho Research Center: Cottage Grove, OR**
  - Partnered with US pellet stove manufacturer
  - Novel injection of air boasts 85% reduction in $PM_{2.5}$, 76% reduction in CO, 92% reduction in BC, and 39% increase in efficiency

- **Davidon Industries: Warwick, RI**
  - Senses gases leaving firebox and controls air delivery and gas temperature
  - Completely mechanical, no electronics or bi-metals
  - Automation shows 77% reduction in PM



- **Kleiss Engineering: Cloverdale, IN**
  - Computer controlled by touchpad using 2 watts of 12 V power– potentially "off-grid"
  - Advanced control algorithms and use of primary and secondary airflows to optimize the entire combustion system
  - Stove is designed for safety and limits maximum temperature, actively monitors sensors for anomalies and closes valves when detected

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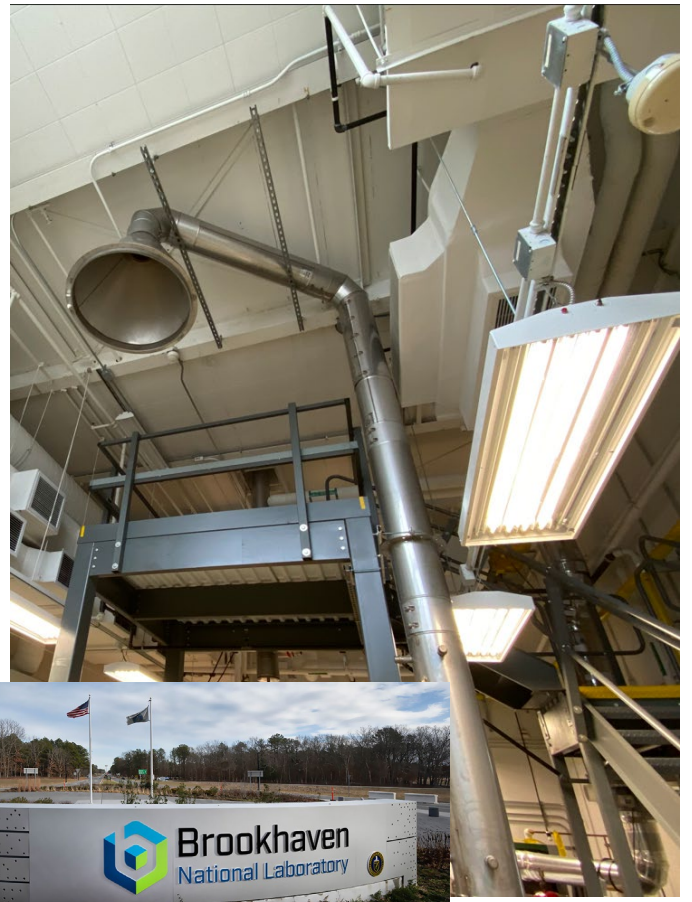
Wood Heater Design Challenge

- Teams joined us at HPBA (March 2023)
- Teams arrive for testing next week!
  - One week of testing
    - Triplicates test planned under realistic operation and use patterns reflecting field operation
    - Time for exploratory R&D testing also planned to help teams
      - Use of real-time instrumentation to help understand transients and burn phases
    - A lot of safety planning with BNL ES&H ahead of time!



Hearth, Patio & Barbecue Expo 2023
MARCH 11-13
KENTUCKY EXPOSITION CENTER
LOUISVILLE, KENTUCKY
HPBExpo.com
HPBA Hearth, Patio & Barbecue Association

https://www.midwesthpba.org/events

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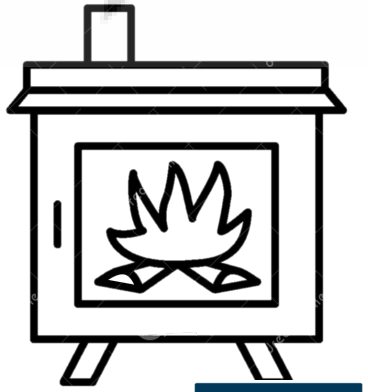
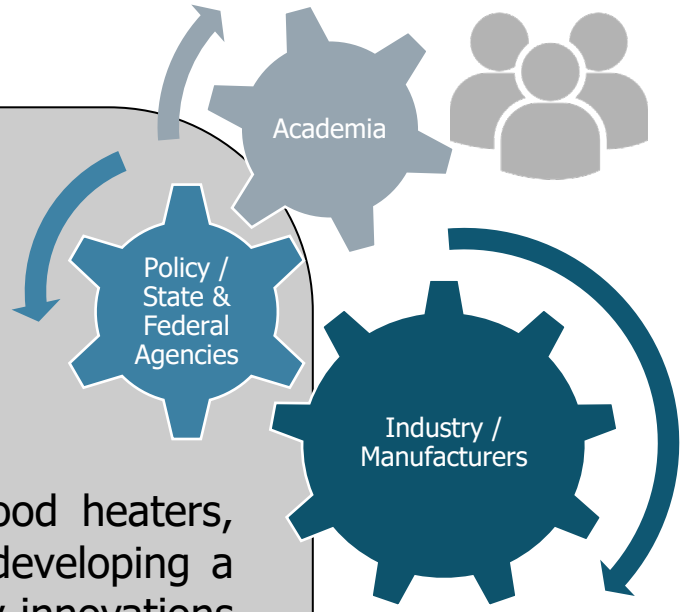
Impact

Direct combustion of biomass in homes is the most common use of woody feedstocks but is the **dominant factor in ambient air quality** in many parts of the U.S.



- Addresses Congressional direction (S. Rept. 115-422) to support development and testing of new domestic manufactured low-emission, high efficiency, residential wood heaters.
- Established compliance for new residential wood heaters, hydronic heaters, and forced-air furnaces by developing a simple testing protocol to accelerate technology innovations and commercialization of clean and efficient wood heaters.
- Enabling this technology innovation will allow millions of families, schools, institutions, and corporations access to affordable, efficient, and clean wood stoves that supports the growing bioeconomy.
- Also supports a parallel BETO initiative to develop advanced biomass combustion products with increased efficiency and reduced air pollutant emissions (DE-FOA-0002029). Performers under this FOA can leverage test methods developed under this project.



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Summary

Project Objectives

- Identify major hurdles preventing innovation of wood heaters
- Identify gaps and improvements with current test methods and opportunities to correlate with in-home performance
- Organize Wood Heater Design Challenge and community engagement workshops

Recommendations for protocol and measurement methods

- **Real-time measurements** of emissions to enable manufacturers to target specific operating phases in developing cleaner products
  - Harmonized evaluation: use simplified instrument suite for both lab and field testing
- Must be **easily conducted** in-house by manufacturers to guide R&D and prepare for certification tests
- Include startup, reload, shutdown, and steady-state performance metrics consistent with other methods
- Can **quickly and affordably provide performance metrics** to guide and inform design decisions prior to investing in costly certification testing

Key Workshop Take-Aways:

- Participants indicated improved combustion technologies and emission testing protocols and regulatory policies need innovating
- Manufacturers need help from National Laboratories for 'detailed prototype modeling and iterative support (new combustion geometries & designs)' and 'design assistance under NDA's'

Future plans:

- Begin testing Slam winners at Brookhaven for Design Challenge!
- Conduct field tests with developed protocol and instrumentation

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Quad Chart Overview

Timeline

- *Start: January 2020*
- *End: December 2023*

	FY22 Costed	Total Award
DOE Funding	*(10/01/2021 – 9/30/2022)*	*$886,612*
Project Cost Share *	*N/A*	

TRL at Project Start: 5
TRL at Project End: 5

Project Goal

1. *Develop simplified wood heater performance test methods that will reduce extensive cost and time associated with repeated certification testing, and provide approach for evaluating wood heaters in the field*
2. *Host 5th Wood Heater Design Challenge*

End of Project Milestone

1. *Demonstrate simplified test method's potential for field evaluation of efficiency and emissions performance. Publish field testing emission results*
2. *Complete 5th Wood Heater Design Challenge, announce winners and publish report*

Project Partners*

- Lawrence Berkeley National Laboratory

Collaborators

- The Alliance for Green Heater
- Distributed Sensing Technologies

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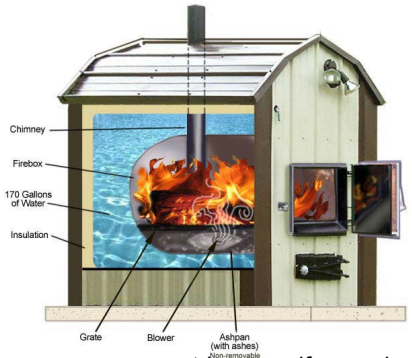
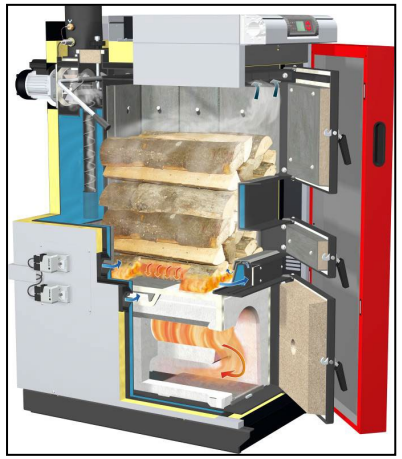
Additional slides

Variety of Wood Heaters

- Room heaters vs central heaters
- Indoor and outdoor central heaters
  - Hydronic vs forced
  - Advanced controls & thermal storage



outdoorwoodfurnaceboiler.com

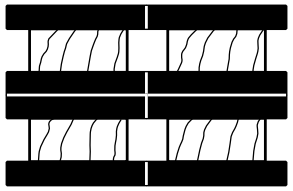


Single Stage Hydronic Heaters vs. Advanced	
Efficiency	
<40% (<<40% at idle)	>80% (at 50-100% load)
Water Volume	
300 gallons	45 gallons
Wood Charge	
250 pounds (2.1 mmBtu)	75 pounds (0.64 mmBtu)
Controls	
Damper: Open/Closed Fan: Hi/Low Fans might be optional	Lambda Sensor; Temp Sensor(s); Variable speed blowers; Advanced Algorithms
PM2.5 Emissions	
0.32+ lb/mmBtu Largely organic	0.03 lb/mmBtu Largely inorganic

Variety of Fuels

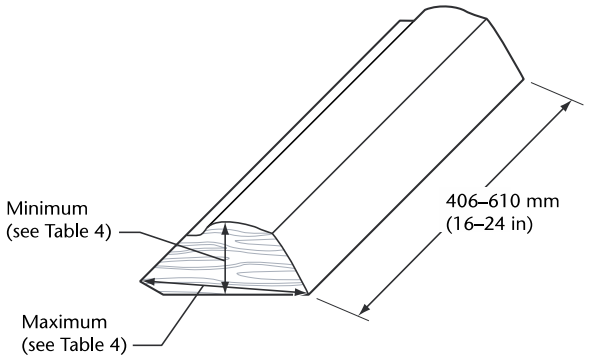
Firewood Heaters

- **Crib:** Standard lumber and wood spacers nailed into a prescribed configuration defined by firebox volume and loading density



2 × 4 in
(38 × 89 mm)

- **Cordwood:** Firewood



Automatic Fed Heaters

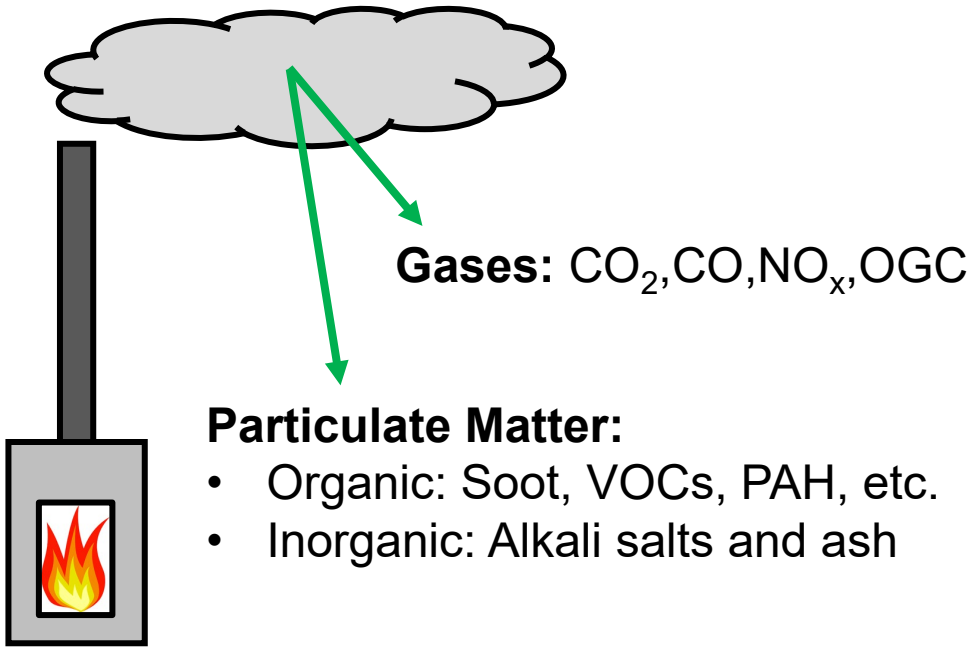
- **Pellets:** Loaded according to manufacturer's instructions
  - Pellet grade or type may be specified in standard (lowest possible grade typically preferred)
- **Chips:** Loaded according to manufacturer's instructions
  - Chip moisture content type may be specified in manual but no standard exists in US

Wood chips of various drying methods

Test measurement requirements

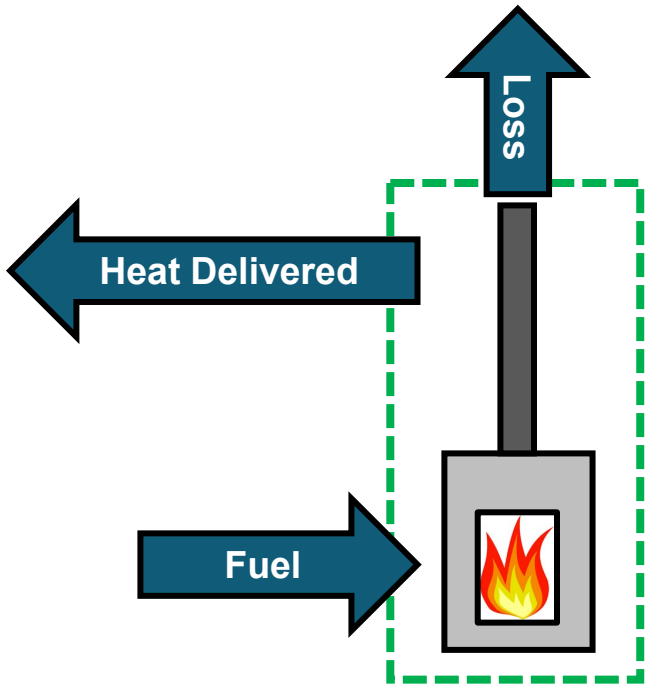
Emissions

- All standards require Particulate Matter (PM) mass emission measurements
- Some standards require gaseous emission measurements



Performance

- Some standards provide methods to evaluate heater performance:
  - Thermal efficiency
  - Combustion efficiency



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