Harmonizing lab and field performance of residential wood heaters

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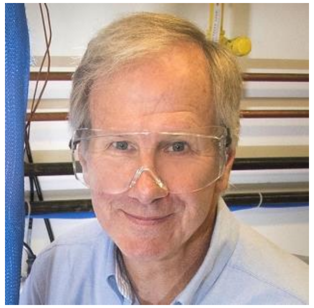

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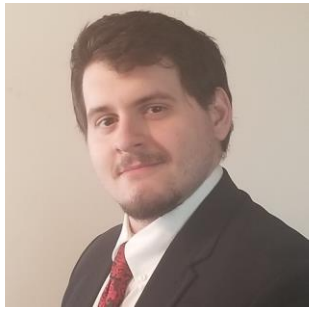

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Department of Energy Wood Heater R&D Funding

FY23 Appropriations Bill

The agreement provides up to $5,000,000 for continued support of the development and testing of new domestic manufactured low-emission, high-efficiency, residential wood heaters that supply easily accessed and affordable renewable energy and have the potential to reduce the national costs associated with thermal energy.

Competitive funding opportunity announcements (FOA) and National Laboratories

- DE-FOA-0002029: FY19 BETO Multi-Topic Funding Opportunity Announcement
- DE-FOA-0002203 - FY20 Bioenergy Technologies FOA
- DE-FOA-0002396 – FY21 BETO Scale-up and Conversion FOA
- Brookhaven National Lab and Lawrence Berkeley Lab

Project Goal

Support innovation of new wood heaters through development and demonstration of low-cost measurement tools and simplified test protocol(s) that help harmonize lab and *in-situ* performance evaluations

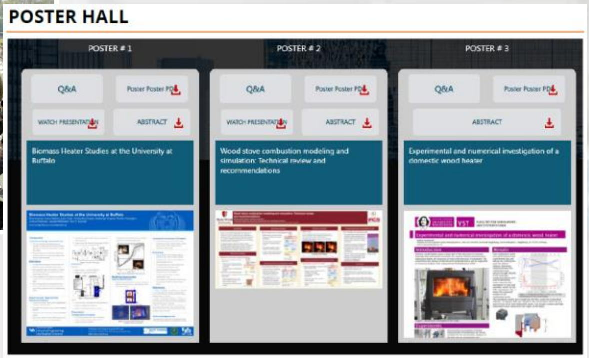
Project Objectives

- Identify challenges and opportunities with innovating wood heaters
- Support the community with R&D needs
- Determine gaps and improvements with current test methods
- Assist community with bridging *in-situ* and laboratory performance

Identify challenges and opportunities: Wood Heater Workshop

Three Workshops in 2022

- Advances in wood heater design and technology
- Advances in instrumentation used for wood heater testing and field data collection
- Adoption of new wood heater technology and integration with other renewables

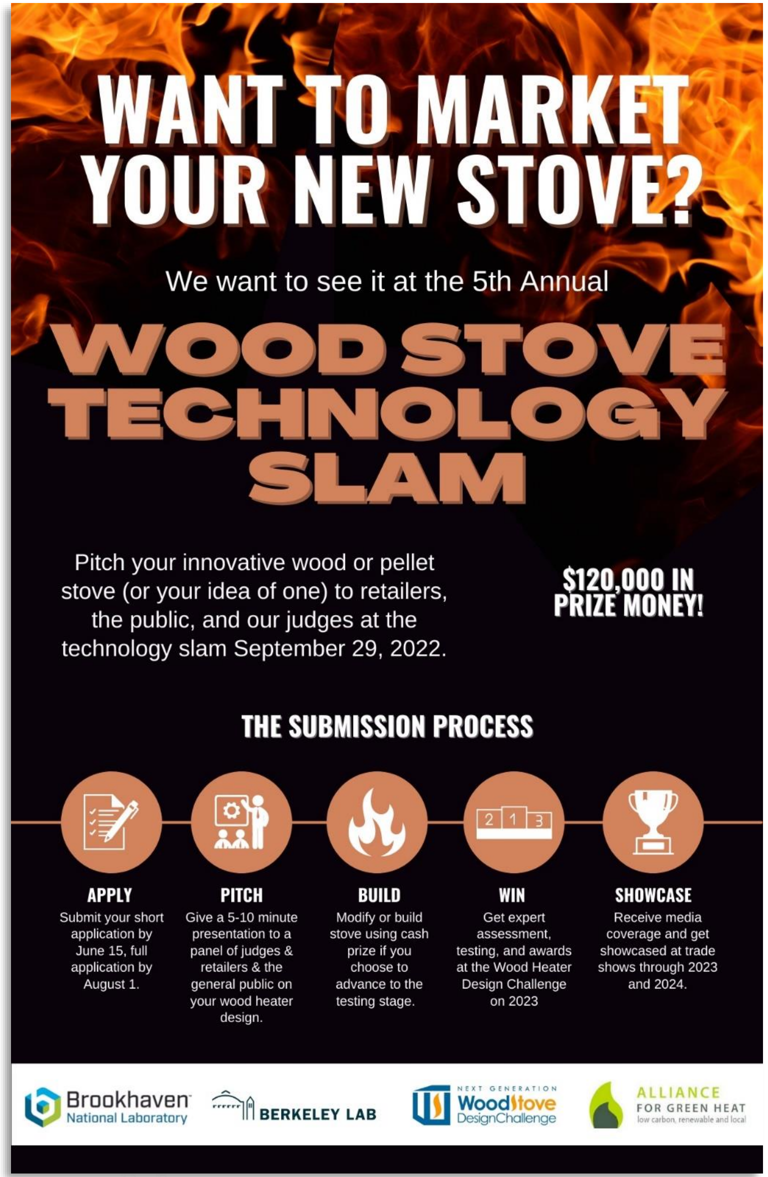


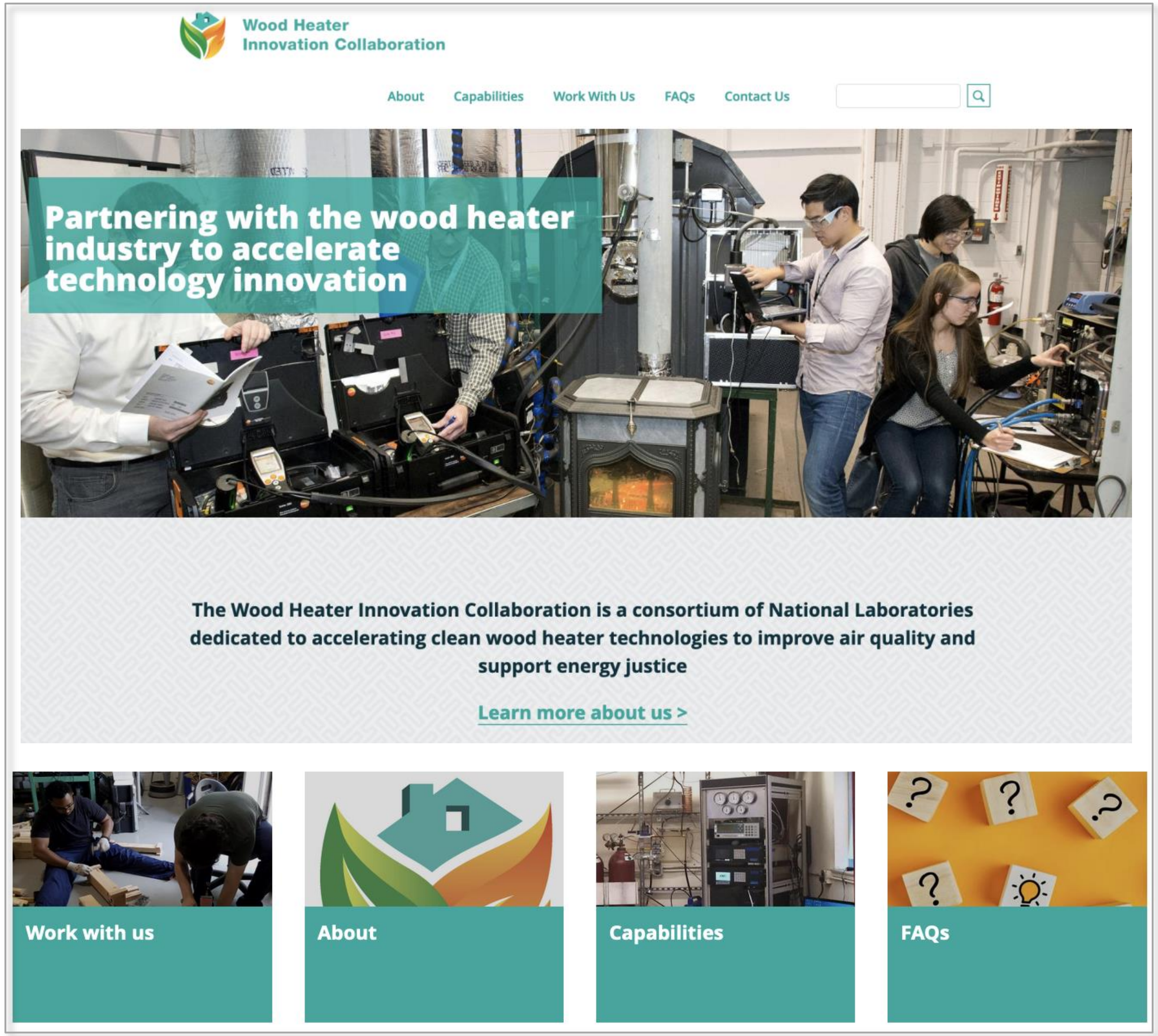
https://www.bnl.gov/woodheater/workshops.php

Major Takeaways

- Field data with time-resolved particulate measurement to better understand user behavior and its impact on wood heater performance
- Affordable, portable, and accurate dilution system for *in-situ* emissions measurements that can be translated to laboratory dilution tunnel tests
- Automation through sensors and controls to help optimize combustion and reduce combustion variability
- Computational modeling tools that predict performance and emissions to reduce R&D time
- Post-combustion technologies capable of reducing start-up emissions and poor-user practices

Support the community with R&D needs





Determining gaps and improvements with current test methods

Literature Review:

- Multiple test standards used for certification of wood heaters evaluating wood heaters in laboratories
- No official standard for field testing wood heaters
- Test standards reviewed include US, Canada, Europe, Australia, New Zealand, and China
- Full publication available in “Renewable and Sustainable Energy Reviews” (https://doi.org/10.1016/j.rser.2023.113501)

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A review of regulatory standard test methods for residential wood heaters and recommendations for their advancement

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A R T I C L E I N F O

Keywords:
Wood heaters
Standardized testing
Air pollution
Thermal performance
Particulate emissions
Emissions regulations

A B S T R A C T

In many regions, residential wood heaters are a leading source of harmful air pollution but only satisfy a small portion of local heating demands. In response, standardized laboratory test methods have been developed to characterize and limit wood heater emissions. While these test methods are a key tool for advancing both wood heater technology and environmental regulations, many of the experimental procedures are outdated and provide few actionable insights for improving heater performance. Furthermore, these test methods vary widely around the world and may not adequately capture the performance of wood heaters operating in residences. This study presents a comprehensive review of standardized wood heater test methods to identify fundamental experimental objectives and regulated performance metrics. Using the results of this review, recommendations are provided to make the test methods more accessible and representative of residential performance, while generating actionable data to motivate heater design improvements. This study elucidates the current state of standard test methods, and the developments needed to advance clean wood heater technologies and public policies.

1. Introduction

Relative to the energy they deliver, residential wood heaters are a large source of particulate matter (PM) pollution [1–3]. While only 9% of homes in the United States (US) used wood heaters in 2020, they contributed about 7% of the nation’s total annual $PM_{2.5}$ emissions [4,5]. Similarly, wood heaters and boilers satisfied about 29% of the European Union’s residential heating needs in 2018 and accounted for over 57% of the health-related social costs attributed to air pollution from the residential heating sector [6]. Given their outsized influence on ambient air quality, many countries have implemented national regulations that limit pollution emissions from residential wood heaters. Along with local regulations, such as mandatory curtailment on days with high pollution levels, national emission limits have proven effective at mitigating adverse impacts on public health and the environment [7–10]. Despite these efforts, residential wood heaters continue to be major drivers of poor air quality in many regions [1,2,5,6].

To mitigate air quality impacts, wood heaters in the US and Europe are required to pass standardized certification tests that demonstrate compliance with regulatory limits. While these tests enable performance comparisons of wood heaters in controlled laboratory environments, they are too cumbersome to perform outside of the laboratory and do not accurately represent in-home performance [11–15]. For instance, many of the test methods neglect to incorporate the impact of startup, reloading, shutdown, user behavior, fuel-wood conditions, and flue draft (i.e., chimney design) on wood heater performance [11,13–15].

This study reviews standard test methods for certification of residential heaters fueled by firewood and wood pellets. This review focuses solely on room heaters that deliver heat directly into the space where they operate. Test methods for central heaters (e.g., boilers, hydronic heaters, and furnaces) will be discussed in a future study. Masonry heaters and fireplaces are not considered in this study because they are not consistently regulated in the US or globally.

For each test method, this study identifies common experimental objectives and regulatory outputs required for characterizing wood heater pollution emissions and thermal performance. The major functional components of each method are categorized and their relative strengths and weaknesses are discussed. This comprehensive review uniquely examines the entire heater test from initial measurements in

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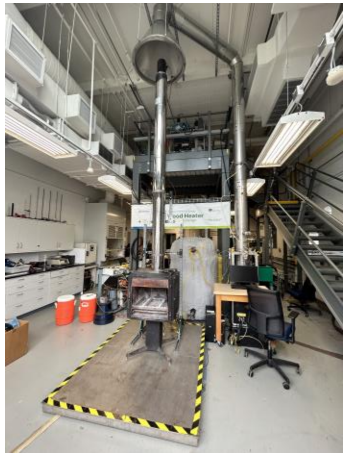
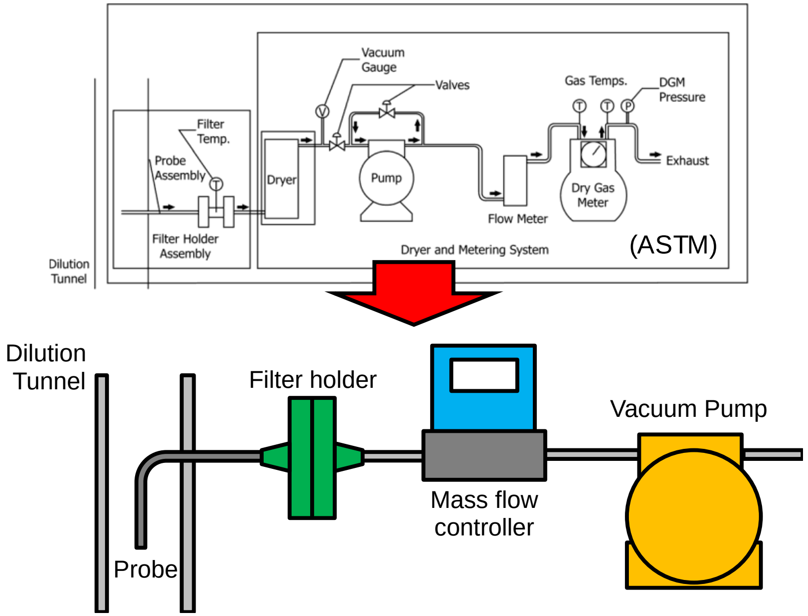
Pain points and gaps when transitioning to *in-situ* testing

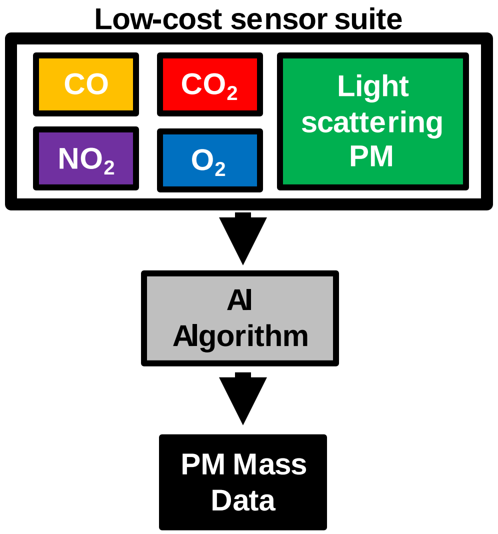
1. Dilution tunnel is big, cumbersome, and complicated
2. Gravimetric PM provides a single, test-integrated measurement that does not capture transient emissions
3. Flue gas flowrate may be too low to measure accurately; calculated flowrate requires burn-rate which may not be measurable
4. Standard lab test cycles do not represent actual heater operation and do not include transient phases (e.g., startup, shutdown)
5. Standard lab equipment may be outdated and result in unnecessary complications

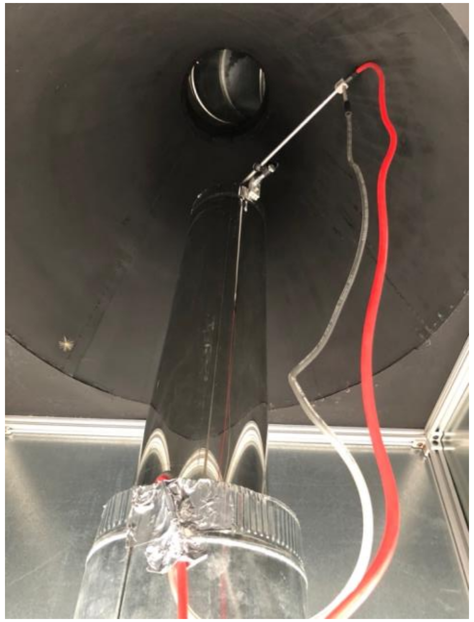


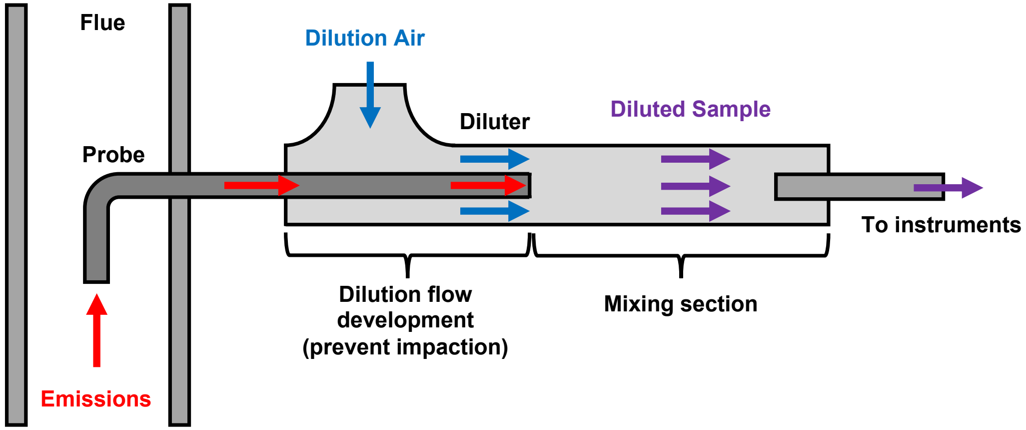


Overcoming challenges with *in-situ* testing

- Sample emissions from the flue and dilute sample prior to instrument measurement
- Use an affordable and portable system for monitoring real-time emissions
- Measure exhaust flow rate directly in the flue (s-type pitot tube or hotwire anemometer)
- Harmonized test protocols and instrumentation needed to compare lab and field measurements and identify sources of uncertainty







Assist community with bridging in-situ and lab performance

- *In-situ* testing Nov 2023
  - Portola, CA
  - North Greenbush, NY
  - Rochester, NY
- Room and central wood heaters
- Purpose
  - Demonstrate robust, affordable, and portable system for monitoring real-time emissions in lab and homes
  - Identify challenges and opportunities with correlating *in-situ* and lab performance

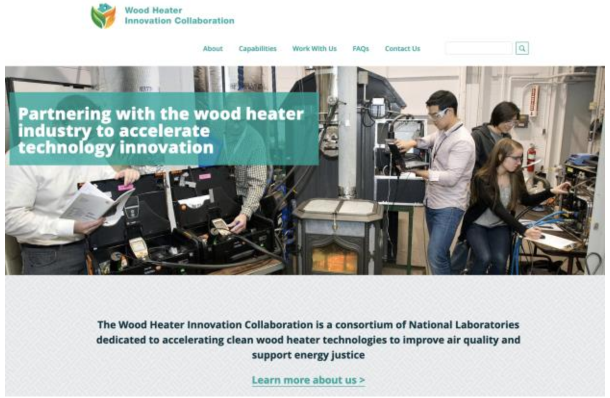
Questions?

Identify challenges and opportunities with innovating wood heaters

Support the community with R&D needs

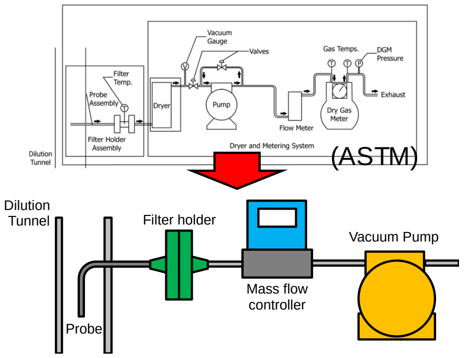
2022 Wood Heater Workshop

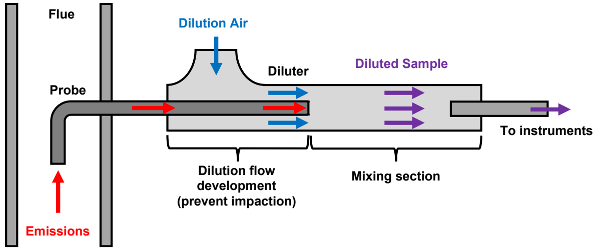
Workshop 1	Workshop 2	Workshop 3
Advances in wood heater design and technology	Advances in instrumentation used for wood heater testing and field data collection	Adoption of new wood heater technology and integration with other renewables



Determine gaps and improvements with current test methods

Assist community with bridging *in-situ* and laboratory performance





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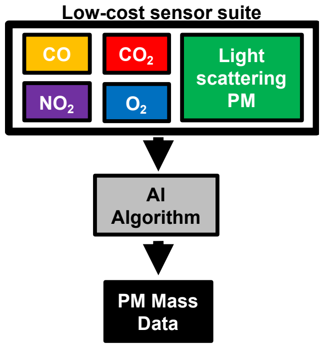


In-Situ Testing Nov 2023

EXTRA SLIDES

Literature Review: Summary of standardized wood heater test methods used for certification

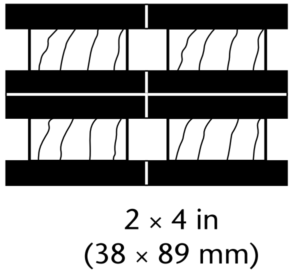
Standard Designation (Country of Origin)	Fuel	Emissions Measurement		Overall Efficiency Determination*	Test cycle				Regulated Performance Metric
		Pollutants Monitored	Emissions Sampling Method		Pretest	Burn Rates	# of required Burn Cycles per Burn Rate	Burn Cycle End Criteria	
EPA Method 28R (United States)	Crib wood per ASTM E2780-10 with exceptions	PM per ASTM E2515-11 with modifications CO per CSA B415.1-10	Dilution tunnel per ASTM E2515-11	Indirect per CSA B415.1-10	Establish bed of embers within prescribed fuel weight limit; operate ≥ 1 h with controls set to first burn rate test	1. Maximum: Fully open controls 2. 1.25 to 1.90 kg/h 3. 0.8 to 1.25 kg/h 4. < 0.8 kg/h	1	≥ 2 h operation & remaining weight of test fuel is 0.00 kg (0.0 lbs) or less for 30 seconds	g of PM per h
ASTM E2779-10 (United States)	Pellets	PM per ASTM E2515-11 with modifications	Dilution Tunnel per ASTM E2515-11	Indirect per CSA B415.1-10	≥ 1 h operation at max burn rate	1. Max achievable 2. ≤ 50% of max 3. Minimum achievable	1	1. Max: 60 min 2. Med: 120 min 3. Min: 180 min	g of PM per h
EPA ALT-140 (United States)	Cordwood	PM per ASTM E2515-11 CO, CO_2	Dilution Tunnel per ASTM E2515-11	Indirect	None stated	1. Start-up 2. High 3. Maintenance 4. Low	3	1. Specified by fuel load calculator 2. 90% test fuel burned 3. 90% test fuel burned 4. 90% test fuel burned	g of PM per h

Standard Designation (Country of Origin)	Fuel	Emissions Measurement		Overall Efficiency Determination*	Test cycle				Regulated Performance Metric
		Pollutants Monitored	Emissions Sampling Method		Pretest	Burn Rates	# of required Burn Cycles per Burn Rate	Burn Cycle End Criteria	
EN 16510-1:2022 (European Union)	All solid fuels	PM, CO, CO2, O2, NOx, OGC	Flue	Indirect	≥ 1 h at a burn rate of nominal output or 33 ±5% for wood logs and 25 ± 5% for peat, lignite or briquettes during slow combustion and recovery tests	1. Nominal (≥ 95% of rated value) 2. Partial load that is a function of nominal 3. Slow combustion (specified by manufacturer)	3 for wood-based fuels 2 for all other fuels	Cordwood – test fuel is exhausted or CO_2 criteria met Pellets - minimum cycle duration	PM, CO, NOx, and OGC in mg/m3 and efficiency**
AS/NZS 4012-2014 & AS/NZS 4013-2014 (Australia/NZ)	Cordwood & Coal	PM (CO Optional)	Dilution Tunnel per AS/NZS4013	Direct	Operate at mean average power to establish bed of embers within prescribed fuel weight limit	1. High: Fully open 2. Low: Minimum setting 3. Medium: midpoint of high and low burn time or set using controls	3	±0.5% of test fuel remains	g of PM per kg of fuel burned and efficiency
PD 6434:1969 & BS 3841-2:1994 (United Kingdom)	Solid fuels	PM CO, CO2, O2, VOC, and OGC recommended using EN or ISO standards	Dilution Tunnel or electro-static precipitator per BS 3841-2:1994	Only heat output required per Domestic Solid Fuel Appliances Approved Council	Operate heater to achieve steady-state conditions. Ignition emissions are ignored.	1. Rated output 2. Minimum output 3. Intermediate output if available	5	Sufficient to establish the effects, on smoke emission, of accumulations of soot, shale or ash within the appliance if these can occur.	g of PM per h
NS 3058-1:1994 & NS 3058-2:1994 (Norway)	Crib wood	PM	Dilution Tunnel per NS3058-2:1994	None specified	≥ 1 h operation at first burn rate settings. weight of charcoal bed must be 20 to 25% of first burn rate fuel charge	Four burn rate categories that depend on heater grade	1	Scale indicates burn cycle fuel is completely consumed	g of PM per h

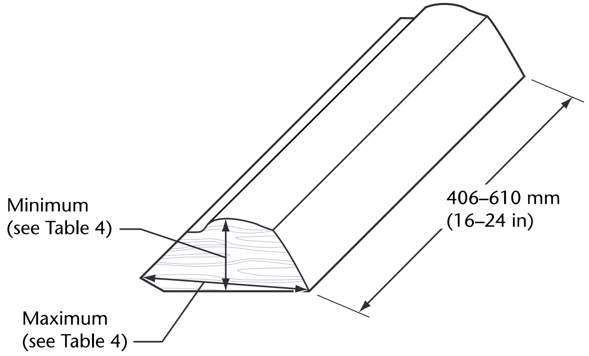
Types of fuel

Firewood Heaters

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



- **Cordwood:** Firewood



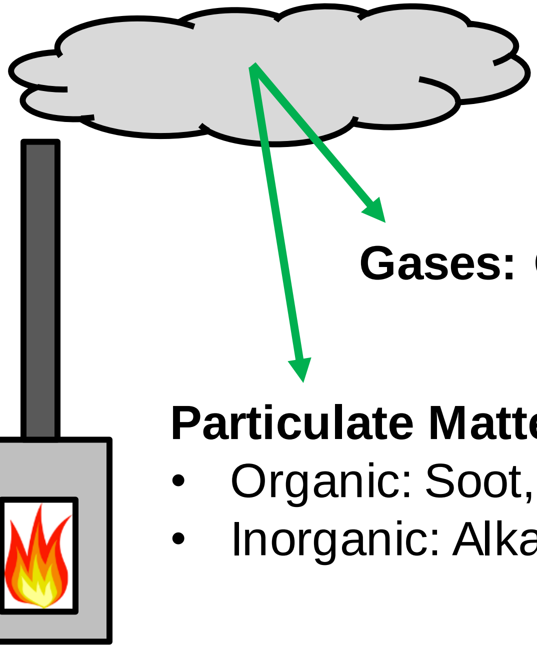
Pellet Heaters

- **Pellets:** Loaded according to manufacturer's instructions
  - Pellet grade or type may be specified in standard (lowest possible grade typically preferred)

Test measurement requirements

Emissions

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



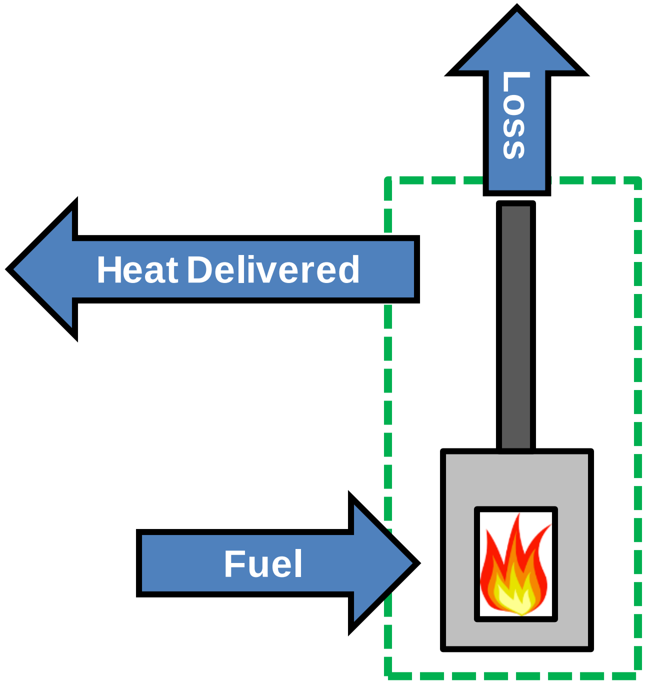
Gases: CO_2,CO,NO_x,OGC

Particulate Matter:

- Organic: Soot, VOCs, PAH, etc.
- Inorganic: Alkali salts and ash

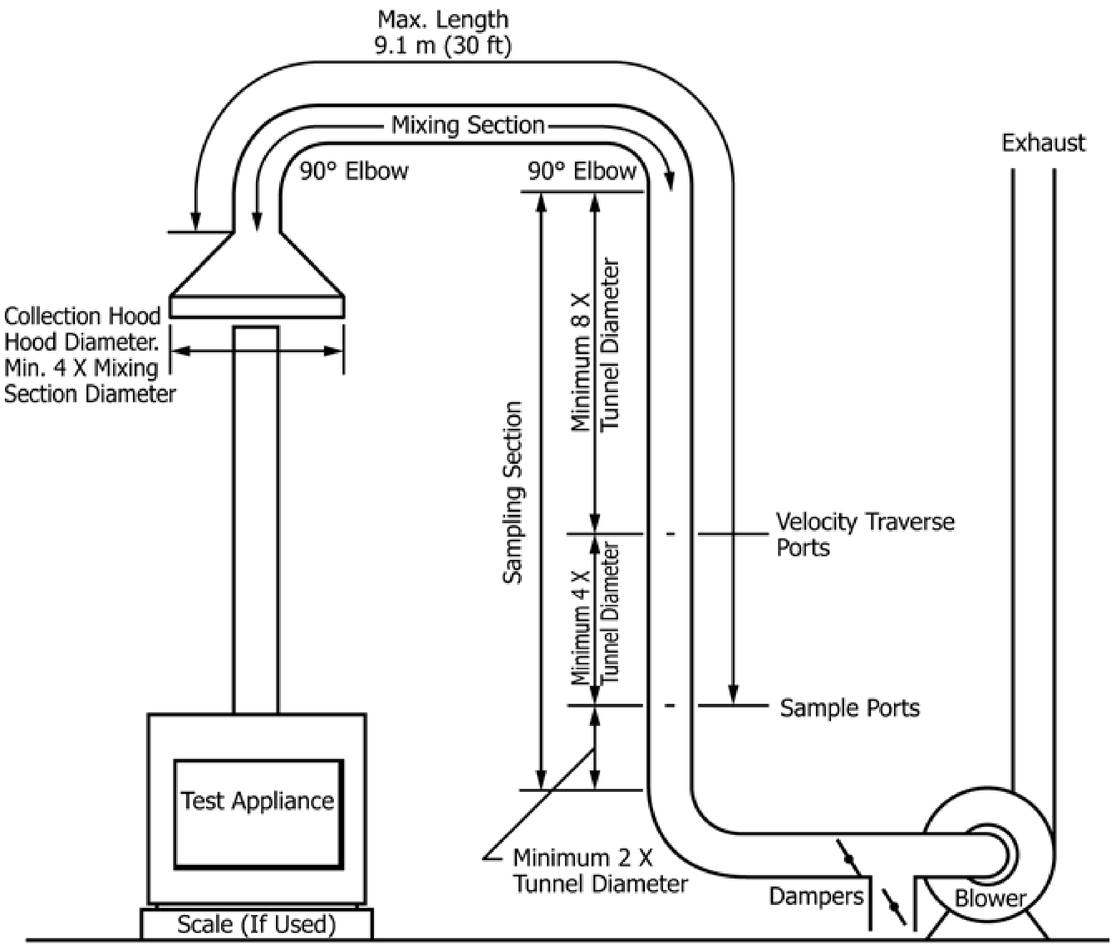
Performance

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



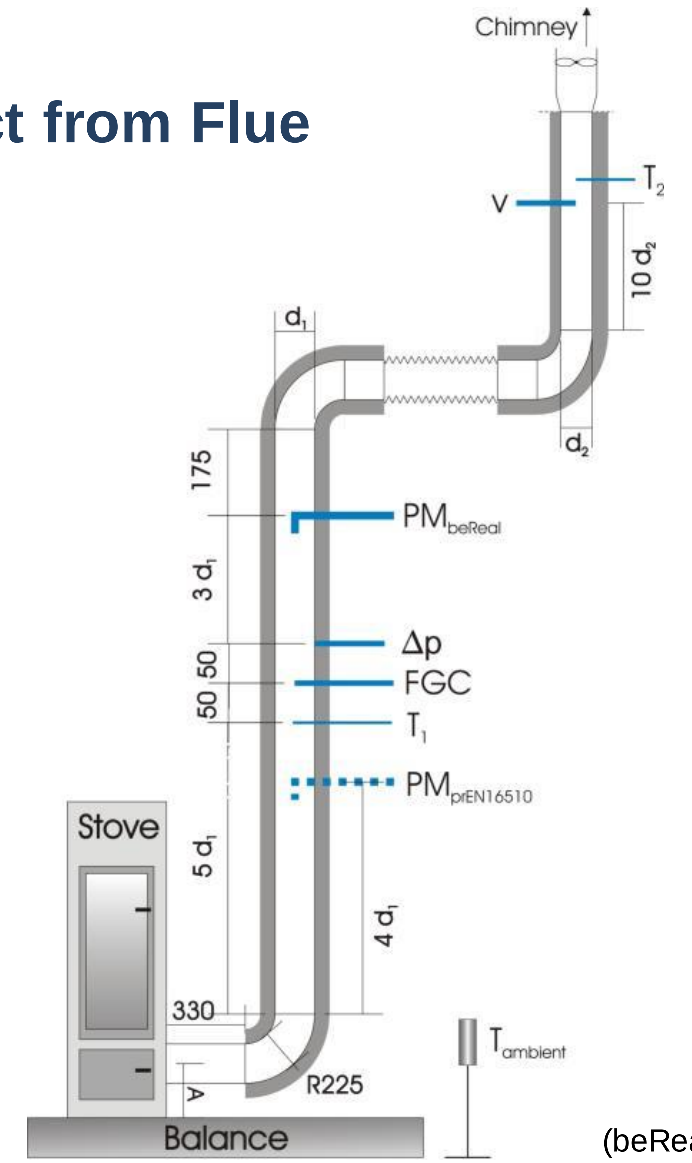
Measuring emissions

Dilution Tunnel



(ASTM E2515-1)

Direct from Flue



(beReal Protocol)

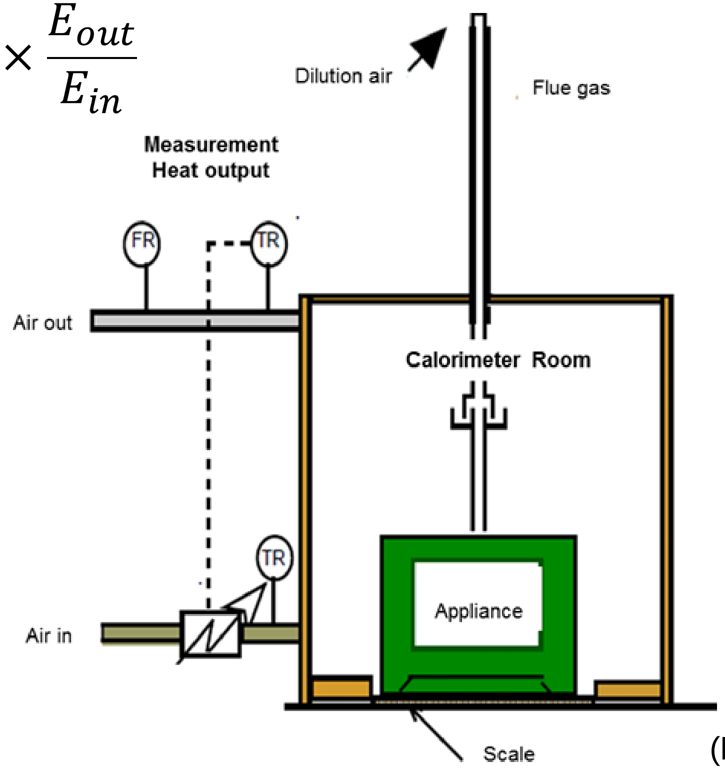
Measuring thermal efficiency

Direct: Insulated calorimeter room

$$E_{out} = m_{air} C_p (T_{out} - T_{in})$$

$$E_{in} = m_{fuel,db} LHV$$

$$\eta = 100 \times \frac{E_{out}}{E_{in}}$$



(ISO/DIS 13336)

Indirect:

Calculated using:

- fuel mass and properties
- flue temperature and gas concentrations
- ambient air temperature

Energy Conservation:

$$E_{in} = E_{out} + E_{loss}$$

Thermal Efficiency:

$$\eta = 100 \times \frac{E_{out}}{E_{in}} = 100 \times \frac{(E_{in} - E_{loss})}{E_{in}}$$

Energy Loss Mechanisms:

$$E_{loss} = E_{chemical} + E_{sensible} + E_{latent}$$