Test Method Primer

Symposium on Understanding and Reducing Residential Wood Combustion Emissions

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BROOKHAVEN NATIONAL LABORATORY
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U.S. DEPARTMENT OF ENERGY | Office of Science

Scope

Basics of test methods -

- How representative is the test compared to how the heating device will be used?
    - Fuel protocol
    - Operation
    - Test conditions
- Technologies
- How efficiency can be measured and what it means
- How emissions are measured (or missed)
- Method comparison

Basics of Any Test Method

- Test methods must provide a fair comparison between products and against emission limits;
- Test method needs to reflect real world operation but be repeatable and not impose an excessive test burden;
- Test methods must be realistic enough to ensure that a "passing" unit will not create a field operation problem;
- Control settings must be documented and reflect installation practices;
- Compromises are inevitable;

How representative is the test compared to how the heating device will be used?

Fuel: What fuel is used for the test and how is it loaded vs the fuel and loading by the operator?

Operation: Is the test duty cycle representative of how the unit will be operated once installed? Does it include:

- Different output levels needed by the load over the year?
- All phases of the burn: cold start, steady state, burn out?

Test conditions vs installed conditions

- Do the emissions measurements accurately reflect the emissions would come out of the stack?
- Is the efficiency measurement representative of delivered heat for the boiler as installed and operated?

Technologies

Space Heating	Central Heaters	
Stoves	**Hydronic Heaters**	**Furnaces**
cordwood	Cordwood (manual feed) high mass	cordwood
wood pellet	Cordwood (manual feed) low mass with external thermal storage	wood pellet
	Pellets (automatic feed) low mass with or without external thermal storage	wood chip
	Chips (automatic feed) low mass with or without external thermal storage	

Relevant Test Methods

Space Heaters (stoves)	Central Heaters
EPA Method 28R ASTM E2779 ASTM E2780 ASTM Draft Cordwood Protocol EN 13240 BeReal Draft	EPA Method 28 WHH EPA Method 28 WHH – PTS ASTM E2618 EN 303-5 CSA B415.1

Fuels used in Testing

Fuel Protocols - Stoves

Test	Fuel Type	Load Volume	Moist. % dry basis
EPA- 28R	CRIB – Doug Fir	7 lb/ft^3	19-25
ASTM E 2779-10	Pellet		per manuf.
ASTM E 2780-10	CRIB-Doug Fir Cordwood in Annex – density range	Crib – 7 lb/ft^3 Cordwood – 10 lb/ft^3	Crib - 19-25 Cord – 18-25
ASTM Draft Cordwood Protocol	Cordwood in density range	10 lb/ft^3 high fire 12 lb/ft^3 low/med	19-25
BeReal Draft	Beech or birch with bark	As per manufacturer	15-25

Fuel Protocols – Central Heaters

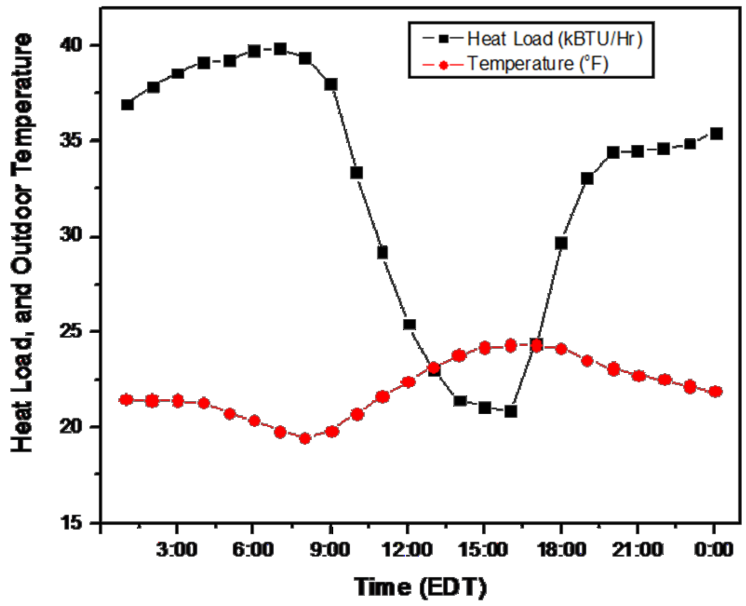
Test	Fuel Type	Load Volume	Moist. % dry basis
EPA 28 WHH	Crib – red or white oak	10 lb/ft^3	19-25
EPA 28 WHH PTS	Cordwood – red or white oak	10 lb/ft^3	19-25
ASTM E 2618-13	Cordwood (density range) and auto-fed. Doug fir crib also	Cord - 10 lb/ft^3	19-25
EN 303-5	Cordwood – beech, birch, oak, spruce or hornbeam	Manufacturers instructions	15-25
CSA B415	Cordwood (density range) and auto-fed. Doug fir crib also	10 lb/ft^3	18-25

Operation

- To understand what the result means, need to understand how the unit will actually operate in the field – this includes system loads, temperatures and controls, reload habits, potential backup systems for low load periods

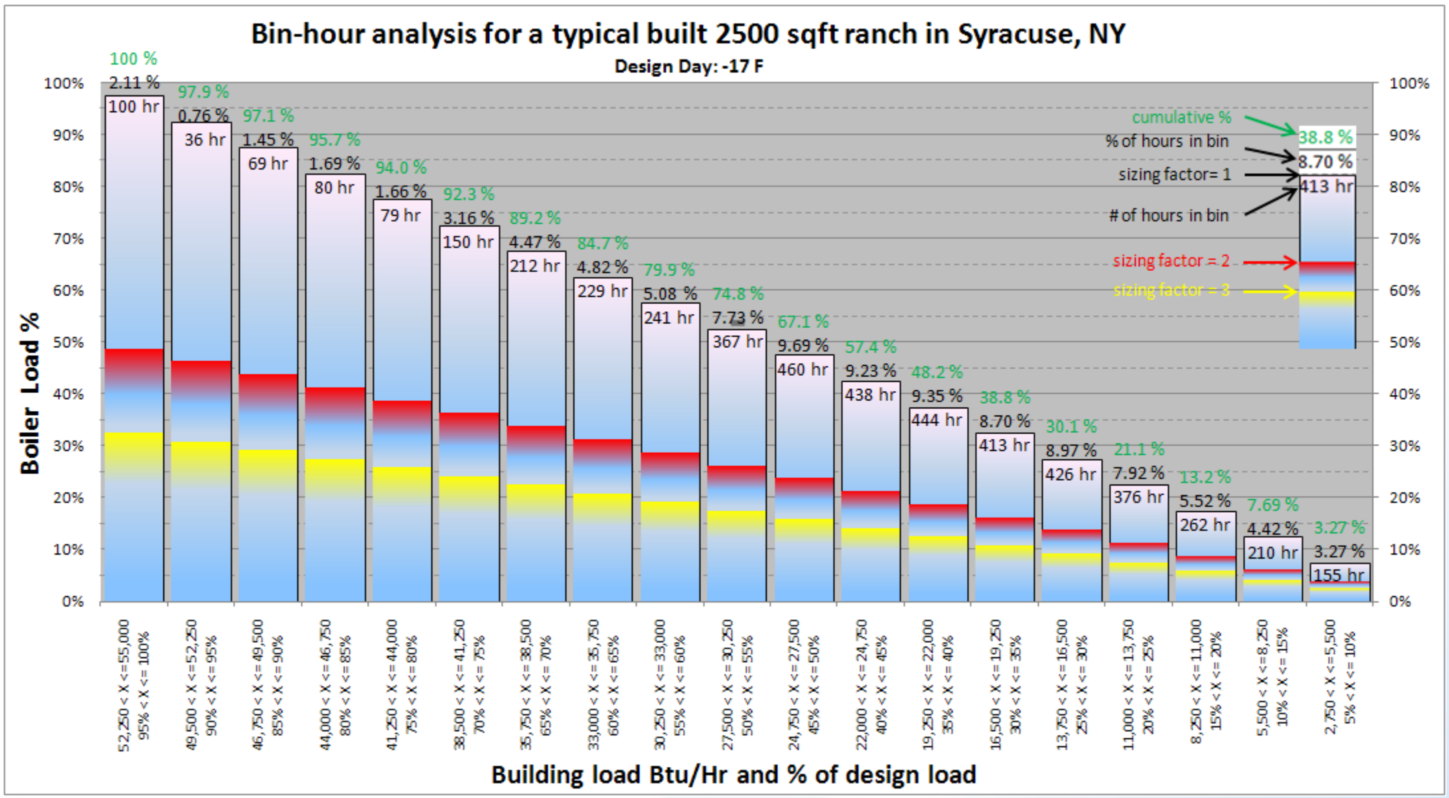
Syracuse, NY Heat Load

Ranch-style
home,
2500 ft^2
R-13



NYSERDA (2012)

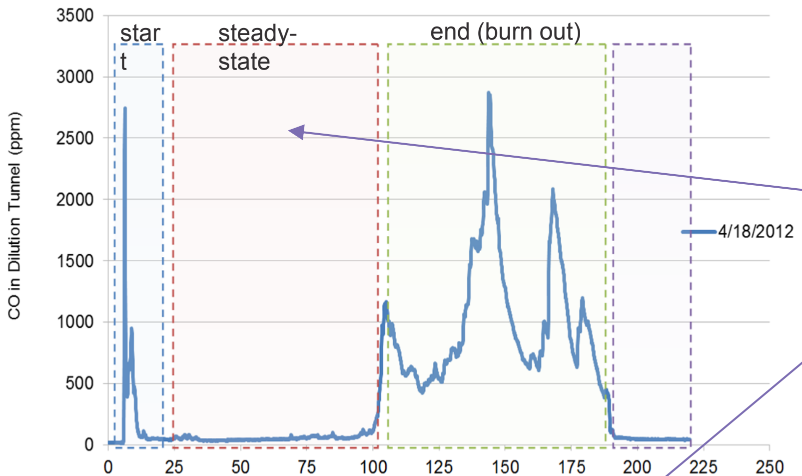
Heat Load Analysis – Impact of oversizing

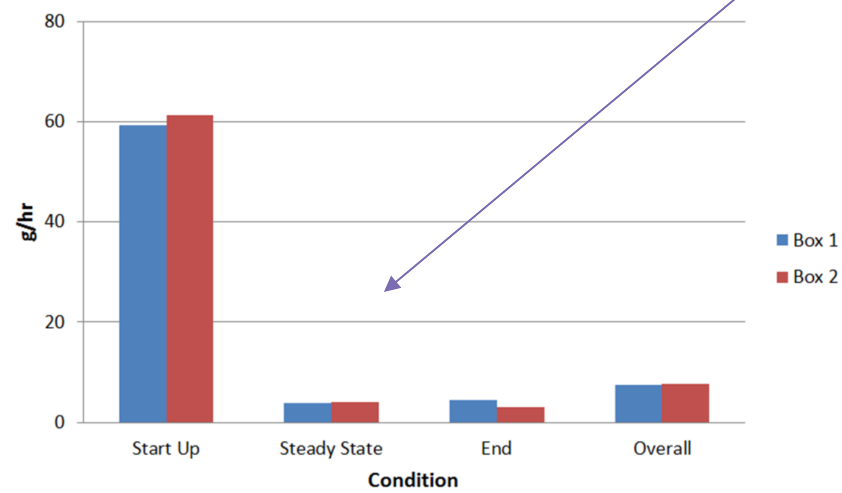


It is important that we evaluate all phases of the burn.

Cordwood- fired boiler with external thermal storage in Category I

BNL-PTS measures emissions from all three phases of the burn.





European Norm 303-5 measures emissions only from the steady state phase, missing 2/3 of the PM emissions.

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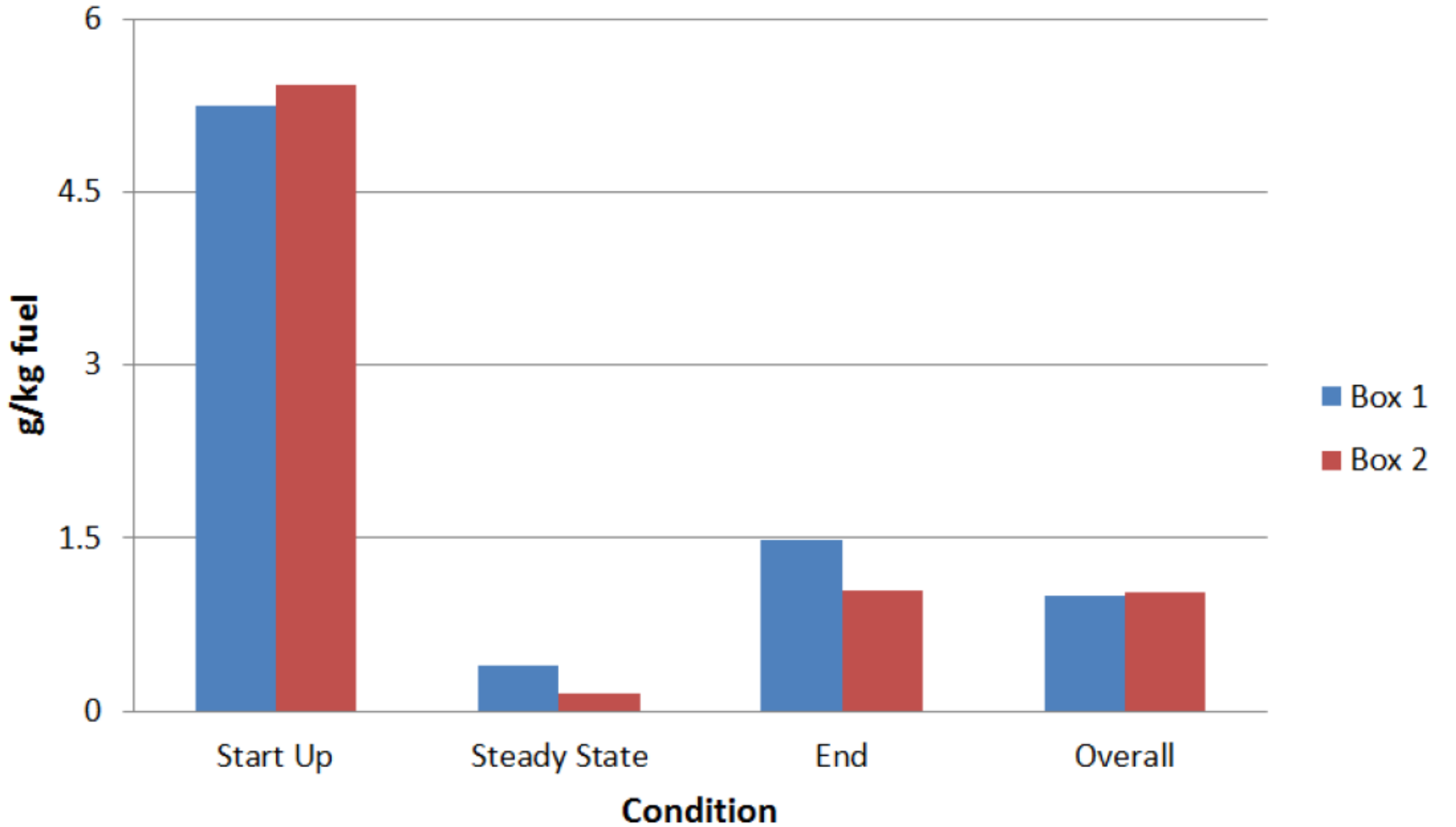
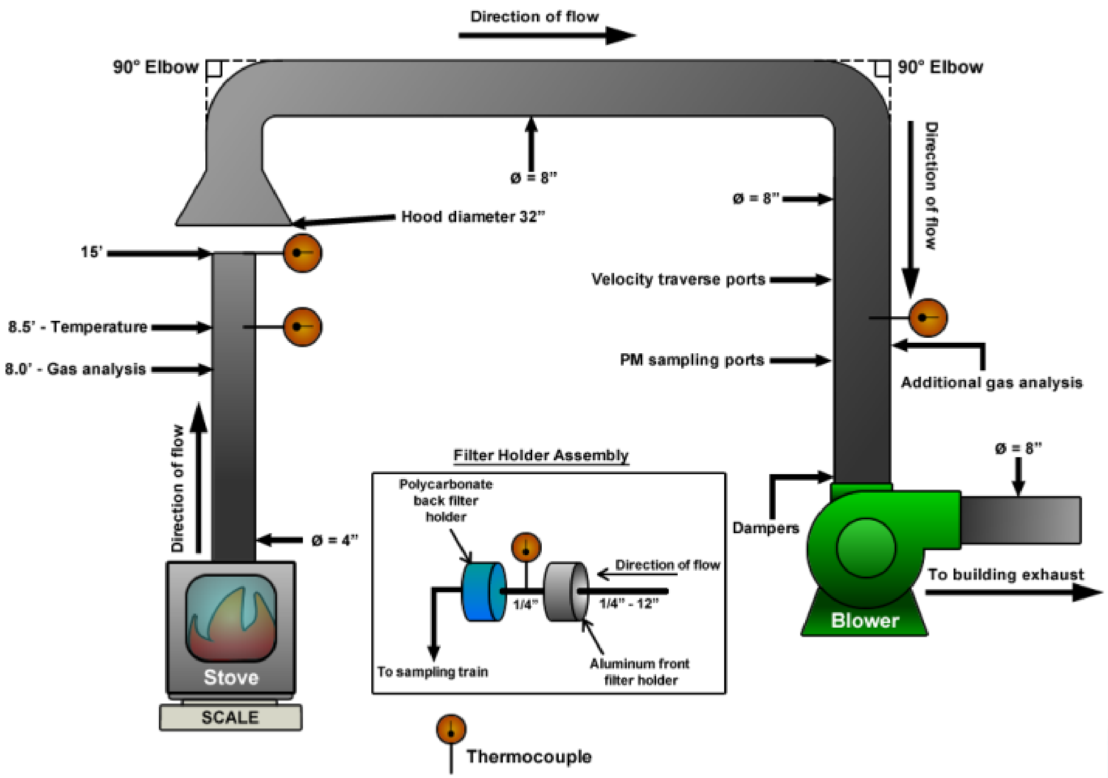
Example – emission factor by phase



Measuring emissions during each phase of operation can help our understanding. It allows for knowing what local, short-term impacts wood-fired appliances can have and set the stage for providing incentives for cleaner-starting units.

EMISSIONS

Dilution Tunnel



TB note – new graphic planned

Test Methods

- US
- Norway

Advantages:

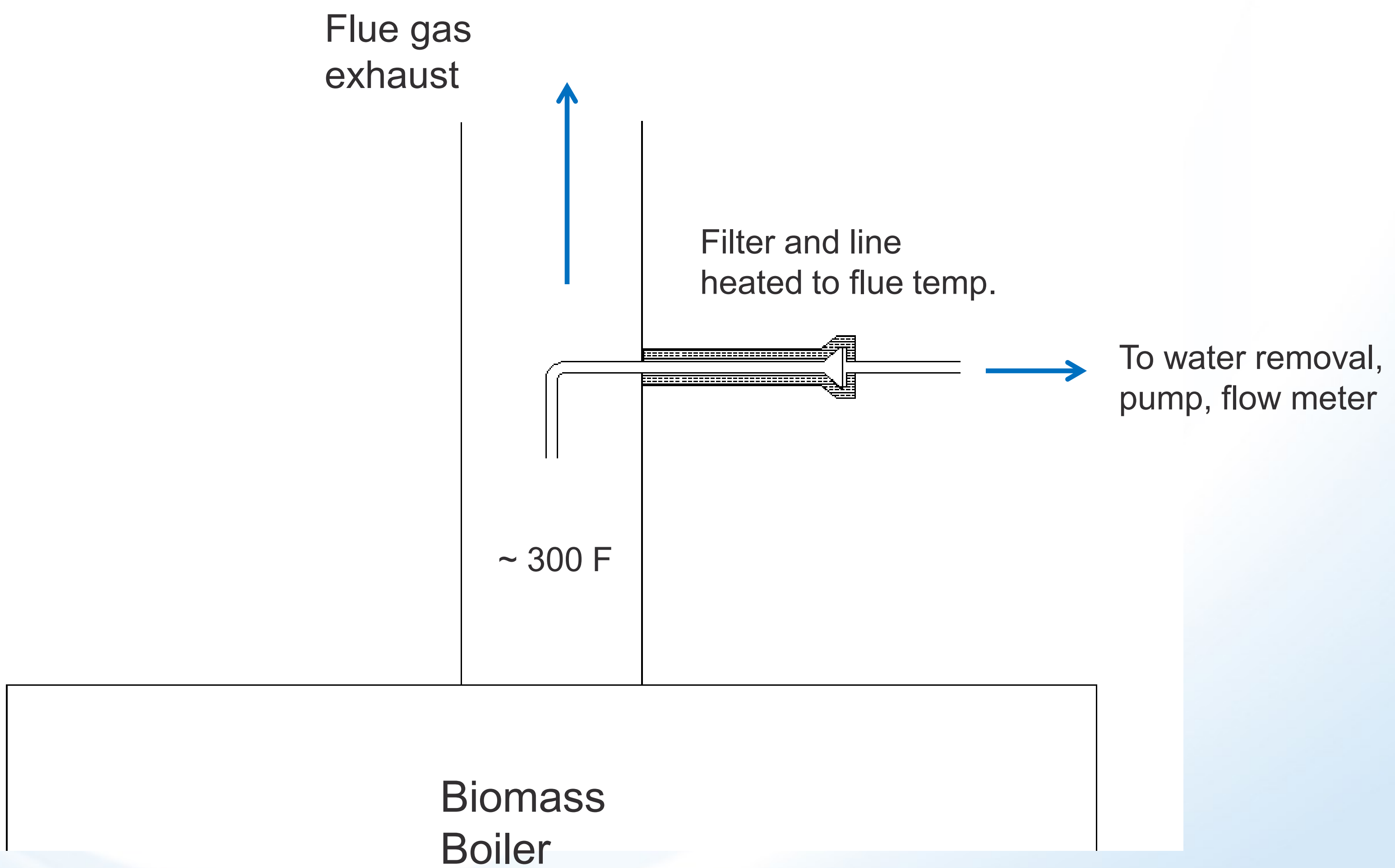
- Semivolatile organics condense (as they would in the ambient air) and are "counted" as particulates;
- Velocity in the dilution tunnel is nearly constant and easily measured. This provides a way to determine emissions over a burn event during which combustion conditions and burn rates vary greatly.

Disadvantages

- More involved setup
- Lower PM concentration

Hot Filter

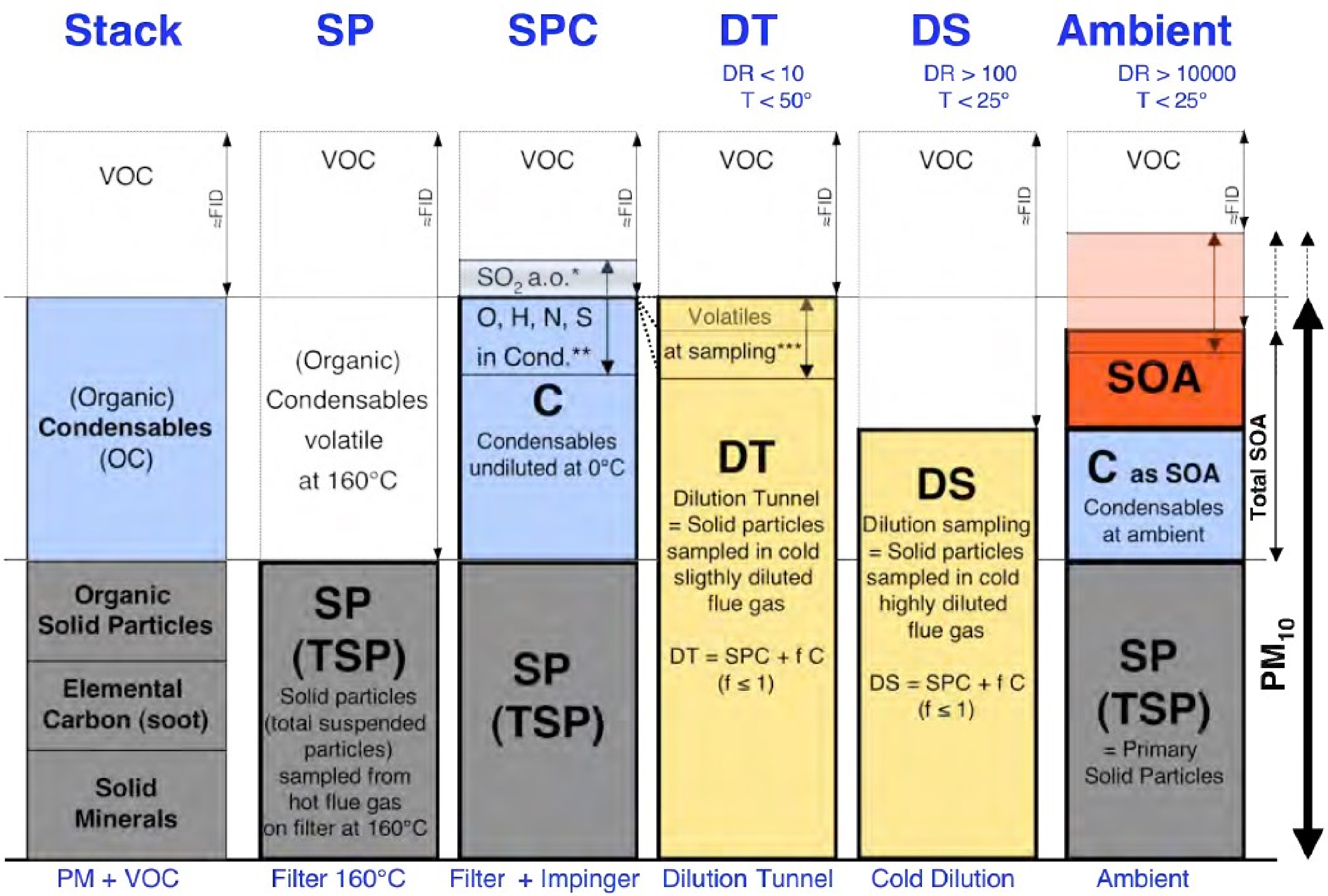
- quartz filter at flue temperature
- pre- and post conditioning at ~ 320 F
- ~ isokinetic



Hot Filter

- Use
  - EN approvals – in some countries
- Advantages
  - Simpler
  - Potential direct comparison to field data
  - Higher PM concentration
- Disadvantages
  - Does not capture condensable organics
  - Does not allow evaluation of emissions over complete burn cycle where flue gas mass flow can change.

Can the dilution tunnel PM emission be determined from hot flue PM + measured organics?



Source: NYSERDA 08-03, 2008, Thomas Nussbaumer, Biomass Combustion in Europe – Overview on Technologies and Regulations

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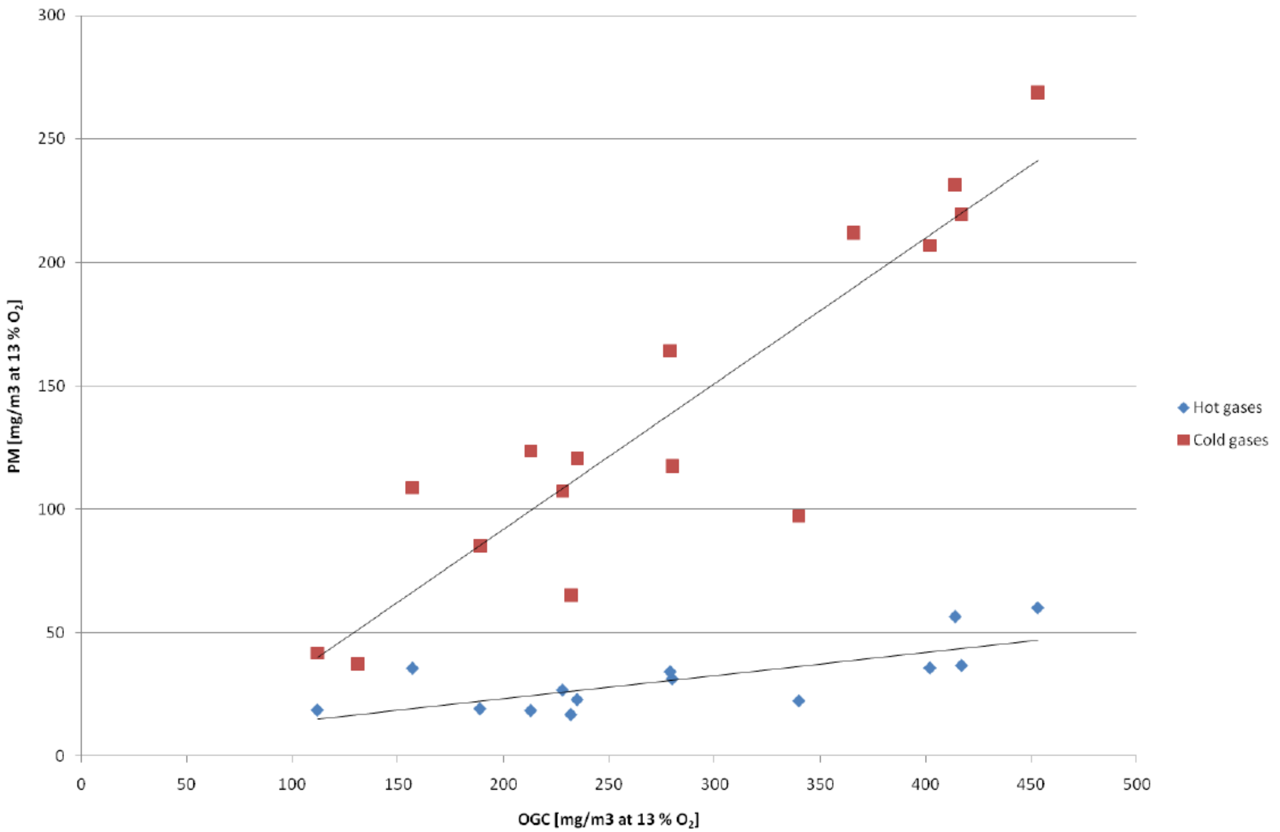
Particulate emission in hot gases vs. cold gases



SP Technical Research Institute of Sweden

Generally – the agreement between hot (flue) and cold (dilution tunnel) PM shows strong scatter – the conversion factor between measured hydrocarbons and dilution tunnel PM is not simple. Source: Henrik Persson, SP Sweden, 2013.

EFFICIENCY

What do you mean by efficiency?

Efficiency has many different meanings

- How well does it burn the wood = combustion efficiency
- How well does it theoretically deliver heat = thermal efficiency by stack loss method
- How well does it actually deliver heat including jacket losses = delivered efficiency

Key items to that factor into efficiency calculations?

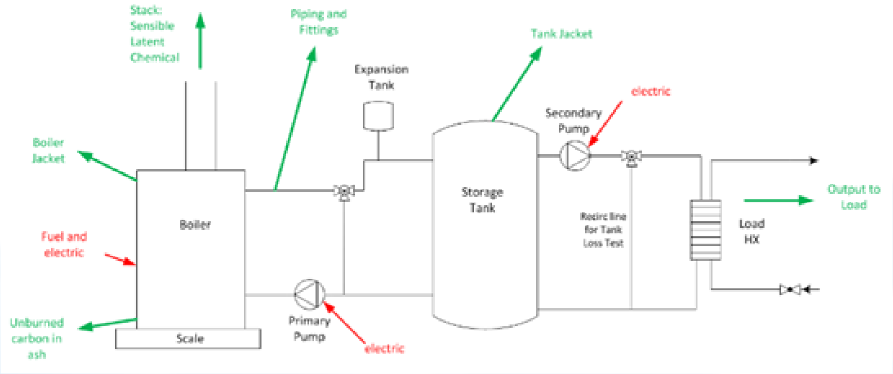
- Lower heating value vs higher heating value
- Annual fuel use efficiency
- high-load steady-state versus realistic duty cycle

Definitions of Efficiency

“Combustion Efficiency”

In wood combustion and engine fields combustion efficiency is used as a measure of the fraction of the fuel’s chemical energy converted to heat. It measures how complete combustion of the fuel is but not what heat is useful.

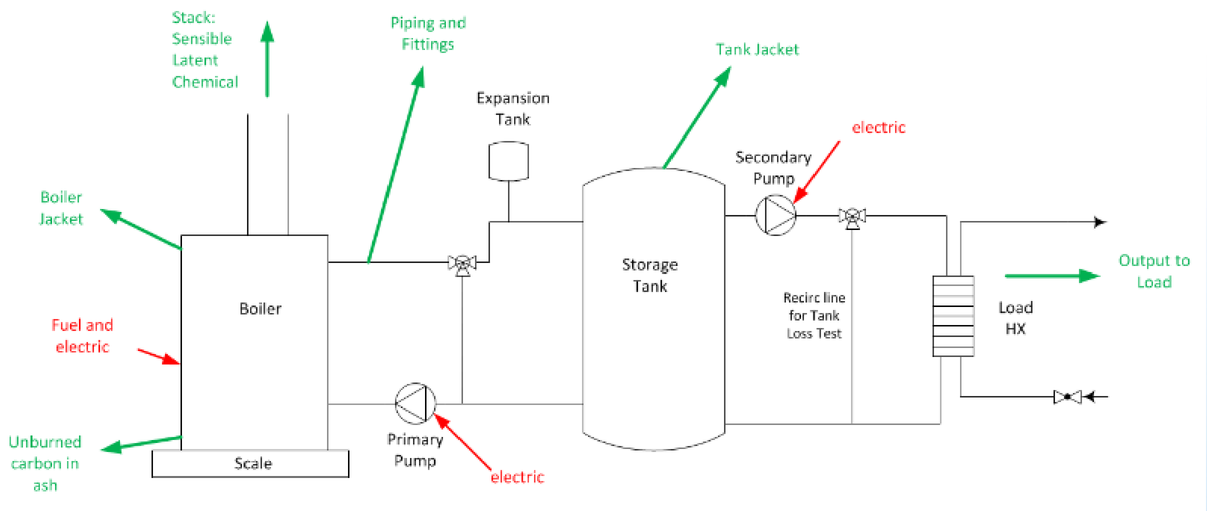
$$Combustion\ Efficiency = \frac{Input\ rate - Flue\ Gas\ Chemical\ Energy\ Loss\ Rate}{Input\ Rate} * 100$$



Definitions of Efficiency

"Stack Loss Method or SLM" CSA B415.1

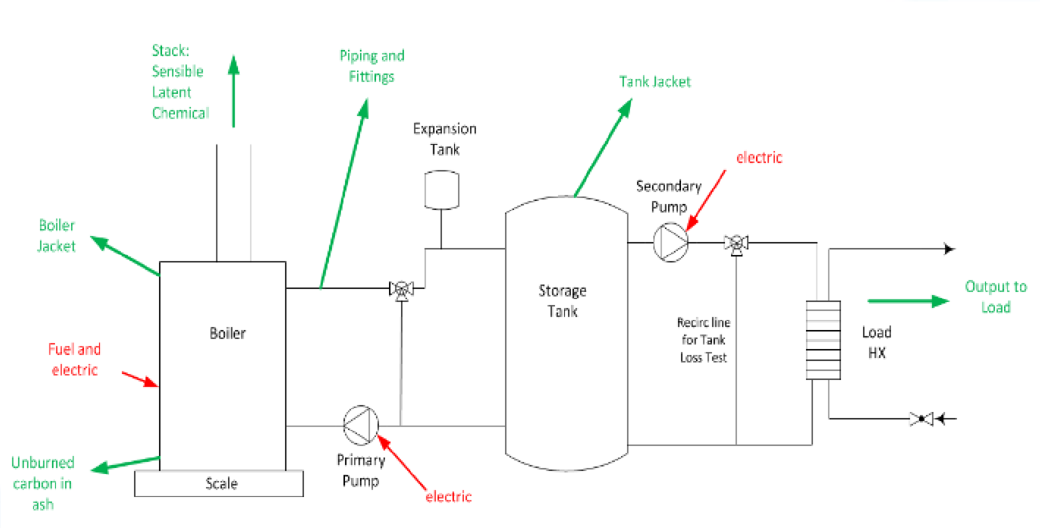
In wood combustion commonly used to mean efficiency based on input minus all flue gas loss (sensible, latent, and chemical) but does not subtract jacket losses.



Definitions of Efficiency

"Delivered Efficiency"

In wood hydronic heater testing it is based on the energy actually delivered to the external cooling load. It accounts for flue gas stack loss, boiler system jacket loss under test conditions (60-75 F), storage tank heat loss during test period (if storage is used), and losses from connecting piping and fittings.



Efficiency Measures for an advanced cordwood boiler

- Combustion efficiency (HHV)
- SLM (HHV)
- Delivered thermal efficiency (HHV)
- M28 WHH-PTS (annual weighting, dilution tunnel, HHV) result versus EN 303-5 results (high load steady-state, hot filter, LHV)

Impact of LHV vs HHV

With LHV, the use of a lower heating value leads to a higher reported efficiency for a heating appliance than is actually delivered as usable energy. The difference depends on water and fuel hydrogen content but is about 10% for biomass. A pellet boiler rated by LHV might be 93% but by HHV it is just 85%.

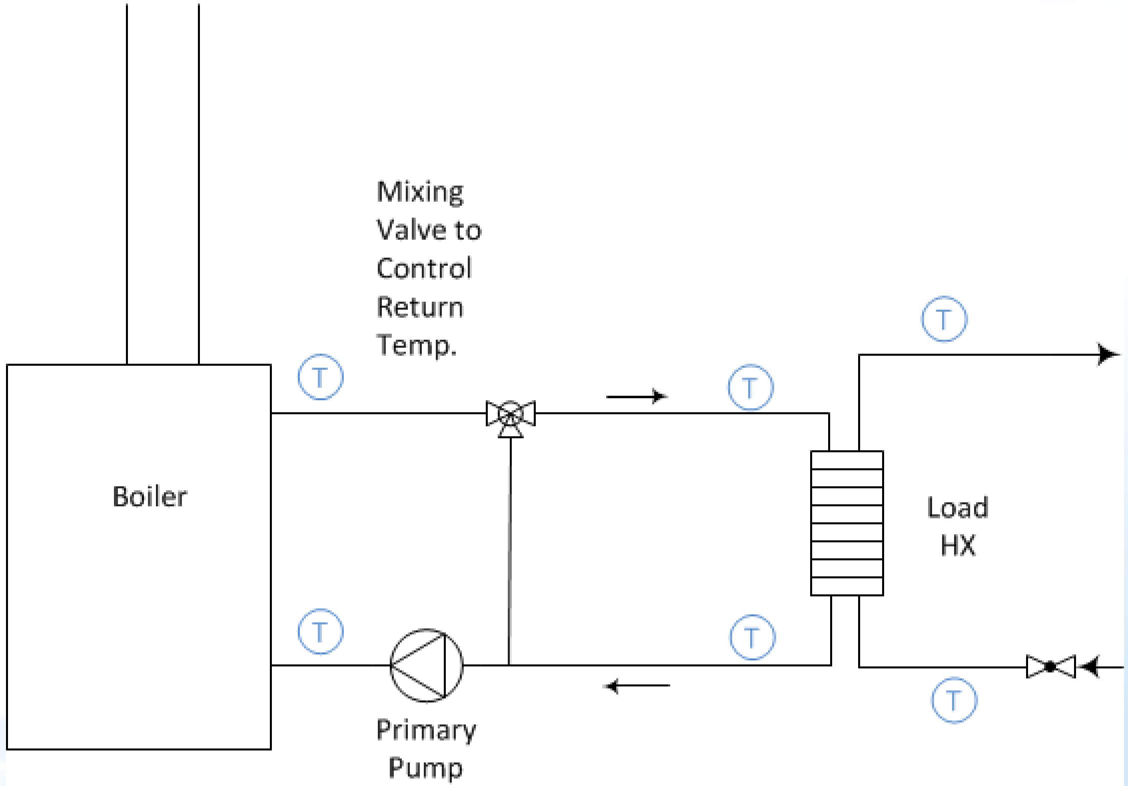
Fuel Mass Input Rate (burn rate)

- For stoves the appliance is positioned on a weigh scale – direct burn rate measurement;
- For cordwood-fired residential boilers the appliance is also tested on a scale and burn rate measured directly;
- For small automatic feed boilers, a small feed hopper can be located on the scale also;
- For very large boilers the scale approach becomes impractical – accurate weight feeders can be used. Accuracy ~ 1%

Source: Acrison.com

Heat Output - Boiler

Direct load side output measurement;
Is heat loss from boiler jacket useful? We consider it not to be useful but in residential oil and gas efficiency testing (AFUE) such jacket loss is considered useful if installed indoors;



Heat Output -Stove

- Stoves heat the surrounding space via convection and radiation from the stove and part of the flue pipe that is within the room;
- Heat output could be calculated by calculation from surface temperatures but requires significant estimation and not considered accurate;
- Heat output could be measured using a calorimeter room approach (done in Australia);
- Stack loss method is the most practical and common method for measuring heat output from a stove.

Jacket losses vs. surrounding air temperature.

- Boiler jacket loss, which is not considered in a stack loss method efficiency, can be 2-5% of the heat input (or greater at low inputs)
- In still air, boiler jacket loss proportional to the difference between boiler temperature and room temperature;
- Boiler jacket loss rate measured in a 70 F room will be 27% higher in a 40 F room;
- In an outdoor environment, where wind is included, jacket loss can be significantly higher. The ASHRAE 103 standard uses a multiplier of 3.3 for outdoor units.

Do test methods reflect field operations: boilers?

- Sizing – units oversized but emission calculations assume perfect sizing.
- ASHRAE has found residential boilers are typically 70% larger than necessary.
- Cordwood-fired boilers typically cycle at loads less than 50% of rated maximum and so cycling operation is a significant part of the operating characteristics.
- Automatic feed (pellet or chip) boilers cycle at loads less than 30% of rated maximum and so still have the potential for significant cycling.

Do test methods reflect field operations: boilers?

- With cordwood boilers, periodic cold starts and regular warm reloads are important parts of the operations in the field and should be captured in test methods.
  - Some boilers are designed with large internal water volumes
  - Some boilers are designed to be low mass but with external water thermal storage to reduce cycling
  - Test methods need to fairly compare and rate performance of systems of these types

Example – EPA Method 28WHH

- Cordwood-fired hydronic heaters without external storage – tested with cribs (not cordwood);
- Four Load Categories at steady output with weighting applied to develop a year-round-use average;
- Delivered efficiency directly measured over cyclic operation, with stack loss method used as a check.
- Cold-start and warm-reload is not part of the test.

	Load	Weighting
Cat IV	100%	0.050
Cat III	25-50%	0.275
Cat II	16-24%	0.238
Cat I	15% or less	0.437

Example – European Method EN303-5

- Cordwood-fired hydronic heaters tested with cordwood;
- Tested at high load steady output.
- Cold-start and warm re-load is not part of the test.
- Tested without external storage.
- PM emissions measured only at full load – 4 short test periods over two "burndown" periods.
- In-stack PM measurements (no dilution tunnel) along with hydrocarbons;
- Efficiency and CO emissions are measured at the minimum load the unit can run at without cycling (typically 30% of full load);
- Procedure also for automatic-feed boilers.

Comparison of Test Methods for Hydronic Heaters

Method	EPA 28 WHH	EPA WHH PTS	ASTM E2618-13	ASTM 2618-13 Annex A1 Full Storage	ASTM 2618-13 Annex A2 Partial Storage	EN303-5	CSA B415-10	ASHRAE 103 (oil and gas boilers)
Cord or Crib	Crib	Cord	Cord	Cord	Cord	Cord	Cord or Crib	N/A
Output/Input or Stack Loss Efficiency	Output/Input[9]	Output/Input[9]	Output/Input[9]	Output/Input[9]	Output/Input[9]	Output/Input[9]	Stack Loss	Stack Loss
Number of Load Categories	4	4 (2 optional)	4	1	4	2[1]	4	2- Transient Test
Cold Start	N	Y[4]	N	Y	Y[4]	N	N	N
Maximum Rate	100%	100%	100%	Tank Reheat	100%	100%	100%	100%
Moderate Rate 1	25-50%	25-50%[8]	25-50%	N/A	25-60%	N/A	25-50%	22%[10]
Moderate Rate 2	16-24%	16-24%[8] "cold" start"	16-24%	N/A	16-24% "cold" start	N/A	16-24%	N/A
Minimum Rate	15% or less	15% or less "cold" start	15% or less	N/A	15% or less "cold" start	50% cordwood/ 30% auto-feed[1]	15% or less	N/A
PM in Dilution Tunnel (DT) or Flue (Hot Filter)	DT	DT	DT	DT	DT	Flue[2]	DT	N/A
Lowest Load for PM (% nominal max)	15	15	15	100	15	100	30	N/A
CO emission factor reporting	Y	Y	N[3]	N[3]	N[3]	Y	Y	N
Report emissions by phase	N	Y	N	N	N	N	N	N/A
Defines testing for Partial Thermal Storage	N	Y	N	N	Y	N	N	N
Defines testing for Full Thermal Storage	N	N	N	Y	N	N	N	N
Allows use of hot bed of coals	Y	High Load Only	Y	N	High Load Only	Y	Y	N/A
Duplicate Runs Required	N	N	N	Y	N	Y[5]	N	N
Applies to Automatically-Fed Boilers	N	N	Y	Y	Y	Y	Y	Y
Jacket Loss Measured	N	N	N	N	N	Y[7]	N	Y[6]

Notes:

1. PM emissions are only measured in one category (max load)
2. Country specific. In Norway a dilution tunnel is used.
3. CO is measured and data reported only for SLM efficiency check
4. Cat I and II tests
5. PM measurements are made during parts of two consecutive burn-down cycles.
6. A method to measure jacket loss is provided if an outdoor unit but, also, an option to use a 1% default is provided. Jacket loss considered useful heat if unit installed indoors.
7. Not a primary measurement - called for as part of a stack loss efficiency check on the output/input efficiiency determination
8. optional
9. Stack Loss Method used as quality control check and reported.
10. Depends on unit design - this is for fixed firing rate unit

Comparison of Test Methods for Stoves

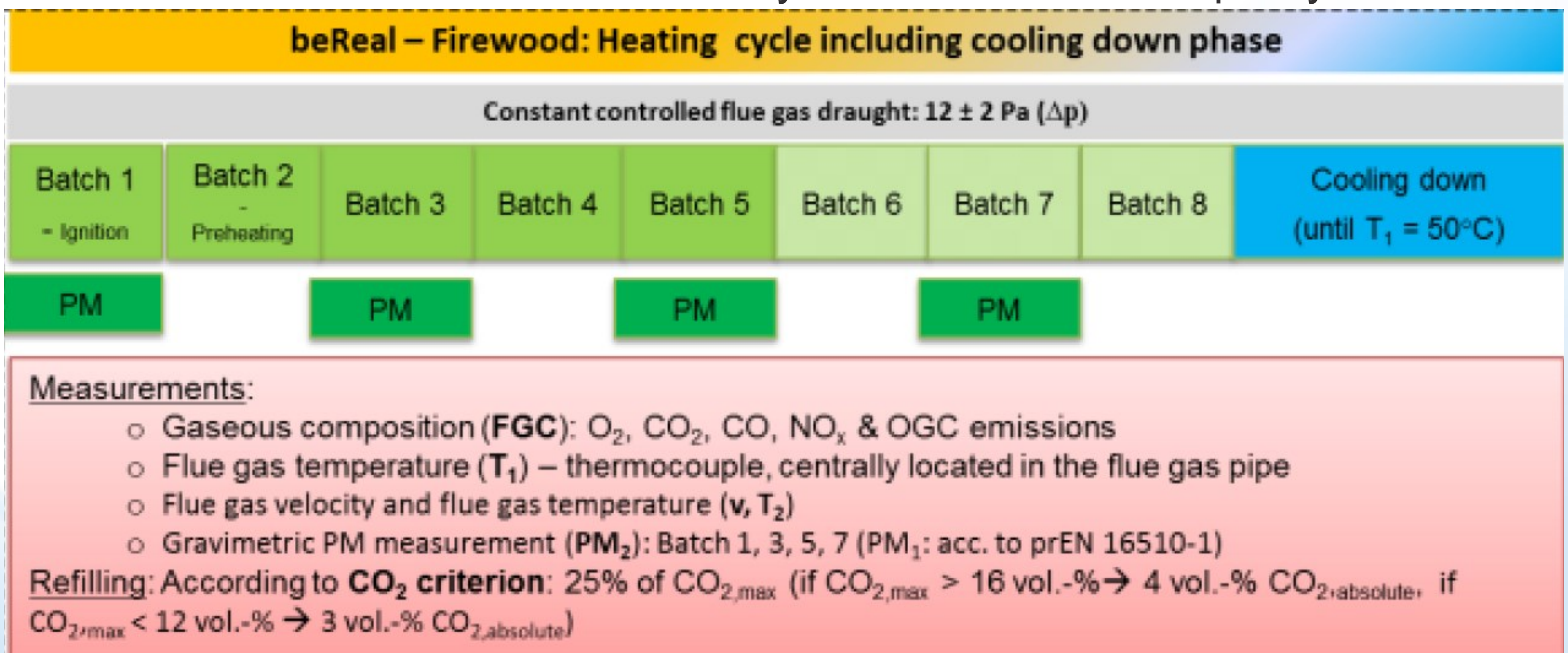
Method	EPA 28 R	ASTM E2779	ASTM E2780	ASTM Draft Cordwood Method	CSA B415.1	BeReal Proposed European Method - Cordwood	BeReal Proposed European Method - Pellets
Fuel Type	Crib - Douglas Fir and pellets	Pelletized and non-pelletized fuels	Doug Fir Crib / Cordwood Annex	Codwood - density range	Cordwood and automatic feed biomass	Cordwood	Pellets
Number of Load Categories	4	3	3	3	4	3	3
Cold Start	No	No	No	High Load Only		Yes	Yes
Maximum Rate	Maximum	Maximum	Maximum	Maximum	100%	100%	100%
Moderate Rate 1	1.25-1.90 kg/hr	50% or less	1.16-1.75 kg/hr	Damper Setting	53-76%	50%[3]	65%
Moderate Rate 2	0.80-1.25 kg/hr	Minimum	0.60-1.15 kg/hr	<1.15 kg/hr[2]	≥ 35 and < 53 %	N/A	N/A
Minimum Rate	<0.80 kg/hr	N/A	N/A	N/A	<35%	Minimum[4]	30%
PM in Dilution Tunnel (DT) or Flue (Hot Filter)	DT	DT	DT	DT	DT	Flue	Flue
Lowest Burn Rate for PM	<0.80 kg/hr[5]	Minimum	0.60-1.15 kg/hr	<1.15 kg/hr[2]	<35%	30%	30%
CO emission factor reporting	Yes[1]	Yes[1]	Yes[1]	Yes	Yes[1]	Yes	Yes
Report emissions by phase	No	No	No	No	No	No	No
Allows use of hot bed of coals	Yes	N/A	Yes	Yes	Yes	No	NA
Duplicate Runs Required	No	N	No	No	No	No	No
Applies to Automatically-Fed Stoves	Yes	Yes	No	No	Yes	No	Yes

Notes:

1. CO is measured and used as part of the stack loss efficiency calculation
2. Damper set at minimum setting. Must yield a burn time of greater than 8 hours or a burn rate under 1.15 kg/hr
3. Fuel Batch Size after Reload - damper settings that define burn rate are as per manufacturer and will be stove specific
4. During burn out phase - damper settings that define burn rate are as per manufacturer and will be stove specific
5. Method 28 allows testing at < 1.0 g/hr for min load and allows testing in Category II twice if Cat I burn rate cannot be sustained.

Comments on the BeReal Method

- Very recently developed as a large, collaborative European project but not yet adopted as a formal standard;
- Guided by a Europe-wide, on-line use survey;
- Different procedures for pellet and cordwood;
- Automated isokinetic flue (hot filter) PM sampling;
- Involves integrated measurements over defined periods at different load conditions including cold start and burnout;
- Data submitted on-line for consistency of calculations and quality control.



Source: G. Reichert et al., 24th European Biomass Conference and Exhibition, June 2016, Amsterdam

Do test methods reflect field operations: stoves?

Same Stove – Different Tests

Model	EPA M28	EN13240	UK
A	3.69 g/hr	15 mg/m^3	2.2 g/hr-high burn 1.8 g/hr-low burn
B	2.86 g/hr	16mg/m3	1 g/hr-high burn 0.9 g/hr-low burn
C	3.2 g/hr	27mg/m3	2.1 g/hr-high burn 2.0 g/hr-low burn

THANK YOU!!

QUESTIONS/COMMENTS?