Summary of Literature Review for Wood Species Impact on Emissions

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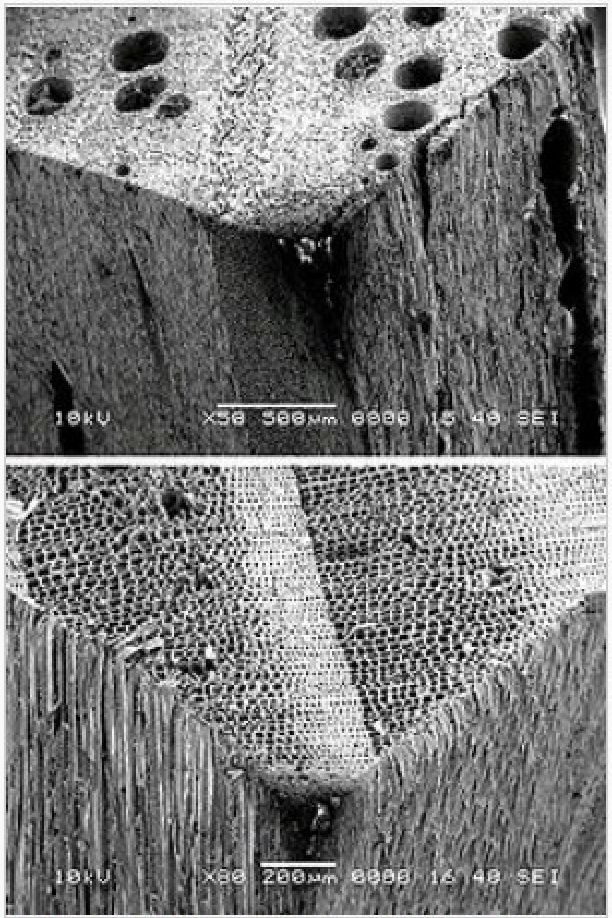
U.S. DEPARTMENT OF ENERGY | Office of Science

Basics of Species

- Hardwood (deciduous)
  - Broad leaf, shed leaves in the fall
  - Higher density but not always
  - Have vessels elements that transport water ("pores")
- Softwood (conifers)
  - Needles, all year
  - Medullary rays and tracheids* transport water and produce sap
  - Faster growing, lower in value



SEM images showing the presence of pores in hardwoods (oak, top) and absence in softwoods (pine, bottom)

* Long, thin longitudinal cells that serve to carry sap – 90% of the volume of the tree.

Soft wood structure

Medullary Rays

- Sheets extending through tree perpendicular to growth rings.
- Consists of parenchyma cells which allow transfer of sap
- Key component to the process of wooded plants healing

Tracheids

- Element of plant vascular tissue
- Consists elongated narrow tube like cells with cell wall with lignin
- Helps transport water from roots to rest of plant

Extractive Components of Wood

Barbara Cole
University of Maine

Wood Extractives

- Non-cell wall components

-Can be removed using solvents,
  e.g. pet. ether, acetone, ethanol, water

- Relatively small molecules ($< C_{40}$)

- Usually comprise 1-5% of the wood

- Under genetic control $\Rightarrow$ vary by species

Softwoods vs. Hardwoods

Softwoods:

- Resin acids: 40-45% of extractives
- Fatty acids: 40-60%
- Monoterpenes (turpentine)
- Phenolics

Hardwoods:

- No resin acids or monoterpenes
- Fatty acids: 60-90%
- Phenolics

Some wood densities from CSA B415 (dried)

Species	Specific gravity
Ash, white	0.63
Beech	0.67
Birch, sweet	0.71
Birch, yellow	0.65
Elm, rock	0.67
Maple, hard (black)	0.60
Maple, hard (sugar)	0.67
Oak, red	0.66
Oak, white	0.71
Pecan	0.73
Pine, southern, longleaf	0.64

Wood Side Hardness (from Wood Handbook)

Species	Side Hardness (N)
Ash, Black	3800
Beech	5,800
Birch	4,000-6,500
Oak, Red	4,700
Oak, White	6,000
Doug-fir	3,200
Pine, Eastern White	1,700
Spruce	1,600-2,600

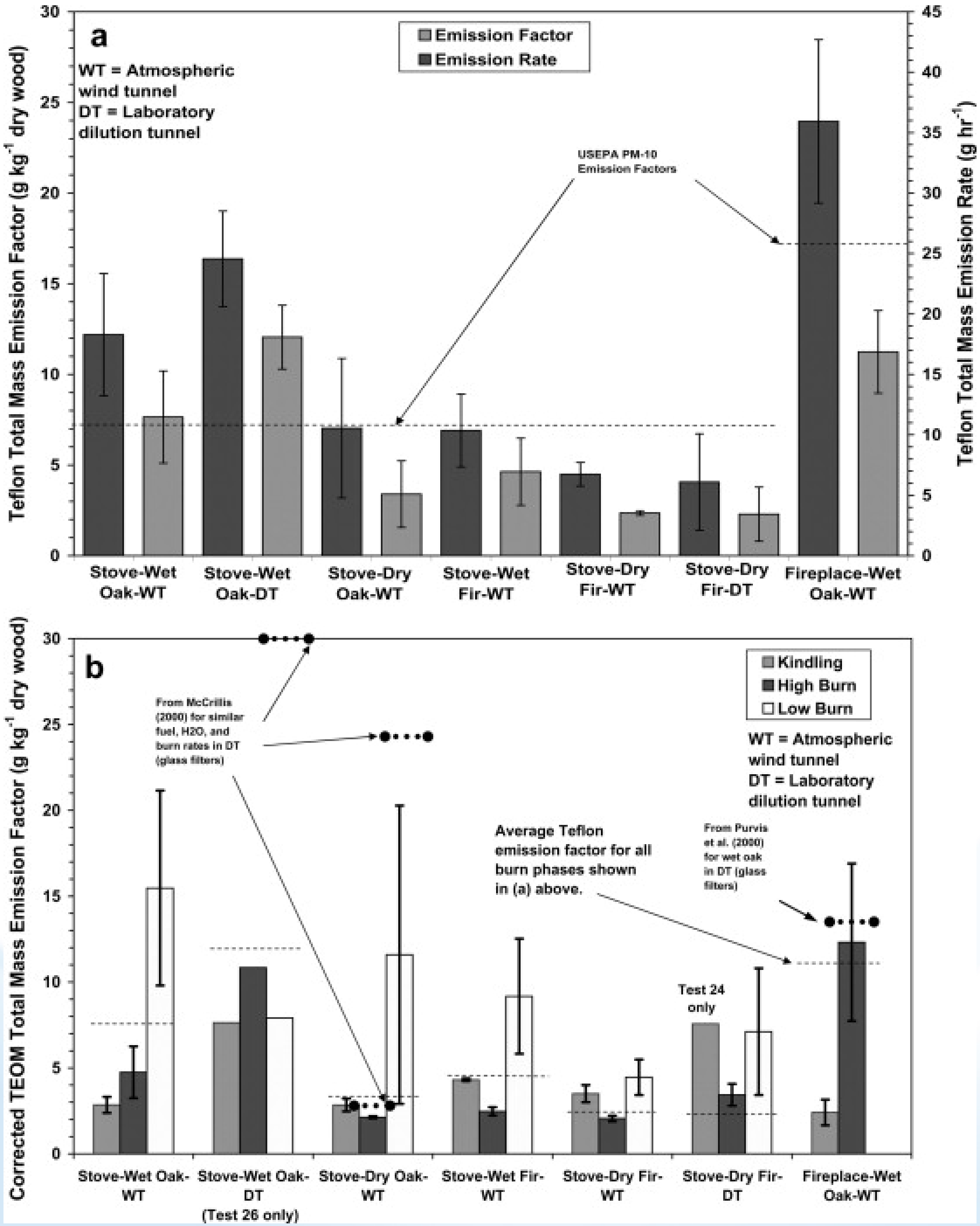
Overview of literature

- Many European studies
  - Different wood species/types (cordwood, pellet, “garden biomass”, etc.)
  - Modern stoves & boilers
  - $PM_{10}, PM_{2.5}, PM_1$, EC, OC, odor data
  - Results show high inter-species variability
    - Location of tree & growth conditions
    - Combustion environment

Applicable literature

- "Evaluation of methods for the physical characterization of the fine particulate emissions from two residential wood combustion appliances", *John S. Kinsey, Peter H. Kariher, Yuanji Dong (2009)*
  - Non-catalytic wood stove
    - 3 burn phases
  - Northern red oak & Douglas fir cord wood
    - Two different moisture levels
  - Wind tunnel with dilution stack sampler & dilution tunnel
    - TEOM, MM5G, Dekati ELPI (particle # conc. & size)
    - CO, CO_2, NO_x, O_2

“Evaluation of methods for the physical characterization of the fine particulate emissions from two residential wood combustion appliances”, *John S. Kinsey, Peter H. Kariher, Yuanji Dong,* Atmospheric Environment **43** (2009) 4959-4967



Total particle mass emissions based on: (a) test average from time-integrated Teflon filter sampling; and (b) average by burn phase from wind tunnel TEOM corrected to an equivalent Teflon filter value. Also shown in (b) are comparable results from prior testing of the same appliance and the test-averaged emission factors from (a) as dashed lines.

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- Chemical Characterization of Fine Particulate Emissions from Fireplace Combustion of Woods Grown in: Northeast, Midwest, West & Southern US
  - *Philip M. Fine, Glen R. Cass, Bernd Simoneit*
  - Identified top 21 wood species in US
    - 18 selected for testing
    - Divided into four groups based on geographical location

Northeastern fuel

Tree species	Moisture content (DB %)
Red maple	*11*
Northern red oak	14
Eastern white pine	*11*
Eastern hemlock	*30*
Paper birch	9
Balsam fir	*9*

Midwestern and Western fuel

Only showing species relevant to our research

Tree species	Moisture content (DB %)
American beech	13
Douglas Fir	19

Methodology

Northeastern

- Moisture content
  - Oven-drying method
  - 9% - 30% MC- dry basis
- Conventional residential masonry heater
  - 6-12” length
  - 3-5” diameter
  - 7-9 crumped newspaper
  - Burn time: 82-136 mins
  - 5-7 kg wood burned
- Sampled at 4 m above fire

Midwesten/Western

- Moisture content
  - Oven-drying method
  - 9 – 54 % MC- dry basis
- Conventional residential masonry heater
  - Burn time: 95-153 mins
  - 5-10 kg wood burned
- Sampled at 4 m above fire

Measurement

- Dilution source sampler
  - Ratio ~ 20-30
  - Cyclone separators
- Looking for:
  - Fine particulate emission rates
  - EC & OC
  - Ion species
  - Elemental species

  - Series of 6 sampling trains operating in parallel
    - 2 for EC/OC
    - 2 for gravimetric mass determination
      - 1 L/min, Teflon filter
    - 2 for gravimetric mass, IC and XRF analyses
      - 15 L/min, Teflon filter1

Applicable results

Only showing species relevant to our research

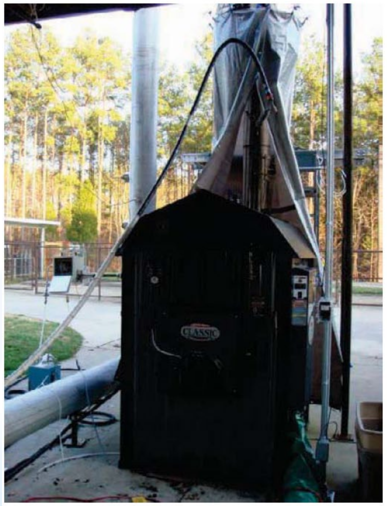
Species	Fine Particulate Emissions (g/kg)
Northern Red Oak	5.7 ± 0.6
Paper Birch	2.7 ± 0.3
American Beech	9.3 ± 1.0
Douglas Fir	4.0 ± 0.8

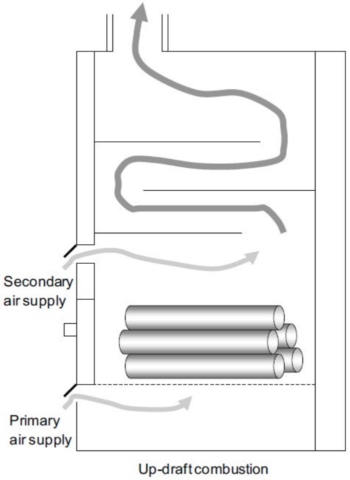
- Uncertainties based solely on analytical & measurement errors
- There was no observed correlation between wood moisture content & fine PM rate.
- Believed increased emissions were a result of sap inclusions within wood
- Average particle size distribution showed little variation from wood to wood
  - Peak 100- 200 nm

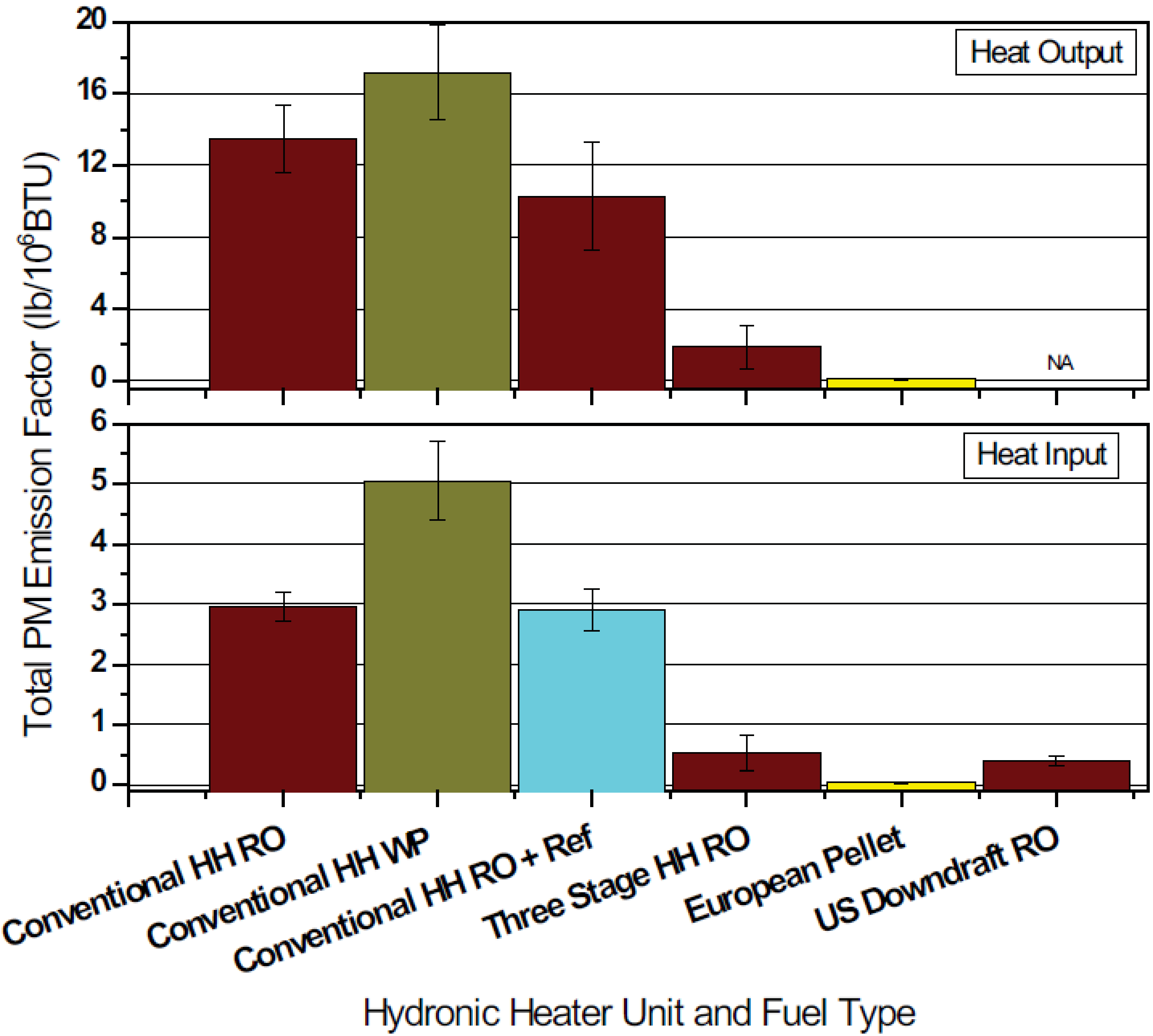
Gullett, B. et.al. Environmental, Energy Market, and Health Characterization of Wood-Fired Hydronic Heater Technologies, Project Final Report, submitted to NYSERDA Report 12-15, 2015

Properties	Fuel		
	Red Oak	Pine	Pellets
Ash	1.46%	0.44%	0.52%
Loss on Drying (LOD)	22.52%	9.68%	7.24%
Volatile Matter	84.23%	88.50%	84.27%
Fixed Carbon	14.31%	11.06%	14.11%
C :Carbon	48.70%	51.72%	50.10%
Cl: Chlorine	38 ppm	36 ppm	44 ppm
H: Hydrogen	5.96%	6.57%	5.86%
N: Nitrogen	<0.5%	<0.5%	<0.5%
S: Sulfur	<0.05%	<0.05%	<0.5%
High Heating Value; KJ/Kg (Btu/lb)	19510 (8388)	21574 (9275)	19831 (8526)

Figure 2-8. Fuels Used in the Study.







Heat Output
Heat Input
NA
Total PM Emission Factor (lb/10^6BTU)
20
16
12
8
4
0
6
5
4
3
2
1
0
Conventional HH RO
Conventional HH WP
Conventional HH RO + Ref
Three Stage HH RO
European Pellet
US Downdraft RO
Hydronic Heater Unit and Fuel Type

Table 3. Hydronic Heater Efficiencies.

Units	Thermal Efficiency (%)		Boiler	Combustion
Conventional HH RO	Average	22	NC	74
	STDV	5		3.0
Conventional HH RO + Ref	Average	31	NC	87
	STDV	2.2		3.4
Conventional HH WP	Average	29	NC	82
	STDV	1.8		3.2
Three Stage HH/RO	Average	30	NC	86
	STDV	3.2		1.8
European Pellet/pellets	Average	44	86	98
	STDV	4.1	3.5	0.16
U.S. Downdraft RO	Average	IM	83	90
	STDV		0.71	0.79

NC = Not calculated. IM = Insufficient measurements taken for this calculation

OMNI / Fairbanks Study, Measurement of Space H

Figure 7 shows the various single room heating, wood-burning appliances tested. The data shows that EPA certified stoves burn cleaner than the older, conventional stoves. Additionally, it appears that for these appliances spruce generally burns cleaner than birch.

Figure 7. Particulate Emissions per Useful Heat Output, Wood Burning Space Heaters

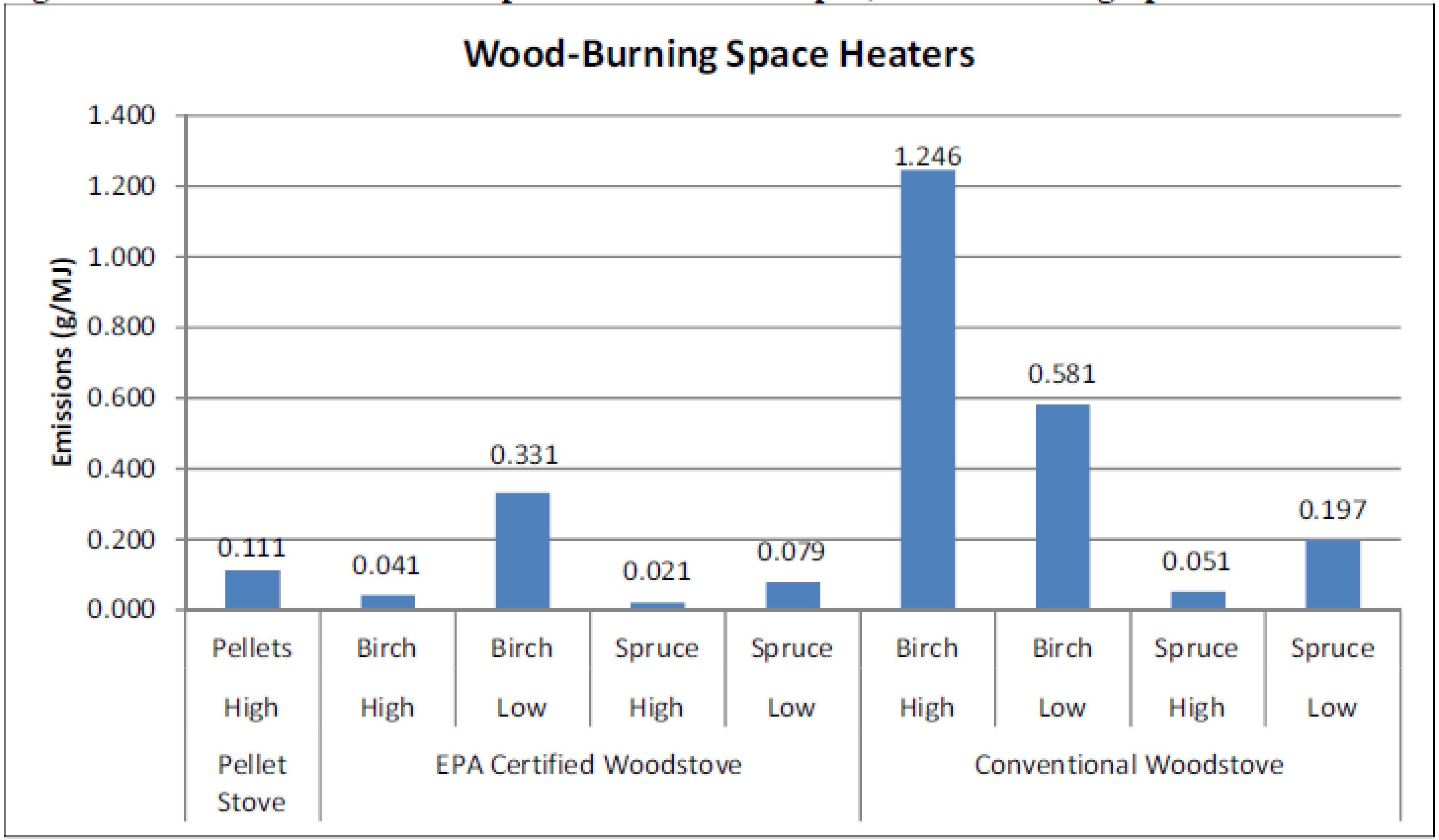
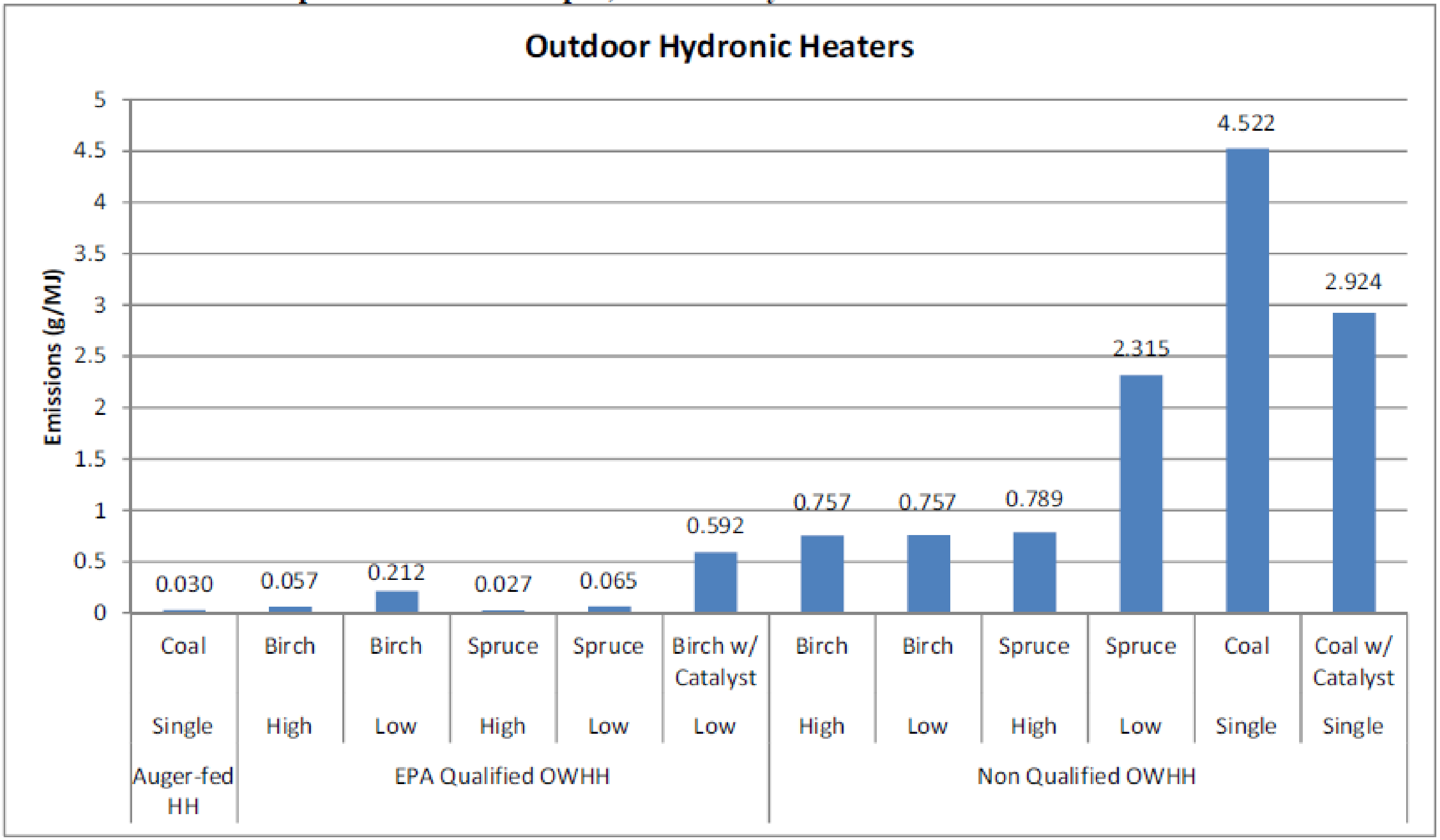


Figure 8. Particulate Emissions per Useful Heat Output, Outdoor Hydronic Heaters



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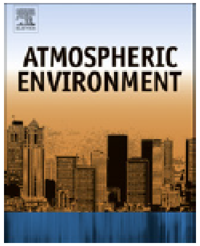

Odor, gaseous and PM_{10} emissions from small scale combustion of wood types indigenous to Central Europe

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2012

Table 2
Sampling and calculation details.

Fuel name	Index	Stove	Burning type	Number of tests	Dilution factor	Wet fuel mass [kg]	Burn rate [kg h^{-1}]	LHV [kJ kg^{-1}]	Average T [°C] in flue gas	MCE factor [%]	O_2 [% v/v]	CO_2 [% v/v]
Wood pellets	WP	B	FL1	2	3	2.3	1.4	17,706	132	99.8	14.2	6.2
	WP	B	FL2	1	3	12.6	1.9	17,706	130	99.7	13.9	6.4
	WP	B	PL	2	3(4)[a]	1.00	0.7	17,706	92	99.6	17.5	3.1
Wood briquetts	BR	A	FL	3	10	2.65	2.0	17,177	183	97.5	15.6	4.8
European hornbeam	EH	A	FL	3	10	2.63	2.5	16,117	184	98.0	14.4	6.0
European beech	EB	A	FL	3	10	2.63	2.8	15,857	195	97.8	13.2	7.1
Black poplar	BPop	A	FL	3	10	2.59	2.2	16,778	109	96.8	15.4	5.0
Turkey oak	TO	A	FL	3	10	2.61	2.7	16,709	196	96.9	13.8	6.5
Sessile oak	SO	A	FL	3	10	2.64	2.1	16,164	145	93.9	16.9	3.5
Pedunculate oak	PO	A	FL	2	10	2.63	2.2	15,750	154	94.8	16.7	3.7
Black locust	BL	A	FL	3	10	2.66	1.9	16,676	149	96.5	16.3	4.2
Silver fir	SF	A	FL	3	10	2.61	2.0	16,686	175	94.3	15.6	4.6
European larch	EL	A	FL	1	10	2.63	2.5	17,162	176	97.7	13.8	6.5
Norway spruce	NS	A	FL	3	10	2.61	2.1	16,481	174	96.9	15.3	5.0
Black pine	BP	A	FL	3	10	2.61	2.3	17,610	179	97.1	14.7	5.4
Scots pine	SP	A	FL	3	10	2.63	2.1	–	170	97.9	14.4	5.8
Dry leaves	L	A	ST	1	15	1.25	5.3	17,364	196	95.5	13.6	6.3
Pine cones	C	A	ST	1	15	1.14	3.3	17,265	175	95.4	11.7	8.3
Pine needles	N	A	ST	1	20	1.14	4.6	18,761	192	95.7	11.7	8.0

FL, full-load operation; PL, part-load operation; ST, special test; LHV, lower heating value; MCE, modified combustion efficiency calculated as a ratio $c_{CO_2}/(c_{CO_2}+c_{CO})$ where c_{CO_2} and c_{CO} are the measured volume mixing ratios of CO_2 and CO.
[a] Different dilution factors of both tests.

Tests with wood logs and “garden biomass” were performed with a modern, 8 kW “chimney type” iron, log wood stove with fireclay lining (“A”). This manually loaded stove is certified to fulfill the current Austrian emission standards defined in state laws, e.g. for Vienna in LGBl. (2005). Combustion air is provided through a grate in the bottom (primary air) and a slit in the back wall (secondary air). Exhaust gases are redirected two times prior to entering the chimney. Airflow is controlled manually via rotary knob connected to a valve system that adjusts both primary and secondary combustion airflow. Our test procedure for log wood and

Table 3
Average emission factors.

Fuel	CO [mg MJ^{-1}]	NO_x [mg MJ^{-1}]	C_xH_y [mg MJ^{-1}]	PM10 [mg MJ^{-1}]	Odor [OU]
WP FL1	118	94	58	21	ND
WPFL2	188	131	5	31	ND
WP PL	245	74	8	16	ND
BR	1482	63	163	32	1804
EH	1234	110	462	41	536
EB	1410	95	234	66	1563
BPop	1856	65	216	20	2843
TO	1816	88	206	59	1781
SO	3681	131	657	222	4226
PO	3253	104	452	57	1973
BL	2000	118	239	67	1689
SF	3497	105	581	100	5217
EL[a]	1263	58	179	21	2422
NS	1901	69	267	53	3815
BP	1710	64	243	101	1589
SP	1189	70	109	53	2134
L[a]	2249	132	1543	626	18963
C[a]	2821	89	1106	<LOD	3524
N[a]	2204	111	1424	85	7346

<LOD, under limit of detection; ND, not detected, ranges given in supplementary material in Table 2s.

[a] Single test.

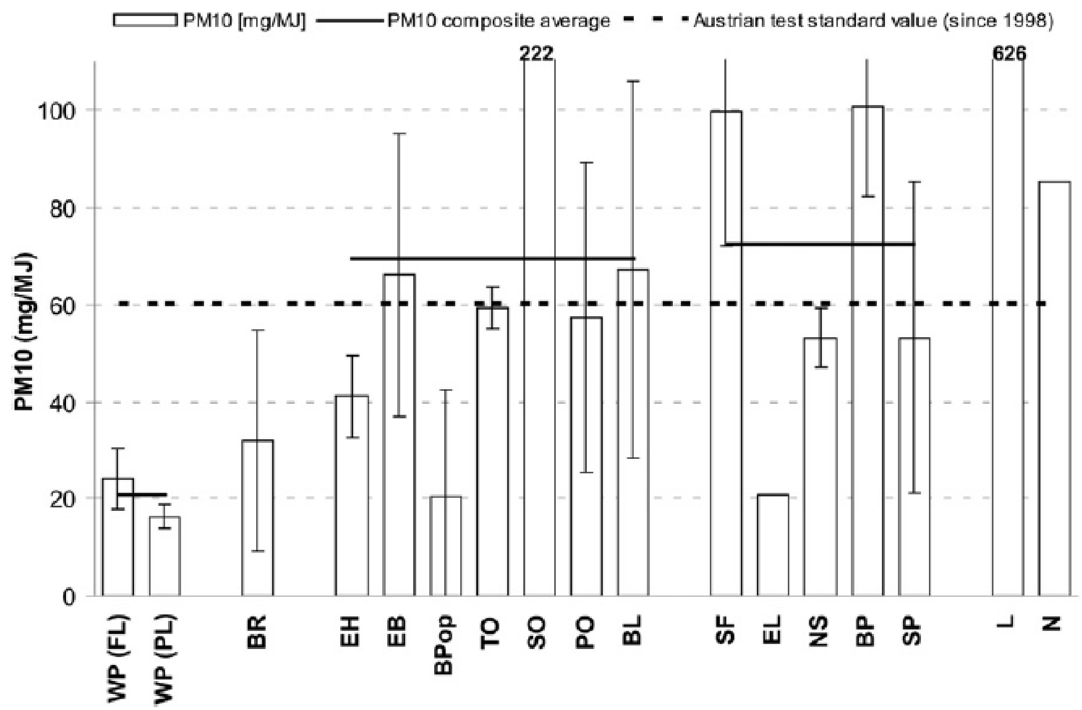

Fig. 1. Average emission rates of PM_{10}. Error whiskers in terms of standard deviation. Dashed line represents the Austrian emission limit for standardized test conditions.