10/16/92

1.10 RESIDENTIAL WOOD STOVES

1.10.1 General[1-3]

Wood stoves are commonly used in residences as space heaters. They are used both as the primary source of residential heat and to supplement conventional heating systems.

Five different categories should be considered when estimating emissions from wood burning devices due to differences in both the magnitude and the composition of the emissions:

the conventional wood stove,

the noncatalytic wood stove,

the catalytic wood stove,

the pellet stove, and

the masonry heater.

Among these categories, there are many variations in device design and operation characteristics.

The conventional stove category comprises all stoves without catalytic combustors not included in the other noncatalytic categories (i. e., noncatalytic and pellet). Conventional stoves do not have any emission reduction technology or design features and, in most cases, were manufactured before July 1, 1986. Stoves of many different airflow designs may be in this category, such as updraft, downdraft, crossdraft and S-flow.

Noncatalytic wood stoves are those units that do not employ catalysts but do have emission reducing technology or features. Typical noncatalytic design includes baffles and secondary combustion chambers.

Catalytic stoves are equipped with a ceramic or metal honeycomb device, called a combustor or converter, that is coated with a noble metal such as platinum or palladium. The catalyst material reduces the ignition temperature of the unburned volatile organic compounds (VOC) and carbon monoxide (CO) in the exhaust gases, thus augmenting their ignition and combustion at normal stove operating temperatures. As these components of the gases burn, the temperature inside the catalyst increases to a point at which the ignition of the gases is essentially self sustain@.

Pellet stoves am those fueled with pellets of sawdust, wood products, and other biomass materials pressed into manageable shapes and sixes. These stoves have active air flow systems and unique grate design to accommodate this type of fuel. Some pellet stove models are subject to the 1988 New Source Performance Standards (NSPS), while others are exempt due to a high air-to-fuel ratio (i.e., greater than 35-to-1).

Masonry heaters are large, enclosed chambers made of masonry products or a combination of masonry products and ceramic materials. These devices are exempt from the 1988 NSPS due to their weight (i.e., greater than 800 kg). Masonry heaters are gaining popularity as a cleaner burning and

heat efficient form of primary and supplemental heat, relative to some other types of wood heaters. In a masonry heater, a complete charge of wood is burned in a relatively short period of time. The use of masonry materials promotes heat transfer. Thus, radiant heat from the heater warms the surrounding area for many hours after the fire has burned out

1.10.2 Emissions[4-30]

The combustion and pyrolysis of wood in wood stoves produce atmospheric emissions of particulate matter, carbon monoxide, nitrogen oxides, organic compounds, mineral residues, and to a lesser extent, sulfur oxides. The quantities and types of emissions are highly variable, depending on a number of factors, including stage of the combustion cycle. During initial burning stages, after a new wood charge is introduced, emissions (primarily VOCs) increase dramatically. After the initial period of high burn rate. There is a charcoal stage of the burn cycle, characterized by a slower bum rate and decreased emissions. Emission rates during this stage are cyclical, characterized by relatively long periods of low emissions and shorter episodes of emission spikes.

Particulate emissions are defined in this discussion as the total catch measured by the EPA Method 5H (Oregon Method 7) sampling train.' A small portion of wood stove particulate emissions includes "solid" particles of elemental carbon and wood. The vast majority of particulate emissions is condensed organic products of incomplete combustion equal to or less than 10 micrometers in aerodynamic diameter (PM-lo). Although reported particle size data are scarce, one reference states that 95 percent of the particles emitted from a wood stove were less than 0.4 micrometers in size.[4]

Sulfur oxides (SO_x) are formed by oxidation of sulfur in the wood. Nitrogen oxides (NO,) are formed by oxidation of fuel and atmospheric nitrogen. Mineral constituents, such as potassium and sodium compounds, are released from the wood matrix during combustion.

The high levels of organic compound and CO emissions are results of incomplete combustion of the wood. Organic constituents of wood smoke vary considerably in both type and volatility. These constituents include simple hydrocarbons of carbon numbers 1 through 7 (Cl - C7) (which exist as gases or which volatilize at ambient conditions) and complex low volatility substances that condense at ambient conditions. These low volatility condensible materials generally are considered to have boiling points below 300°C (572°F).

Polycyclic organic matter (POM) is an important component of the condensible fraction of wood smoke. POM contains a wide range of compounds, including organic compounds formed through incomplete combustion by the combination of free radical species in the flame zone. This group which is classified as a Hazardous Air Pollutant (HAP) under Title III of the 1990 Clean Air Act Amendments contains the subgroup of hydrocarbons called Polycyclic Aromatic Hydrocarbons (PAH).

Emission factors and their ratings for wood combustion in residential wood stoves, pellet stoves and masonry heaters are presented in Tables 1.10-l through 1.10-8. These tables include emission factors for criteria pollutants (PM-IO, CO, NO,, SO,), CO_2, Total Organic Compounds (TOC), speciated organic compounds, PAH, and some elements. The emission factors are presented by wood heater type. PM-10 and CO emission factors are further classified by stove certification category. Phase II stoves are those certified to meet the July 1, 1990 EPA standards; Phase I stoves meet the July 1.1988 EPA standards; and Pm-Phase I stoves do not meet any of the EPA standards

but in most cases do meet the Oregon 1986 certification standards.[1] The emission factors for PM and CO in Tables 1.10-l and 1.10-2 are averages, derived entirely from field test data obtained under actual operating conditions. Still, there is a potential for higher emissions from some wood stove, pellet stove and masonry heater models.

As mentioned, particulate emissions are defined as the total emissions equivalent to that collected by EPA Method 5H. This method employs a heated filter followed by three impingers, an unheated filter, and a final impinger. Particulate emissions 'factors are presented as values equivalent to that collected with Method 5H. Conversions are employed, as appropriate, for data collected with other methods. See Reference 2 for detailed discussions of EPA Methods 5H and 28.

Table 1.10-7 shows net efficiency by device type, determined entirely from field test data. Net or overall efficiency is the product of combustion efficiency multiplied by heat transfer efficiency. Wood heater efficiency is an important parameter used, along with emission factors and percent degradation, when calculating PM-10 emission reduction credits. Percent degradation is related to the loss in effectiveness of a wood stove control device or catalyst over a period of operation. Control degradation for any stove, including noncatalytic wood stoves, may also occur as a result of deteriorated seals and gaskets, misaligned baffles and bypass mechanisms, broken refractories, or other damaged functional components. The increase in emissions which can result from control degradation has not been quantified. However, recent wood stove testing in Colorado and Oregon should produce results which allow estimation of emissions as a function of stove age.

- note: masonry heaters generally don't suffer age degradation by virtue of the combustion + construction principles inherent in their design.

TABLE 1.10-l. (ENGLISH UNITS) EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a]

Pollutant/ EPA Certification[b]	Emission Factor Rating	Wood Stove Type[c]			Pellet Stove Type[d]		Masonry Heater
		Conv. lb/ton	Non-Cat lb/ton	Cat lb/ton	Certified lb/ton	Exempt lb/ton	Exempt[e] lb/ton
PM-10[f,g]							
Pm-Phase I	B	30.6	25.8	24.2			
Phase I	B		20.0	19.6			
Phase II	B		14.6	16.2	4.2		
All	B	30.6	19.6	20.4	4.2	8.8	5.6
Carbon Monoxide[f]							
Pm-Phase I	B	230.8					
Phase I	B			104.4			
Phase II	B		140.8	107.0	39.4		
All	B	230.8	140.8	104.8	39.4	52.2	149.0
Nitrogen Oxides[f]		2.8[h]		2.4	13.8[i]		
Sulfur Oxides[f]	B	0.4	0.4	0.4	0.4		
Carbon Dioxide[j]	C				2,951.6	3,671.2	3,849.4
Total Organic Compounds[k]							
Methane	E	64.0		26.0			
Non-Methane	E	28.0		17.2			

a. Units are in (lbs. of pollutant/ton of dry wood burned).
b. Pm-Phase I = not certified to 1988 EPA emission standards; Phase I = certified to 1988 EPA emission standards; Phase II = certified to 1990 EPA emission standards; All = average of emission factors for all devices.
c. Conv = Conventional; Non-Cat = Noncatalytic; Cat = Catalytic.
d. Certified = Certified pursuant to 1988 NSPS; Exempt = Exempt from 1988 NSPS (i.e., air:fuel ratio >35: 1).
e. Exempt = Exempt from 1988 NSPS (i.e., weight >800 kg).
f. References 5-13, 22-26, 28.
g. Defined as equivalent to total catch by EPA method 5H train
h. Rating = C.
i. Rating = E.
j. References 12, 22-26, 28.
k. References 14, 15, 18. The data used to develop the emission factors showed a high degree of variability within the source population. The use of these emission factors on specific sources may not be appropriate.

TABLE 1.10-2. (METRIC UNITS) EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a]

Pollutant/ EPA Certification[b]	Emission Factor Rating	Wood Stove Type[c]			Pellet Stove Type[d]		Masonry Heater
		Conv. g/kg	Non-Cat g/kg	Cat g/kg	Certified g/kg	Exempt g/kg	Exempt[e] g/kg
PM-10[f,g]							
Pm-Phase I	B	15.3	12.9	12.1			
Phase I	B		10.0	9.8			
Phase II	B		7.3	8.1	2.1		
All	B	15.3	9.8	10.2	2.1	4.4	2.8
Carbon Monoxide[f]							
Pm-Phase I	B	115.4					
Phase I	B			52.2			
Phase II	B		70.4	53.5	19.7		
All	B	115.4	70.4	52.4	19.7	26.1	74.5
Nitrogen Oxides[f]		1.4[h]		1.0[i]	6.9[i]		
Sulfur Oxides[f]	B	0.2	0.2	0.2	0.2		
Carbon Dioxide[j]	C				1,475.8	1,835.6	1,924.7
Total Organic Compounds[k]							
Methane	E	32.0		13.0			
Non-Methane	E	14.0		8.6			

a. Units are in (grams of pollutant/kg of dry wood burned).
b. Pm-Phase I = not certified to 1988 EPA emission standards; Phase I = certified to 1988 EPA emission standards; Phase II = certified to 1990 EPA emission standards; All = average of emission factors for all devices.
c. Conv = Conventional; Non-Cat = Noncatalytic; Cat = Catalytic.
d. Certified = Certified pursuant to 1988 NSPS; Exempt = Exempt from 1988 NSPS (i.e., air:fuel ratio >35:1).
e. Exempt = Exempt from 1988 NSPS (i.e., weight >800 kg).
f. References 5-13, 22-26, 28.
g. Defined as equivalent to total catch by EPA method 5H train
h. Rating = C.
i. Rating = E.
j. References 12, 22-26, 28.
k. References 14, 15, 18. The data used to develop the emission factors showed a high degree of variability within the source population. The use of these emission factors on specific sources may not be appropriate.

TABLE 1.10-3. (ENGLISH AND METRIC UNITS) ORGANIC COMPOUND EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[18]
(Emission Factor Rating: E)[a]

Compounds	WOOD STOVE TYPE[b]			
	Conventional		catalytic	
	lb/ton	g/kg	lb/ton	g/kg
Ethane	1.470	0.735	1.376	0.688
Ethylene	4.490	i.245	3.482	1.741
Acetylene	1.124	0.562	0.564	0.282
Propane	0.358	0.179	0.158	0.079
Propene	1.244	0.622	0.734	0.367
i-Butane	0.028	0.014	0.010	0.005
n-Butane	0.056	0.028	0.014	0.007
Butenes[c]	1.192	0.596	0.714	0.357
Pentenes[d]	0.616	0.308	0.150	0.075
Benzene	1.938	0.969	1.464	0.732
Toluene	0.730	0.365	0.520	0.260
Furan	0.342	0.171	0.124	0.062
Methyl Ethyl Ketone	0.290	0.145	0.062	0.031
2-Methyl Furan	0.656	0.328	0.084	0.042
2,5-Dimethyl Furan	0.162	0.081	0.002	0.011
Furfural	0.486	0.243	0.146	0.073
0-Xylene	0.202	0.101	0.186	0.093

a. The data used to develop the emission factors showed a high degree of variability within the source population. The use of these emission factors on specific sources may not be appropriate.
b. Units are in lb/ton (lbs. of pollutant/ton of dry wood burned).
c. 1-butene, i-butene, t-2-butene, c-2-butene, 2-me-1-butene, 2-me-butene are reported as butenes.
d. 1-pentene, t-2-pentene, and c-2-pentene are reported as pentenes.

TABLE 1.10-4. (ENGLISH UNITS) POLYCYCLIC AROMATIC HYDROCARBON (PAH) EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a]
(Emission Factor Rating: E)[b]

Pollutant	STOVE TYPE			
	Conventional[c] lb/ton	Noncatalytic[d] lb/ton	Catalytic[e] lb/ton	Exempt Pellet[f] lb/ton
PAH				
Acenaphthene	0.010	0.010	0.006	
Acenaphthylene	0.212	0.032	0.068	
Anthracene	0.014	0.009	0.008	
Benzo(a)Anthracene	0.020	<0.001	0.024	
Benzo(b)Fluoranthene	0.006	0.004	0.004	2.60E-05
Benzo(g,h,i)Fluoranthene		0.028	0.006	
Benzo(k)Fluoranthene	0.002	<0.001	0.002	
Benzo(g,h,i)Perylene	0.004	0.020	0.002	
Benzo(a)Pyrene	0.004	0.006	0.004	
Benzo(e)Pyrene	0.012	0.002	0.004	
Biphenyl		0.022		
Chrysene	0.012	0.010	0.010	7.52E-05
Dibenzo(a,h)Anthracene	0.000	0.004	0.002	
7,12-Dimethylbenz(a)Anthracene		0.004		
Fluoranthene	0.020	0.008	0.012	5.48E-05
Fluorene	0.024	0.014	0.014	
Indeno(1,2,3,cd)Pyrene	0.000	0.020	0.004	
9-Methylanthracene		0.004		
12-Methylbenz(a)Anthracene		0.002		
3-Methylchlolanthrene		co.001		
1-Methylphenanthmne		0.030		
Naphthalene	0.288	0.144	0.186	
Nitronaphthalene		0.000		
Perylene		0.002		
Phenanthrene	0.078	0.118	0.489	3.32E-05
Phenanthrol		0.000		
Phenol		<0.001		
Pyrene	0.024	0.008	0.010	4.84E-05
PAH Total	0.730	0.500	0.414	

a. Units are in lb/ton (lbs. of pollutant/ton of dry wood burned).
b. The data used to develop these emission factors showed a high degree of variability within the source population and/or came from a small number of sources. The use of these emission factors on specific sources may not be appropriate.
c. Reference 18.
d. References 16,19-21.
e. References 15-19.
f. Reference 28. Exempt = Exempt from 1988 NSPS (i.e., air:fuel ratio >35:1).

TABLE 1.10-5. (METRIC UNITS) POLYCYCLIC AROMATIC HYDROCARBON (PAH) EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a]
(Emission Factor Rating: E)[b]

Pollutant	STOVE TYPE			
	Conventional[c] g/kg	Noncatalytic[d] g/kg	Catalytic[e] g/kg	Exempt Pelletf g/kg
PAH				
Acenaphthene	0.005	0.005	0.003	
Acenaphthylene	0.106	0.016	0.034	
Anthracene	0.007	0.004	0.004	
Benzo(a)Anthracene	0.010	<0.001	0.012	
Benzo(b)Fluoranthene	0.003	0.002	0.002	1.30E-05
Benzo(g,h,i)Fluoranthene		0.014	0.003	
Benzo(k)Fluoranthene	0.001	<0.001	0.001	
Benzo(g,h,i)Perylene	0.002	0.010	0.001	
Benzo(a)Pyrene	0.002	0.003	0.002	
Benzo(e)Pyrene	0.006	0.001	0.002	
Biphenyl		0.011		
Chrysene	0.006	0.005	0.005	3.76E-05
Dibenzo(a,h)Anthracene	0.000	0.002	0.001	
7,12-Dimethylbenz(a)Anthracene		0.002		
Fluoranthene	0.010	0.004	0.006	2.74E-05
Fluorene	0.012	0.007	0.007	
Indeno(1,2,3,cd)Pyrene	0.000	0.010	0.002	
9-Methylanthracene		0.002		
12-Methylbenz(a)Anthracene		0.001		
3-Methylchlolanthrene		<0.001		
1-Methylphenanthrene		0.015		
Naphthalene	0.144	0.072	0.093	
Nitronaphthalene		0.000		
Perylene		0.001		
Phenantbmne	0.039	0.059	0.024	1.66E-05
Phenanthrol		0.000		
Phenol		<0.001		
Pyrene	0.012	0.004	0.005	2.42E-05
PAH Total	0.365	0.250	0.207	

a. Units are in g/kg (grams of pollutant/kg of dry wood burned).
b. The data used to develop these emission factors showed a high degree of variability within the source population and/or came from a small number of sources. The use of these emission factors on specific sources may not be appropriate.
c. Reference 18.
d. References 16,19-21.
e. References 15-19.
f. Reference 28. Exempt = Exempt from 1988 NSPS (i.e., air:fuel ratio >35:1).

TABLE 1.10-6. (ENGLISH AND METRIC UN-ITS) TRACE ELEMENT EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a]
(Emission Factor Rating: E)[b]

Element	WOOD STOVE TYPE					
	Conventional		Noncatalytic		catalytic	
	lb/ton	g/kg	lb/ton	g/kg	lb/ton	g/kg
Cadmium (Cd)	2.2E-05	l.lE-05	2.0E-05	1 .0E-05	4.6E-05	2.3E-05
Chromium (Cr)	<1.0E-06	<1.0E-06	<1.0E-06	<1.0E-05	<1.0E-06	<1.0-E06
Manganese (Mn)	1.7E-04	8.7E-05	1.4E-04	7.0E-05	2.2E-04	1.1E-04
Nickel (Ni)	1.4E-05	7.0E-06	2.0E-05	1 .OE-05	2.2E-06	1.0E-06

a. Units are in lb/ton (lbs. of pollutant/ton of dry wood burned) and g/kg (grams of pollutant/kg of dry wood burned). Emission factors are based on data from References 15 and 18.
b. The data used to develop these emission factors showed a high degree of variability within the source population. The use of these emission factors on a specific source may not be appropriate.

TABLE 1.10-7. SUMMARY OF WOOD HEATER NET EFFICIENCIES[a]

Wood Heater Type	Net Efficiency (%)	Reference
Wood Stoves		
Conventional	54	27
Non-Catalytic	68	10, 13.27
catalytic	68	7, 27
Pellet Stoves[b]		
Certified	68	12
Exempt	56	28
Masonry Heaters		
All	58	29

a. Net efficiency is a function of both combustion efficiency and heat transfer efficiency. The percentages shown here are based on data collected from in-home testing.
b. Certified = Certified pursuant to 1988 NSPS.
Exempt = Exempt from 1988 NSPS (i.e., air:fuel ratio >35:1).

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