Emission Factors for Aged Uncertified Residential Cordwood Heaters

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Residential cordwood heaters have been documented as being appreciable contributors to emission inventories compiled in North America. In the United States, federal regulations required all wood heaters sold after July 1, 1990, to be certified for low particulate emissions. Because of the robust construction of cast iron and plate steel heaters, many uncertified cordwood heaters sold prior to July 1, 1990, are still in service. However, after 18 or more years of use many show changes in efficiency and emissions primarily due to loss of air control. Deterioration of gasket materials, thermal warping of doors and air control systems, and breaches in the unit due to corrosion are responsible. Updated emission factor data for aged wood heaters are presented here as well as a discussion of additional measurement needs. Particulate, carbon monoxide, formaldehyde, benzene, methane, polycyclic aromatic hydrocarbon (PAH), and other hazardous air pollutants (HAP) emission factors have been tabulated. The impact of the decrease in efficiency on effective emission factors, i.e., additional fuel required for a given heat demand, is also discussed. Finally, as non-methane volatile organic compound (NMVOC) emissions are on the same order of magnitude as primary particulate emissions, NMVOC data and the contribution of secondary organic aerosols (SOA) formed from them, to overall airshed particulate levels are discussed.

INTRODUCTION

There are approximately 12 million conventional cordwood heaters still in use that were sold prior to the July 1, 1990, NSPS deadline for the sale of uncertified heaters[1]. There are literally hundreds of different models and of the 12 million still in homes about seven million are freestanding stoves and about five million are fireplace inserts. There are considerable differences in design, shape and size among models. Notably these differences include such factors as: (1) differences in cast iron versus steel plate construction, (2) various firebox sizes, (3) different air inlet and air control systems, (4) some models are thermostatically controlled (using multiple designs) and some are not, and (5) differences in direct fire versus under fire air designs.

Basing emission factors on a limited number of tests is a more serious problem for conventional cordwood heaters than for many other particulate sources because of the high variability that is characteristic of them. It has been well documented that combustion conditions such as temperature, available oxygen, and residence time will influence the production of particles and volatile organic compounds (VOC) as well as their chemical makeup. In addition to the many hundreds of models of cordwood-burning heaters in use, many dozens of tree species are commonly used for fuel, draft characteristics vary from home to home (chimney conditions), household altitude is variable, there are variations in wood seasoning and storage practices (wood moisture), and there are wide variations in home occupant operation of wood-burning devices (burn rate, burn duration, damper setting, kindling

approach, etc.). Each of these parameters has significant impacts on combustion conditions and will affect emissions. Beyond the variability in cordwood heater emissions, which is due primarily to the differences in combustion, the variability in the chemical makeup of wood is an additional source of the differences seen in the data as specific compounds will be formed by the rearrangement, oxidation and combining of compounds contained in the wood fuel and their intermediate products of incomplete combustion. Wood is composed of lignin, cellulose, hemicelluloses, and resins. The ratios of these major chemical groups vary from tree species to tree species, particularly in wood from deciduous versus coniferous trees. The resin content, for example, which is much higher in conifers as compared to deciduous trees, may be particularly important for such pollutants as phenols, benzene and polycyclic organic material (POM) emissions as resins are composed of polyaromatic structures.

Because emissions from the combustion of wood are predominately composed of organic compounds, secondary organic aerosols (SOA) can be formed in the atmosphere from vapor phase emissions, and both particulate and vapor phase emissions contain a number of toxic organic compounds. Neither the formation of SOA nor, with the exception of a few classes of compounds, the emissions of toxic air pollutants from conventional cordwood heaters have been well studied. Most attention has been focused on the mass of primary particulate emissions.

PARTICULATE EMISSION FACTOR DATA BASE

Currently, the most credible and most widely used source of particulate emission factors for conventional uncertified cordwood heaters is the U.S. EPA's Emission Factor Documentation for AP-42: Section 1.10, Residential Wood Stoves[2]. The average particulate emission factor (30.6 lb/ton [15.3 g/kg]) provided in AP-42, on a 5H equivalency basis, for conventional cordwood heaters is lower than is representative of the United States as a whole and particularly lower than for regions with mild climates.

AP-42 is a compilation of data from, by in large, unrelated and uncoordinated studies and, as such, the values it presents are not derived from a normal distribution of data. Importantly, the burn rate conditions under which the particulate data for pre-EPA-certified conventional cordwood heaters were collected are skewed. It is a well known fact that particulate emission factors (mass particles/mass wood) from cordwood heaters at lower burn rate conditions are higher than from higher burn rate conditions. Lower burn rates are usually achieved by restricting airflow with the heater's air controls. Air restriction favors wood pyrolysis and the formation of products of incomplete combustion (PIC) rather than complete, efficient combustion conditions. Higher particulate emissions at lower burn rates are particularly significant for pre-EPA-certified conventional heaters that do not have secondary combustion or catalyst mitigation of particles produced during the primary combustion. The conventional cordwood heater data included in AP-42 are primarily from in-home measurements predominately from homes in colder climates[3-8], which is concomitant with higher woodstove burn rates. Further, households selected for participation in the in-home studies were "serious" cordwood heater users whereas U.S. Census Bureau (American Housing Survey) data[9] show that most cordwood heaters are used for supplemental heat not as the major source of household heat, again suggesting that the data in AP-42 represents emissions at higher than average actual in-home burn rate conditions. Nationally, the ratio of households that characterize their use of cordwood heaters (stoves plus fireplace inserts) in 2005 as "other heating equipment" as compared to "main heating equipment" is over 9:1.

Table 1 contrasts the heater-weighted heating degree days (HDD) associated with the locations of the in-home tests, which represent the principal source of data used to develop the AP-42 emission factor for conventional cordwood heaters with the U.S. population-weighed HDD. As can be seen, in reviewing the tabulation, heater-weighed HDD (10,190 HDD) associated with the locations of the in-home tests used in the calculation of the AP-42 emission factor is more than twice what is experienced by the U.S. as a whole (4540 HDD). Also, as previously noted, the households selected for participation in the in-home studies were, by-in-large, "serious" wood burners.

Table 1. Heating degree day (HDD) comparison of the conventional cordwood heater AP-42 database with the national average.

Conventional cordwood heaters, AP-42 database		
Glens Falls, NY	3 in-home heaters	7150 HDD
Waterbury, VT	3 in-home heaters	7790 HDD
Klamath Falls, OR	7 in-home heaters	6600 HDD
Crested Butte, CO	18 in-home heaters	11,300 HDD
Portland, OR	2 in-home heaters	4369 HDD
Whitehorse, Yukon	16 in-home heaters	12,260 HDD
Weighted (by number of heaters) average HDD of conventional cordwood heater database		10,190 HDD
U.S. average (population weighted)		4540 HDD

In addition to lower burn rates potentially producing higher emissions in milder climates, the fact that the highest emission rates occur during the kindling phase of a burn is also significant. There are data that suggest that as much as one-half of the total emissions for an individual burn period for non-catalytic heaters occur during the kindling phase (first 17% of a burn). In warmer climates fires tend to be started and allowed to burn out more frequently than in colder climates hence the kindling phase portion of the burn period will contribute relatively more to the overall emissions in warmer climates than in colder ones.

To illustrate the magnitude of the effect of lower burn rates on particulate emission factors for pre-EPA-certified conventional cordwood heaters two approaches were taken. These were: (1) the effect of burn rate on creosote formation in chimneys was used to qualitatively illustrate the large increase in emission factors expected from lower burn rates, and (2) the effect of burn rate on particulate emissions factors was estimated by using all relative data that could be found in published literature or in technical reports. In both cases, only data for non-certified, non-catalytic, non-research, commercially available cordwood heaters were utilized to insure that the trends were representative of non-certified conventional heaters in actual use.

Creosote accumulation is related to particulate emissions since they are both primarily the product of organic compounds that are emitted and subsequently condensed and/or captured on the interior of chimney pipes or onto a filter substrates, respectively. Using creosote accumulation data as a surrogate for particulate emissions, the strong inverse trend of particulate emissions with burn rate can be seen (Table 2).

Table 2. The effect of burn rate on creosote accumulation from conventional cordwood heaters[10].

Burn rate	Fuel moisture (%)	Creosote accumulation, piñon pine (g/kg)	Creosote accumulation, oak (g/kg)
Low	5	9.2	16.5
	15	11.0	16.6
	25	9.5	19.4
Medium	5	9.8	4.1
	15	8.0	2.9
	25	5.4	2.3
High	5	6.4	2.7
	15	3.9	0.88
	25	2.2	0.40

A number of studies have directly measured emission factors at multiple burn rates. The data from all relative studies that met the previously listed criteria for measuring particulate emissions from conventional cordwood heaters at both high and low burn rates (a total of 11 studies could be found) illustrate the difference in emission factors between the high and low burn rates. (See Table 3 and Figure 1.) While it is difficult to compare the results of these studies on an absolute basis, as different particulate sampling equipment, different fuel types, different heater models, different reporting conventions, and different ways to define burn rate and to classify burn rates as either "high" or "low" were used in each study, the inverse relationship between burn rates and emission factors is clear (Figure 2). The average increase in emissions (expressed as a ratio) of the eleven studies when comparing emissions from a low burn rate to those tests with a high burn rate was a factor of 4.2.

Table 3. The effect of burn rate on particulate emissions from conventional cordwood heaters.

Study number for Figures 1 and 2	Reference	High burn rate			Low burn rate			Ratio of low to high burn emission factors
		Emission factor (g/kg)	Burn rate (kg/hr)	n	Emission factor (g/kg)	Burn rate (kg/hr)	n	
1	Leese and Harkins, 1989[11]	3.1	6.6	4	11.1	2.0	6	3.6
2	Zielinska et al., 1998[12]	3.5	7.1	2	7.7	3.8	3	2.2
3	Hayden and Braaten, 1991[13]	4.2	2.2	2	14.0	1.1	4	3.3
4	Burnet et al., 1990[14]	5.8	2.9	2	25.1	1.4	2	4.3
5	Knight, 1982[15]	2.7	8.9	6	47.9	2.9	4	17.7
6	Kowalczk et al., 1981[16]	23.6	3.7	2	62.6	1.6	2	2.6
7	McCrillis and Merrill, 1985[17]	15.5	4.8	1	46.6	1.1	1	3.0
8	Burnet et al., 1986[18]	13.3	3.2	3	22.7	1.4	3	1.7
9	Kosel, 1980[19]	29.0	4.8	1	53.4	1.2	1	1.8
10	OMNI, 1988[20]	7.6	4.0	1	30.4	0.7	1	4.0
11	Jordan and Seen, 2005[21]	13.5	2.7	7	33.6	0.7	5	2.5
Average		11.1	4.6	-	32.3	1.6	-	2.9, 4.2*

Note: Data for mid-burn conditions were not used in table, only the high and low burn conditions are compared
*2.9 is the ratio of the averages and 4.2 is the average of the ratios

Figure 1. The effect of burn rate on particulate emissions for conventional cordwood heaters (Study numbers are defined in Table 3.).

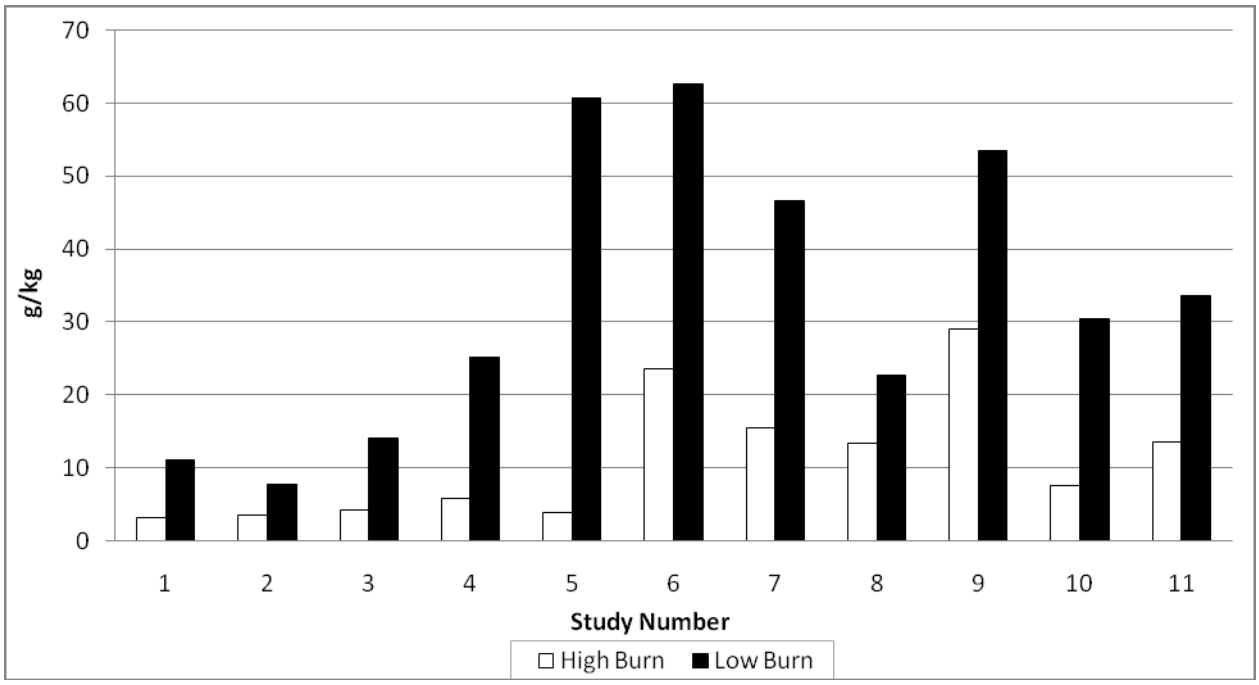
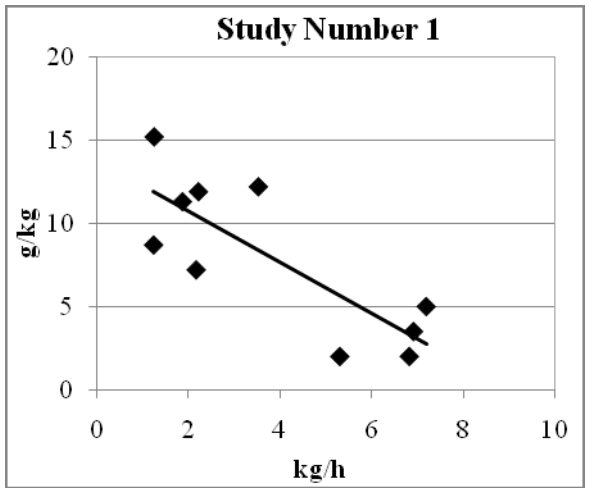
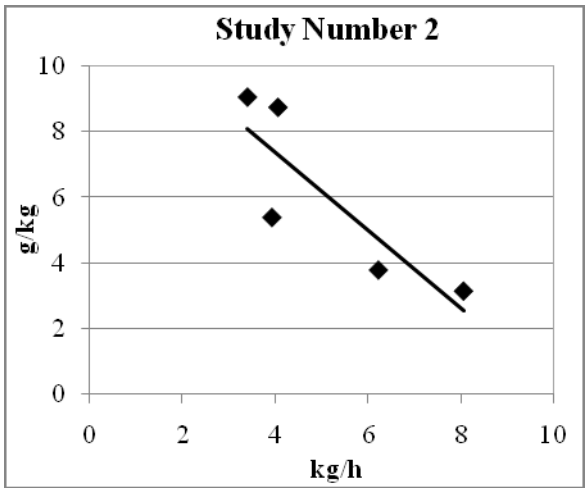
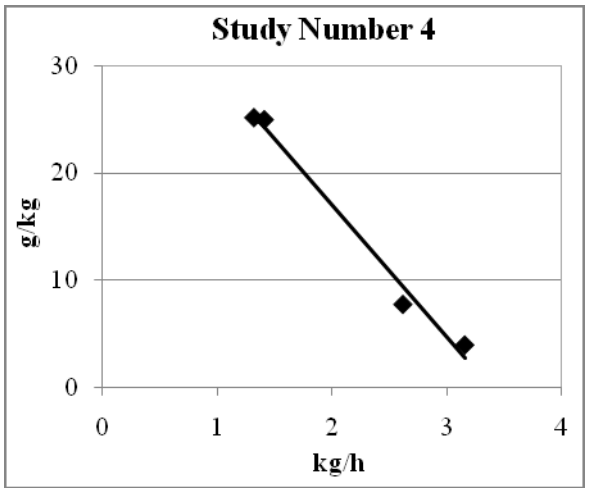
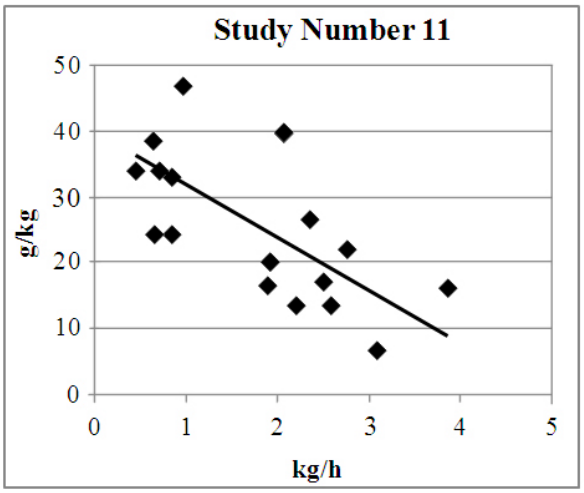


Figure 2. The relationship between burn rates and emission factors for pre-EPA-certified conventional cordwood heaters (Study numbers are defined in Table 3.)









Because uncertified conventional wood heaters are at a minimum 18 years old, many have undergone degradation with use. Common degradation observed in old, heavily used heaters includes deterioration of gasket materials, thermal warping of doors and air control systems, and breaches in the unit due to corrosion. The net effect of these problems generally increases excess air passing through the combustion zone, which ironically, may cause particulate emission factors to actually decrease for many units (Figure 3). Unlike degradation of certified wood heaters, in which secondary combustion systems are usually compromised, the effect of degradation of uncertified models, without sophisticated emission control design, is generally to preclude air-limited "dampered-down" conditions which produce the highest emission factors. However, with excess air, the efficiency of the units also decreases, perhaps approaching the inefficiency of fireplaces (Table 4). Lower efficiency increases the effective emission factor, as more wood is needed to be burnt to satisfy the same heating demand. At the extreme, as with open fireplaces, the latter effect probably more than out weighs the lowering of emission factors, particularly when the increase in cold outside air that is drawn into the house is taken into consideration.

Figure 3. The effect of excess air on emission factors[22].

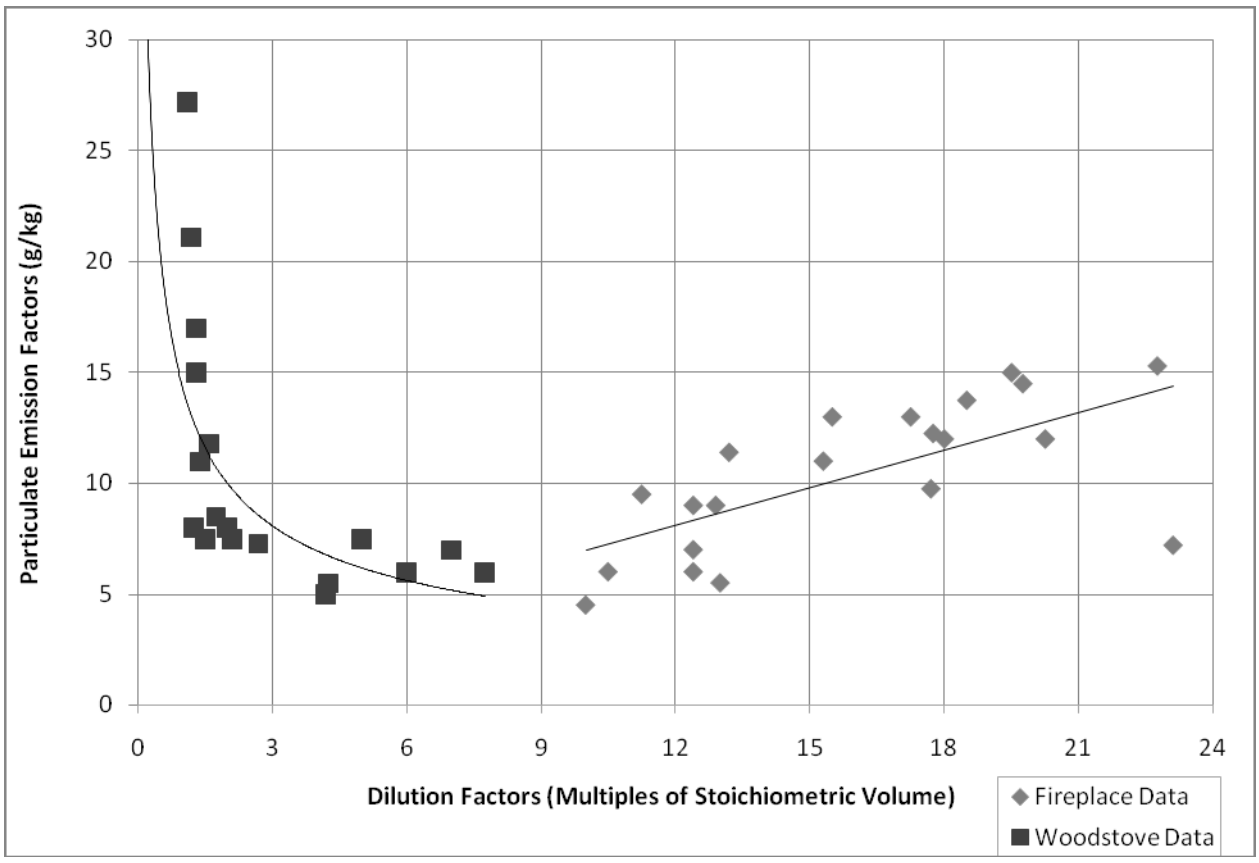


Table 4. Efficiencies by appliance type.

Appliance type	Efficiency
Conventional cordwood heater[2]	54%
Conventional cordwood heater[23]	40%-65%
Cordwood fireplaces (n = 14)[24]	12%-32%
Cordwood fireplaces[23]	5%-15%

Besides the large effects of burn rates, cold- versus hot-starts (high emissions during start up), and heater degradation, other factors can affect emission factors from uncertified conventional heaters. These include, the characteristics of a given heater model, the particulate sampling methods used to measure the emissions, the chimney (draft) characteristics, altitude, the tree species used for fuel, and the fuel moisture. Also, it needs to be remembered that while the majority of particulate material (PM) is PM_{10} and $PM_{2.5}$, limited data suggest that a measurable fraction is less than PM_{10} and $PM_{2.5}$, respectively, and that between the two common measurement and reporting methods (5G and 5H), 5G tends to under-predict emission factors and 5H tends to over-predict emission factors, with 5G being a more precise measurement method than 5H. (See the companion paper addressing certified wood heaters for a detailed discussion of the factors discussed in this paragraph[25].)

A review of recent studies of aged, uncertified heaters was conducted (Table 5). The range of average emission factors reported spanned over one order of magnitude from 2.95 g/kg to 33.6 g/kg (5G equivalent) as compared to the single AP-42 value of 15.3 g/kg (5H equivalent), which corresponds to roughly 12.3 g/kg (5G equivalent). These studies included a range of burn rates, fuels, start scenarios, etc. Consequently, (1) based on the number variables that can affect emission factors from conventional cordwood stoves, (2) the fact that the AP-42 data are most applicable to cold climates, and (3) the fact that conventional cordwood heaters have aged significantly (lower efficiencies with more fuel consumption) since the studies used in AP-42 compilation, it is recommended that focused, direct measurements of emission factors be made for conventional heaters using locally representative heaters, fuels, and burn scenarios for regional emission inventories or for use with local change-out programs.

Table 5. Particulate emission factors (5G equivalent) for aged uncertified heaters.

Start scenario	Burn rate (kg/h) avg. ± s.d.	Fuel	N	Description	5G Emission factor (g/kg) avg. ± s.d.	Reference
Hot	Not provided, estimated as 2.4	Maple cordwood	3	Single heater, "typical light burning fires"	2.95 ± 2.05	Environment Canada, 2000[26] and Intertek, 2000[27]
	Not provided, estimates as 2.5	Spruce cordwood	3		18.2 ± 5.7	
Cold	2.60 ± 0.70* 2.39 ± 0.422§ 1.81 ± 0.273† (same burn, burn rates, calculated by different methods)	Oak cordwood	5	Average of 5 different conventional heaters, "middle range burning scenarios"	7.5 ± 8.7	Pitzman et al., 2006[28]
Hot	2.70 ± 0.64	White gum cordwood	7	Single heater, burn rates controlled with air inlet	13.5 ± 4.1	Jordan and Seen, 2003[21]
	1.58 ± 0.70		5		30.6 ± 7.6	
	0.72 ± 0.20		5		33.6 ± 9.6	
Hot	4.60± 1.08	Mixed hardwood and oak cordwood	6	Single heater	4.35 ± 1.97	McDonald et al., 2000[29]
Cold	4.04 ± 0.42	Oak cordwood	3	Single exempt heater	4.87 ± 0.91	McCrillis, 2000[30]

* The end of burn defined as when no fuel is remaining as determined by mass.
§ The end of burn defined as when the temperature in the chimney one foot (30 cm) above the heater is 200º F (93º C).
†The end of burn defined as when the temperature in the chimney one foot (30 cm) above the heater is 100º F (38º C).

SECONDARY ORGANIC AEROSOLS

Methane and non-methane volatile organic compounds (NMVOC) are emitted on the same order of magnitude as each other and at the same order of magnitude as primary particles from conventional cordwood heaters. The formation of secondary organic aerosols (SOA) from NMVOC has been of concern. To date, there has not been adequate data collected to definitively calculate the impact of SOA, but some factors are clear. Lighter (C1-C6) NMVOC promote SOA formation by providing oxidizing free radicals. Heavier NMVOC (C7-C15), particularly aromatic compounds, are direct precursors to SOA. Further, it has been suggested that acidic particles may increase SOA formation. Residential wood combustion (RWC) emissions contain constituents in all three categories – light VOC, heavy VOC and acidic compounds. To provide a sense of scale of the relative importance of potential SOA formation Table 6 summarizes some key data for a typical non-EPA-certified conventional cordwood heater.

Table 6. Typical emission factors from uncertified conventional cordwood heaters illustrating the potential relative magnitude of SOA formation.*

Pollutant	Representative emission factors (g/kg)
Major pollutant categories	
primary particles (5H equivalent)	17
methane	32
carbon monoxide	78
NMVOC (appx. 1/3 not identified)	18
Selected C1-C6 NMVOC potentially providing free radicals for SOA	
ethyne (acetylene)	1.1
C2-C6 alkanes	1.7
C2-C6 alkenes	3.7
acetone	0.4
methanal (formaldehyde)	0.2
ethanal (acetaldehyde)	0.4
methanol	3.2
benzene	1.2
C7-C15 VOC potential reactants	
toluene	0.2
xylenes (o, m and p)	0.07
total gaseous PAH	0.05
total semi-volatile XAD catch**	~2
Selected acid compounds in particles enhancing SOA formation***	
acetic acid	0.4
propionic acid	0.2
lactic acid	0.5

*Data from references 29-32.
**The total semi-volatile XAD catch is a reasonable surrogate for C7-C15 VOC. Semi-volatile compounds are generally defined as compounds with boiling points greater than 100°C.
***The pH of the water impinger of a U.S. EPA Method 5 sampling train, after the collection of a particulate sample was measured as 3.3 and had a classical carboxylic acid titration curve. See reference 18.

As can be seen in reviewing that data in Table 6, the amount of organic SOA that can be formed will be considerably smaller as compared to primary particles emitted. The total emission factor of the

sum of C7-C15 potential reactants, as estimated by the total semi-volatile catch, is approximately 2 g/kg, (as compared 17 g/kg for primary particles). The 2 g/kg emission factor represents the upper limit on the direct contribution of SOA to total atmospheric particles from RWC even if all the C7 through C15 organic compounds in the vapor phase are oxidized and condense as particles in the atmosphere. The oxidizing effect and subsequent SOA formation of C1-C6 NMVOC from RWC on atmospheric VOC from sources other than RWC should also be small, as in 2002; only 4.5% of the total VOC nationwide was from RWC[32]. Additionally the overall significance of SOA formation is less than the total mass of VOC emission might suggest because RWC emissions are temporally separated from times of maximum SOA formation. Maximum SOA formation occurs during the summertime when there is higher solar insolation and temperature not during the heating season. Again, while there are no data to accurately predict the absolute magnitude of SOA formation from RWC emissions, the data and the general state-of-knowledge of atmospheric chemistry suggest that the overall contribution of SOA will be relatively minor (probably well less than 10%) as compared to primary particles.

TOXIC AIR POLLUTANTS

Far more important for RWC, in terms of health and environmental impact, than the mass of particles either directly emitted (primary particles) or subsequently formed from emitted vapors in the atmosphere (SOA) are the "air toxics" and hazardous air pollutants (HAP) associated with particulate emissions or emitted in the gas (vapor) phase. (HAP are a very small regulation defined subset of the total number of air toxics possible.) The composition of air emissions from residential wood combustion, while quite variable, is dominated by carbon monoxide and organic compounds. Many recognized toxic organic compounds are emitted both in sub-micron particles (solid and liquid phases) and as vapors. The make up of particles, again while quite variable, is generally reported as between 70% and 99% organic compounds, with the remaining fraction being predominately elemental carbon. The relative ratio between the organic compound fraction and the elemental carbon fraction is largely dependent on combustion temperature and efficiency, with well-oxygenated hot fires having a lower organic carbon to elemental carbon ratio and those burning under cooler oxygen-starved conditions having a higher organic compound to elemental carbon ratio. Usually only about 1% of particles are reported as being inorganic salts (namely composed of calcium, magnesium, sodium, potassium, ammonium, zinc, nitrate, sulfate, chloride, and carbonate). Elemental carbon and the inorganic salts emitted from RWC are relatively benign. Often overlooked is the fact that a measurable amount of nitrogen oxides are emitted from wood combustion due to the nitrogen content, primarily from the amino acids, in biomass fuels. Both nitrogen dioxide (NO_2) and nitric oxide (NO) are emitted from RWC. Nitric oxide is oxidized to nitrogen dioxide in the atmosphere. Nitrogen dioxide is toxic, is a federal criteria pollutant, forms secondary aerosols in the atmosphere, contributes to regional haze, is responsible for the characteristic brown coloration sometimes seen over urban areas, and is an ozone precursor.

Since most organic compounds that make up particles and NMVOC are products of incomplete combustion (PIC) of wood, and wood is made up primarily of the very large and complex molecules (cellulose, hemicelluloses, lignin and polymeric resins), literally hundreds of different hydrocarbons and oxygenated compounds are possible in RWC emissions. Many of these can be considered toxic by any standard measure. For example, a cursory review of the Title III Hazardous Air Pollutants (HAP) list reveals a number of pollutants associated with biomass combustion. Table 7 is a tabulation of these compounds that are either primarily in the vapor phase at atmospheric temperatures and pressures or are semi-volatile and are partitioned between the vapor and particulate phases and hence contribute to both NMVOC and particles. Representative emission factors from uncertified conventional cordwood heaters for the HAP are presented in the table to provide insight into their relative importance. Not included in the table are organic air toxics primarily in the particulate phase nor the two important inorganic toxic air pollutants emitted from RWC (that are not on the HAP list) – nitrogen dioxide and carbon monoxide.

Table 7. Title III hazardous air pollutants present in NMVOC emitted from residential wood combustion.*

Pollutant	Emission Factor	Predominately vapor phase (V) or semi-volatile (SV)
Acetaldehyde	0.308 g/kg	V
Acetophenone	0.010 g/kg	SV
Acrolein	0.046 g/kg	V
Benzene	1.08 g/kg	V
Biphenyl	2.43 mg/kg	SV
1,3-Butadiene	0.197 g/kg	V
Catechol	0.331 g/kg	SV
o, m and p-Creosols	0.080 g/kg	SV
Dibenzofurans	1.9 mg/kg	SV
Ethyl benzene	ND	SV
Formaldehyde	0.727 g/kg	V
Hexachlorbenzene	13 ng/kg (certified non-cat heater)	SV
Hexane	0.012 g/kg (n-hexane)	V
Methanol	3.24 g/kg	V
Naphthalene	0.091 g/kg	SV
Phenol	0.147 g/kg	SV
Polychlorinated biphenyls	0.50 pg/kg (PCB_{TEQ})	SV
Propionaldehyde	0.096 g/kg	V
Styrene	0.117 g/kg	SV
2,3,7,8-Tetrachlordibenzo-p-dioxin	2.30 ng/kg ($Dioxin_{TEQ}$)	SV
Toluene	0.320 g/kg	SV
o, m and p-Xylenes	0.099 g/kg	SV
Polycylic Organic Matter	0.315 g/kg (16-PAH)	SV

*Unless otherwise noted the data are for uncertified conventional cordwood heaters. Data are from references 21, 29, 30, 33, 34.

SUMMARY

The single AP-42 particulate emission factor for uncertified conventional wood heaters is smaller than what would be expected in mild climates primarily due to differences in burn rates and start-up scenarios between cold climates used to develop the database and milder climates. Because of regional differences in fuels and regional differences in operational parameters, considerable variability in emissions between heaters in different parts of the country can be expected. Consequently, it is recommended that direct measurements be made with representative local wood heaters, fuels, and operational conditions for use with local emission inventories or for support of woodstove change-out programs rather than defaulting to a non-representative national average value. AP-42 also does not take into account the effect of heater aging. This is significant as uncertified conventional cordwood heaters are now 18 years old or older. They are now, as a group, less efficient and consume more fuel for the same heating demand.

The contribution of secondary organic aerosols (SOA) as compared to primary particulate is small (probably less than 10% of the total).

Finally, while most attention has been focused on particles because of PM_{10} and $PM_{2.5}$ non-attainment, toxic air pollutant emissions from conventional cordwood heaters represent a far more significant human health and environmental concern. Notably, because the largest fraction of air toxics are in the gas (vapor) phase and U.S. EPA-certified wood heaters are more effective in combusting carbon monoxide and organic vapors than particles, the benefit of the replacement of conventional cordwood heaters with certified cordwood heaters may be more significant to human health and the environment than is judged by particulate reductions alone.

REFERENCES

1. Houck, J.E. and Keithley, C., "Enormous Opportunity", Hearth and Home, September 2004, pp. 130-137.

2. U.S. Environmental Protection Agency, *Compilation of Air Pollution Emission Factors – Volume 1: Stationary Point and Area Sources, AP-42, Chapter 1.10, Residential Wood Stoves*, Research Triangle Park, NC, revised October 1996, http://www.epa.gov/ttn/chief/ap42/ch01/final/c01s10.pdf.

3. Burnet, P.G., "The Northeast Cooperative Woodstove Study, Volume 1," Prepared for U.S. Environmental Protection Agency by OMNI Environmental Services, Inc., Beaverton, OR, 1987, EPA-600/7-87-026a.

4. Jaasma, D.R., Champion, M.R., and Gundappa, M., "Field Performance of Woodburning and Coalburning Appliances in Crested Butte during the 1989-90 Heating Season", Prepared for the U.S. Environmental Protection Agency by Virginia Polytechnic Institute and State University, Blacksburg, VA, 1991, EPA-600/7-91-005.

5. Dernbach, S., "Woodstove Field Performance in Klamath Falls", Prepared for Wood Heating Alliance Oregon by Elements Unlimited, Portland, OR, 1990.

6. Barnett, S.G., "In-Home Evaluation of Emission Characteristics of EPA-Certified High Technology Non-Catalytic Woodstoves in Klamath Falls, Oregon, 1990", Prepared for Canada Centre for Minerals and Energy Technology; Energy, Mines, and Resources by OMNI Environmental Services, Inc., Beaverton, OR, 1990.

7. Simons, C.A., Christiansen, P.D., Houck, J.E., and Pritchett, L.C., "Woodstove Emission Sampling Methods Comparability Analysis and In-situ Evaluation of New Technology Woodstoves," Prepared for U.S. Department of Energy Pacific Northwest and Alaska Regional Biomass Program, Bonneville Power Administration by OMNI Environmental Services, Inc., Beaverton, OR, 1988,Task G, DOE/BP-18508-6.

8. Simons, C.A., Christiansen, P.D., Pritchett, L.C., and Beyerman, G.A., "Whitehorse Efficient Woodheat Demonstration," Prepared for The City of Whitehorse, Yukon by OMNI Environmental Services, Inc., Beaverton, OR, 1987.

9. American Housing Survey, *American Housing Survey for the United States: 2005*, August, 2006, http://www.census.gov/prod/2006pubs/h150-05.pdf.

10. Shelton, J.W. and McGrath, J., "The Effect of Fuel Moisture Content, Species and Power Output on Creosote Formation", Shelton Energy Research, Santa Fe, NM, 1981.

11. Leese, K.E. and Harkins, S.M., "Effects of Burn Rate, Wood Species, Moisture Content and Weight of Wood Load on Woodstove Emissions", Prepared for U.S. Environmental Protection Agency by Research Triangle Institute, Research Triangle Park, NC, 1989, EPA-600/2-89-025.

12. Zielinska, B., Watson, J.G., Chow, J.C., Fujita, E., Richards, L.W., Neff, W., Dietrich, D., and Hering, S., "Northern Front Range Air Quality Study", Prepared for Colorado State University by Desert Research Institute, Reno, NV, 1998.

13. Hayden, A.C.S. and Braaten, R.W., "Reduction of Fireplace and Woodstove Pollutant Emissions through the Use of Manufactured Firelogs", *Proceedings 84th Annual Meeting Air and Waste Management Association*, Vancouver, BC, June, 1991.

14. Burnet, P.G., Houck, J.E., and Roholt, R.B., "Effects of Appliance Type and Operating Variables on Woodstove Emissions", Prepared for U.S. Environmental Protection Agency by OMNI Environmental Services, Inc., Beaverton, OR, 1990, Volume 1, EPA-600/2-90-001a.

15. Knight, C.V., "Emission and Thermal Performance Mapping for an Unbaffled, Air-tight Wood Appliance and a Box-Type Catalytic Appliance", Presented at the Residential Wood and Coal Combustion Conference, Louisville, KY, March, 1982.

16. Kowalczk, J.F., Bosserman, P.B., and Tombleson, B.J., "Particulate Emissions from New Low Emission Wood Stove Designs Measured by EPA Method V", Presented at the 1981 International Conference on Residential Solid Fuels, Oregon Department of Environmental Quality, June, 1981.

17. McCrillis, R.C. and Merrill, R.G., "Emissions Control Effectiveness of a Woodstove Catalyst and Emission Measurement Methods Comparison", Presented at the 78th Annual Meeting of the Air and Waste Management Association, Detroit, MI, 1985.

18. Burnet, P.G., Edmisten, N.G., Tiegs, P.E., Houck, J.E., and Yoder, R.A., "Particulate, Carbon Monoxide, and Acid Emission Factors for Residential Wood Burning Stoves", 1986, J. Air Poll. Contr. Assoc., v. 36, n. 9, pp. 1012-1018.

19. Kosel, P.H., *Emissions from Residential Fireplaces*, State of California Air Resources Board, Stationary Source Control Division, Sacramento, CA, April, 1980, Engineering Evaluation Branch Report no. C-80-027.

20. "Environmental Impacts of Advanced Residential and Institutional (Woody) Biomass Combustion Systems", Prepared for the Bonneville Power Administration by OMNI Environmental Services, Inc, Beaverton, OR, January, 1988.

21. Jordan. T.B. and Seen, A. J., "Effect of Airflow Setting on the Organic Composition of Woodheater Emissions", Environ. Sci. Technol. 2005, v. 39, n. 10, pp. 3601-3610.

22. "The Effects of Fireplace Design Features on Emissions", Prepared for The Hearth Products Association, by OMNI-Test Laboratories, Inc., Beaverton, OR, 1999.

23. Shelton, J.W., *Jay Shelton's Solid Fuel Encyclopedia;* Storey Communications, Inc., Pownal, VT, 1983.

24. Modera, M.P. and Sonderegger, R.C., "Determination of In-Situ Performance of Fireplaces", Lawrence Berkeley Laboratory, University of California, August 1980, U.S. Department of Energy contract W-7405-ENG-48.

25. Houck, J.E., Pitzman, L.Y., and Tiegs, P., "Emission Factors for New Certified Residential Wood Heaters", Presented at the 17th International Emission Inventory Conference – Inventory Evolution – Portal to Improved Air Quality, Portland, OR, June 2008.

26. Environment Canada, "Characterization of Organic Compounds from Selected Residential Wood Stoves", report ERMD 2000-01, June 2000.

27. "Test of Two Wood Burning Stoves for Emissions per Highlights of EPA Method 5G-3", Prepared for Environment Canada by Intertek Testing Services NA Ltd., Lachine, PQ, 2000.

28. Pitzman, L., Eagle, B., Smith, R., and Houck, J.E., "Conventional Heater Baseline Study", Prepared for Hearth, Patio and Barbecue Association by OMNI Environmental Services, Inc., Beaverton, OR, 2006.

29. McDonald, J.D., Zielinska, B., Fujita, E.M., Sagebiel, J.C., Chow, J.C., and Watson J.G., "Fine Particle and Gaseous Emission Rates from Residential Wood Combustion", Environ. Sci. Technol., 2000, v. 34, n. 11, pp. 2080-2091.

30. McCrillis, R.C., *Wood Stove Emissions: Particle Size and Chemical Composition*, U.S. Environmental Protection Agency, Research Triangle Park, NC, 2000, EPA-600/R-00-050.

31. Houck J.E. and Eagle, B.N., "Task 4, Technical Memorandum 2 (Emission Inventory), Control Analysis and Documentation for Residential Wood Combustion in the MANE-VU Region", Prepared for Mid-Atlantic Regional Air Management Association by OMNI Environmental Services, Inc., Beaverton, OR, 2006, http://www.marama.org/visibility/ResWoodCombustion/Task4Final_082906.pdf.

32. Houck, J.E., "Volatile Acid Analysis of Woodstove Emissions", Presented at the Hearth, Patio and Barbecue Association, HPA Hearth & Home EXP 2000, Solid Fuel Technical Committee Meeting, Baltimore, MD, March 19, 2000.

32. U.S. Environmental Protection Agency, National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data, http://www.epa.gov/ttn/chief/trends/.

33. Gullett, B.K., Touati, A., and Hays, M.D., "PCDD/F, PCB, HxCBz, PAH, and PM Emission Factors for Fireplace and Woodstove Combustion in the San Francisco Bay Region", Environ. Sci. Technol., 2003, v. 37, n. 9, pp. 1758-1765.

34. Crouch, J. and Houck, J.E., "Comment on "PCDD/F, PCB, HxCBz, PAH, and PM Emission Factors for Fireplace and Woodstove Combustion in the San Francisco Bay Region", Environ. Sci. Technol., 2003, v. 38, n. 6, pp. 1910-1911.

KEY WORDS

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