Review of Wood Heater and Fireplace Emission Factors

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ABSTRACT

Wood heater and fireplace air pollutant emissions factors that are generally used in the calculation of emission inventories are those compiled in the U.S. Environmental Protection Agency's AP-42 and Locating and Estimating (L&E) documents. For a number of pollutants the AP-42/L& E emission factors for wood heaters and fireplaces are based on a limited number of tests on few models. In addition, much of the data making up the wood heater emission factor database are from older models.

In particular, two significant emission factor categories, which have a wider and more current database than is represented in the EPA documents, are polycyclic organic matter (POM) from wood heaters, and particles and carbon monoxide from fireplaces. Residential wood combustion (RWC) has been implicated as a major source of POM. New POM data for Phase 2 certified stoves and another conventional stove are now available that allow for the revision of POM emission factors.

Fireplace emissions are becoming increasingly more important due to the fact fireplaces are installed in the construction of new homes. The number of fireplaces is growing more rapidly in comparison with the number of wood stoves. Already, in the South and West census regions, nearly one quarter of the total cordwood used for RWC is burned in fireplaces. By using data from reports that were not widely distributed and from new reports, particulate and carbon monoxide emission factors for fireplaces were developed based on a largely expanded number of individual fireplace tests.

The appropriateness of expressing particulate emissions as "5H equivalent" was also evaluated. Method 5H is a wood heater certification method not a method designed to provide real-world particulate emission values.

A large number of fireplaces use manufactured wax/sawdust firelogs for fuel. No emission factors for wax/sawdust firelogs have been included in AP-42. Emission data for the use of manufactured wax/sawdust firelogs are provided here. These emission data are significant not only because manufactured firelogs are widely used but because they also provide emission reductions when used in lieu of cordwood.

INTRODUCTION

Air pollution emission factors for residential wood combustion (RWC) need to be revised for three primary reasons: (1) Limited data have been used to represent a large number of appliances and variables. There are many hundreds of types or models of wood burning devices in use, many dozens of tree species are commonly used for wood fuel, draft characteristics vary from home to home (chimney conditions), household altitude is variable, there are variations in fuel wood seasoning and storage practices (wood moisture), and there are wide variations in the operation of wood burning devices in the home (burn rate, burn duration, damper setting, kindling approach, etc.). Each of these parameters have significant impacts on combustion conditions and will change emissions. The measurement of emissions from a very limited number of models and burning conditions to represent the estimated 9.8 million wood stoves, 7.3 million wood burning fireplace inserts, 27 million wood burning fireplaces without inserts, and 0.3 million pellet stoves in homes (1999) in the United States has the potential of producing very non-representative emission data. (2) Semi-volatile organic compounds as well as water soluble organic compounds, such as alcohols, aldehydes and organic acids, make up a very large fraction of RWC emissions. The choice of sampling approaches changes the capture efficiency of emissions and the partitioning between gas and particulate phases. For example, there have been a number of different particulate sampling approaches which will produce different emission factors for the same set to test conditions., and, (3) Since 1990 there has been considerable improvement in new RWC appliance performance, i.e., lower emission factors, which is not represented adequately in the EPA emission factor compilations simply due to the age of many studies. Related to this is the fact that the federal wood heater certification manufacturing and sale requirements were put in place between 1988 and 1992. Studies prior to this generally did not evaluate current state-of-the-art appliances. In addition, there is general recognition that there has been improvement in both cordwood and pellet stoves since the first introduction of high technology models in the late 80's and early 90's.

It is beyond the scope of this limited paper to provide revised emission factors for all air pollutants for all RWC appliance types. Four topics were selected to illustrate the revisions and improvements possible in RWC emission data. These were: (1) POM emissions from wood heaters, (2) particles and carbon monoxide from fireplaces, (3) emission data from manufactured wax/sawdust firelogs burned in fireplaces, and, (4) an evaluation of the effects of particulate sampling approaches on emission factors.

POLYCYCLIC ORGANIC MATTER FROM WOOD STOVES

Residential wood combustion has been identified as a source of polycyclic organic matter (POM). Polycyclic aromatic hydrocarbons (PAH) are a subset of POM. Sixteen (and seven) specific PAH compounds have been used as indicators of POM emission levels and they are generally used in emission inventories in that role. They are referred to as 16-PAH and 7-PAH. The seven compounds that make up the 7-PAH group are carcinogens.

Emission factors for a number of PAH compounds for conventional, catalytic and high technology non-catalytic stoves have been compiled in AP-42[1]. 16-PAH and 7-PAH emission factors based on that PAH data are provided in EPA's Locating and Estimating (L & E)document[2]. Review of the references used to develop the AP-42 PAH emission factors revealed that no references published more recently than 1986 were used to develop the high technology non-catalytic emission factors and that no references published more recently than 1990 were used to develop the catalytic emission factors. Consequently, no certified stoves were among the stoves that were used to develop the high technology non-catalytic emission factors and only one phase 2 certified stove, along with uncertified models and one Oregon certified model, was used to develop the catalytic emission factors. In addition, the conventional stove emission factors in AP-42 were based only on one stove.

Two new studies (one sponsored by the U.S. EPA[3] and one by Environment Canada[4]) have recently been published that contain data for phase 2 stoves and therefore contain data more representative of stoves now manufactured and sold than the AP-42 data. (All wood stoves sold after July 1, 1992 have had to be phase 2 certified.) The EPA sponsored study measured emissions from phase 2 stoves that were used at least seven years in homes to take into account normal performance degradation. A total of 16 used phase 2 stoves were tested for multiple one-week periods for a total of 43 runs for that study.

The Environment Canada study tested a new phase 2 certified stove in the laboratory under realistic burn conditions (six runs). This study also tested one more conventional stove under realistic use conditions (six runs).

The test results from the two new studies were combined with part of the AP-42 referenced data[5] containing the one phase 2 stove and the one conventional stove to produce more realistic 7-PAH and 16-PAH results. A comparison between the updated and currently published emission factors is shown in Table 1. As can be seen, the updated emission factors for all three stove categories, for both 7-PAH and 16-PAH, are lower than the currently published emission factors. In addition, the difference in the emission factors between conventional stoves and phase 2 certified stoves is larger than the difference shown for conventional stoves and older model catalytic or high technology non-catalytic stoves.

FIREPLACE PARTICULATE AND CARBON MONOXIDE EMISSIONS

A comprehensive literature review was conducted to establish the range and distribution of fireplace carbon monoxide and particulate emissions. Twenty four unique sources (not including multiple reports and publications based on the same tests)were found to contain relevant data. Sixteen of these[6-21] are not included in the particulate or carbon monoxide calculations used to derive the values tabulated in AP-42. Some of these sources are recent publications or had limited distribution.

The tests used to develop the database represent a “cross section” of fireplace types and fireplace usage characteristics. The tests have been conducted over a 32-year period. Tests were conducted on masonry and metal manufactured fireplaces of various sizes, various sizes and styles of grates were used, some tests were conducted without grates, different chimney heights and types were used, some tests employed hot starts, some tests employed cold starts, and a variety of cordwood and dimensional lumber fuel types were used.

Carbon monoxide emission factors (g/dry kg) were compiled. The emission factor data are based on 277 tests on 70 fireplace models. The mean was 64.1 g/dry kg and the standard deviation was 40.7 g/dry kg. The results are compiled in Table 2 and plotted in Figure 1. For comparison purposes, the carbon monoxide emission factor value listed in AP-42 is 126 g/dry kg.

Particulate emission factors (g/dry kg) were compiled. Because there have been a number of test methods used to measure particulate emissions, results were all converted to Method 5H equivalent values to put them on the same basis. Conversion of data collected with the Automated Woodstove Emission Sampler (AWES), the Virginia Polytechnic Institute (VPI) sampler and Method 5G-like dilution sampling systems to Method 5H equivalent values was conducted with equations developed for the U.S. Environmental Protection Agency[22]. Data collected with the Emission Sampling System (ESS) developed for the Washington state certification program[14] and for the Northern Sonoma County method[21] were converted to Method 5H equivalent values with the relationship developed with simultaneous testing with Method 5H and the ESS[21] Historical data collected with a Method 5 sampler were converted to Method 5H equivalents by developing a relationship between the values obtained with a Method 5H sampler and the same sampler with the particulate material collected on the back filter removed from the calculation. (The key physical difference between a Method 5H sampler and a Method 5 sampler is that the Method 5 sampler does not have a back filter but the Method 5H does). Based on 20 data points, the relationship between Method 5H and Method 5 was determined to be: Method 5H = 1.11898 (Method 5) - 0.9374, $R^2 = 0.9815$.

The emission factor data are based on 388 tests on 112 models. The mean was 11.8 g/dry kg and the standard deviation was 11.6 g/dry kg. The results are compiled in Table 3 and plotted in Figure 2. For comparison purposes, the particulate emission factor value listed in AP-42 is 17.3 g/dry kg[23].

MANUFACTURED FIRELOGS

It has been estimated that 100 million wax-sawdust firelogs or 0.8 million wood cord equivalents are burned each year[24]. Based on survey data, wax-sawdust firelogs were burned some of the time in 30% of fireplaces and exclusively in 12% of the fireplaces during the 1994-1995 heating season[25].

Wax-sawdust firelogs are composed of approximately 40% to 60% wax with the remaining portion sawdust. Waxes obtained from petroleum refineries are typically used. The heat content of wax-sawdust firelogs is much higher than that of cordwood (15,700 Btu/lb. for wax-sawdust firelogs as compared to 8900 Btu/lb. for Douglas fir) and their moisture content is much lower (3% as compared to 20% for well-seasoned cordwood). There are two types of manufactured firelogs, densified firelogs and wax-sawdust firelogs. Wax-sawdust firelogs, discussed here, are used in much greater numbers than densified logs and are for use exclusively in fireplaces. They require no kindling, and are designed for one-at-a-time use. While several sizes of firelogs are commercially available, those with a burn duration of about three to four hours, which is the typical fireplace usage period, are most popular.

There have been a number of studies that have evaluated the reduction in particulate and carbon monoxide emissions achievable with wax-sawdust firelogs as compared with cordwood[9,12,17 & 26]. These studies used emission rates (g/hr) rather than emission factors (g/kg fuel) or emissions per unit of heat (g/Mj) to compare emissions. This was done since the heat content is different for wax-sawdust firelogs than for a cordwood and their prescribed usage (one log burned at a time without the use of kindling) is also different than for cordwood. That is, the average emission rates over a normal burn cycle for both cordwood and firelogs provide the best measure for comparison of the total amount of air pollutants that are released into the environment when a standard fireplace is used in a normal fashion with either fuel type. The results of all studies showed substantial reduction in particulate matter (PM) and carbon monoxide (CO) emissions. The average reduction in particulate emissions for the studies was 69% and the average reduction in carbon monoxide emissions was 88%. Because virtually all particles emitted from cordwood and firelogs burned in fireplaces are sub-micron in diameter, reductions documented for total particulate matter (PM) emissions are also representative of reductions in PM_{10} and $PM_{2.5}$ particles. The emission reductions for the most representative use scenarios provide the best assessment of the level of pollutant reductions that can be reasonably expected in an airshed through the use of firelogs.

Research was conducted on the most realistic use scenarios for both cordwood and firelogs and emission measurements of particles, carbon monoxide and air toxics were made for them[13]. The most representative fireplace scenario for cordwood consists of seasoned oak fuel, 3-hour wood addition period, a standard factory-supplied grate and an approximately 3 kg/hr burn rate. The most representative firelog scenario consists of burning a “4-hour” firelog following manufacturer’s instructions (one at a time on a grate with bar spacing less than 3 inches) and tapping the log with a fireplace poker when visible flames start to flicker out. In both cases the most common/typical fireplace and chimney set-up which consisted of a 36- inch radiant fireplace, no glass doors, and a 16.5 ft chimney height was used.

The overall results of the study are illustrated in Figure 3 and can be simply stated. Emissions of key air pollutants (particles, carbon monoxide, formaldehyde, benzene, and 16-PAH) were reduced in the range from 69% to 90% through the use of wax-sawdust firelogs in fireplaces. Emission rates for both oak cordwood and firelogs are shown in Figure 3. Since the nominal weight of firelogs used in the test was 6 lbs. (2.7 kg), emission factors (g/kg) and perhaps more importantly total emissions per six pound log can be calculated from the data. (The weighted average weight of firelogs sold in the U.S. is estimated, based on sales numbers, as 4.95 lbs.). It should be noted that since the overwhelming majority of particles emitted from both cordwood and firelogs are less than 2.5 μm, the values for PM, PM_{10} and $PM_{2.5}$ for a given test were within the uncertainties of the methods and also that the values as shown in Figure 3 are essentially 5G equivalents. The corresponding PM 5H equivalent for the 46.1 g/hr value shown in Figure 3 for cordwood is 51.9 g/hr and the corresponding PM 5H equivalent for the 12.4 g/hr value for a firelog is 15.8 g/hr (based on the conversion factor used for AP-42).

PARTICULATE COLLECTION AND REPORTING

As previously noted, particulate emissions have been measured by a variety of methods (viz., EPA methods 5, 5G and 5H, with the AWES, VPI and ESS samplers, and with various custom dilution systems) and equations have been developed to relate results from each method to a "5H equivalent" value to allow for comparisons. The correlation between methods is generally not good primarily because of the organic makeup of RWC emissions[27] and the various uses of filters, resins and impingers by the different methods to collect emissions. Figure 4, for example, shows the poor correlation between Methods 5G and 5H data generated independently by three laboratories in the emission rate range characteristic of new and used phase 2 wood heaters. Table 4 shows the magnitude of the difference between results directly obtained with Method 5G and the corresponding equivalent Method 5H values obtained by two standard conversion equations

In addition to the "scatter" seen in the correlations between methods, the selection of 5H equivalent values as the format for compiling particulate emissions is inappropriate since Method 5H is a certification method (not a method for collecting representative real-world emissions) and is designed for wood heaters only. (It is not for appliances with high amounts of excess air such as fireplaces.) It is generally believed that a dilution tunnel with the tunnel and filter temperatures near a given wintertime ambient temperature would produce the most representative particle emission factors for RWC.

CONCLUSIONS

- 16-PAH and 7-PAH values for phase 2 stoves are lower than the values currently compiled for high technology catalytic and non-catalytic stoves. The revised values for the conventional stove category are also lower and the difference between conventional stoves and phase 2 stoves is greater than the difference between conventional stoves and the published values for high technology catalytic and non-catalytic stoves.
- Particulate and carbon monoxide emission factors for wood burning fireplaces based on an expanded database are lower than the values compiled in AP-42.
- Emission data for wax/sawdust firelogs burned in fireplaces are important to include in RWC emission compilations due to the wide spread use of the fuel. Emissions from their use are lower than for cordwood.
- The interconversion of particulate emission factors determined by different samplers has a high uncertainty associated with it. The use as of "5H equivalent" as measure of emission factors needs to be viewed with caution since Method 5H is strictly a certification method for wood heaters.
- Upon review of existing reports and publications, a number of other revisions/updates in RWC emission factors are appropriate and possible using existing data. Notably, these include the revision of emission factors for pellet stoves to be representative of new models, the revision of conventional and certified stove particulate emission factors, the addition of emission factors for densified manufactured fuel, and the revision of volatile organic compound/ hazardous air pollutant emission factors for both wood stoves and fireplaces.

REFERENCES

1. U.S. Environmental Protection Agency, *Compilation of Air Pollution Emission Factors – Volume 1: Stationary Point and Area Sources,* AP-42, Chapter 1.10, Research Triangle Park, NC, revised October 1996, pp 1.10-1-1.10-10.

2. U.S. Environmental Protection Agency, *Locating and Estimating Air Emissions from Sources of Polycyclic Organic Matter*, Research Triangle Park, NC, 1998, EPA-4545/R-98-014.
3. Fisher, L.H., Houck, J.E., Tiegs, P.E., and McGaughey, J., *Long-Term Performance of EPA-Certified Phase 2 Woodstoves, Klamath Falls and Portland, Oregon: 1998/1999*, Prepared for U.S. Environmental Protection Agency by OMNI Environmental Services, Inc., Beaverton, OR, 2000, EPA-600/R-00-100.
4. Environment Canada, *Characterization of Organic Compounds from Selected Residential Wood Stoves and Fuels*, Ottawa, ON, 2000, report ERMD 2000-01.
5. 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, EPA-600/2-90-001.
6. Barnett, S.G., *In-Home Fireplace Performance: Comparison of a Conventional Fireplace with a Retrofit Firecrest Masonry Insert in the Zagelow Residence Vancouver, Washington*, Prepared for Mutual Materials Company, by OMNI Environmental Services, Inc., Beaverton, OR, 1991.
7. Barnett, S.G., *Particulate and Carbon Monoxide Emissions from a Bellfire 28 Rosin Fireplace Using a Simulated Real-World Test Procedure*, Prepared for Sleepy Hollow Chimney, Inc., by OMNI Environmental Services, Inc., Beaverton, OR, 1992.
8. Barnett, S.G., *Summary Report of the In-Home Emissions and Efficiency Performance of Five Commercially Available Masonry Heaters*, OMNI Environmental Services, Inc., Prepared for The Masonry Heater Association, by OMNI Environmental Services, Inc., Beaverton, OR, 1992.
9. Bighouse, R.D., and Houck, J.E., *Evaluation of Emissions and Energy Efficiencies of Residential Wood Combustion Devices using Manufactured Fuels*, Prepared for Oregon Department of Energy, by OMNI Environmental Services, Inc., Beaverton, OR, 1993.
10. Clayton, L., Karels, G., Ong, C., and Ping, T., *Emissions from Residential Type Fireplaces*, Bay Area Air Pollution Control District, San Francisco, CA, 1968.
11. DeAngelis, D.G., Ruffin, D.S., and Reznik, R.B., *Preliminary Characterization of Emissions from Wood-Fired Residential Combustion Equipment*, Prepared for U.S. Environmental Protection Agency, by Monsanto Research Corporation, Dayton, OH, 1980, EPA-600/7-80-040.
12. Hayden, A.C.S., and Braaten, R.W., "Reduction of Fireplace and Woodstove Pollutant Emissions through the Use of Manufactured Firelogs," Presented at the 84th Annual Meeting and Exhibition of the Air and Waste Management Association, Vancouver, BC, 1991, paper 91-129.1.
13. Houck, J.E., Scott, A.T., Sorenson, J.T., Davis, B.S., and Caron,C., "Comparison of Air Emissions between Cordwood and Wax-Sawdust Firelogs Burned in Residential Fireplaces", Presented at the Joint International Specialty Conference: Recent Advances in the Science and Management of Air Toxics, Banff, Alberta, 2000.
14. OMNI Environmental Services Inc., Reports on forty-five fireplace tests submitted to the Washington State Department of Ecology, Olympia, WA, pursuant to WAC 51-309-3102 and UBC Standard 31-2, 1995-2000.
15. OMNI-Test Laboratories, Inc., *The Effects of Fireplace Design Features on Emissions*, Prepared for the Fireplace Manufacturer's Caucus of The Hearth Products Association, Arlington VA, 2000.
16. Shelton, J. W., and Gay, L, *Colorado Fireplace Report*, Prepared for Colorado Air Pollution Control Division by Shelton Research, Inc., Santa Fe, NM, 1987.
17. Shelton, J.W., *Testing of Sawdust-wax Firelogs in an Open Fireplace*, Prepared for Conros Corp., Duraflame Inc., and Pine Mountain Corporation by Shelton Research, Inc., Santa Fe, NM, 1988.
18. Shelton, J.W., Sorensen, D., Stern, C.H., and Jaasma, D.R., *Fireplace Emission Test Method Development*, Prepared for Wood heating Alliance and Fireplace Emissions Research Coalition, by Shelton Research, Inc. Santa Fe, NM, and Virginia Polytechnic Institute, Blacksburg, VA, 1990.

19. Stern, C.H., and, Jaasma, D.R., *Study of Emissions from Masonry Fireplaces*, Prepared for Brick Institute of America, by Virginia Polytechnic Institute, Blacksburg, VA 1991.
20. Stern, C.H., Jaasma, D.R., and Shelton J.W., *Masonry Heater Emissions Test Method Development*, Prepared for Wood Heating Alliance by Virginia Polytechnic Institute, Blacksburg, VA and Shelton, Research, Inc., Santa Fe, NM, 1990.
21. Tiegs, P.E., and Houck, J.E., *Evaluation of an Emission Testing Protocol for Wood -Burning Fireplaces and Masonry Heaters*, Prepared for Northern Sonoma County Air Pollution Control District, by OMNI Environmental Services, Inc., Beaverton, OR, 2000.
22. E.H. Pechan and Associates, Inc., *Emission Factor Documentation for AP-42 Section 1.10*, Appendix A, report to U.S. Environmental Protection Agency Research Triangle Park, NC, 1993.
23. U.S. Environmental Protection Agency, *Compilation of Air Pollution Emission Factors – Volume 1: Stationary Point and Area Sources,* AP-42, Chapter 1.9, Research Triangle Park, NC, revised October 1996.
24. Buckley, J.T. "A Steadily Burning Passion — Gas Fireplaces Stoke Love of Hearth," *USA Today*, January 5, 1998, pp. 1D and 2D.
25. Vista Marketing Research, *Fireplace Owner Survey Usage and Attitude Report*, Prepared for Durflame, Inc., Stockton, CA, 1996.
26. Aiken, M., *Canadian Firelog Ltd. Emission Testing*, Prepared for Canadian Firelog Ltd., by B.C. Research, Vancouver, BC, 1987.
27. Purvis, C.R., McCrillis, R.C., and Kariher, P.H., " Fine Particulate Matter (PM) and Organic Speciation of Fireplace Emissions," *Environ. Science Technol*., 2000, 34, 1653-1658.

Table 1. Comparison of updated 16-PAH and 7-PAH emission factors with values derived from L&E/AP-42 Documents.

Emission Factor Category	Catalytic Stoves		High-Technology Non-Catalytic Stoves		Conventional Stoves	
	7-PAH (g/kg)	16-PAH (g/kg)	7-PAH (g/kg)	16-PAH (g/kg)	7-PAH (g/kg)	16-PAH (g/kg)
L&E/AP-42	0.024	0.314	0.024	0.314	0.022	0.359
Updated	0.005[1] (phase 2)	0.161[1] (phase 2)	0.003[2] (phase 2)	0.127[2] (phase 2)	0.020[3]	0.223[3]

1. Average of 5 used phase 2 certified stoves (13 tests) and one new phase 2 certified stove (2 tests), references 3 & 5.
2. Average of 11 used phase 2 certified stoves (30 tests) and 1 new phase 2 stove (6 tests), references 3 & 4.
3. Average of 2 conventional stoves (18 tests) using 4 wood types, 4 burn rate categories, 2 altitude categories, references 4 & 5.

Table 2. Distribution of fireplace carbon monoxide emissions factors (g/dry kg)

Comments	Maximum Value of Interval (g/dry kg)	Cumulative Number of Data Points	Cumulative Percentage	Number of Data Points in Interval
	10	16	6%	16
	22	34	12%	18
Mean - SD	23.4	42	15%	8
	30	59	21%	17
	40	73	26%	14
	50	112	40%	39
	60	135	49%	23
Mean	64.1	150	54%	15
	70	160	58%	25
	80	192	69%	32
	90	221	80%	29
	100	236	85%	15
Mean + SD	104.7	240	87%	4
	110	246	89%	10
	120	257	93%	11
	130	262	95%	5
	140	266	96%	4
	150	270	97%	4
	175	272	98%	2
	200	274	99%	2
	225	275	99%	1
	250	275	99%	0
	275	276	100%	1
	300	277	100%	1

Number of models=70
Number of tests=277
SD=Standard Deviation= 40.7 g/dry kg

Table 3. Fireplace particulate emission factors (expressed as 5H equivalents)

Comments	Maximum Value of Interval (g/dry kg)	Cumulative Number of Data Points	Cumulative Percentage	Number of Data Points in Interval
Mean - SD	0.3	0	0	0
	1.2	8	2	8
	3.5	46	12	46
	4	58	15	50
	6	104	27	46
	8	148	38	44
	10	198	51	50
Mean	11.8	235	61	37
	14	275	71	40
	16	304	78	29
	18	328	85	24
	20	346	89	18
Mean + SD	23.4	361	93	15
	25	366	94	20
	30	378	97	12
	35	381	98	3
	45	383	99	2
	50	385	99	2
	55	385	99	0
	60	385	99	0
	65	386	99	1
	80	387	100	1
	170	388	100	1

Number of models=112
Number of tests=388
SD=Standard Deviation=11.6 g/dry kg

Table 4. Conversion of 5G to 5H particulate values

Measured	Calculated		Difference			% Difference	
5G (g/hr)	5H (g/hr)[1]	5H (g/hr)[2]	5G-5H[1]	5G-5H[2]	5H[1]-5H[2]	5G-5H[1] / 5G	5G-5H[2] / 5G
0.2	0.48	0.38	-0.28	-0.18	0.10	-139%	-89%
0.4	0.85	0.71	-0.45	-0.31	0.14	-113%	-77%
0.6	1.19	1.02	-0.59	-0.42	0.17	-99%	-70%
0.8	1.51	1.32	-0.71	-0.52	0.19	-89%	-65%
1	1.82	1.62	-0.82	-0.62	0.20	-82%	-62%
2	3.24	3.03	-1.24	-1.03	0.20	-62%	-52%
3	4.53	4.38	-1.53	-1.38	0.15	-51%	-46%
4	5.75	5.68	-1.75	-1.68	0.07	-44%	-42%
5	**6.92**	**6.95**	-1.92	-1.95	**-0.03**	-38%	-39%
6	8.05	8.19	-2.05	-2.19	-0.14	-34%	-37%
7	9.15	9.42	-2.15	-2.42	-0.27	-31%	-35%
8	10.22	10.63	-2.22	-2.63	-0.41	-28%	-33%
9	11.27	11.83	-2.27	-2.83	-0.55	-25%	-31%
10	12.30	13.01	-2.30	-3.01	-0.70	-23%	-30%
15	17.23	18.78	-2.23	-3.78	-1.55	-15%	-25%
20	21.87	24.36	-1.87	-4.36	-2.49	-9%	-22%
25	26.32	29.81	-1.32	-4.81	-3.49	-5%	-19%
30	30.63	35.16	-0.63	-5.16	-4.53	-2%	-17%
35	**34.81**	40.42	**0.19**	-5.42	-5.62	**1%**	-15%
40	38.88	45.62	1.12	-5.62	-6.73	3%	-14%
45	42.88	50.75	2.12	-5.75	-7.87	5%	-13%
50	46.80	55.82	3.20	-5.82	-9.03	6%	-12%
55	50.65	60.85	4.35	-5.85	-10.20	8%	-11%
60	54.44	65.84	5.56	-5.84	-11.40	9%	-10%
65	58.18	70.78	6.82	-5.78	-12.60	10%	-9%
70	61.87	75.69	8.13	-5.69	-13.82	12%	-8%
75	65.52	80.57	9.48	-5.57	-15.05	13%	-7%
80	69.13	85.42	10.87	-5.42	-16.29	14%	-7%
85	72.69	90.23	12.31	-5.23	-17.54	14%	-6%
90	76.22	95.02	13.78	-5.02	-18.80	15%	-6%
95	79.72	99.79	15.28	-4.79	-20.07	16%	-5%
100	83.19	104.53	16.81	-4.53	-21.34	17%	-5%
110	90.04	113.95	19.96	-3.95	-23.91	18%	-4%
120	96.78	123.28	23.22	-3.28	-26.50	19%	-3%
130	103.43	132.55	26.57	-2.55	-29.12	20%	-2%
140	109.99	141.74	30.01	-1.74	-31.75	21%	-1%
150	116.47	150.87	33.53	-0.87	-34.40	22%	-1%
160	122.88	**159.95**	37.12	**0.05**	-37.06	23%	**0%**
170	129.22	168.97	40.78	1.03	-39.74	24%	1%

[1] **40CFR: $5H = 1.820(5G)^{0.830}$ (g/hr)**

[2] **AP 42: $5H = 1.619(5G)^{0.905}$ (g/hr)**

Figure 1. Cumulative fireplace carbon monoxide emissions factor distribution.
(x = mean, — = mean ± SD)

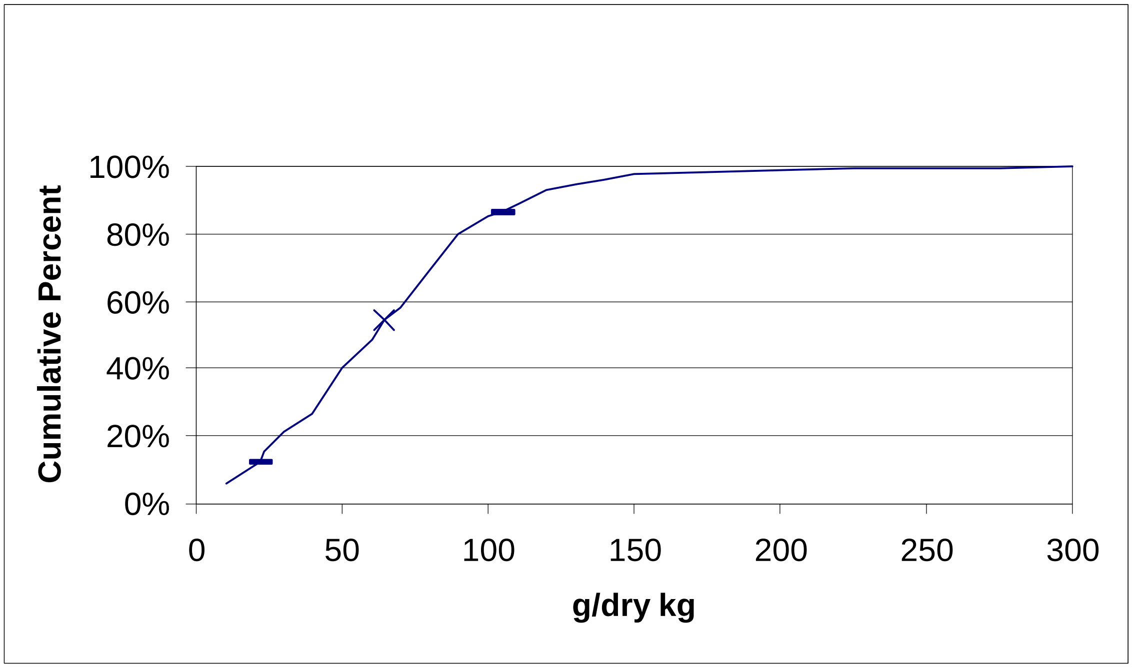

Figure 2. Cumulative fireplace particulate emissions factor distribution.
(x = mean, — = mean ± SD)

Figure 3. Comparison of air emission rates for representative cordwood and firelog use scenarios

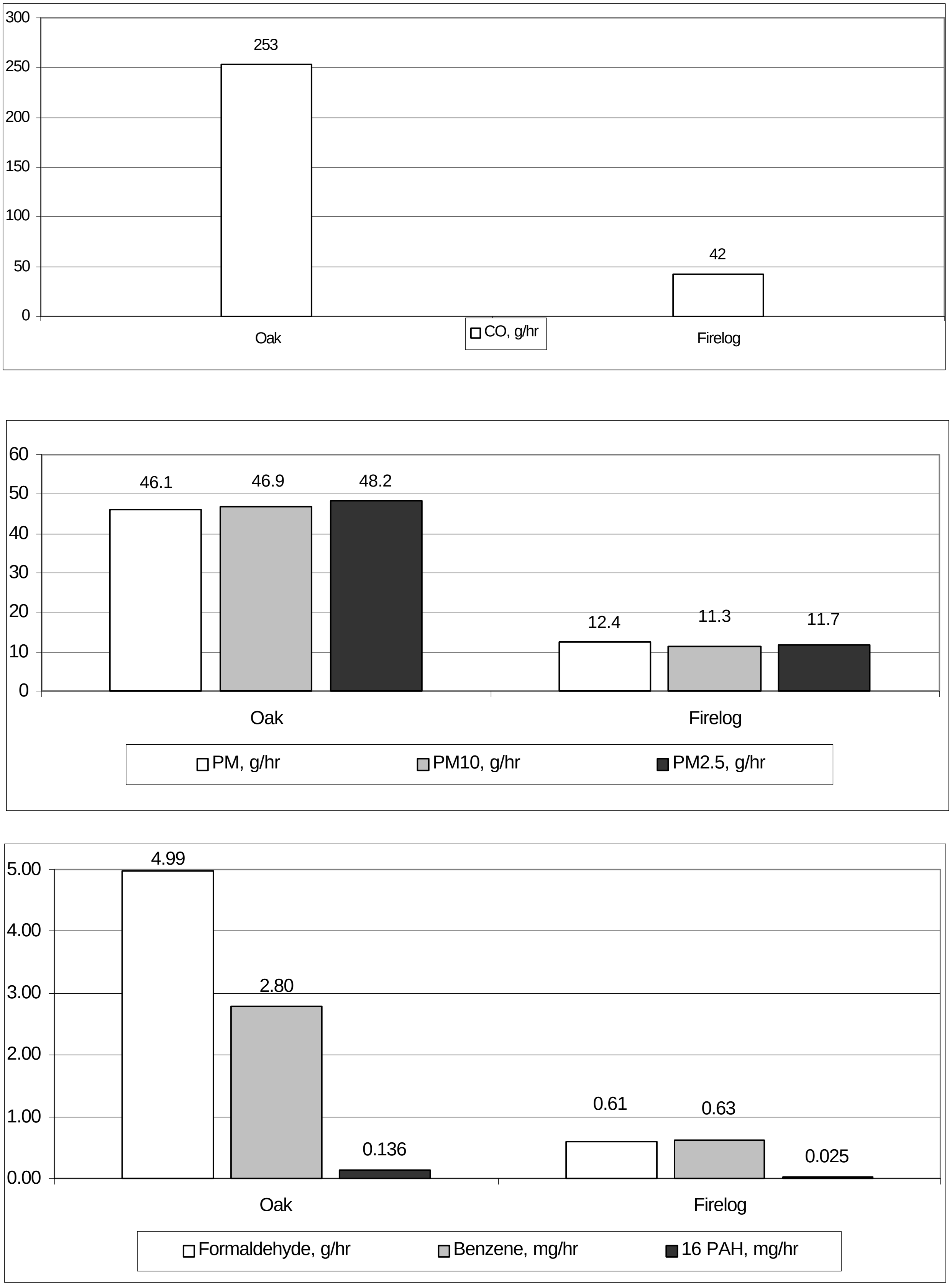

Figure 4. Method 5G-5H correlation