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Section 1.10
#29

EMISSION FACTOR DOCUMENTATION FOR AP-42 SECTION 1.10, RESIDENTIAL WOOD STOVES

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EPA Contract No. 68-D0-0120
EPA Work Assignment Officer: Michael Hamlin

Office of Air Quality Planning and Standards
Office of Air And Radiation
U.S. Environmental Protection Agency
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1. INTRODUCTION

Emission factors are the basis for emission estimates made by State and local air pollution control agencies, industry and manufacturers of both pollution-generating and controlling equipment. Beginning in 1972, the U.S. Environmental Protection Agency (EPA) has published "Compilation of Air Pollutant Emission Factors" (AP-42) to make emission factors available to regulators and industry. An emission factor relates the quantity (weight) of a pollutant to a unit of activity from the source. Uses of AP-42 emission factors include:

- Estimates of area-wide emissions;
- Estimates for a specific facility emissions; and
- Evaluation of emissions relative to ambient air quality.

This emission factor document provides background information and analysis used to review and revise emission factors located in AP-42 Chapter 1, Section 1.10: Residential Wood Stoves. The current revision updates section 1.10 to include any new data for criteria and non-criteria pollutants.

This report contains five chapters, including the introduction (Chapter 1). Chapter 2, describes the types of wood stoves, and characterizes wood stove combustion emissions and controls. Chapter 3 describes the procedure used to rank emissions data and emission factors. Chapter 4 explains the development of new emission factors for carbon monoxide (CO), particulate matter (PM), and hazardous air pollutants (HAPs), including an explanation of the data base used to calculate emission factors. Chapter 5 contains the actual, revised AP-42 section for residential wood stoves. Appendix A includes sample calculations and EPA Method 5G

correlation equations. Appendix B contains the current AP-42 section with hand-written remarks depicting the changes which will be made as part of this revision.

2. SOURCE DESCRIPTION

Residential wood combustion (RWC) is an emission category which primarily consists of emissions from wood stoves and fireplaces. In some airsheds RWC emissions can be the main source of air pollution and cause violations of the National Ambient Air Quality Standard (NAAQS) for PM with an aerodynamic diameter of 10 micrometers or less (PM-10).

Regulations to control emissions from wood stoves were first undertaken by EPA in 1988 with promulgation of the New Source Performance Standards (NSPS)[1]. NSPS provides emission limits on wood stoves manufactured and/or sold in the U.S. A phase-in of the emission limits allowed time for the wood stove industry to develop cleaner and more efficient devices. Emission limits were applied to two broad categories of wood stoves: catalytic and noncatalytic. Catalytic wood stoves utilize a catalytic combustor (see section 2.4 of this report for an explanation) and noncatalytic stoves include all other wood stoves. Other wood heaters which are exempt from NSPS have been developed and are capable of achieving reduced emissions. These exempt devices include some models of pellet stoves (exempt due to an air-to-fuel ratio greater than 35-to-1) and masonry heaters (exempt due to a mass weight greater than 800 kg). Table 2-1 summarizes the 1988 NSPS.

Wood stoves are a popular source of primary and secondary heating for residences. A 1988 survey conducted for the Consumer Product Safety Commission (CPSC) estimates that there are 9.7 million wood and coal stoves in use in the U.S.[2] About 95 percent (8.9 million stoves) burn wood exclusively. The survey also reports that wood and coal stoves are the most intensively used type of space heater in terms

TABLE 2-1. SUMMARY OF THE NEW SOURCE PERFORMANCE STANDARDS FOR RESIDENTIAL WOOD STOVES

	WOOD STOVE TYPE	
	Catalytic	NonCatalytic
Phase I		
Emission Limit (g/hr)	5.5	8.5
Effective date-for manufacture	7/1/88	7/1/88
Effective date-for sales	7/1/90	7/1/90
Phase II		
Emission Limit (g/hr)	4.1	7.5
Effective date-for manufacture	7/1/90	7/1/90
Effective date-for sales	7/1/91	7/1/92

of average usage per heater (2100 hours) and total average annual usage (20 billion hours).

Based on known variations in construction, combustion and emissions characteristics, there are generally considered to be at least four categories of wood stoves: (1) Catalytic, which use catalytic combustion technology; (2) Noncatalytic, which use noncatalytic emission reduction technology (e.g., secondary combustion chambers); (3) Pellet, which burn densified biomass pellet fuel in a specialized firebox; and (4) Conventional, which includes all other types of wood stoves not included in the other three categories, and which do not use emission reduction technology. Another type of wood burning device which is used as both a primary and secondary heat source in residences is the masonry heater.

2.1 PROCESS DESCRIPTION

A wood stove is an enclosed wood heater which controls burning or burn time by restricting the amount of air that can be used for combustion. Controlling the amount of air a fire needs for complete combustion controls the amount of the fuel converted to heat, while the remainder is primarily emitted in the form of CO, PM and condensable organics.

A pellet stove uses recycled biomass fuel, usually wood, which is compressed and shaped into pellet form, about one inch long. The pellets are loaded into a hopper and fed to the fire by use of an auger which is run by an electric motor. The rate of combustion is controlled by the amount of fuel fed into the firebox. This compares to the wood stove which uses air flow as a method of control. The pellet stoves, therefore, burn cleaner and are more efficient than wood stoves. Disadvantages of the pellet stove compared to the wood stove are that regular cleaning is needed to prevent build up of dust and ash in air passages which can greatly affect stove efficiency, and in the event of a power failure the auger stops and the stove cannot operate.

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.

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.[3] Table 2-1 provides a summary of net efficiencies, by wood heater type. These efficiencies were calculated entirely from field test data. 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.

TABLE 2-2. SUMMARY OF WOOD HEATER NET EFFICIENCIES

Wood Heater Type	Efficiency %		
	Range	Average	Reference
Conventional	41.7-63.1	53.6	4
Noncatalytic	66.2-72.6	68.3	4, 5, 6
Pellet - Certified	57.6-75.2	67.5	7
- Exempt	33.4-70.5	55.5	8
Catalytic	63.0-78.4	67.9	4, 9
Masonry Heater	54-65	58.4	10

2.2 EMISSIONS

Wood stove emissions are by-products of incomplete combustion, and include particulate matter (mainly PM-10), (CO), oxides of sulfur (SO_x) and of nitrogen (NO_x), volatile organic compounds (VOCs), and HAPs including polycyclic organic material (POM). POM is a class of compounds which contains a sub-set known as Polycyclic Aromatic Hydrocarbons (PAHs). An important fuel characteristic which contributes to PM-10 emissions from wood stoves is moisture content. Other important characteristics which affect emissions are burn rate and flame intensity.

One estimate indicates that the annual emissions from wood stoves in the U.S. are 0.8 tons of PM-10, 4.7 million tons of CO, and 1.0 million tons of VOCs.[a] The effect of these emissions is worsened in two ways. First, by adverse meteorology during the wood burning season (i.e., wintertime temperature inversions). Second, large regional variations in proportions of households actively using wood stoves (e.g., 21.4% of the households in the Mountain region versus 8.6% of the households in the Middle Atlantic region) also affect emissions.

2.3 CONTROL TECHNOLOGY

In order to decrease PM and CO emissions from wood stoves, combustion efficiency must increase. Increasing burn rate and flame intensity results in better efficiency. Both catalytic and noncatalytic control techniques increase efficiency and decrease emissions.[3] Catalytic combustors reduce emissions by using a ceramic catalyst coated with a noble metal (e.g., palladium or platinum) which allows organics and other combustibles to burn at temperatures much lower than required in a noncatalytic firebox. Older, noncatalytic wood stoves reduce emissions by directing unburned hydrocarbons (HCs) and CO into a secondary chamber, where mixing with fresh, preheated makeup air enhances further combustion. Current noncatalytic NSPS wood stove inject fresh secondary air into the top are of the primary combustion chamber, allowing ignition of the unburned HCs. Multiple air channels, some with their own controls, coupled with baffles which trap and retain heat in the top of the firebox, facilitate this combustion.

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[a] These values are based on the 1985 National Acid Precipitation Assessment Program (NAPAP) estimates for RWC emissions, with the following assumptions based on discussions with RWC experts: 66 percent of the total RWC emissions are from wood stoves, 100 percent of the total suspended particulate emissions are PM-10, and a 5 percent increase in all RWC pollutants since 1985 due to growth which exceeds reductions from change-over to new technology stoves.

REFERENCES FOR CHAPTER 2

1. "Standard of Performance for New Stationary Sources: New Residential Wood Heaters," Federal Register, Volume 53, Number 38, Section 40 CFR, Part 60, February 1988.

2. Zamula, W.W., "Room Heating Equipment Exposure Survey," Final Report, U.S. Consumer Product Safety Commission, Directorate for Economic Analysis, OMB Control No. 3041-0083, Washington, DC, March 1989.

3. "Guidance Document for Residential Wood Combustion Emission Control Measures," EPA-450/2-89-015, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC, September 1989; including Errata Sheet, June 1991.

4. Barnett, S.G. and R.D. Bighouse, "In-Home Demonstrations of the Reduction of Woodstove Emissions from the use of Densified Logs," Oregon Department of Energy and U.S. Environmental Protection Agency, July 1992.

5. Dernbach, S., "Woodstove Field Performance In Klamath Falls, OR," Wood Heating Alliance, Washington, DC, April 1990.

6. Barnett, S.G., "In-Home Evaluation of Emission Characteristics of EPA-Certified High-Tech Non-Catalytic Woodstoves in Klamath Falls, OR, 1990," prepared for the Canada Center for Mineral and Energy Technology, Energy, Mines and Resources, Canada, DSS File No. 145Q, 23440-9-9230, June 1, 1990.

7. Barnett, S.G., and R.B. Roholt, "In-home Performance of Certified Pellet Stoves In Medford And Klamath Falls, OR," U.S. Department of Energy Report No. PS407-02, July 1990.

8. Barnett, S.G. and P.G. Fields, "In-Home Performance of Exempt Pellet Stoves in Medford, Oregon," U.S. Department of Energy, Oregon Department of Energy, Tennessee Valley Authority, and Oregon Department of Environmental Quality, July 1991.

9. Barnett, S.G., "Field Performance of Advanced Technology Woodstoves In Glens Falls, N.Y. 1988-1989," Vol. 1, New York State Energy Research And Development Authority, Albany, NY, October 1989.

10. Barnett, S.G., "Summary Report of the In-Home Emissions and Efficiency Performance of Five Commercially Available Masonry Heaters," the Masonry Heater Association, May 1992.

3. GENERAL EMISSION DATA REVIEW AND ANALYSIS PROCEDURE

3.1 DATA SEARCH AND SCREENING

The first step in updating the wood stove emission factor data base was to contact experts in the field of residential wood combustion in order to determine if new test data were available since the last AP-42 update.[1,2,3] A recent update of AP-42 emission factors for wood stoves provides a current data base on which to add new data.

3.2 EMISSION DATA QUALITY RATING SYSTEM

The quality and quantity of the new test data were ranked pursuant to EPA guidance and assigned a quality ranking based on the following criteria:[4,5]

A - Tests performed using sound methodology and reported in enough detail to provide adequate validation. These tests may not be EPA reference method tests, although such reference methods are preferred and to be used as a guide.

B - Tests performed using sound methodology, but lacking enough detail to provide adequate validation.

C - Tests performed using an unproven or new methodology, or are lacking a significant amount of background data.

D - Tests performed using a generally unacceptable method, but the method may provide an order-of-magnitude value for the source.

Guidelines to evaluate the data for sound methodology and adequate detail were:

- Source operation. The source was operating within typical parameters during the test and the parameters are well documented.
- Sampling procedures. If actual procedures deviated from standard methods during the test, the deviations are well documented and evaluated to determine their influence on the test results.
- Sampling and process data. If a large spread between test results cannot be explained by information contained in the test report, then the data are suspect and are given a lower rating.
- Analysis and calculations. The test reports should contain original raw data sheets. Nomenclature and equations used are compared with those specified by EPA to establish equivalency. The depth of calculation review is determined by the reviewers' confidence in the ability and conscientiousness of the tester. Interpreted ability is, in turn, based on factors such as consistency of results and completeness of other areas of the test report.

3.3 EMISSION FACTOR QUALITY RATING SYSTEM

After evaluating emissions data and calculating new emission factors, a quality rating of the emission factor was determined based on the following criteria:

A - Excellent: The emission factor was developed from only A-rated source data, and taken from many randomly chosen facilities. The source category is specific enough to minimize variability within the source population.

B - Above average: The emission factor was developed from only A-rated source data, but it is not clear if the facilities tested represent a random sample of the population. As with the A-rated emission factor, the source category is specific enough to minimize variability within the source population.

C - Average: The emission factor was developed from only A- and B-rated source data, and from a reasonable number of facilities. It is not clear if the facilities tested represent a random sample of the population. As with the A-rated emission factor, the source category is specific enough to minimize variability within the source population.

D - Below average: The emission factor was developed from only A- and B-rated source data, and from a small number of facilities. There may be reason to suspect that these facilities do not represent a random sample of the population. Also, there may be evidence of variability with the source population. Any limitations on the use of this emission factor are noted in the emission factor table.

E - Poor: The emission factor was developed from C- and D-rated source data. There may be reason to suspect that the facilities tested do not represent a random sample of the population. Also, there may be evidence of variability with the source population. Any limitations on the use of this emission factor are noted in the emission factor table.

REFERENCES FOR CHAPTER 3

1. Verbal Communication from Robert C. McCrillis, U.S. Environmental Protection Agency, Research Triangle Park, NC, to Paula G. Fields and George E. Weant, E.H. Pechan and Associates, Inc., Rancho Cordova, CA, April-May, 1992.

2. Written Communication from Stockton G. Barnett, OMNI Environmental Services, Inc., Beaverton, OR, to Paula G. Fields, E.H. Pechan and Associates, Inc., Rancho Cordova, CA, May 18, 1992.

3. Written Communication from Paul Tiegs, OMNI Environmental Services, Inc., Beaverton, OR, to George E. Weant, E.H. Pechan and Associates, Inc., Durham, NC, March 26, 1992.

4. Technical Procedures for Developing AP-42 Emission Factors and Preparing AP-42 Sections, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC, March 1992.

5. "Clarification to AP-42 Procedures Document," Memo from J. Southerland, Emission Factor and Methodologies Section, U.S. Environmental Protection Agency, Research Triangle Park, NC, April 1992.

4. EMISSION FACTOR DEVELOPMENT

This chapter describes the test data and methodology used to review and revise the emission factors for residential wood stoves. This chapter discusses existing wood stove data sets and introduces new test data for HAPs from wood stoves and pellet stoves. The chapter ends with a discussion of emission factor data base and calculations.

4.1 REVIEW OF EXISTING DATA SETS

The AP-42 emission factors for residential wood stoves were last reviewed and revised in September 1991, and subsequently published as part of AP-42, Supplement D. The data base of emissions testing results was edited to include the most recent test data available during the 1991 revisions. The existing criteria pollutant emission factors and their ratings were used as a basis for the current update. During the current revision to AP-42 Chapter 1, Section 1.10, the 1991 emission factor documentation was reviewed to determine if it contained any non-criteria emissions data. As a result, some HAP data (i.e., PAH) for wood stoves were obtained.[1,2,3,4,5] These data, which included emission rates and/or factors for PAH and elemental HAPs, were all rated "D." Also, "B" rated CO_2 data were obtained for certified pellet stoves.[6]

It should be noted that during the review of the existing data base, the PM emission factors were recalculated due to a change in the correlation equations which adjust the field-collected data to equivalent EPA method 5G values. (See section 4.3.1.1 for details of these calculations).

4.2 REVIEW OF NEW DATA SETS

One report each on wood stove testing and exempt pellet stove testing were obtained.[7,8] Preliminary data from wood stoves tested in Crested Butte, Colorado and Klamath Falls, Oregon were obtained.[9,10] Five test reports on masonry heaters were obtained. [11,12,13,14,15]

4.2.1 Reference 7 - Wood Stoves

This report contained wood stove test data for PM, speciated organic compounds, and HAPs taken from 12 tests on a conventional stove and two tests on a catalytic stove. These tests were conducted in Boise, Idaho as part of the Integrated Air Cancer Project (IACP) sponsored by EPA and were deliberately complementary to another IACP test series performed on a noncatalytic stove.[2] A wood stove dilution sampler (WS^2) was used to collect particulate samples and a modified ambient sampler was used to collect organic compound samples. The data from this test series were variable between test runs (i.e., this test was intended to examine wood stove emissions based on variability of wood type, altitude and burn rate). PM data from this reference were not included in emission factor development due to the inability to relate the particulate emissions to equivalent EPA Method 5H emissions. Organic and PAH emissions data were used in emission factor development; each data set was given a rating of "D." Organic compound data from Reference 2 were not used for emission factor development, as many problems were encountered during the testing as documented in the report.

4.2.2 Reference 8 - Exempt Pellet Stoves

Reference 8 reported PM, CO, CO_2 and PAH emissions from six exempt pellet stoves under in-home burning conditions in Medford, Oregon during 1991. Exempt pellet stoves are stoves which are excluded from the emissions certification process because they operate at an air-to-fuel ratio in excess of 35-to-1. The PM and CO data were rated "A." The CO_2 data were rated "B." The PAH were rated "D" based on the testing method. A summary of the PM, CO and CO_2 pellet stove data is shown in Table 4-1.

TABLE 4-1. SUMMARY OF EMISSIONS DATA FROM EXEMPT PELLET STOVES[3]

	HOUSE IDENTIFICATION							
	P01	P02	P03	P04	P05	P06	AVERAGE	DATA RATING
Sample Dates (1991)	1/25-2/21	1/28-13/1	1/26-2/21	1/24-2/19	1/25-2/19	1/29-2/21		
Total Burn Time (hrs)	587	533	578	527	591	464		
Avg. Burn Rate: dry kg/hr	0.68	0.84	0.48	0.49	0.54	0.47	0.58	
Avg. PM Emissions: g/kg	1.35	3.27	6.33	2.81	5.69	4.52	3.99	A
Avg. CO Emissions: g/kg	8.23	20.52	38.76	16.33	33.73	38.96	26.09	A
Avg. CO_2 Emissions: g/kg	1,827.3	1,895.4	1,838.4	1,856.0	1,876.3	1,719.8	1,835.6	B

4.2.3 References 9 and 10 - Preliminary Data on Wood Stoves

During the winter of 1991-1992, two separate series of in-home emissions tests were conducted on wood stoves in Crested Butte (two noncatalytic Phase II stoves, six catalytic Phase I and two catalytic Phase II stoves) and Klamath Falls (four conventional stoves, three noncatalytic Phase II stoves and two catalytic Phase II stoves). The results of these tests are important in that these stoves have been tested in prior years (excluding the Klamath Falls conventional wood stoves) and the results should provide some insight into the effect of stove degradation on emissions. Degradation mainly affects catalytic components. However, over time, warpage of other internal parts can cause leaks which contribute to increased emissions. Results of these two tests are summarized in Table 4-2, even though the data cannot be included in emission factor development pending evaluation of the test reports. A preferred approach for tracking degradation might be to extract from the existing data base any emissions data for stoves with test results from multiple years, and add in the most recent year's data to form a separate "degradation" data base. In fact, work has already begun to develop this type of data base.

4.2.4 References 11, 13, 13, 14, 15 - Masonry Heaters

References 11 through 15 reported emissions from five types of masonry heaters under in-home burning conditions. All five references reported PM, CO and CO_2 emissions. These data were rated "A." A summary of the test data from all five test series is shown in Table 4-3.

Reference 11 also reported emissions for a "Russian" style masonry heater which was constructed by a mason from a plan that was later changed. Emissions from this unit were not included in the emission factor development since this unit is not commercially available and is probably not representative of the general masonry heater population in terms of construction or emissions.

TABLE 4-2. SUMMARY OF "PRELIMINARY" EMISSIONS DATA FROM WOOD STOVES IN CRESTED BUTTE AND KLAMATH FALLS

	Crested Butte Test Series[a] Sampler = VPI			Klamath Falls Test Series[b] Sampler = AWES		
EPA Certification:[c]	Cat-PI	Non-Cat-PII	Cat-PII	Conv	Non-Cat-PII	Cat-PII
Sample Start Dates	2/11/92	2/6/92	2/10/92	1/8/92	1/7/92	1/7/92
Total Burn Time (hrs)	2450	258	332	630	483	335
Avg. Burn Rate						
Dry kg/hr	0.80	0.80	1.13	1.48	1.30	1.37
Avg. PM Emissions:						
g/kg	16.33	12.82	9.91	23.66	4.26	8.24
g/hr	13.05	10.22	11.15	34.95	5.54	11.28
Avg. CO Emissions:						
g/kg	80	105	57	161.21	50.35	57.35
g/hr	63	80	66	202.54	62.75	76.86
VOC Emissions	NA	NA	NA			
g/kg				19.74	13.30	14.14
g/hr				24.80	16.61	19.13

a. Wood burned includes apple, oak, pine and spruce.
b. Wood burned includes logdepole pine, douglas fir and juniper.
c. Cat-PI means Catalytic, Phase I certified; N-Cat-PII means Noncatalytic, Phase II certified; Cat-PII means catalytic, Phase II certified; Conv means conventional.
NA = No data available.

TABLE 4-3. SUMMARY OF NEW IN-HOME EMISSIONS DATA FOR MASONRY HEATERS[11-15]

Sample Dates	1991 - 1992
Fuels	Douglas Fir, Alder
Average Fuel Moisture	19%
Total Burn Time	135.1 hours
Total Burn Cycles	41
Average Burn Rate	4.73 dry kg/hr
Average Emissions:[a]	
PM	2.8 g/kg
CO	74.5 g/kg
CO_2	1,924.7 g/kg

a. These data were collected using an AWES unit, and have been converted to M5H equivalent values. See section 4.3.1.1 of this report for an explanation of the conversion calculations, and Appendix A for a sample calculation.

4.3 EMISSION FACTOR METHODOLOGY

A Lotus1-2-3™ spreadsheet was used to compile PM and CO emissions data and calculate emission factors as part of the 1991 revision to the AP-42 section on residential wood stoves. The 1991 spreadsheets were updated during the current revision to include new correlation equations used to calculate equivalent EPA Method 5H values for PM from field-test data. (See section 4.3.1.1 for details of these calculations). New spreadsheets were developed to calculate PM, CO and speciated organic compound emission factors from new references. Also, new spreadsheets were developed to calculate emission factors for noncriteria pollutants (i.e., CO_2 and PAH).

4.3.1 Criteria Pollutant Emission Factor Development

Emission factors for NO_x (rated "E"), SO_x (rated "B"), were not changed from the 1991 emission factors. Emission factors for CO and PM were revised using

existing emission factors (rated "B") and new data (rated "A") resulting in new composite CO and PM emission factors, both rated "B." Emission factors for total organic compounds (TOC) were revised and rated "E" based on limited data showing high variability.

4.3.1.1 PM Emission Factor Development. The EPA Method 5H (M5H) is the basis for New Source Performance Standards (NSPS) for wood stoves, and was used as the reference method for evaluating wood stove, pellet stove and masonry heater particulate emission test results. The new PM test data for wood stoves (Klamath Falls), exempt pellet stoves and masonry heaters were collected using an Automated Wood Stove Emissions Sampler (AWES). Other new PM test data for wood stoves (Crested Butte) were collected using a field sampler developed at Virginia Polytechnic Institute (VPI). The results of these two test procedures are related to the EPA Method 5G (M5G) by the following equations:

$$M5G = 0.8635 \times (AWES)^{0.9289}$$

$$M5G = 0.6748 \times (VPI)^{1.007}$$

After the AWES and VPI data were converted to equivalent M5G values, the following equation was used to convert the M5G values to equivalent M5H values:

$$M5H = 1.619 \times (M5G)^{0.905}$$

These equations were developed by performing a linear regression on data taken from simultaneous AWES-M5G, VPI-M5G tests.[16,17,18,19] A sample calculation using these conversion equations along with the graphical results of the linear regression of AWES-M5G and VPI-M5G data are shown in Appendix A. It should be noted that the AWES-M5G and VPI-M5G equations have recently been revised and the new equations are used in emission factor development for the first time in this revision. Also, all previously collected VPI and AWES data have been revised using these new correlation equations.

4.3.2 Non-Criteria Pollutant Emission Factor Development

The "D" rated PAH data from references 1 through 5, 7 and 8 were compiled, resulting in "E" rated emission factors for wood stoves and exempt pellet stoves. The "D" rated data for trace elements from references 4 and 7 were compiled resulting in "E" rated emission factors for wood stoves. The "D" rated speciated organic data from reference 7 resulted in "E" rated emission factors for wood stoves.

Emission factors for CO_2 from pellet stoves and masonry heaters were calculated using the ratio of percent CO_2 to percent CO. This method was used since only the values of percent CO_2 were obtained from the test data. These data (rated "B") produced "C" rated emission factors.

4.4 EMISSION FACTOR RESULTS

A complete set of emission factors, which includes new and unrevised factors, is found in Chapter 5 as part of the revised AP-42 Chapter 1, Section 1.10.

REFERENCES FOR CHAPTER 4

1. Cottone, L.E., and E. Mesner, "Test Method Evaluations and Emissions Testing for Rating Wood Stoves," EPA-600/2-86-100, U.S. Environmental Protection Agency, Research Triangle Park, NC, October 1986.

2. Leese, K.E., and S.M. Harkins,"Effects of Burn Rate, Wood Species, Moisture Content, and Weight of Wood Loaded on Wood Stove Emissions," EPA-600/2-89-025, U.S. Environmental Protection Agency, Research Triangle Park, NC, May 1989.

3. Allen, J.M., et al., "Study of the Effectiveness of a Catalytic Combustion Device on a Wood Burning Appliance," EPA-600/7-84-046, U.S. Environmental Protection Agency, Research Triangle Park, NC, March 1984.

4. "Residential Wood Heater Test Report," Phase II Testing, Vol. 1, TVA, Div. of Energy, Conservation and Rates, Chattanooga, TN, August 1983.

5. Truesdale, R.S., and J.G. Cleland, "Residential Stove Emissions from Coal and Other Alternative Fuels Combustion," in Papers Presented at the Specialty Conference on Residential Wood and Coal Combustion, Louisville, KY, March 1982.

6. Barnett, S.G. and R.B. Roholt, "In-Home Performance of Certified Pellet Stoves in Medford and Klamath Falls, Oregon," U.S. Department of Energy Report No. PS407-02, July 1990.

7. Burnet, P.G., et al., "Effects of Appliance Type and Operating Variables on Woodstove Emissions," Volume I., Report and Appendices A-C, EPA-600/2-90-001a, U.S. Environmental Protection Agency, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, January 1990.

8. Barnett, S.G., and P.G. Fields, "In-Home Performance of Exempt Pellet Stoves in Medford, Oregon," OMNI Environmental Services, Inc., Beaverton, OR, July 1991.

9. Written communication from Robert C. McCrillis, U.S. Environmental Protection Agency, Research Triangle Park, NC, to Paula G. Fields, E.H. Pechan and Associates, Inc., Rancho Cordova, CA, May 18, 1992.

REFERENCES FOR CHAPTER 4 (Continued)

10. Written communication from Stockton G. Barnett, OMNI Environmental Services, Inc., Beaverton, OR, to Paula G. Fields, E.H. Pechan and Associates, Inc., Rancho Cordova, CA, May 18, 1992.

11. Barnett, S.G., "In-Home Evaluation of Emissions From Masonry Fireplaces and Heaters," OMNI Environmental Services, Inc., Beaverton, OR, September 1991.

12. Barnett, S.G., "In-Home Evaluation of Emissions From a Grundofen Masonry Heater," OMNI Environmental Services, Inc., Beaverton, OR, January 1992.

13. Barnett, S.G., "In-Home Evaluation of Emissions From a Tulikivi KTU 2100 Masonry Heater," OMNI Environmental Services, Inc., Beaverton, OR, March 1992.

14. Barnett, S.G., "In-Home Evaluation of Emissions From a Royal Crown 2000 Masonry Heater," OMNI Environmental Services, Inc., Beaverton, OR, March 1992.

15. Barnett, S.G., "In-Home Evaluation of Emissions From a Biofire 4x3 Masonry Heater," OMNI Environmental Services, Inc., Beaverton, OR, March 1992.

16. Barnett, S.G., "Relationship of the AWES to EPA Methods 5H and 5G," OMNI Environmental Services, Inc., Beaverton, OR, December 1991.

17. Burnet, P.G., "The Northeast Cooperative Woodstove Study," Volume 1, EPA-600/7-87-026a, U.S. Environmental Protection Agency, Research Triangle Park, NC, November 1987.

18. McCrillis, R.C., "Long-Term Wood Stove Catalysts Performance Under Simulated Residential Use," EPA-600/0-87-157, U.S. Environmental Protection Agency, Research Triangle Park, NC, June 1987.

19. Memorandum from P.R. Westlin, U.S. Environmental Protection agency, Research Triangle Park, NC, to J. Kowalczyk, Oregon Department of Environmental Quality, Portland, Oregon, July 13, 1986.

5. AP-42 SECTION 1.10: RESIDENTIAL WOOD STOVES

The revision to Section 1.10 of AP-42 is presented in the following pages as it would appear in the AP-42 document.

1.10 RESIDENTIAL WOOD STOVES

1.10.1 General[1,2]

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 sustaining.

Pellet stoves are those fueled with pellets of sawdust, wood products, and other biomass materials pressed into manageable shapes and sizes. 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

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 burn 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.[1] 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-10). 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.[3]

Sulfur oxides (SO_x) are formed by oxidation of sulfur in the wood. Nitrogen oxides (NO_x) 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 (C1 - 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 sub-group 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 1.10-1 through 1.10-8. The analysis leading to the revision of these emission factors is contained in the emission factor documentation.[29] These tables include emission factors for criteria pollutants (PM-10, CO, NO_x, SO_x), 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 only the July 1, 1988 EPA standards; and Pre-Phase I stoves do not meet any of the EPA standards but in most cases do necessarily meet the Oregon 1986 certification standards.[1] The emission factors for PM and CO in Tables 1.10-1 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.

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.

TABLE 1.10-1. (ENGLISH UNITS) EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a]
(Source Classification Codes)

Pollutant/EPA Certification[b]	Emission Factor Rating	Wood Stove Type			Pellet Stove Type[c] (SCC 2104008053)		Masonry Heater (SCC 2104008055)
		Conventional (SCC 2104008051)	Noncatalytic (SCC 2104008050)	Catalytic (SCC 2104008030)	Certified	Exempt	Exempt[d]
PM-10[e]							
Pre-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[e]							
Pre-Phase I	B	230.8		104.4			
Phase I	B		140.8	107.0	39.4		
Phase II	B		140.8	104.4	39.4	52.2	149.0
All	B	230.8					
Nitrogen Oxides[e]		2.8[f]		2.0[g]	13.8[g]		
Sulfur Oxides[e]	B	0.4	0.4	0.4	0.4		
Carbon Dioxide[h]	C				2,951.6	3,671.2	3,849.4
TOC[j]	E	48.6		24.2			
Methane	E	4.8		8.6			
TNMOC	E	43.8		15.6			

[a]Units are in lbs. of pollutant/ton of dry wood burned.
[b]Pre-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]Certified = Certified pursuant to 1988 NSPS; Exempt = Exempt from 1988 NSPS (i.e., air : ratio >35:1).
[d]Exempt = Exempt from 1988 NSPS (i.e., device weight >800 kg).
[e]References 6 - 14, 23 - 27, 29. PM-10 is defined as equivalent to total catch by EPA method 5H train.
[f]Rating = C.
[g]Rating = E.
[h]References 13, 24 - 27, 29.
[j]References 13, 17 - 18. TOC = Total organic compounds; TNMOC = Total nonmethane organic compounds. Data show a high degree of variability within the source population. Factors may not be accurate for individual sources.

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

Pollutant/EPA Certification[b]	Emission Factor Rating	Wood Stove Type			Pellet Stove Type[c] (SCC 2104008053)		Masonry Heater (SCC 2104008055)
		Conventional (SCC 2104008051)	Noncatalytic (SCC 2104008050)	Catalytic (SCC 2104008030)	Certified	Exempt	Exempt[d]
PM-10[e]							
Pre-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[e]							
Pre-Phase I	B	115.4					
Phase I	B			52.2			
Phase II	B		70.4		19.7		
All	B	115.4	70.4	52.2	19.7	26.1	74.5
Nitrogen Oxides[e]		1.4[f]		1.0[g]	6.9[g]		
Sulfur Oxides[e]	B	0.2	0.2	0.2	0.2		
Carbon Dioxide[h]	C				1,475.8	1,835.6	1,924.7
TOC[j]	E	24.3		12.1			
Methane	E	2.4		4.3			
TNMOC	E	21.9		7.8			

[a]Units are in grams of pollutant/kg of dry wood burned.
[b]Pre-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]Certified = Certified pursuant to 1988 NSPS; Exempt = Exempt from 1988 NSPS (i.e., air : fuel >35:1).
[d]Exempt = Exempt from 1988 NSPS (i.e., device weight >800 kg).
[e]References 6 - 14, 23 - 27, 29. PM-10 is defined as equivalent to total catch by EPA method 5H train.
[f]Rating = C.
[g]Rating = E.
[h]References 13, 24 - 27, 29.
[j]References 13, 17 - 18. TOC = Total organic compounds; TNMOC = Total nonmethane organic compounds. Data show a high degree of variability within the source population. Factors may not be accurate for individual sources.

TABLE 1.10-3. (ENGLISH AND METRIC UNITS) ORGANIC COMPOUND EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a]
(Source Classification Codes)

(EMISSION FACTOR RATING: E)[b]

Compounds	WOOD STOVE TYPE			
	Conventional (SCC 2104008051)		Catalytic (SCC 2104008030)	
	lb/ton	g/kg	lb/ton	g/kg
Ethane	1.470	0.735	1.376	0.688
Ethylene	4.490	2.245	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
O-Xylene	0.202	0.101	0.186	0.093

[a]Reference 17. Units are in lbs. of pollutant/ton of dry wood burned and grams of pollutant/kg of dry wood burned.
[b]Data show a high degree of variability within the source population. Factors may not be accurate for individual sources.
[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]
(Source Classification Codes)

(EMISSION FACTOR RATING: E)[b]

Pollutant	STOVE TYPE			
	Conventional[c] (SCC 2104008051)	Noncatalytic[d] (SCC 2104008050)	Catalytic[e] (SCC 2104008030)	Exempt Pellet[f] (SCC 2104008053)
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		<0.001		
1-Methylphenanthrene		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 lbs. of pollutant/ton of dry wood burned.
[b]Data show a high degree of variability within the source population and/or came from a small number of sources. Factors may not be accurate for individual sources.
[c]Reference 17.
[d]References 15, 18 - 20.
[e]References 14 - 18.
[f]Reference 27. Exempt = Exempt from 1988 NSPS (i.e., air : fuel >35:1).

TABLE 1.10-5. (METRIC UNITS) POLYCYCLIC AROMATIC HYDROCARBON (PAH) EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a]
(Source Classification Codes)

(Emission Factor Rating: E)[b]

Pollutant	STOVE TYPE			
	Conventional[c] (SCC 2104008051)	Noncatalytic[d] (SCC 2104008050)	Catalytic[e] (SCC 2104008030)	Exempt Pellet[f] (SCC 2104008053)
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		
Phenanthrene	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 grams of pollutant/kg of dry wood burned.
[b]Data show a high degree of variability within the source population and/or came from a small number of sources. Factors may not be accurate for individual sources.
[c]Reference 17.
[d]References 15, 18 - 20.
[e]References 14 - 18.
[f]Reference 27. Exempt = Exempt from 1988 NSPS (i.e., air : fuel >35:1).

TABLE 1.10-6. (ENGLISH AND METRIC UNITS) TRACE ELEMENT EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a]
(Source Classification Codes)

(EMISSION FACTOR RATING: E)[b]

Element	WOOD STOVE TYPE					
	Conventional (SCC 2104008051)		Noncatalytic (SCC 2104008050)		Catalytic (SCC 2104008030)	
	lb/ton	g/kg	lb/ton	g/kg	lb/ton	g/kg
Cadmium (Cd)	2.2E-05	1.1E-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	1.0E-05	2.2E-06	1.0E-06

[a]References 14, 17. Units are in lbs. of pollutant/ton of dry wood burned and 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. Factors may not be accurate for individual sources.

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

Wood Heater Type	Source Classification Code	Net Efficiency (%)	Reference
Wood Stoves			
Conventional	2104008051	54	26
Noncatalytic	2104008050	68	9, 12, 26
Catalytic	2104008030	68	6, 26
Pellet Stoves[b]			
Certified	2104008053	68	11
Exempt		56	27
Masonry Heaters			
All	2104008055	58	28

[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 >35:1).

References for Section 1.10

1. Standards Of Performance For New Stationary Sources: New Residential Wood Heaters, 53 FR 5573, February 26, 1988.

2. Gay, R., and J. Shah, Technical Support Document For Residential Wood Combustion, EPA-450/4-85-012, U.S. Environmental Protection Agency, Research Triangle Park, NC, February 1986.

3. Rau, J.A., and J.J. Huntzicker, Composition And Size Distribution Of Residential Wood Smoke Aerosols, Presented at the 21st Annual Meeting of the Air and Waste Management Association, Pacific Northwest International Section, Portland, OR, November 1984.

4. Simons, C.A., et al., Whitehorse Efficient Woodheat Demonstration, The City of Whitehorse, Whitehorse, Yukon, Canada, September 1987.

5. Simons, C.A., et al., Woodstove Emission Sampling Methods Comparability Analysis And In-situ Evaluation Of New Technology Woodstoves, EPA-600/7-89-002, U.S. Environmental Protection Agency, Cincinnati, OH, January 1989.

6. Barnett, S.G., Field Performance Of Advanced Technology Woodstoves In Glens Falls, N.Y. 1988-1989., Vol. 1, New York State Energy Research and Development Authority, Albany, NY, October 1989.

7. Burnet, P.G., The Northeast Cooperative Woodstove Study, Volume 1, EPA-600/7-87-026a, U.S. Environmental Protection Agency, Cincinnati, OH, November 1987.

8. Jaasma, D.R., and M.R. Champion, Field Performance Of Woodburning Stoves In Crested Butte During The 1989-90 Heating Season, Town of Crested Butte, Crested Butte, CO, September 1990.

9. Dernbach, S., Woodstove Field Performance In Klamath Falls, OR, Wood Heating Alliance, Washington, DC, April 1990.

10. Simons, C.A., and S.K. Jones, Performance Evaluation Of The Best Existing Stove Technology (BEST) Hybrid Woodstove And Catalytic Retrofit Device, Oregon Department of Environmental Quality, Portland, OR, July 1989.

11. Barnett, S.G., and R.B. Roholt, In-home Performance Of Certified Pellet Stoves In Medford And Klamath Falls, OR, U.S. Department of Energy Report No. PS407-02, July 1990.

12. Barnett, S.G., In-Home Evaluation of Emission Characteristics of EPA-Certified High-Tech Non-Catalytic Woodstoves in Klamath Falls, OR, 1990, prepared for the Canada Center for Mineral and Energy Technology, Energy, Mines and Resources, Canada, DSS File No. 145Q, 23440-9-9230, June 1, 1990.

13. McCrillis, R.C., and R.G. Merrill, Emission 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.

References for Section 1.10 (Continued)

14. Leese, K.E., and S.M. Harkins, Effects Of Burn Rate, Wood Species, Moisture Content And Weight Of Wood Loaded On Woodstove Emissions, EPA 600/2-89-025, U.S. Environmental Protection Agency, Cincinnati, OH, May 1989.

15. Allen, J.M., and W.M. Cooke, Control Of Emissions From Residential Wood Burning By Combustion Modification, EPA-600/7-81-091, U.S. Environmental Protection Agency, Cincinnati, OH, May 1981.

16. DeAngelis, D.G., et al., Preliminary Characterization Of Emissions From Wood-fired Residential Combustion Equipment, EPA-600/7-80-040, U.S. Environmental Protection Agency, Cincinnati, OH, March 1980.

17. Burnet, P.G., et al., Effects of Appliance Type and Operating Variables on Woodstove Emissions, Vol. I., Report and Appendices 6-C, EPA-600/2-90-001a, U.S. Environmental Protection Agency, Research Triangle Park, NC, January 1990.

18. Cottone, L.E., and E. Mesner, Test Method Evaluations and Emissions Testing for Rating Wood Stoves, EPA-600/2-86-100, U.S. Environmental Protection Agency, Research Triangle Park, NC, October 1986.

19. Residential Wood Heater Test Report, Phase II Testing, Vol. 1, TVA, Division of Energy, Construction and Rates, Chattanooga, TN, August 1983.

20. Truesdale, R.S. and J.G. Cleland, Residential Stove Emissions from Coal and Other Alternative Fuels Combustion, in papers at the Specialty Conference on Residential Wood and Coal Combustion, Louisville, KY, March 1982.

21. Barnett, S.G., In-Home Evaluation of Emissions From Masonry Fireplaces and Heaters, OMNI Environmental Services, Inc., Beaverton, OR, September 1991.

22. Barnett, S.G., In-Home Evaluation of Emissions From a Grundofen Masonry Heater, OMNI Environmental Services, Inc., Beaverton, OR, January 1992.

23. Barnett, S.G., In-Home Evaluation of Emissions From a Tulikivi KTU 2100 Masonry Heater, OMNI Environmental Services, Inc., Beaverton, OR, March 1992.

24. Barnett, S.G., In-Home Evaluation of Emissions From a Royal Crown 2000 Masonry Heater, OMNI Environmental Services, Inc., Beaverton, OR, March 1992.

25. Barnett, S.G., In-Home Evaluation of Emissions From a Biofire 4x3 Masonry Heater, OMNI Environmental Services, Inc., Beaverton, OR, March 1992.

26. Barnett, S.G. and R.D. Bighouse, In-Home Demonstrations of the Reduction of Woodstove Emissions from the use of Densified Logs, Oregon Department of Energy and U.S. Environmental Protection Agency, July 1992.

27. Barnett, S.G. and P.G. Fields, In-Home Performance of Exempt Pellet Stoves in Medford, Oregon, U. S. Department of Energy, Oregon Department of Energy, Tennessee Valley Authority, and Oregon Department of Environmental Quality, July 1991.

28. Barnett, S.G., Summary Report of the In-Home Emissions and Efficiency Performance of Five Commercially Available Masonry Heaters, the Masonry Heater Association, May 1992.

29. Emission Factor Documentation for AP-42 Section 1.10, Residential Wood Stoves, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC, April 1993.

APPENDIX A

SAMPLE CALCULATIONS AND EPA METHOD 5G CORRELATION EQUATIONS

SAMPLE CALCULATIONS

GIVEN:

Particulate sampling using AWES and VPI units

$$Emission\ Rate = 9.8\ \frac{g}{hr}$$

$$Burn\ Rate = 1.47\ \frac{kg}{hr}$$

FIND:

Equivalent M5H Emission Factor (g/kg, lb/ton)

SOLUTION:

AWES: Convert g/hr to M5G equivalent

$$M5G = 0.8635(9.8)^{0.9288} = 7.2\ g/hr$$

$$M5H = 1.619(7.2)^{0.905} = 9.7\ g/hr$$

Calculate g/kg

$$\frac{9.7\ g/hr}{1.47\ kg/hr} = 6.6\ g/kg = 13.1\ lb/ton$$

VPI: Convert g/hr to M5G equivalent

$$M5G = 0.6748(9.8)^{1.007} = 6.7\ g/hr$$

Convert M5G to M5H

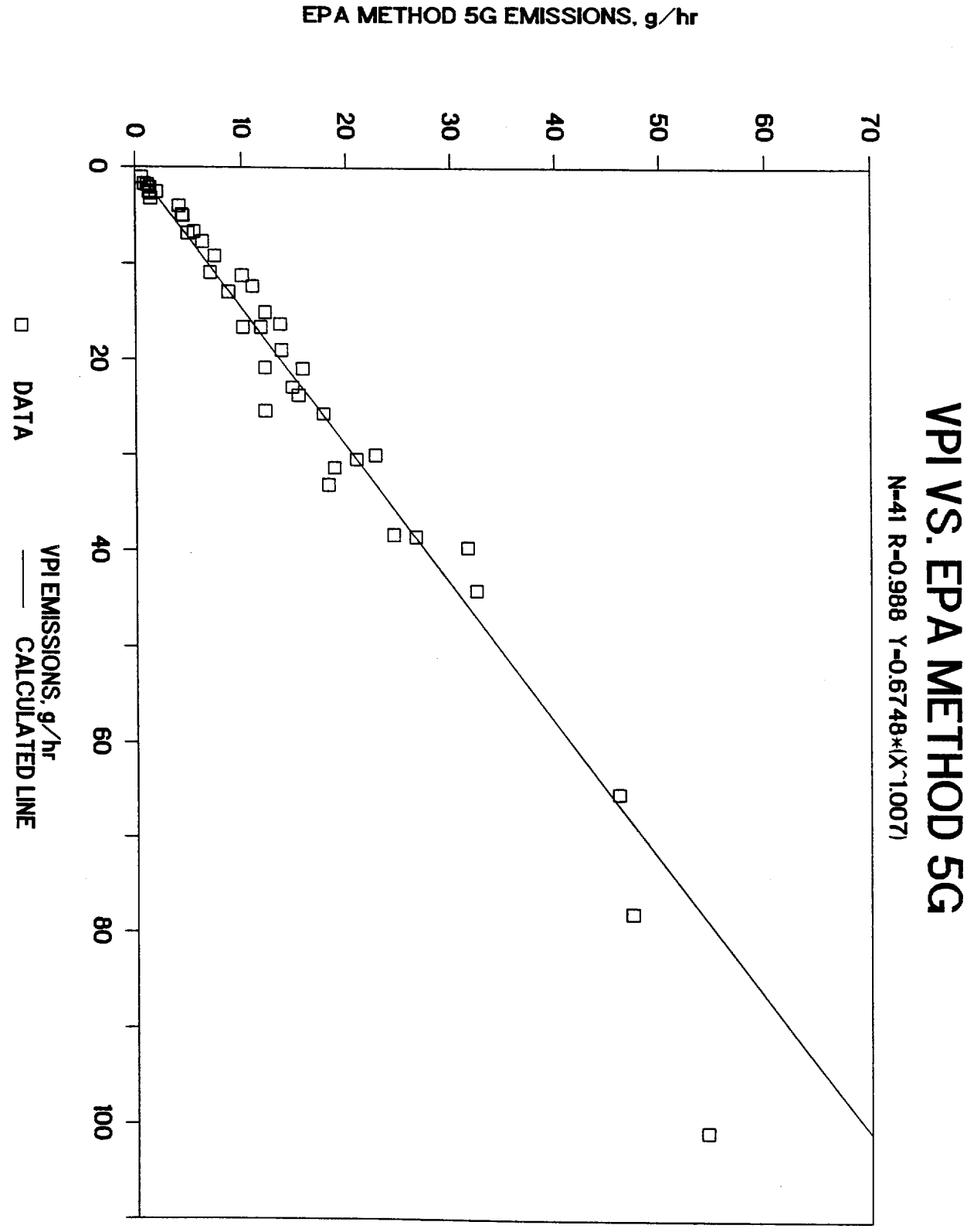
$$M5H = 1.619(6.7)^{0.905} = 9.1\ g/hr$$

Calculate g/kg

$$\frac{9.1\ g/hr}{1.47\ kg/hr} = 6.2\ g/kg = 12.4\ lb/ton$$

APPENDIX B

MARKED-UP PREVIOUS AP-42 SECTION 1.10


VPI VS. EPA METHOD 5G
N=41 R=0.988 Y=0.6748*(X^1.007)
EPA METHOD 5G EMISSIONS, g/hr
VPI EMISSIONS, g/hr
DATA
CALCULATED LINE
0
10
20
30
40
50
60
70
0
20
40
60
80
100

VPI ==========

Reference:

G.E. Weant, "Emissions Factor Document for AP-42: Section 1.10, Residential Wood Stoves", Engineering-Science, December 1991 Prepared for U.S. EPA, OAQPS, RTP, NC 27711

Revised: 9/10/92 per:

D.R. Jaasma, et.al, "Woodstove Smoke and CO Emissions: Comparison of Reverence Methods with the VPI Sampler", in Proceedings, 83rd Annual AWMA Meeting, Paper 90-80.5, June 1990.

5G	LN 5G	VPI	LN VPI
0.6	-0.51919387	1.0	0.00000000
0.9	-0.13926207	1.8	0.55961579
1.1	0.12663265	1.8	0.58778666
1.3	0.24686008	2.5	0.91629073
1.4	0.31481074	2.7	0.99325177
1.4	0.32570014	2.1	0.74193734
1.4	0.36464311	3.2	1.16315081
2.0	0.66782937	2.6	0.93609336
4.1	1.41098697	4.0	1.38629436
4.4	1.47017585	4.9	1.58923521
4.5	1.50407740	5.0	1.60943791
4.9	1.58923521	6.8	1.91692261
5.5	1.70656462	6.7	1.90210753
6.3	1.84054963	7.7	2.04122033
7.1	1.95302762	10.9	2.38876279
7.5	2.01356880	9.2	2.21920348
8.8	2.17304572	12.9	2.55722731
10.1	2.30757263	11.2	2.41591378
10.1	2.31648800	16.6	2.80940270
11.1	2.40694511	12.3	2.50959926
11.9	2.47401421	16.6	2.80940270
12.2	2.50389195	20.8	3.03495299
12.3	2.50715726	25.4	3.23474917
12.3	2.50959926	15.0	2.70805020
13.7	2.61958322	16.3	2.78809291
13.8	2.62756295	19.0	2.94180393
14.9	2.69799987	22.9	3.13113691
15.5	2.73760900	23.8	3.16758253
15.8	2.76190687	20.9	3.03974916
17.8	2.87919846	25.7	3.24649099
18.3	2.90690106	33.1	3.49953328
18.8	2.93598227	31.3	3.44361810
21.0	3.04309284	30.4	3.41444261
22.8	3.12478490	30.0	3.40119738
24.5	3.19867312	38.3	3.64544990
26.6	3.28241385	38.5	3.65065824
31.6	3.45189050	39.6	3.67882912
32.5	3.48000856	44.1	3.78645978
46.1	3.83081295	65.3	4.17899204
47.4	3.85862223	77.9	4.35542595
54.6	3.99911771	100.7	4.61214580

Regression Output:

Constant	-0.3934
Std Err of Y Est	0.1947
R Squared	0.9730
No. of Observations	41
Degrees of Freedom	39
X Coefficient(s)	1.0067
Std Err of Coef.	0.0268
R	0.986417

5G = C * (VPI) ^A

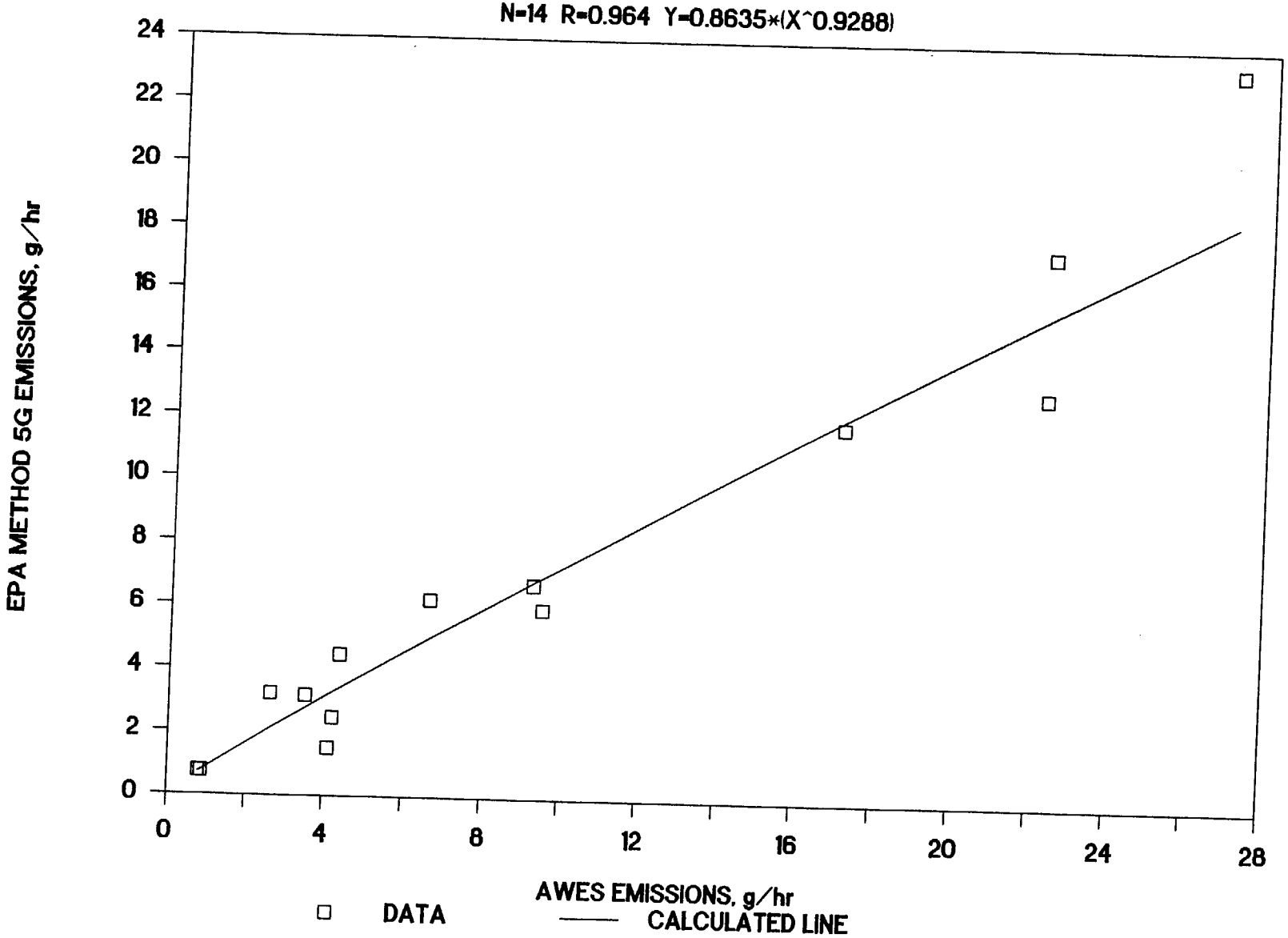
C = exp(Constant)= 0.6748

A = X Coefficient= 1.007

5G = 0.6748*(VPI)^1.007

AWES VS. EPA METHOD 5G

N=14 R=0.964 Y=0.8635*(X^0.9288)



September 3, 1992

AWES ==========

Reference S.G. Barnett, "Relationship of the AWES to EPA Methods 5H and 5G
OMNI Environmental Services, December 15, 1991
Prepared for R.C. McCrillis, U.S. EPA, AEERL, RTP, NC 27711

5G	LN 5G	AWES	LN AWES
23.3	3.148453360	27.1	3.2995337279
3.15	1.147402452	3.5	1.2527629685
1.5	0.405465108	4.1	1.4109869737
2.47	0.904218150	4.2	1.4350845253
0.74	-0.30110509	0.87	-0.139262067
0.74	-0.30110509	0.8	-0.223143551
12.9	2.557227311	22.3	3.1045866785
17.4	2.856470206	22.4	3.1090609589
6.73	1.906575143	9.25	2.2246235515
11.82	2.469793012	17.13	2.8408313123
3.21	1.166270937	2.6	0.955511445
5.95	1.783391219	9.5	2.2512917986
6.2	1.824549292	6.61	1.8885836539
4.43	1.488399584	4.35	1.4701758451

Regression Output:

Constant		-0.146718836
Std Err of Y Est		0.3029377109
R Squared		0.9277539421
No. of Observations		14
Degrees of Freedom		12
X Coefficient(s)	0.928837	
Std Err of Coef.	0.074823	
R	0.963199	

==========

5G = C * (AWES) ^A
C = exp(Constant)= 0.8635
A = X Coefficient= 0.9288
5G = 0.8635*(AWES)^0.9288

1.10 RESIDENTIAL WOOD STOVES

1.10.1 General[1-3]

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

Because of differences in both the magnitude and the composition of wood stove emissions, four different categories of stove should be considered when estimating emissions:

- the conventional wood stove,
- the noncatalytic wood stove,
- the pellet stove, and
- the catalytic wood stove.

add masonry Heaters

Among these categories, there are many variations in wood stove 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 that do have emission reducing technology or features, such as baffles and secondary combustion chambers.

Pellet stoves are those fueled with pellets of sawdust, wood products, and other biomass materials pressed into manageable shapes and sizes. These stoves have a specially designed or modified grate to accommodate this type of fuel.

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 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 sustaining.

Add masonry Heaters

1.10.2 Emissions

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 the stages of the combustion cycle. During initial burning stages, after a new wood charge is introduced, emissions increase dramatically and are primarily VOCs. After the initial period of high burn rate, there is a charcoal stage of the burn cycle, characterized by a slower burn 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.[1] 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-10). The particulate emission values shown in Table 1.10-1 for the Phase II stoves are estimates of emissions produced by wood heaters expected to be available over the next few years as cleaner, more reliable wood stoves are manufactured to meet the New Source Performance Standards.[1] The emission values in Table 1.10-1 are derived entirely from field test data on the best available wood stoves in actual operating conditions. Still, there is a potential for higher emissions from some wood stove models.

The emission factors in Table 1.10-1 are presented by stove type. Particulate and carbon monoxide 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 Pre-Phase I stoves do not meet any of the EPA standards but in most cases do meet the Oregon 1986 certification standards.[1]

Wood stove control devices may lose efficiency over a period of operation. Control degradation for any stoves, 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 from such control degradation has not been quantified.

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 are formed by oxidation of sulfur in the wood. Nitrogen oxides 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 carbon monoxide 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 (C1 - 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 contains some potentially carcinogenic compounds, such as benzo(a)pyrene.

Table 1.10-1 EMISSION FACTORS FOR COMBUSTION IN RESIDENTIAL WOOD STOVES

Stove Type	Particulate ≤10μm[a,b,c]				Carbon Monoxide[a,b]				Volatile Organics[d]				
	All Stoves	Pre-Phase I	Phase I	Phase II	All Stoves	Pre-Phase I	Phase I	Phase II	Nitrogen oxides[b]	Sulfur oxides[b]	Nonmethane	Methane	Efficiency[e] %
Conventional	14.9 (29.8)	14.9 (29.8)	-	-	115.4 (230.8)	115.4 230.8	-	-	1.4 (2.8)[f]	0.2 (0.4)	14.0 (28.0)	32.0 (64.0)	52
Noncatalytic	9.3 (18.6)	12.3 (24.6)	9.5 (19.0)	7.0 (14.0)	70.4 (140.8)	-	-	70.4 (140.8)	-	0.2 (0.4)	-	-	63
Pellet	1.9 (3.8)	-	-	1.9 (3.8)	19.7 (39.4)	-	-	19.7 (39.4)	6.9 (13.8)[g]	0.2 (0.4)	-	-	78
Catalytic	9.7 (19.4)	11.6 (23.2)	9.4 (18.8)	7.7 (15.4)	52.4 (104.8)	-	52.2 (104.4)	53.5 (107.0)	1.0 (2.0)	0.2 (0.4)	8.6 (17.2)	13.0 (26.0)	72

[a]Units are g/kg (lb/ton) of dry wood burned. Pre-phase I stoves are those not certified to 1990 EPA emission standards. Phase I stoves are those certified to 1988 EPA standards, Phase II stoves certified to 1990 EPA emission standards. Dash = no data.

[b]References 5 - 12. Emission Factor Rating for particulate, CO, and SO_x: B; for NO_x: E.

[c]Reference 1. Defined as equivalent to total catch by EPA Method 5H train.

[d]References 13 - 14. Emission Factor Rating: E. Calculated by adding the estimated mass of simple hydrocarbon material C1-C7 data to total chromatographic organics.

[e]Reference 1. The product of combustion and heat transfer efficiencies. Values are averages of laboratory test results.

[f]References 15 - 16. Emission Factor Rating: C.

[g]Reference 13. Based on a single data point.

Redo: Separate tables for Criteria/Noncriteria gaseous; Organics; Toxics/HAPs

Recalc PM_{10} emissions w/ new correlation equations

Add category for exempt pellet & N. heaters

Emission factors and their ratings for wood combustion in residential wood stoves are presented in Table 1.10-1.

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 and carbon monoxide emissions data used to develop the factors in Table 1.10-1 are all from data collected during field testing programs, and they are presented as values equivalent to that collected with Method 5H.[8] Conversions are employed, as appropriate, for data collected with other methods. See Reference 2 for detailed discussions of EPA Methods 5H and 28. Emission factors in Table 1.10-1 for other pollutants have been developed from data collected during laboratory testing programs.

References for Section 1.10

1. Standards Of Performance For New Stationary Sources: New Residential Wood Heaters, 53 FR 5860, February 26, 1988.

2. G. E. Weant, Emission Factor Documentation For AP-42 Section 1.10: Residential Wood Stoves, EPA-450/4-89-007, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1989.

3. R. Gay and J. Shah, Technical Support Document For Residential Wood Combustion, EPA-450/4-85-012, U. S. Environmental Protection Agency, Research Triangle Park, NC, February 1986.

4. J. A. Rau and J. J. Huntzicker, "Composition And Size Distribution Of Residential Wood Smoke Aerosols", Presented at the 21st Annual Meeting of the Air and Waste Management Association, Pacific Northwest International Section, Portland, OR, November 1984.

5. C. A. Simons, et al., Whitehorse Efficient Woodheat Demonstration, The City of Whitehorse, Whitehorse, Yukon, Canada, September 1987.

6. C. A. Simons, et al., Woodstove Emission Sampling Methods Comparability Analysis And In-situ Evaluation Of New Technology Woodstoves, EPA-600/7-89-002, U. S. Environmental Protection Agency, Cincinnati, OH, January 1989.

7. S. G. Barnett, Field Performance Of Advanced Technology Woodstoves In Glens Falls, N.Y. 1988-1989., Vol. 1, New York State Energy Research And Development Authority, Albany, NY, October 1989.

8. P. G. Barnett, The Northeast Cooperative Woodstove Study, Volume 1, EPA-600/7-87-026a, U. S. Environmental Protection Agency, Cincinnati, OH, November 1978.

9. D. R. Jaasma and M. R. Champion, Field Performance Of Woodburning Stoves In Crested Butte During The 1989-90 Heating Season, Town of Crested Butte, Crested Butte, CO, September 1990.

10. S. Dernbach, Woodstove Field Performance In Klamath Falls, OR, Wood Heating Alliance, Washington, DC, April 1990.

11. C. A. Simons and S. K. Jones, Performance Evaluation Of The Best Existing Stove Technology (BEST) Hybrid Woodstove And Catalytic Retrofit Device, Oregon Department Of Environmental Quality, Portland, OR, July 1989.

12. S. G. Barnett and R. B. Roholt, In-home Performance Of Certified Pellet Stoves In Medford And Klamath Falls, OR, U. S. Department Of Energy Report No. PS407-02, July 1990.

13. R. C. McCrillis and R. G. Merrill, "Emission 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.

14. K. E. Leese and S. M. Harkins, Effects Of Burn Rate, Wood Species, Moisture Content And Weight Of Wood Loaded On Woodstove Emissions, EPA 600/2-89-025, U. S. Environmental Protection Agency, Cincinnati, OH, May 1989.

15. J. M. Allen and W. M. Cooke, Control Of Emissions From Residential Wood Burning By Combustion Modification, EPA-600/7-81-091, U. S. Environmental Protection Agency, Cincinnati, OH, May 1981.

16. D. G. Deangelis, et al., Preliminary Characterization Of Emissions From Wood-fired Residential Combustion Equipment, EPA-600/7-80-040, U. S. Environmental Protection Agency, Cincinnati, OH, March 1980.