WOODSTOVE EMISSION MEASUREMENT METHODS: COMPARISON AND EMISSION FACTORS UPDATE

ROBERT C. MCCRILLIS
U.S. Environmental Protection Agency, Air and Energy Engineering Research Laboratory, Research Triangle Park, North Carolina 27711, U.S.A.

and

DENNIS R. JAASMA
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, U.S.A.

Abstract. On February 26, 1988, the U.S. Environmental Protection Agency promulgated Standards of Performance for residential wood heaters, or woodstoves. Over the past several years, a number of field studies have been undertaken to determine the actual level of emission reduction achieved by new technology woodstoves in everyday use. These studies have required the development and use of particulate and gaseous emission sampling equipment compatible with operation in private houses. Since woodstoves are tested for certification in the laboratory using EPA Methods 5G and 5H, it is of substantial interest to determine the correlation between these regulatory methods and the in–house equipment. Two in–house sampling systems have been used most widely. One is an intermittent, pump–driven particulate sampler which collects particulate and condensable organics on a filter and organic adsorbent resin. Oxygen concentration is measured by a sensor in the sample line. The sampler is controlled by a data logger which also records other parameters of interest. The second system uses an evacuated cylinder as the motive force. Particulate and condensable organics are collected in a condenser and dual filter. The sampler operates continuously whenever the stack temperature is above the set point. Average stack gas concentrations are measured from the evacuated cylinder at the conclusion of the sampling period. Both samplers were designed to operate unattended for 1–week periods. A large number of tests have been run comparing Methods 5G and 5H to both of the field samplers. This paper presents these comparison data and determines the relationships between laboratory certification sampling methods and field samplers.

1. Introduction

Use of wood as a residential house heating fuel in the U.S. has been estimated to contribute up to 90% of the polynuclear organic material (POM) attributable to stationary sources and 50% from all sources [1]. POM is known to include numerous carcinogenic compounds. In localities were wood is the predominant house heating fuel, woodstoves have been shown to contribute as much as 80% of the ambient PM_{10} concentration during winter months.

The U.S. Environmental Protection Agency (EPA) initiated development of regulations for new woodstoves in April 1985 [2]. The final rule was promulgated on February 26, 1988 [3]. New stoves manufactured after July 1, 1988, were subject to the Phase I particulate emission limits. Stoves manufactured after July 1, 1990, are subject to the more stringent Phase II particulate emission limits. Prototypes of each model stove must pass an emission test performed in a laboratory for that model line to be certified for manufacture and sale.

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With new technology woodstoves mandated by regulations, there was interest in determining the performance of these stoves in actual domestic use. Several field studies have been undertaken in North America since 1985 to establish the emission rates of typical, uncontrolled conventional technology stoves and the degree of emission control achieved by newer stoves designed to reduce emissions. This paper summarizes all of the data from these studies, reviews data comparing field emission values to laboratory certification methods, and presents recommended emission factors for PM_{10} and carbon monoxide (CO) emissions based on the field data.

2. Discussion

2.1. Field Studies

The current woodstove emission factors in AP–42 [4] are based on field study data generated through 1988. Since then, several additional field studies have been completed, bringing the total to 10. Each of these studies is described briefly below. Complete details of each study are available in the references cited. Individual house emission and burnrate averages were calculated for each study. The overall average for each technology type presented at the end of this paper is the average of the house averages across all studies. For the catalytic and low emission noncatalytic technologies, four averages are calculated for each technology: average of all stoves, average for all stoves not EPA certified, average for the models certified to the EPA 1988 (Phase I) standard, and average for the models certified to the EPA 1990 (Phase II) standard.

2.1.1. NCWS I

The first major field study of woodstoves in normal consumer use in North America was a 2–year study in 66 houses in Waterbury, Vermont, and Glens Falls, New York, over the 1985–86 and 1986–87 heating seasons [5]. This study is formally known as the Northeast Cooperative Woodstove Study (NCWS) Phase I but is often referred to as the CONEG (Coalition of Northeastern Governors) study after one of the sponsors. Stove performance was closely monitored in 44 of these houses, which included 17 with catalytic models, 11 with noncatalytic low emission models, 10 with add–on or retrofit devices, and 6 with conventional stoves. Of the new technology stoves, there were in general four houses with each model. Another group of 20 houses switched stoves between seasons; in this group only creosote deposition and wood use were measured. Sponsors of this study included the New York State Energy Research and Development Authority (NYSERDA), the CONEG Policy Research Centre, Inc., and the EPA. Particulate emission samples were collected using the automated woodstove emission sampler (AWES) [6].

2.1.2. Whitehorse

During the winter of 1986–87, two additional 1-year field studies were undertaken. One of these, the Whitehorse Efficient Woodheat Demonstration, was named after the city in which the test took place, Whitehorse, Yukon, Canada [7]. Funding was provided by the City of Whitehorse and by Energy, Mines and Resources, Canada. This study evaluated new technology stoves in 14 houses over one heating season. Each participant's conventional stove was tested for three 1-week periods during December 1986 and early January 1987. Their new technology stove was then installed and, after 2–3 weeks to get used to the new appliance, tested for five 1-week periods. Sampling equipment and methodology closely paralleled that followed in the NCWS Phase I work.

2.1.3. Northwest

The other field study undertaken during the winter of 1986–87 was in the Portland, Oregon, area and consisted of six houses, one each with two different model catalytic, low emission noncatalytic, and conventional technology stoves [8]. The four new technology models were certified to the EPA 1988 standard. Sampling equipment and methodologies were essentially the same as those used in NCWS Phase I.

2.1.4. NCWS II

During the year following publication of the NCWS I final report [5], a number of tasks were completed to better understand the results to date and to prepare for another round of field testing. Two tasks, inspection of stoves in the NCWS I and laboratory testing of catalysts, showed that the relatively poor field performance of the catalytic stoves could be attributed, in part, to degradation of stove components such as bypass dampers and catalysts. For both catalytic and noncatalytic low emission technologies, the flue system seemed to exert a significant impact. Uninsulated chimneys on an outside wall led to higher emissions. There was also some indication that user operating practices may have contributed. In preparation for the next round of field testing (NCWS III), a list of desirable design criteria was developed and used to make the initial stove selections. A stress test was also developed and used to help make final stove selections [9].

2.1.5. NCWS III

The second round of field tests in the NCWS took place during the winter of 1988–89 [9]. Three catalytic and two low emission noncatalytic model stoves were tested in 25 houses in Glens Falls, New York. Each model stove was tested in five houses. All five stove models were EPA certified to the 1988 standards and were judged capable of meeting the EPA 1990 standards. Samples were collected and analyzed following procedures similar to those used in NCWS Phase I. A sensor was added to the bypass handles on the catalytic stoves to record the time of bypass activation and the interval between activations. Stove selection involved an evaluation of their

potential for degradation and a stress test to further test durability. House selection factors emphasized those factors which would lead to good stove performance; in all cases, flues in the participants' houses were upgraded for the study. Sampling equipment and methodology were updated but not substantively changed from the earlier NCWS work.

2.1.6. Crested Butte I and II

The Crested Butte I study took place in Crested Butte, Colorado, during the winter of 1988–89 [10]. Involving 13 houses, the study focused on the emissions from 11 conventional stoves during the winter before 'the big changeout' to certified stoves. Two catalytic stoves were also tested. Source samples were obtained with a sampler developed by Virginia Polytechnic Institute and State University (VPI) which uses an evacuated tank in place of a pump to draw sample from the stack. The sampler operates continuously whenever the stack temperature is above the set point. Crested Butte II [11] was conducted the following winter (1989–90) using the same equipment. The Phase II study included 25 houses: 7 had conventional stoves, 11 had catalytic stoves, 5 had low emission noncatalytic stoves, and 2 had coal stoves. In addition, samples were taken in the stack of a coal-fired commercial boiler.

2.1.7. K. Falls/CCRL

The Canadian Combustion Research Laboratory (CCRL) sponsored a study during the winter of 1989–90 in Klamath Falls, Oregon, of a Canadian-manufactured low emission noncatalytic stove in three houses [12]. All emission samples were obtained with the AWES system.

2.1.8. K. Falls/WHA

The Wood Heating Alliance (WHA) also sponsored a field study during the winter of 1989–90 in Klamath Falls, Oregon [13]. This study involved six houses: three had conventional stoves, three had catalytic stoves, and three had low emission noncatalytic stoves. Three of the conventional stove houses were changed to clean burning stoves during the study. Particulate emission samples were obtained with the AWES system. The six clean burning stoves were certified to EPA's 1990 (Phase II) standard.

2.1.9. BEST Stove/Retrofit

During the winter of 1988–89, the Oregon Department of Environmental Quality (ODEQ) sponsored a program to develop and field test a stove incorporating all the desirable features of a low emission noncatalytic stove *and* a properly sized catalyst and bypass damper. The theory was that the stove would be operated as a catalytic stove but, in the event of a failure in the catalyst system such as a leaky bypass damper, the noncatalytic features would serve as a backup control measure. This hybrid design came to be known as the BEST stove, for best existing stove

technology, ODEQ also designed and built an improved catalyst add-on device. Three BEST stoves and three add-on devices were tested during the 1988–89 winter [14]. The three BEST stoves were tested again during the next winter (1989–90) [15]. Since these devices are prototypes and are not available commercially, their emission results are not included in the average emission factors discussed later in this paper. All emission sampling was performed using the AWES system.

2.1.10. Pellet

The Department of Energy, through the Northwest Regional Biomass Program administered by Bonneville Power Authority, funded a field study of certified pellet stoves during the winter of 1989–90 [16]. Two stove models were evaluated in six houses. The AWES system was used to collect particulate emission samples. Because emission levels were expected to be low, the AWES sampling cycle was set for 1 minute on, 14 minutes off. Otherwise, the system was set up and operated as before. This study continued during the winter of 1990–91, with EPA cosponsorship, evaluating exempt pellet stoves in the same communities.

2.2. Method Correlation

The 10 field studies described above, with a total of 137 house/stove combinations tested, constitute the available data base. Particulate emissions during these studies have been measured by one of two methods, the AWES system and the evacuated tank sampler (VPI). Emission factors presented in AP–42 [4], however, are as measured by EPA Method 5H. Therefore, the field data must be converted to 5H equivalent values before comparing to current published factors. The CO samples were collected in an evacuated tank or bag with the average concentration measured at the end of the sample period and therefore need no additional conversion. Several studies, discussed in the following paragraphs, have been undertaken to develop the correlations between EPA methods and the field sampling systems.

2.2.1. AWES to EPA Method 5G

The AWES system has been used in the majority of the field studies. There are three data subsets comparing AWES to EPA Method 5G and/or 5H. The first consists of six regulatory type burns, three on an Earth Stove Model 1000C stove and three on a Fisher Tech IV insert. Duplicate Oregon Method 7 (OM7) [17] sampling trains were run in the dilution tunnel, and a single AWES sampler in the stack. (OM7 was subsequently adopted with minor modification by EPA as Method 5H.) Each burn lasted several hours. The AWES sampler was set up to sample on a 1 minute on, 4 minutes off cycle. These data are reported in the final report for NCWS [5]. The EPA Method 5H sampling train consists of a heated sample probe, heated line, and heated filter, followed by four impingers with an unheated filter located between impingers 3 and 4, with appropriate pumps and volume measurement devices. The particulate matter caught in the full train is recovered and weighed. Normally, the

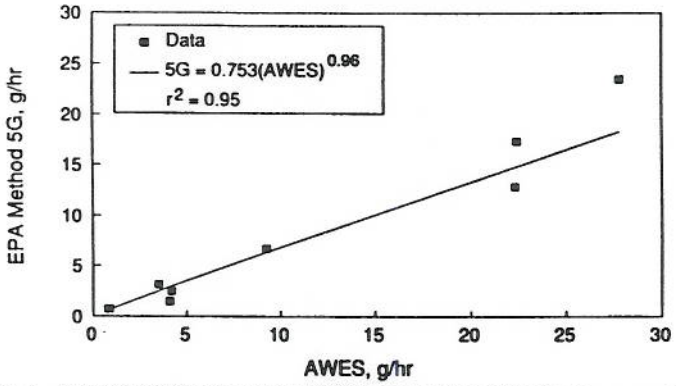

Fig. 1. EPA Method 5G compared to AWES sampler data with least squares curve fit.

5H train is used to collect a sample from the stack, although it can also be used to collect a sample from the dilution tunnel.

The second data subset, taken as part of the Northwest Project [8], consisted of a series of three 1-week simulated in-house tests in the laboratory and one 1-week test in the field comparing EPA Methods 5G and 5H to the AWES system. One laboratory test used a popular conventional stove operated as one might in western Oregon, burning Douglas fir. Two laboratory tests used a catalytic stove certified to EPA Phase I; during one test it was operated on a western Oregon cycle with Douglas fir. During the other test, eastern hardwood was burned on a northeastern U.S. cycle as determined from the NCWS I data. EPA Method 5H trains were run in the stack and Method 5H in the dilution tunnel. During the in-house tests, only Method 5G was run in the dilution tunnel.

The third data subset is derived from the ongoing effort to develop a method for establishing a stove's durability. In the course of this project, periodic emission measurements are made to determine whether or not any emission control degradation has occurred. Each emission measurement is made over a 24-hour simulated consumer cycle burning cordwood. Emissions are measured by EPA Method 5G and, simultaneously, by the AWES. To date, this project has yielded five simultaneous EPA Method 5G – AWES data points.

After reviewing these three data subsets, it was decided that the AWES – 5G correlation would be used to convert the AWES data to Method 5G. The 5G values thus derived would then be converted to 5H using the 5G to 5H equation discussed later in this paper. The results of this test series are shown in Figure 1, with the best fit line used for converting AWES to 5G. The equation for this line,

$$\text{Method 5G} = 0.753\ (\text{AWES})^{0.96} \tag{1}$$

is very nearly a straight line with a slope of 0.753 and a correlation coefficient $r^2 = 0.95$ indicating that this is a strong correlation. Equation (1) was used to

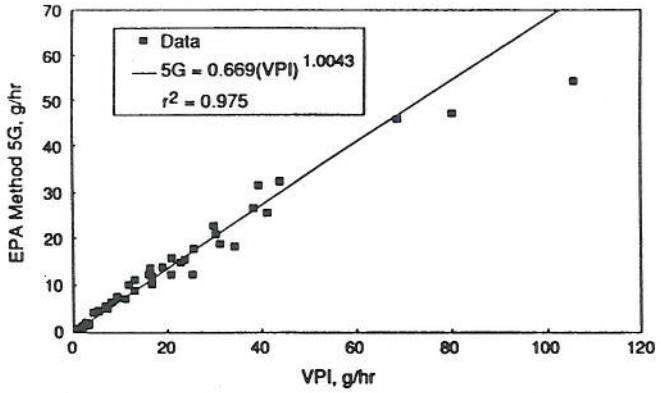

Fig. 2. EPA Method 5G compared to the VPI sampler showing data with the least squares curve fit.

convert each house average to 5G in the studies using the AWES system.

2.2.2. VPI to EPA Method 5G

Jaasma, Champion, and Shelton [18] performed a series of fifteen 1-day emission tests comparing the VPI evacuated tank sampler to EPA Method 5G. Eight of these tests were performed in Blacksburg, Virginia, and seven in Santa Fe, New Mexico. Under EPA contract, Engineering-Science completed sixteen 1-day emission tests at their Research Triangle Park, North Carolina, facility and twelve 1-week emission tests at a rented facility in Crested Butte, Colorado [19]. This data set, shown in Figure 2, yields a correlation of

$$\text{Method 5G} = 0.669\ (\text{VPI})^{1.0043} \tag{2}$$

a very nearly straight line with a slope of 0.669 and a correlation coefficient $r^2 = 0.975$, indicating a strong correlation. Equation (2) was used to convert all particulate emission values generated with the VPI system to the equivalent Method 5G value. The EPA Method 5G sampling train consists of an unheated probe, unheated sample line, and unheated back-to-back filters with appropriate pumps and volume measurement devices. The particulate matter caught in the probe, sample line, and filters is recovered and weighed. The 5G train is used to collect a sample from the dilution tunnel but not from the stack. The 5G values must be converted to 5H for final analysis.

2.2.3. EPA Methods 5G to 5H

Included in the woodheater NSPS promulgation [3] was the equation

$$\text{Method 5H} = 1.82\ (5\text{G})^{0.83} \tag{3}$$

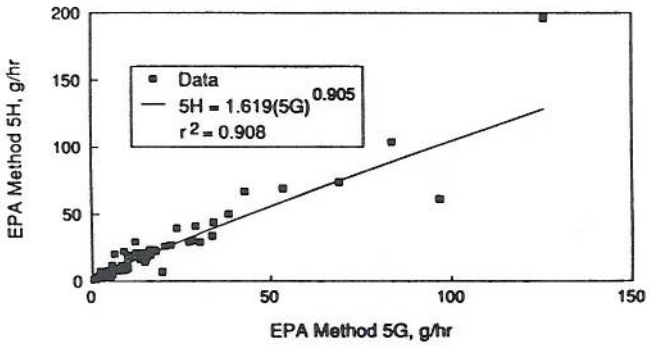

Fig. 3. EPA Methods 5H and 5G full range data compared.

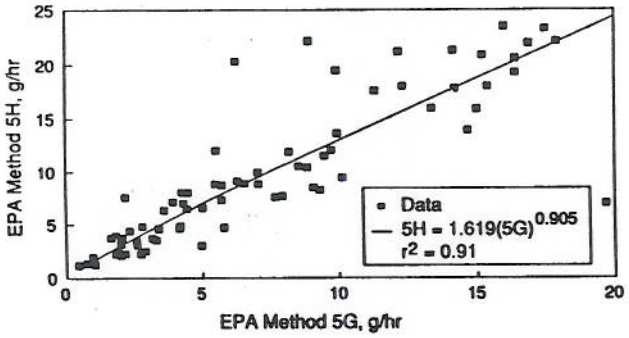

Fig. 4. EPA Methods 5H and 5G low range data compared.

for converting from 5G to 5H. Equation (3) fits the data at the low emission end of the spectrum quite well but is unsatisfactory at values of 5G > 6 g/hr. A new least squares fit to the available data was run, yielding the equation

$$\text{Method 5H} = 1.619\ (5G)^{0.905} \tag{4}$$

which, as shown in Figures 3 and 4, does a very adequate job of fitting the entire range of data. This correlation is based on 92 data points, some of which have been published previously [20]. The correlation coefficient is $r^2 = 0.908$, indicating some scatter to the data. Equation (4) was used to convert all Method 5G particulate emission values to their equivalent Method 5H values.

2.3. Emission Rates

In the preceding paragraphs, all woodstove field data taken since 1985 were reviewed and average grams per hour particulate emission rates were calculated for

TABLE I
Woodstove field studies grams per hour particulate emissions summary data in Method 5H equivalent values

Study Name	Woodstove Technology			
	Conventional	Catalytic	Noncatalytic	Pellet
Northeast Phase I	16.8	14.5	10.3	
Northeast Phase III	*	7.9	9.9	
Whitehorse	18.6	11.0	12.6	
Northwest	16.6	18.6	11.9	
Crested Butte I and II	26.3	8.9	9.4	
K. Falls (CCRL)			6.1	
K. Falls (WHA)	33.0	6.3	5.1	
Pellet				1.3
Average of all stoves	22.3	10.7	9.2	1.3
Average pre-Phase I stoves	22.3	14.1	12.5	1.3
Average Phase I stoves		10.2	9.4	
Average Phase II stoves		7.6	7.3	1.3

* blank means no data were taken for that technology.

each house in each study. These grams per hour house particulate averages were then converted to the equivalent Method 5H value using the appropriate equations discussed above. Average burnrates in kilograms per hour were also calculated for each house in each study. The next step was to calculate average grams per hour emission rates and kilograms per hour burnrates for each technology type across all field studies. For the catalytic and low emission noncatalytic technologies, four averages were calculated: average of all stoves; average of stoves built prior to, and not certified to, the EPA 1988 Phase I NSPS; average of stoves certified to the EPA 1988 NSPS; and average of the stoves certified to the EPA 1990 standard. These results are shown in Tables I (particulates), II (CO), and III (burnrate). Emissions factors in other units, such as grams per kilogram, can be calculated from these tables.

3. Summary and Conclusions

Data from a number of woodstove field studies completed since 1985 have been reviewed and average particulate and CO emission rates and burnrates have been calculated for each technology type. These data were generated in the field using one of two sampling systems, the automated woodstove emission sampler (AWES) and the evacuated tank sampler (VPI). Data primarily from laboratory studies comparing these sampling systems to the regulatory methods 5G and 5H and comparing 5G to 5H have been presented and the correlations between methods have been

TABLE II
Woodstove field studies grams per hour carbon monoxide emissions summary data

Study Name	Woodstove Technology			
	Conventional	Catalytic	Noncatalytic	Pellet
Crested Butte I and II	166.8	48.7	77.0	*
Pellet				13.8
Overall average	166.8	48.7	77.0	13.8
Average Phase I stoves		49.8		
Average Phase II stoves		42.6	77.0	13.8

* blank means no data were taken for that technology.

TABLE III
Woodstove field studies dry kilograms per hour burnrate summary data

Study Name	Woodstove Technology			
	Conventional	Catalytic	Noncatalytic	Pellet
Northeast Phase I	1.65	1.18	0.97	
Northeast Phase III	*	1.08	1.02	
Whitehorse	1.46	1.36	1.06	
Northwest	1.15	1.18	0.99	
Crested Butte I and II	1.45	0.93	1.09	
K. Falls (CCRL)			0.97	
K. Falls (WHA)	1.84	1.13	1.04	
Pellet				0.70
Average of all stoves	1.49	1.10	1.01	0.70
Average pre-Phase I stoves	1.49	1.22	1.02	
Average Phase I stoves		1.08	0.99	
Average Phase II stoves		0.98	1.04	0.70

* blank means no data were taken for that technology.

determined. These correlations were used to develop the final set of particulate data shown in Table I. Comparing these data to the latest set of woodstove particulate emission factors published by EPA [4], it can be seen that there is little change for three of the four technologies. For EPA Phase II 1990 certified catalytic stoves, the average particulate emission factor calculated here is 7.8 g/kg (from Table I, 7.6 g/hr divided by 0.98 kg/hr from Table III), compared to a value of 6.6 g/kg in AP–42. The new value, representing an 18% increase, is based on a much larger data base compared to the current AP–42 value, and is, therefore, felt to be more representative of actual field performance of catalytic stoves.

With regard to the CO emission rates, the EPA 1990 certified noncatalytic

technology is the only one showing an emission factor that is significantly different from AP–42. The emission factor presented here is 57% of the current (9/90) AP–42 value. Since the CO average here was developed from a much larger data base than was available in 1988 when the AP–42 value was calculated, it is felt that the value presented here is more representative of current noncatalytic low emission stove performance.

Finally, it is interesting to compare the average burnrates across technologies. There is an apparent trend of decreasing burnrate as combustion efficiency increases. The lowest efficiency technology, conventional stoves, has the highest burnrate. Catalytic and low emission noncatalytic technologies are more efficient and are operated at a lower burnrate. Pellet stoves, the most efficient, are burned at the lowest fuel consumption rate. This correlation is reasonable, since the user is interested in net heat into the house. This conclusion was borne out in the NCWS I study which showed that, on average, the houses with catalytic and low emission noncatalytic stoves burned 20% less wood over the heating season. This efficiency effect seems to explain about 50% of the difference in burnrate in field studies. Other factors, such as stove firebox size (conventional stoves are largest, low emission noncatalytic stoves are smallest of stick burning stoves), may explain most of the remaining difference.

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