Emission Factors for New Certified Residential Wood Heaters

James E. Houck and Lyrik Y. Pitzman
OMNI Environmental Services, Inc.
13327 NE Airport Way
Portland, OR 97230
houck@omni-test.com
pitzman@omni-envirnomental.com

Paul Tiegs
OMNI-Test Laboratories, Inc.
13327 NE Airport Way
Portland, OR 97230
paultiegs@omni-test.com

Woodstove change-out programs, which entail the replacement of old uncertified wood heaters with new lower-emitting EPA certified wood heaters, have become a recognized strategy to reduce ambient particulate levels. To assess the benefit of particulate emission reductions affected by change outs, accurate emission factors for new model certified wood heaters are needed. Standards of performance (NSPS) for new residential wood heaters were promulgated February 26, 1988. The standards include test methods and procedures for particulate emission measurement. These test methods and procedures can best be described as "benchmark" and emission rates obtained from them are only loosely predictive of actual in-home emission factors. Independent of NSPS certification, the U.S. EPA has also compiled emission factors for certified woodstoves in its AP-42 document. The particulate emission factors for cordwood heaters contained in the AP-42 document have not been revised since 1991 and are based on the earliest certified models or their prototypes with most measurements made as part of studies conducted in the late 1980s. Considerable improvements have been made in certified wood heaters and in the last two decades and improvements needed in the certification process have become apparent as well. A review of recent particulate data for certified cordwood heaters with recommendations for revising emission factors and the NSPS test methods to make them more predictive of real-world emissions are provided here.

INTRODUCTION

Currently, the most credible and most widely used source to document the particulate emission reduction benefit of replacing old conventional uncertified cordwood heaters with certified cordwood heaters is the U.S. EPA's Emission Factor Documentation for AP-42: Chapter 1, Section 1.10, Residential Wood Stoves[1]. While various estimates have been made regarding particulate emission benefits, to the authors' knowledge, AP-42 is the only significant "overview" source of data available. Unfortunately, even though the AP-42 compilation obtained from a literature review presents particulate values for the various wood heater types it lacks currency. No particulate data for cordwood heaters collected more recently than 1991 are included in the compilations. As of July 1, 1992, all wood heaters sold are required to be Phase 2 certified[2,3]. (Some Phase 2 cordwood heaters were manufactured and sold before the 1992 requirement became effective and hence are included in the AP-42 compilation.) It is generally recognized in the hearth industry that the performance of Phase 2 certified cordwood heaters has improved considerably since the earliest models.

Another shortcoming of AP-42 is that it is a compilation of data from unrelated and uncoordinated studies and, as such, the values it presents are not derived from a normal distribution of data. For example, the burn rate conditions under which the particulate data were collected are skewed. It is a well known fact that particulate emission factors (mass particles/mass wood) from cordwood

heaters at lower burn rate conditions are higher than from higher burn rate conditions[4,5]. Lower burn rates are usually achieved by restricting airflow with the heater's air controls. Air restriction favors wood pyrolysis and the formation of products of incomplete combustion (PIC) rather than complete, efficient combustion conditions[6]. U.S. Census Bureau (American Housing Survey) data[7] show that most cordwood heaters are used for supplemental heat not as the major source of household heat, again suggesting that the data in AP-42 represents emissions at higher than average actual in-home burn rate conditions. Nationally, the ratio of households that characterize their use of wood heaters (freestanding stoves plus fireplace inserts) in 2005 as "other heating equipment" as compared to "main heating equipment" is about 9:1. Finally it should be noted that when determining the benefits of changing out an older conventional cordwood heater with a modern heater, not only do emission factors need to be taken into consideration but efficiencies also need to be considered. Certified cordwood heaters have higher efficiencies than pre-EPA-certified conventional cordwood heaters, therefore less wood is burned for a given heat demand producing less emissions.

For the certification of wood heaters, three key test methods support the standards of performance (NSPS) as published in the Federal Register[2] and codified in 40CFR[3]. These are Method 28[8] (which is essentially for the operation of the wood heater during testing, fuel specifications, and data treatment), and two methods (Method 5G[5] and Method 5H[10]) for particulate sampling. Due to the large number of variables associated with residential wood heaters and their operation, all common operational scenarios could not be incorporated into the testing procedures. In addition, the need for reproducibility in the certification methods necessitated divergence from some real-world operational scenarios. Finally, due to the paucity of relevant data prior to the 1988 promulgation of standards, some aspects of the testing methods do not simulate the real-world usage as well as they could based on our current understanding. The net effect of these issues is that while the NSPS for wood heaters, did and continues to, provide a commercial and regulatory expediency for the issue of air emissions from wood heaters, the emission data generated do not predict actual emission factors well and the certification methods could be refined considerably to allow for a more realistic target around which new technology wood heaters could be designed. Of considerable significance is the regionalism of wood heater usage and commensurate differences in air emissions not being addressed by the certification process. Regional differences due to climate and socio-demographic factors which include such parameter as burn rates, hot versus cold starts, wood moisture content, hardwood versus softwood fuel, the age distribution of wood heaters, and the level of reliance on wood heaters (main heat source vs. secondary heat source) can all cause differences in emission factors from region to region.

VARIABILITY IN EMISSIONS AMONG CERTIFIED WOOD HEATER MODELS

As of March 12, 2008 the total number of certified wood heater models was 705[11]. Most of these are cordwood heaters (in contrast to pellet heaters) and most are Phase 2 (in contrast to the earliest Phase 1 models and "grandfathered" Oregon models). Phase 2 certified woodstoves have an emission limit of 7.5 g/h for non-catalytic cordwood heaters and 4.1 g/h for catalytic models. The certified emission levels for the various models range by over a factor of 10, from a low of 0.6 g/h to the emission limit value of 7.5 g/h.

On average, the particulate emissions of certified cordwood heaters have decreased since the earliest models commensurate with improved design and durability. Table 1 is a comparison of the mean certified 5H emission rate (g/h) for old and newer catalytic and non-catalytic Phase 2 cordwood heaters. The average emission rates for Phase 2 certified heaters certified during the first five years of the NSPS rule and the average for newer stoves (either first certified or renewed between 2000 and 2005) were obtained from U.S. EPA records[11]. The 1988 through 1992 period was selected as it was concurrent with the Phase 2 stoves that were included in the AP-42 document for the purposes of tabulating particulate emission factors. The 2000 to 2005 period was selected as heaters certified during that time would be more representative of those installed as part of recent or current change out programs. For both Phase 2 catalytic and Phase 2 non-catalytic stoves, the percentage of reduction in

the average certification particulate emission rate from the earliest certified Phase 2 models to those that were first certified or renewed between 2000 and 2005 were calculated. The smaller reduction seen with catalytic woodstoves as compared to non-catalytic wood heaters is consistent with the level of engineering that is involved in mitigating particulate emissions with non-catalytic approaches versus the use of a catalyst. The design and engineering of a heater to produce lower particulate emissions without the use of a catalyst is complex and has evolved with experience whereas the placement of a catalyst in an exhaust stream is more straightforward and catalyst application for particulate control has not changed as much from the earlier models.

Table 1. Comparison of average certified emission rates for old and new Phase 2 cordwood heaters.

Time period	Woodstove type	Number of heaters	Average emission rate (g/h, 5H equivalent)	Percent reduction (%)
First five years of certification (1988-1992)	Non-catalytic	115	5.1	-
	Catalytic	110	2.9	-
Wood heaters certified or renewed between 2000 and 2005	Non-catalytic	137	4.1	19.6
	Catalytic	23	2.7	6.9

PARTICULATE SIZE

A large fraction of particles formed from residential wood combustion is made up of condensed organic compounds and are submicron in size[6,12]. While not correct, total PM, PM_{10}, and $PM_{2.5}$ are often used interchangeably. For example, AP-42 states, "PM-10 is defined as equivalent to total catch by EPA method 5H train." Most inventories have considered the AP-42 values as either PM_{10} or $PM_{2.5}$ and essentially equivalent to each other. Research into the size distribution of particles from a certified catalytic model showed that PM_{10} averaged about 88% of the total particulate catch and $PM_{2.5}$ averaged about 80% and research with a certified non-catalytic model showed that PM_{10} averaged about 94% and $PM_{2.5}$ about 92% of the total catch[13]. Hence while the majority of PM is $PM_{2.5}$ and PM_{10}, they are not equivalent and using PM as a surrogate for $PM_{2.5}$ or PM_{10} over predicts emission factors.

PARTICULATE SAMPLING METHODS

There have been a number of particulate sampling methods used to measure particulate emissions from cordwood heaters. They include, EPA Method 5, EPA Method 5G, EPA Method 5H, EPA Modified Method 5 (Method 23), Oregon Method 7, the VPI method, the AWES method, the ESS method, an ASTM method, the SRI dilution tunnel, the Condar sampler, the SASS method, and a variety of novel research methods. Because most residential wood combustion particles are formed by condensed organic compounds, which are trapped with different efficiencies by each particulate sampling method, the methods can produce considerably different particulate emission results. Equations have been developed to relate the data for the more common measurement techniques[14-16], but, with the exception for some specific sets of conditions, they have not shown a particularly good correlation. This lack of correlation adds uncertainty to compilations such as presented here and in AP-42. The most common method to present particulate data is in the form of 5H equivalents. The 5H method collects particles onto a heated filter, onto a backup filter and in a series of impingers immersed

in ice water. In contrast, Method 5G, the other method specified by the NSPS, is based on a dilution tunnel approach that collects particles from a cooled and diluted plume onto a filter. It is generally agreed that a dilution tunnel approach collects particles in a more realistic fashion and more closely simulates the formation of particles once emissions from chimneys mix and cool in the ambient air than a method such as Method 5H based on the old industrial stack sampling Method 5[12,17,18]. Because both vapor and particulate emissions from cordwood heaters are predominately made up of organic compounds with varying vapor pressures, lower dilution tunnel temperatures shift the partitioning between vapor and particulate phases toward the particulate phase producing a larger emission factor. While Method 5G is a dilution tunnel, its flow rate is set relatively low (140 dscf/min [4 dscm/min]) and the collection filter temperature is allowed to reach 32 º C (90 º F). Consequently, particulate emissions determined by the method would be smaller than if tunnel temperatures more closely approximated typical heating season temperatures. Conversely, Method 5H passes emissions directly through ice water which can trap and chemically transform polar vapor phase, low molecular weight carboxylic acids, alcohols, and aldehydes which would not normally form particles in the atmosphere, and therefore it is generally believe that Method 5H over predicts emission factors. (Carboxylic acids, alcohols, and aldehydes, in aggregate, typically have an emission factor in the few grams per kilogram dry wood range[19-23].) The relationship between 5H and 5G is not linear and the magnitude of values derived from 5H is greater than that from 5G (Table 2) and as previously noted it is believed that the use of 5H equivalent values published in AP-42 for use in emission inventory calculations over predicts the impact from certified stoves.

Table 2. Comparison of 5H and 5G emission rates.

5H (g/h)	Equivalent 5G (g/h) NSPS conversion*	Equivalent 5G (g/h) AP-42 conversion**
1	0.48	0.59
2	1.1	1.3
4.1 (cat. limit)	2.7	2.8
5	3.4	3.5
7	5.1	5.0
7.5 (non-cat. limit)	5.5	5.4
10	7.8	7.5
12	9.7	9.2
15	12.7	11.7
20	18.0	16.1

* $5H = (1.82) \times (5G)^{0.83}$
** $5H = (1.619) \times (5G)^{0.905}$

PARTICULATE EMISSION REPORTING CONVENTIONS

There are three common conventions for reporting emissions. These are: (1) The mass of particles per mass of dry fuel burned. – This is correctly referred to as an emission factor and is most useful for emission inventory purposes. It is the convention used in AP-42. Emission factors for particles are generally reported in units of g/kg, kg/Mg, or lb/ton. Emission factors in the units of lb/ton can be converted to the units of g/kg or kg/Mg by the simple multiplication by 0.5. (2) The mass or particles per time. – This is correctly referred to as an emission rate. The NSPS certification testing uses emission rates. A difficulty in comparing emission rate data from different sources is that there is no standard definition of when a fire is completed; therefore the same inherent particulate emissions can be represented by different emission rate values depending on the method used to define fire duration, i.e., the numerator in the mass/time value would be the same but the denominator would be different.

Emission rates are usually reported as g/h. (3) The mass of emissions per unit of energy (either available in the fuel or delivered to the home). – This convention is most useful when comparing very different fuels (e.g., natural gas versus cordwood). If it is in the terms of mass of emissions per unit of heat delivered, efficiencies need to be measured. The units of g/Mj are usually used. The various reporting convention and units have caused some confusion when comparing data from different studies.

EMISSIONS DURING START-UP

A disproportional amount of particulate emissions occur during the kindling phase (start up) before efficient combustion and particulate mitigation (secondary combustion or catalytic activity) is underway[24-26]. Because a "hot start" is used for the certification method, i.e., particulate sampling is started after a fuel charge is added to an already hot coal bed, the emission values are not representative of the common "cold start" where emissions from the start up are a significant fraction of the total emissions. This is particularly true for catalytic cordwood heaters as during the kindling phase the catalyst is physically bypassed by manually channeling combustion gases around it. Particulate emissions for catalytic heaters during the kindling phase can range from two to five times higher than from a fuel load once the fire is established[24]. This suggests that certification values for catalytic cordwood heaters are an even less accurate predictor for real-world in-home performance of a catalytic stove than for a non-catalytic stove.

Based on a 2004 Hearth, Patio and Barbecue Association survey[27] the average freestanding woodstove length of use was 5.8 hours. A second survey conducted by the Hearth, Patio and Barbecue Association in 2006 yielded an average of 4.8 hours[28]. With a national average length of use per occasion between 4.8 hours and 5.8 hours it is clear that a cold start is part of most wood heater use events. Consequently, a cold start test method is appropriate to simulate the typical in-home use of a wood heater. However, in some cold climates, particularly in rural settings where wood combustion is more likely to be the primary source of heat, hot start-up scenarios may be more common. The same 2004 Hearth, Patio and Barbecue Association survey that produced the 5.8 hour average also showed that 44% of stoves that were owned were used eight or more hours per occasion (Table 3) – these stoves are more likely not to have regular cold start-ups.

Table 3. Typical length of use of a freestanding stove per occasion.

Length of use per occasion (hours)	Percent of total freestanding stoves owned (n = 539)
Never burned	10%
1 hour or less	3%
1 to 3 hours	12%
3 to 5 hours	15%
5 to 7 hours	16%
8 or more hours	44%

BURN RATES

As with emission rates discussed previously, a difficulty with comparing burn rates from different studies is that different criteria have been used to determine when a fire is out; therefore the same fire can have different burn rates assigned to it depending on what end point criteria are used. There have been three basic ways to define when a fire is out: (1) temperature measured in the stack, (2) weight of fuel remaining or the change in the fuel weight with time, and (3) methods based on the carbon dioxide or oxygen gas concentrations in the chimney. Even among the three basic approaches different measurement methods and thresholds have been used. Further, the difference between hot

starts and cold starts complicates the comparison of burn rates between different studies or testing protocols.

In the development of certification Method 28, a weighting scheme was formulated for burn rates to be used as part of the certification process. Both burn rate categories at which the wood heater is actually operated during testing and the adjustment of values obtained from the testing based on the probability distribution of burn rates were developed. The probability distribution was from in-home measurements made by OMNI Environmental Services, Inc. in Oregon, New York, and Vermont. (See reference 3 in 40 CFR Part 60, Appendix A, Method 288.) The in-home instrumentation did not distinguish between hot and cold start scenarios and the end point of the burn rate was defined as 100º F in the chimney at 1 foot (30 cm) above the heater. These data were applied to Method 28 which, quite differently, uses a hot start test protocol with the burn rate based on the mass of fuel remaining at the completion of the sampling test run. In contrast to the 100º F (38º C) end point of the in-home studies, Method 28 tests with a non-catalytic stove at a medium high burn rate (1.6 kg/h) and at a high burn rate (3.7 kg/h) showed that at the end point defined by the Method 28 procedure, the temperatures in the chimney at these two burn rates were 418º F (214º C) and 739º F (393ºC), respectively, not 100º F (38º C). Because of these differences the burn rate categories and probability distribution presented in Method 28 are effectively skewed as compared to the data from which they were derived. In addition, the data from Oregon, New York, and Vermont were adjusted to represent a national weighting scheme, hence even if representative of the national distribution, significant regional differences in typical burn rates, which are critical to local emission inventories, are not taken into consideration.

The normal fuel consumption rate (burn rate) for a given heater can vary by more than a factor of five, with the more common range being about three (e.g., 1 dry kg/h to 3 dry kg/h). Burn rates vary with local heating demand, house and chimney characteristics, and occupant preferences[29]. Emission rates and emission factors vary significantly with burn rates.

HEATER DEGRADATION

Structurally wood heaters and particularly catalysts degrade with use and emission factors increase[30-34]. The rate of degradation depends on the heater model, the intensity of fires, and the total number of fires. For catalysts, the rule-of-thumb is that catalysts need to be replaced on the average of every five years. As catalysts degrade, the particulate emission rate increases and the wood heater efficiency decreases. Because most catalytic heaters depend on the catalyst to mitigate particulate emissions usually there are minimal other design features incorporated into the heater for particulate reduction. Consequently, when a catalyst is fully degraded the particulate emissions of a catalyst heater generally is similar to that of an uncertified conventional heater. The issue of catalyst degradation is reflected in the lower NSPS "passing" threshold for catalytic heaters (4.1 g/h) as compared to non-catalytic heaters (7.5 g/h). At the time of the NSPS promulgation, the reasoning behind the lower requirement for a catalyst heater was that over the normal life of the catalyst, the average performance of the heater will be similar to that of a non-catalyst heater that does not change its emission performance as significantly with time. Similarly, the higher emission factor for catalytic Phase 2 heaters (16.2 lbs/ton [8.1 g/kg]) listed in AP-42 as compared to non-catalytic Phase 2 heaters (14.6 lbs/ton [7.3 g/kg]) is probably a reflection of testing appliances that have undergone some degradation.

In general, the field studies showed that emissions from both non-catalytic and catalytic heaters increased with use and that some heaters showed physical deterioration[32-34]. The level of deterioration appeared to be related to how "hard" the heaters were used. Those that were burned at high burning rates with high draft chimney conditions showed the most wear. Some models appeared to have less deterioration than others. Catalytic heaters were more susceptible to deterioration than non-catalytic stoves due to damage to the catalyst itself and the catalyst bypass which is a sealing/moving part. Damage to non-catalytic heaters was primarily to the baffle/secondary air system.

TREE SPECIES

Hardwood and softwood are the two major divisions in wood fuel types. The term hardwood is used synonymously with wood from deciduous trees, that is, trees that, with some uncommon exceptions such as western live oak species, lose their leaves every autumn. Oak, maple, hickory and birch are examples of deciduous trees. The term softwood is used synonymously with wood from coniferous trees, that is, evergreens. (A few conifers do lose their needles and by definition are not "evergreen.")

There is considerable variability in the burning characteristics among wood from the various species within the broad classifications of hardwood and softwood. However, in general, hardwood provides longer burning fires, is denser, dries (seasons) slower, and contains more total heat per volume (cord) but less total heat per unit of mass as compared to softwood. Because hardwood seasons slower, it is often burned when it is wetter than softwood. Softwood has a higher heat content per unit of mass because it contains more resin than hardwood and resin has about twice the heat content as the other two most common components making up wood – cellulose and lignin. Some studies have concluded that hardwoods burn cleaner that softwoods, i.e., emit less air emissions and produce less creosote, while others claim the opposite. Perhaps both claims are true with hardwood performing better in some heaters and some chimney scenarios and vice versa, or perhaps the difference in results is due to differences in moisture contents commonly encountered because of the different drying rates. Anecdotally, it has been stated that heaters from Australia designed to burn primarily hardwoods do not perform well in the NSPS certification test, which specifies softwood – Douglas fir. It has been well documented that when wood that is either too dry or too wet it produces higher air emissions. Compounding this effect is the fact that equilibrium wood moisture after seasoning is different in different parts of the country due to different characteristic regional relative humidity.

Hardwood use is dominant in most of the East and Midwest while hardwood and softwood usage is mixed in the West (Table 4) [35-37]. The two most common species groups with similar availability for residential fuel in the United States are pine and oak. When the usual preference for hardwood is taken into consideration the balance tips toward oak. White oak, northern red oak, black oak and chestnut oak are the most common oak species used for fuel. Among pines, loblolly pine, ponderosa pine, eastern white pine and shortleaf pine are the most common species used for fuel. Interestingly, red maple is the single most common wood species used for fuel in the East due to its wide geographic range. Similarly, Douglas fir is a commonly used fuel in the West due to its wide geographic range there. In addition to the oaks, pines, red maple and Douglas fir, yellow poplar and sugar maple are also in the top ten tree species used for fuel. Many minor hardwood species, when taken in aggregate along with oak and maple, make hardwood, as a group, the most common fuel type in the United States.

Table 4. Hardwood and softwood fuel usage by state.

U.S. Census Division	State	Hardwood	Softwood
New England	Connecticut	87%	13%
	Maine	44%	56%
	Massachusetts	75%	25%
	New Hampshire	64%	36%
	Rhode Island	84%	16%
	Vermont	71%	29%
Middle Atlantic	New Jersey	70%	30%
	New York	82%	18%
	Pennsylvania	93%	7%
South Atlantic	Delaware	86%	14%
	Florida	68%	32%
	Georgia	74%	26%
	Maryland	86%	14%
	North Carolina	75%	25%
	South Carolina	81%	19%
	Virginia	68%	32%
	West Virginia	75%	25%
East South Central	Alabama	84%	16%
	Kentucky	77%	23%
	Mississippi	83%	17%
	Tennessee	90%	10%
East North Central	Indiana	98%	2%
	Michigan	97%	3%
	Wisconsin	96%	4%
West South Central	Arkansas	84%	16%
	Louisiana	84%	16%
West North Central	Kansas	99%	1%
	Minnesota	98%	2%
	Missouri	99%	1%
	Nebraska	96%	4%
	North Dakota	96%	4%
	South Dakota	80%	20%
Mountain	Colorado	27%	73%
Pacific	California	69%	31%

Data from U.S. Forest Service and reports to Tennessee Valley Authority and U.S. EPA.

A western softwood, Douglas fir, is specified for the U.S. EPA certification of wood heaters. Hardwood will produce different emission results.

W**OOD MOISTURE**

The term “dry wood” is often misunderstood. For example, the AP-42 emission factors are based on dry fuel weight. This simply reflects a mathematical operation to remove the weight of moisture in the fuel so that all tests are on an equal basis. This does not mean that the tests were done with dry fuel, only that the weight of the moisture was mathematically removed to provide uniformity and to permit comparisons. To add to the confusion, if a cordwood dealer or home user refers to dry cordwood they mean wood with a low amount of moisture (less than 20%), not bone dry as used in AP-

42. Additionally, there is often confusion with the term "wet wood." Wet wood, when scientifically testing woodstoves, is the weight of the wood with the moisture (the wood could have very little or very high moisture content) but to a home user or wood dealer it would mean wood with a very high moisture content, e.g., typically more than 30%. The amount of moisture can be reported in two different and unequal ways, dry basis (db) or wet basis (wb). (The former is the weight of the water in the wood divided by the weight of the dry wood converted to percent; the latter is the weight of the water in the wood divided by the total weight of wood plus water converted to percent.) Because some reports of wood heater testing do not specify which moisture reporting convention was used, nor provide quantitative moisture content at all, interpreting and comparing emission factors (mass pollutants/mass dry wood) between studies is often compounded.

Wood moisture was measured in residential wood piles as part of a number of wood heater field studies[32,34,38-58]. A total of 820 measurements were made in New York, Vermont, Colorado, Yukon Territory, Washington, and Oregon. The average wood moisture was 24.1% (db) with a standard deviation of 12.9% (Table 5). The NSPS certification Method 28 specifies fuel moisture to be between 19% and 25% (db). The field studies in New York and Vermont [34,40,45] showed wood fuel in residential wood piles ranged from 17% to 41% (db) and a field study in Portland, Oregon[32] found that some residential woodpiles had wood moisture over a 100% (db), i.e., there was more water in the fuel than fuel itself. Both very dry wood and very wet wood have been demonstrated to produce higher particulate emissions than from wood near the center of the range (approximately 15% to 25%).

Table 5. Cordwood fuel moisture.

Parameter	Value
Mean	24.1% dry basis
Standard deviation	12.9% (absolute percent)
Median	21.4% dry basis
Mode	17.0% dry basis
Sample size	820 (n)

DIMENSIONAL LUMBER VERSUS CORDWOOD

The NSPS wood heater certification Method 28 specifies 2"x 4" and 4"x 4" dimensional lumber made into cribs with prescribed geometry and dimensions for the fuel charge. It is generally believed that these cribs burn somewhat cleaner than cordwood due to uniform air flow (no dead spaces) and due to the fact that there is no bark or large knots. A field study using manufactured densified firelogs found that there was on average a 24% to 52% reduction in PM emissions as compared to cordwood[55]. These reductions were attributed to the uniform geometry of the logs, lack of knots and bark, and to their lower moisture content. There are currently no definitive data to document the possible difference between dimensional lumber cribs and normal bulk cordwood.

EFFECTIVE EMISSION FACTORS – EFFICENCY

Certified wood heaters are more efficient than pre-EPA-certified conventional wood heaters. When a particulate reduction benefit analysis is conducted not only do the differences in emission factors need to be taken into consideration but the differences in efficiencies also need to be considered. This is because wood heaters with higher efficiencies will burn less wood, which means less total particulate emissions for a given heating demand. There are numerous ways to measure and report efficiencies[59-73]. There is no universally, or even generally, accepted standardized method to measure or report efficiencies, and in fact it is still an area of contention. The contention is often exacerbated by the competitiveness of marketing claims. Key measurement methods include those based on: (1) room

calorimetry, (2) flue gas loss, and (3) in-situ co-heating. There are two fundamental ways to report efficiencies: (1) One way includes the latent energy associated with the state change of water vapor to liquid water (heat of vaporization), uses the fuel higher heating value, and is the method normally reported in North America. (2) The second way does not include the latent energy associated with the state change of water vapor to liquid water, uses the fuel lower heating value, and is the normally reported convention in Europe. (A reasonable intuitive physical interpretation of the North American convention is that water condenses in the first eight feet of chimney whereas for the European convention it is still in the vapor phase at that point.) Efficiencies reported by the North American method, in general, run about 10% (relative) lower than for the same stove with efficiencies reported by the European method. The details of various measurement methods and the two fundamental reporting conventions are outside the scope of this review, other than to note that they add uncertainty to comparisons.

Even though there is considerable uncertainty and confusion caused by the various measurement techniques and the two fundamental reporting conventions, differences in efficiencies can be taken into consideration in estimating the benefits of woodstove change outs because what is important for these estimations is the relative differences between pre-EPA-certified conventional cordwood heaters and certified cordwood heaters, not absolute values.

The NSPS wood certification protocol does not require efficiency to be measured but assigns default values[74]. The default values are 63% for certified non-catalytic wood heaters and 72% for certified catalytic wood heaters. AP-42 also lists efficiencies, but, except for conventional wood heaters, they have been superseded by more recent data. All are based on limited data sets. The efficiency for conventional wood heaters listed in AP-42 is 54%. Notably, it also needs to be taken into account that the efficiency of catalyst wood heaters will become significantly lower with use (catalyst degradation). After reviewing all significant efficiency-related reports and publications that could be located, OMNI has used its best professional judgment to approximate reasonable efficiencies for conventional cordwood heaters, certified catalytic cordwood heaters, and certified non-catalytic cordwood heaters. These data are shown in Table 4 for heaters over their lifetime and are on the "North American" reporting convention basis. More realistic efficiencies (the European reporting convention) would be approximately 10% (relative) more than shown in Table 4, as water does not condense in the first eight feet of chimney pipe where the heat could be transferred to the living space of the home from the normal use of wood heaters.

Table 6. Efficiencies by heater type.

Appliance Type	Efficiency
Conventional cordwood heater	54%
Non-catalytic cordwood heater	63%
Catalytic cordwood heater	63%

In summary, the higher efficiencies of certified cordwood heaters as compared to conventional cordwood heaters should be taken into consideration when calculating the benefits of a woodstove change out program. The fact that certified cordwood heaters use less wood than conventional woodstoves for the same heating demand means that less PM will be emitted.

EMISSION FACTORS FOR CERTIFED WOOD HEATERS BASED ON BEST AVAILABLE DATA

The combination of: (1) the variability of emissions among models with newer models often having lower emissions, (2) the difference in emissions produced by hot and cold starts, (3) the change

in emissions with burn rates, (4) the effect that tree species and fuel moisture have on emissions, and (5) the increase of emissions with heater use (due to heater degradation) when all are taken together, suggest that using only two emission factors, one for Phase 2 certified catalytic heaters (8.1 g/dry kg) and one for Phase 2 certified non-catalytic heaters (7.3 g/dry kg) heaters as published in AP-42, is simplistic and most likely inaccurate. Further, because AP-42 presents the emission factors in the format of "5H-equivalent" and without regard to the size distribution, if all else is equal, the published emission factors are higher than they are in fact, particularly for $PM_{2.5}$ and $PM_{10.}$ Also, because the AP-42 emission factors are derived from studies using different sampling methods, with conversions between the different methods and 5H equivalency being imperfect, uncertainty is added.

Different average emission factors can be expected in regions of different climate and socio-demographic makeup. For example, emission factors will be lower at higher burn rates and hot start scenarios characteristic of colder climates as compared to emission factors produced by lower burn rates and cold start scenarios characteristic of warmer climates. Similarly, it can reasonably be expected, again if all else is equal, that emission factors will be higher in economically depressed areas where a higher fraction of cordwood heaters are older, heavily used models, many of which may have undergone degradation as contrasted to more affluent areas were newer, lower emitting, less used models are more prevalent. Finally, relative hardwood versus softwood fuel availability and typical fuel moisture levels in response to different average atmospheric humidity are clearly regional.

A review of credible recent studies reporting emission factors confirms that a range of emission factors can be expected from modern certified wood heaters (Table 7). In each study the measurements were made with a Method 5G-type approach, which provides some consistency and results that more closely simulate actual emission factors, albeit dilution chamber temperatures were variable among studies and were warmer than would be typical of ambient heating season temperatures. Both hot and cold starts were used, both modern certified catalyst and non-catalyst heaters were used, both dimensional lumber and cordwood were used, both hardwood and softwood were used, and various burn rates was used. The average emission factor values for the different sets of conditions spanned nearly two orders of magnitude from a low of 0.64 g/kg to a high of 35.7 g/kg. The magnitude of these emission factors are probably lower than they are in reality due to the fact that the diluted air in the 5G dilution tunnels were warmer than typical heating season ambient temperatures and hence fewer semi-volatile organic compounds in the vapor phase condensed into particles. Conversely, due to the size distribution of particles emitted from wood heaters the magnitude of the emission factors would need to be reduced somewhat to apply to $PM_{2.5}$ and PM_{10}.

Table 7. 5G emission factors for modern certified wood heaters.

Start scenario	Burn rate (kg/h)* Avg. ± S.D.	Fuel†	n	Description	5G emission factor (g/kg) Avg. ± S.D.	Reference
Hot	2.05 ± 1.35	Doug. fir dl	12	certified non-cat.	3.41 ± 2.38	Tiegs & Houck, 2000[16]
Hot	0.75 ± 0.03	Doug. fir dl	3	certification tests on 26 non-cat. models	2.32 ± 0.50	OMNI-Test Lab. 3/06 to 1/08 tests
	0.99 ± 0.13		49		3.23 ± 2.32	
	1.50 ± 0.17		33		1.86 ± 1.19	
	2.51 ± 0.44		26		1.55 ± 0.84	
Cold	not provided, estimated as 1.1 to 2.2	one run oak cw, one run Doug. fir cw	2	certified cat.	1.7 (avg.)	Fine, et al., 2004[75]
Hot	3.52 ± 0.71	white gum cw	5	high tech. Australian stove similar in design to a U.S. certified heater	2.86 ± 1.60	Jordan & Seen, 2005[76]
	2.15 ± 0.22		3		12.9 ± 7.3	
	1.42 ± 0.44		5		35.7 ± 9.6	
Hot	not provided, estimated as 2.4	3 runs spruce cw, 3 runs maple cw	6	certified non-cat.	0.64 ± 0.17	Environment Canada, 2000[77], Intertek 2000[78]
Cold	not provided, estimated as 2.3	oak cw	3	certified non-cat.	8.2 (avg. estimated from data in publication)	Gullett et al., 2003[79], Crouch and Houck 2004[80]
Cold (one run was hot start)	1.97 ± 0.68	oak cw	11	certified cat.	7.73 ± 5.95	U.S. EPA, 2000[13]
	1.94 ± 0.99		7	certified non-cat.	22.9 ± 10.7	

*S.D. = standard deviation
†dl = dimensional lumber
cw = cordwood

RECOMMENDATIONS FOR DEVELOPMENT OF CERTIFIED WOOD HEATER EMISSION FACTORS FOR REGIONAL EMISSION INVENTORIES AND FOR IMPROVEMENT OF THE CERTIFICATION METHOD

It is clear from the review of the existing emission factor data and issues that have been found to influence particulate emissions that both focused testing to refine real-world emission factors and revisions in the emission factor certification methods are needed. A well designed certification process could be predictive of real-world emissions and also provide a more realistic operational target for certification. Arguably more realistic testing parameters would have the effect of forcing new heater models to have optimized performance under more typical usage conditions. The process could also be designed to quantify emissions characteristic of different regions of the country.

Some key elements of a revised certification test method that would be predictive of real-world emissions and independent studies to supply supporting information and adjustment factors for the certification process would include:

- Cooled 5G-like dilution tunnel – Samples should be collected with diluted emissions and filters kept below 65º F (18º C). (Sixty-five degrees Fahrenheit is the basis for heating degree days (HDD) at which heating is assumed to be needed.) An independent study should be done with representative certified stoves to provide correction factors for emissions at lower ambient temperatures to be provided as part of the certification method, which would allow adjustments for different regional climates.

- Emission factors for different burn rates reported independently. – Only a single weighted "national" value is currently reported. An independent distribution survey/study of burn rates for different regions of the country should be done. Unlike the current method, the burn rates in the test method should be defined in the same way as in the survey/study.

- Both hot and cold starts.

- Both hardwood and softwood fuel and an option for testing manufactured biomass fuels.

- Emissions reported as emission factors (g/kg) rather than emission rates (g/hr). (Emission rates cannot be used in emission inventories nor do they fairly account for different size heaters with different heat outputs.)

- Efficiency testing part of the certification process. – Credit and acknowledgment for high efficiency should be provided.

- An independent study of particulate size distribution in a cooled dilution tunnel with representative certified stoves. – Adjustment factors so that $PM_{2.5}$ and PM_{10} emission factors can be estimated from the total particulate catch (PM) could be provided with the certification method.

- Either an independent study relating cordwood fires with dimensional lumber cribs or the use of multiple cordwood runs with the certification process to mitigate variability. (Dimensional lumber cribs are now used to optimize reproducibility. Cordwood fires are much more variable but are more representative of real-world fires.)

- An independent study of wood moisture by region and a study with representative certified wood heaters to measure the effect of moisture on burn rates and emission factors. – One or more wood moisture ranges could be used with certification process with possible adjustment factors to be applied to the particulate emission factors for different regions of the country. Different average moisture values and adjustment factors may be appropriate for hardwood in contrast to softwood.

REFERENCES

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

2. U.S. Federal Register, "Standards of Performance for New Stationary Sources, New Residential Wood Heaters; Final Rule", February 26, 1988, v. 53, n. 38.

3. U.S. Code of Federal Regulations, "Standard of Performance for New Residential Wood Heaters", February, 2000, 40 CFR, Part 60, Subpart AAA.

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

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

6. Rau, J.A., *Residential Wood Combustion Aerosol Characterization as a Function of Size and Source Apportionment Using Chemical Mass Balance Modeling*, Ph.D. Dissertation, Oregon Graduate Center, Beaverton, OR, 1986.

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

8. U.S. Code of Federal Regulations, "Certification and Auditing of Wood Heaters", 40 CFR, Part 60, Appendix A, Method 28, http://www.epa.gov/ttn/emc/methods/method28.html.

9. U.S. Code of Federal Regulations, "Determination of Particulate Matter Emissions from Wood Heaters from a Dilution Tunnel Sampling Location", 40 CFR, Part 60, Appendix A, Method 5G, http://www.epa.gov/ttn/emc/methods/method5g.html.

10. U.S. Code of Federal Regulations, "Determination of Particulate Emissions form Wood Heaters from a Stack Location", 40 CFR, Part 60, Appendix A, Method 5H, http://www.epa.gov/ttn/emc/methods/method5h.html.

11. U.S. Environmental Protection Agency, *List of EPA Certified Wood Stoves*, March 12, 2008, http://www.epa.gov/oecaerth/resources/publications/monitoring/caa/woodstoves/certifiedwood.pdf.

12. Houck, J.E., Chow, J.C., Watson, J.G., Simons, C.A., Pritchett, L.C., Goulet, J.M., and Frazier, C.A., "Determination of Particle Size Distribution and Chemical Composition of Particulate Matter from Selected Sources in California", Prepared for the California Air Resources Board by OMNI Environmental Services, Inc., Beaverton, OR, NTIS PB89-232805, 1989.

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

14. McCrillis, R.C., and Jaasma, D.R., "Woodstove Emission Measurement Methods: Comparison and Emission Factors Update", Environmental Monitoring and Assessment, 1993, v. 24, pp 1-12.

15. "Emission Factor Documentation for AP-42 Section 1.9, Residential Fireplaces", Prepared for U.S. Environmental Protection Agency by E.H. Pechan & Associates, Rancho Cordova, CA, 68-D1-0146, 1993.

16. Tiegs, P.E. and Houck, J.E., "Evaluation of the Northern Sonoma County Wood-Burning Fireplace and Masonry Heater Emissions Testing Protocols", Prepared for Northern Sonoma County Air Quality Management District by OMNI Environmental Services, Inc, Beaverton, OR, 2000.

17. Houck, J.E., "Source Sampling for Receptor Modeling" *Receptor Modeling in Air Quality Management*, P. K. Hopke, ed., Elsevier Science Publishers, 1991, pp. 45-82.

18. Houck, J.E., Cooper J.A ., and Larson E.R, "Dilution Sampling for Chemical Receptor Source Fingerprinting", *Proceedings 75th Annual Air Pollution Control Association Meeting*, 1982, paper 82-61M.2.

19. DeAngelis, D.G. and Ruffin, D.S., "Preliminary Characterization of Emissions from Wood-fired Residential Combustion Equipment", Prepared for U.S. Environmental Protection Agency by Monsanto Research Corporation, Dayton, OH, 1980, EPA-600/7-80-040.

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

21. Hedberg, E., Kristensson, A., Ohlsson, M., Johansson, C., Johansson, P.K., Swietlicki, E., Vesely, V., Wideqvist, U., and Westerholm, R., "Chemical and Physical Characterization of Emissions from Birch Wood Combustion in a Wood Stove, Atmos. Env., 2002, v. 36, pp. 4823-4837.

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

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

24. Shelton, J.W. and Gay, L.W., "Evaluation of Low-Emission Wood Stoves", Prepared for California Air Resources Board by Shelton Research, Inc., Santa Fe, NM, report number 1086, contract A3-122-32, 1986.

25. Hueglin, Ch., Gaegauf, Ch., Kunzel, S. and Burtscher, H., "Characterization of Wood Combustion Particles: Morphology, Mobility, and Photoelectric Activity", Environ. Sci. Technol., 1997, v. 31, n. 12, pp. 3439-3447.

26. U.S. Environmental Protection Agency, *Emission Factor Documentation for AP-42: Section 1.10, Residential Wood Stoves*, Research Triangle Park, NC, 1983, EPA-450/4-82-003.

27. Hearth, Patio and Barbecue Association, *2004 Consumer Attitude and Usage Survey: Hearth Products*, Arlington, VA, 2004.

28. Hearth, Patio and Barbecue Association, *2006 Fireplace/Freestanding Stove Lifestyle Usage & Attitude Study*, Arlington, VA, 2006.

29. "Woodstove Burn Rate Effects on Particulate Emissions", Prepared for the U.S. Environmental Protection Agency, Emission Standards and Engineering Division by Radian Corporation, Research Triangle Park, NC, DCN No. 86-231-020-25-01, January 1986.

30. Bighouse, R.D., Barnett, S. G., Houck, J.E., and Tiegs, P.E., "Woodstove Durability

Testing Protocol", Prepared for the U.S. Environmental Protection Agency by OMNI Environmental Services, Inc., Beaverton, OR, 1994, EPA-600/R-94-193 (NTIS PB95-136164).

31. Bighouse, R.D., Houck, J.E., Barnett, S.G., and McCrillis, R.C., "Stress Testing of Woodstoves" *In Proceedings of the Air and Waste Management Association 86th Annual Meeting*, Denver, CO, June 14-18, 1993, paper 93-RP-136.05.

32. Fisher, L.H., Houck, J.E., and Tiegs, P.E., "Long-Term Performance of EPA-Certified Phase 2 Woodstoves, Klamath Falls and Portland, Oregon: 1998/1999", Prepared for the U.S. Environmental Protection Agency by OMNI Environmental Services Inc., Beaverton, OR, 2000, EPA-600/R-00-100.

33. Champion, M. and Jaasma, D.R., "Degradation of Emissions Control Performance of Wood Stoves in Crested Butte, CO", Prepared for the U.S. Environmental Protection Agency by Virginia Polytechnic Institute and State University, Blacksburg, VA, 1998, EPA-600/R-98-158 (NTIS PB99-127995).

34. Barnett, S.G. and Fesperman, J., "Field Performance of Advanced Technology Woodstoves in Their Second Season of Use in Glens Falls, New York, 1990", Prepared for Canada Centre for Minerals and Energy Technology; Energy, Mines, and Resources by OMNI Environmental Services, Inc., Beaverton, OR, 1990.

35. Fine, P.M., Cass, G.R., and Simoneit, B.R.T., "Chemical Characterization of Fine Particle Emissions from the Fireplace Combustion of Woods Grown in the Northeastern United States", Environ. Sci. Technol., 2001, v. 35, n. 13, pp. 2665-2675.

36. Fine, P.M., Cass, G.R., and Simoneit, B.R.T., "Chemical Characterization of Fine Particle Emissions from the Fireplace Combustion of Woods Grown in the Southern United States", Environ. Sci. Technol., 2002, v. 36, n. 7, pp. 1442-1451.

37. Fine, P.M., Cass, G.R., and Simoneit, B.R.T., "Chemical Characterization of Fine Particle Emissions from the Fireplace Combustion of Woods Grown in the Midwestern and Western United States", Environ. Eng. Sci., 2004 v 21, n.3, pp. 387-409.

38. "An In-situ Performance Evaluation of Catalytic Retrofit Devices", Prepared for Oregon Department of Environmental Quality by OMNI Environmental Services, Inc., Beaverton, OR, 1987.

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

40. Burnet, P., "Data Sheets for the Northeast Cooperative Woodstove Study", Prepared for the U.S. Environmental Protection Agency by OMNI Environmental Service, Inc., Beaverton, OR, 1988, EPA/600/S7-87/026.

41. "Particulate Emission Test, Emission Control System Inspection and Leak Check, Blaze King Stove in Home P02", Prepared for Oregon Department of Environmental Quality by OMNI Environmental Services, Inc., Beaverton, OR, 1988.

42. Simons, C.A., Christiansen, P.D., Houck, J.E., and Pritchett, L.C., "Woodstove Emission Sampling Methods Comparability Analysis and In-situ Evaluation of New Technology Woodstoves," Prepared for U.S. Department of Energy Pacific Northwest and Alaska Regional Biomass Program, Bonneville

Power Administration by OMNI Environmental Services, Inc., Beaverton, OR, 1988,Task G, DOE/BP-18508-6.

43. Jaasma, D.R., and Champion, M.R., "Field Performance of Woodburning Stoves in Crested Butte during the 1988-89 Heating Season," Prepared for Town of Crested Butte, Colorado Department of Health, and Region 8 U.S. Environmental Protection Agency by Virginia Polytechnic Institute and State University, Blacksburg, VA, 1989.

44. Simons, C.A. and Jones S.K., "Performance Evaluation of the Best Existing Stove Technology (BEST) Hybrid Woodstove and Catalytic Retrofit Device," Prepared for Oregon Department of Environmental Quality by OMNI Environmental Services, Inc., Beaverton, OR, 1989.

45. Barnett, S.G., "Field Performance of Advanced Technology Woodstoves in Glens Falls NY, 1988-89", Prepared for U.S. Environmental Protection Agency by OMNI Environmental Services Inc., Beaverton, OR, 1990, EPA-600/7-90-019a.

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

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

48. Roholt, R.B. and Houck, J.E., "Field Performance of Best Existing Technology (BEST) Hybrid Woodstoves in Their Second Year of Use," Prepared for Oregon Department of Environmental Quality by OMNI Environmental Services, Inc., Beaverton, OR, 1990.

49. Barnett, S.G., "In-home Evaluation of Emissions from Masonry Fireplaces and Heaters", Prepared for Western States Clay Products Association by OMNI Environmental Services, Inc. Beaverton, OR, 1991.

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

51. Barnett, S.G., "In-home Evaluation of Emissions from a Biofire 4 x 3 Masonry Heater", Prepared for Biofire, Inc. by OMNI Environmental Services, Inc, Beaverton, OR, 1992.

52. Barnett, S.G., "In-Home Evaluation of Emissions from a Grundofen Masonry Heater", Prepared for Mutual Materials Company, the Masonry Heater Association and Dietmeyer, Ward and Stroud by OMNI Environmental Services, Inc., Beaverton, OR, 1992.

53. Barnett, S.G., "In-home Evaluation of Emissions from a Tulikivi KTU 2100 MasonryHeater", Prepared for The Tulikivi Group by OMNI Environmental Services, Inc., Beaverton, OR, 1992.

54. Barnett, S.G., "Particulate and Carbon Monoxide Emissions from a Bellfire 28 Rosin Fireplace Using a Simulated Real-World Test Procedure", Prepared for Sleepy Hollow Chimney, Inc. by OMNI Environmental Services, Inc., Beaverton, OR, 1992.

55. Barnett, S.G. and Bighouse, R.D., “In-home Demonstration of the Reduction of Woodstove Emissions from the Use of Densified Logs”, Prepared for Bonneville Power Administration by OMNI Environmental Services, Inc., Beaverton, OR, 1992, DOE/BP-35836-1.

56. Barnett, S.G., “Summary Report of the In-Home Emissions and Efficiency Performance of Five Commercially Available Masonry Heaters”, Prepared for The Masonry Heater Association by OMNI Environmental Services, Inc., 1993.

57. Jaasma, D.R., Stern, C.H., and Champion, M.R., “ Field Performance of Woodburning Stoves in Crested Butte during the 1991-92 Heating Season”, Prepared for the U.S. Environmental Protection Agency by Virginia Polytechnic Institute and State University, Blacksburg, VA, 1994, EPA-600/R-94-061.

58. Correll, R., Jaasma, D.R., and Mukkamala, Y., “Field Performance of Woodburning Stoves in Colorado during the 1995-96 Heating Season”, Prepared for the U.S. Environmental Protection Agency by Virginia Polytechnic Institute and State University, Blacksburg, VA, 1997, EPA-600/R-97-112.

59. Houck, J.E. and Tiegs, P.E., “Efficiency Is in the Eye of the Beholder, Hearth & Home Magazine, November 2005, pp. 114-125.

60. Houck, J.E. and Tiegs, P.E., “Wood: The Untold Story”, Hearth & Home Magazine, August, 2001, pp. 24-32.

61. Shelton, J.W., *Thermal Performance Testing Methods for Residential Solid Fuel Heaters*, Shelton Energy Research, Santa Fe, NM, 1981.

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

63. Shelton, J.W., Graeser, L. and Jaasma, D., “Sensitivity Study of Traditional Flue Loss Methods for Determining Efficiencies of Solid Fuel Heaters”, Shelton Research, Inc., In Proceedings, The Annual Meeting of the American Society of Mechanical Engineers, 1984.

64. Gaegauf, C.K., and Macquat, Y., “Comparison of Draft ISO- and CEN-Standards to Determine Efficiency and Emissions of Solid Fuel Burning Appliances”, In Proceedings First World Conference and Exhibition on Biomass for Energy and Industry, Sevilla, Spain, June 2000.

65. “ASHRAE Standard, Method of Testing for Performance Rating of Woodburning Appliances”, ANSI/ASHRAE 106-1984.

66. “Australian/New Zealand Standard, Domestic Solid Fuel Burning Appliances – Method for Determination of Power Output and Efficiency”, AZ/NZS 4012:1999.

67. U.S. Federal Register, “Standards of Performance for New Stationary Sources; Total Combustible Carbon Method for Determination of Energy Efficiency of Wood Heaters”, August 20, 1990, v. 55, n.161, pp. 33925-33935.

68. Canadian Standards Association, “Performance Testing of Solid-Fuel-Burning Heating Appliances”, B415.1-00, December 2000.

69. Barnett, S.G., *Handbook for Measuring Woodstove Emissions and Efficiency Using the Condar Sampling System*, 1985.

70. Shelton, J.W., “Overview of Efficiency Measuring Methods”, Shelton Research, Inc., Santa Fe, NM, 1985.

71. Shelton, J.W., “Critical Assessment of Various Flue Loss Methods for Solid Fuel Heater Efficiency Measurement”, Shelton Research, Inc., Proceedings of the Annual Meeting of the American Society of Heating, Refrigerating & Air Conditioning Engineers, 1985.

72. Shelton, J.W., “ASTM Emissions and Efficiency Tests on Four Stoves”, Prepared for Wood Heating Alliance by Shelton Research, Inc., Santa Fe, NM, 1985.

73. Tiegs, P.E. and Burnet, P.G., “Improving Flue Loss Methods for Measuring Wood Heater Thermal Performance”, OMNI Environmental Services, Inc., Beaverton, OR, 1986.

74. U.S. Federal Register, “Standards for Particulate Matter”, February 26, 1988, v. 53, n. 38, Section 60.536.

75. Fine, P.M., Cass, G.R., and Simoneit, B.R.T., “Chemical Characterization of Fine Particle Emissions from the Wood Stove Combustion of Prevalent United States Tree Species”, 2004 Env. Eng. Sci., v. 21, n. 6, pp. 705-721.

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

77. Environment Canada, “Characterization of Organic Compounds from Selected Residential Wood Stoves”, report ERMD 2000-01, June 2000.

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

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

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

KEY WORDS

Residential Wood Combustion
Emission Factors
Wood Heater Certification
Certified Wood Heaters