$PM_{2.5}$ Emission Reduction Benefits of Replacing Conventional Uncertified Cordwood Stoves with Certified Cordwood Stoves or Modern Pellet Stoves

Prepared for
Hearth, Patio and Barbecue Association
1601 N. Kent Street, Suite 1001
Arlington, VA 22209

Prepared by
James E. Houck and David R. Broderick
OMNI Environmental Services, Inc.
5465 SW Western Ave., Suite G
Beaverton, OR 97005

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Table of Contents

List of Tables

List of Figures

1. Introduction

OMNI Environmental Services, Inc. (OMNI) under contract with the Hearth, Patio and Barbecue Association (HPBA) conducted a review of published literature and technical reports for the purpose of estimating the reductions in $PM_{2.5}$ emissions that are realized by replacing old conventional pre-EPA-certified cordwood stoves with certified cordwood stoves or modern pellet stoves (changeouts). It is OMNI's understanding that the U.S. Environmental Protection Agency (EPA) is in the process of developing State Implementation Plan (SIP) guidance for calculating the emission reduction benefits for woodstove changeouts for which these data are needed. In addition, emission reduction data are needed to support economic, health, and environmental benefit estimates achievable from EPA's new wood stove/smoke reduction initiative.

Currently, the most credible and most widely used source to document the particulate emission reduction benefit of replacing old conventional uncertified cordwood stoves with certified cordwood stoves or modern pellet stoves is the U.S. EPA's Emission Factor Documentation for AP-42: 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 and it has been used as the starting point for the estimates presented here. Unfortunately, even though the AP-42 compilation presents particulate values for the various wood heater types, obtained from a literature review, it lacks currency. No particulate data for cordwood or pellet stoves collected more recently than 1992 are included in the compilations. As of July 1, 1992, all wood heaters sold are required to be phase 2 certified[2]. Separately, pellet stoves became popular in the mid- to late 1980's. Consequently, emission factors of only the earlier models of phase 2 certified cordwood stoves and pellet stoves contribute to the particulate values compiled in AP-42. (Some phase 2 cordwood stoves 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 both phase 2 certified cordwood stoves and pellet stoves has improved considerably since the earliest models.

Another shortcoming of AP-42 is that it is a compilation of data from, by in large, unrelated and uncoordinated studies and, as such, the values it presents are not derived from a normal distribution of data. For example, the burn rate conditions under which the particulate data for pre-EPA-certified conventional cordwood stoves were collected are skewed. It is a well known fact that particulate emission factors (mass particles/mass wood) from cordwood stoves at lower burn rate conditions are higher than from higher burn rate conditions. Lower burn rates are usually achieved by restricting airflow with the stove's air controls. Air restriction favors wood pyrolysis and the formation of products of incomplete combustion (PIC) rather than complete, efficient combustion conditions. Higher particulate emissions at lower burn rates are particularly relevant to pre-EPA-certified conventional stoves that do not have secondary combustion or catalyst mitigation of particles produced during the primary combustion. The conventional cordwood stove data included in AP-42 are primarily from in-home measurements predominately from homes in colder climates[3-6], which is consistent with higher woodstove burn rates. Further, households selected for participation in the in-home studies were "serious" woodstove users whereas U.S. Census Bureau (American Housing Survey) data[7] show that most woodstoves 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 (stoves plus fireplace inserts) in 2003 as "other heating equipment" as compared to "main heating equipment" is over 6:1. Finally, OMNI believes two laboratory studies[8,9] were included along with the four in-home studies[3-6] in the calculation of conventional woodstove emission factors in AP-42. (There is no documentation in AP-42 as to which studies were actually used to calculate the particulate values presented and the references for the various stove types are grouped together without specifying which sources were used for which stove types.) Each of the two laboratory studies tested only one stove model and the operation of these two stoves during most of the testing was not representative of actual in-home usage of wood heaters for a variety of reasons (hot-to-hot test conditions, dimensional lumber rather than cordwood, burn rates well outside the norm, etc.). In summary, when an adjustment is made for the higher than normal burn rates that make up the in-home data base and the data from the two stoves tested under laboratory conditions are not included in the calculation of a mean value, the result is that the predicted emission factor for a typical pre-EPA-certified conventional woodstove is higher than is presented in AP-42.

Finally it should be noted that when determining the benefits of changing out an older conventional stove with a modern stove, not only do emission factors need to be taken into consideration but efficiencies also need to be considered. Certified cordwood stoves and pellet stoves have higher efficiencies than pre-EPA-certified conventional cordwood stoves, therefore less wood is burned for a given heat demand producing less emissions.

2. Certified Cordwood Stoves

The particulate emissions of certified cordwood stoves have decreased since the earliest models. Table 1 is a comparison of the mean certified 5H emission rate (g/hr) for old and new catalytic and non-catalytic phase 2 cordwood stoves. The average for phase 2 certified stoves certified during the first five years of the NSPS rule[10] and the average for stoves that are currently certified (either first certified or renewed within the last five years) and that can be sold today were obtained from U.S. EPA records[11]. The 1988 through 1992 time period was selected as it is concurrent with the phase 2 stoves that were included in the AP-42 document for the purposes of calculating particulate emission factors (lb/ton). 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 are certified for sale today and could be used in a woodstove changeout program was calculated (Table 1). It is generally believed, and is in fact the cornerstone of the NSPS for wood heaters, that the certification emission rates are in a relative sense a surrogate for actual emissions from the in-home use of woodstoves under real-world conditions[10]. Therefore the percentage reduction calculated for the new certified stoves as compared to the old ones was applied to the emission factors tabulated in AP-42 to provide a more accurate estimate of emission factors representative of current certified stoves. The emission factor of 14.6 lbs/ton for non-catalytic phase 2 woodstoves published in AP-42 was adjusted to 11.7 lbs/ton by this process to represent modern stoves. Similarly, the emission factor of 16.2 lbs/ton for catalytic phase 2 woodstove was adjusted to 15.1 lbs/ton. The smaller adjustment for catalytic woodstoves as compared to non-catalytic woodstoves 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 stove 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 straight forward and catalyst application for particulate control has not changed as much from the earlier models.

In summary, the phase 2 cordwood stoves available for woodstove changeouts today have lower particulate emissions than tabulated in AP-42 and revised emission factors should be used when calculating the emission benefits associated with the replacement of a conventional uncertified woodstoves with a certified one.

Table 1
Comparison of Average Certified Emission Rates for Old and New Phase 2 Cordwood Stoves

Time Period	Woodstove Type	Number of Stoves	Average Emission Rate (g/hr, 5H equivalent)	Percent Reduction (%)
First 5 years of certification (1988-1992)	Non-catalytic	115	5.1	-
	Catalytic	110	2.9	-
Currently certified woodstoves (certified or renewed in the last 5 years)	Non-catalytic	137	4.1	19.6
	Catalytic	23	2.7	6.9

3. Pellet Stoves

Pellet stoves have improved dramatically both in reliability and particulate emissions, since the earlier models included in AP-42[12-15]. The difference in the terms “certified” and “exempt” is currently meaningless, since nearly all pellet stoves operate in excess of a 35:1 air-to-fuel ratio at one of their burn rates, therefore manufacturers can choose to not certify them (i.e., claim the 35:1 exemption). Most modern exempt pellet stoves are equivalent to currently certified pellet stoves. The decision to certify or not to certify a pellet stove for most manufacturers is a trade off between cost and having the sales benefit of being certified, e.g., being able to sell them in some jurisdictions that allow only EPA-certified devices.

There have been a total of 27 pellet stove models certified. Only four are currently certified (first certified or have had their certification renewed in the last five years). The average 5H equivalent emission rate of the four currently certified models is 1.4 g/hr. The operation of pellet stoves (in contrast to cordwood stoves) during the certification process is very similar to their actual real-world operation in a home, i.e., the certification testing is done using commercial fuel available to a home user, the pellet stove is at its normal steady state condition, and at normal burn rates fixed by the pellet stove's controls. Because the certification testing conditions are similar to in-home usage for pellet stoves, an emission factor can be directly estimated for them from the certification emission rate by simply dividing it by the median burn rate (1.16 dry kg/hr) listed in the certification test protocol[16]. This median burn rate is within the low-normal range of operation of most pellet stoves. The average emission factor for the four currently certified pellet stoves thus calculated is 2.5 lbs/ton, which, as previously noted, can also be applied to exempt pellet stoves. The emission factors in AP-42 are 8.8 lbs/ton and 4.2 lbs/ton for exempt and certified pellet stoves, respectively.

In summary, modern pellet stoves available today for changeouts have particulate emission factors lower than tabulated in AP-42 and revised emission factors should be used when calculating the emission benefits associated with the replacement of a conventional uncertified woodstoves with a pellet stove.

4. Conventional Stoves

OMNI adjusted the conventional cordwood stove emission factor listed in AP-42. As previously noted, this was necessary for two reasons: (1) It appeared that two of the studies used to calculate the AP-42 value were laboratory studies and did not represent normal in-home use of woodstoves. When using only the in-home tests of conventional woodstoves referenced in AP-42, the average emission factor was calculated as 35.9 lbs/ton as compared to the 30.6 lbs/ton value listed in AP-42. (2) The in-home studies that were used for calculating the AP-42 value were predominately from households located in colder climates suggesting that the stoves were operated under higher than average burn rates. Higher burn rates produce lower particulate emission factors, i.e., at lower and more representative burn rates, higher emission factors would be expected. Table 2 contrasts the test-weighted heating degree days (HDD) associated with the locations of the in-home tests used to develop the AP-42 emission factor for conventional cordwood stoves with (1) U.S. population-weighed HDD and with (2) the HDD values characteristic of the 36 $PM_{2.5}$ nonattainment areas east of the Mississippi River. As can be seen, in reviewing the tabulation, there is a dramatic difference between the test-weighed HDD associated with the locations of the in-home tests used in the calculation of the AP-42 emission factor (9490 HDD) and what is (1) experienced by the U.S. as a whole (4540 HDD) and (2) the average of the eastern $PM_{2.5}$ nonattainment areas (4660 HDD). Significantly, the HDD value weighted by location of the stoves tested is more than twice the average population weighted HDD for the United States and more than twice the average HDD of the 36 $PM_{2.5}$ nonattainment areas east of the Mississippi River. Also as previously noted, the households selected for participation in the in-home studies were, by-in-large, "serious" wood burners. In contrast, the American Housing Survey reported that by a ratio of more than six to one, that nationally, home occupants characterize their use of wood heaters as "other heating equipment" as compared to "main heating equipment."[7] This further suggests that the burn rates used in developing the AP-42 emission factor were on the average higher than what is typical for actual, in-home use.

Table 2
Heating Degree Day (HDD) Comparison of Conventional Woodstove Database with the National Average and Eastern $PM_{2.5}$ Nonattainment Areas

Conventional Woodstoves, AP-42 Database		
Glens Falls, NY	3 in-home stoves	7150 HDD
Waterbury, VT	3 in-home stoves	7790 HDD
Klamath Falls, OR	7 in-home stoves	6600 HDD
Crested Butte, CO	18 in-home stoves	11,300 HDD
Weighted (by number of stoves) Average HDD of Conventional Woodstove Database		**9490 HDD**
U.S.		
Average (population weighted)		**4540 HDD**
36 $PM_{2.5}$ Nonattainment areas East of the Mississippi River		
	Average	**4660 HDD**
	Maximum	6210 HDD
	Minimum	2350 HDD
	Standard Deviation	1070 HDD

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

Creosote accumulation is related to particulate emissions since they are both primarily the product of organic compounds that are emitted and subsequently condensed and/or captured on the interior of chimney pipes or onto a filter substrates, respectively. Using creosote accumulation data as a surrogate for particulate emissions, the strong inverse trend of particulate emissions with burn rate can be seen (Table 3).

Table 3
The Effect of Burn Rate on Creosote Accumulation from a Conventional Woodstove*

Burn Rate	Fuel Moisture (%)	Creosote Accumulation, Piñon Pine (g/kg)	Creosote Accumulation, Oak (g/kg)
Low	5	9.2	16.5
	15	11.0	16.6
	25	9.5	19.4
Medium	5	9.8	4.1
	15	8.0	2.9
	25	5.4	2.3
High	5	6.4	2.7
	15	3.9	0.88
	25	2.2	0.40

*Data from reference 17

A number of studies have directly measured emission factors at multiple burn rates. The data from all relative studies that met the criteria of measuring particulate emissions from conventional woodstoves at both high and low burn rates (a total of ten studies could be found) were used to calculate the percentage difference in emission factors between the high and low burn rates. (See Table 4 and Figure 1.) While it is difficult to compare the results of these studies on an absolute basis, as different particulate sampling equipment, different fuel types, different stove models, different reporting conventions, and different ways to define burn rate and to classify burn rates as either “high” or “low” were used in each study, the inverse relationship between burn rates and emission factors is clear. (See Figure 2.) OMNI calculated the percentage difference in emission factors between high and low burn rates for each study and made an estimate, perhaps best described as semi-quantitative, of the increase in particulate emissions that reasonably could be expected from more representative and lower burn rates than the higher burn rates associated with AP-42. The average increase in emissions of the ten studies when comparing emissions from a high burn rate to those tests with low burn rates is 344%. In terms of burn rate distribution, it was assumed that the low burn rate in each study represented the 0 percentile and the high burn rate in each study represented the 100-percentile. To be conservative, it was further assumed that an average woodstove represents the 50-percentile and that the high HDD test locations used in AP-42 are at the high end of the spectrum, i.e., the 75-percentile, hence it was calculated that the average increase in particulate emissions from the AP-42 test group at the 75-percentile, to the average (50-percentile) corresponds to an increase of 86% (one quarter of the 344%). The 35.9 lbs/ton value discussed earlier was increased by 86% to 66.8 lb/ton to account for the lower burn rate effects on particulate emissions.

Table 4
The Effect of Burn Rate on Particulate Emissions from Conventional Woodstoves

Reference	High Burn Rate			Low Burn Rate			Difference in PM, % of High Burn PM
	PM, g/kg	Burn rate, kg/hr	n	PM, g/kg	Burn rate, kg/hr	n	
9	3.1	6.6	4	11.1	2.0	6	258
18*	3.5	7.1	2	7.7	3.8	3	120
19*	4.2	2.2	2	14.0	1.1	4	233
20**	5.8	2.9	2	25.1	1.4	2	333
21***	2.7	8.9	6	47.9	2.9	4	1674
22	23.6	3.7	2	62.6	1.6	2	165
8	15.5	4.8	1	46.6	1.1	1	201
23	13.3	3.2	3	22.7	1.4	3	71
24	29.0	4.8	1	53.4	1.2	1	84
25	7.6	4.0	1	30.4	0.7	1	300
avg	-	-	-	-	-	-	344

*Two runs with mid-burn rates were omitted.
**Three runs with mid-burn rates were omitted.
***Four runs with mid-burn rates were omitted.

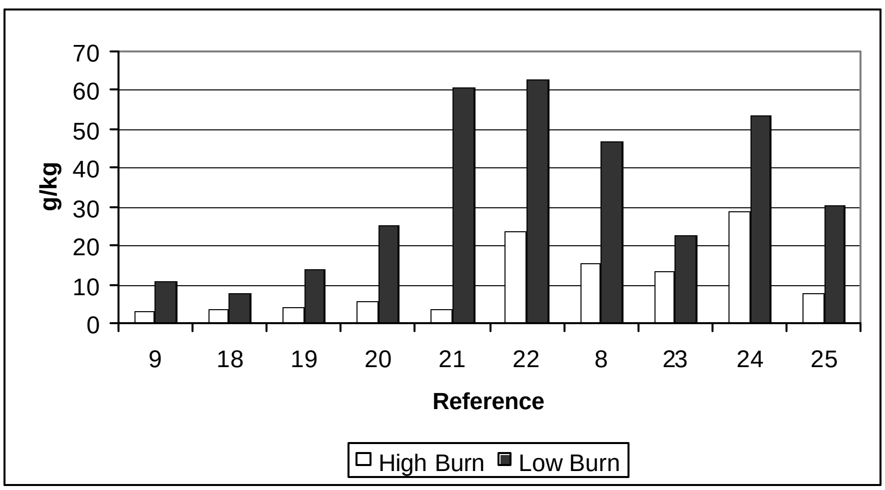

Figure 1. The Effect of Burn Rate on Particulate Emissions for Conventional Woodstoves

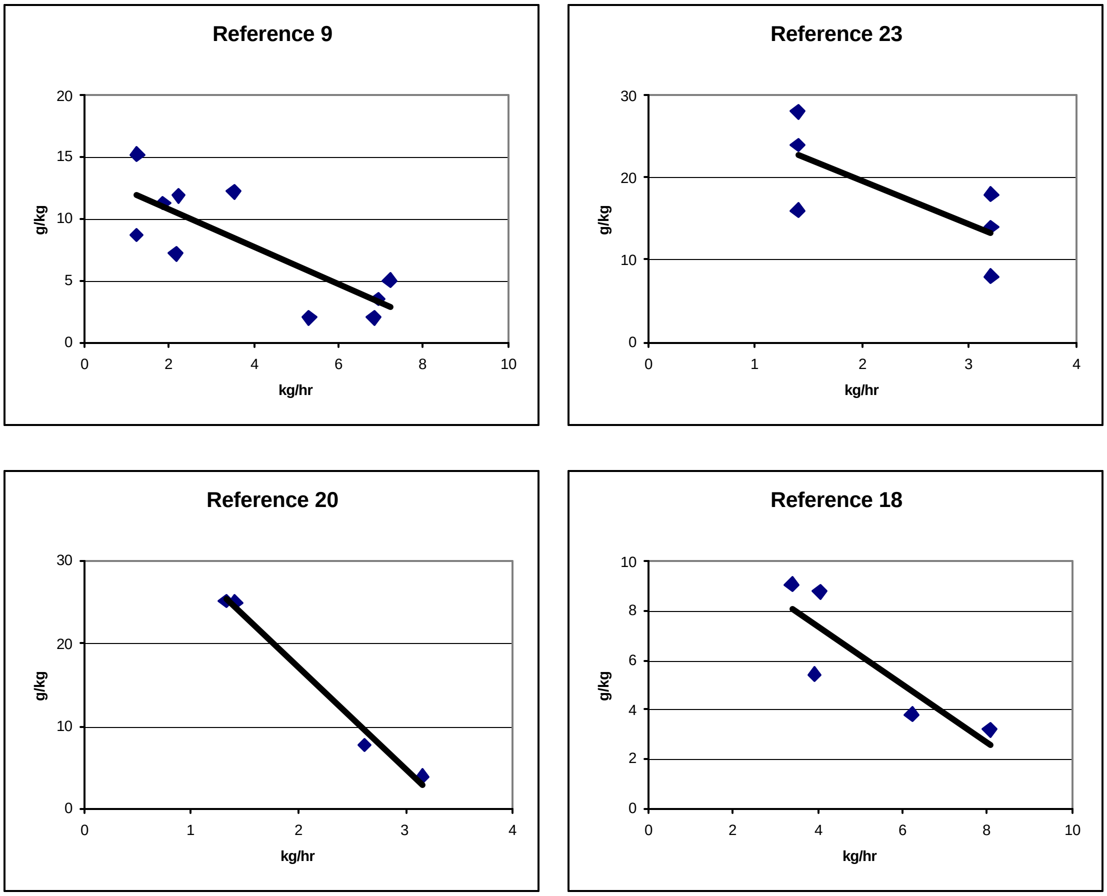

Figure 2. The Relationship between Burn Rates and Emission Factors for Pre-EPA Certified Conventional Stoves

In summary, conventional cordwood stoves in the U.S. as a whole and in the eastern U.S. $PM_{2.5}$ nonattainment areas have significantly higher emission factors than listed in AP-42 and revised emission factors should be used when calculating the emission benefits associated with the replacement of conventional uncertified woodstoves with a certified ones.

5. Efficiencies

Certified woodstoves and pellet stoves are more efficient than pre-EPA-certified conventional woodstoves. 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 stoves 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[26-40]. 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 liquid water to water vapor (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 liquid water to water vapor, 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) higher 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 this analysis.

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 calculating the benefits of woodstove changeouts because what is important for these calculations is the relative differences between pre-EPA-certified conventional cordwood stoves, certified cordwood stoves, and modern pellet stoves, not absolute values.

The NSPS wood certification protocol does not require efficiency to be measured but assigns default values[41]. The default values are 63% for certified non-catalytic woodstoves, 72% for certified catalytic woodstoves, and 78% for certified pellet stoves. AP-42 also lists efficiencies, but, except for pre-EPA-certified conventional woodstoves, they have been superceeded by more recent data. All are based on limited data sets. The efficiency for conventional woodstoves listed in AP-42 is 54%. Taking into account that the efficiency of catalyst stoves will become lower with use (catalyst degradation) and that modern exempt and certified pellet stoves are essentially the same, OMNI has used its best professional judgment to approximate, after reviewing all significant efficiency related reports and publications that could be located[1,26-41], reasonable efficiencies for pre-EPA-certified conventional cordwood stoves, certified catalytic cordwood stoves, certified non-catalytic cordwood stoves, and modern pellet stoves. These data are shown in Table 5 and are on the "North American" reporting convention basis.

Table 5
Efficiencies by Stove Type

Appliance Type	Efficiency
Conventional Cordwood Stove	54%
Non-catalytic Cordwood Stove	63%
Catalytic Cordwood Stove	63%
Pellet Stove	78%

In summary, the higher efficiencies of certified cordwood stoves and modern pellet stoves as compared to pre-EPA-certified conventional cordwood stoves should be taken into consideration when calculating the benefits of a woodstove changeout program. The fact that certified cordwood stoves and modern pellet stoves use less wood than conventional woodstoves for the same heating demand means that less $PM_{2.5}$ will be emitted.

6. $PM_{2.5}$ Emission Benefits

Table 6 summarizes the AP-42 emission factors, which are typically used for emission reduction benefits, and the adjusted emission factors calculated as outlined in this document.

Table 6
Cordwood and Pellet Stove $PM_{2.5}$ Emission Factors

	Conventional Woodstove (lb/ton)	Catalytic Certified Woodstove (lb/ton)	Non-catalytic Certified Woodstove (lb/ton)	Pellet Stove	
				Exempt (lb/ton)	Certified (lb/ton)
AP-42 Emission Factors	30.6	16.2	14.6	8.8	4.2
Adjusted Emission Factors	66.8	15.1	11.7	2.5	2.5

Table 7 shows the benefit in pounds of $PM_{2.5}$/ton dry fuel from a woodstove changeout on a per stove basis. The first row illustrates the benefit calculated by using AP-42 emission factors, the second row illustrates the benefit calculated by using the adjusted emission factors developed in this work, and the last row illustrates the benefit by utilizing the adjusted emission factors plus taking into account the improved efficiencies of new, modern stoves.

Table 7
$PM_{2.5}$ Emission Reduction Benefits with Changeout on a Per Stove Basis

Benefit calculated when using:	Conventional to Catalytic Certified Woodstove (lb/ton)	Conventional to Non-catalytic Certified Woodstove (lb/ton)	Conventional to Exempt Pellet Stove (lb/ton)	Conventional to Certified Pellet Stove (lb/ton)
AP-42 Emission Factors	14.4	16.0	21.8	26.4
Adjusted Emission Factors	51.7	55.1	64.3	64.3
Adjusted Emission Factors with Efficiency	53.9	56.8	65.1	65.1

Example calculations shown in Appendix B

To illustrate the potential reduction in $PM_{2.5}$ emissions through changeout, a realistic woodstove changeout scenario is presented. The hypothetical changeout consists of replacing 100 conventional woodstoves with 60 non-catalytic certified woodstoves, 20 catalytic certified woodstoves, and 20 modern pellet stoves. The average national annual cordwood usage value of 1.75 cord/stove[42] and cord-to-mass conversion factor of 1.4 tons/cord (typical of the eastern United States[43]) were used in the calculation of the annual $PM_{2.5}$ reduction. The amount of wood used by the new stoves was adjusted to reflect their increased efficiency. The resulting annual benefit for the realistic hypothetical changeout of 100 old conventional stoves is 14,180 pounds of $PM_{2.5}$, which corresponds to an 87% reduction in $PM_{2.5}$.

Table 8
Annual $PM_{2.5}$ Emission Reduction for a 100-Stove Hypothetical Changeout

Stoves	Fuel Use (tons dry fuel/ stove)	$PM_{2.5}$ Emission Factor (lbs/ton)	$PM_{2.5}$ Emissions (lbs/heating season)
100 Conventional Woodstoves	2.45	66.8	16,366
60 Non-catalytic Woodstoves	2.10	11.7	1470
20 Catalytic Woodstoves	2.10	15.1	634
20 Pellet Stoves	1.70	2.5	85
Annual Benefit for Changing Out 100 Stoves			14,177 (or 87 %)

7. Conclusions

Review of the existing published literature and reports supports significant $PM_{2.5}$ emission benefits for the replacement of conventional pre-EPA-certified cordwood stoves with phase 2 catalytic certified cordwood stoves, phase 2 non-catalytic certified cordwood stoves, and modern pellet stoves. The $PM_{2.5}$ reduction benefits per stove have been calculated as: (1) 53.9 lb $PM_{2.5}$/ton cordwood (dry basis) for the replacement of a conventional pre-EPA-certified cordwood stove with a phase 2 catalytic certified cordwood stove, (2) 56.8 lb $PM_{2.5}$/ton cordwood (dry basis) for the replacement of a conventional pre-EPA-certified cordwood stove with a phase 2 non-catalytic certified cordwood stove, and (3) 65.1 lb $PM_{2.5}$/ton fuel (dry basis) for the replacement of a conventional pre-EPA-certified cordwood stove with a modern pellet stove.

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Appendix A
Terminology, Conventions, and Problematic Issues

There are several regulatory, hearth industry, and air quality terms/issues associated with wood heaters that have caused considerable confusion and errors when dealing with wood heaters and their relation to air quality. These are:

- **Woodburning Fireplace Inserts** – Woodburning fireplace inserts, sometimes referred to as woodstove inserts, are cordwood stoves or pellet stoves designed to fit into an existing fireplace cavity. They are wood heaters as defined by the NSPS[1] and as such are required to be certified. Their emissions are essentially the same as freestanding cordwood stoves or pellet stoves and are grouped together here and in AP-42 with them. The term also causes several other problems: (1) manufactured fireplaces that are "inserted" into a wall are sometimes confused with fireplace inserts, (2) there are gas-fueled inserts that are sometimes simply referred to as inserts and are not separated from cordwood- or pellet-fueled inserts, and (3) because a fireplace must already be in a home to install a fireplace insert, in the development of activity data there can be a "double counting" of both the fireplace and the fireplace insert or the fireplace/fireplace insert set can be incorrectly counted as a simple fireplace.

- **Particulate Size** – The overwhelming majority of particles formed from residential wood combustion are condensed organic compounds and are submicron in size. While not rigorously correct, total PM, PM_{10}, and $PM_{2.5}$ are 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. There has not been adequate research conducted to accurately define the relationship among PM, PM_{10}, and $PM_{2.5}$ for residential wood combustion. Certainly the overwhelming majority of PM is $PM_{2.5}$. The submicron portion of PM for residential wood combustion has been generally considered to be in the 90% range. $PM_{2.5}$, PM_{10}, and PM have been used interchangeably in this analysis.

- **Particulate Sampling Methods** – There have been a number of particulate sampling methods used to measure particulate emissions from woodstoves. They include, EPA Method 5, EPA Method 5G, EPA Method 5H, EPA Modified Method 5 (Method 23), Oregon Method 7, VPI, AWES, ESS, an ASTM method, SRI dilution tunnel, Condar, SASS, 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[2-4], 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[5].

- **Wood 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 of 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., more than typically 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.)

- **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 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/hr. (3) The mass of emissions per unit of energy (either available in the fuel or delivered to the home). The convention is most useful when comparing very different fuels or heating appliances. 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.

- **Burn Rates –** As with emissions rates discussed in the previous section, 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 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.

- **Catalyst Degradation** – Catalysts degrade with use. While the rate of degradation depends on the stove model, the intensity of fires, and the total number of fires, the rule-of-thumb is that catalysts need to be replaced on the average of every five years. As the catalyst degrades, the particulate emission rate increases and the woodstove efficiency decreases. Because most catalytic stoves depend on the catalyst to mitigate particulate emissions usually there are minimal other design features incorporated into the stove for particulate reduction. Consequently, when a catalyst is fully degraded the particulate emissions of a catalyst stove is similar to that of an uncertified conventional stove. The issue of catalyst degradation is reflected in the lower NSPS "passing" threshold for catalytic stoves (4.1 g/hr) as compared to non-catalytic stoves (7.5 g/hr)1. At the time of promulgation, the reasoning behind the lower requirement for a catalyst stove was that over the normal life of the catalyst, the average performance of the stove will be similar to that of a non-catalyst stove that does not change its emission performance significantly with time. Similarly, the higher emission factor for catalytic phase 2 stoves (16.2 lbs/ton) listed in AP-42 as compared to non-catalytic phase 2 stoves (14.6 lbs/ton) is probably a reflection of testing appliances that have undergone some degradation.

- **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. This is particularly true for catalytic woodstoves as during the kindling phase the catalyst is physically bypassed by manually channeling combustion gases around it. Particulate emissions for catalytic stoves during the kindling phase range from two to five times higher than from a fuel load once the fire is established[6]. This suggests that certification values for catalytic woodstove are less accurate predictors for real-world in-home performance of a catalytic stove than for a non-catalytic stove.

- **Cord-to-Mass Conversion** – The activity (the amount) of cordwood used is usually reported in cords. Emission factors are reported in mass of pollutant per mass of dry wood, therefore cords need to be converted into mass for emission inventories and benefit analyses. The mass of wood in a cord varies with wood species with the most significant factor being the difference in the mass of hardwood (deciduous trees) versus softwood (coniferous trees). The conversion values reported in the literature range from approximately 1.2 tons/dry cord to about 1.8 tons/dry cord. OMNI's review of the type of trees used for fuel for most of the non-attainment areas east of the Mississippi River revealed that a value of approximately 1.4 tons/dry cord would be appropriate in most cases[7]. Nevertheless, a conversion factor needs to be developed for each area of interest based on the tree species used for fuel. It should also be noted that the mass of a cord of wood (128 ft^3) does not correspond to wood density due to the voids present in a stacked cord of wood.

References Appendix A

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Appendix B
Calculations

Calculations for Table 6: Adjusted Emission Factors

AP-42 conventional woodstove emission factor = 30.6 lb $PM_{2.5}$/ton fuel. (This is based on four in-home studies and two laboratory studies. The laboratory tests were based on only two stove models and the stoves were not operated representatively of real-world use.)

The average value when only using the in-home tests referenced by AP-42 = 35.9 lb $PM_{2.5}$/ton fuel.

The in-home test areas do not represent the $PM_{2.5}$ nonattainment areas east of the Mississippi River due to the very high HDD of the in-home test areas. Higher burn rates with commensurately lower particulate emissions are characteristic of colder climates. To adjust the emission factors to be more representative of lower burn rates, emission factor data from high and low burn rates from ten reports were identified. Using the data from the ten reports, the average increase in emission factors when going from the high burn rates to the low burn rates was calculated as 344%. With no data to correlate HDD to burn rate, it was assumed that the low burn rate represented the 0 percentile in each report and the high burn rate represented the 100-percentile in each report. Assuming that the average woodstove represents the 50-percentile and that the high HDD test locations used in AP-42 are at the high end of the spectrum, i.e., the 75-percentile, it was calculated that the average increase in particulate emissions from the AP-42 test group at the 75-percentile, to the average (50-percentile) corresponds to an increase of 86% (one quarter of the 344%). The 35.9 lb $PM_{2.5}$/ton value discussed earlier was increased by 86% to 66.8 lb $PM_{2.5}$/ton to account for the lower burn rate effects on particulate emissions. In summary, the adjusted conventional woodstove emission factor = (In-home Emission Factor) + (Increase), i.e., 35.9 lb $PM_{2.5}$/ton + ([35.9 lb $PM_{2.5}$/ton] X 0.25 X 3.44) = 68.8 lb $PM_{2.5}$/ton.

AP-42 catalytic certified woodstove emission factor = 16.2 lb $PM_{2.5}$/ton. (This was based on only the first generation of phase 2 certified woodstoves.)

Adjusted catalytic certified woodstove emission factor = emission factor multiplied by the average certification value of phase 2 stoves certified in the last 5 years divided by the average certification value of phase 2 stoves certified in the first five years of the certification program, i.e., (16.2 lb $PM_{2.5}$/ton) X ([2.7 g $PM_{2.5}$ /hr]/[2.9 g $PM_{2.5}$ /hr]) = 14.7 lb $PM_{2.5}$/ton

AP-42 noncatalytic certified woodstove emission factor = 14.6 lb $PM_{2.5}$/ton. (This was based on only the first generation of phase 2 certified woodstoves.)

Adjusted noncatalytic certified woodstove emission factor = emission factor multiplied by the average certification value of phase 2 stoves certified in the last 5 years divided by the average certification value of phase 2 stoves certified in the first five years of the certification program, i.e., (14.6 lb $PM_{2.5}$/ton) X ([4.1 g $PM_{2.5}$/hr] / [5.1 g $PM_{2.5}$ /hr]) = 11.7 lb $PM_{2.5}$/ton.

AP-42 has emission factors for exempt and certified pellet stoves but today there is little distinction between the performances of either. Today the average certification value of certified pellet stoves is 1.4 g $PM_{2.5}$ /hr. The certification tests are run at a realistic 1.16 kg fuel /hr burn rate.

Adjusted pellet stove emission factor = (1.43 g $PM_{2.5}$/hr) / (1.16 kg fuel/hr) X (2 [lb/ton]/ [g/kg]) = 2.5 lb $PM_{2.5}$/ton.

Example Calculation for Table 7: Reduction Benefits with Changeout of a Conventional Woodstove with a Noncatalytic Certified Woodstove

Reduction benefit = conventional woodstove emission factor – noncatalytic certified woodstove emission factor.

1) Reduction benefit using AP-42 emission factors.

(30.6 lb $PM_{2.5}$/ton dry wood) – (14.6 lb $PM_{2.5}$/ton dry wood) = 16.0 lb $PM_{2.5}$/ton dry wood.

2) Reduction benefit using adjusted AP-42 emission factors.

(66.8 lb $PM_{2.5}$/ton dry wood) – (11.7 lb $PM_{2.5}$/ton dry wood) = 55.1 lb $PM_{2.5}$/ton dry wood.

3) Reduction benefit using adjusted AP-42 emission factors and accounting for increase in efficiency.

(66.8 lb $PM_{2.5}$/ton dry wood) – ([11.7 lb $PM_{2.5}$/ton dry wood] X [54 % $_{\text{eff. conv.}}$ / 63 % $_{\text{eff. noncat}}$]) = 56.8 lb $PM_{2.5}$/ton dry wood.

Example Calculation for Table 8: Annual $PM_{2.5}$ Reduction from a Hypothetical 100-Stove Changeout

Mass fuel use = (Cord Use) X (Cord-to-Mass Conversion).

(1.75 cord/stove/year) X (1.4 tons/cord) = 2.45 tons/stove/year.

$PM_{2.5}$ emissions from 100 conventional woodstoves = (Mass Fuel Use) X (Emission Factor) X 100.

(2.45 tons/stove/year) X (66.8 lb $PM_{2.5}$/ton) X 100 = 16,366 lb $PM_{2.5}$/year.

$PM_{2.5}$ emissions from 60 noncatalytic certified woodstoves = (Fuel Use Adjusted for Efficiencies) X (Emission Factor) X 60.

(2.45 tons/stove/year) X (54 $\%_{eff.\ conv.}$ / 63 $\%_{eff.\ noncat.}$) X (11.7 lb $PM_{2.5}$ /ton) X 60 = 1474 lb $PM_{2.5}$/year.

$PM_{2.5}$ emissions from 20 catalytic certified woodstoves = (Fuel Use Adjusted for Efficiencies) X (Emission Factor) X 20.

(2.45 tons/stove/year) X (54 $\%_{eff.\ conv.}$ / 63 $\%_{eff.\ cat.}$) X (15.1 lb $PM_{2.5}$ /ton) X 20 = 634 lb $PM_{2.5}$/year.

$PM_{2.5}$ emissions from 20 pellet woodstoves = (Fuel Use Adjusted for Efficiencies) X Emission Factor) X 20.

(2.45 tons/stove/year) X (54 $\%_{eff.\ conv.}$ / 78 $\%_{eff.\ pellet}$) X (2.5 lb $PM_{2.5}$ /ton) X 20 = 85 lb $PM_{2.5}$/year

Benefit of changeout = (emissions from 100 conventional stoves) – (emissions from 60 noncatalytic woodstoves) – (emissions from 20 catalytic certified woodstove) – (emissions from 20 pellet stoves).

(16,366 lb $PM_{2.5}$/year) – (1474 lb $PM_{2.5}$/year) – (634 lb $PM_{2.5}$/year) – (85 lb $PM_{2.5}$/year) = 14,173 lb $PM_{2.5}$/year.