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Residential Wood Combustion Technology Review
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Abstract

A review of the current states-of-the-art of residential wood combustion (RWC) was conducted. The key environmental parameter of concern was the air emission of particles. The technological status of all major RWC categories was reviewed. These were cordwood stoves, fireplaces, masonry heaters, pellet stoves, and wood-fired central heating furnaces. Advances in technology achieved since the mid-1980's were the primary focus. These study objectives were accomplished by reviewing the published literature and by interviewing nationally recognized RWC experts.

The key findings of the review included: (1) The NSPS certification procedure only qualitatively predicts the level of emissions from wood heaters under actual use in homes, (2) Wood stove durability varies with model and a method to assess the durability problem is controversial, (3) Nationally the overwhelming majority of RWC air emissions are from non-certified devices (primarily from older non-certified woodstoves), (4) New technology appliances and fuels can reduce emissions significantly, (5) The ISO and EPA NSPS test procedures are quite dissimilar and data generated by the two procedures would not be comparable, and, (6) The effect of wood moisture and wood type on particulate emission appears to be real but to be less than an order of magnitude.

Executive Summary

A review of the current states-of-the-art of residential wood combustion (RWC) was conducted. The key environmental parameter of concern was the air emission of particles. The technological status of all major RWC categories was reviewed. These were cordwood stoves, fireplaces, masonry heaters, pellet stoves, and wood-fired central heating furnaces. Advances in technology achieved since the mid-1980's were the primary focus. In addition to RWC technology, several other related topics were reviewed. These topics included: (1) The evaluation of the U.S. Environmental Protection Agency (EPA) and the International Organization for Standardization (ISO) test methods for wood stoves, (2) The evaluation of in-home, long-term durability and emission performance of certified wood stoves, and, (3) The assessment of the effects of fuel wood types (tree species) and moisture on particulate emission factors. These study objectives were accomplished by reviewing the published literature and by interviewing nationally recognized RWC experts.

Taken as a group, the durability of currently manufactured certified Phase II wood stoves has improved and their particulate emissions are lower than the earliest Phase II models that became available circa 1990. However, there appears to be considerable variation by model within the group and the improvements seen over the earliest models have been described as marginal. Certainly, as a group, Phase II models are better than Phase I models and superior to uncertified models. There has been little incentive for manufacturers to improve durability beyond severe problems that would precipitate warranty claims. (Cordwood stove sales for 1997 were less than one-half of their 1990 level.) The efficacy of a laboratory stress test developed to predict long-term, in-home performance is controversial. The deterioration of catalytic activity often seen in catalytic wood stoves in a three to five year time frame and the identification of viable approaches to ensure catalyst inspection/replacement continue to be unaddressed problems. Wood stoves are designed out of necessity to pass the EPA certification test. It is generally recognized the these tests do not simulate the way that a stove is used in the “real world.” Consequently, emission results obtained from certification tests are only roughly predictive of how a wood stove will perform under actual in-home use. However, the general perception is that stoves that show low emissions in the certification testing will also do well in homes. The current status of stove efficiencies is difficult to assess since, while there is an efficiency test method published in the Federal Register, efficiency testing is not required during the certification process.

The EPA certification procedure has been described as an art. Achieving a successful low burn rate condition and coal bed preparation are particularly challenging and they are quite unlike how a stove is usually used in a home.

There are two particulate test methods that can be used as part of the certification procedure, Method 5G and Method 5H. To make the results obtained from these two methods comparable a conversion equation was developed. The data available to develop the conversion equation were limited. The equation has been widely criticized and it is generally believed that after the conversion the 5G method will produce higher emission values than the 5H method. Method 5G is more precise and less difficult (and less costly) than 5H. It is the opinion of many that only the

5G method should be used, but if the two methods are continued to be used, the relationship between 5G and 5H should be re-evaluated.

With regards to the ISO 13336 test standard, at its current status of development, it is too different from the EPA certification methods to have anything but a qualitative correlation (i.e., stoves that show low emissions in the EPA certification will probably also show low emissions using the ISO 13336 test standard). Although the ISO 13336 standard is not final at this time, there is significant work being done in New Zealand, Australia, and in Europe to make the standard compatible or at least correlatable to the U.S. EPA methods and the European Community standards now being developed.

Approximately one quarter of the cordwood burned annually in residences in the United States is in fireplaces. There is no federal certification for fireplaces, although two states (Washington and Colorado) now have a certification program. Some fireplaces are used as significant heat sources and some are used for aesthetic or minor heating purposes. For fireplaces used as significant heat sources there are a number of older technologies (e.g., glass doors, heat convection tubes, and shaped masonry fireboxes) that effectively reduce emissions. In addition, there are certified cordwood and pellet inserts as well as gas inserts that can be installed within the fireplace that reduce effective emissions dramatically. For fireplaces used for aesthetic or minor heating purposes decorative gas logs and wax firelogs can be used to reduce emissions. There has been some research on cleaner burning fireplaces that minimize under-fire air and that utilize secondary combustion to reduce emissions but they are not yet commercially available. There is no significant marketing or, with the possible exception of the two state standards, no regulatory incentives to manufacture low emission fireplaces.

The technological status of three other less common RWC categories was also reviewed. These were: pellet stoves, masonry heaters and wood-fired central heating furnaces. There are about 0.3 million pellet stoves currently in homes. There are certified and exempt units. Modern pellet stoves (both certified and exempt) are very efficient and have very low emissions. Many early models had mechanical and electronic problems. These problems have been largely solved and new units have a good performance record. Pellet fuels have also become standardized which contributes to the success of pellet stoves. Masonry heaters produce low particulate emissions through high-temperature, short-duration combustion of cordwood that transfers heat to a high masonry mass. The masonry mass radiates heat after the fire is out. Masonry heaters are exempt from certification and few are in use due to their high cost. Less than 0.3 million wood-fired central furnaces were in use in 1993. They are exempt from certification. Little research has been conducted on them. The limited emission data that are available show their emission factors to be higher than conventional wood stoves.

The effect of wood type (tree species) and wood moisture on emission factors cannot be accurately quantified with existing data. Due to the physical and chemical differences in hardwoods and softwoods it would be reasonable to expect that their particulate emission factors would be different. However, based on limited data, the effect of wood type and wood moisture on emission factors appears to be smaller than an order of magnitude.

Table of Contents

Volume 1

Volume 2 - This volume is available from NTIS: Order #PB99-122129

List of Tables

1. Introduction

Air emissions from residential wood combustion (RWC) became a topical issue in the 1980's. Of most concern were particulate (PM), polycyclic organic matter (POM) and carbon monoxide (CO) emissions. The perceived need to reduce air emissions was the impetus behind the New Source Performance Standard (NSPS)[1] certification requirement for wood heaters and for the considerable RWC design and emissions research conducted in that decade. Manufacturers of wood heaters made major product changes in the late 1980's to meet the July 1, 1990 NSPS deadline that required all heaters manufactured after that date to be certified to Phase II emission limits. Emissions and appliance design research has also been conducted on other RWC appliance types currently exempt from the NSPS certification requirements: i.e., cookstoves, furnaces, appliances with air to fuel ratios greater than 35:1, and appliances weighing more than 800 kilograms.

Two key issues that continue to be of concern are (1) that the emission control performance of wood stoves operated in homes does not match laboratory certification results, and (2) that in-home emission control performance for some stoves becomes poorer over time. Other unresolved issues include how fuel moisture and fuel wood effect emissions, the efficacy of, and relationships between test methodologies, and the effectiveness and feasibility of routine appliance maintenance for reducing emissions. The difficulty in resolving or quantifying cause-and-effect relationships for these issues as well as for other RWC questions is due to the large number of interrelated variables associated with RWC. There are many hundreds of types and models of wood burning devices in use, many dozens of tree species are commonly used for wood fuel, draft characteristics vary (e.g., chimney and temperature conditions), household altitude is variable, there are variations in fuel wood seasoning and storage practices (i.e., wood moisture) and there are wide variations in the operation of wood burning devices (e.g., burn rate, burn duration, damper setting, kindling approach).

To assess the current level of understanding of key issues and to evaluate the overall states-of-the-art of RWC, OMNI Environmental Services. Inc. (OMNI) was contracted by the U.S. Environmental Protection Agency (EPA) to review the published literature and to interview recognized experts in the RWC field. Emphasis was placed on the advances made and knowledge gained since the 1980's. Nine RWC experts were interviewed. The experts interviewed included representatives from the hearth products industry, academia, government researchers and wood stove testing laboratories. An interview briefing package containing a list of topics for discussion was prepared and provided to each interviewee prior to being interviewed. In addition to the nine experts, OMNI staff have provided narrative and organizational input. OMNI is one of the oldest research and testing facilities for RWC. It developed the first certification testing protocol (for the State of Oregon) and has been conducting RWC testing and research since 1979. The Hearth Products Association (HPA) which is a trade organization representing the hearth products and solid fuel industries also provided comments. These comments were unsolicited and outside the scope of this project, however because they represented a synopsis of the opinions of 27 industry experts expressed at an HPA-sponsored technical committee meeting, they were incorporated into this review. OMNI has also prepared a preliminary list of relevant RWC literature which was distributed to each of the interviewees with a request for any additional available literature not contained in the preliminary list. With the references supplied by the expert interviewees included, a total of 417 references were compiled for the review.

A broad spectrum of residential wood burning technology was evaluated. Twelve topics identified by the EPA provided the basis for the interviews, for the HPA comments and for the literature review. These were:

- State-of-the-art of wood stove combustion and emission control technologies
- State-of-the-art of fireplace emission control technology
- State-of-the-art of wood-fired central heating furnace emission control technology
- State-of-the-art of pellet-fired wood stove technology
- Ramifications of the International Organization for Standardization (ISO) draft standard WD 13336[2]
- Correspondence between in-home and laboratory emission test results
- EPA Method 28[3] strengths and weaknesses
- EPA Methods 5G[4] and 5H[5] correlations
- Performance deterioration of EPA-certified wood stoves in the field
- Stress (durability) test pros and cons
- Feasibility of developing separate emission factors for dry and wet wood and for softwood and hardwood species classes
- Routine maintenance of appliances

For many issues, a consensus among the experts was not obtained. In these cases key conflicting viewpoints have been presented. In some cases, minority viewpoints were not discussed in the text because the published literature and the comments from the other experts clearly did not support them. However, for the sake of including all viewpoints, complete review transcripts are contained in Appendix B to this report.

A summary of the findings for each of the twelve topics constitutes the body of the report. The list of published literature is contained in Appendix A. The list of expert interviews, the interview briefing package and the individual interview summaries are provided in Appendix B. A list of the attendees at the HPA technical committee meeting and the synopsis of the attendees opinions provided by the HPA are in Appendix C.

2. Review Topics

2.1 State-of-the-Art of Cordwood Stove Combustion and Emissions Control Technologies

Based on commercial marketing surveys there are an estimated 9.3 million cordwood stoves in use in the United States. From HPA surveys of manufacturers it is estimated that about 0.6 million of these are certified, non-catalytic cordwood stoves and about 0.4 million are certified catalytic cordwood stoves (i.e., there are about 8.3 million old conventional cordwood stoves and about 1.0 million certified cordwood stoves in use in the United States). The term “conventional” is used in this report to indicate non-certified wood burning stoves that were primarily produced before the advent and use of design factors for reducing or controlling wood stove pollutant emissions. All stoves manufactured after July 1, 1988 and sold after July 1, 1990 had to be certified to Phase I particulate emission levels. All stoves manufactured after July 1, 1990 and sold after July 1, 1992 had to be certified to the lower Phase II particulate emission levels. On August 12, 1997, 121 non-catalytic cordwood stove models and 87 catalytic cordwood stove models (including fireplace inserts) were listed as certified to Phase II standards.

Particulate emission factors and efficiencies for conventional and phase II certified cordwood stoves have been tabulated by EPA in AP-42[6]. The general consensus among interviewees is that the emission factor given in AP-42 for conventional wood stoves is lower than the average that would be representative of the United States as a whole and that due to improvements in certified wood stoves, emission factors in AP-42 for Phase II certified cordwood stoves are higher than for newly manufactured appliances. There is persuasive, albeit anecdotal, evidence for both assertions.

The average emission factor for conventional wood stoves is based on studies conducted in homes in Vermont; upstate New York; Portland, Oregon; Whitehorse, Yukon; Klamath Falls, Oregon; and Crested Butte, Colorado. The average value reported in AP-42 is weighted based on the number of tests. The total number of tests that make up the data base is 141. There were 53 tests conducted in Whitehorse and 59 tests conducted in Crested Butte, consequently the average is determined to a large part by the Whitehorse and Crested Butte data. The heating degree day (HDD) value for Whitehorse is 9545 and for Crested Butte it is 11,500, both of which are much higher than most of the wood burning areas of the United States. For example, in 1993 the U.S. Department of Energy (DOE) reported that 32% of the cordwood consumed in the United States for RWC was consumed in the South census region[7]. It has been well established that higher burn rates (hotter more complete combustion conditions) characteristic of colder climates produce lower emissions. Therefore it is reasonable that the actual national average particulate emission factor for conventional wood stoves is higher than the generally accepted value reported in AP-42. (Several caveats should also be noted in regards to the effect of the Crested Butte data on the calculation of the national average emission factor value. While the effect of a colder climate [i.e., higher burn rate] would be to reduce the magnitude of emission factors, the effect of Crested Butte's unusual 8850 foot [2697 meter] altitude and the effect of the dry wood burned in many of the homes during the studies would tend to increase the emission factor. In addition a different sampling system was used in Crested Butte than in the other studies which may cause the data to be offset with respect to the other data [see Section 2.6].)

In addition, to lower burn rates potentially producing higher emissions in milder climates the fact that the highest emission rates occur during the kindling phase of a burn is also significant. There are some data that suggest that as much as one-half of the total emissions for an individual burn period for non-catalytic stoves occur during the kindling phase (first 17% of a burn) and more than 50% occur for that time period for catalytic stoves[8]. In warmer climates fires tend to be started and allowed to burn out more frequently than in colder climates hence the kindling phase portion of the burn period will contribute relatively more to the overall emissions in warmer climates than in colder ones. Another related observation was that stoves purchased in the Western United States tend to have larger fireboxes than those purchased elsewhere, hence if all else is equal stoves in the Western United States will have higher emissions since emissions tend to be higher for larger firebox appliances for a given burn rate because combustion temperatures are not as high in a larger firebox.

The emission factors for Phase II certified stoves in AP-42 are also based on studies conducted in homes. The data set is also over represented by stoves located in colder climates although not as much so as for the conventional stove data set. The key issue for emission factors given in AP-42 for Phase II certified stoves is the fact that they are based on studies conducted in homes during the 1989/90 heating season or earlier. Consequently, only the earliest Phase II certified models or models that eventually became Phase II certified, were included in the averages for AP-42. Manufacturer representatives commented that improvements have been made on many of the certified models in regard to the durability of construction materials, there have been many new models introduced and certified since July 1, 1990 and many models that had durability issues or that were manufactured by smaller less established companies are no longer available. This is supported by the observation that more than one third of the wood stove models listed in the EPA August 12, 1997 certified stove list are no longer offered. The key motivation for improved durability has been financial due to the cost of repairing or replacing stoves under warranty.

Using AP-42 data as a starting point, Table 2.1-1 was prepared. It represents the AP-42 data qualitatively adjusted based on "best professional judgment" to take into consideration climate and model improvement factors. This table was provided to the nine experts and to the HPA technical committee for comment. While a spectrum of comments was received, the overall consensus appeared to be that the values shown in Table 2.1-1 were reasonable. Table 2.1-1 also shows the percent reduction in emission factors achievable with the replacement of conventional cordwood stoves with certified catalytic and non-catalytic models.

The efficiency of a wood heater is an important factor in assessing emissions and in comparing emission reductions offered by new technology appliances since a more efficient device will use less wood to provide the same heat which produces an effective emissions reduction. Efficiencies of cordwood stoves have been tabulated in AP-42 based on field studies. The interviewees noted, as with emission factors, there is a range of efficiency values for a given technology type but in general agreed that the average values shown in AP-42 are more-or-less reasonable with the exception of the value for catalytic cordwood stoves which should be slightly higher to reflect newer or well maintained units. The catalytic cordwood stove value shown in AP-42 is 68%. The default efficiency value used for U.S. EPA NSPS certification is 72%. The latter value was felt to be more representative of new or well-maintained catalytic stoves. Efficiency values are given in Table 2.1-2 along with particulate emissions in units of mass particles per amount of heat delivered. Table 2.1-2 also shows the percent reduction in emissions when a conventional cordwood stove is replaced with a certified catalytic or non-catalytic cordwood stove. One very relevant comment was that for non-catalytic stoves, some less efficient units may produce less emissions (if all else is equal) since higher temperature gases which produce a greater sensible heat loss may also promote tertiary combustion downstream of the baffle. Unfortunately, the relationship between efficiency and emission factors cannot be determined since efficiency testing is not required during the certification process and default values are usually used.

There is currently no strong impetus to improve or test wood stove efficiency. There is a well documented efficiency test method published as a proposed method by the U.S. EPA[9]. Opinions among experts were split regarding the appropriateness of testing efficiency. Some felt that a requirement to test efficiency would add additional and unacceptable costs for appliances that have a small market, plus many of the manufacturers feel they are already over regulated. Others felt that adding efficiency to the emission testing would only add a very small incremental cost to certification testing since most of the information needed for efficiency calculations is already obtained during the NSPS certification process as it now stands.

Related to the determination of efficiency is the use of emissions per unit of heat delivered to rank the performance of stoves since efficiency is needed to calculate emissions in this fashion. Some felt that since emissions in the units of mass of particles per mass of fuel burned (g/kg) and mass of particles per hour of stove operation (g/hr) are already in common use, that another unit (g/MJ or lb/MBtu) may cause confusion and may require additional education of the public and regulators. Others felt it was the most appropriate way to assess emissions since the emissions per amount of heat delivered is the environmental “bottom line” for a heating appliance.

Table 2.1-1

"Best Professional Judgement" Particulate Emissions Factors and Their Reduction by the Use of Alternatives to Conventional Stoves and Cordwood

Appliance	Particulate Emissions Factor		
	Pounds/Ton	Grams/Kilogram	Reduction (%)
Conventional Stove	37	18.5	--
Non-Catalytic Stove	12	6	68
Catalytic Stove *	13	6.2	65
Pellet Stove	4	2	89
Masonry Heater	6	3	84
Conventional Stove with Densified Fuel	25	14	24

* With a well maintained catalyst after normal use, on the average a newer catalyst will produce lower emissions and an older catalyst higher emissions.

The general perception is that the emission reduction performance of Phase II wood stoves has improved marginally over the earliest certified models. They have become more reliable and durable. For example, most manufacturers originally offered only one-year warranties, now prorated five-year warranties are common. The major incentive for the improvements has been the cost of warranty replacements and marketplace competition.

Laboratory and in-home research has shown that exposure to high temperature during very high burn rates and under high draft conditions accelerates the degradation process. For non-catalytic stoves, warping and cracking of the baffles and secondary air tubes are the most common form of degradation seen and can cause higher emissions due to their adverse effects on secondary combustion characteristics. The two most common degradation effects seen in catalytic stoves are damage to the catalyst bypass and the deterioration of the catalyst itself either through physical breaking, pealing or plugging or through the loss of catalytic activity. Under normal use the emissions of particles from most catalytic wood stoves will increase, in some cases reaching conventional stove levels within five years of use due to the loss of catalytic activity.

It should be noted that the routine replacement of a catalyst is a simple procedure for many models. The catalyst bypass is susceptible to damage due to the fact that it is a moving part. If it does not seal properly a fraction of the emissions bypasses the catalyst and enters the atmosphere

Table 2.1-2

"Best Professional Judgement" Efficiencies, Particulate Emission per Unit of Heat Delivered, and Effective Pollutant Reduction by the Use of Alternatives to Conventional Stoves and Cordwood

Appliances	Efficiency (%)	Mass Particulate Emissions/Delivered Heat		
		lb/MBtu	g/MJ	Reduction (%)
Conventional	54	3.89	1.68	-
Non-cat. Stove	68	1.14	0.49	71
Catalytic Stove*	72	1.02	0.44	74
Pellet Stove	78	0.31	0.13	92
Masonry Heater	58	0.59	0.25	85
Conv. with Densified Fuel	57	2.79	1.20	27

*With a well maintained catalyst after normal use, on the average a newer catalyst will produce lower emissions and an older catalyst higher emissions.

untreated. In most cases the repair of a catalyst bypass system needs to be performed at the manufacturer's facility. Another minor problem common to both catalytic and non-catalytic stoves, is the deterioration of the fuel loading door gasket material causing leaks and commensurate excess combustion air. Faulty door gaskets are typically noticeable to casual observers and easily replaceable.

As discussed previously, most interviewees felt that performance and durability improvements have occurred since the advent of Phase II of the U.S. EPA NSPS but they have been marginal. They also felt that further improvements are possible but there is little incentive at this time for the improvement of fundamental catalyst technology applied to RWC since the current technology meets NSPS requirements and because there are so few catalytic wood stoves currently being sold. It should be noted however, that some early models of catalysts failed due to substrate disintegration and this problem was addressed and is not seen in current models. There is also little incentive for a wood stove manufacturer to change the design of a wood stove even slightly to improve performance because all new, updated safety and emissions testing would need to be performed for the "new model."

An interesting observation was made by one interviewee. If a catalyst were used that would withstand temperatures just a few hundred degrees higher than those currently generated in a wood stove catalyst, even if it cost 50% more than currently used catalysts, there would be a dramatic improvement in performance and durability. The current cost of a catalyst represents less than 10% of the costs of a catalyst stove.

Beyond the issue of catalysts, the overall opinion regarding future wood stove performance improvements was relatively consistent: they can be made but there is little incentive to do so. Stoves are designed to pass safety and EPA certification tests and to garner a market share primarily through cost and appearance. The reduction of emissions under in-home use conditions and post warranty durability are not important market factors. With the exception of addressing gross durability issues which cause warranty problems it is unlikely that significant improvements will be made in wood stove durability.

One additional point is worth noting. State and local air quality authorities can require wood stove emission limits lower than those required by the EPA which, of course, can provide impetus for improvements in wood stove designs. The State of Washington's regulation (Washington Administrative Code 150-31-200) is an example of a more stringent regulation. Once stoves are designed to meet more stringent state or local regulations, they will be sold in other jurisdictions as well.

Non-catalytic stoves obtain their emission reduction with the use of geometry, secondary air, heat retaining refractory material and insulation. These factors are "tuned" to optimize lower emissions from the burn cycle requirements specified in the U.S. EPA NSPS Method 28 certification procedure. Most challenging is combining these factors to produce low emissions at the low burn rate conditions and within the constraints of the five-minute test period start-up procedures specified in Method 28. It is generally felt that the low burn rate and five-minute start-up procedure specified in Method 28 are "artificial" in that stoves are not used in homes in a manner that approximates the Method 28 low burn rate and start up procedure. The other major comment is that stoves are designed to produce low emissions while burning dimensional lumber with fixed spacing, not cordwood loaded in a stove in the "normal" fashion.

Catalytic stoves are less sensitive to burn rates and patterns than non-catalytic stoves since once the catalyst is "ignited" emission reduction is controlled by the catalyst. Similarly, the internal design of a catalytic stove, other than designing the unit to avoid direct flame impingement on the catalyst surfaces and optimizing its temperature exposure, requires less engineering than a non-catalytic stove. As a consequence of catalyst being less sensitive to stove design, catalytic stoves with larger fireboxes than non-catalytic stoves can achieve low enough emissions to be certified.

As previously discussed, in home use, a large fraction of the particulate emissions from wood stoves occurs during the kindling phase before the stove reaches its optimum operating temperatures and in the case of catalytic stoves, before the catalyst is ignited. Also as previously discussed, the problem of high emissions during the kindling phase is relatively more important in warmer climates or in the spring and fall when the stoves are allowed to burn out between fuel loads and there are more cold starts. The use of high heat content starter wax logs or the use of natural gas to rapidly bring temperatures up to the point at which secondary combustion occurs or to reach the ignition temperature of the catalyst, have the potential of reducing emissions significantly. Preheating the catalyst with an electric heater has also been suggested. However, again, there are no significant incentives for advancing current technologies.

The use of densified fuel logs as a fuel has been shown to reduce particulate emissions in the 20% to 30% range as compared to cordwood (Tables 2.1-1 and 2.1-2). Densified fuel is most readily available in the Western United States. For the purposes of this discussion, the term “densified fuel” is used to describe those manufactured fuel logs which contain only compressed wood materials (e.g., chips, sawdust, etc.) in contrast to wax fire logs which contain about 60% petroleum wax and are burned in fireplaces. Densified fuel is clean, uniform in size, and convenient, however it costs about 70% more than cordwood. Some interviewees felt densified fuel offered a viable option for reducing emissions, others felt that it did not since many wood stove users are low income and either cut their own fuel wood or could not afford the additional cost of densified fuel. In urban or suburban areas where air quality is more often an issue the use of densified fuel may be more viable than in rural areas. Not only is wood cutting less of an option in urban and suburban areas but the distribution of a commercial product such as densified fuel is easier there. It is also the opinion of some interviewees that wood stove users in urban and suburban areas are on the average more affluent than in rural areas, hence the added cost of purchasing fuel is less of an issue for suburban and urban wood users. In any case, it was expressed that densified fuel does offer the potential to significantly reduce emissions during short-term episodic air pollution events when burned as a cordwood replacement in existing certified or conventional wood stoves.

The discussion on masonry heaters has been included in this section along with wood stoves because masonry heaters are more closely allied to wood stoves in their use than to fireplaces. Like wood stoves, they burn cordwood primarily for heating whereas fireplaces are more often used for aesthetic, recreational, or only for minor heating purposes. The emission factors and efficiencies given in AP-42 and shown in Tables 2.1-1 and 2.1-2 for masonry heaters are based on in-home studies conducted in the early 1990’s. Most interviewees were in agreement that the values are reasonable for the emission factor and efficiency of the current state-of-the-art masonry heater, although it was noted that there is a range of values for different models and operation conditions. Masonry heaters achieve their low emissions by burning wood at a high rate (i.e., high temperature complete-combustion conditions) during a short time period. A large mass of masonry material is heated rapidly by the high-temperature fast-burning fuel load. The “stored heat” is then radiated from the masonry materials into the space being heated after the fire is out. Efficient heat transfer is achieved by a folded flue system which runs through the masonry material. In contrast to fireplaces, which are most often located along the outside wall of a home, masonry heaters are generally located toward the center of a home to facilitate heat transfer and also in contrast to fireplaces, masonry heaters typically have combustion air controls.

Because masonry heaters weigh in excess of 800 kg, they are exempt from EPA NSPS certification requirements. However, both the State of Colorado's Regulation 4 and Canada's R-2000 high-efficiency home program have certification procedures for masonry heaters. Some interviewees felt that there should be no EPA certification required for masonry heaters because there are so few in use. The majority felt that they should be certified to provide them with a level of credibility and acceptance, however, those who felt that they should be certified agreed that the certification protocol would need to be conceptually and practically quite unlike that used for wood stoves due to the typical single, high burn rate and large mass of masonry heaters. Emissions expressed in g/hr units are meaningless for masonry heaters due to the fact that their heat release is not contemporaneous with their fuel burn cycle. Emissions expressed in g/kg or g/MJ are more meaningful.

Because masonry heaters and masonry fireplaces can be similar in appearance and construction, conceptually there could be units that would fall between those that are clearly masonry heaters and those that are clearly fireplaces. It was felt important that a definition be established distinguishing the two appliance types. One suggestion for delineating the two appliance types was an efficiency threshold in the 40% to 50% range, another was to develop a narrative description of the flue and air control systems. The Masonry Heater Association of North America (MHA) has developed a definition based on construction materials, techniques, and specifications along with surface temperature performance requirements.

2.2 State-of-the-Art of Fireplace Emissions Control Technology

There are 27 million fireplaces currently in U.S. homes. Some fireplaces are used as supplemental heat sources, some are used for only aesthetic or minor heating purposes and some are even used as a primary heat source. There are two structural types of fireplaces — manufactured metal fireplaces (referred to as zero-clearance or factory-built fireplaces) and site-built masonry fireplaces. Industry experts estimate that about 20% of existing fireplaces are masonry and 80% are factory-built. There were approximately 0.4 million factory-built fireplaces sold in 1997. Factory-built fireplaces are designed to last 40 years or more. Masonry fireplaces can last indefinitely. Consequently, the 27 million fireplaces currently in homes will be available for use well into the future.

The emission factor for fireplaces given in AP-42 is 17.3 g/kg. This value was estimated by the EPA using limited field and laboratory data. Estimates from more recent (albeit also limited) data, produces a value of about 12.5 g/kg. The typical burn rate of a fireplace is 3 kg/hr. The emission rates corresponding to an emission factors of 12.5 g/kg and 17.3 g/kg with a burn rate of 3 kg/hr are 37.5 g/hr and 51.9 g/hr. There has been some data suggesting that 60 g/hr is a more representative fireplace emission rate. Clearly, the particulate emission rate from a fireplace is dependent on what the "typical" burn rate is. There was no consensus of opinions among the interviewees on how reasonable these emission values were for fireplaces. Some thought they were too low, some thought were too high and some thought they were reasonable. It is recognized that the data base is very small and emissions are very variable.

A large number (albeit the minority) of fireplaces are used as significant supplemental heat sources. Fireplace inserts are designed for increased efficiency, and based on national surveys there are 7.1 million fireplaces with inserts in them. (The term “insert” as used in the survey is not what is often thought of as an insert. It most likely encompassed a variety of older fireplace designs and accessories, such as double-shell convection designs, convection tubes, blowers, etc. Some of the survey respondents also may have confused a zero-clearance fireplace unit with the term “insert.”) Some fireplaces are even used as primary heat sources. In 1993, 0.4 million households used wood burning fireplaces as their main source of heat.

Fireplaces utilizing older technology may be able to reach efficiency levels in the 40% range. Older technologies that increase efficiencies and effectively reduce emissions by requiring less wood to provide the same heat include double-shell convection designs, convection tubes, the use of blowers to transfer heat, glass doors, and masonry fireplaces with contoured fire chambers (e.g., Rosin and Rumford designs). The open radiant fireplace, with an efficiency potential of approximately 7% is the simplest and most common fundamental unit. Efficiencies, emissions in units of mass particles per unit of heat delivered and effective emission reductions obtained with these older technologies as compared to simple open radiant fireplaces are shown in Table 2.2-1. In reviewing the data in Table 2.2-1 it should be noted that the effective efficiency of a given fireplace varies with outside temperature and chimney draft.

Certified non-catalytic, certified catalytic, and pellet inserts can be installed into and used in existing factory-built and masonry fireplaces. They are essentially wood stoves designed to be installed into fireplace firebox/hearth cavities. If properly installed, their performance is similar to that of their stove counterparts, albeit their efficiencies are slightly lower since convection and radiation of heat is more restricted by their fireplace cavity surroundings and fireplaces are often located along an outer wall. There are an estimated 0.5 million certified cordwood inserts and 0.2 million pellet inserts in use. The EPA lists four catalytic and six non-catalytic insert models as certified. Efficiencies, emission factors in units of mass particles per unit of heat delivered and effective emission reductions obtained with certified cordwood and pellet inserts as compared to simple open radiant fireplaces are shown in Table 2.2-1.

Over the last 10 years, the use of natural gas and liquified petroleum gas (LPG) in place of cordwood has become widespread in fireplaces used for primary and supplemental heating purposes. Three types of gas units have the “fireplace-look.” They are gas fireplace inserts, decorative gas fireplaces, and gas fireplace heaters. All have negligible particulate emissions, compared with cordwood fireplaces. Therefore, particulate reductions are near 100%. The environmental “downside” of the nearly 100% particulate reduction is that both natural gas and LPG are, of course, fossil fuels, not renewable biomass fuels. Gas fireplace inserts, like certified cordwood and pellet inserts, can be put into existing fireplaces. Decorative gas fireplaces and gas fireplace heaters are generally designed for new construction. Gas fireplace heaters are more sophisticated than decorative gas fireplaces, as they are designed more for efficiency whereas decorative gas fireplaces are designed more for flame presentation aesthetics.

Table 2.2-1

“Best Professional Judgement” Efficiencies, Particulate Emissions per Unit of Heat Delivered, and Effective Pollutant Reduction by the Use of Alternatives to Open Radiant Fireplaces and Cordwood

Appliance/ Fuel	Thermal Efficiency (%)	Mass of Particulate Emissions/Delivered Heat (g/MJ)	Reduction (%)
Conventional Open Radiant Fireplace	7	8.6	-
Double-Shell Convection, Natural Draft	13	4.6	46
Convection Tubes, “C” Shaped, Glass Doors	15	4.0	53
Double Shell Convection, Blower, Glass Doors	32	1.9	78
EPA Certified Non-Catalytic Insert	66	0.50	94
Certified Catalytic Insert*	70	0.45	95
Pellet Stove Insert	76	0.13	98
Gas-Fired Insert	75	Negligible	-100
Gas-Fired Fireplace	50	Negligible	-100
Certified Catalytic “Fireplace-Like” Wood Stove	70	0.45	95
Masonry Fireplace With Shaped Fire Chambers and Glass Doors	42	1.2	86

*With a well maintained catalyst after normal use, on the average a newer catalyst will produce lower emissions and an older catalyst higher emissions.

Some certified wood stoves are designed to have the appearance of fireplaces, to be "zero-clearance" units, and capable of being installed at the time of construction. The effective emission reduction they can offer over simple open radiant fireplaces is on the order of 95%. These units are sometimes called EPA certified fireplaces but, in fact, meet all of the EPA NSPS definition specifications for an "affected facility" wood stove (i.e., one that is subject to the NSPS regulation).

In addition to the large number of fireplaces used for supplemental heating purposes, even more fireplaces are used for aesthetic or minor heating purposes. During the 1994-1995 heating season, 17% of surveyed fireplace owners reported burning wood once or twice a season, 13% reported burning wood once or twice a month, and 18% reported burning once or twice a week. The sum of these three categories corresponds to about 13 million fireplaces in the United States. Even though these statistics do not provide an exact number of fireplaces used for aesthetic and minor heating purposes, they do illustrate the relative magnitude of use. As these data indicate, many fireplaces are used very infrequently. Of the 27 million total fireplaces in the United States, survey data suggest that only 16 million of them were used to burn wood in any given 12-month period.

As with wood stoves which are designed and used for the utility of residential space heating, it is important to use the most appropriate reporting units for providing a means for comparison between fireplaces. Unlike wood stoves however, fireplaces can be used partially or totally as space heaters or they can be used partially or totally for aesthetic or recreational purposes. In the case of appliances used as sources of heat (i.e., wood stoves and "heating fireplaces"), the use of emissions mass per unit of heat delivered (i.e., grams/MegaJoule), is appropriate. In this sense, masonry heaters can be considered a special case of a "heating fireplace." In the case of appliances used strictly for aesthetic or recreational purposes however, emissions rates (grams/hour) or emissions factors (grams/kilogram of fuel burned) provide for better comparisons. For emissions inventory purposes, having g/hr information for a population of fireplaces would only require the determination of population usage hours for calculating an estimated total airshed impact. On the other hand having g/kg information for a population of fireplaces would only require the determination of total wood usage by the population for calculating an estimated total airshed impact.

The burn rate of a fireplace used only for aesthetic purposes is mostly related to the size of a typical sustained "warm" aesthetic fire, typically about 3 kg of cordwood per hour. The amount of wood burned and the resulting emissions are not directly related to heat demand, but are more or less constant for a given appliance. Wax fire logs typically have a fixed burn rate associated with them. Manufacturers of wax logs generally recommend a one-at-a-time usage rate with each log having a specified burn duration. Since most wax fire logs burn in the range of 0.7 to 1.3 kg/hour, it more appropriate to use the mass of emissions per hour (i.e., g/hr) reporting units when a fireplace burning cordwood for aesthetic purposes is compared to a fireplace burning wax fire logs.

Manufactured wax fire logs are widely used in fireplaces nationwide. One hundred million manufactured logs are burned each year. Manufactured logs were burned some of the time in 30% of the fireplaces and exclusively in 12% of the fireplaces during the 1994-1995 heating season. Typical wax fire logs are composed of approximately 60% wax and 40% sawdust. Paraffin or microcrystalline waxes are used. The heat content of wax logs is much higher than that of wood, and their moisture content is much lower. They are exclusively for use in fireplaces (not wood stoves), they typically require no kindling, and, as previously noted, are typically designed for one-at-a-time use. Particulate emissions rates from fireplaces burning wax fire logs in the prescribed manner is about 68% lower than when burning cordwood.

There have been improvements in the design of cordwood fireplaces that minimize the underfire air supply and maximize combustion conditions with the introduction of secondary air. At least one such unit not currently in commercial production reportedly had very low emissions. Therefore, some new fireplaces may have emission rates lower than currently manufactured units. However, little data are available.

There is no federal certification requirements for fireplaces. They are exempt from EPA certification because their air-to-fuel ratios are in excess of the 35:1. The states of Washington (WAC 150-31-200) and Colorado (Regulation 4) have fireplace standards and currently provide the only regulatory impetus for the manufacture of fireplaces with low emissions. Two local air quality authorities in California (i.e., Northern Sonoma County and San Louis Obispo County) are in the process of developing fireplace emissions standards.

An alternative to burning cordwood in fireplaces for aesthetic or recreational purposes is decorative gas log systems. They are known to have negligible particulate emissions at all heat input levels and therefore, as with wax fire logs, the emission rate (g/hr) reporting units may be appropriate when comparing emissions from fireplaces burning cordwood and used for aesthetic or recreational purposes with those using gas logs.

The use of decorative gas logs has become very popular. During the 1994-1995 heating season, 17% of fireplaces used gas as fuel mostly for decorative gas logs. Decorative gas logs are designed to be used in masonry or factory-built fireplaces. Gas log sets consist of a control valve and burner assembly, a grate, and imitation logs made of cast refractory or cement. Their functions are primarily for aesthetics with flame appearance being the primary design criterion. Decorative gas logs have negligible particulate emissions, compared with cordwood-burning fireplaces. Therefore, particulate reductions are nearly 100%, compared with fireplaces burning cordwood. As with gas fireplaces and inserts, either natural gas or LPG can be used with decorative gas logs.

2.3 State-of-the-Art of Wood-Fired Central Heating Furnace Emission Control Technology

There are less than 10 manufacturers of wood furnaces and less than 20 models available. In 1993 less than 0.3 million were used in the U.S. No data were found that provided estimates to be made on annual sales. They are most popular in the upper Midwest. Some models burn cordwood, some wood chips, some sawdust and some pellets. They are used more widely in Europe and in Canada than in the U.S.

Wood-fired furnaces most commonly heat water, which is circulated into the home, either through a heat exchanger coil in the cental air duct or directly into the living space through baseboard radiators. Since many homes do not have the space or the type of flue system needed for in-home installation, many current furnaces are designed to be standalone units located adjacent to the house enclosed to look like a small utility building. Most current wood-fired furnaces consist of a combustion chamber in the front and a boiler in the back of the unit. Hot gases generated in the combustion chamber pass around horizontal boiler tubes. In single-pass designs, the gases then exit through the stack, while in double pass designs the gases flow horizontally back to the front into a separate compartment above the combustion chamber and then out the stack. The latter designs should be more energy efficient, although no data were found to substantiate this supposition. There are some who also think the double pass design burns cleaner due to the longer flame path, but, again no data were found on this subject. Since the temperature of the gases exiting the boiler after the first pass are only in the range of 250-400EC, it seems unlikely that there would be any additional combustion after the first pass.

The furnace control system regulates the draft as needed to maintain boiler water temperature. When water temperature drops below the set point the draft opens which, in most designs, means the forced-draft fan is turned on. When the water temperature rises above the upper set point, the fans shuts off, reducing the draft to the low fire setting. A manually operated shutter on the fan inlet provides a means of fine tuning the unit to local weather conditions, stack height, house size, etc. When properly sized to the heating need, these furnaces need to be stoked 1-2 times per day. The smaller units will accept a fuel load of 18-25 kg of wood. On the basis of two fuel loadings per day such a unit is rated at 120 MJ/hour heat output. Recent testing of units showed that their typical efficiencies were in the 50% range.

A search of the literature for emission data turned up few references. A recent review article covering some limited work done in Canada and Sweden, a very recent EPA emission test report for two furnace models and two papers presented at conferences in the early 1980's were the only relevant literature found. The particulate emission factor for furnaces operated in their typical intermittent firing mode (draft controlled) are roughly a factor of two higher than for conventional stoves. Furnaces burning wood chips and pellets have much lower emission factors.

Wood-fired central heating furnaces are exempt devices, i.e., there is no U.S. certification for them. There is however an applicable draft Canadian emissions standard (CSAB415.2). The opinions of the interviewees were split as to the appropriateness of certifying them. Some felt that since so few were in use and those were predominately in rural areas where air quality is typically not an issue that it made little sense to go through the considerable effort and expense to developed a certification procedure and require new models to be tested. Others felt that to provide an even playing field for all RWC appliances that they should be certified and that being certifiable may enhance their marketability. It was noted by several interviewees that some outside residential wood-fired boilers have very high emissions and have created some localized concerns.

2.4 State-of-the-Art of Pellet-Fired Wood Stove Technology

There are an estimated 0.3 million pellet stoves currently in use. During the 1995-1996 heating season, 654,000 tons of pellets were sold. Nearly all pellet stoves have been sold since 1989. Many pellet stoves manufactured during the first several years of their availability had serious durability issues with electronic and moving parts that failed. The RWC experts that were interviewed agreed that these issues were addressed and that new units are dramatically improved. Some early pellet stove manufacturers went out of business because of these durability issues. To the experts' knowledge none of the early models are currently available. There are two categories of pellet stoves — EPA-certified and exempt. There are five models listed as certified by the U.S. EPA as of August 12, 1997. Appliances with a greater than a 35 to 1 air-to-fuel ratio are exempt from certification. Early models with the high air-to-fuel ratio had lower efficiencies than certified models due to sensible heat loss out the exhaust. This is not the case with newer models, since the high air-to-fuel ratio needs to be demonstrated only at low burn rates to obtain the exemption. At more normal burn rates, the air-to-fuel ratio is much lower for exempt models.

Efficiency values for pellet stoves shown in AP-42 (i.e., 68% for certified and 56% for exempt) were based on field studies conducted during the 1989/1990 heating season for certified pellet stoves and during the 1990/1991 heating season for exempt pellet stoves. (The data in AP-42 are erroneously listed as for Phase II certified pellet stoves, the stoves used to derive the values were certified as Phase I units.) The default efficiency value used in the certification process is 78%. Based on the interviews with RWC experts, the 78% efficiency is probably closer to the efficiency of newly manufactured units and is shown in Table 2.1-2 here. The emission factors shown in AP-42 for certified and exempt pellet stoves (2.1 g/kg and 4.4 g/kg, respectively) are also based on the 1989/1990 and 1990/1991 field studies and the certified values are erroneously listed as for Phase II units.

It was generally agreed that the 2 g/kg emission factor value shown in Table 2.1-1 is applicable to both currently manufactured certified and exempt pellet stoves and that most units produce lower emissions than even 2 g/kg. This observation is supported by certification test data of Phase II units. Unlike for cordwood stoves, realistic fuel and reasonably realistic fueling practices are prescribed by the Method 28 certification procedure for pellet stoves. The five pellet stove models that have been certified as Phase II units have certified emission rates ranging from 1.3

g/hr to 2.7 g/hr. The typical in-home burn rate of a pellet stove is approximately 3 lbs/hr (1.36 kg/hr). Based on this burn rate, the corresponding emission factors for the certified stoves would range from 0.96 g/kg to 1.98 g/kg.

The opinions among the interviewees regarding certification were split. Some felt that the 35:1 air-to-fuel ratio should be dropped and that all pellet stoves should be required to be certified since certification gives the units credibility and since emissions levels are listed for certified units it provides an incentive to improve them further. Others felt that since “their emissions are so low and they apparently have lower $PM_{2.5}$ and PM_{10} to total particulate ratios, as compared to cordwood stoves (see following discussion), certification would serve no purpose. Another suggestion was that a very simplified certification testing procedure would be appropriate for pellet-fired stoves. The simple test method would verify that air-to-fuel ratios are below a specified level at all burn rates and that carbon monoxide is below a certain percentage of the total flue gas carbon compound content.

Some early models of pellet stoves had problems with clinker formation in their fire pot. This problem was mitigated by both improved stove design and improved pellet fuel. The Pellet Fuel Institute (PFI) has provided inorganic ash content standards for residential pellet fuels. Most major pellet fuel manufacturers guarantee their product to these standards (<1% ash for premium grade and <3% ash for standard grade). The reduced ash content lessens fire pot clinker formation. The PFI also recommended that the pellets have less than a 300 ppm water-soluble sodium content. Sodium salts cause corrosion to the firebox. The PFI requests manufacturers to proved a guaranteed analysis listing ash and sodium content.

The $PM_{2.5}$ fraction of pellet stove particulate emissions is believed to be smaller than for cordwood stoves. Cordwood stove emissions are composed primarily of condensed organic compounds that are mostly submicron in size, whereas pellet stove emissions due to the more complete combustion characteristic of a pellet stove are believed to contain a higher fraction of entrained inorganic ash that is typically composed of larger particles. This perception is supported by some very limited data that shows that the ratio of the mass of particles collected on the back half (ice water impingers) to the front half (heated filter) of EPA Method 5 sampling trains is lower for pellet stoves than for cordwood stoves.

2.5 Ramifications of the International Organization for Standardization (ISO) Draft Standard WD 13336

Since approximately 1990, significant efforts have been made by hearth products industry members, primarily from New Zealand and Australia, to develop International Organization for Standardization (ISO, Geneva, Switzerland) test standards for measuring pollutant emissions and thermal efficiency, and for determining performance margins for safe wood stove operations. All of these test standards are currently in active development and classified in “draft” status. The last full meeting of ISO Technical Committee (TC) 116, Subcommittee 3 for individual heating appliances was held in Langenbruck, Switzerland on November 18-20, 1998.

Interviews conducted for this technology review project indicate that the current draft ISO test standards for measuring pollutant emissions and thermal efficiency have not been widely distributed and read by hearth products industry members in North America. In addition, since the draft ISO standards have not been adopted, nor are they expected to be adopted by any jurisdictions in any of the major markets serviced by most of the hearth products manufacturers in North America, there has been no compelling reason for North American hearth products manufacturers to become involved or to contribute to the further development of the standards.

Most interviewees felt that having one international test standard that was recognized in all, or at least the major markets of the world, is a good idea and some effort should be made by representatives from each of the major market areas to develop the ISO standards with this goal in mind. It was also expressed that if no final ISO standards could be developed that were acceptable to all jurisdictions in the major market areas of the world, the goal should be to develop standards that are compatible with other widely used test standards (i.e., where only one test is required with the application of possibly different calculation procedures or different pass/no-pass criteria being required by different jurisdictions). If it is not possible to make the test methods compatible, the ISO test standards should be developed so that they are at least correlatable (i.e., where there is a consistency between the results of the non-ISO methods that can be expressed consistently with a mathematical formula). One interviewee felt that because there has been such extensive use and knowledge gained with the U.S. EPA NSPS methods over the last 12 years, with some minor improvements or “corrections,” they could serve as the basis for an international emissions test standard. Another pertinent point should be made that if further development is undertaken on the ISO draft standards or the U.S. EPA NSPS test standards are revisited for the purposes of developing improvements or making corrections, the Canadian Standards Association (CSA) test standard B-415 and the proposed European Community (Comit’e Europ’een de Normalisation [CEN] Technical Committee [TC]295 Working Group [WG] 5, Brussels, Belgium) test standards should also be reviewed for their relevance to an international, worldwide set of standards.

For the purposes of this review, Table 2.5-1 was prepared for presenting a first-level comparison of the primary differences between the present ISO draft WD 13336 standard and the U.S. EPA NSPS standards for operating wood stoves and for sampling particulate emissions from wood stoves during test periods. It should be noted that there are many additional differences between these standards but only those which are considered to have the most potential to produce major differences in test results between the methods are presented in Table 2.5-1.

All interviewed North American market manufacturers indicated that the current U.S. EPA methods should not be replaced by an ISO standard at this time. Until there is more familiarity with the draft ISO standards, it not expected that this sentiment will change any time soon.

Table 2.5-1

Comparison of the Draft ISO 13336 Test Standards and the U.S. EPA NSPS Test-Standard Methods 5G, 5H, and 28 for Wood Stoves

Test Standard/ Method	Emissions Sampling Technique	Fuel Spacing	Fuel Species	Thermal Efficiency	Burn Rate Requirements	Units
ISO 13336: Wood Stove Operation and Emissions Sampling	Dilution Tunnel	0.75 Inches	Many Including Coal	Calorimeter Room	Low, Medium, High Based on Percentage of Maximum	g/kg
U.S. EPA 28 Wood Stove Operation	NA	1.5 Inches	Douglas Fir	NR	Specified Burn Rate Categories: <1, 1-1.25, 1.26-1.5, and Maximum kg/hr	NA
U.S. EPA 5G Emissions Sampling	Dilution Tunnel	NA	NA	NR	NA	g/hr
U.S. EPA 5H Emissions Sampling	Direct Flue-Gas	NA	NA	NR	NA	g/hr

NA = Not Applicable, NR = None Required

2.6 Correspondence Between In-Home and Laboratory Emissions Test Results

The overwhelming majority of laboratory emission tests have been for the certification of wood stoves. There has also been some research testing of wood stoves or other RWC appliances in the laboratory, most of which has been done in the 1980's. In-home studies of stove emissions have been conducted in the Glens Falls, New York area; the Waterbury, Vermont area; Whitehorse, Yukon; Klamath Falls, Oregon; Medford, Oregon; Portland, Oregon; and Crested Butte, Colorado. In-home studies of fireplaces and masonry heaters have been conducted at various locations in western Oregon and Washington.

The data for the certification tests are based on testing with Method 5G or Method 5H following the Method 28 stove operating procedures (40 CFR Part 60, Appendix A). The data for the field studies are based on tests conducted with a sampler referred to as the Automated Woodstove Emissions Sampler (AWES) except for data for Crested Butte, Colorado which was based on tests conducted with a sampler referred to as the Virginia Polytechnic Institute (VPI) sampler. Most research laboratory tests have utilized Method 5 samplers or samplers developed from EPA's Method 5 train. These include Method 5 itself, Method 5H, Modified Method 5 (i.e., Method 23) and Oregon's Method 7. Some laboratory testing utilized a dilution tunnel prior to sampling with a Method 5-based sampling train. Some utilized a research dilution sampler developed by the Southern Research Institute (SRI) referred to as the Woodstove Sampling System (WSS).

In the development of emission factors for AP-42, data obtained from the two in-home samplers were converted to their equivalent Method 5G values first, then the 5G values were converted to equivalent Method 5H values. For the AWES sampler the equation used to convert results to Method 5G values was:

$$\text{Method 5G} = 0.8653 \text{ x } \text{AWES}^{0.9289}.$$

For the VPI sampler the equation used was:

$$\text{Method 5G} = 0.6748 \text{ x } \text{VPI}^{1.007}.$$

These equations were developed by performing linear regression on data taken form simultaneous AWES-M5G and VPI-M5G tests. The 5G equivalent data were then converted to method 5H equivalent values by the equation:

$$\text{Method 5H} = 1.619 \text{ x Method } \text{5G}^{0.905}.$$

While the correlation between the methods is reasonable there will be some bias between using data generated by the different sampling methods. This is particularly important when comparing in-home data and laboratory data, because laboratory certification data are all either based on Method 5G or 5H and research laboratory data are mostly based on method 5-type samplers whereas all in-home data are based either on the AWES or VPI sampler.

The issue of correspondence between in-home and laboratory emissions usually refers to the correspondence between in-home wood stove data and wood stove certification data (not research laboratory testing or the testing of appliances other than wood stoves) since the purpose of the certification process was to reduce air quality impacts from wood stoves. The interviewees were in general agreement that emission values obtained from certification tests only roughly predict in-home performance. While, as discussed, there may be some bias due to the sampling method, the key issue is the burning conditions and fuel characteristics prescribed by Method 28. Method 28 requires that Douglas fir 2 x 4's and 4 x 4's with a 19% to 25% (dry basis) moisture content made into cribs with fixed spacings be burned, that a coal bed be established before the testing is started (no kindling phase emissions), that fixed burn rates are used, that a 15-foot stack that freely communicates with non-pressurized indoor air is used, and that unrealistic air control settings be used. The air control prescribed by Method 28 is unrealistic for several reasons. First, the air control setting cannot be changed after the initial five minutes of the Method 28 test regardless of the state of the burning conditions. Second, there are no stops for the air settings for the medium-low and medium-high burn rates prescribed by the Method 28 protocol, consequently they are not generally reproduced by the in-home operator. Third, the in-home operator often loads the stove and "dampers-down" the unit at the same time for an "all night" burn at the end of the day — a condition which is not simulated by the Method 28 protocol. In addition to the actual testing procedures, data reduction prescribed by Method 28 produces unrealistic values because emissions rates are burn-rate weighted. The weighting factors were designed to be representative of the distribution of wood stove burn rates of the nation as a whole. The geographical distribution of in-home burn rate data is very limited.

In summary, burning cordwood in-home under real-world conditions is unlike that conducted following Method 28. The certification process should be viewed as a licensing process and it needs to be emphasized that emission rates obtained from it are not closely correlatable to emissions from actual in-home use.

2.7 EPA Method 28 Strengths and Weaknesses

The U.S. EPA NSPS Method 28 (40 CFR Part 60, Appendix A) which specifies wood stove operating and fueling requirements during wood stove test periods, has, since its promulgation in 1987, been a target for criticism by EPA-accredited wood stove testing laboratories and hearth product industry research and development departments. Complaints range from the method being too flexible, allowing or generating large and misleading variability in test results, to the method being too restrictive, not allowing enough flexibility to demonstrate the true clean and efficient burning capabilities of many wood burning stove models.

Specifically, some interviewees felt that there is no need to measure emissions from a full series of four separate burn rates or burn-rate categories as required by Method 28. Since intermediate burn rates (i.e., medium-low and medium-high) results always fall within the results obtained at the low and the high settings, they felt that it is only necessary to test for emissions at these low and high settings. Related to this was the comment that the Method 28 low burn rate requirements should not be expressed in absolute values but should be expressed as a percentage of the fuel load burned per hour. For example, instead of the present requirement for the low burn rate to be below 1.0 kg/hour, the low burn requirement could be expressed as a percentage (e.g., less than 20%) of the test fuel load weight calculated as described in Method 28 based on the firebox volume of the individual stove.

It is also generally recognized that with the current Method 28, there are many ways to affect burn cycle patterns and results while staying within the required Method 28 operating and fueling specifications. These include:

- Using higher or lower average moisture content fuel loads ranging from 19% to 25% (dry basis) to increase or decrease burn rates and/or emissions rates,

- Placing higher or lower moisture content fuel pieces at different locations within the firebox (e.g., bottom/top or back/front) to control the timing, location, and temperature regimes of pyrolysis products and volatile gas releases into secondary combustion zones,

- Placing higher or lower fuel density pieces at different locations within the firebox to control the timing, location, and temperature regimes of pyrolysis products and volatile gas releases into secondary combustion zones. There are no Method 28 fuel density specifications and Douglas fir wood densities vary up to 60% from low to high density fuel pieces,

- Starting the test at the high or low end of the allowed coal-bed size range (i.e., 20% to 25% of the test fuel load weight) to affect the start-up pattern and the ultimate average burn rate and emissions characteristics for the fuel load,

- Starting the test at high or low average firebox/stove temperatures which also affects the start-up pattern and ultimately the average burn rate for the fuel load. The desired relative firebox/stove temperature can be obtained by both managing how much of the coal bed is present at test start-up and managing how the stove is operated before the required one-hour, no-adjustment pre-burn period is started, and,

- Using fuel load weights at the high or low end of the Method-28-allowed fuel weight limits (i.e., 7 pounds per cubic foot of firebox volume, plus or minus 10%). Fuel load weight differences of 10% can affect burn rates and measured emissions rates. It is well known that smaller fuel loads produce lower emissions rates at any burn rate.

Although the effects of these factors have not been quantified, the overall concern is that EPA NSPS testing can be manipulated and a practiced technician can prepare custom results.

In addition to the pragmatic concerns about the conduct of Method 28 (and associated methods 28A and 5H) and the perception that the methods are in part an art, there are also controversial mathematical/conceptual issues associated with them as well.

For example, many interviewees believed that the weighting scheme used for calculating average wood stove emissions rates is flawed in that for any geographic location, even one that represents an “average” U.S. heating climate, there will be a very wide range of use patterns: from fall to winter to spring, between large and small homes and between low versus high indoor temperature preferences. Taking into consideration that there are many geographic locations within the U.S., with very different heating requirements and patterns, it was suggested that a simple arithmetic average of emissions measured at different heat output rates be used rather than the complex weighting scheme currently required by the method. It was theorized by one interviewee that a survey of current wood stove use in the U.S. would most likely show a shift from their use as primary heating sources more characteristic of the time when the NSPS was being developed, to currently a higher percentage of use as secondary heating sources. If this shift is real, it gives added rationale for changing the current weighting scheme.

Another mathematical/conceptual issue is that the equations used to calculate the air-to-fuel ratios (A/Fs) in Method 28A and to determine flue gas flow rates in Method 5H do not adequately take into account volatile organic compound emissions. The results of calculations with the equations are used both for determining the exempt/nonexempt status of wood burning appliances under the NSPS A/F exemption specification (i.e., being more or less than 35:1) and in the determination of particulate emission rates using Method 5H.

For the calculation of A/F the following equation is used.

$$A/F = \frac{\left[\ (N_T x M_d) - 510\ \right]}{1000},$$

where, M_d is the dry molecular weight of the wood stove flue gases,

N_T is the total moles of dry exhaust gas per unit mass of wood burned. N_T in both methods 5G and 28A is defined by the equation,

$$N_T = \frac{42.5}{(Y_{CO_2} + Y_{CO} + Y_{HC})},$$

where, Y_{CO2} is the mole fraction of carbon dioxide measured in the dry wood stove flue gases,

Y_{CO} is the mole fraction of carbon monoxide measured in the dry wood stove flue gases,

Y_{HC} is the mole fraction of gaseous hydrocarbon compounds in the dry wood stove flue gases. Method 28A and Method 5H specify Y_{HC} as a constant. The value for catalytic wood stoves is 0.0088, for non-catalytic wood stoves it is 0.0132, and for pellet-fired stoves it is 0.0080.

A problem occurs when the Y_{HC} constant is used in the equation to calculate the N_T value.

Methods 28A and 5H define the hydrocarbon mole fraction (Y_{HC}) as a constant regardless of how efficient the combustion process or how concentrated the other flue gas combustion byproducts (i.e., CO_2 and CO). The problem this can cause can be illustrated by performing some simple calculations using a non-catalytic wood stove as an example. Mathematically if the value of 0.0132 is used for Y_{HC}(the constant value of Y_{HC} for a non-catalytic wood stove) and the A/F of of the unit is 35:1 or more, the sum of CO_2 plus CO mole fractions in the wood stove flue gases must be equal to or less than 0.0214. (This CO_2 plus CO mole fraction value of 0.0214 was obtained by first estimating M_d as 28.95 g/g-mole, setting the A/F equation equal to 35, and solving for N_T. The corresponding N_T value is equal to 1226.598 g-mole of dry exhaust gas per kilogram of wood burned. By putting the Method-28A-specified hydrocarbon mole fraction value of 0.0132 into the N_T equation, setting the N_T equation equal to 1226.598 g-mole/kg, and solving for Y_{CO2} plus Y_{CO}, the value of 0.0214 was obtained.)

The 0.0214 value means that the assumed (or more correctly defined) Y_{HC} value of 0.0132 is a very substantial 38.2% of the total carbon mass flow in the non-catalytic wood stove when the A/F is at 35:1; i.e.,

$$\frac{0.0132}{0.0214 + 0.0132} = 0.382 \text{ x } 100 = \ 38.2\%.$$

If the combustion process being tested is efficient with the corresponding actual flue gas Y_{HC} negligible, there would be an additional 61.8% of excess unneeded air flowing through the wood stove before it would be calculated to exceed the 35:1 A/F required for the EPA NSPS A/F exemption. (Another way to intuitively understand this effect is to considered that if hydrocarbons artificially account for 38.2% of the concentration of carbon containing gases, the value for the sum of CO_2 and CO mole fractions will have to be in practice reduced by the same amount. Because the number of atoms of CO_2 and CO cannot be changed, the only way this can be accomplished is to increase the total flow by 61.8%.) A primary implication of this Y_{HC}-generated need for additional excess air to meet the 35:1 A/F exemption, is the fact that any and all excess air above the optimal level for efficient combustion in wood stoves only serves to carry additional combustion generated heat out of the stove and into the atmosphere ultimately resulting in significantly reduced wood stove thermal efficiencies. This, of course, results directly in the need for users to burn more wood and an effective higher emissions factor.

In a similar fashion and perhaps more importantly, the same Method-28A-specified Y_{HC} values that cause excess flue gas flow rates to be needed to obtain calculated A/Fs greater than 35:1, also cause the flue gas flow rates calculated by Method 5H to be up to about 61.8% lower than the flow rates would be if actual flue gas Y_{HC} values were negligible. Since Method 5H emissions rate results are the product of the measured flue gas emissions concentrations and the calculated flue gas flow rates, the Method 5H emissions-rate values could also be lower than actual value depending on the A/F and the real concentration of Y_{HC} in the flue gases.

Two other related points are relevant to make. First, the term hydrocarbons (generally abbreviated "HC") is a misnomer in that many oxygenated organic compounds will be present along with hydrocarbons in the vapor phase particularly at typical flue gas temperatures and second, while a large fraction of the organic compounds in flue gas vapors will be single carbon compounds (e.g., methane, methanol, formaldehyde), some will have two or more carbon atoms which further complicates the effects of using fixed Y_{HC} values.

Because there has not been any widespread recognition of these volatile organic compound problems, there were no strong opinions among interviewees on how best to correct the problem. Two suggestions were:

- Measure or approximate total wood stove flue gas volatile organic compounds during tests using a heated sample line with a flame ionization detector calibrated to a surrogate compound such as methane, butane, propane, or

- Determine if there is a relationship between another indicator of incomplete combustion in wood stoves (i.e., carbon monoxide) and use that relationship in the N_T equations.

Another mathematical/conceptual issue regards the Method 28A calculation of fuel factor (F_o) values using measured flue gas concentrations. This calculation is performed using the equation:

$$F_o = \frac{20.9 - \%O_2}{\%CO_2} .$$

The F_o values obtained with the equation are used as a check of the proper operation of test equipment. In practice, the F_o values are usually calculated and reviewed for each ten minute average CO_2 and O_2 data set. (If carbon monoxide levels are measurable the CO_2 and O_2 values are adjusted.) Method 28A states that F_o values "calculated beyond the acceptable range of 1.000 and 1.120, should be investigated before the results can be accepted" [by EPA]. Accredited wood stove test laboratories as well as research and development laboratories operated by hearth products manufacturers have often found F_o values below 1.000 and above 1.120 levels with testing equipment operating properly and within specifications. Based on extensive calibration and retest work which has been done, it appears the primary reason for the frequent occurrence of apparent flue gas chemical imbalances (i.e., F_o values outside the 1.000 to 1.120 range) is the fact that fuel combustion in wood stoves is a batch process. Different fuel characteristics and burning conditions which occur over the course of the batch process change the relative O_2 and CO_2 (and CO) flue gas concentrations.

For example, at the beginning of a burn cycle when the fuel load heats up, wood tends to burn more volatile compounds which contain most of the hydrogen and oxygen in the fuel ("fuel oxygen"). At the end of a burn cycle, wood tends to burn mostly high carbon content charcoal-like materials. To add further complication, at the very start of the burn cycle proportionately more of the starting coal bed (containing a high carbon content) specified by Method 28 burns than the fuel load, especially at the Method 28 low burn condition.

Two other factors which can change with combustion conditions over the course a wood stove batch burn cycle that can affect the F_o values are (1) the relative proportion of fuel oxygen versus atmospheric oxygen consumed to produce combustion gases and (2) the amount of hydrogen combining with oxygen to produce water.

When carbon uses predominately fuel oxygen for burning, there is a greater than one to one replacement of atmospheric oxygen with CO_2. Under normal circumstances fuel oxygen would not be exclusively used as compared to atmospheric oxygen during any portion of the batch process but this phenomenon occurs with varying degrees during different parts of a burn cycle.

The water produced by combustion of hydrogen will not be measured as a component of the volume in the flue gases (flue gas percentages are measured against total dry flue gas) and, therefore, the CO_2 produced by combustion will become effectively a larger percentage of the total dry flue gases when more hydrogen is converted to water. Another way of conceptually understanding this effect is to consider that hydrogen would be using up atmospheric oxygen with no measurable replacement to take up the volume like there is when carbon burns with atmospheric oxygen; i.e., one carbon atom uses one O_2 molecule from the atmosphere to make one CO_2 molecule which replaces, on a one-to-one volume-per-volume basis, the one atmospheric O_2 molecule. Therefore, when carbon burns with atomospheric oxygen, the sum of the remaining atmospheric oxygen present in flue gas and the carbon dioxide produced will be 20.9% (with a small correction for CO and volatile organic compounds).

If flue gas results from pellet stoves, wood chip or sawdust-fired boilers that operate on virtually a steady-state basis were being analyzed then short-term F_o factors of 1.000 to 1.120 may be appropriate. However, for the batch combustion processes of a wood stove, the F_o method using 10 minute averages over the course of the burn cycle does not provide a valid quality assurance check since not only does the chemistry of the fuel change from the beginning of a burn to the end but the combustion conditions at the beginning and end of a test change as well. Only average F_o values should be calculated for the burning of a complete fuel load, not for any single test segment.

In conclusion of the Method 28 issues it was expressed by several interviewees that the Random Compliance Audits (RCAs) described in 40 CFR Part 60, Subpart AAA should be conducted on a regular or consistent basis. It is felt by many manufacturers in the hearth products industry that there has been some abuse of the NSPS test methods and the NSPS-specified exemptions. It is a widespread belief that “policing” by the use of RCAs would be of benefit to the industry.

2.8 EPA Methods 5G and 5H Correlations

The general perception among interviewees was that although the performance of Method 5H generally results in lower measured emissions rates, it is a very complicated and difficult method to perform. Its multi-step and multi-component sample train complexities are compounded by the use of a tracer gas flow measurement procedure making the overall method fraught with many points of potential error and it is not surprising that the Method-5G-to-Method-5H conversion equation does not reflect industry experience with the two methods. There is no question among most interviewees that Method 5G is more precise than Method 5H and that it probably reflects actual wood stove emissions more consistently than Method 5H.

Several interviewees also stated that if the EPA ever eliminates Method 5H, the relationship between Methods 5G and 5H should first be established with much greater certainty than is obtained using the Method 5G conversion equation. It was the experience of several interviewees that the present Method 5G to Method 5H conversion equation penalizes the use of Method 5G especially at lower measured emissions rates. All interviewees felt a concern that any change in the Method 5G conversion equation not increase the current stringency of the NSPS. Some concern was also expressed that because the regulators dealing with wood stove emissions control strategies, industry research and sales people, and consumers are now familiar with the current emissions rates, there should be no drastic change from the present use of Method 5H emissions equivalents.

Another reason there are observed differences between Method 5G and 5H results may be that in paragraph 5.2.2.2 of Method 5H it is stated that the average of the flue gas CO_2 and CO mole fractions should be used in the carbon balance calculations for total test average flue gas flow rates. To be correct, the method should first calculate the carbon balance flue gas flow rate for each test interval (i.e., 5- or 10-minute period). Then an average of the individual test interval flow rates should be calculated.

An example of the mathematically correct procedure for obtaining average flue gas flow rates is used in the EPA Method 2 Equation 2-9 (40 CFR Part 60, Appendix A). In Method 2, the velocity for each traverse point and test interval must be calculated before an average of traverse points or test intervals is calculated. Or more correctly in the case of Equation 2-9, the square root of the pitot velocity pressure for each individual sample point or test interval must be calculated before a total test period average is calculated.

When performing multiple arithmetic functions, the proper order of adding and multiplying or multiplying and adding must be followed or incorrect results are generated. In the case of the Method 5H carbon balance flue gas flow rates, if Equation 5H-7 is not carried out for each test interval before an average flow rate is calculated, the correct amount of weighting is not provided for the CO_2 + CO measurements made for each test period time interval. Experience indicates that the errors generated by following the instructions in Method 5H paragraph 5.2.2.2 are generally small (i.e., less than 5%), but not insignificant.

2.9 Performance Deterioration of EPA-Certified Wood Stoves in the Field

Performance deterioration (particulate emission increase) has been monitored in the field in four communities by retesting stoves after one or more heating seasons of use. Most of the stoves that were part of the in-field performance studies were Phase I, not Phase II stoves. One stove that was studied was a research stove developed by the Oregon Department of Environmental Quality (the "BEST" stove) and has never been available commercially. The studies have been conducted in Glens Falls, New York; Crested Butte, Colorado; Klamath Falls, Oregon; and Medford, Oregon. The stoves in the Glens Falls study were originally tested in the 1988-89 heating season and retested and inspected in the 1989-1990 heating season. They were all phase I units. The stoves in the Crested Butte study were originally tested in the 1988-89 heating season. Some stoves were retested after one or more heating seasons during the 1989-90, 1991-92 and 1995-1996 heating seasons. Some stoves were Phase I and some were Phase II. Also, as part of the Crested Butte study, some old certified stoves were only tested once but because of the fact that they had been in use for some years, information on degradation was obtained from a single testing and inspection. The stoves in Klamath Falls study were originally tested in the 1989-90 heating season and retested in the 1991-92 heating season. They were Phase II stoves. The stoves tested in Medford were all the Oregon Department of Environmental Quality BEST stove model and were first tested in the 1988-89 heating season and subsequently retested in the 1989-90 heating season. It should be noted that among all the studies a total of only six Phase II certified stoves were emission tested in more than one heating season (five in Klamath Falls and one in Crested Butte). There has been concern about both the Glens Falls and Crested Butte stove usage being on the extreme end of the spectrum of in-home stove use. Many homes in Glens Falls were multiple stories with high draft conditions plus, while not extreme, the heating degree day value for Glens Falls (7500 HDD) is on the higher end of the spectrum typical of the United States. In the case of Crested Butte, the heating degree day value is extremely high (11,500 HDD) as compared to most of the continental United States.

In general, the field studies showed that emissions increased with time and that some stoves showed physical deterioration. The level of deterioration appeared to be related to how "hard" the stoves 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 then others. Catalytic stoves 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 stove was primarily to the baffle/secondary air system.

Several interviewees pointed out that wood stove design has improved since the early Phase I and even Phase II models. Warranty claims, as noted previously, have been the primary driving force for the improvements. Also as previously noted, more than one third of the certified stoves listed by EPA are not currently available. Not surprisingly some of these stoves had durability issues and are not commercially available for that reason. A representative of one manufacturer noted that he attended the 1993 "Manufacturers Seminar on Woodstove Stress Testing" which was based on EPA-sponsored research[10] and improved the quality of the materials they used in manufacturing their stove models based on the information presented. Two concrete improvements cited by interviewees were that in their stoves catalysts are positioned vertically rather than horizontally now to allow ash to fall out and to prevent plugging and that catalyst bypass systems are now made more "robust."

Some interviewees felt that catalyst could last longer than five years if properly maintained. Others noted that under extended high temperature use a catalyst could fail very rapidly. Once a catalyst fails, the emissions for some models would be close to those from a conventional uncertified stove, particularly if the stove is designed in such a fashion that the catalyst removes virtually all the organic emissions. Other better engineered catalyst stoves with improved combustion design (secondary combustion, heat retaining refractory, etc.), with a failed catalyst, would have emission levels closer to that of certified non-catalytic stoves. Some interviewees noted, that while catalytic stoves were most susceptible to deterioration, non-catalytic stove also can be damaged by high temperature, over drafting conditions.

Most interviewees felt that some type of home owner training on the use and maintenance of wood stoves was appropriate and that it might best be accomplished at the time of purchase. An instructional video as part of the purchase package was mentioned. Most interviewees felt that it was inappropriate to include the costs of an inspection and catalyst replacement program in the purchase cost of a new unit, particularly since sales are declining.

2.10 Stress (Durability) Test Pros and Cons

As discussed in Section 2.9, wood stove field studies have shown that some newer technology wood stoves designed to have low particulate emissions have degraded in performance and have shown physical deterioration after as little as one season of use. It is generally believed that most damage to the wood stoves occurs during those occasional times when the wood stove is operated at exceptionally high temperatures. A method to test the long-term durability of wood stove models in the laboratory in a one to two week time frame has been developed and has come to be referred to as a "stress test"[10].

At the time of its development the most valuable aspect of the stress test was felt to be its ability to simulate in-home wood stove aging and degradation over a short time period in the laboratory. The short-time required for the test would permit modifications to be made in stove design and manufacturing during the period when a given stove model was in development, rather than having to wait for one or more seasons of use for degradation to be discovered. The biggest environmental "plus" of the stress test would be to increase the probability that low particulate emission provided by new technology stoves are realized in actual long-term in-home use.

The opinions of the interviewees seemed to be split as to the applicability of a stress test. One faction felt that a stress test would improve wood stove performance and that it might even be appropriate to include it as part of the certification process. Although some of these interviewees that felt that a stress test was appropriate had caveats on its use. These included the concern that the stress test as developed might have been too severe, with the related observation that there is a difference between acute and chronic stress which is not addressed in the stress test, and the point that because draft conditions strongly influence the combustion rate and temperature, draft should be taken into consideration in the testing. One interviewee felt that some form of stress testing may be appropriate for certification but that the NSPS should not be "piece mealed" but completely redone. As part of such a new NSPS testing protocol, it was suggested that a range of draft conditions should be defined to which the model is certified. It was noted that the stress test is important since some of failure mechanisms such as the loss of catalytic activity or damage to secondary air tubes may go unnoticed by a homeowner and hence it is critical to minimize the occurrence of these failures by stove design.

A number of interviewees felt that the stress test was inappropriate and that it should not be part of the certification process. It was felt that the economic disincentives of warranty claims provides enough impetus to manufacturers to build quality long-lasting appliances. However as previously noted, some degradation which can cause increased emissions may go unnoticed by the home operator and its repair will not be initiated by a warranty claim. It was also noted that the stress test only evaluates damage caused by high temperatures and, as with other products designed for in-home use, there are other factors besides temperature that could cause damage to wood stoves under real-world consumer use. Some interviewees were against the stress test because it would add a cost to wood stoves which already have a poor market.

2.11 Feasibility of Developing Separate Emission Factors for Dry and Wet Wood and for Softwood and Hardwood Species

A review of the RWC literature and the responses of the interviewees revealed that there is little data to quantify either the effect of fuel tree species or of moisture on particulate emissions of wood burned in home heating appliances. Most interviewees believed that fuel moisture has a larger effect on emissions than tree species. Part of the concern regarding the effect of fuel tree species and wood moisture on particulate emission rates stems from the fact that the certification Method 28 specifies that only Douglas fir 2 x 4's and 4 x4's with a moisture content of 19% to 25% (dry basis) can be used in the certification of wood stoves. Discounting the issue of dimensional lumber, clearly wood from many other tree species with different moisture contents are burned nationally in homes. For example, the U.S. Department of Agriculture, in cooperation with the Oregon State University Extension Service, listed the fuel wood characteristics of 47 tree species in a recent RWC guidance circular[11] and an in-home emission study[12] of 28 homes in upstate New York and Vermont showed that the average moisture content of wood in the home woodpiles ranged from 17% to 41% (dry basis). Even from the limited number of homes included in the in-home studies from which AP-42 emission factors were derived and from which wood stove durability was assessed there were over 31 descriptions of wood types. These were: ash, aspen, apple, alder, beech, birch, black cherry, cedar, unspecified cherry, Douglas fir, elm, fir, unspecified hardwoods, hornbeam, juniper, lodgepole pine, laurel, unspecified maple, madrone, unspecified oak, unspecified pine, pinion pine, poplar, red fir, red oak, unspecified spruce, unspecified soft wood, white fir, white oak, white pine, and yellow pine. Most of the unspecified categories were mixtures of different tree species and in some cases the same generic term (e.g., oak) was used in different parts of the country which suggests that different tree species made up the cordwood even within the same category.

There are physical and chemical differences in softwoods (conifers) and hardwoods (deciduous trees) that may influence particulate emission rates. The average heat content and density of softwoods and hardwoods are distinct although there is considerable overlap. The reported[13] average higher heat content of 10 hardwood tree species is 8100 Btu/lb dry wood (18.8 MJ/kg) with a standard deviation of 215 Btu/lb (0.5 MJ/kg) and for eight softwood species it is 8746 Btu/lb (20.3 MJ/kg) with a standard deviation of 861 Btu/lb (2.0 MJ/kg). The average heat content of softwood is higher than for hardwood because the resin content is on the average higher in wood from conifers than from deciduous trees. The resin content in conifers is reported to range form 0.8% to 25%, whereas its content in deciduous trees is from 0.7% to 3%. The higher heat content of resin is 17,400 Btu/lb (40.4 MJ/kg) as compared to about 8000 Btu/lb (20.0 MJ/kg) for dry wood without resin. Softwood also has on the average a slightly higher heat content because it usually contains more lignin than hardwood. Lignin has a higher heat content than cellulose. The average density of wood from 22 deciduous tree species is 2689 lbs/dry cord (1.222 metric tons/cord) and for wood from 14 conifer tree species it is 2007 lbs/dry cord (0.912 metric tons/cord)[11].

There has been some limited data from laboratory studies suggesting that pine may produce lower emissions than oak in RWC appliances. The average difference in emission factors from changing from pine to oak shown in two of these studies was in the 30 to 40% range, however, in both cases the effect was below the 90% confidence limit (bound) probably due to the complicating effect of the large number of variables. Results from other laboratory studies suggest that emissions from oak are lower than from pine or fir. Most laboratory studies did not reach any conclusions on the effect of wood type. A number of the interviewees felt that oak produced lower emission than softwood. $PM_{2.5}$ (particles with aerodynamic diameters less than 2.5 microns) emission data compiled by the U.S. Forest Service[14] for slash and brush burning revealed that there is little inherent differences in particulate emission factors from the combustion of wood from various wood species under these conditions. The standard deviation around the mean emission factor of 21.1 g/kg of fuel consumed based on a total of 45 tests on a variety of species was only 3.2 g/kg or 15% of the mean. Species and mixtures tested by the U.S. Forest Service were Douglas fir/hemlock, hardwoods, ponderosa pine/lodgepole pine, mixed conifer, juniper sagebrush and chaparral. The probable small effect of tree species on emission rates was anecdotally noted by one interviewee who pointed out that a well-designed wood stove seems to burn either hardwood or softwood equally as well.

In regards to the effect of wood moisture on particulate emission factors, the general consensus is that the lowest emissions occur with wood moisture in the 15% to 25% range (dry basis). High moisture reduces combustion temperature and hence combustion is more incomplete. Alternatively, low moisture produces high temperatures which allows volatile organic compounds to be vaporized and escape without being combusted, some which condense to form particles after leaving the stack. One laboratory study examined the effect of burning cured cordwood (15.0% and 12.3% moisture content on a dry basis) versus uncured cordwood (31.8% and 34.9% moisture content on a dry basis). The average particulate emission factor for the drier wood was about 13% lower at a 90% confidence limit. While the magnitude of the effect was small, the moisture levels of both the cured and uncured wood were not far from the apparent optimal moisture levels and hence do not represent the extremes. Interestingly, even though the moisture range in cordwood studied did not represent the entire range of cordwood moisture, the magnitude of the effect seems to be small which is contrary to the opinion of many interviewees.

The difficulty in retrospectively using existing field and laboratory data to isolate and quantify the effect of moisture or tree species is due to the fact that there are so many interrelated variables (appliance type, fuel tree species, altitude, burn rate, fuel moisture, fuel size, kindling characteristics, etc.) that were not controlled in the studies. Technically the feasibility of developing emission factors for moisture or wood type is straight forward if an experiment is designed to do so. This was noted by one interviewee who stated that the fuel type and moisture effect has not been quantified simply because there has been not been an adequate study funded to specifically do it. One pragmatic suggestion regarding the certification was that instead of burning one fuel type at four different burn rates as it is done now that it would make more sense to burn different fuels with different moisture contents from which an average is calculated or to burn a mixture of fuel types with different moisture contents at each burn rate.

2.12 Routine Maintenance of Appliances

There was agreement among the interviewees that it would be a sound practice for maintenance training and/or a manual to be provided to homeowners at the time of purchase of a wood stove. The use of a video format was suggested. Some manufacturers and retailers are already providing manuals, video and/or training. Several interviewees did point out that the cost of a service contract added to the purchase price of the unit would not be appropriate. Wood stoves already have a small market share as compared to other home heating options. In addition, service contracts traditionally are optional not mandatory. In the case of catalyst stoves particularly, they did not feel the added cost, at the time of purchase, of catalyst replacement (that would probably be needed in a three to five year time frame) would work since it would make catalyst units more unpopular than they already are. Alternatively, some interviewees felt that for catalyst stoves, such a program may be the only way to increase the probability that reduced particulate emissions would be long-term.

There was general agreement that routine maintenance was a good idea, as it is for nearly all appliances. It was noted that it is less critical for pellet stoves in terms of emissions since generally if there is a malfunction they do not operate. Routine maintenance/inspection for cordwood stoves should consist of checking and replacing if necessary door, bypass and window seal gaskets; moving parts (e.g., the catalyst bypass system); baffles; air tubes; and bypass seals. Baffles should be checked for warps and cracks, air tubes for leaks and plugging. The replacement of baffles and air tubes can be done in the home for some models. The replacement of baffles and air tubes for other models would require returning the unit to the factory or to a metal repair shop. For catalyst stoves, the inspection and replacement, as necessary, of the catalyst is, of course, a key element of the maintenance program. The inspection should include a visual determination that there is no physical damage or no plugging and if possible the catalyst should be observed during operation to determine if it has the typical glowing appearance of a properly functioning catalyst. Also stove cleaning should be part of the maintenance program, including removing any accumulated ash from the catalyst and air tubes. It was noted that since chimney sweeping is generally recommended once a year that utilizing chimney sweeps for routine maintenance would be a good approach.

3. Conclusions

Residential wood combustion is unlike many other sources of particulate matter. The effect that technologies, fuel properties and combustion conditions have on particulate emissions are characteristic of point sources, but since there are an estimated 25 million RWC appliances dispersed over wide geographic areas and in use nationwide, emission inventories and most regulatory controls treat them as area sources. Residential wood combustion appliances, as emission sources, are extremely heterogeneous. There are many hundreds of types and models of wood burning devices currently in use in the U.S. They are so durable that the manufacturers of many are no longer in business. Many dozens of tree species as well as various manufactured fuels are burned in them; home settings vary dramatically in terms of climate, altitude, and chimney characteristics; and homeowner burning practices also vary widely (e.g., fuel seasoning, burning patterns, burning rates, kindling approaches). Because there are so many models and home settings and so many different ways that RWC appliances can be used, combined with the fact that they are in private homes where personal preferences and behavior are not controllable, it is very difficult to quantify generic wood-burning emissions cause and effect relationships. Further, since many manufacturers compete for market share, there is understandably, much relevant technical and sales information which is considered confidential.

Based on the review of existing literature and interviews with recognized RWC experts, a number of conclusions regarding the states-of-the-art of RWC and allied subjects have been reached. These are as follows:

- The particulate emission factor published in AP-42[6] for conventional wood stoves is most likely lower than the actual national average.

- Taken as a group, the durability of currently manufactured certified Phase II wood stoves has improved and their particulate emissions are lower than the earliest Phase II models that became available circa 1990. However, there appears to be considerable variation by model within the group and the improvements seen over the earliest models have been described as marginal. Certainly, as a group, Phase II models are better than Phase I and superior to uncertified models.

- There has been little incentive for manufacturers to improve durability beyond severe problems that would precipitate warranty claims or to improve durability to make units last without deterioration beyond the typical prorated warranty period of five years.

- The efficacy of the laboratory durability “stress” test developed to predict long-term, in-home performance of wood stoves, is controversial.

- The significant deterioration of catalytic activity often seen in catalytic wood stoves in a three- to five-year time frame and the identification of viable approaches to ensure catalyst inspection/replacement continues to be an unaddressed problem.

- In addition to deterioration of the catalyst, damage to catalyst bypass dampers and seals has been noted under in-home use of certified catalyst stoves. Long-term degradation has also be seen in certified non-catalytic stoves. Deterioration in non-catalytic stoves is mostly restricted to baffles and secondary air tubes. Door gaskets also appear to commonly wear out in all stoves. High temperature conditions accelerate the degradation of stove components. High draft conditions (mostly caused by unusually tall chimneys) tend to increase the probably of high burn rates and commensurate high-temperature damage.

- The EPA NSPS wood stove operating procedure (i.e., Method 28) does not represent the“real world” use of wood stoves. Wood stoves are designed, out of necessity, to pass the certification test and consequently, their design is not necessarily optimal for low emission performance under actual in-home use. Similarly, the emissions values obtained from EPA NSPS certification is only roughly predictive of emissions under in-home use.

- There has been little incentive to increase the thermal efficiency of wood stoves. Increased thermal efficiency, in effect, reduces emissions since less fuel is consumed to produce the same amount of heat. There is an efficiency test method published in the Federal Register, but efficiency testing is not required in the EPA NSPS certification process.

- The improvement in wood stove technology has not progressed rapidly in part due to economic considerations. The primary indicator of this conclusion is that the market for wood stoves has been declining. Cordwood stove sales for 1997 were less than one-half of their 1990 level.

- Performance of the EPA NSPS wood stove operating procedures has been described as an art. A technician, skillful in manipulating parameters within the specifications of Method 28, can influence test results significantly. In addition, the Method-28A-specified values of flue gas hydrocarbon compounds (i.e., Y_{HC}) used in calculating air-to-fuel ratios, effectively requires additional excess air to be needed in order to attain calculated air-to-fuel ratios of 35:1. This is significant for affected facilities in that any unneeded excess air reduces thermal efficiency.

- There are two particulate sampling methods used in the EPA NSPS certification process, Method 5G and Method 5H. To make the results obtained from these two methods comparable, a conversion equation is used. The data available at the time the conversion equation was developed, were limited. The equation has been widely criticized and it is generally believed that after conversion, Method 5G results produce higher “equivalent” emission values than if Method 5H had been used for emissions sampling. Method 5G is more precise and less difficult (and less costly) than Method 5H. It is the opinion of many that only Method 5G should be used. However, if the two methods continue to be used, the relationship between Methods 5G and 5H should be re-evaluated.

- There are two issues that may account for some of the perceived differences observed between Method 5G and 5H results. The first is the use of assumed values for flue gas hydrocarbon compounds (i.e., Y_{HC}). The assumed values, when used in Method 5H calculations, can reduce flue gas flow and emissions rate results. The second is the improper calculation of flue gas flow rate averages in Method 5H. The Method 5H carbon-balance calculation of flue gas flow rate averages is carried out by first averaging the 5- or 10-minute test interval concentration values for CO and CO_2 separately and then calculating the average flow rate for the test period from those constituent averages. To be mathematically correct, flue gas flow rates should be calculated from the CO and CO_2 concentrations for each 5- or 10-minute test interval and then those calculated test interval flow rates should be averaged.

- The EPA NSPS certification test methods and the draft International Standards Organization (ISO) test methods are quite different at this time. The relationship of values generated by the two standards are expected to be only qualitative at best. A major revision in the NSPS protocols or a major revision to the draft ISO method would be necessary to make the two testing procedures compatible.

- Many interviewees would like to see the NSPS protocols completely revised. Related to this, many would like to see some type of certification procedure required for all wood burning appliances, including masonry heaters, furnaces, all pellet stoves, fireplaces, and cookstoves. It is felt that this would provide “an even playing field,” provide incentives to improve their performance and provide credibility for the appliances which may actually improve their marketability.

- Manufactured densified fuel logs burned in wood stoves has been shown to reduce emissions in the 20% to 30% range. Manufactured densified fuel logs are more expensive than cordwood and are more available in the Western United States.

- Masonry heaters have relatively low emission factors and presumably low mass of emissions per unit of useful heat delivered as compared to cordwood stoves. They are exempt from EPA NSPS certification and there are few in use due to their high cost.

C Wood-burning fireplaces are used as primary or supplemental heat sources and for aesthetic purposes. For fireplaces used as supplemental heat sources there are both old technologies (e.g., glass doors, heat convection tubes and contoured masonry fireboxes) and new technologies (pellet, certified cordwood, and gas inserts) that can increase the useful heat and reduce effective emissions. For fireplaces used for aesthetic purposes, wax fire logs and decorative gas log inserts can be used to reduce emissions. There has been research showing that lower emissions can be produced in fireplaces by minimizing under-fire air and by enhancing secondary combustion. Other than the certification requirements of two states, there is little impetus to develop and manufacture fireplaces that produce low emissions.

C Particulate emissions from pellet stoves are very low and efficiencies are high as compared to cordwood stoves. Some pellet stoves currently on the market are EPA NSPS certified and some are exempt from certification due to having air-to-fuel ratios greater than 35:1 (usually at the lowest burn rate). There is most likely little difference in performance between exempt and certified models for currently manufactured pellet stoves. Many early models sold in the 1988/90 time period had mechanical and electronic problems. These problems have been largely solved and new units have a good performance record. Pellet fuels have also become standardized which contributes to the growing success of pellet stoves.

C Wood-fired central heating furnaces are not widely used. They are more commonly used in Canada and Europe than in the U.S. In the U.S. they are most widely used in the upper Midwest. There has been little research on their emission performance. Based on limited data cordwood furnace emissions appear to be higher than emissions from conventional wood stoves. Furnaces burning wood chips or pellets have much lower emission factors than those utilizing cordwood.

C The effect of wood type (tree species) and wood moisture on emission factors cannot be accurately quantified with existing data. The effect of wood type and moisture content appear to be relatively small. In both cases the effect appears to be less than an order of magnitude.

C It was a general consensus among interviewees that routine maintenance programs could improve the long-term performance of EPA NSPS certified stoves and that some type of maintenance training should be provided to the home owner at the time of purchase.

4. References

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