The $PM_{2.5}$ Reduction Potential of New Technology Home Heating Appliances and Fuels

James E. Houck and Paul E. Tiegs
OMNI Environmental Services, Inc.
5465 SW Western Ave. Beaverton,
OR 97005

Robert C. McCrillis
U.S. Environmental Protection Agency National
Risk Management Research Laboratory Research
Triangle Park, NC 27711

John Crouch and Carter Keithley
Hearth Products Association 1601
North Kent St., Suite 1001
Arlington, VA 22204

ABSTRACT
Reduction in emission of particles less than 2.5µm aerodynamic diameter ($PM_{2.5}$) from residential wood stoves and fireplaces by the replacement of existing units with new technology appliances and by using alternate fuels is discussed. Percentage emission reductions for each type of new technology and alternate fuel are presented. A description of each of the technology types and fuels is also provided. Predicted reductions in $PM_{2.5}$ emissions by appliance replacement and changes in fuel usage were calculated regionally by census division and by population increments in each of the census divisions. The reduction by population increments was calculated to provide insight into the magnitude of reductions that could reasonably be expected in a given city or nonattainment area in each of the census divisions.

INTRODUCTION
Residential wood combustion (RWC) has been identified as the dominant source or as a major contributor of particles less than 10µm in aerodynamic diameter (PM_{10}) in a number of PM_{10} nonattainment areas in the Western U.S. National PM_{10} emissions from RWC in 1995 have been estimated as 3.24×10^8 kg[1], or about 2% of total PM_{10} emissions. Well over 80% of particulate emissions from RWC are $PM_{2.5}$[2]. On a regional average basis, RWC is estimated to account for 8 and 5.7% of $PM_{2.5}$ in the Western and Eastern U.S., respectively[3]. Consequently, unless emissions from RWC are reduced, RWC will be a significant source in many future $PM_{2.5}$ nonattainment areas.

In 1993, 9% of the 96.6 million households nationwide used a wood stove[4]. Also in 1993, 46% of the 55.5 million single family detached homes had fireplaces[5]. Currently a fireplace is the third most popular amenity for a single family detached home after a two-car garage and central air conditioning[6]. Almost two-thirds of new single family detached homes have a fireplace, and about 5% have two or more fireplaces[5]. In 1993, about 9% of the Nation's space heating energy demand was met by RWC[4]. $PM_{2.5}$ reduction solutions based on moratoriums or bans on the installation or use of RWC appliances are not responsible in terms of the national need for the utilization of renewable energy resources, and they are contrary to the life styles of most American families.

It is estimated, based on commercial surveys, that there are currently 9.6 million wood stoves (including pellet stoves) and 7.1 million fireplace inserts (a total of 16.7 million appliances) used as significant heating appliances nationwide[7]. However, Hearth Products Association (HPA) manufacturer surveys show that only about 1.8 million of them are new technology appliances (1.0 million certified cordwood stoves + 0.3 million pellet stoves + 0.5 million certified fireplace inserts)[8]. In addition to the existing 7.1 million fireplaces with inserts, there are more than 20 million fireplaces without inserts (for a total of more than 27 million fireplaces)[5, 7]. Most of the fireplaces without inserts are used for aesthetic enjoyment or as a minor secondary source of heat. (Only 60 to 70% of installed fireplaces are used in any given year[5, 9].) More than 8 million cords of wood were burned in fireplaces in 1997, and about 0.8 million cord equivalents of that amount were manufactured wax logs. The wide gap between the total number of appliances and the number of low-emission, high technology units in homes, as well as the difference in the amount of cordwood and manufactured wax logs burned in fireplaces, provides the opportunity for reduction in atmospheric $PM_{2.5}$ levels by replacing older technology units with high technology ones or by changing fueling practices in fireplaces.

New technology appliances and fuels provide large reductions in $PM_{2.5}$ as compared with conventional wood stoves and traditional open radiant fireplaces burning cordwood. For the approximately 8.3 million old technology wood stoves currently in use, their replacement with certified catalytic stoves, certified non-catalytic stoves, pellet stoves, or masonry heaters, or the use of manufactured densified fuel in place of cordwood all provide $PM_{2.5}$ reductions. For fireplaces used as significant heating sources, there is a wide range of options to reduce $PM_{2.5}$ emissions. Some of these options can be retrofit into existing units, while others are practical only during home construction or remodeling. Options include simple older measures such as installing glass doors, double shell convection design, the use of blowers, the use of convection tubes, and masonry fireplaces with specially shaped fire chambers. Higher technology options include the use of certified cordwood, pellets, or gas inserts; or the installation of certified wood stoves or gas appliances that have the "fireplace look." For fireplaces used for aesthetic and minor heating purposes, the use of manufactured wax logs or decorative gas logs provides $PM_{2.5}$ emission reductions.

The findings of the research conducted by OMNI Environmental Services, Inc. (OMNI) for the U.S. Environmental Protection Agency (U.S. EPA) and HPA are provided here. The establishment of the current state-of-the-art of RWC technology was a key objective of the research conducted for the U.S. EPA. It was accomplished by reviewing literature published since the late 1970's and by formally interviewing recognized RWC experts in the appliance manufacturing industry, academia, and wood stove testing laboratories. The establishment of the numbers and types of wood burning appliances in use and their characteristic emissions and efficiencies were the key objectives of the research conducted for the HPA. This research was accomplished by reviewing governmental surveys, HPA manufacturer and other commercial surveys, emissions studies, and by interviewing HPA members. By combining the results of the U.S. EPA and HPA research, the potential for reducing RWC $PM_{2.5}$ emissions by using the various new technology options was documented. A description of the new technologies available with their corresponding emissions and efficiencies are provided. Calculated $PM_{2.5}$ emission reductions, compared to either conventional wood stoves or open radiant fireplaces burning cordwood, are also provided. In addition, the $PM_{2.5}$ reductions that would be achievable nationally, by census division and by 100,000 population increments in each census division, from the use of new technology appliances and manufactured fuels were calculated. The latter calculation was done to allow estimates to be made of the $PM_{2.5}$ reduction potentials in given cities or nonattainment areas based on population.

COMPARATIVE EMISSIONS UNITS

Particulate emissions from RWC have traditionally been reported in three ways: (1) emission factors [i.e., mass of emissions per mass of dry fuel burned (g/kg or lb/ton)], (2) emission rates [i.e., mass of emissions per time of appliance operation (g/hr)], and (3) mass of emissions per unit of heat delivered (g/MJ or lb/million Btu). The use of mass of emissions per unit of heat delivered (g/MJ) allows for the comparison of emissions for heating appliances with different efficiencies. Emission factors (g/kg) do not take into account that higher efficiency appliances will burn less wood to produce the same heat as lower efficiency appliances and therefore will have effectively lower emissions, even if their emission factors are comparable. Emission factors (g/kg) are, therefore, inappropriate for comparing emissions.

Emission rates (g/hr) do not take into account the amount of heat produced by an appliance. To be useful, they would need to be indexed to efficiency and the amount of fuel burned. Emission rates (g/hr) are, therefore, inappropriate for comparing emissions. Some confusion over the use of emission rates (g/hr) has occurred from the use of emission rates in the U.S. EPA certification program for wood stoves. The U.S. EPA certification process is a method to evaluate the relative performance of wood stoves under specific burn rates and conditions using dimensional lumber and permits those with acceptable emissions performance to be sold. It is generally recognized that the certification emission rates (g/hr) are different (lower and not directly correlatable) than the emission rates that the same appliances will have in homes under "real-world" use. Certification numbers cannot be used in the development of emission inventories. Emissions in terms of mass emissions per unit of heat delivered (g/MJ) are compared in Table 1 for alternatives to conventional stoves burning cordwood and in Table 2 for alternatives to conventional open radiant fireplaces burning cordwood.

Unlike the case of appliances used as significant sources of heat, the use of emissions per unit of heat (g/MJ) delivered for comparison of emissions for fireplaces, used primarily for aesthetic or minor heating purposes, is inappropriate. In this case, emission rates (g/hr) do provide for a better comparison. The burn rate of a fireplace used for aesthetic or minor heating purposes is mostly related to the size of a typical sustainable "warm" aesthetic fire characteristic of fireplaces (about 3 kg/hr). That is, the amount of wood burned and the corresponding emissions are not directly related to heat demand, but are more or less constant for a given appliance. In addition, one of the two alternatives to fireplaces burning cordwood, the use of manufactured wax logs, has a fixed burn rate associated with it. The manufacturers of wax logs generally recommend one-at-a-time usage with a specified burn duration per log. The other alternative, decorative gas log systems, have negligible particulate emissions at all heat output levels. Consequently, emission rates (g/hr) were used to compare emissions and emission reductions for fireplace alternatives for a fireplace used for aesthetic and minor heating purposes (Table 3).

WOOD STOVE/HEATERS

There are an estimated 8.3 million conventional wood burning stoves currently in use[7, 8]. Wood stoves are designed for a lifetime of about 40 years. Consequently, without regulatory impetus the replacement of existing wood stoves with new technology devices will be a slow process. Estimates of the average efficiency and emissions of conventional wood stoves are 54% and 1.68 g/MJ, respectively (Table 1). The efficiency and emissions estimates have been based on a number of field studies[10-15] and interviews with RWC experts. Average emissions for conventional wood stoves may be higher than the 1.68 g/MJ since most of the studies were conducted in cold climates with stoves operating at higher burn rates. High burn rates tend to produce lower emissions than low burn rates. The consequence of this is that the $PM_{2.5}$ reductions calculated for the various alternatives to conventional stoves burning cordwood may be conservative, and the actual reduction achievable may be greater. While we report average efficiencies and emissions values, it is widely recognized that efficiencies and emissions are highly variable for conventional cordwood stoves. This is due to the facts that there are hundreds of wood stove models in use, many dozens of tree species are commonly used for fuel wood, draft characteristics (chimney conditions) vary from home to home, household altitude is variable, there are variations in fuel seasoning and storage practices (wood moisture), and there are wide variations in home owner operation of wood burning devices (e.g., burn rate, damper setting, kindling approach). To provide more accurate percent $PM_{2.5}$ reduction values in a specific airshed, measurement of conventional stove efficiencies and emissions in that airshed would be appropriate to produce average values more reflective of local conventional wood stove usage.

Low emission alternatives to conventional stoves burning cordwood are certified non-catalytic wood stoves, certified catalytic wood stoves, certified pellet stoves, exempt pellet stoves, masonry heaters, and the use of manufactured densified fuel.

Certified non-catalytic wood stoves

There are an estimated 0.6 million certified non-catalytic wood stoves currently in use[8]. There are 119 models listed as certified by the U.S. EPA as of August 12, 1997. All wood heaters manufactured after July 1, 1988, and sold after July 1, 1990, had to meet Phase I emission limits. All wood heaters manufactured after July 1, 1990, and sold after July 1, 1992, had to meet Phase II emission limits. Phase I and II emission limits for non-catalytic wood stoves are 8.5 and 7.5 g/hr, respectively. Non-catalytic technology achieves the reduction in emissions primarily by using secondary combustion air and heat-retaining refractory materials that promote complete combustion. A substantial fraction of emissions from non-catalytic wood stoves occur during fire start-up, before efficient combustion is achieved. The average efficiency and emission values for certified non-catalytic wood stoves are based on a number of field studies[10-13, 15-17] and interviews with RWC experts. The efficiencies and emissions for new non-catalytic stoves are shown in Table 1. It is estimated that, when new, certified non-catalytic wood stoves can reduce emissions by 71%, compared with conventional stoves. The emission control effectiveness of this technology does not seem to degrade as rapidly as for catalytic technology[14, 15, 18]. In those instances where physical damage has been observed, it seemed to be associated with extended operation at high firing rates[19]. In a project to develop a "stress test," it was found that stoves operated for 2 weeks under this high temperature regime degraded the equivalent of 1-2 years of the most extreme in-home use observed during field studies[20].

Certified catalytic wood stoves

There are an estimated 0.4 million certified catalytic wood stoves currently in use[8]. There are 83 models listed as certified by the U.S. EPA as of August 12, 1997. Phase I and II emission limits had to be met for catalytic stoves in the same time frames as for non-catalytic stoves. For catalytic stoves, the Phase I and II limits are 5.5 and 4.1 g/hr, respectively. The limits are lower for catalytic stoves than for non-catalytic stoves because their emissions increase with time as catalyst performance becomes poorer. As with non-catalytic stoves, emissions are at their highest during start-up for catalytic stoves. Not only is combustion not efficient during the fire start-up period, but also the catalyst needs to be heated before it functions. The average efficiency and emission values for certified catalytic wood stoves are based on a number of field studies[10, 11, 13, 15, 16] and interviews with RWC experts. The efficiencies and emissions for new catalysts are shown in Table 1. It is estimated that certified catalytic wood stoves with new catalysts can reduce emissions by 74%, compared with conventional stoves. The emission control effectiveness of most catalytic stoves in typical residential use has been shown to decrease over time[14, 15, 16, 18, 19]. In some cases, this is due to decreased catalytic activity; in other cases it is due to deterioration of other, emission-critical components, such as the bypass damper. As with non-catalytic stoves, most of the damage occurs during the relatively brief periods of maximum temperature operation. In a project to develop a "stress test", it was found that stoves operated for 2 weeks under this high temperature regime degraded the equivalent of 1-2 years of the most extreme in-home use observed during field studies.[20] The catalyst is particularly sensitive to high temperatures.

Pellet stoves

There are an estimated 0.3 million pellet stoves currently in use[8]. During the 1995-1996 heating season, 654,000 tons of pellets were sold[21]. Nearly all pellet stoves have been sold since 1989. There are two categories of pellet stoves — 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. Efficiency and emission values for pellet stoves are based on field studies[22, 23] and interviews with RWC experts. The efficiencies and emissions are shown in Table 1.

It is estimated that pellet stoves can reduce particulate emissions by 92%, compared with conventional cordwood stoves. Reduction in $PM_{2.5}$ is expected to be even greater than the reduction of total particulate since 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 products that are mostly submicron in size[2], whereas pellet stove emissions are believed to contain a higher fraction of entrained inorganic ash that is characteristically composed of larger particles.

Masonry heaters

Masonry heaters are exempt from U.S. EPA certification and, in fact, the certification procedure is not applicable to their design or intended mode of operation. The state of Colorado does, however, have a 6.0 g/kg emission limitation applicable to masonry heaters. Masonry heaters are more costly than cordwood or pellet stoves: for that reason, many fewer of them are in place. However, because of their aesthetic appeal, many of them are the centerpieces of homes and are often installed in more expensive houses. They achieve their low emissions by burning a large mass of cordwood in a short time period. The high burn rate enhances complete high-temperature combustion and commensurate low emissions. The short-duration, high-burn heats a large masonry mass that radiates heat to the living space well after the fire is out. To enhance transfer of the heat to the masonry material, the exhaust gas is routed through a "folded" pathway through the appliance. The appliance is generally installed in the center of the home rather than along an exterior wall to facilitate radiant heating. The average efficiency and emission values for masonry heaters are based on field studies[24] and interviews with RWC experts. The efficiencies and emissions are shown in Table 1. It is estimated that masonry heaters can reduce emissions by 85%, compared with conventional stoves.

Densified fuel

Manufactured densified fuel is commonly used in cordwood stoves due to its convenience and good burning characteristics. It is typically composed of compressed sawdust. Its density ranges from 1.1 to 1.3 g/cm^3, compared to wood, which typically ranges from 0.3 to 0.8 g/cm^3 depending on the species, and its moisture content is in the 6 to 10% range compared with quality cordwood that has a moisture content of around 20%[14, 25]. The dense, clean, low moisture fuel produces lower emissions than cordwood when burned in conventional stoves. Its cost during the 1991-1992 heating season in the Pacific Northwest averaged about 1.4 times that of cordwood[14]. The average efficiency and emission values for conventional stoves burning densified fuel are based on field and laboratory studies[14, 25] and interviews with RWC experts. The efficiencies and emission values are shown in Table 1. It is estimated that the use of densified fuel in conventional stoves can reduce emissions by 27%, compared with conventional stoves using cordwood. Not surprisingly, when densified fuel was burned in certified stoves, further reductions in emissions were achieved over the certified stove burning cordwood alone (Table 1)[14, 25]. It should be noted that quality densified fuel has been made from a variety of biomass materials besides sawdust. These include straw, rice hulls, waste paper, cardboard, nut shells, palm boughs, and peat. The emissions from these products vary, but are generally lower than from cordwood.

FIREPLACES USED AS A HEAT SOURCE

There are an estimated 27 million fireplaces currently in homes[5]. There are two structural types of fireplaces — manufactured metal fireplaces (referred to as zero-clearance fireplaces) and masonry fireplaces. Zero-clearance 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.

A large number of fireplaces are used as significant supplemental heat sources since fireplace inserts are designed for increased efficiency, and there are 7.1 million fireplaces with inserts in them[8]. A small number of fireplaces are even used as primary heat sources. In 1993, 0.4 million households used wood burning fireplaces as their main source of heat[4]. Many existing fireplaces are more efficient than simple open radiant fireplaces due to well established older technological improvements. It has often been stated that fireplaces are used only for aesthetic purposes due to their low efficiencies (around 7% for open radiant fireplaces). However, some fireplaces utilizing older technology can reach efficiency levels in the 40% range[25]. 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 shaped fire chambers (e.g., Rumford and Rosin fireplaces). Efficiency and emission values for open radiant fireplaces and various older technologies are shown in Table 2. They are based on field and laboratory studies[24, 26] and interviews with RWC experts. Some older technologies, such as glass doors and convection tubes, can be added to existing open radiant fireplaces to reduce effective emissions. The open radiant fireplace, with an efficiency value of 7% and emission value of 8.55 g/MJ, was used for comparison purposes in Table 2 since it is the simplest fundamental unit.

There is no federal protocol for testing fireplace emissions. There is, however, a state of Washington testing protocol for non-masonry fireplaces (7.3 g/kg emission limit), and there is a Northern Sonoma County, California, testing protocol currently in the process of development for masonry fireplaces.

Certified cordwood and pellet inserts

Certified non-catalytic, certified catalytic and pellet inserts can be used in existing zero-clearance and masonry fireplaces. They are essentially stoves modified to fit into a fireplace. If properly installed, their performance is similar to that of their stove counterparts, albeit their efficiencies are slightly poorer since convection and radiation of heat is more restricted by their location in the fireplace cavity. There are an estimated 0.5 million certified cordwood inserts and 0.2 million pellet inserts in use[8]. As of August, 12, 1997, the U.S. EPA listed four catalytic and six non-catalytic insert models as certified. The emission reductions they provide over the use of a simple open radiant fireplace range from 94 to 98% (Table 2).

Gas units

Three types of gas units have the "fireplace-look." They are gas fireplace inserts, decorative gas fireplaces, and gas fireplace heaters. All have negligible $PM_{2.5}$ emissions, compared with cordwood fireplaces. Therefore, particulate reductions are near 100%. They can utilize either natural gas or liquefied petroleum gas (LPG) which 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 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.

Fireplace-like wood stoves

Some wood stoves have been designed to have the appearance of fireplaces, to be "zero-clearance" units, and capable of being installed at the time of construction. The emission reductions they offer over simple open radiant fireplaces are on the order of 95% (Table 2).

FIREPLACES USED FOR AESTHETIC AND MINOR HEATING PURPOSES

Of the 20.4 million households that burned wood in 1993, 9.6 million burned less than half a cord per year, and 5.6 million reported burning wood an average of less than 1 hour per week[4]. During the 1994-1995 heating season, 17% of fireplace owners reporting burning wood once or twice a season, 13%

reported once or twice a month, and 18% once or twice a week[9]. The sum of these three categories during the 1994-1995 heating season corresponds to about 13 million fireplaces. While none of these statistics provides a clear picture of the number of fireplaces used for aesthetic and minor heating purposes, they do illustrate its magnitude. Table 3 lists the typical emission rate (60 g/hr) of a simple open radiant fireplace obtained from field and laboratory studies[24, 25] and interviews with RWC experts. The emission rates from open radiant fireplaces were used to compare the emission reductions possible with manufactured wax logs and decorative gas logs. It should be noted that there have been some general improvements in the design of fireplaces that minimize the under-fire air supply and maximize combustion conditions with the introduction of secondary air. Therefore some new fireplaces have emission rates lower than the typical 60 g/hr value.

Manufactured wax logs

Manufactured wax logs are widely used in fireplaces nationwide. It has been estimated that 100 million manufactured logs are burned each year (0.8 million wood cord equivalents)[6]. 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[9]. They 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 (34.8 MJ/kg for wax logs, compared to 21.0 MJ/kg for Douglas fir), and their moisture content is much lower, compared with cordwood (3% compared to 20% for good quality cordwood)[25]. They are exclusively for use in fireplaces (not wood stoves), they require no kindling, and are designed for one-at-a-time use. The emissions rate of 19 g/hr shown in Table 3 for wax logs is based on laboratory tests[25, 27, 28]. The $PM_{2.5}$ reduction achievable with wax logs, compared to cordwood when a fireplace is used for aesthetic or minor heating purposes, is calculated as 68% (Table 3).

Decorative gas logs

The use of decorative gas logs has become popular. During the 1994-1995 heating season, 17% of fireplaces used gas as fuel[9]. (While most gas units are decorative gas logs, this percentage also includes gas fireplace inserts, decorative gas fireplaces, and gas fireplace heaters.) Decorative gas logs are designed to be used in existing masonry or factory-built zero-clearance fireplaces. Gas log sets consist of a valve and burner assembly, a grate, and imitation logs made of cast refractory or cement. Their functions are strictly for aesthetics with flame appearance being the primary design criterion. The flame appearance is achieved by burning a high volume of gas without consideration for efficiency. Decorative gas logs have negligible $PM_{2.5}$ emissions, compared with cordwood fireplaces. Therefore, particulate reductions are near 100%, compared with fireplaces burning cordwood. As with gas fireplaces and inserts, either natural gas or LPG can be used with decorative gas logs.

REGIONAL AND AIRSHED $PM_{2.5}$ EMISSION REDUCTION

The magnitude of potential $PM_{2.5}$ reductions obtainable by the replacement of old technology wood stoves and fireplace inserts with newer, higher efficiency, lower emission units is graphically illustrated in Figure 1. Similarly the magnitude of potential $PM_{2.5}$ reductions from fireplaces used for aesthetic and minor heating purposes can be appreciated when the total number of fireplaces in use for those purposes is considered. While it is difficult to draw the exact line between aesthetic/minor heating usage of fireplaces and significant heating usage, as noted above there appear to be about 13 million fireplaces in the former category. Based on the data for individual appliances obtained from field and laboratory measurements and interviews with industry experts, overall $PM_{2.5}$ reductions of 70% for wood stoves and 50% for fireplaces were used to calculate $PM_{2.5}$ reductions on a national basis, by census division and by 100,000 population increments in each census division (Table 4). As can be seen by reviewing the data in Tables 1-3, the 70 and 50% values were conservative, and even greater reductions may be achievable.

The reductions per 100,000 population increments were calculated to allow estimates to be made of the $PM_{2.5}$ reduction potentials in given cities or nonattainment areas based on population. The reductions shown in Table 4 need to be “fined- tuned” for the ratio of fuel usage in fireplaces and wood stoves characteristic of a given area. Nationally, the ratio is estimated as 72% in wood stoves and 28% in fireplaces[29]. This ratio was used for the calculation of data shown in Table 4. The reductions also need to be fine-tuned for the local conventional wood stove usage and age distribution (e.g., heating degree days, typical age of homes). Although the data presented in Table 4 are approximate and meant to be illustrative only, they do show the large reduction in $PM_{2.5}$ levels that can be expected with appliance replacement and fuel usage changes.

CONCLUSIONS

Whether based on direct measurements or predictions from emission inventories, particulate levels attributed to RWC have been from emissions primarily from old technology appliances burning cordwood. Because most PM_{10} from RWC is also $PM_{2.5}$, RWC will become relatively more important in the future. RWC utilizes a renewable energy source and represents an important part of the Nation’s space heating budget. The use of fireplaces is a valued household activity for many Americans. New appliances and fuels can reduce $PM_{2.5}$ emissions from RWC appliances dramatically. The replacement of existing appliances with new technology units or the use of alternative fuels can reduce atmospheric $PM_{2.5}$ levels, as well as preserve renewable energy use and traditional household practices. The implications for emission reduction credits, emission trading, state implementation plan options, and wood burning appliance trade-out programs (tax and/or market incentive programs which encourage users to replace old technology, cordwood-burning stoves with new, low emission ones) are significant. Routine maintenance of the new technology stoves will be required to ensure continued low emission performance over the life of the appliance.

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Table 1. Particulate emission reduction from alternatives to conventional stoves burning cordwood.[a]

Appliance/Fuel	Efficiency (%)	Mass particulate emissions per delivered heat (g/MJ)[b]	Reduction (%)
Conventional	54	1.68	-
Certified non-catalytic	68	0.49	71
Certified catalytic[c]	72	0.44	74
Pellet stove	78	0.13[d]	92
Masonry heater	58	0.25	85
Conventional/densified fuel	57	1.20	27
Certified non-catalytic/densified fuel	70	0.21	88

a. Data from references 10-17 and 22-25. Adjustments have been made in the values based on interviews with RWC experts to reflect the current state-of-the art of wood heater technology and understanding of combustion parameters.
b. g/MJ = grams/megajoule.
c. Stoves with new catalyst.
d. A smaller fraction of pellet stove particulate emissions are less than $PM_{2.5}$ than for other categories.

Table 2. Particulate emission reduction from alternatives to conventional open radiant fireplaces burning cordwood for space heating.[a]

Appliance/Fuel	Efficiency (%)	Mass particulate emissions per delivered heat (g/MJ)[b]	Reduction (%)
Conventional open radiant fireplace	7	8.55	-
Double shell convection, natural draft	13	4.60	46
Convection tube, "C" shaped, glass door	15	3.99	53
Double shell convection, blower, glass doors	32	1.87	78
Certified non-catalytic insert	66	0.50	94
Certified catalytic insert[c]	70	0.45	95
Pellet stove insert	76	0.13[d]	98
Gas insert	75	Negligible	~100
Gas fireplace	50	Negligible	~100
Certified catalytic "fireplace-like" woodstove[c]	70	0.45	95
Masonry fireplace with shaped fire chambers and glass doors	42	1.22	86

a. Data from references 24-26. Adjustments have been made in the values based on interviews with RWC experts to reflect the current state-of-the art of fireplace technology and understanding of combustion parameters.
b. g/MJ = grams/megajoule.
c. Unit with new catalyst.
d. A smaller fraction of pellet insert emissions are less than $PM_{2.5}$ than for other categories.

Table 3. Particulate emission reduction from alternatives to conventional open radiant fireplaces burning cordwood for aesthetic and minor heating purposes.[a]

Appliance/Fuel	Mass particulate emissions per unit time (g/hr)	Reduction (%)
Conventional radiant fireplace	60	-
Manufactured wax logs	19	68
Decorative gas logs	Negligible	~100

a. Data from references 25, 27, and 28.

Table 4. Approximate $PM_{2.5}$ emission reduction by census division and per 100,000 population increments by replacement of conventional woodstoves (at least 70% reduction in emissions), and by reduction of fireplace emissions by 50% through the use of new technology inserts and alternate fuels.

Census Division	Population $x10^6$	Total Households $x10^6$	RWC Households $x10^6$	Cords $x10^6$	$PM_{2.5}$ Reduction[a]			
					by division		per typical 100,000 population	
					lb x 10^6	g x 10^9	lb x 10^3	g x 10^6
New England	14	5.1	1.1	2.3	61	28	433	196
Middle Atlantic	38	14.4	2.4	4.8	125	57	325	148
East North Central	44	16.4	2.6	3.4	91	41	209	95
West North Central	18	6.9	1.5	2.1	54	24	302	137
South Atlantic	46	17.4	3.9	4.7	123	56	271	123
East South Central	16	6.0	1.3	2.4	64	29	397	180
West South Central	27	10.1	2.0	1.7	46	21	170	77
Mountain	14	5.4	1.3	1.5	39	18	277	126
Pacific	40	15.0	4.4	4.5	116	53	290	132
National	257	96.7	20.5	27.4	719	327	297	135

a. In 1995, National RWC PM_{10} = 956x10^6 lb[1]

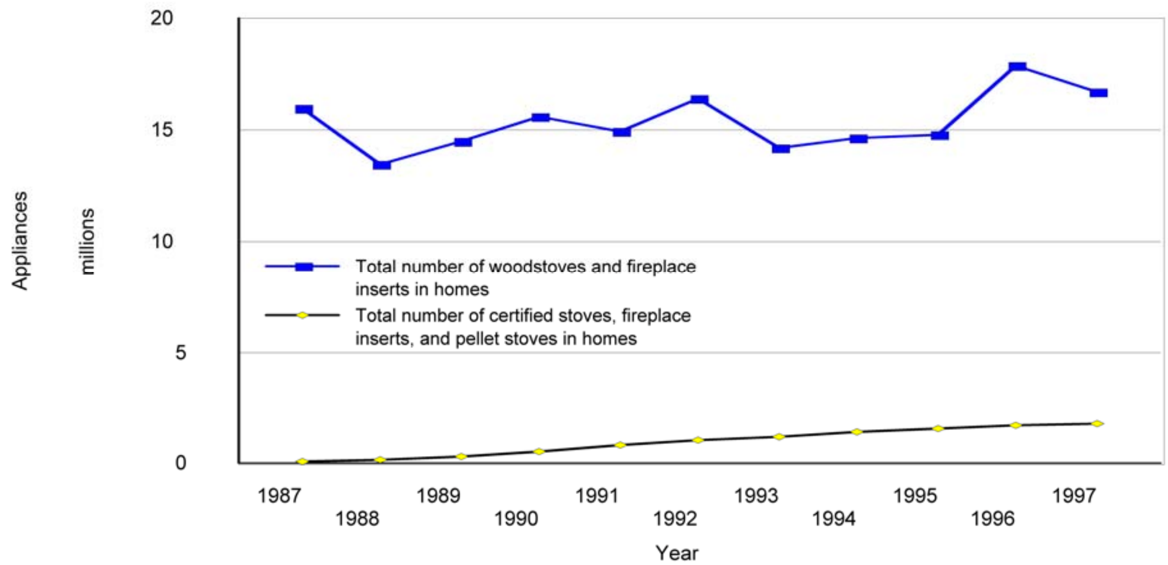

Figure 1. Replacement opportunity for low-emission units.