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Residential Wood Combustion Study

1980-1982 Executive Summary

Residential Wood Combustion Study

Executive Summary

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Disclaimer

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Executive Summary

Residential Wood Combustion Study for Region 10, U.S. Environmental Protection Agency

Between 1900 and 1970, this country saw a massive shift in home heating from coal and wood to the newer, cleaner sources of heat such as oil and electricity. With the large price increases and supply uncertainties of the 1970s for the newer energy sources, however, many homeowners began to look again at the use of wood for home heating.

This renewed interest in residential wood combustion has been particularly intense in the Pacific Northwest, where firewood is readily available. Wood burned in woodstoves in Portland, Oregon, for example, was estimated to have increased from less than 50,000 cords per year in 1970 to over 150,000 cords per year in 1980.

During these same years, major air pollution control efforts by industries have substantially reduced the emissions from these sources in the Pacific Northwest. Despite these efforts, levels of particulate air pollution in the ambient air for many Pacific Northwest cities are still of concern. Residential wood combustion has been identified in several cities as the major contributor to these high wintertime particulate levels. (A Medford study showed residential wood combustion produced up to 86% of the fine particulate during 24-hour, worst case time periods.)

These increased levels of residential wood combustion are of considerable concern to the public and to air pollution control agencies for a number of reasons. Smoke from wood combustion is relatively rich in carcinogens, toxic pollutants, and substances irritating to the respiratory tract. In addition, particulate from woodsmoke tends to consist largely of fine or respirable particulate, which is recognized as being much more of public health concern than more coarse particulate. Fine particulate can lodge within the lungs, whereas more coarse particulate is trapped in the upper respiratory tract and is expelled. The wood smoke problem is compounded by the fact that the smoke is emitted close to the ground in residential areas, as opposed to emissions through tall industrial stacks.

In addition to the obvious public health concerns about residential wood combustion, visibility reduction and limits on the airshed capacity are important. Under current environmental laws, each state is required to have a plan for making sure all areas are within acceptable ambient air pollution levels, and for ensuring that the air quality is not allowed to deteriorate. For some of those cities having air pollution problems, extensive studies have been performed to establish an "airshed capacity."[1] Residential wood combustion is now responsible for a large percentage of this airshed capacity in several cities, limiting the amount of industrial growth that can occur without very expensive air pollution control measures to further reduce those industrial emissions. As most cities wish to have the ability to attract new industry, this lack of an adequate margin for growth is of major concern.

Because of public health, esthetic, and economic growth considerations, residential wood combustion has become a focus of air pollution control agency interest in the last few years. This study was commissioned by the U.S. Environmental Protection Agency, Region 10, to provide some of the necessary information for interested agencies. It was conducted in 1980-81, and was designed to answer these questions for the Pacific Northwest:

- How serious is the current air pollution problem due to residential wood combustion?
- Will this problem increase over the next 20 years, and if so, how much?
- What are the most effective and realistic strategies to reduce the air pollution impact of residential wood combustion?

Seven individual areas of study were completed to help answer these questions for the Pacific Northwest. These were:

Task 1—Ambient Air Quality Impact Analysis. Evaluates current impact of residential wood combustion on ambient air quality.

Task 2a—Current and Projected Air Quality Impacts: Projects impact on ambient air quality by residential wood combustion through the year 2000.

Task 2b—Household Information Survey. Relates findings of household surveys in three metropolitan areas: Portland, Oregon and Spokane and Seattle, Washington.

Task 3—Wood Fuel Use Projection. Projects likely residential wood use in Portland, Spokane, and Seattle through year 2000.

Task 4—Technical Analysis of Wood Stoves. Evaluates existing literature and test results on promising wood stove designs and operating procedures, which could reduce the air pollution emissions from residential wood combustion.

Task 5—Emissions Testing of Wood Stoves. Relates results of emissions tests on "state-of-the-art" wood stoves and add-on devices, evaluates alternative test procedures, and evaluates the effect of wood moisture content on emissions.

Task 6—Control Strategy Analysis. Evaluates and ranks possible control strategies, including expected emission reductions, projected cost, and other significant advantages and disadvantages of each proposed control strategy.

Task 7—Indoor Air Quality. Tests and evaluates results of indoor air sampling for several homes having wood stoves.

Significant findings for this project are:

- Residential wood combustion contributed an average of 75%, 84%, and 81% of the fine (less than 2.5 micron diameter) particulate in the three Portland, Seattle, and Spokane neighborhoods, respectively. These neighborhoods were chosen for special testing because of apparently high levels of woodburning activity. The sampling was done in February, 1981, and is considered typical of reasonable worst-case impacts.
- The contribution of residential wood combustion to fine particulate at nine other monitoring sites in Pacific Northwest cities ranged from 20% to 93%. This sampling was done from October, 1980 to March, 1981. It should be noted that these values are based

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[1] Airshed capacity is the amount of emissions possible in an area without exceeding ambient air standards.

on a small number of samples and may not represent the worst possible fine particulate levels from RWC.

- Average ambient air levels of benzo (a) pyrene, a known carcinogen, were measured at levels approximately equivalent to that of smoking two to six cigarettes/day. The highest level of benzo (a) pyrene measured was approximately equivalent to that of smoking four to sixteen cigarettes/ day.

- The household survey in three small neighborhoods in Portland, Oregon, the Seattle, Washington, metropolitan area (Bellevue) and Spokane, Washington showed 48%, 85%, and 80% respectively of the households had used a wood burning device (wood stoves or fireplaces) in the previous 12 months. The average wood use per woodburning household varied from 2.0 cords/year (Portland) to 1.2 cords/ year (Seattle), with Spokane residents burning 1.9 cords/year.

- Without a major effort to control the levels of woodburning, it is projected that 24-hour worst case fine particulate will increase from the 1981 levels, 53%, 27%, and 21% in Portland, Seattle, and Spokane, respectively, by the year 2000. Much of this increase will result from an anticipated shift from fireplace use to dirtier but more energy efficient wood stoves.

- By the year 2000, wood use is projected to increase by 41%, 19%, and 7% in the Portland, Seattle, and Spokane metropolitan areas, respectively over 1981 levels. These projections are based on a computer model developed by Norman Marshall, Dartmouth College. The model is largely driven by the relative cost of wood heat to oil, gas, and electricity. These projections should be used with care, as they are based on projected fuel costs which are difficult to estimate accurately.

- State-of-the-art wood stoves and add-on devices were not shown to emit substantially less pollutants under the chosen operating conditions than the standard, box type stove, except for a ceramic stove in this 1981 testing. However, the ceramic stove was operated at a much higher burn rate (per manufacturer's direction), and high burn rates are associated with lowered emissions. Since the time of this testing, numerous advanced designed wood stoves have been developed, some of which have demonstrated very low emissions in testing by other researchers.

- Other test results showed that wood dried to a moisture content of 25-35% on a dry basis (approximately equal to that from six to nine months air drying) had the least emissions. Of the simplified test procedures evaluated, only the carbon monoxide and total hydrocarbon tests had a reasonable correlation with EPA method 5 for particulate, which was used as the standard. However, extensive additional data would be needed to confirm these correlations before such methods could be used in an ongoing test program. The carbon monoxide and total hydrocarbon tests cost about $4,200 for a nine-test series, as opposed to $15,000 for EPA method 5.

- Because of the lack of standardized test procedures nationwide and the relatively few tests done, it was not possible at the time of the study to definitely identify any significantly cleaner stoves or devices from available literature and test results. However, several methods are currently available to reduce emissions from existing woodstoves. The include proper sizing of the stove, drying wood before burning, and burning hot fires.

- The two types of control strategies that appear to be the most promising are limiting new stoves sold to cleaner burning models, and increased public education as to proper stove choice, wood storage practices, and stove operating procedures. The particulate emissions reductions from these types of control strategies are estimated at from 39% (mandatory stove certification, only clean-burning stoves sold) to 6.2% (encourage burning of dry firewood).

- With proper stove maintenance, indoor pollution levels should not increase when wood stoves are used. One home with a leaky stove did have higher indoor pollution levels, with exposure equivalent to smoking 10 to 38 cigarettes per day for benzo (a) pyrene. However, the testing was done during relatively mild weather and may not be typical of worst case, heavier burning.

An executive summary for each task is presented in the following sections. Each summary includes a brief discussion of study methods and the major findings. These summaries are based on the full reports, which are referenced at the end of this report.

Task 1
Ambient Air Quality Impact Analysis

The increasing use of wood as a source of residential heat is a phenomenon common to many states in the Pacific Northwest. Residential Wood Combustion (RWC) carries a significant potential for adverse health effects to large segments of the population. The impact of residential wood combustion emissions is especially severe because plume impacts typically occur at ground level very near the source. In addition, the areas of highest RWC emission density often coincide with the areas of maximum population density, the highest RWC emission rates occur at times when most people are in those residential neighborhoods, and most particulate emissions are within the size range deposited within the lungs. RWC emissions are relatively rich in carcinogenic organics, toxic pollutants, and respiratory irritants. For all of these reasons, wood smoke represents an important problem that is of growing public concern.

RWC emissions are becoming increasingly important as a major contributor to violations of current particulate air quality standards and are implicated in issues related to visibility reduction, odors, and public health. New attention being focused on fine particulate with the proposal of an Inhalable Particulate National Ambient Air Quality Standard by EPA on March 20, 1984, also has caused concern about the RWC impact on 24-hour standard attainment. The continuing economic pressures to expand the use of wood for residential heating, and the limited regulatory pressures restricting the use of wood, may cause additional concern about the impact of RWC emissions on public health, esthetics, and the future "livability" of many communities.

The purpose of this task was to evaluate the current impact on ambient air quality by RWC in the Pacific Northwest. The testing occurred in the 1980-81 heating season in eight cities, and included evaluation of fine and total suspended particulate as well as seven carcinogenic compounds. Samples were selected to correspond to the maximum impact from RWC, and represent "worst case" ambient conditions measured during the field program. Elemental and carbonaceous components were analyzed to assist in the Chemical Mass Balance methods used in identifying the fraction of the total sample attributable to RWC and other sources.

A detailed household wood use survey was conducted around three of the monitoring sites, under Task 2B of this study. Further interpretation of the RWC impact estimates as they relate to projected increases in wood use is included in Task 2A.

Sampling Methodology

A comprehensive ambient air sampling and analysis program was conducted in eight cities in Oregon, Washington, and Idaho during the October, 1980-March, 1981 space heating season to provide an assessment of current maximum 24-hour RWC impacts on particulate air quality. Seventy-seven selected fine particle samples were analyzed for 35 trace elements, carbon, polynuclear aromatic hydrocarbon (PAH) compounds, and Carbon-14. The quantitative impact of RWC on ambient air was then evaluated.

Site Selection. Data from 12 historical ambient air data collection sites and three new sites were included in the study, with the three new sites located in residential areas with apparently significant RWC activities (as evidenced by wood piles, stove pipes, and wood smoke). For each of these three new monitoring sites, a companion site in a nonresidential area was established to provide background information if no adequate background site was already in operation as part of the existing monitoring network. The other nine sites already were in operation for routine ambient air monitoring, and were located largely in commercial or industrial areas. The cities providing data were Seattle, Spokane, Tacoma, Longview, and Yakima, Washington; Boise, Idaho; and Portland and Medford, Oregon.

Timing and Selection of Samples. The three special ambient sites were sampled between January 31, 1981 and March 10, 1981. Samples analyzed from the other sites were gathered between October, 1980 and March, 1981. Samples were collected on the weekends (when RWC emissions are expected to be the greatest) and on one day in the middle of the week.

Not all samples collected were analyzed because of cost constraints. Seventy-seven samples were selected for analyses from those days when the impact from RWC would be expected to be the greatest because of cold temperatures, an inversion, and low wind speed conditions. High nephelometer readings, which indicate high fine particulate levels, also were used to select samples for analysis.

Sampling Equipment. Five types of samplers were used for this project. Brief descriptions of each sampler, the monitoring site having the device, and the analytical use of the collected samples are given in Table 1.

Table 1
Sampling and Analytical Protocol

Sampling Device Name	Information Provided by Sampling Device	Site Locations Having Sampling Device	Analyses Performed on Sample
Hi-Vol	Collects total suspended particulate (<30 um)	All 15 sites except Lake Sammamish (Seattle area) and County Health (Spokane area)	Weighing (to determine TSP), gas chromatography/ mass spectroscopy (PAH analysis), Carbon-14
Sierra Model 235 High Volume Cascade Impactor	Collects respirable particulate (<2 um) on glass fiber filter	Country Homes (Spokane), Turnbull (Spokane), Newport Way (Seattle area), Lake Sammamish (Seattle area), Marcus Whitman School (Portland), Carus (Portland), County Courthouse (Medford)	Weighing (to determine fine particullate concentration), elemental/organic carbon (chemical mass balance and PAH)
Dichotomous sampler	Collects respirable particulate (<2.5 um) and coarse particulate (2.5-15 um) on teflon filter	All 15 sites	Weighing (fine particulate), X-ray fluorescence and neutron activation analysis (trace elements for chemical mass balance)
Size selective inlet sampler (SSI)	Collects particulate < 15 um on glass fiber filter	Fairview & Liberty (Boise)	Gas chromatography/ mass spectroscopy (PAH), Carbon-14
Integrating nephelometer	Measures the light scattering characteristics of ambient air (associated with fine particulate)	Fire Station 12 (Tacoma), County Courthouse (Yakima)	Not used except to indicate days of high fine particulate to assist in sample selection

Analyses Performed

Analyses of the chosen samples were performed to measure the concentrations of (1) certain carcinogens associated with wood smoke, (2) total suspended and respirable particulates, and (3) various other elements and carbon forms so that the contribution of RWC could be determined.

Fourteen carcinogens have been associated with wood smoke. Seven polynuclear aromatic hydrocarbons (PAH) known to be carcinogens were tested. Samples for PAH analyses were collected using Sierra Cascade Impactors, Hi-Vols, and the Size Selective Inlet sampler. Gas chromatography/mass spectroscopy was used for the analysis.

Total suspended particulate levels were collected with the Hi-Vols. Fine particulate levels were measured using the Sierra Cascade Impactor ($< 2.0\ \mu m$) and the dichotomous sampler ($< 2.5\ \mu m$).

The concentrations of 35 trace elements, needed for the Chemical Mass Balance analysis, were determined using X-ray fluorescence and neutron activation analysis. In addition to the ambient samples collected by the dichotomous samplers, resuspended local soil samples were analyzed for the trace elements. Soil samples were collected in Boise, Seattle, and Spokane and were used to help determine the ambient sample fraction attributable to airborne soils or road dust. Fine particulate source emission chemistry from other emission sources (such as RWC and transportation) were determined from other studies, such as the Portland Aerosol Characterization Study.

Samples were evaluated for elemental and organic carbon, both for the PAH analyses and for the Chemical Mass Balance evaluation. Carbon-12 and Carbon-14 were analyzed as an independent means of validating the Chemical Mass Balance estimates of RWC impacts, as described below.

Fingerprinting RWC Emissions

Two methods were used for determining the fraction of the ambient fine particulate that is attributable to RWC and other sources. The Chemical Mass Balance (CMB) Model served as the primary tool, and the newly developed Carbon-14 Assessment Method was used to verify the results of the CMB method.

The CMB Model starts with emission samples of all significant emission sources, including geologic (road dust), transportation, residual oil combustion, major industries, residential wood combustion, and other significant sources. These emission samples from the different sources are analyzed for a long list of trace elements and other distinguishing compounds, in an effort to uniquely identify each source category.

Ambient samples collected are similarly analyzed. Using the Chemical Mass Balance Model, the contribution of the different emission sources can be determined for any specific ambient monitoring site, provided the individual source categories have been properly identified.

Measurements of Carbon-14 were used to validate CMB-derived RWC impact estimates. The radioisotope Carbon-14 recently has been identified as a unique trace of contemporary carbon sources (such as RWC or slashburning), since fossil fuels have essentially no Carbon-14 (the fossil fuels are old enough that the Carbon-14 has stabilized to Carbon-12). Because of the timing and location of the ambient sampling, interferences with other contemporary carbon sources such as slashburning were eliminated, leaving RWC as the most likely source of all the Carbon-14 measured. Representative firewood samples from Portland, Boise, Spokane, and Seattle were obtained and analyzed to determine the Carbon-14 levels of the wood burned in each community—an important factor in calculating the C-14 content of the ambient aerosol. Results of the Carbon-14 analysis were found to be consistent with RWC impact estimates developed by the CMB technique within the limits of experimental error.

Results

Ambient air quality studies conducted during the 1980-81 space heating season in eight Pacific Northwest communities clearly indicate that RWC emissions are the most important contributor to the fine particle mass less than $2\mu m$. Since the program design sought to determine maximum RWC impacts, the following conclusions reflect reasonable worst case impact conditions rather than, for example, annual average source impacts representative of each community's airshed.

Key findings of Task 1, then include the following:

1) RWC emissions typically account for 66% to 75% of the fine particle mass in residential areas, while transportation sources contribute 5%, secondary sulfate, 5.6%, and all industrial sources less than 0.5% (see Table 2).

2) Background RWC impacts were found to range from 3-12 $\mu g/m^3$, 24-hour average—a factor of ten lower than the urban sites, suggesting that 70-80% of the RWC impact is related to local sources.

3) Maximum 24-hour impacts (fine particle mass) exceeded $60\mu g/m^3$, at residential sites located in Seattle, Spokane, Portland, Medford, and Boise. Impacts at industrial sites in Longview, Seattle, and Tacoma were significantly lower.

4) The highest impacts measured in this study (Boise—128 $\mu g/m^3$, 8 hour average (fine particle mass)) must be considered as upper limit estimates requiring further verification.

5) PAH concentrations measured at urban sites were a factor of ten higher than those measured at the rural sites (see Table 3). Although the measured PAH concentrations should be of concern, there are no direct dose-response relationship currently available in the literature upon which to base a quantitative assessment of public health risk. However, some qualitative comparison may be possible from the benzo (a) pyrene (B(a)P) measured at the sites. This carcinogen is also present in cigarette smoke. The levels of B(a)P measured at the sites were equivalent to that from two to six cigarettes smoked per day for the average B(a)P concentrations recorded at the sites, and that from four to sixteen cigarettes smoked per day for the highest (B(a)P) level measured at the monitoring sites.

Table 2

Impact of Residential Wood Combustion Based on Ambient Monitoring and Chemical Mass Balance October, 1980 - March, 1981

City	Site Name	Land Use of Site Area	Number of Samples	Average Total Fine Particulate (ug/m^3)^2	Average RWC Percent of Fine Particulate^3	RWC Contribution-24 hour Maximum Fine Particulate (ug/m^3)^3	RWC Contribution-24 hour Minimum Fine Particulate (ug/m^3)^3
Portland, OR	Whitman School[1]	Residential	12	45.4	75.1%	61.7 ± 15.7	13.7 − 3.9
Medford, OR	Courthouse	Commercial	2	—	20.3%	62.2 ± 19.0	53.1 ± 18.8
Seattle, WA[4]	Newport Way[1]	Residential	10	36.1	83.8%	48.8 ± 13.8	8.2 ± 2.6
Seattle, WA	South Park	Residential	2	—	65.8%	68.2 ± 19.9	65.9 ± 19.6
Seattle, WA	Georgetown	Industrial	3	39.7	73.4%	35.5 ± 24.3	20.4 ± 15.3
Spokane, WA	Country Homes[1]	Residential	15	55.0	81.0%	68.1 ± 16.0	19.9 ± 12.6
Spokane, WA	County Health	Commercial	1	53.1	64.7%	—	—
Spokane, WA	Crown Zellerbach	Industrial	4	37.0	45.3%	19.1 ± 17.3	14.9 ± 12.3
Tacoma, WA	Fire Station #12	Industrial	4	47.0	74.9%	44.3 ± 32.2	20.3 ± 14.6
Yakima, WA	Courthouse	Commercial	4	53.8	93.1%	55.1 ± 32.4	48.0 ± 37.7
Longview, WA	City Shops	Commercial	4	41.8	61.4%	40.5 ± 24.1	14.2 ± 9.2
Boise, ID	Fairview & Liberty Streets	Commercial	9	121.8*	69.5%*	127.9 ± 29.9*	50.0 ± 13.4*

[1] Monitoring sites specifically established for this task

[2] Fine particulate is defined as less than 2.5 um

[3] Determined by means of chemical mass balance analysis

*Based on fraction < 15 um Estimate unvalidated

[4] Actually located in Bellevue, Washington, which is in the Seattle area

Table 3

Average PAH Concentration for Residential Sites (ng/m^3)* (1980 - '81 Heating Season)

PAH Group	Arithmetic Mean	Standard Deviation	Maximum Value	Minimum Value
Benzo(a)Anthracene	19.5	17.3	50.7	0.6
Benzofluoranthenes	7.4	5.2	18.1	0.3**
Benzo(a)Pyrene	4.1	3.1	11.1	0.3**
Fluoranthene	10.6	13.2	42.2	0.3**
Pyrene	14.4	18.9	69.9	0.3**
Dibenzanthracenes	0.3	0.4	1.4	0.05
Benzo(ghi)perylene	2.7	1.9	6.6	0.2

*24-hour average of 15 selected samples

**One-half minimum detectable concentration

Task 2a

Current & Projected Air Quality Impacts

This task brings together the results of Task 1 (Ambient Air Quality Impact Analysis), Task 2B (Household Information Survey), and Task 3 (Wood Fuel Use Projection).

The impact of the fine particulate generated by residential wood combustion (RWC) on visibility reduction and the 24-hour worst case fine particulate levels were projected to the year 2000, for the cities of Portland, Oregon and Seattle and Spokane, Washington.

Worst Case 24-Hour Impact

In each of these three cities, a one mile square residential area was chosen for study. Each area clearly had extensive RWC activity, as evidenced by many woodpiles, chimneys, and woodstove stacks. An ambient air monitor was sited in the middle of each of the three areas with samples collected in February, 1981. Eight hundred households in each square mile area were surveyed as to their woodburning practices in general and specifically in February, 1981. Between 36% and 58% of the surveyed households responded.

Using the household survey results and the ambient monitoring data, a relationship between the amount of wood burned and the fine particulate ($< 2.5\ \mu m$ diameter) measured at the ambient monitoring stations was established. These ratios were different for each city, since each city has different meteorological and pollution dispersion characteristics. The results are briefly summarized in Table 4 for a 24-hour, worst case condition.

In order to project the most likely worst-case 24-hour fine particulate levels, the results shown in Table 4 were combined with the wood use and emissions projections through year 2000 made in Task 3 for the three metropolitan areas. The projected 24-hour worst case fine particulate levels are shown in Table 5. These results show a 53%, 27%, and 21% increase from 1981 fine particulate levels (due to RWC and non-RWC) by the year 2000 for Portland, Seattle, and Spokane respectively, for a typical neighborhood with heavy RWC use. However, much of this increase is expected to occur by 1985. Increases from 1981 in total fine particulate levels are projected at 28%, 27%, and 12% for Portland, Seattle, and Spokane respectively by 1985.

A number of assumptions were made to extend the results of the three square mile survey areas to the three metropolitan areas. These are:

- Wood use projections for the metropolitan areas can be used to predict the wood use in the survey neighborhoods.
- The survey neighborhoods are typical of neighborhoods with heavy RWC use.
- The meteorology and pollution dispersion characteristics of the survey areas are typical of the cities in which they are located.
- The background or non-RWC fine particulate levels will remain the same through year 2000.
- The meteorology, pollution dispersion, and wood burning practices during February, 1981 were typical of a reasonable worst-case RWC month.

The projected particulate emissions, cords of wood burned, and fine particulate impacts are shown graphically in Figure 1.

Table 4

Comparison of Wood Burned to Fine Particulate Measured at Three Sites in February, 1981
24 Hour Worst Case Condition

		Fine Particulate*, Ambient Air		Fine Particulate Ambient Air Impact/ Ton Emissions
City/Site	Particulate Emissions	Attributable to RWC	Total	
Portland/ Marcus Whitman	12 2 tons/month	14 9 ug/m^3	19 8 ug/m^3	$\frac{1\ 2\ \text{ug m}^3}{\text{ton}}$
Seattle/ Newport Way[1]	6 5 tons/month	25 2 ug/m^3	34 7 ug/m^3	$\frac{3\ 8\ \text{ug/m}^3}{\text{ton}}$
Spokane/ Country Home	7 1 tons/month	33 2 UG/m^3	39 7 ug/m^3	$\frac{4.6\ \text{ug/m}^3}{\text{ton}}$

* 2 5 um diameter
[1] Actually located in Bellevue, Washington, within the Seattle Metropolitan area

Table 5

Estimated Future RWC Fine Particulate Impacts
(24 Hour Reasonable Worst Case)

		Fine Particulate, Ambient Air - ug/m^3		Projected % Change in Total Ambient Air, Fine Particulate Over Next Five Years
City/Site	Year	Attributable to RWC	Total	
Portland	1981*	14 9*	19 8*	+28%
(Marcus Whitman)	1985	20 4	25 3	−2%
	1990	19 9	24.8	+21%
	1995	23 1	28 0	+ 8%
	2000	25 3	30 2	—
Seattle	1981*	25 2*	34 7*	+27%
(Newport Way[1])	1985	34 7	44 2	0%
	1990	34 7	44 2	3%
	1995	36 0	45 5	−3%
	2000	34 7	44 2	—
Spokane	1981*	33 2*	39 7*	+12%
(Country Home)	1985	38 1	44 6	+ 3%
	1990	39 3	45 8	+ 5%
	1995	41 7	48 2	0%
	2000	41 7	48 2	—

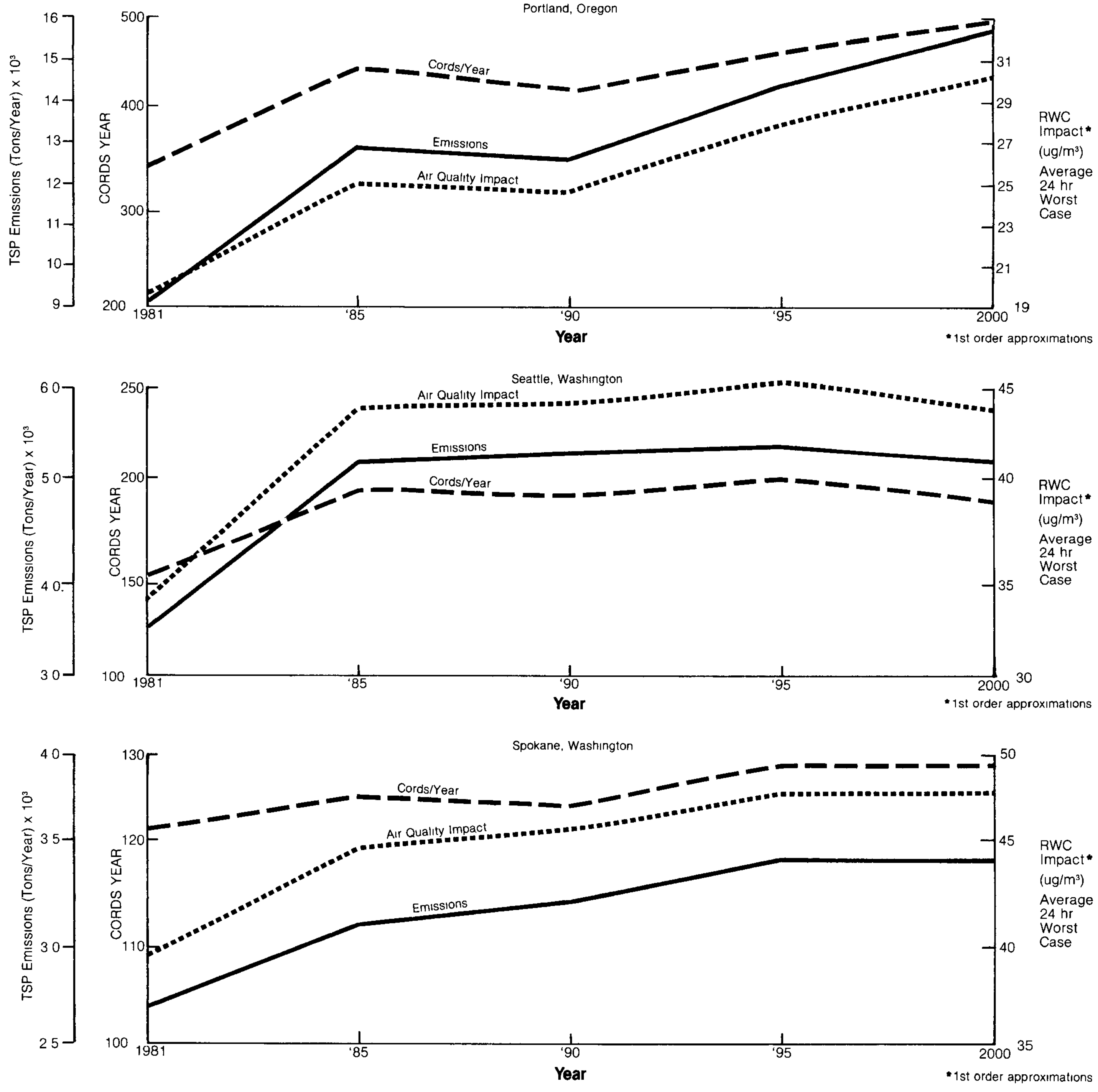
*Actual Measured Data
[1]Actually located in Bellevue, Washington, within the Seattle Metropolitan area

Visibility Reduction

The reduction of visibility is of particular concern to Pacific Northwest communities with scenic views. Fine particulate is primarily responsible for the reduction in visibility in urban areas.

Research cited in Task 2 has shown a definite link between visual range (measured in kilometers) and light scattering or B_{scat} (measured in kilometer $^{-1}$). Further, a high correlation between B_{scat} (measured by a device called an integrating nephelometer) and fine mass has been found in a Portland study. Using these two relationships, it is estimated that in Portland, by the year 2000, there will be an additional decrease in visual range of about 4 miles in average 24-hour worst case conditions.

Figure 1
Trends for Wood Use and
Air Quality Impacts



Task 2b

Household Information Survey

Surveys on residential wood combustion practices were conducted in Portland, Oregon, and Seattle and Spokane, Washington in the Spring of 1981. Each survey area was selected to include a one-mile square area around a temporary air monitoring station that had been operating during Feburary 1981 so that the survey information could be correlated to the ambient data. Results of the surveys will be used to help predict citywide residential wood use trends and, in turn, to help develop possible control strategies to reduce air pollutants from woodburning devices. The survey results are summarized in this report by means of data presented in chart form.

The surveys were mailed to a random selection of 800 households for each of the three cities by an industry trade association in Portland and by state university associations in Seattle and Spokane. The response rates were 58 percent for Spokane, 48 percent for Seattle, and 36 percent for Portland. All responses were sent to Del Green Associates, Inc., for evaluation.

Data from the surveys were coded, keypunched onto computer cards, and entered into a computer using the Statistical Package for the Social Sciences (SPSS). A quality assurance check of every tenth survey revealed an error rate of 19 out of 11,340 (0.2%) for recording of responses.

Summary statistics for the responses were calculated separately for each of the three survey areas, all of which were chosen because they were in residential areas with evidence of substantial woodburning activities. In interpreting the results, which are summarized in Table 6, one must remember that the survey areas were one square mile each within much larger urban areas; thus, the results cannot necessarily be assumed to be representative of their respective citywide areas.

The Portland survey area (Multnomah County, immediately adjacent to Southeast Portland but outside the city limits) was a working-class community with an average annual household income of $18,400 and production work as the predominant occupation of the head of the household. The homes were relatively old (average age of 36 years) and small (1400 square feet), with single family residences prevailing. Fireplaces were the most common type of woodburning device (36.9% of homes), closely followed by wood stoves at 31.7%. More than half the wood burned was in wood stoves, however.

Seattle's survey area (Bellevue, a community four miles due east of Seattle across Lake Washington) was an upper middle-class neighborhood with an average annual household income of $35,000 and predominantly newer (1962), large (2300 square feet), single family residences owned by the occupants. Fireplaces were present in 97.1% of the homes, with wood stoves in only 13.5%.

The Spokane survey area (located just north and outside the city limits) was a community characterized by newer (1961), medium-sized (1700 square feet), single family homes. The average annual family income was $27,000. Fireplaces were by far the predominant woodburning devices, with 97% of the households surveyed having one or more. Only 11.7% of the homes had wood stoves, but 22.8% of the wood used was burned in wood stoves.

Results and Conclusions

The surveys show (see Table 6) that although relatively few households use wood as their primary heat source (5-14%), most families now use wood at least as a secondary source of heat (1.0-1.6 cord/year/household). Based on the respondent's anticipated future wood use and plans to purchase new woodburning units, it appears likely that wood use will continue to increase substantially, at least for the short term.

Of major concern to regulatory agencies considering pollution control

Table 6

Summary of Survey Results

Parameter	Portland	Seattle	Spokane
Number of households returning questionnaire	288	380	443
Number of questionnaires sent out	800	800	800
Total number of households in survey area (excluding apartments without chimneys, and trailer parks) - based on homes with listed or unlisted phones	2082	1429	930
Households using a wood burning unit within last 12 months	49.7%	84.5%	79.7%
Households using wood as a primary source of heat	14.2%	5.8%	5.0%
Households having:			
Wood stove	31.7%	13.5%	11.7%
Fireplaces	36.9%	97.1%	97.0%
Woodburning furnace	1.6%	0.6%	1.3%
Any woodburning device	58.7%	—	—
No woodburning device	41.3%	1.3%	3.4%
Estimated total number of cords of wood burned in last 12 months (all households in survey area)	2070 cords/yr	1450 cords/yr	1470 cords/yr
% of wood burned in each type of device:			
Woodstove	56.5%	25.3%	22.8%
Fireplace	39.3%	74.6%	76.5%
Woodburning furnace	4.2%	0.1%	0.8%
Average wood use per household (all surveyed)	1.0 cords/yr	1.0 cords/yr	1.6 cords/yr
Average wood use per woodburning household	2.0 cords/yr	1.2 cords/yr	1.9 cords/yr
Households planning to buy woodburning unit	16.5%	23.9%	20.4%
Plans for 1981-82 wood burning compared to 1980-81 (all households)			
More	31.9%	27.8%	27.7%
Same	59.9%	60.7%	62.9%
Less	9.0%	11.5%	9.3%

strategies is how wood for home heating is obtained and how it is seasoned and stored before use. This study shows that 50-70% of the wood burned was chopped by homeowners, 65% was aged over one year, and 75% was stored under cover. In all three cities, the surveys show that those who chop their own firewood burn significantly more wood than those who purchase their firewood. The surveys showed no significant difference in wood storage and aging practices between the three metropolitan areas.

No other consistently reliable correlations between wood use practices and demographic variables were found for the three cities surveyed. Comparison of the results of this study with those of other wood burning surveys conducted in the Pacific Northwest in 1979 and 1980 was difficult because of wide differences in the survey questions and populations sampled.

Task 3
Wood Fuel Use Projection

Under this task, wood use projections using 1980 as a base line through the year 2000 were determined for the Portland metropolitan area, the City of Seattle, and the City of Spokane. An estimate of the projected total suspended particulate (TSP) contribution from residential wood combustion also was made. The short-term wood use projection (through 1983) was based on recent trends in wood use. The long-term trends were determined using a residential wood use trend model developed by another researcher.

Short-Term Trend Methodology

The short-term trends were determined using household wood use surveys and firewood cutting permits in the recent past and projecting these values into the near future. Ambient air monitoring data was examined as an indirect indicator of wood use, but had limited usefulness in the trend analysis either because the data had not been collected consistently and completely over the years needed, or because the measured parameter could not be linked solely to residential wood combustion. The Light Scattering Coefficient (B_{scat}) was the most useful ambient data available. The B_{scat} measures the degree to which small particles in the air scatter light (wood smoke particulate consists of 90% small particles). The trends in B_{scat} values were very close to those indicated by firewood cutting permits. It should be noted that B_{scat} values will be affected by other sources of fine particulate emissions, however.

Firewood cutting permits issued for publicly owned forests near the three cities were used as the best data available. Records have been kept on an annual basis for the number of permits issued, although not the actual amount of wood cut. The firewood taken from the public lands consists largely of branches and cull logs left behind after logging operations have been completed. Other sources of firewood, such as lumber mill scraps and wood from private lands, normally are not known as to quantity. Household wood use survey data is more accurate than the permit data, but is not available on a frequent enough basis for use in trends analysis. The survey data was used with the firewood cutting permit data to quantify the wood burned (i.e., if 10,000 permits were issued in a given year when a survey showed 500,000 cords of wood were burned, then if 20,000 permits were issued in another year about 1,000,000 cords of wood were burned in that year).

Long-Term Trend Methodology

After a review of existing trend analyses for residential wood use, a model developed by Norman Marshall (Dartmouth College) was determined to be the best available. This model was modified and used with input data mostly from the Pacific Northwest. The major assumption that drives the model is that as conventional fuel sources increase in cost, wood use will increase subject to such factors as cost of wood stove installation and the inconvenience of using wood compared to conventional fuels.

The major factors included in Marshall's model are listed in Table 7, along with the principal source of data. The effect of possible regulations can be included in the model if desired for control strategy development, but have been excluded for this evaluation.

A detailed check (or calibration) of the model was conducted for the Portland data and less detailed calibrations for Seattle and Spokane. Portland received the most detailed check since there was much better survey data available to conduct the evaluation. Briefly, the calibration consisted of comparing the actual wood use trends between 1970 and 1980 with what the model predicted, using 1970 input data. The model was verified in all three cities as being reasonably accurate.

One major area of uncertainty is the projected costs of fuel, particularly wood. The availability of wood is expected to drop in the next twenty years as timber harvests level off in terms of board feet of lumber, while the harvest shifts to second growth timber with its 70-90% less residue than old growth. Another factor of unknown dimension will be the competition for the diminishing wood residues by other users, including industrial boilers and

Table 7
Major Factors Included in Wood Use Trend Projection Using Marshall's Modified Model

Factor	Source of Input Data/Basis of Assumption
1 Initial number of households and projected growth	Local planning agencies
2 Heating requirements per household	Utilities' estimates of Btu's/1000 square feet for various fuels in 1970, plus average home size from Portland Real Estate Report, were used for Portland This data was adjusted for Seattle and Spokane based on different climates. Utility assumptions of 25% decrease in heating requirements by 2000 based on conservation
3 Historical conventional fuel prices and fuel usage split	Utilities
4 Historical wood prices	Classified ads in each city
5 Future conventional fuel prices and fuel usage split	Bonneville Power Administration, utilities and Oregon Department of Energy projections
6 Future wood prices (after inflation)	Assumed to be 2% (the same as conventional fuels) since no better estimates were available
7 Efficiencies of home heating devices over time	Several papers by researchers
8 Change in wood stove purchases as market is saturated	Factor developed by Marshall
9 Cost of wood stove installation based on fraction of house to be heated	Factor developed by Marshall
10 Effect of self-cut wood on price	Marshall's factor modified by forest resources available per capita
11 Effect of payback period	Marshall's factor modified by different climate and heating requirements
12 Fireplace use	Assumed to decrease proportionally with wood price increase

particleboard producers. This increasing competition for diminishing logging residues is expected to be at least partially relieved by private woodlots increasing firewood production. Since no wood cost projections from knowledgeable sources were available, a factor of +2%/year real cost increase (after inflation) was chosen for wood, to coincide with the utilities' projected cost increases of the conventional fuels. Table 8 shows the effect on the modelled results if this value is changed to 0%/year change and +5%/year change. As indicated, the projected change in residential wood combustion between 1980 and 2000 varies from +80% if real wood prices remain constant, to -31% if real wood prices increase 5%/year. Any significant departures of fuel costs for the conventional fuels can be expected to similarly impact wood use trends.

Significant Findings

For all three cities, residential wood combustion increased rapidly in the late 1970s, but now is leveling off and is expected to remain at a relatively constant level until 1990. Between 1990 and 2000, Portland wood use will increase by 17%, Seattle wood use will drop by 5%, and Spokane wood use will increase by 2%. Between 1980 and 2000, wood use will increase by 37% in Portland, 17% in Seattle, and 7% in Spokane. For all three cities, the most rapid growth is projected to occur in 1980-85 (26% for Portland and Seattle, 4% for Spokane). These results are summarized in Table 9.

Another projected shift in burning practices is away from inefficient fireplaces towards wood stoves and wood furnaces. Fireplaces are so inefficient at heating (-10 to +20%), that their use is considered primarily for esthetic purposes rather than for heating. As fuel costs increase, it is expected that fireplace use will drop sharply both because more fireplaces are converted to more efficient burning devices and because wood will become increasingly too expensive to burn in an open fireplace only for esthetic reasons. Wood burning in open fireplaces is projected to drop in all three cities.

This shift from open fireplaces to wood stoves will have a significant impact on total suspended particulate from residential wood combustion. Under current operating practices, wood stoves emit almost twice as much particulate as fireplaces. In Portland, for example, wood use is projected to increase by 37% by year 2000, but the total suspended particulate emissions are projected to increase by 76% due to the switch from fireplaces to wood stoves. This data and the wood use by wood stoves and furnaces, and fireplaces is listed in Table 10.

Table 8

Comparison of Wood Use Trends in Portland, Assuming Different Rates of Wood Cost Increases
Years 1980 - 2000

Annual Change in Real Wood Cost (after Inflation)[1]	Cords/Year Wood Burned		% Change in Wood Use
	1980	2000	1980 - 2000
+2%/Year[2]	350,000	460,000	+31%
0%/Year	350,000	630,000	+80%
+5%/Year	350,000	240,000[3]	—31%

[1] 1970 to 1980, average cord wood prices increased 217% compared to a 110% increase in the consumer price index, equivalent to a real price rate increase of 4.2%/year, compounded

[2] This rate of price increase was used in the detailed wood use trend analyses, and approximately equals the projected rate of conventional fuel price increases (2.08%/year)

[3] This approximates the amount of wood burned in 1970

Table 9

Best Estimate Projections of Residential Wood Fuel Use for Portland, Seattle, Spokane (1980 - 2000) and Corresponding Particulate Emissions

Year	Number of Households	Stove/Furnace Wood Usage (1000 cords/yr.)	Fireplace Wood Usage (1000 cords/yr.)	Total Wood Usage (1000 cords/yr.)	Total Particulate Emissions (1000 tons/yr.)
PORTLAND METROPOLITAN AREA					
1980	471,850	150	190	340	9.3
1985	537,800	240	190	430	12.8
1990	603,750	240	170	410	12.5
1995	669,700	300	150	450	14.5
2000	735,650	340	140	480	15.9
CITY OF SEATTLE					
1980	220,000	45	110	155	3.7
1985	246,180	85	100	185	5.1
1990	269,720	85	100	185	5.1
1995	294,360	90	100	190	5.3
2000	323,180	85	100	185	5.1
CITY OF SPOKANE					
1980	70,920	28	93	121	2.7
1985	77,940	42	84	126	3.1
1990	83,960	45	81	126	3.2
1995	90,910	51	78	129	3.4
2000	98,860	54	75	129	3.4

Table 10

Residential Wood Use and Total Suspended Particulate Trends, Assuming 2% per Year Real Increase in Price of Wood (Years 1980 - 2000)

	Wood Stoves and Furnaces Cords/Year			Fireplaces Cords/Year			Total Cords/Year Burned			% Increase in TSP from RWC
City	1980	2000	% Change	1980	2000	% Change	1980	2000	% Change	1980-2000
Portland Metro Area	150,000	340,000	+125%	200,000	140,000	—30%	350,000	480,000	+37%	+76%
City of Seattle	45,000	85,000	+ 89%	110,000	100,000	— 9%	155,000	185,000	+19%	+40%
City of Spokane	28,000	54,000	+ 93%	93,000	75,500	—19%	121,000	129,000	+ 7%	+26%

Task 4

Technical Analysis of Wood Stoves: *Combustion Principles, Design Considerations, Operating Techniques*

Design and operation of residential wood combustion devices influence both performance and emissions. Important design considerations include mechanisms to increase thermal efficiency and improve combustion efficiency. Both these efficiencies must be relatively high to have an overall efficient residential wood combustion (RWC) device. Until the last five years or so, levels of residential wood combustion were low enough that there was no real demand for improved stove designs which increase efficiencies and decrease emissions. There remains considerable room for improvement in the design of stoves. Since this study was conducted, many improved units have appeared. It is expected that in the next few years the emerging stove technology will result in substantial emission reductions, possibly by as much as 75%.

Task 4 consisted of a thorough literature search and evaluation of existing data on woodburning devices and operating procedures. Major areas of investigation were:

- Emission rates from various types of woodburning devices, particularly fireplaces and wood stoves.
- Changes in emission rates when different add-on devices or stove design modifications are made.
- Evaluation of emerging stove technology.
- Effects on emission rates of such operating variables as fuel type, fuel moisture content, combustion air, and firing rate.

Several difficulties were encountered in compiling this information. The interest in emissions from residential wood combustion was relatively new at the time of this report, and little data existed. Much of this data is from stove manufacturers in support of their marketing efforts. The sampling methods and operating conditions during testing (wood type, size, moisture content, firing rate, etc.) usually were not consistent, making comparisons between devices very difficult. Little or no hard data was available on new technology. The data therefore has been presented in generalized terms.

Summary of Significant Findings

General Combustion Principles and Emissions

The term "efficiency" when used in conjunction with a wood-burning device is the measure of how much net energy is available and useful per energy unit (such as British Thermal Unit or Btu) contained in the wood. The overall efficiency is a combination of the "combustion efficiency" and the "thermal efficiency." Modifications that affect either type of efficiency will affect the emissions.

Combustion efficiency refers to the percent of the potential energy available in the wood that is actually released during burning. Final combustion products are carbon dioxide and water. Products of incomplete combustion include such pollutants as carbon monoxide, unburned or partially burned particles of wood, hydrocarbons and ash. Incomplete combustion and the associated pollutants can result from insufficient oxygen, low temperatures in the combustion zone, and insufficient time or mixing of oxygen and fuel to allow complete combustion. Many of the modifications proposed by stove manufacturers are designed to improve the combustion efficiency, which reduces air pollution per unit of wood while increasing the amount of heat per unit of wood burned.

A measure of thermal efficiency is the percent of the heat generated by combustion that is useable and released to the room(s) to be heated. Hot exhaust gases comprise the heat that is lost. For maximum thermal efficiency, the exhaust gases should be as cool as possible while still allowing a proper draft (to pull the smoke out of the house) and not having excessive condensation of water or creosote deposits in the chimney. Creosote is another name for hydrocarbons in the exhaust gases that have condensed onto the cooler stove pipe or chimney forming a sticky residue which can ignite and cause a fire hazard. An example of a thermally efficient operation would be a banked, slow-burning, oxygen starved fire in a wood stove, since most of the heat generated is released to the room. Such burning practices are thermally efficient, but the combustion efficiency is very low. Smoldering fires release large amounts of pollutants and are undesirable from an air pollution standpoint.

Many of the modifications, add-ons, and new stove technologies are designed to improve the combustion efficiency, the thermal efficiency, or both. In general, the following features have been investigated or included:

- Limit combustion air to the minimum required to sustain combustion, and thereby minimize the amount of cold air pulled into the house (thermal efficiency).
- Combustion air introduced at those points where combustion is occurring (thermal and combustion efficiency).
- Pre-heating combustion air to aid combustion (combustion efficiency).
- Require the hot gases to follow a longer path, allowing more complete combustion and better heat capture (combustion and thermal efficiency).
- Afterburning of exhaust gases, usually with the aid of a catalyst (combustion and thermal efficiency).

These features will be discussed in more detail in later sections.

Fireplaces

Fireplaces generally are inefficient, and can actually cause a net drop in house temperatures under some circumstances. As the outside temperature approaches 10 °F, more energy is lost (as cold air is pulled into the house) than energy released by the fire. Depending on the outside temperature, the overall efficiency of fireplaces varies from -10 to 20%.

The rate at which wood is burned appeared to be the most important variable affecting the emissions from fireplaces. A hot full fire burns the cleanest. Glass doors which are closed during fireplace use, limiting the amount of combustion air, are net energy losers, since the glass reduces the gross heat output by 50-55%. Glass doors are effective in reducing the loss of warm room air up the chimney when the fire has burned down.

Air circulation or heat transfer systems have a limited effect on the efficiency of fireplaces. Various studies report from a 2.5% (without fans) to 8.6% improvement in efficiency from heat transfer systems.

Wood Stoves

Wood stoves come in many configurations, with an overall efficiency of from 40 to 70% depending on the design. Fireplace inserts are very similar to wood stoves, except that the existing chimney is used rather than a stove pipe. The following discussion includes fireplace inserts.

One of the more common variations among wood stoves is the air flow path. The types of stoves in use are the updraft, downdraft, cross draft, diagonal flow, and "S" flow. Studies by the State University of New York of the efficiency of stoves with these configurations found no significant differences among them.

Regulating the draft does improve the efficiency of stoves. These air controls can be manual or automatic. A barometric damper in the stack or a thermostatic damper at the stove air inlet can be used to regulate the air into the combustion chamber. By regulating the air, enough oxygen can be introduced to sustain adequate combustion without allowing excess air which cools the fire, inhibits combustion, and draws too much cold air into the house.

Sizing a wood stove to the intended area to be heated is very important in minimizing air emissions. The complete report includes detailed instructions on sizing a stove for a particular application. The cleanest, most efficient fires are those that use a fairly high burn rate. Many stoves are oversized for the intended use, so that brisk fires cannot be maintained without overheating the room. Instead, homeowners with oversized stoves tend to burn wood in their stoves at a slow rate by starving the fire of oxygen. These slow, smoldering fires waste wood, create pollution, and can cause fire hazards through an excessive build-up of creosote in the stove pipes.

Wood-Fired Furnaces

Wood furnaces are not widely used at this time and were not investigated in depth. The efficiency of furnaces is similar to wood stoves, about 40 to 75%.

Catalysts and Afterburners

Afterburners are devices for introducing a secondary fuel into the exhaust stream and igniting to burn up the incompletely combusted portions of the exhaust gas. Such devices are not in common use, and no data was found on the emissions from afterburners on wood stoves.

Catalysts also allow the combustion of exhaust gases, by lowering the ignition temperature to a level that can be found in stack gases. At least 400°F is required for a noble metal catalyst to work. In theory, the catalyst promotes the chemical reaction of oxidation (or burning) without itself being used up. Adequate oxygen and unburned combustion products (such as hydrocarbons or carbon monoxide) are required in addition to the catalyst to sustain this secondary combustion.

The use of catalysts is relatively recent and little data existed at the time of the study. It does appear that proper stove operation can be very important to satisfactory catalyst operation, as can placement of the catalyst within the stove. The stack gases have to be kept hot, which may cause overheating of the room if the stove is oversized. The catalyst can be "poisoned" by metals present in magazine inks and pressed wood resins. The catalyst can be fouled by creosote formed when the stove is not burning hot enough for the catalyst to function. There also are questions regarding possible hazardous or toxic materials resulting from the catalytic combustion process that have yet to be answered.

Add-On Pollution Control Devices

The only system identified as being specifically for pollution control was a stainless steel wire mesh inserted into the exhaust stack. This device is designed to accumulate condensible hydrocarbons when the gas stream is cooler, and burn the accumulated creosote when gas temperatures rise. A study by the Oregon Department of Environmental Quality showed a 50% reduction in particulate levels, but source tests conducted in Task 5 of this study showed no decrease in emissions.

Heat Storage Systems

In theory, a combustion device that can store and slowly release heat will be more efficient, more comfortable, and require less operator attention. Many stoves now include fire-brick linings of the combustion chamber to accomplish this. No technical data was available that furnished a comparison of either emissions or stove efficiencies, however.

Wood Selection and Preparation

Proper selection and preparation of the wood to be burned can have a significant impact both on the overall efficiency and the emissions. High moisture content wood have a lower effective Btu content than dry wood, since energy is required to evaporate the moisture during combustion. The moisture also may interfere with the combustion process by cooling the fire. Emissions are greater from wet wood both because more wood is required for a given Btu output and because of the decreased combustion efficiency.

Overly dried wood, such as kiln dried scraps from lumber mills, also can cause excessive emissions. The dried wood burns too fast for complete combustion, with the result of unburned components escaping as pollutants. Optimal moisture content is 10-20%, which corresponds to air drying for 3 to 12 months (depending on the wood species and climate). Properly dried wood has significantly more heating value per unit of wood burned than green wood.

Log size affects the emissions, largely through the rate of combustion. Large logs burn too slowly to generate hot enough temperatures for complete combustion, whereas small logs burn too quickly with unburned combustion products escaping up the stack. The optimal log size is 3½ to 5″ in diameter both for combustion efficiency and minimizing emissions.

Wood species selection has an effect on emissions. Although most wood species have about the same Btu value per pound, other burning characteristics will vary. Hardwoods are denser and have a higher Btu value per volume than softwoods, and therefore require less frequent fire charging. The Btu value varies from 24 to 31 million Btu's per cord for other species such as ponderosa pine and western red-cedar. Douglas Fir, commonly used in the Northwest, has a heating value in between these extremes. Woods also vary in their tendency to form ash and creosote. For example, at least one study has found that creosote formation is higher when soft wood is burned than when hard wood is burned.

Operation

Proper operation of the woodburning device affects the amount of wood burned, the comfort of the heat produced, and the pollutants emitted. In general, operating practices which promote complete combustion will minimize the wood used and the pollutants emitted. The information on the effect of burn rate on emissions from wood stoves in conflicting. Wood stoves do burn cleanest when the firing chamber is filled 30% by volume with wood logs should be laid so that air can be circulated freely during combustion. A charging rate of about once per two hours appears to be the optimum in maintaining consistent burning conditions, and minimizing emissions, without being too demanding on the operator.

The stove must be properly sized for the specific installation; the bigger is not necessarily better. Overnight banking of the fire should not be used; air dampers should be left open to promote complete combustion. A stack or surface thermometer should be used to monitor stove operation and ensure a hot fire without excessive stack heat loss.

Proper operation is also important for fireplaces. Due to their very low (possibly negative) efficiency, fireplace use should be avoided in extremely cold weather. Hot, full fires should be burned to reduce emissions. Fireplaces with glass doors should be operated with the doors opened during burning, then closed during the burn down period and when the fireplace is not in use.

Task 5

Emissions Testing of Wood Stoves

Under this Task, a number of different woodstoves were tested for particulate and gaseous pollutants. The three major objectives were to: 1) identify the effect of wood moisture on emissions; 2) evaluate several simpler, less expensive test methods that might be used as an alternative to the relatively expensive particulate measurement test; and 3) test the emissions from state-of-the-art, improved stoves and add-on devices.

Test Procedures

The tests were conducted by OMNI Environmental Services, Portland, Oregon between June and October 1981, under laboratory conditions. It was known from previous research that many variables can affect the emission rate from woodstoves, including burn rate, wood moisture content, type of wood, wood size, and size of each batch of wood burned. A standard burn procedure was therefore established, to minimize the effects of these variables as much as possible. The single exception was the series of tests for the effect of wood moisture on emissions, where the wood moisture content was deliberately varied. The standard burn procedure was:

- A constant heat output was maintained, at a low to moderate burn rate typical of Pacific Northwest burning practices. This burn rate was about 2.5 kg wood/hour (5.5# wood/hour). The constant heat output was maintained by adjustments of air inlets and/or damper, based on the combustion chamber temperature.[1]
- One single charge of wood was fed to a hot bed of coals. The test period ran from when the wood was well lit until it had been reduced to 10% of the original weight.
- Seasoned Douglas fir wood (except for wood moisture tests) of 12″ to 16″ girth was used.
- The door to the stove was opened for 30 seconds to three minutes at the start of each run, to ensure the fire was well lit. After that, the door was normally only opened once, towards the end of the burn cycle, to redistribute the wood.
- The stove was located on a weighing platform, so that it could be determined when 90% by weight of the wood had been burned.

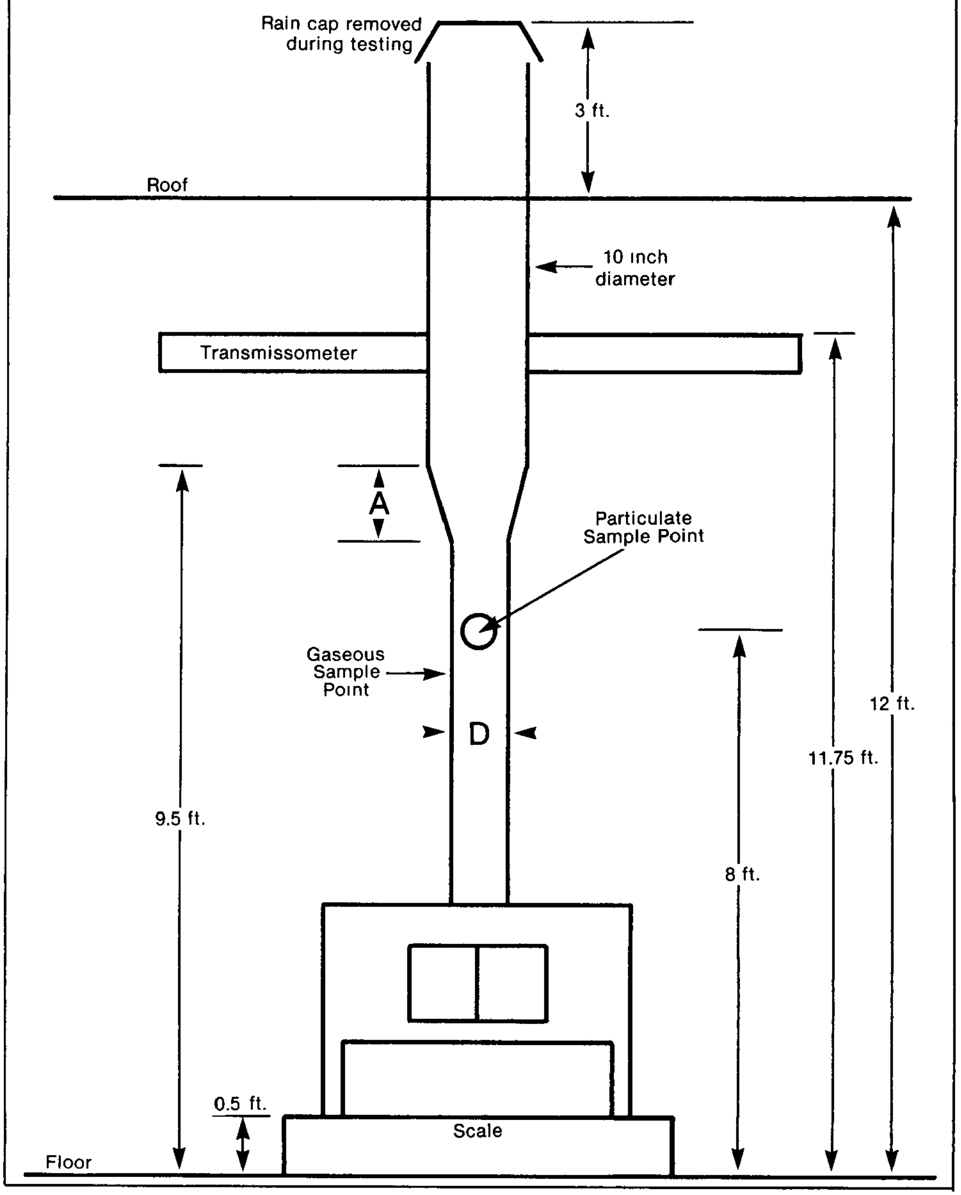
The tests conducted for each run were particulate, carbon monoxide, carbon dioxide, oxygen, opacity, total hydrocarbon, creosote deposition, and smoke spot density. The particulate test was modified EPA Method 5, with an unheated filter after the third impinger to collect condensible hydrocarbons. The test procedures for the other parameters measured are discussed in the section on simplified test methods. Figure 2 shows the stove and testing configuration.

Figure 2

Test Site Configuration

A - Length of reduction is 0.6 ft. when **D** = 8 in. and is 1.3 ft. when **D** = 6 in.

D - 8 in. for all runs except runs 14 and 15 when **D** = 6 in.



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[1] The one exception was the ceramic stove. A much higher burn rate was used for this stove, as recommended by the manufacturer. Also, the burn rate could not be adjusted for this stove because there were not adjustable air inlets.

Effect of Wood Moisture Content on Stove Emissions

An airtight box stove, typical of those common in the Pacific Northwest, was used for this test series. Two test series were run for the following moisture levels: low—12% moisture content on a wet wood basis (14% on dry basis)[1], medium—20 to 21% moisture content on a wet wood basis (25 to 26% on dry basis), and high—56% moisture content on a wet wood basis (126% on dry basis). The results are shown in a tabular form in Table 11 (summary of all test results), and graphically in Figure 3.

The lowest particulate emissions were measured for the medium moisture content level. The dryer wood tended to burn faster, and to maintain a constant heat output when the air inlets were restricted. It is believed that the high emissions from burning the dry wood were due to the incomplete combustion resulting from the combustion air restriction and the extremely rapid burning rate of the low moisture wood.

Figure 3
Particulate Emissions Results: Fuel Moisture Tests

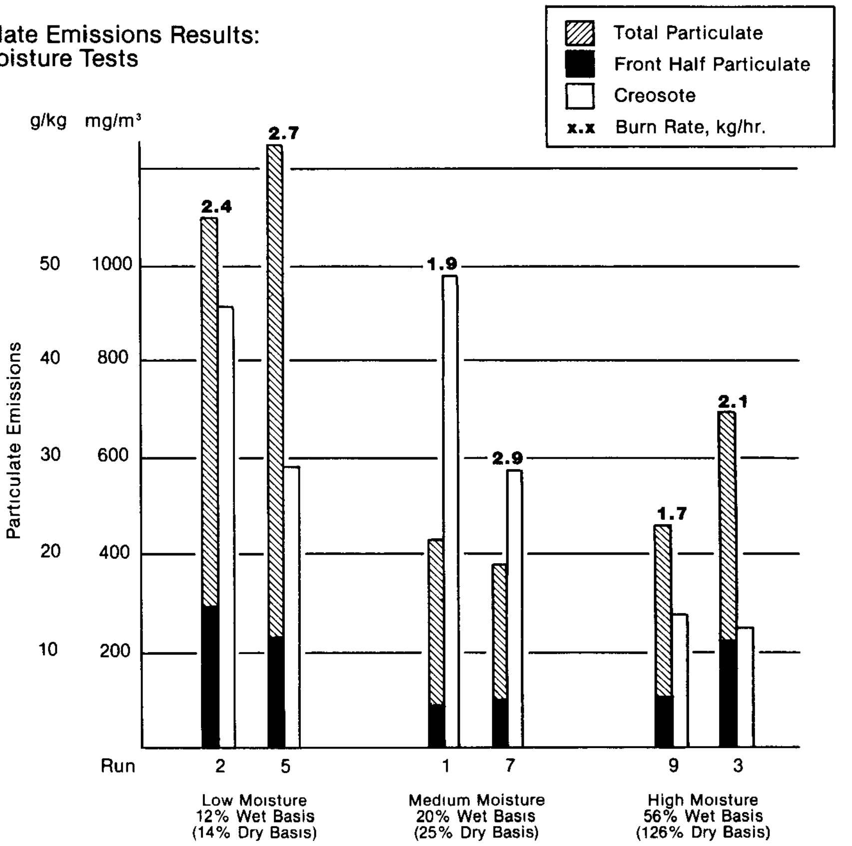

Table 11
Emissions Summary

Test Run	STOVE TYPE/Test	Burn Rate (lb/hr)[1]	Particulate Emissions Total[2] g/dscm	lb/hr	g/kg[4]	Front Half[3] g/kg[4]	(%)[5]	Cresote[6] mg/m²-kg	Carbon Monoxide g/kg[4]	Gaseous HC g/kg[4] [7]	Opacity[8] %	Stack Gas Flow SCFM (DSCM)	Excess Air %
1	Box-21% moisture content[9]	1 9 (4 1)	1 3	0 09	22	6 3	(29)	969	190	13.8	36	30 (1060)	230
2	Box-12% moisture content[9]	2 4 (5 3)	3 4	0 28	54	14 0	(27)	917	189	16.9	30	38 (1350)	160
3	Box-56% moisture content[9]	2 1 (4 7)	1 5	0 16	34	11 0	(33	218	160	10.5	20	50 (1750)	180
4	Box-12% moisture content[9] cold start	8 1 (17 8)	3 6	0 72	40	9 6	(24)	216	210	11 9	40	91 (3230)	140
5	Box-12% moisture content[9]	2 7y (6 0)	5 0	0 37	62	11 0	(17)	592	220	12.1	37	34 (1200)	180
6	Box-19% moisture content[9] cold start	5 8 (12 8)	3 8	0 54	42	8 3	(20)	291	170	9.2	46	66 (2320)	140
7	Box-20% moisture content[9]	2 9 (6 4)	1 5	0 12	19	4 4	(23)	568	160	8 8	28	36 (1270)	170
8	Box-56% moisture content[9] cold start	2 0 (4 5)	0 9	0 11	24	6 1	(25)	109	190	11 1	20	55 (1950)	410
9	Box-56% moisture content[9]	1 7 (3 7)	1 2	0 08	22	4 8	(22)	240	110	6 6	11	32 (1130)	320
10	Box/Catalytic Add-on	2 1 (4 6)	1 3	0 10	22	3 7	(17)	223	110	8 0	24	37 (1320)	380
11	Box/Catalytic Add-on	2 6 (5 8)	1 3	0 09	17	3 3	(20)	190	90	6.2	16	32 (1130)	240
12	Box/Non-Catalytic Add-on	2 4 (5 4)	1 8	0 21	38	7 4	(20)	273	200	11.8	22	54 (1890)	320
13	Box/Non-Catalytic Add-on	2 2 (4 9)	1 8	0 17	35	6 1	(17)	337	160	9.3	23	42 (1490)	280
14	Catalytic Box	1 7 (3 7)	2 2	0 14	38	5 9	(16)	379	120	10.7	10	30 (1060)	140
15	Catalytic Box	2 2 (4 9)	1 5	0 11	23	4 8	(21)	273	50	7 3	10	34 (1200)	172
16	Catalytic/Secondary Air	3 0 (6 7)	0 6	0 09	14	3 5	(25)	88	80	3 9	5	71 (2500)	347
17	Catalytic/Secondary Air	2 1 (4 7)	1 2	0 14	30	5 7	(19)	317	150	5 8	13	56 (1960)	498
18	Ceramic	6 4 (14 2)	0 2	0 02	1	0 63	(53)	56	20	0 4	0	52 (1850)	63
19	Ceramic	3 9 (8 7)	0 1	0 01	2	0 97	(49)	27	50	0 6	0	49 (1720)	97

[1] Dry Basis
[2] Oregon DEQ Method 7
[3] EPA Method 5
[4] Mass Emissions per Mass Dry Fuel Consumed
[5] Percent of Total Emissions
[6] Average of two measurements locations
[7] As Hexane
[8] Visual Observer
[9] Wet Basis = $\frac{\text{(Weight of moisture)}}{\text{(Total weight of wood including moisture} \times 100\%)}$

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1. Dry wood basis refers to the percentage of the moisture weight compared to the weight of the dry wood (0% moisture content). This can be calculated as follows: $\%\ \text{moisture content dry basis} = \frac{\text{weight of moisture}}{\text{weight of wet log} - \text{weight of moisture}} \times 100\%$

Evaluation of Simplified Test Procedures

The standard test method for total particulate, EPA Method 5, is expensive both in the initial price of the equipment and to run each test. For the series of nine tests recommended for certification of an individual brand of stove, for example, using EPA Method 5 would cost about $15,000. This high cost makes it very difficult to conduct the necessary basic research into ways of reducing emissions from woodstoves, as well as making it difficult for stove manufacturers to experiment with stove design. This task evaluated the more likely alternate test methods, and how well the results compared with the EPA Method 5 particulate tests. The pollutants and/or alternative methods evaluated were: carbon monoxide, total hydrocarbon, creosote deposition, opacity, and smoke spot density.

The carbon monoxide and total hydrocarbon tests both showed a reasonable correlation to particulate emissions, once a correction for excess air was made. The linear correlation coefficient was 0.80. For both tests, a non-dispersive infrared (NDIR) analyzer was used, since both tests involve measuring concentrations rather than total emissions by weight. The amount of air going up the stack will very much influence the concentration values (amount of particulate per unit volume of air) recorded even though the total pounds of emissions remain the same. To correct for this and to allow a comparison with the total particulate by weight, the concentration values were corrected to their values when the air in excess of the theoretical minimum required for complete combustion (excess air) was considered zero. The correction factor is based on the theoretical CO_2 concentration at complete combustion and the actual measured CO_2.

These tests have several advantages. They are relatively inexpensive—about $4,200 for a nine-test series, compared to $15,000 for the EPA Method 5 particulate tests. They also give immediate results, and allow the emissions to be quantified in different parts of the combustion cycle rather than just one value for the entire cycle. One disadvantage in using the NDIR to measure total hydrocarbon is that the instrument may have a varying response to different types of hydrocarbons. The NDIR should produce useful results under similar testing conditions, however.

Creosote deposition was measured by weighing small steel plates before and after suspending in the stove flues during a burn cycle. These plates, each three inches by five inches, were placed in the flue at two different levels. The weights of creosote deposits were then compared to each other and to the particulate measured by EPA Method 5.

The precision between the pairs of values for creosote was poor, with a correlation coefficient of only 0.62. The average of the pair values had a good correlation (correlation coefficient of 0.82) with the measured particulate, but only if two of the 19 tests were thrown out. If all 19 tests were used, the correlation coefficient drops to 0.52, indicating a poor match between creosote and particulate emissions.

Opacity* as determined by a trained observer or by a transmissometer located in the stack correlated very well with particulate **concentration,** (0.80) but not as well with total particulate (0.69-0.76). There are no simple correction factors for opacity to account for the excess air. Since we are interested in the relation of opacity to total particulate, opacity was not shown to be a good alternative method.

The smoke spot density measurements were not useful as a predictor of particulate emissions. In this test method, a given volume of stack gases are pulled through a filter paper. The spot left on the filter paper is then measured for darkness. The test was not sensitive enough, and showed little or no relationship to particulate emissions.

In summary, the carbon monoxide and total hydrocarbon measurements offer the best alternative method. They are much less expensive than the EPA Method 5. Since they do not directly measure particulate, however, their usefulness is greater as a screening tool for research and stove design experimentation, rather than for certification where greater precision is required. Table 12 is a summary of the simplified test procedures.

Table 12
Simplified Test Procedures Summarized

				Estimated Cost[2]		
Method/ Description	**Correlation to Total Particulate[1]**	**Advantages**	**Disadvantages**	**Capital Investment**	**Per Run**	**Per Series (9 tests)**
Total Particulate/EPA Method 5, modified to include filter for condensible hydrocarbons	1	• Accurate measurement of emissions, including condensibles • Integrated sample over entire burn cycle	• Expensive • Long sample time required (1-hr minimum); not ideal for measuring discrete periods within burn. • Experience with method required	$20,500[3] [4]	$2,100	$15,000

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* The opacity of a smoke plume is a measure of how much a background object, such a tree or building, is visually obscured by the smoke plume.

Table 12 (Continued)
Simplified Test Procedures Summarized

				Estimated Cost[2]		
Method/ Description	**Correlation to Total Particulate[1]**	**Advantages**	**Disadvantages**	**Capital Investment**	**Per Run**	**Per Series (9 tests)**
Filterable Particulate	20-50% of total particulate mass basis. Correlation coefficient not determined	• Accurate measurement of emissions • Integrates sample over entire burn cycle. • Slightly less expensive than total particulate method.	• Does not measure condensible particulates • Expensive • Long sample time required (1-hr minimum), not ideal for measuring discrete periods within burn Experience with method required.	20,500[3] [4]	1,900	12,500
High Volume/ Not Tested	—	• Short sample time enables measurement of discrete periods within burn	• Expensive • Collection efficiency for condensible organics unknown. • Multiple samples required to obtain measurements for entire burn cycle.	16,500	$1,900	$12,600
Carbon monoxide/ Orsat and Nondispersive Infrared (NDIR)	0 8	• Provides instantaneous and continuous output, excellent for monitoring burn cycle Inexpensive to use once capital investment incurred. • Suitable for screening method, using cheaper, less accurate instrumentation • Suitable for field monitoring	• No direct measurement of particulate.	$13,500[5] 600-2600[6] [8]	$560 280	$4,200 —
Total Hydrocarbon/NDIR	0 8	• Same as Carbon monoxide	• Same as Carbon monoxide • Potential for variable response to different HC species	23,500[5] 4500-6700[7] [8]	560 280	4,200 —
Creosote/2 small steel plates weighed before and after, averaged.	0 8 (17 of 19 tests) 0 5 (19 of 19 tests)	• Uncomplicated to use. • Inexpensive (low level of effort) • No significant capital investment • Capable of measuring discrete periods within burn cycle.	• Not direct measurement of particulate emitted to atmosphere • Results likely dependent upon numerous variables such as stack temperature, and excess air.	1,000	250	2,800

(Continued on Page 21)
Footnotes on Page 21

Table 12 (Continued)

Simplified Test Procedures Summarized

				Estimated Cost[2]		
Method/ Description	**Correlation to Total Particulate[1]**	**Advantages**	**Disadvantages**	**Capital Investment**	**Per Run**	**Per Series (9 tests)**
Opacity/Transmissometer or visible emission inspector.	0 8	• Inexpensive to use. • Little or no capital investment. • Suitable for field monitoring (visible) emission observer)	• Does not directly measure particulate. • Results highly dependent upon excess air levels	\$0 - 1,000[8]	\$280	\$2,800
Smoke spot density/Bacharach Smoke Spot Tester	0 6	• Inexpensive to use • Low capital investment. • Easy to use • Very short measurement time, may be used to monitor discrete periods within burn cycle • Convenient for field monitoring.	• Results dependent upon excess air levels • Large number of measurements required over entire burn cycle. • Little correlation to total particulate	75 00[8]	280	2,800

[1] Correlation coefficient determined from this study, using EPA Method 5 as the basis of comparison

[2] See Appendix D of the full report for basis of cost estimates.

[3] Includes laboratory quality, CO, CO_2, and O_2 monitors for accurate and continuous determination of stack gas composition for determining stack gas volumetric flow by stoichiometry. Subtract \$12,500 for monitors and add \$3,000 for orsat and low velocity flow measurement instrumentation equipment (net change—\$9,500) if orsat/velocity methods to be used.

[4] Add \$5,000-\$10,000 for flame ionization detector if total hydrocarbons analysis is desired

[5] Delete \$1,000 if platform balance not to be used to monitor fuel consumption rate (necessary for emissions as g/kg basis) and results to be reported as concentration adjusted for excess air.

[6] If used as a screening test with orsat or less accurate instrumentation to determine emissions (CO concentration adjusted for excess air).

[7] If used as a screening test with orsat or less accurate instrumentation (e.g., NDIR instead of heated FID) to determine emissions (hydrocarbon concentration adjusted for excess air)

[8] Add \$1,000 if platform balance to be used to monitor fuel consumption rate

Improved Technology Stoves and Add-on Devices

Based on a literature review, three areas of stove technology were chosen for testing. These were catalytic, modified technology, and combined technology woodstoves. The two add-on or retrofit devices tested were catalytic and non-catalytic units. These units are described in Table 13. (overleaf)

The tests were run as explained previously in the "Test Procedures" section. That is, one load of wood with 25-30% moisture content was introduced to a hot bed of coals and a low to moderate burn rate was maintained. Where catalysts were present, the manufacturer's recommended minimum temperatures were also maintained. The one exception to this was the ceramic stove. This stove did not have an adjustable air inlet and the burn rate could not be regulated. The burn rate was significantly higher (5.4 versus 2.5 kg/hour).

The emission testing results are shown in detail in Table 11. These results indicate that none of the improved units except the ceramic stove tested better than the standard box stove under burning conditions similar to those that typically occur in Northwest homes. The ceramic stove did have substantially lower emissions, however the very high burn rate compared to the other units may have contributed to some or all of this emissions reduction. The burn rate used was considered marginal for proper catalyst operation for those units having catalysts, although they were typical for Northwest homes.

A literature review showed that other researchers have found similar improved technology devices result in lower emissions. The test results are limited, however, and are difficult to compare to this study because of different burn rates, wood species and moisture content, and other different operating parameters.

Table 13

Descriptions of Improved Technology Stoves and Add-on Devices Tested

Type of Stove/ Device	General Description of Stove/Device	Firebox Volume	Stove Surface Area	Secondary Tertiary Air	Baffles	Particulate Emissions/ Weight Wood Burned[1]
Catalytic Stove	Modified welded steel box stove. Catalyst-precious metal on ceramic honeycomb support	2 6 ft^1	25 4 ft^2	Preheated secondary combustion air-introduced at catalyst	After catalyst	30 5 g/kg
Catalytic/modified combustion stove	Catalyst-precious metal on flat ceramic plates	3 0 ft^1	35 ft^2	Secondary-preheated, above grate Tertiary-preheated, at catalyst plates	Before and after catalyst	22 g/kg
Ceramic stove (modified technology)	Cast ceramic stove, spherical combustion chamber Air space between chamber and outer shell No controls on air flow Heat exchanger	3 2 ft^1	22 3 ft^2	None	None	1 5 g/kg[2]
Catalytic retrofit device	Placed in flue just above stove collar. Precious metal catalyst on ceramic honeycomb Heat exchanger	——	——	Secondary air prior to catalyst	——	22 g/kg
Non-catalytic retrofit device	Steel wire mesh pad Filters particulate, either burns on pad or is removed and cleaned	——	——	None	——	27 5 g/kg

[1] Weight of wood is on a dry basis For comparison, the box stove tests (no add-ons) under similar wood moisture and firing conditions had 20.5 g/kg emissions

[2] Much higher burn rate used, as recommended by the manufacturer

Task 6
Control Strategy Analysis

The growth in residential wood combustion has been identified as a significant contributor to non-attainment of total suspended particulate (TSP) ambient standards in several Pacific Northwest cities. Under the Clean Air Act, each state is required to prepare a legal implementation plan for bringing each non-complying geographical area into compliance. Traditionally, these state-prepared control strategies for particulate have focused on industrial emissions and have been successful in substantially reducing the industrial contributions. Attention is turning now towards possible control of remaining major particulate contributors, including residential wood combustion. Task 6 examines and evaluates possible control strategies to reduce residential wood combustion emissions.

Seventy-five possible control strategies were selected, including those strategies that have been implemented somewhere in the world, those suggested by knowledgeable air pollution control agency personnel, and those suggested by project members. A systematic ranking system was developed using the Keppner-Tregoe evaluation process (see Table 14) and each of the 75 control strategies ranked. The fifteen highest ranking strategies were further evaluated as to costs, projected emissions reductions, and significant advantages and disadvantages.

Table 14
Criteria and Weight Factors Used in Keppner-Tregoe Analysis

	CRITERIA	WEIGHT FACTOR*
MUST Criteria		
1	Reduce air pollution impacts from RCW	Mandatory
2	Meet legal requirements	Mandatory
3.	Widely applicable to RWC equipment or operating practices	Mandatory
4	Must not increase safety hazard	Mandatory
5	Can be implemented within five years, unless long-term benefits great	Mandatory
WANT Criteria		
1	Reduce average RWC emissions/household	13
2	Reduce number of RWC households	13
3	Widely applicable	10
4	Maximum public acceptance	9
5	Discourage worst appliances/practices	9
6	Minimum consumer cost	6
7	Uses proven technology	5
8	Minimum circumvention of control measure possible	4
9	Maximum agency administrative feasibility	3
10.	Encourages innovative technology	2
11	Minimum free market interference	2
12.	Promotes conservation/use of renewable resources (except wood)	1

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*These weight factors were calculated using an analytic tool called "paired comparison" For further details, see Appendix B of the complete report on Task 6.

The ranking and evaluation process necessarily included two major sources of uncertainty. These are the assumptions required to be made because of lack of data (costs and projected emission reductions, for example), and the somewhat subjective values assigned during the ranking process. Such factors as the response to public education programs, public acceptance of control strategies, and the political feasibility in passing the necessary laws, were particularly difficult to assess quantitatively. Any specific control strategy development would require in-depth analysis of local conditions and re-evaluation of these control strategies. However, this study should assist control agency personnel in the initial selection of possible control strategies for further evaluation. The fifteen highest ranking strategies are briefly described in the following pages. A summary of the costs and expected particulate reduction for each strategy is shown in Table 15. (overleaf)

Table 15

Summary of Estimated Costs and Particulate Emissions Reduction Benefits for Fifteen RWC Emission Control Strategies

Control Strategy	Costs			% Particulate Reduction				Cost per % Particulate Reduction			
	Start-up	Admin./Year	Other	1985*	1990	1995	2000	1985*	1990	1995	2000
1 Mandatory testing/certification, tax credit	$ 50,000	$ 130,000	$400/unit tax credit	3	11	30	39	$ 600,000/%[1]	$ 175,000/%[1]	$ 64,300/%[1]	$ 49,500/%[1]
2 Mandatory testing/certification, no tax credit	50,000	130,00	——	2	8	22	30	65,000/%	16,200/%	5,900/%	4,300/%
3 Encourage use of larger pieces of firewood	——	45,000	——	11 5	11 5	11 5	11 5	3,900/%	3,900/%	3,900/%	3 900/%
4 Mandatory testing/labeling, tax credit for cleaner units	50,000	160,000	$400/unit tax credit	1	5	15	21	1,330,000/%[2]	266,000/%[2]	88,700/%[2]	63,300/%[2]
5 Encourage use of other fuels and energy sources	UNKNOWN										
6 Government funded research and development	UNKNOWN										
7 Promote proper sizing of wood stoves	——	45,000	——	——	7	——	10 5	——	6,400/%	——	4,300/%
8 Mandatory testing/labeling, no tax credit	50,000	130,000	——	1	3	8	11	140,000/%	45,000/%	16,700/%	12,000/%
9 Mandatory weatherization — all households Cost effective	——	150,000	$1450 per household	——	3 5	16 4	——	——	9,100/%[3]	21,400/%[3]	——
10 Stove testing/rating by Trade Association	50,000	130,000[4]	——	1	3	8	11	140,000/%	45,000/%	16,700/%	12,000/%
11 Mandatory cost effective weatherization — New or replacement RWC households	——	50,000	$1450 per household	——	3 5	11 5	——	——	14,300/%[3]	7,100/%[3]	——
12 Encourage burning of dry firewood	——	45,000	——	6 2	6 2	6 2	6 2	7,300/%	7,300/%	7,300/%	7,300/%
13 Curtailment of RWC during air pollution episodes	25,000	8,000	——	33[5]	33[5]	33[5]	33[5]	400/%[5]	400/%[5]	400/%[5]	400/%[5]
14 Annual inspection/maintenance of installed units	——	1,000,000	——	UNKNOWN							
15 Require underfire air for new fireplaces	——	——	$100/fireplace[6]	——	1	——	2	——	200,000/%[6]	——	100,000/%[6]

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*Assume 1980 as base year

[1] Assume 5000 new wood stoves/year sold, 90% are certified

[2] Assume 5000 new wood stoves/year sold, 60% are certified

[3] Fuel savings exceed cost of weatherization Annual costs only for administrative expenses

[4] Costs paid by private sector

[5] Reduces particulate emissions only during episodes Effect on annual TSP levels unknown

[6] Assume 2000 new fireplaces each year

Fifteen highest ranking strategies:

Mandatory certification of woodstoves. Only clean stoves can be sold. Tax credit of $400 to purchaser.

Strategy rank: #1

Expected % paticulate reduction by year 2000: 39%

Expected cost: $130,000 year administrative costs plus $400/ stove

This strategy would require that all models of wood stoves and furnaces be tested, and that only units capable of emitting less than 5 grams particulate/kilogram of wood burned could be sold. This level of emissions is approximately one-fourth as great as emitted by the average stove in 1982. A tax credit or rebate of $400 would be given to help defray the cost to the consumer of these cleaner units, expected to be about $1200 each. It is assumed that an average woodstove has a 10-year life, and therefore about 10% of the woodstoves will be replaced each year. This strategy is expected to be very effective in the amount of particulate reduction. The cost of the program for the tax credits, and the resistance of consumers to the extra cost and limit on their choice of stoves are major drawbacks. Depending on the size of the geographical area, a larger or smaller percentage of new or replacement stoves may be "bootleg," i.e., cheaper, dirtier stoves. If a relatively small area is chosen for mandatory certification, it is expected there will be a larger percentage of dirty stoves. Overall, it was assumed that about 90% of new or replacement stoves would be the cleaner units, with the remaining 10% uncertified dirtier stoves. The cost of the tax credit program for cleaner woodstoves seems reasonable, since it is comparable to the amount of money currently spent in Oregon on tax credits to reduce particulate emissions from industries.

Another drawback in some jurisdictions is the legal prohibition from regulating residential heating. Where such laws exist, they would have to be changed before mandatory certification could occur.

Mandatory certification of woodstoves. Only clean stoves can be sold. No tax credit.

Strategy rank: #2

Expected % particulate reduction by year 2000: 30%

Expected cost: $130,000/year

This strategy is the same as #1 above, but without a tax credit. It is considerably cheaper, but less effective in particulate emission reduction as it is expected that more consumers will buy dirtier, uncertified stoves. It was estimated that only about 60% of the new or replacement woodstoves purchased would be certified clean-burning stoves, with the remaining stoves bought from other nearby areas where uncertified stoves are sold. This strategy would likely face some public opposition because of the high cost of the certified stoves, with no off-setting tax credit.

Encourage use of larger firewood piece size through public education.

Strategy rank: #3

Expected % particulate reduction by year 2000: 11.5%

Expected cost: $45,000/year

Based on very limited test data, it has been demonstrated that increasing the log diameter by two inches decreases the emissions by 32-36% for log diameter sizes commonly used in woodstoves (two to six inches). Researchers speculate that this phenomena exists because the volatile organic fraction is released too quickly from small logs, and escapes up the stack before it can be combusted. Since this method of emission reduction actually results in less work and inconvenience for the woodstove user, it is expected to be readily accepted. However, these test results should be confirmed prior to such a public education program being started.

Mandatory testing and labeling of all new woodstoves, but all stoves can be sold. Tax credit for cleaner units.

Strategy rank: #4

Expected % particulate reduction by year 2000: 21%

Expected cost: $130,000/year administrative costs plus $400/ stove tax credit

It was assumed that even with a tax credit, only about 40% of the woodstoves purchased would be the cleaner units. Dirtier units would continue to be purchased because of their much lower cost.

Encourage use of other fuels and energy sources.

Strategy rank: #5

Expected % particulate reduction by year 2000: unknown

Expected cost: unknown

This strategy assumes that the use of conventional energy sources such as oil, gas, and electricity, and alternative energy sources such as solar energy, would be encouraged. Whether or not such a strategy is practical is a major drawback, particularly where increasing oil usage is involved. Wood use would also be discouraged under this strategy by restricting the time of year and amount of wood removed from public lands, and by encouraging alternative uses for the wood, such as using the wood for fuel in industrial boilers.

Government-financed research and development.

Strategy rank: #6

Expected % particulate reduction by year 2000: unknown

Expected cost: unknown

This strategy assumes that the government would encourage and offer financial support for a major research effort. Areas to be researched include developing less polluting woodburning units, improving operator practices, and developing a better and cheaper standardized emissions test procedure. The support to be offered could include a staffed emissions test facility free for promising research, tax credits for research, and substantial awards for the designer of exceptionally clean-burning units.

Quantifying the benefits of such an effort is not possible. However, research is clearly an important factor in reducing RWC emissions over the next 20 years.

Promote downsizing of stoves through public education.

Strategy rank: #7

Expected % particulate reduction by year 2000: 10.5%

Expected cost: $45,000/year

Many woodstoves now in operation are too large for the space to be heated, with users shutting down the air supply to the stoves to slow down the fire and to prevent overheating the area. These smouldering, slow fires result in very high emissions. By encouraging properly-sized stoves, the average charge size is reduced, brisker fires produce an equivalent amount of heat, and emissions are reduced.

There are a number of advantages to the woodstove owner in having a smaller stove: the unit itself is cheaper; less wood will be burned for the same amount of heat output; and the safety problem from creosote accumulation will be reduced. The major disadvantage will be that more frequent stoking with less wood will be required, which is an inconvenience to the user.

Mandatory testing and labeling of all new woodstoves, but all stoves can be sold. No tax credits for cleaner units.

Strategy rank: #8

Expected % particulate reduction by year 2000: 11%

Expected cost: $130,000/year

This is the same as #4 above, except without tax credits for cleaner units. It was assumed that without a tax credit only about 20% of the new units purchased would be clean-burning.

Mandatory weatherization of all households to cost effective level.

Strategy rank: #9

Expected % particulate reduction by year 2000: 16.4%

Expected cost: $150,000/year plus $1450/household weatherized

It is assumed under this strategy that about half of the households with woodstoves would weatherize. Of those houses weatherized, there would be 15% fewer burn days (marginally cool days), and that 40% less wood would be burned on days when the woodstove is used. It is further assumed that financing would be no- or low-interest loans, to be made by the government or local utility.

Such a weatherization program has obvious benefits in reducing the conventional energy usage, such as oil or gas, that are commonly used to supplement wood heat in homes having woodstoves. Some areas already have such financing assistance available. The cooperation of government or the utilities in helping to finance each home's weatherization obviously is a key element in this strategy.

Stove testing and rating by trade associations.

Strategy rank: #10

Expected % particulate reduction by year 2000: 11%

Expected cost: $130,000/year (paid by trade associations)

This strategy assumes that a trade association would voluntarily test and rate all woodstoves, and further, that the association would widely publicize such results. There are some precedents for such a program: the testing of electrical equipment by the Underwriters' Laboratory, and the testing of refrigeration units by the Air Conditioning and Refrigeration Institute. However, whether or not this program would be instituted for woodstoves is unknown. The level of particulate reduction and cost are assumed to be the same as for the government testing and labeling strategy, #8, described above.

Mandatory weatherization for households buying new or replacement woodstoves.

Strategy rank: #11

Expected % particulate reduction by year 2000: 11.5%

Expected cost: $50,000/year plus $1450 per household insulated

This is the same as strategy #9 above, except that not all houses would have to be weatherized. This has the advantage of affecting fewer households, which will reduce the cost. It is expected that more people will be tempted to circumvent this strategy by installing woodstoves without weatherizing, since they may feel they are being unfairly singled out for substantial cost for insulation. The estimated circumvention rate is 30%, which reduces the percentage particulate reduction expected by that same percentage over strategy #9, where all houses are weatherized.

Encourage burning of dry firewood.

Strategy rank: #12

Expected % particulate reduction by year 2000: 6.2%

Expected cost: $45,000/year

Some tests have shown that reducing the moisture content of firewood to 25% results in better combustion efficiency and less emissions. This strategy assumes that through public education, the number of households properly covering woodpiles can be increased. Vendors selling more than 10 cords/year of wood would also be required to state the moisture content of wood sold. An additional reduction in emissions is possible if fall cutting of firewood on public lands was prohibited, since the firewood would then have been seasoned at least six months prior to use. However, it was expected that forestry officials may object to this as their goal is to have the extra wood removed as soon as possible to allow reforestation.

Curtailment of residential wood combustion during air pollution episodes.

Strategy rank: #13

Expected % particulate reduction by year 2000: 33% (only during episodes)

Expected cost: $8,000/year

Voluntary curtailment of RWC would be requested whenever a specific 24-hour particulate level was exceeded. Mandatory curtailment of RWC would be implemented if the voluntary approach was not effective. Enforcement would be by visual opacity checks during the day. A strong public education program would be included to encourage the public's cooperation.

Annual inspection/maintenance of installed units.

Strategy rank: #14

Expected % particulate reduction by year 2000: unknown

Expected cost: $1,000,000/year

This strategy, if implemented, would be most effective in reducing emissions from stoves with catalysts (with a limited life), and more sophisticated stoves expected in the next ten years (which may require frequent adjustment and maintenance for optimum performance). However, this strategy would have high cost and expected high public resistance.

Require underfire air for new fireplaces.

Strategy rank: #15

Expected % particulate reduction by year 2000: 2%

Expected cost: $100/fireplace, 1000-3000 fireplaces to be constructed per year.

Based on limited testing, a 40% reduction in emissions was found comparing similar fireplaces and burning practices, but with one fireplace having underfire air. If further testing confirms these results, it will be a relatively easy way to reduce fireplace emissions. This strategy would be implemented as part of the requirements for a building permit.

Task 7

Indoor Air Quality

Recent increases in the use of residential wood combustion appliances and home weatherization have focused new concern on public health risks associated with indoor particulate air pollutants from wood stoves. Several known carcinogens as well as substantial fine particulate emissions have been identified with woodstoves. The purpose of Task 7 was to develop a better understanding of the indoor particulate and polynuclear aromatic hydrocarbon concentrations (PAH) during appliance use, thereby providing a basis upon which future indoor exposure levels can be assessed.

Five homes in the Portland area were chosen for indoor sampling. A range of house ages and weatherization status were chosen, along with one mobile home. Sampling occurred over ten days in May, 1981.

Sampling Methods

In order to separate impacts associated with wood smoke from other indoor sources of particulate and gases, each home was tested for five days with the wood stove operating, and five days without the stove operating. A low volume sampler with a 30 μm inlet restriction operated for 24-hour periods at a flow rate of 70 liters per minute. The sampler intake was located at least two meters from the stove and at a height of one meter.

Samplers were positioned outside of each home. One 24-hour sample was collected (concurrently with an indoor sample) to measure lead levels. (A comparison of the lead levels inside and out allowed a qualitative evaluation of the rate of air exchange into the house, since lead very quickly settles out inside a structure).

Analyses Performed

Each indoor sample was first weighed, and then analyzed for seven PAH compounds using gas chromatography/mass spectroscopy. Lead was determined by X-ray fluorescence.

Results

No significant difference in four of the five homes between burn and non-burn days was found for either particulate mass or PAH concentrations. The fifth home did have much higher levels of particulate and PAH on burn days. This large difference was traced to fugitive smoke leaks from the stove, particularly during wood charging. The sample results for total particulate mass and lead are shown in Table 16. Table 17 includes the results for the seven PAH compounds tested.

Table 16

Residential Wood Combustion
Indoor Sampling Program
Summary of Analytical Results for Mass and Lead

Home Number	Home Type	Particulate (ug/m^3) No-Burn (A)	Burning (B)	Difference (B-A)	Lead (ug/m^3) Indoor (C)	Outdoor (D)	Ratio C/D	Average Mass of Wood Burned Per Day (Kg/day)
1	Older Home	50.5	73.6	23.1	5.05 X 10^{-2}	1.10 X 10^{-1}	.45	18
2	New Tract Home	16.5	23.0	6.5[1]	3.83 X 10^{-2}	8.04 X 10^{-2}	.47	19.5
3	Airtight Home	18.7	19.5	0.8[1]	7.54 X 10^{-2}	1.95 X 10^{-1}	.38	17.5
4	Mobile Home	32.9	38.6[2]	5.7[1]	2.42 X 10^{-2}	2.65 X 10^{-2}	.91	5.8
5	Rural Home	insufficient data	77.4[2]	—	2.82 X 10^{-2}	2.94 X 10^{-2}	.96	10.7

[1] Statistically insignificant at 95% confidence interval

[2] 5 day average based on 4, 24 hour filters

Table 17

Residential Wood Combustion
Indoor Sampling Program
- Summary of PAH Composite Results (ng/m^3) -

Home Number	Fluoranthene No-Burn	Fluoranthene Burn	Pyrene No-Burn	Pyrene Burn	Benz(a)anthracene No-Burn	Benz(a)anthracene Burn	Benzofluoranthenes[1] No-Burn	Benzofluoranthenes[1] Burn	Benzo(a)pyrene No-Burn	Benzo(a)pyrene Burn	Dibenzanthracenes[1] No-Burn	Dibenzanthracenes[1] Burn	Benzo(ghi)perylene No-Burn	Benzo(ghi)perylene Burn
1	0.1	1.4	0.2	3.0	—*	41.3	0.3	51.3	—	26.3	—	2.4	—	14.9
2(A)	0.3	0.3	0.8	0.7	0.2	0.3	0.2	0.4	0.1	0.3	—	0.2	—	0.6
3	0.1	0.1	0.1	0.1	—	0.05	0.05	0.4	—	0.2	—	0.2	—	0.3
4	0.3	0.2	0.4	0.7	0.1	0.2	0.4	0.6	0.2	0.3	0.3	0.2	0.4	0.5
5(B)	0.2	0.1	0.3	0.3	—	—	—	—	—	—	—			

* Blank values indicate specie concentration below minimum detection limit.

[1] Benzo(b)fluoranthene and dibenz(a,h)anthracene were not completely resolvable from their isomers, and results were reported as benzofluroanthenes and dibenzanthracenes.

(A) No-burn samples from Home 2 consisted of 3, 24 hour samples due to power failure.

(B) No-burn samples from Home 5 consisted of 2, 24 hour samples due to equipment failure

The minimum detectable concentration for fluoranthene, pyrene, benz(a)anthracene, benzofluoranthenes and benzo(a)pyrene was approximately .05 ng/m^3. The minimum detectable concentration for benzo(ghi)perylene and dibenzathracenes was approximately .1 ng/m^3.

It should be noted that testing occurred during relatively mild weather, and does not reflect "worst case" conditions. Average wood use during this study was 50-60% of the wood use expected in colder weather. Stoves were operated an average of 5.6 hours/day on days when the stoves were used.

The results clearly indicate that improper stove maintenance or operation can cause indoor particulate levels and PAH compounds concentrations much higher than under optimum stove operation. The benzo(a)pyrene (B(a)P) exposure levels seen in the one house with a leaky stove approximate the equivalent of 10 to 38 cigarettes per day for the inhabitants. B(a)P is a known carcinogen. The house in question was older and had an average air exchange rate, indicating B(a)P levels could be even higher for an "airtight" home.

Comparison With Other Studies

The results from this study were comparable with other studies, considering the lack of uniform testing conditions. Table 18 compares the results of this study with five other studies.

Table 18

Comparison of This Survey with Other Surveys

	Respirable Particulate			Benzo(a)pyrene (B(a)P)		
Study	**Number of Samples**	**Concentration Indoor On Burn Day ug/m^3**	**Concentration Indoor On Non-burn ug/m^3**	**Number of Samples**	**Concentration Indoor On Burn Day ng/m^3**	**Concentration Outside ng/m^3**
This survey	45	46.4	29.7	45	5.4	0.1
Spengler and Ju[1]	85	27.5	18.0	—	—	—
G. Benton et.al[2]	8	33.2	—	—	—	—
GEOMET[3]	28	49.0	28.0	2	11.4[6]	0.6
Butler, et al.[4]	—	—	—	—	2.1	2.9

[1] J.D Spengler and C Ju, "Room-to-Room Variations in Concentration of Respirable Particulates in Residences", *Environmental Science and Technology,* Vol 15, No 5, May 1981

[2] G Benton, D Miller, M Reimold, and R. Sisson, "A Study of Occupant Exposure to Particulates and Gases from Woodstoves in Homes", *Proceedings of the 1981 International Conference on Residential Solid Fuels,* June 1981

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[4] J.D. Butler and P Crossley, "An Appraisal of Relative Airborne Suburban Concentrations of Polycyclic Aromatic Hydrocarbons Monitored Indoors and Outdoors", *The Science of the Total Environment,* Elsevier Scientific Publishing Company, Amsterdam (1979)

[5] Indoors on non-burn day

[6] Maximum of 22 sampled residences

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