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Long - Term Performance of EPA-Certified Phase 2 Woodstoves, Klamath Falls and Portland, Oregon: 1998/1999

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Disclaimer

Executive Summary

Woodstoves have been identified as a major source of particulate and polycyclic organic matter (POM) emissions. For this reason, new source performance standards (NSPS) were promulgated for wood heaters. Wood heaters sold after July 1, 1992, had to be certified for low emissions, meet the most stringent requirements of the NSPS, and are referred to as Phase 2 certified. Of concern has been the fact that laboratory and field studies have shown that certified wood heaters can physically degrade with use and their air emissions commensurately increase.

The objective of this study was to evaluate the condition and air emissions from old phase 2 certified wood heaters installed in homes and used regularly for home heating since the 1992/1993 heating season or earlier. Study stoves were inspected and their conditions were documented. Particulate and POM samples were collected from the stoves during normal in-home use with an automated woodstove emission sampler (AWES). The AWES was developed specifically for the in-home collection of air emission samples from residential wood burning appliances and data developed from its use have previously been used to calculate particulate emission factors published in AP-42. In addition to data obtained from the use of the AWES, ancillary information such as the history of each woodstove, installation characteristics and cordwood properties were compiled for the study.

Sixteen stoves were evaluated in the study, eight in Klamath Falls, Oregon, and eight in Portland, Oregon. All 16 stoves showed the effects of use. However, only six were degraded to the point that it was speculated that their condition would significantly affect air emissions.

An extensive data base from 43 week-long test runs was developed. No direct statistical correlation between emissions and wood moisture, burn rate or the conditions of the stoves could be made due to the number of variables associated with the real-world in-home use of woodstoves. However, the particulate emissions for stoves in homes in Portland were on the average higher than for stoves in homes in Klamath Falls. This result is consistent with the average higher fuel moisture content and burn rate characteristic of the Portland portion of the study as compared to the Klamath Falls portion.

The particulate emission factors of the certified Phase 2 stoves evaluated in this study appear to have increased with use, but on the average, after about seven years they still have lower emissions than uncertified conventional stoves. In addition, it was clear from the results that the emission rates for Phase 2 stove models reported as part of the NSPS certification process do not represent emission levels of same stove models inhomes after extended use.

The data demonstrate that particulate emissions can not be used as a surrogate measurement for POM emissions of woodstoves. Further, POM emission factors, as based on the 7-PAH and 16-PAH values, determined from the in-home use of woodstoves in this study were lower than the POM emission factors previously published in AP-42. This observation is significant because the AP-42 emission factors are the basis for the national emission inventory of POM for which residential wood combustion was identified as the single largest source.

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Section 1.0

Introduction

Residential wood combustion (RWC) has been identified as a major source of particulate matter (PM) and polycyclic organic matter (POM) air emissions. During 1997, RWC contributed an estimated 12% of the sum of the total PM_{10} emissions attributed to all fuel combustion, industrial process, and transportation sources combined (1). RWC was also identified as the largest single source of POM during 1990 (2). Approximately 72% of the cordwood burned annually in the United States in the category of residential wood combustion is in woodstoves (2). (The remaining 28% is mostly burned in fireplaces.) There were an estimated 9.3 million woodstoves in homes during the 1997-1998 heating season (3).

Due to the level of emissions attributed to woodstoves, standards of performance were promulgated for new residential wood heaters (4). All wood heaters sold after July 1, 1992, have to meet the most stringent Phase 2 particulate emission limits of the standards. These standards were 4.1 gram per hour for catalytic stoves and 7.5 grams per hour for non-catalytic stoves. The limits for catalytic stoves were set lower than non-catalytic stoves since the presumed deterioration of the catalyst over time was estimated to result in emissions from catalytic wood heaters over their useful lifetimes approximately equal to non-catalyic wood heaters.

Furthermore, there has been concern about the overall physical deterioration of wood stoves with use and the commensurate increase in air emissions. This concern has been confirmed in both laboratory (5,6) and in-home studies (7-9). Physical degradation coupled with higher PM emissions has been documented for some stoves. Not only are accurate airshed inventories of PM and POM fundamentally important for health and environmental assessments, state and local agencies in areas of PM_{10} nonattainment have been directed to take performance degradation into consideration in their State Implementation Plans (SIPs) when calculating credits from replacing non-certified stoves with certified stoves (10). The replacement of non-certified stoves with Phase 2 certified stoves remains a viable option for reducing airshed pollutant levels and obtaining PM_{10} SIP credits because, as of 1997, more than 80% of the woodstoves in use were still older non-certified units (11). In addition, because over 90% of the PM_{10} emissions from residential wood combustion are also $PM_{2.5}$, emission credits may be very important for possible future $PM_{2.5}$ nonattainment areas.

The primary objective of the study was to select Phase 2 stoves that were installed in homes prior to the fall of 1992 in order to assess the level of long-term degradation and potential increase in PM and POM air emissions of older Phase 2 certified stoves under actual in-home usage. Woodstoves in homes in both Portland, Oregon, and Klamath Falls, Oregon, were selected because Portland is in U.S. climate zone three and Klamath Falls is in U.S. climate zone two. The average heating degree day (HDD) value for Portland is 4109 and the average HDD for Klamath Falls is 6600. The intent behind the selection of stoves in the two climatologically dissimilar cities was to produce results more widely applicable to woodstove usage in the nation as a whole than if homes in a single city were selected. In addition, nine Phase 2 stoves installed in homes in Klamath Falls were previously studied during the 1989-1990 and 1991-1992 heating seasons (8,12,13). Therefore, a secondary objective of the study was to utilize as many of these homes as possible in the current study to help document phase 2 stove degradation and commensurate emission increase.

Fifteen homes were targeted for study during the 1998-1999 heating season. Two in the study group were homes in Klamath Falls that had phase 2 woodstoves that were part of the earlier studies. Emission samples were collected for three one-week periods from woodstoves in each home using the Automated Woodstove Emission Sampler (AWES) previously developed by OMNI Environmental Services, Inc., for similar studies. Samples collected with the AWES were analyzed for particulate matter and organic compounds. The specific organic compounds analyzed included the seven and sixteen POM compounds needed to calculate the 7-PAH and 16-PAH values, respectively, which are used as surrogate indicators for POM. The PM and POM surrogate emission factors (mass of pollutant emissions per unit mass of fuel) were compared against their emission factors tabulated in AP-42 for woodstoves (14). The PM emission rates (mass of pollutant emissions per time of stove operation) measured under actual in-home use for each woodstove model were compared against their certified emission values listed by the U.S. Environmental Protection Agency (15). The PM emissions from this study and from the previous studies were compared for the stoves in the Klamath Falls homes that were part of earlier studies. Cordwood tree species, cordwood moisture, the amount of cordwood burned, burn rates, ambient temperature during testing, a description of woodstove use in each home, chimney characteristics, and the condition of the stoves were also documented as part of the study. Photographs of each stove’s installation and components that showed degradation have been included as Appendix A.

Section 2.0

Methodology

The basis of the study was the use of the AWES for sample and data collection. A description of the AWES is provided in Section 2.1. Woodstove selection and inspection and cordwood characterization are discussed in Section 2.2. Details of the field sampling program, supporting laboratory procedures and data reduction are provided in Section 2.3.

2.1 Automated Woodstove Emission Sampler

The AWES was developed to quantify emissions of particles for residential wood burning appliances while they are in normal in-home use. It is small in size and operates unattended in home settings. Due to the temporal variability in emissions from wood burning appliances, the AWES is also designed to collect long-term integrated samples necessary to provide mean values. Studies conducted with the AWES have provided the majority of the data base used for particulate emission factors development by the U.S. Environmental Protection Agency for residential wood combustion (14). The AWES has been used to quantify emissions from woodstoves, masonry heaters, pellet stoves, and fireplaces (5-8,12,13,16-36). Due to its extensive use, the AWES has undergone U.S. Environmental Protection Agency supported quality assurance evaluations during the period 1986 to 1992 (Appendix B).

A schematic diagram of the AWES is shown in Figure 2-1. Detailed descriptions of its principles of operation, supporting laboratory requirements, calibration, associated data reduction and uncertainty estimates have been published in U.S. Environmental Protection Agency and U.S. Department of Energy reports (16,19) and quality assurance plans (Appendix B).

For sampling purposes, the AWES is placed adjacent to the wood-burning appliance in study homes. For woodstove applications, a stainless steel inlet probe is typically attached to the chimney (stove pipe) 30 cm above the flue collar of the stove. Sample is withdrawn at a rate of approximately one liter per minute. The flow rate is maintained by a calibrated orifice. Particulate samples, including condensible particles, are captured with a heated filter followed by an XAD-2® resin cartridge. All interconnecting tubing, holders and hardware exposed to the sample are made either of stainless steel or Teflon® to maintain sample integrity. After sample collection, the chimney gas is passed through silica gel to protect downstream components from condensate. The oxygen content of the chimney gas is measured with an electrochemical cell.

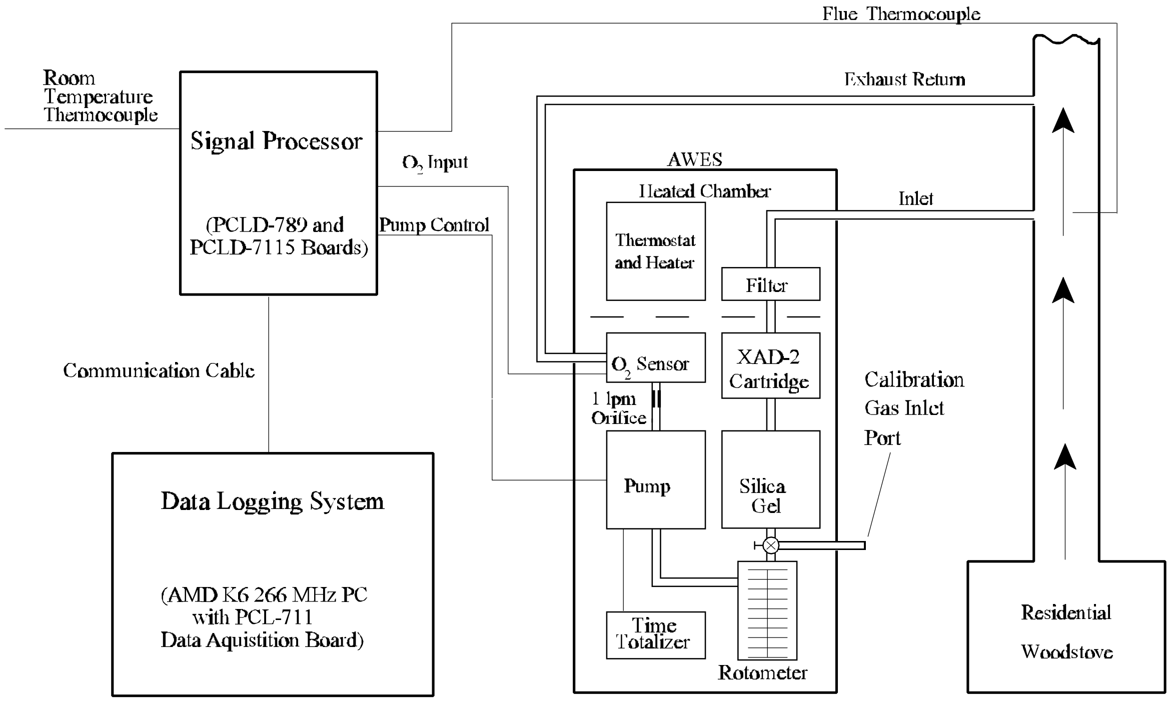

Figure 2-1

Schematic Diagram of the Automated Woodstove Emission Sampler

The sample flow is then returned to the wood-burning appliance chimney above the point where the sample was withdrawn. Room temperature and chimney gas temperature are measured with type K thermocouples. The chimney gas temperature is measured within the chimney at the same location as the sample is withdrawn.

A key component of the AWES is the data logging system. The system records date, time, oxygen content, room temperature, and chimney gas temperature at regular intervals. The oxygen content of the chimney gas, along with the mass of wood burned, allows for the estimation of total chimney gas flow during sampling which is needed for the subsequent calculation of emission rates and emission factors. The record of chimney gas temperatures allows for the total time of appliance operation over the course of the sampling duration to be determined. In addition to data recording, the system is programed to control the sampling frequency, sampling duration and sampling period. For this study, the AWES was programed to sample for two minutes once every 15 minutes for one week. The system is further programed to turn the sampling pump on during the programmed two minute sampling time only if the woodstove is in operation as determined by the chimney temperature in order to avoid collection of sample material when the appliance is not in operation. A threshold chimney temperature of 100°F (38°C) was used as an indicator of woodstove operation.

2.2 Woodstoves, Fuel, and Ambient Temperature

A total of 15 woodstoves, eight in Klamath Falls and seven in Portland, were targeted for study. One home in Klamath Falls was dropped from the study after one week due to a family crisis. An additional home was added to the study in Portland to replace the dropped home. Out of the nine possible phase 2 certified woodstoves that were part of previous studies in Klamath Falls two were included in this study. An attempt was made to include the other seven in the current study but it was not possible either due to stove replacement since the last studies or an unwillingness of the current home occupants to participate in this study. Tables 2-1 and 2-2 list the home codes, woodstove models, and chimney characteristics for all installations. The chimney characteristics were documented because draft and commensurate fire intensity which is affected by chimney height have been implicated in the degradation of woodstove components. A photograph of each stove was taken to illustrate its installation (Appendix A).

Table 2-1

Home Code, Model, and Chimney Characteristics for Klamath Falls Woodstoves

Home Code	Stove Model[a]	Chimney Characteristics
KF01	Quadrafire 2100 Non-Catalytic	8 Foot Vertical Rise Single Story Home
KF02[b]	Pacific Energy Super 27 Non-Catalytic	27 Foot Vertical Rise Two Story A-Frame
KF03[c]	Haughs 171E Non-Catalytic	14 Foot Vertical Rise Two Story Home
KF04	Earthstove 1003C Catalytic	14 Foot Vertical Rise Single Story Home
KF05	Pacific Energy Super 27 Non-Catalytic	18 Foot Vertical Rise Single Story Home
KF06	Waterford 104 MKII Non-Catalytic	21 Foot Vertical Rise Two Story Home
KF07	Earthstove 1400HT Non-Catalytic	14 Foot Vertical Rise Single Story Home
KF08	Country T-Top Non-Catalytic	20 Foot Vertical Rise Two Story A-Frame

[a] All stoves were installed prior to the 1992/1993 heating season.

[b] Stove in home KF02 in this study was referred to as Home 3 or CK03 in the 1990 Energy, Mines and Resources Canada (EMRC) Study[13].

[c] Stove designated as KF03 in this study was referred to as H-5 or WK05 in the 1990 Wood Heating Alliance (WHA) Study[12]. Additionally, this stove was referred to as KF04 in the 1992 Bonneville Power Administration (BPA) study[8].

Table 2-2

Home Code, Model, and Chimney Characteristics for Portland Woodstoves

Home Code	Stove[a]	Chimney/House
P01	Trailblazer Genesis 2000 Catalytic	8 Foot Vertical Rise Single Story Manufactured Home
P02	Lopi Answer Series Non-Catalytic	15 Foot Vertical Rise Single Story Home
P03	Lopi 380-96 Non-Catalytic	11 Foot Vertical Rise Single Story Manufactured Home
P04	Lopi Flush Bay-96[b] Catalytic	22 Foot Vertical Rise Two Story Home
P05	Lopi Flex-95 Catalytic	22 Foot Vertical Rise Two Story Home
P06	Pacific Energy Super 27 Non-Catalytic	10 Foot Vertical Rise Single Story Home
P07	Lopi 520-96 Non-Catalytic	13 Foot Vertical Rise Single Story Home
P08	Vermont Castings Defiant Encored[c] Catalytic	24 Foot Vertical Rise Two Story Home

[a] All stoves were installed prior to the 1992/1993 heating season.

[b] Lopi Flush Bay-96 is now called Freedom.

[c] The Vermont Castings Defiant Encore stove was installed when stove was EPA Phase I certified. Since the installation, the stove has been added to EPA Phase II certification list without changes to the stove's design.

Each stove was inspected and the home occupants were interviewed regarding its historical and current usage. A description was made and photographs were taken of any components that showed degradation (Appendix A).

Participants in the study were either provided with, or reimbursed for the cost of locally available cordwood fuel. Fuel moisture was measured with a Delmhorst moisture meter. If the meter indicated that the wood moisture was greater than 30% (dry basis), the moisture content was determined through drying/gravimetric analysis in the laboratory. Average fuel moisture by week and by home was based on measurements on approximately 10% of the cordwood fuel pieces. Pre-weighed bundles of wood were provided to the occupants of each home prior to each week of sampling. A portable spring scale was used to measure the wood weight. The unused pieces of each bundle were weighed at the end of the sampling week. The amount of wood burned during the week-long tests was calculated by adding the weights of the bundles used (including the weight of wood used in the partly consumed bundles).

Wood Data for Klamath Falls are compiled in Table 2-3. Wood Data for Portland are compiled in Table 2-4. Lodgepole pine, ponderosa pine, juniper and Douglas fir cordwood was used in the Klamath Falls appliances. Douglas fir, maple, alder, oak, birch, lodgepole pine and cherry cordwood was used in the Portland appliances. The mass burned, percentage of the wood burned, and moisture content of cordwood by species in each home during each sampling week are shown in Tables 2-3 and 2-4. The average wood moisture by cordwood tree species ranged from 9.8% to 26.8% on a dry basis (9.0% to 21.1% on a wet basis) for Klamath Falls and from 18.1% to 112.1% on a dry basis (15.3% to 52.8% on a wet basis) for Portland.

The elemental composition (carbon, oxygen, nitrogen and hydrogen) was determined for each species of wood by proximate/ultimate analysis (ASTM D3178). Elemental data were used to calculate the stoichiometric volume of gas produced from a given mass of wood burned during sampling which is, in turn, were used in conjunction with AWES oxygen measurements to estimate the total chimney gas flow.

Average outdoor temperatures were calculated for each sampling week as an indicator of heating demand. The average values were calculated from the daily average temperatures recorded at nearby weather stations for Klamath Falls (37) and Portland (38). The recorded daily average temperatures were simply the average of the daily high and low temperatures in each location.

2.3 Field Measurements, Laboratory Support, and Data Reduction

The principal field and laboratory measurements with associated uncertainties used to calculate the emission and ancillary results are listed in Table 2-5. Fuel measurements as discussed in Section 2.2, infield measurements made by the AWES, laboratory measurements made on the collected samples, and measurements associated with AWES calibration are included in this table.

Table 2-3

Wood Data for Klamath Falls Homes

Home Code	Sampling Week	Mass Burned (Wet lbs)	Species	% Species	Moisture % (Dry Basis)
KF01	A	296.3	Lodgepole	100	20.2
	B	319.4	Lodgepole	100	24.5
	C	170.3	Ponderosa	100	31.4
KF02	A	432.7	Ponderosa	100	20.8
	B	457.3	Ponderosa	100	21.5
	C	313.8	Ponderosa	100	19.6
KF03[a]	B	280.0	Lodgepole	95	14.6
		14.7	Juniper	5	13.2
	C	346.9	Lodgepole	95	18.8
		18.3	Juniper	5	18.3
KF04[a]	A	203.0	Lodgepole	50	21.8
		203.0	Douglas Fir	50	21.4
	B	467.0	Lodgepole	100	19.5
KF05	A	303.2	Juniper	100	10.4
	B	155.7	Juniper	100	9.8
	C	379.3	Juniper	100	11.3
KF06[a]	A	277.5	Lodgepole	100	11.7
KF07	A	349.2	Lodgepole	100	12.6
	B	294.5	Lodgepole	100	11.7
	C	496.5	Lodgepole	100	15.8
KF08	A	525.1	Ponderosa	100	26.8
	B	522.1	Ponderosa	100	25.4
	C	567.6	Ponderosa	100	15.7

[a] There are no data for week A for KF03 and week C for KF04 due to loss of sample and/or laboratory data. There are no data for weeks B and C for KF06 due to death in the family.

Table 2-4

Wood Data for Portland Homes

Home Code	Sampling Week	Mass Burned (Wet lbs)	Species	% Species	Moisture % (Dry Basis)[a]
P01	A	573.1	Douglas Fir	100	24.0
	B	557.1	Douglas Fir	100	21.0
	C	570.3	Douglas Fir	100	22.8
P02	A	51.8	Maple	20	105.3
		13.0	Douglas Fir	5	36.4
		194.3	Alder	75	106.6
	B	227.5	Oak	100	18.5
	C	110.1	Douglas Fir	50	35.4
		110.1	Oak	50	19.1
P03	A	71.6	Douglas Fir	100	18.3
	B	160.4	Douglas Fir	100	18.3
	C	94.0	Douglas Fir	50	19.8
		94.0	Birch	50	27.0
P04	A	184.1	Oak	100	18.3
	B	286.3	Oak	100	18.5
	C	200.7	Oak	100	18.4
P05	A	53.5	Lodgepole	50	20.6
		53.5	Cherry	50	18.1
	B	36.0	Lodgepole	50	19.8
		36.0	Cherry	50	18.2
	C	42.0	Lodgepole	50	19.3
		42.0	Cherry	50	18.8

(Continued)

[a] See equation 6.

Table 2-4 (continued)

Wood Data for Portland Homes

Home Code	Sampling Week	Mass Burned (Wet lbs)	Species	% Species	Moisture % (Dry Basis)[a]
P06	A	181.7	Maple	20	105.3
		48.4	Douglas Fir	5	36.4
		678.4	Alder	75	106.6
	B	164.4	Maple	20	104.2
		41.1	Douglas Fir	5	38
		616.3	Alder	75	112.1
	C	155.0	Maple	20	101.1
		38.7	Douglas Fir	5	35.4
		581.1	Alder	75	107.9
P07	A	214.6	Maple	20	105.3
		53.7	Douglas Fir	5	36.4
		804.9	Alder	75	106.6
	B	227.9	Maple	20	104.2
		57.0	Douglas Fir	5	38
		854.7	Alder	75	112.1
	C	894.4	Douglas Fir	100	24.8
P08[b]	A	46.7	Douglas Fir	10	21.8
		419.9	Oak	90	25.1
	B	16.8	Douglas Fir	10	21.9
		151.1	Oak	90	25.4

[a] See equation 6.

[b] There are no data for week C for P08 due to loss of sample data.

Table 2-5

Principal Field and Laboratory Measurements

Parameters	Units	Method of Determination	Estimated Precision	Estimated Accuracy
1. Wood Fuel Weight	kg	Spring Scale	± 0.1%	± 0.1%
2. Wood Fuel Moisture	% by Mass (Dry Basis)	ASTM D2016 (>30%)	± 10%	± 5%
		Delmhorst Model RC Moisture Meter (<30%)	± 1% Absolute	± 1% Absolute
3. C, O, N, H Composition of Wood	% by Mass	ASTM D3178	± 1% Absolute	± 1% Absolute
4. Mass of Particles Collected on Filter	mg	Analytical Balance	± 0.3%	± 0.3%
5. Mass of Particles Collected in Probe and Connecting Tubing	mg	Removal/Solvent Evaporation/Analytical Balance	± 0.3%	± 0.3%
6. Mass of Semi-Volatiles Collected on XAD-2®	mg	Extraction/Solvent Evaporation/Analytical Balance	± 0.3%	± 0.3%
7. Sample Flow Rate	l/min	Bubble Flow Meter/Digital Timer	± 3%	± 2%

(Continued)

Table 2-5 (continued)

Principal Field and Laboratory Measurements

Parameters	Units	Method of Determination	Estimated Precision	Estimated Accuracy
8. Chimney Gas O_2	% by Volume	AWES/Electrochemical Sensor	± 0.8% absolute	± 0.8% Absolute
9. Mean Barometric Pressure (for Flow Calibration)	in. Hg	Mercury Barometer	± 0.5 mm Hg	± 0.5 mm Hg
10. Duration of Sampling	min	Data Logger Internal Clock	± 0.1%	± 0.1%
11. Temperature (Chimney, Ambient)	°F	Type K Thermocouple	± 4 °F or ± 0.75% (Whichever is Greatest)	± 4 °F or ± 0.75% (Whichever is Greatest)
12. Sampling Period	min	Data Logger Internal Clock	± 0.1%	± 0.1%
13. POM Compounds Contained in Particles	µg	EPA SW-846 Method 8270C	± 20%	± 20%
14. POM Compounds Contained in Vapor Phase	µg	EPA SW-846 Method 8270C	± 20%	± 20%

Laboratory measurements were made on three AWES sample components:

1. The probe and interconnecting tubing;
2. The heated filter; and
3. The XAD-2® resin cartridge.

For this study since both PM and POM surrogates were measured, the sample material was split into two portions for analysis. Figure 2-2 is a flow chart summarizing the analysis procedures. The sample probe and tubing connecting the probe to the heated filter were rinsed with a 50/50 mixture of methylene chloride and methanol. A stainless steel wire brush was used to remove material from the sample probe prior to the 50/50 methylene chloride/methanol mixture rinse. Both the removed material and solvent rinse were collected in a single beaker. One half of the mixture was taken to dryness and weighed to calculate its PM content. One half was combined with the XAD-2® extract and reduced to 5 mL volume for organic compound analysis by gas chromatography/mass spectrometry (SW-846 Method 8270C).

The pre-weighed filter was placed in a desiccator until a constant weight was achieved. The difference between pre-and post-weights allowed for the mass of particles collected on the filter to be determined. The filter was spiked and then extracted with methylene chloride, reduced in volume to 5 mL and analyzed for organic compounds by SW-846 Method 8270C.

Surrogates and matrix spikes were added to the XAD-2® resin cartridge for the POM determination. The resin was then extracted with a Soxhlet extractor using methylene chloride. One half of the extract was evaporated to dryness for mass (PM) determination and one half was added to the probe and interconnecting tubing rinse for organic compound analysis by SW 846 Method 8270C.

The masses of PM and POM surrogates contained in each of the three components were added to obtain the total mass captured with the AWES system.

Table 2-6 lists the intermediate and final parameters derived from the field and laboratory measurements. Except for the POM compound emission factors and rates (items 10 and 11 in Table 2-6), the precision and accuracy uncertainties for the intermediate and final derived parameters were determined from the estimated uncertainties of the principal field and laboratory measurements shown in Table 2.5 following standard propagation of error procedures (16,19). The uncertainties for the POM compound emission factors and rates shown in Table 2-6 were estimated from data from similar studies (23,25,39,40).

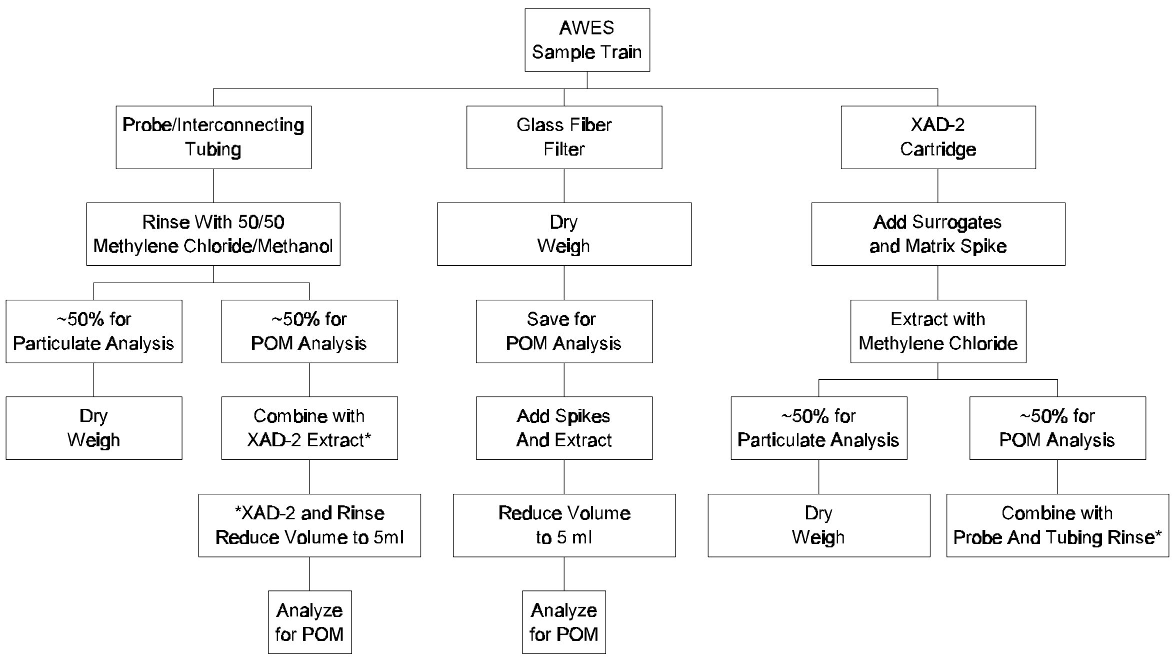

Figure 2-2

Flow Chart Summarizing Analysis Procedures

Table 2-6

Derived Parameters

Parameters	Units	Method of Determination	Estimated Precision	Estimated Accuracy
1. Mass Particles/Volume of Chimney Gas	g/m^3	AWES Data Logger System/Lab Support	± 8%	± 5%
2.Mass Particles/Mass Dry Wood Burned	g/kg (Dry)	AWES Data Logger System/Lab Support	± 16%	± 17%
3. Mass Particles/Time of Stove Operation	g/hr	AWES Data Logger System/Lab Support	± 20%	± 18%
4. Dry Mass of Wood Burned	kg	Fuel Scale	± 0.1%	± 0.1%
5. Percent of Time Stove in Operation	%	Type K Thermocouple/Data Logger	± 3%	± 3%
6. Mean Fuel Moisture by Species	% (Dry Basis)	<30% – Delmhorst Moisture Meter	< ± 2% Absolute	< ± 2% Absolute
		>30% – Gravimetric Analysis	± 4%	± 2%
7. Mean Wood Burn Rate	kg/hr (Dry)	Fuel Scale/Data Logger	± 0.1%	± 0.1%
8. Mean Chimney Gas Oxygen Concentration	% by Volume	Electrochemical Sensor/Data Logger	± 0.3% Absolute	± 0.69% Absolute Uncorrected ± 0.2% Absolute Corrected
9. Mean Chimney Gas Temperature	°F	Type K Thermocouple/Data Logger	± 4 °F or ± 0.75% (Whichever is Greatest)	± 4 °F or ± 0.75% (Whichever is Greatest)
10. Mass of POM Compounds/Mass Dry Wood Burned	µg/kg (Dry)	AWES Data Logging System/ Lab Support	± 50%	± 50%
11. Mass of POM Compounds/Time of Stove Operation	µg/kg (Dry)	AWES Data Logging System/ Lab Support	± 50%	± 50%

The following formulas were used to calculate the derived parameters listed in Table 2-6.

Mass of particles/volume of chimney gas = $$\frac{(MP)}{(FR)(SD)} \qquad (1)$$

where:

MP	=	Mass of particles collected by the AWES (sum of the particles collected on the probe and interconnecting tubing, on the filter, and on the XAD-2® resin)
FR	=	Flow rate of the AWES, and
SD	=	Sampling duration of the AWES.

Mass of particles/mass dry wood burned = $$\frac{(MP)(SV)}{(FR)(SD)\left(1-\left[\%O_2/20.9\%\right]\right)} \qquad (2)$$

where:

Mass particulate emissions (MP) = $$(MP)\frac{(TF)}{(FR)(SD)}$$

Total chimney gas volume (TF) = $$\frac{(SV)(MDW)}{\left(1-\frac{\%O_2}{20.9\%}\right)}$$

SV	=	Volume of chimney gas per unit mass of dry wood from the stoichiometric combustion of wood, obtained from proximate/ultimate analysis data and a small correction for carbon monoxide levels characteristic of EPA-certified Phase 2 woodstove emissions,
MDW	=	Mass of dry wood burned during sampling (see equation 4), and,
$\%O_2$	=	Percent of oxygen in chimney gas measured with the AWES.

Mass particulate emissions/time of stove operations =

$$\frac{(MP)(SV)(MDW)(100)}{(FR)(SD)(SP)(WO)\left(1-\left[\%O_2/20.9\%\right]\right)} \qquad (3)$$

where:

SP = Sampling period (usually one week), and,

WO = Percent of time stove in operation (see equation 6).

Dry mass of wood burned = $$\sum_{i=1}^{n} X_i\left(\frac{MWW}{1+MDC_i}\right) \qquad (4)$$

where:

i = the wood species,

X_i = the fraction of the total wood of the i^{th} species used,

MDC_i = the mean moisture content (dry basis) of species *i* (see equation 6), and

MWW = Mass of wet wood burned. The wood used for the duration of the testing was pre-weighed. Fuel use was the difference between amount of weighed wood at the start of the test, and the amount of weighed wood remaining at the end of the test. The data were summed over the time periods of interest.

Fraction of time stove was in operation

The woodstove was determined to be in operation whenever chimney gas temperatures exceeded 38˚ C (100˚ F). Temperature was determined continuously by a thermocouple and the value was recorded every fifteen minutes. The fraction of time the stove was operating was calculated as follows:

Percent of time woodstove operates (WO) =

$$\frac{\text{\# of readings where } Tf \geq 100°F}{\text{Total \# of readings}} X 100\%. \qquad \textbf{(5)}$$

Mean fuel moisture by species

Mean fuel moisture was determined each week by successive measurements of fuel stockpiled for immediate burning. The average moisture for each species of fuel wood was determined from at least ten percent or more of the total wood pieces for each species of wood for each sampling week.

Average weekly fuel moisture (dry basis) for species *i* (MDC_i) = $\frac{1}{n}\sum_{j=1}^{n} MC_j$ (6)

where:

MC_j = Moisture value of the j^{th} measurement ($n \geq 6$).

When a moisture meter reading exceeded 30 percent moisture (dry basis), a sample was taken and moisture determined by the standard oven drying technique (ASTM D2016) In these cases:

$$MDC_i = \frac{W_{BD} - W_{AD}}{W_{AD}} \qquad (6a)$$

where:

MDC_i = Dry basis moisture content of species *i*,

W_{BD} = Weight of sample before drying, and

W_{AD} = Weight of sample after oven drying.

Mean Wood Burn Rate

$$\text{Mean wood burn rate} = \frac{(MDW)(100)}{(SP)(WO)} \qquad (7)$$

where:

MDN = Mass of dry wood burned during sampling (see equation 4),

SP = Sampling period, and

WO = Percent of time stove in operation (see equation 6).

Mean Chimney Gas Oxygen Content in Percent

$$\text{Mean chimney gas oxygen content in percent } (\% O_2) = \frac{1}{n}\sum_{i=1}^{n} O_{2i} \qquad (8)$$

where:

$O_{2,i}$ = oxygen concentration of the chimney gas of the i^{th} reading (%), and

n = total number of valid readings.

Chimney oxygen was recorded every fifteen minutes and averaged over each sampling week or fraction of the sampling week of interest.

Mean Chimney Gas Temperature

$$\text{Mean chimney gas temperature } (T_f) = \frac{1}{n}\sum_{i}^{n} (T_f)_i \qquad (9)$$

where:

$(T_f)_i$ = Mean chimney gas temperature for the i^{th} valid reading, and

n = Number of valid readings in the sampling period.

Mass of POM compounds / mass of dry wood burned

The mass of each individual 7-PAH and 16-PAH compound's emissions were summed to get the 7-PAH and 16-PAH POM surrogate mass emission values, respectively. By substituting these values for the particulate mass emission value (MP) in equation 2, the emission factors (mass POM surrogate/ mass of dry wood) for the 7-PAH and 16-PAH POM surrogates were calculated. The seven and 16 individual compounds that make up the 7-PAH and 16-PAH surrogates are listed in Table 2-7.

Table 2-7

7-PAH and 16-PAH Surrogates for POM

1	Acenaphthene
2	Acenaphthylene
3	Anthracene
4	Benzo(a)anthracene*
5	Benzo(a)pyrene*
6	Benzo(b)fluoranthene*
7	Benzo(g,h,i)perylene
8	Benzo(k)fluoranthene*
9	Chrysene*
10	Dibenzo(a,h)anthracene*
11	Fluoranthene
12	Fluorene
13	Indeno(1,2,3-cd)pyrene*
14	Naphthalene
15	Phenanthrene
16	Pyrene

* 7-PAH Compounds

$$\text{Mass of POM/mass dry wood burned} = \frac{(\text{PAH})(\text{SV})}{(\text{FR})(\text{SD})\left(1-\left[\%\text{O}_2/20.9\%\right]\right)} \quad (10)$$

where:

$$\text{Mass of PAH emissions (PAH)} = (\text{PAH})\frac{(\text{TF})}{(\text{FR})(\text{SD})},$$

$$\text{Total chimney gas volume (TF)} = \frac{(\text{SV})(\text{MDW})}{\left(1-\frac{\%\text{O}_2}{20.9\%}\right)},$$

SV = Volume of chimney gas per unit mass of dry wood from the stoichiometric combustion of wood, obtained from proximate/ultimate analysis data and a small correction for carbon monoxide levels characteristic of EPA-certified Phase 2 woodstove emissions,

MDW = Mass of dry wood burned during sampling (see equation 4), and

$\%O_2$ = Percent of oxygen in chimney gas measured with the AWES.

Mass of POM compounds/time of stove operation

The 7-PAH and 16-PAH POM surrogate mass emission values were substituted for the particulate mass emission value (MP) in equation 3 to calculate the emission rates (mass POM surrogate/ time of stove operation) for the 7-PAH and 16-PAH surrogates.

Mass particulate emissions/time of stove operations =

$$\frac{(\text{PAH})(\text{SV})(\text{MDW})(100)}{(\text{FR})(\text{SD})(\text{SP})(\text{WO})\left(1-\left[\%\text{O}_2/20.9\%\right]\right)} \quad (11)$$

where:

SP = Sampling period (usually one week), and

WO = Percent of time stove in operation (see equation 6).

In the conduct of field measurements, laboratory support and data reduction tasks, the quality assurance procedures that have been developed for previous U.S. EPA studies (see Appendix B) were followed. In addition a project specific quality assurance plan was developed and approved for this study. Two key quality assurance activities were an independent check of 10% of the data reduction and the processing of field blanks.

Section 3.0

Results and Discussion

The results are presented in three sections. The condition of the stoves along with their history and current use and a description the home settings is provided in Section 3.1. Particulate emission results are presented Section 3.2. POM emission results are presented in Section 3.3.

3.1 Condition of Stoves

Table 3-1 lists the home code, stove model, and a summary of the stove condition and usage for homes in Klamath Falls. Photographs of these stoves and degraded components are provided in Appendix A. A narrative description for the stoves in Klamath Falls by home code (home codes KF01 through KF08) follows.

KF01 The QuadraFire 2100 (Appendix A, Photograph 1) was installed September 10, 1991 and has been owned and operated by the same person. It is located in a dusty environment in a ceramic shop with poor insulation. It is in overall good condition except for the ceramic blanket which is pushed up partially blocking the exhaust flow (Appendix A, Photograph 2). The blanket installation was repaired before testing was conducted for this study. The stove is used as the primary heat source for the small business and is usually operated for more than 16 hours per day during the heating season. The chimney is cleaned and inspected once per year. The owners of the business live adjacent to the shop and use an oil furnace as a supplemental heating source when the shop is unoccupied.

The owner typically burns two to three cords of lodgepole pine cordwood a year, and feels that the stove has heated the shop well. However, the owner noted that the stove was difficult to light, and sometimes initially difficult to keep burning. These problems were probably due to the ceramic blanket partially blocking the exhaust flow.

KF02 The Pacific Energy Super 27 (Appendix A, Photograph 3) was provided to the homeowner as part of the 1990 Wood Heating Alliance (WHA) study (12). The home is a two-story A-frame style. The previous owners had the baffle replaced (Appendix A, Photograph 4) approximately six years prior to the study with an identical baffle because the baffle assembly had degraded to the point that the stove would not heat the home adequately. The baffle was replaced by a professional installer. Otherwise, the

Table 3-1

Home Code, Model, and Condition for Klamath Falls Woodstoves

Home Code	Stove Model[a]	Stove Condition and Usage
KF01	Quadrafire 2100 Non-Catalytic	Impaired / Normal Wear[d] Minimal Use during Heating Season
KF02[b]	Pacific Energy Super 27 Non-Catalytic	Impaired / Normal Wear[d] Extensive Use during Heating Season
KF03[c]	Haughs 171E Non-Catalytic	Normal Wear Extensive Use during Heating Season
KF04	Earthstove 1003C Catalytic	Normal Wear Extensive Use during Heating Season
KF05	Pacific Energy Super 27 Non-Catalytic	Impaired Regular Use during Heating Season
KF06	Waterford 104 MKII Non-Catalytic	Impaired Regular Use during Heating Season
KF07	Earthstove 1400HT Non-Catalytic	Normal Wear Extensive Use during Heating Season
KF08	Country T-Top Non-Catalytic	Normal Wear Extensive Use during Heating Season

[a] All stoves were installed prior to the 1992/1993 heating season.

[b] Stove in home KF02 in this study was referred to as Home 3 or CK03 in the 1990 Energy, Mines and Resources Canada (EMRC) Study (13).

[c] Stove designated as KF03 in this study was referred to as H-5 or WK05 in the 1990 Wood Heating Alliance (WHA) Study (12). Additionally, this stove was referred to as KF04 in the 1992 Bonneville Power Administration (BPA) study (8).

[d] The stove was impaired by use but was repaired and in the “normal wear” condition at the time of this study.

installation has not changed since the WHA study. The chimney system is inspected and cleaned once a year.

The owner typically burns five cords of lodgepole pine or ponderosa pine each burning season. The unit is used as the primary heat source and fired 24 hours per day. The owner feels that it heats the home well.

KF03 The Haughs 171E woodstove (Appendix A, Photograph 5) was given to the current owner as part of the 1990 WHA study (12) and was also used in the 1992 Bonneville Administration (BPA) study (19). It is in overall good condition showing only normal wear, with the exception of cracking along the rear level of secondary air ports (Appendix A, Photograph 6). The unit has been operated and maintained by the same home owners that participated in the 1990 and 1992 studies and there have been no changes in the installation of this unit.

They feel that the stove has heated the home well. Approximately five cords of mixed juniper, cedar, and lodgepole pine are burned per heating season.

KF04 The Earthstove model 1003-C (Appendix A, Photograph 7) was installed in early 1992. It is designed for mobile home installation getting its combustion air from outside the home. It is in good overall condition. The owner felt that the catalytic combustor was no longer working and needed replacement. Visual inspection did reveal some thermal wear. However, temperatures observed in the flue and at the installed catalyst temperature indicator during testing showed that the catalyst was in proper working order. The door gasket was in good condition, as were the refractory elements.

The owner felt that the unit heated the home well. It is used as the primary heat source, and fired 24 hours per day. Typically, four to five cords of Douglas fir are burned per heating season.

KF05 The Pacific Energy Super 27 (Appendix A, Photograph 8) was installed November 23, 1991, and has been owned and operated by the same person. It is in overall fair condition with the exception that the front right portion of the baffle area and the ceramic blanket are degraded (Appendix A, Photograph 9). The stove is used as the primary heat source and operated for more than 16 hours per day during the heating season. The chimney is cleaned and inspected once per year.

The owner uses the stove as the primary heat source during the burning season, and feels that it heats the home well. Typically two to three cords of juniper are burned per year.

KF06 The Waterford MKII (Appendix A, Photograph 10) was installed on July 12, 1991, and has been operated by the same owners. The chimney is cleaned and inspected once per year. It is in good operating condition except for the front portion of the baffle which is in a severely degraded state (Appendix A, Photograph 11). Such degradation is probably either the result of thermal or chemical breakdown of the baffle material. Chemical breakdown such as was seen on the baffle can be caused by burning trash. Thermal breakdown can be caused by intense fire conditions such as can be caused by a strong draft which is in turn can be caused by a tall chimney. It is interesting to note that the chimney in this home is tall (approximately 21 feet total vertical rise).

This stove and a Phase I certified woodstove located in another part of the house are used as the primary heat sources during the burning season. The owner feels that the Waterford stove does a good job of heating the section of house in which it is located. Three to four cords of mixed lodgepole pine and Douglas fir are burned in the stove annually.

KF07 The Earthstove 1400 HT (Appendix A, Photograph 12) insert was installed early 1992, and has been owned and operated by the same person. The stove is fitted with a stainless steel flue collar and stainless steel lined flue. The refractory elements show some wear (Appendix A, Photograph 13). The steel components of the stove are in good condition. However, the secondary inlet tube shows some warping (Appendix A, Photograph 14). The door gasket is in fair condition, with some degradation on the combustion side of the glass seal.

The owner typically burns three to five cords of lodgepole pine per year. The stove is used as the primary source of heat. The owner feels that the unit has done a great job heating the home, and mentioned that it can easily overheat the house.

KF08 The Country T-Top woodstove (Appendix A, Photograph 15) was installed during the 1992/1993 heating season. The stove is the only source of heat for the home and is fired continuously during the burning season. The firebox is in overall good condition. The secondary air tubes show some flaking on their surfaces. The door gasket is in usable but degraded condition.

The stove is used as the primary heat source for the home. The owner burns four to five cords of lodgepole pine per winter, and is satisfied with the performance of the stove.

Table 3-2 lists the home code, stove model, and a summary of the stove condition and usage for homes in Portland. Photographs of these stoves and degraded components are provided in Appendix A. A narrative description for the stoves in Portland by home code (home codes P01 through P08) follows.

Table 3-2

Home Code, Model, and Condition for Portland Woodstoves

Home	Stove[a]	Stove Condition and Usage
P01	Trailblazer Genesis 2000 Catalytic	Impaired Extensive Use All Year Long
P02	Lopi Answer Series Non-Catalytic	Impaired Minimal Use during Heating Season
P03	Lopi 380-96 Non-Catalytic	Normal Wear Minimal Use during Heating Season
P04	Lopi Flush Bay-96[b] Catalytic	Normal Wear Minimal Use during Heating Season.
P05	Lopi Flex-95 Catalytic	Normal Wear Minimal Use during Heating Season
P06	Pacific Energy Super 27 Non-Catalytic	Normal Wear Extensive Use during Heating Season
P07	Lopi 520-96 Non-Catalytic	Normal Wear Extensive Use during Heating Season
P08	Vermont Castings Defiant Encore[c] Catalytic	Normal Wear Regular Use during Heating Season

[a] All stoves were installed prior to the 1992/1993 heating season.

[b] Lopi Flush Bay-96 is now called Freedom.

[c] The Vermont Castings Defiant Encore stove was installed when stove was EPA Phase I certified. Since the installation, the stove has been added to EPA Phase II certification list without changes to the stove's design.

P01 The Genesis 2000 (Appendix A, Photograph 16) was installed on September of 1991. The unit has been used as the primary heat source in the home since installation and is operated 24 hours a day. The unit is in overall fair condition. The baffle (Appendix A, Photograph 17) and catalyst (Appendix A, Photograph 18) are operational but show significant thermal degradation.

The stove is used as the primary source of heat in this home and is actually fired 24 hours per day, all year long. The unit is used all year long not just in the burning season due to the fact that the home is located at higher elevation outside the Portland metropolitan area where the climate is cooler. The homeowner does not like to restart the stove. Hence, even in the summer it is allowed to operate in the "dampered down" mode during the daytime. Approximately twelve cords of wood are burned per year.

P02 The LOPI Answer series (Appendix A, Photograph 19) was installed in 1991 and has been owned and operated by the same person. The baffle refractory is in good condition. The firebox side and rear refractory show some degradation. The door and window gasket are in good condition, as is the front secondary air tube. However, the support for the front secondary air tube has degraded to the point where it has lost structural strength (Appendix A, Photograph 20). The rear secondary air tube is partially blocked by creosote (Appendix A, Photograph 21). The creosote buildup indicates that the unit is typically operated with combustion air restricted (the damper shutdown). The thermal degradation of the front secondary air tube support indicates that the unit receives most of its combustion air though the front of the unit.

The unit is used part time by the owners who feel satisfied about the stove's ability to heat their home. They typically burn one to two cords of mixed oak and Douglas fir per year.

P03 The LOPI 380-96 (Appendix A, Photograph 22) was installed in October of 1992, and owned and operated by the same person. Overall the stove is in excellent condition. It is only used part-time during the burning season. The door and window gaskets are still in excellent condition, as are the fire brick, fire brick hangers, and secondary air tubes.

The primary heat source for the home is a heat pump. The owner is satisfied with the performance of the stove. One to two cords of mixed Douglas fir and birch are burned each year.

P04 The LOPI Flushbay-96 (Appendix A, Photograph 23) was installed in 1992 by the existing owner. It is equipped with a flexible stainless steel flue pipe at the flue collar that leads to a solid vertical stainless steel liner. The unit's door and glass seals are in excellent condition. The firebox refractory is in good condition. However, the secondary air tube shows signs of warping and flaking (Appendix A, Photograph 24), but is still in good functional condition.

The unit is used part time by the owner who feels satisfied about the stove's ability to heat the home. Typically, one to two cords of oak are burned per year.

P05 The LOPI Flex-95 (Appendix A, Photograph 25) was installed in November of 1990, and has been owned and operated by the same person. The baffle refractory and baffle supports, along with the secondary air tube, are all in good condition. The side and rear fire brick show cracks, but no visible sign of thermal degradation. It is likely that the cracks in the fire brick are from physical impact. The catalyst is in good operating condition but shows fly ash accumulation. The Interam seal surrounding the catalyst has been disturbed and dislodged in places (Appendix A, Photograph 26). This is apparently from removing and replacing the catalyst without replacing the Interam seal.

The owner typically burns one to two cords of mixed cherry and lodgepole pine per year. The stove is used part time during the heating season. The owner is satisfied with its performance.

P06 The Pacific Energy Super 27 (Appendix A, Photograph 27) was installed in 1990. After the initial installation, the stove was temporarily removed for floor repair and replaced back into the original installation configuration. The door gasket is in good condition, while the fire brick shows some thermal wear. The unit is in fair operational condition except for a sagging baffle (Appendix A, Photograph 28). Although the baffle sags, there are no visible cracks in it.

At the time of this study, the stove was the home's only source of heat. An oil furnace in the home was not operational. The owner typically burns one to two cords per year. However, three to four cords were burned during the study year due to the oil furnace not being in service. The owner feels that the stove heats the home well.

P07 The LOPI 520-96 (Appendix A, Photograph 29) is in overall good condition. It was installed in October 1992. It is used extensively during the heating season. The stove was the only working source of heat in the home at the time of the study, and was used 24 hours a day. The door gasket and baffle are all in good condition, while the secondary air tube shows signs of flaking (Appendix A, Photograph 30). However, the air tube is still in good operational condition.

The owner typically burns two to three cords per winter, but burned four to five cords during the winter of the current study because an oil furnace which is normally used was not operational during the study period. The owner is satisfied with the heating performance of the stove.

P08 The Vermont Castings Defiant Encore (Appendix A, Photograph 31) is in good working condition, including the door gaskets and refractory elements. It was installed in 1989. The unit has a top vented exhaust rising about four feet where it is connected to a terra cotta lined masonry chimney. The chimney cap allows rain into the chimney. The water makes its way to the connection where it drips out into the back left corner of the stove.

The unit is used as a secondary heat source for the home. The owners indicated that they are happy with the stove. They typically burn one to two cords of oak per year.

Out of the sixteen stoves inspected, six degraded to the point of probably impairing emission performance. Two of these were repaired by the homeowner prior to conducting emission testing for this study. Consequently, the emission results of this study represent emissions from 12 units in the "normal wear" condition and from four units in a significantly degraded condition. Because there were so many variables (burn rate, cordwood tree species, wood moisture, chimney height, historical burning practices, and stove model) there was no clear cause and effect relationship observed. It was, however, noted by the inspector, that in general, routine stove maintenance had not been done and that this maintenance and/or minor repairs would have kept all stoves in acceptable working condition.

3.2 Particulate Matter Emissions

The results for each of the 43 valid one-week testing runs are summarized in Appendix C and in Tables 3-3 through 3-6. Emissions were determined for a range of normal wood burning practices such as occur in actual home installations. For example, week-long averages of burn rates ranged from 0.6 dry kg of wood per hour to 2.0 dry kg of wood per hour and average wood moisture contents ranged from 9.8% to 105.0% on a dry basis (8.9% to 51.2% on a wet basis). It should be noted that not only are the emission results representative of the range of actual emissions from the in-home use of woodstoves, they also represent credible mean values for each set of conditions since they inherently average the emissions from a considerable mass of wood combusted over numerous burn cycles during each sampling week. The amount of wood burned over the one-week tests ranged from 77.3 kg to 517.4 kg (58.8 kg to 325.4 kg on a dry basis).

Not surprisingly, emission factors and emission rates calculated for the week-long tests were variable. The factors ranged from 1.9 g/ dry kg to 20.8 g/dry kg and the rates ranged from 1.7 g/hr to 40.3 g/hr. There was no clear relationship between the condition of an individual stove and its particulate emissions. In addition, there was no clear statistical relationship (no R^2 values greater than 0.9) between emission factors and either burn rate or fuel moisture for catalytic stoves, non-catalytic stoves or for both categories combined. While it is a generally accepted fact that lower burn rates, wet wood and degraded stoves tend to produce higher emission factors, there were, as previously discussed, so many inherent variables that the effects of individual parameters were unable to be determined.

Average fuel moisture, particulate emissions, burn rate and outdoor temperature are shown in Table 3-7 for Klamath Falls and in Table 3-8 for Portland. A summary of particulate emission results by stove grouping (catalytic, non-catalytic and all stoves) and city are presented

Table 3-3

Individual Test Results for Klamath Falls Stoves KF01 – KF04

Home Code	KF01			KF02			KF03[a]		KF04[a]	
Stove Model	Quadrafire 2100 Non-Catalytic			Pacific Energy Super 27 Non-Catalytic			Haughs 171E Non-Catalytic		Earthstove 1003-C Catalytic	
Week	A	B	C	A	B	C	B	C	A	B
Start Date	11/25/98	12/04/98	12/10/98	11/08/98	12/02/98	12/09/98	11/22/98	12/06/98	11/14/98	12/02/98
End Date	12/02/98	12/10/98	12/16/98	11/15/98	12/09/98	12/16/98	11/29/98	12/13/98	11/21/98	12/09/98
Total Data Collection Hours	168.0	141.0	142.8	168.0	168.0	168.0	168.0	168.0	168.0	167.0
% Time Stove Burned	54.9	66.3	30.3	100.0	97.5	79.6	85.0	95.2	100.0	100.0
Avg. Stack Temp. (°F)	478	493	482	448	412	374	430	475	398	510
Avg. %O_2 (Flue >100 °F)	15.87	15.54	16.29	14.53	14.52	15.15	17.58	16.52	15.42	12.59
Fuel Mass (Wet kg)	134.5	145.0	77.3	196.4	207.6	142.5	133.8	165.8	184.4	212.2
Fuel Moisture (% Dry Basis)	20.2	24.5	31.4	20.8	21.5	19.6	14.5	18.8	21.6	19.5
AWES Flow Rate (l/min)	0.985	0.985	0.985	1.124	1.124	1.124	1.038	1.038	1.042	1.042
Sample Time (min)/Cycle (min)	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15
Indoor Ambient Temp. (°F)	70	62	72	67	57	54	75	71	75	71
Outdoor Ambient Temp. (˚F)	37	17	30	33	22	29	38	23	37	2

(Continued)

Table 3-3 (continued)

Individual Test Results for Klamath Falls Stoves KF01 – KF04

Home Code	KF01			KF02			KF03[a]		KF04[a]	
Stove Model	Quadrafire 2100 Non-Catalytic			Pacific Energy Super 27 Non-Catalytic			Haughs 171E Non-Catalytic		Earthstove 1002-C Catalytic	
Week	A	B	C	A	B	C	B	C	A	B
Rinse Particulate (g)	91.2	163.1	39.2	307.2	193.6	250.5	60.4	88.4	461.9	439.7
XAD-2® Particulate (g)	57.0	41.4	6.1	103.0	126.4	42.9	30.4	17.2	448.3	458.8
Filter Particulate (g)	139.0	102.4	29.9	136.3	159.6	87.7	55.0	7.4	386.5	687.7
Total Particulate (g) (Blank Subtracted)	287.2	343.4	75.2	546.5	479.6	381.1	145.8	113.0	1296.7	1586.2
Fuel Mass (Dry kg)	111.9	116.5	58.8	162.6	170.9	119.1	116.8	139.6	151.6	177.6
Burn Rate (kg (Dry)/hr)	1.2	1.2	1.4	1.0	1.0	0.9	0.8	0.9	0.9	1.1
Emission Factor (g/kg (Dry))	7.8	8.7	4.8	5.7	5.1	5.5	3.7	1.9	17.5	14.2
Emission Rate (g/hr)	9.5	10.8	6.5	5.5	5.3	4.9	3.0	1.7	15.8	15.1
Concentration (mg/m^3)	395	466	221	362	326	317	123	85	926	1,139

[a] There are no data for week A for KF03 and week C for KF04 due to loss of sample and/or laboratory data.

Table 3-4

Individual Test Results for Klamath Falls Stoves KF05 – KF08

Home Code	KF05			KF06	KF07			KF08		
Stove Model	Pacific Energy Super 27 Non-Catalytic			Waterford 104.MKII Non-Catalytic	Earthstove 1400HT Non-Catalytic			Country T-Top Non-Catalytic		
Week	A	B	C	A[a]	A	B	C	A	B	C
Start Date	11/08/98	11/22/98	12/08/98	11/10/98	11/08/98	11/22/98	12/06/98	11/08/98	11/22/98	12/05/98
End Date	11/15/98	11/25/98	12/15/98	11/17/98	11/16/98	11/29/98	12/13/98	11/15/98	11/30/98	12/13/98
Total Data Collection Hours	168.0	78.5	168.0	168.0	168.3	168.0	168.0	168.0	172.8	171.0
% Time Stove Burned	89.7	96.2	91.1	100.0	99.7	95.4	98.7	100.0	98.3	99.7
Avg. Stack Temp. (°F)	446	404	470	431	424	457	484	384	428	446
Avg. %O_2 (Flue >100 °F)	16.28	16.73	15.71	16.00	16.72	16.83	15.64	16.47	17.48	16.08
Fuel Mass (Wet kg)	137.7	70.7	172.2	126.0	158.5	133.7	225.4	238.4	237.1	257.7
Fuel Moisture (% Dry Basis)	10.4	9.8	11.3	11.7	12.6	11.7	15.8	26.8	25.4	25.7
AWES Flow Rate (l/min)	1.069	1.069	1.069	1.145	1.109	1.109	1.109	1.058	1.058	1.058
Sample Time (min)/Cycle (min)	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15
Indoor Ambient Temp. (°F)	75	74	63	77	75	70	74	79	75	74
Outdoor Ambient Temp. (˚F)	33	40	28	35	33	38	23	33	38	21

(Continued)

Table 3-4 (continued)

Individual Test Results for Klamath Falls Stoves KF05 – KF08

Home Code	**KF05**			**KF06**	**KF07**			**KF08**		
Stove Model	**Pacific Energy Super 27 Non-Catalytic**			**Waterford 104.MKII Non-Catalytic**	**Earthstove 1400HT Non-Catalytic**			**Country T-Top Non-Catalytic**		
Week	**A**	**B**	**C**	**A[a]**	**A**	**B**	**C**	**A**	**B**	**C**
Rinse Particulate (g)	147.4	128.1	74.0	214.0	265.6	202.2	313.1	313.5	236.4	212.0
XAD-2® Particulate (g)	92.4	24.6	49.6	83.1	123.0	103.7	93.1	95.3	26.2	65.5
Filter Particulate (g)	69.0	41.3	68.7	157.6	233.3	154.0	232.5	153.2	342.0	89.0
Total Particulate (g) (Blank Subtracted)	308.8	194.0	192.3	454.6	621.9	459.9	638.7	561.9	604.5	366.5
Fuel Mass (Dry kg)	124.7	64.4	154.7	112.8	140.8	119.7	194.7	188.0	189.0	205.0
Burn Rate (kg (Dry)/hr)	0.8	0.9	1.0	0.7	0.8	0.7	1.2	1.1	1.1	1.2
Emission Factor (g/kg (Dry))	5.2	7.2	2.8	6.0	9.9	7.9	8.2	8.9	12.3	5.2
Emission Rate (g/hr)	4.3	6.1	2.8	4.0	8.3	5.9	9.7	9.9	13.6	6.3
Concentration (mg/m^3)	240	300	147	295	418	324	434	395	421	254

[a] There are no data for weeks B and C for KF06 due to death in the family.

Table 3-5

Individual Test Results for Portland Stoves P01 – P04

Home Code	P01			P02			P03			P04		
Stove Model	HES Trailblazer 2000-C Catalytic			LOPI Answer Series Non-Catalytic			LOPI 380-96 Non-Catalytic			LOPI Flushbay-96 Catalytic		
Week	A	B	C	A	B	C	A	B	C	A	B	C
Start Date	01/11/99	01/19/99	01/26/99	01/13/99	01/20/99	01/27/99	01/12/99	01/19/99	01/26/99	01/13/99	01/20/99	01/27/99
End Date	01/19/99	01/26/99	02/02/99	01/20/99	01/27/99	02/03/99	01/19/99	01/26/99	02/02/99	01/20/99	01/27/99	02/03/99
Total Data Collection Hours	171.3	168.3	168.0	168.0	166.8	168.0	168.8	168.8	168.0	168.3	168.0	168.0
% Time Stove Burned	100.0	100.0	100.0	54.9	68.8	65.2	20.1	35.1	40.9	56.6	69.6	69.5
Avg. Stack Temp. (°F)	413	443	457	311	339	324	356	370	367	285	327	279
Avg. %O_2 (Flue >100 °F)	14.66	14.44	13.90	18.13	16.50	17.00	17.65	17.89	17.76	17.16	16.70	17.62
Fuel Mass (Wet kg)	260.2	252.9	258.9	117.6	103.3	99.9	32.5	72.8	85.4	83.6	130.0	91.1
Fuel Moisture (% Dry Basis)	24.0	21.0	22.8	101.2	18.5	26.7	18.3	18.3	23.3	18.3	18.5	18.4
AWES Flow Rate (l/min)	1.058	1.058	1.058	1.124	1.124	1.124	1.069	1.069	1.069	1.145	1.145	1.145
Sample Time (min)/Cycle (min)	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15
Indoor Ambient Temp. (°F)	80	71	72	76	78	71	80	74	74	77	75	75
Outdoor Ambient Temp. (˚F)	47	42	45	48	41	45	48	42	45	48	41	45

(Continued)

Table 3-5 (continued)

Individual Test Results for Portland Stoves P01 – P04

Home Code	P01			P02			P03			P04		
Stove Model	HES Trailblazer 2000-C Catalytic			LOPI Answer Series Non-Catalytic			LOPI 380-96 Non-Catalytic			LOPI Flushbay-96 Catalytic		
Week	A	B	C	A	B	C	A	B	C	A	B	C
Rinse Particulate (g)	428.5	376.7	682.1	201.4	272.5	271.8	49.0	81.0	85.9	97.4	118.2	133.7
XAD-2® Particulate (g)	262.2	260.2	230.9	75.3	232.4	96.1	11.9	14.6	23.2	34.5	39.3	27.4
Filter Particulate (g)	625.3	506.5	385.5	182.2	335.2	199.9	(5.0)	13.5	1.3	47.9	71.2	50.7
Total Particulate (g) (Blank Subtracted)	1,316.0	1,143.4	1,298.5	458.9	840.1	567.8	55.8	109.1	110.4	179.8	228.7	211.8
Fuel Mass (Dry kg)	209.8	209.0	210.9	58.5	87.2	78.9	27.5	61.5	69.2	70.7	109.7	77.0
Burn Rate (kg (Dry)/hr)	1.2	1.2	1.3	0.6	0.8	0.7	0.8	1.0	1.0	0.7	0.9	0.7
Emission Factor (g/kg (Dry))	15.0	12.9	13.5	19.4	17.5	14.3	5.9	7.1	5.8	5.4	5.0	5.9
Emission Rate (g/hr)	18.4	16.0	16.9	12.3	13.3	10.3	4.7	7.4	5.8	4.0	4.7	3.9
Concentration (mg/m^3)	908	803	913	553	814	577	192	215	188	206	213	198

Table 3-6

Individual Test Results for Portland Stoves P05 – P08

Home Code	P05			P06			P07			P08[a]	
Stove Model	LOPI Flex-95 Catalytic			Pacific Energy Super 27 Non-Catalytic			LOPI 520/96 Non-Catalytic			Vermont Castings Defiant Encore Catalytic	
Week	A	B	C	A	B	C	A	B	C	A	B
Start Date	01/14/99	01/22/99	01/30/99	01/23/99	01/30/99	02/07/99	01/20/99	01/27/99	02/03/99	01/22/99	01/29/99
End Date	01/21/99	01/29/99	02/06/99	01/30/99	02/06/99	02/14/99	01/27/99	02/03/99	02/10/99	01/29/99	02/05/99
Total Data Collection Hours	167.3	168.0	168.0	168.0	168.0	166.8	168.0	168.0	168.0	133.3	97.8
% Time Stove Burned	12.0	19.9	20.1	82.7	84.5	91.6	100.0	100.0	100.0	98.3	38.4
Avg. Stack Temp. (°F)	334	403	372	475	464	485	348	327	342	343	383
Avg. %O_2 (Flue >100 °F)	18.50	18.12	18.32	15.52	15.55	14.07	15.14	15.14	14.13	16.93	16.72
Fuel Mass (Wet kg)	48.6	32.7	38.1	412.5	373.1	351.7	487.2	517.4	406.1	211.8	76.2
Fuel Moisture (% Dry Basis)	19.3	19.0	19.0	100.8	105.0	101.2	101.2	105.0	24.8	24.8	25.0
AWES Flow Rate (l/min)	1.038	1.038	1.038	1.042	1.042	1.042	1.109	1.109	1.109	1.078	1.078
Sample Time (min)/Cycle (min)	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15	2/15
Indoor Ambient Temp. (°F)	73	72	70	71	69	72	69	69	71	71	74
Outdoor Ambient Temp. (˚F)	48	42	44	42	44	41	41	45	41	42	44

(Continued)

Table 3-6 (continued)

Individual Test Results for Portland Stoves P05 – P08

Home Code	P05			P06			P07			P08[a]	
Stove	**LOPI Flex-95 Catalytic**			**Pacific Energy Super 27 Non-Catalytic**			**LOPI 520/96 Non-Catalytic**			**Vermont Castings Defiant Encore Catalytic**	
Week	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**
Rinse Particulate (g)	37.6	51.8	19.2	233.0	284.5	313.0	334.2	407.6	503.1	370.8	105.0
XAD-2® Particulate (g)	6.0	3.9	6.4	69.2	355.7	109.3	326.3	313.1	367.9	182.7	33.9
Filter Particulate (g)	-15.5	-5.7	6.4	286.2	322.6	362.8	974.1	916.5	1238.7	252.9	73.4
Total Particulate (g) (Blank Subtracted)	28.1	50.0	32.0	588.3	962.8	785.1	1634.6	1637.2	2109.7	806.4	212.3
Fuel Mass (Dry kg)	40.7	27.5	32.0	205.4	182.0	174.9	242.2	252.4	325.4	169.8	61.0
Burn Rate (kg (Dry)/hr)	2.0	0.8	0.9	1.5	1.3	1.1	1.4	1.5	1.9	1.3	1.6
Emission Factor (g/kg (Dry))	7.0	6.4	4.4	9.1	14.7	8.7	18.4	18.5	20.8	17.7	15.5
Emission Rate (g/hr)	14.3	5.3	4.2	13.5	18.9	10.0	26.6	27.7	40.3	23.0	25.2
Concentration (mg/m^3)	169	180	114	508	813	616	1,097	1,099	1,416	714	657

[a] There are no data for week C for P08 due to loss of sample data.

Table 3-7

Average Fuel Moisture, Particulate Emissions, Burn Rate, and Outdoor Temperature for Stoves in Klamath Falls

Home Code	Number of Runs	Fuel Moisture % (Dry Basis)	Average			
			Burn Rate kg (Dry)/hr	Emission Factor g/kg (Dry)	Emission Rate g/hr	Outdoor[b] Temperature ˚F
KF01	3	25.37 ± 4.61	1.27 ± 0.09	7.10 ± 1.67	8.93 ± 1.80	28 ± 4 n=22
KF02	3	20.63 ± 0.78	0.97 ± 0.05	5.43 ± 0.25	5.23 ± 0.25	28 ± 7 n=24
KF03	2	16.55	0.85	2.80	2.35	31 ± 5 n=16
KF04[a]	2	20.55	1.00	15.85	15.45	30 ± 7 n=16
KF05	3	10.55 ± 0.62	0.90 ± 0.08	5.07 ± 1.80	4.40 ± 1.35	34 ± 4 n=20
KF06	1	11.70	0.70	6.00	4.00	35 ± 5 n=8
KF07	3	13.37 ± 1.76	0.90 ± 0.22	8.67 ± 0.88	7.97 ± 1.57	31 ± 5 n=25
KF08	3	25.97 ± 0.60	1.13 ± 0.05	8.80 ± 2.90	9.93 ± 2.98	31 ± 4 n=24
All Stoves	20	18.68 ± 6.09	1.00 ± 0.19	7.43 ± 3.73	7.45 ± 3.94	31 ± 2 n=155
Catalytic Stoves	2	20.55	1.0	15.9	15.5	30 ± 3 n=16
Non-Catalytic Stoves	18	18.47 ± 6.38	0.99 ± 0.19	6.49 ± 2.53	6.56 ± 3.06	31 ± 2 n=139

[a] Catalytic Stove

[b] The outdoor temperature is the average of the high and low for each day over the sample period.
The value "n" is the number of days averaged over the sample period.
Values are followed by "± Standard Deviation".

Table 3-8

Average Fuel Moisture, Particulate Emissions, Burn Rate, and Outdoor Temperature for Stoves in Portland

Home Code	Number of Runs	Fuel Moisture % (Dry Basis)	Average			
			Burn Rate kg (Dry)/hr	Emission Factor g/kg (Dry)	Emission Rate g/hr	Outdoor[b] Temperature ˚F
P01[a]	3	22.60 ± 1.23	1.23 ± 0.05	13.80 ± 0.88	17.10 ± 0.99	45 ± 4 n=25
P02	3	48.80 ± 37.20	0.70 ± 0.08	17.07 ± 2.10	11.97 ± 1.25	45 ± 4 n=24
P03	3	19.97 ± 2.36	0.93 ± 0.09	6.27 ± 0.59	5.97 ± 1.11	45 ± 4 n=24
P04[a]	3	18.40 ± 0.08	0.77± 0.09	5.43 ± 0.37	4.20 ± 0.36	45 ± 4 n=24
P05[a]	3	19.10 ± 0.14	1.23 ± 0.54	5.93 ± 1.11	7.93 ± 4.52	44 ± 4 n=24
P06	3	102.33 ± 1.89	1.30 ± 0.16	10.83 ± 2.74	14.13 ± 3.66	42 ± 3 n=24
P07	3	77.00 ± 36.94	1.60 ± 0.22	19.23 ± 1.11	31.53 ± 6.22	43 ± 3 n=24
P08[a]	2	24.90	1.45	16.60	24.10	43 ± 4 n=16
All Stoves	23	42.37 ± 35.77	1.14 ± 0.38	11.69 ±5.42	14.20 ± 9.30	44 ± 1 n=185
Catalytic Stoves	11	20.92 ± 2.59	1.15 ± 0.38	9.88 ± 4.78	12.35 ± 7.80	44 ± 1 n=89
Non-Catalytic Stoves	12	62.03 ± 40.47	1.13 ± 0.37	13.35 ± 5.44	15.90 ± 10.20	44 ± 1 n=96

[a] Catalytic Stove

[b] The outdoor temperature is the average of the high and low for each day over the sample period.
The value "n" is the number of days averaged over the sample period.
Values are followed by "± Standard Deviation".

in Table 3-9. One significant result of this study is the difference in average emissions between stoves tested in Portland and Klamath Falls. On the average, emission factors and emission rates for stoves in Portland (11.69 g/kg and 14.20 g/hr, respectively) were considerably higher than for stoves in Klamath Falls (7.43 g/kg and 7.45 g/hr, respectively). This observation is consistent with the fact that the moisture was more than two times higher, on the average, for wood burned in Portland than for wood burned in Klamath Falls. In addition, the differences are consistent with the fact that the burn rates for woodstoves in Portland were, on the average, slightly higher than for woodstoves in Klamath Falls. The increased burn rate would tend to make the differences between emission rates relatively higher than emission factors for the two cities as seen in the values of the two cities. (Higher burn rates tend to decrease emission factors but increase emission rates.)

A comparison of average particulate emission factors for study stoves with U.S. EPA emission factor values tabulated in AP-42 (14) is provided in Table 3-10. A key finding of this study is illustrated in the table. The average emission factors for the old catalytic and non-catalytic stoves (12.23 g/kg and 10.30 g/kg) evaluated in this study were higher than the respective emission factors (8.1 g/kg and 7.3 g/kg) for newer units of both types listed in AP-42, but were lower than the emission factor listed in AP-42 for conventional uncertified stoves (15.3 g/kg). In other words, particulate emissions of the certified stoves evaluated in this study appear to have become higher with use, but after about seven years they still on the average have lower emissions than uncertified conventional stoves.

A comparison of current and past emission factors for the two stoves in Klamath Falls that were part of earlier studies is provided in Table 3-11. Fuel type, fuel moisture, burn rates and the number of week-long tests used to calculate the mean emission factors for current and past studies are also included in the table for comparison purposes. As can be seen, the emission performance of the stove in home KF02 degraded with time. The emission performance of the stove in home KF03 in the current study remained about the same as reported in the 1991/1992 heating season study. However, the emission factor for the same stove in the 1989/1990 heating season study was higher than for either of the two later studies. The higher emission factor in the 1989/1990 study cannot be readily explained. However, it is probably simply a reflection of the variability often seen in woodstove emissions when different fuels are burned and different burning patterns are used.

A comparison between average emission rates based on multiple week-long tests for each stove and the U.S. EPA certification value for each model is provided in Table 3-12. Another key finding of this study is that there is no correlation between actual emission rates of older stoves and their original certification value, that is, emission rates reported in the certification process do not represent emission levels of stoves in homes after extended use.

Table 3-9

Summary of Particulate Emission Results

		Average				
	Stove Group	**Fuel Moisture[a] % (Dry Basis)**	**Burn Rate kg (Dry)/hr**	**Emission Factor g/kg (Dry)**	**Emission Rate g/hr**	**Outdoor Temperature ˚F**
Klamath Falls	**All Stoves (8 Stoves, 20 Runs)**	18.68 ± 6.09	1.00 ± 0.19	7.43 ± 3.73	7.45 ± 3.94	31 ± 2 n=155
	Catalytic Stoves (1 Stove, 2 Runs)	20.55	1.0	15.9	15.5	30 ± 3 n=16
	Non-Catalytic Stoves (7 Stoves, 18 Runs)	18.47 ± 6.38	0.99 ± 0.19	6.49 ± 2.53	6.56 ± 3.06	31 ± 2 n=139
Portland	**All Stoves (8 Stoves, 23 Runs)**	42.37 ± 35.77	1.14 ± 0.38	11.69 ±5.42	14.20 ± 9.30	44 ± 1 n=185
	Catalytic Stoves (4 Stoves, 11 Runs)	20.92 ± 2.59	1.15 ± 0.38	9.88 ± 4.78	12.35 ± 7.80	44 ± 1 n=89
	Non-Catalytic Stoves (4 Stoves, 12 Runs)	62.03 ± 40.47	1.13 ± 0.37	13.35 ± 5.44	15.90 ± 10.20	44 ± 1 n=96
Overall Study	**All Stoves (16 Stoves, 43 Runs)**	31.35 ± 29.00	1.07 ± 0.31	9.71 ± 5.17	11.06 ± 8.05	37 ± 8 n=340
	Catalytic Stoves (5 Stoves, 13 Runs)	20.86 ± 2.42	1.12 ± 0.36	10.80± 4.94	12.83 ± 7.26	41 ± 6 n=105
	Non-Catalytic Stoves (11 Stoves, 30 Runs)	35.89 ± 33.69	1.05 ± 0.29	9.23 ± 5.20	10.30 ± 8.26	36 ± 8 n=235

[a] Values are followed by "± Standard Deviation".

Table 3-10

Comparison of Average Particulate Emission Factors (5H Adjusted) to AP-42 Values

	Stove Group	Measurement Technique	Method 5H Equivalent Emission Factor[a] g/kg (Dry)
Study	**All Stoves (16 Stoves, 43 Runs)**	AWES Sampler	11.06
	Catalytic Stoves (5 Stoves, 13 Runs)	AWES Sampler	12.83
	Non-Catalytic Stoves 11 Stoves, 30 Runs)	AWES Sampler	10.30
AP-42	**Catalytic**	AWES and VPI Sampler[b]	8.1
	Non-Catalytic	AWES and VPI Sampler[b]	7.3
	Conventional	AWES and VPI Sampler[b]	15.3

[a] Reference 14.

[b] The VPI sampler is a sampling train consisting of:
a condensate trap, dual filter pack, DrieRite dessicant trap, and evacuated canister developed by Jaasma, et al., at the Virgina Polytechnic Institute and State University.

Table 3-11

Comparison of Particulate Emission Factors of Stoves in Current Study to Particulate Emission Factors for the Same Stoves from Previous Studies

Home Code/ Stove Model	Study	Heating Season	Fuel	Fuel Moisture % (Dry Basis)[d]	Burn Rate kg (Dry)/hr	Emission Factor g/kg (Dry)
KF02 Pacific Energy Super 27 Non-Catalytic	Current	1998/1999	Ponderosa	20.63 ± 0.78	0.97 ± 0.05	5.43 ± 0.25 (n=3)
	EMRC[a]	1989/1990	Red Fir	16.9 ± 0.63	1.21 ± 0.24	2.78 ± 0.10 (n=4)
KF03 Haughs 171E Non-Catalytic	Current	1998/1999	95% Lodgepole 5% Juniper	16.55	0.85	2.80 (n=2)
	BPA[b]	1991/1992	Douglas Fir Lodgepole	13.9	1.15	2.77 (n=1)
	WHA[c]	1989/1990	Juniper	16.3	0.88	7.0 (n=2)

[a] Reference 13.

[b] Reference 8.

[c] Reference 12.

[d] Values are followed by "± Standard Deviation".

Table 3-12

Comparison of Stove Particulate Emission Rates to U.S. EPA Certification Values[a]

Home Code	Stove Model	Catalytic	Number of Runs	Emission Rate (g/hr)	
				Study Average[d]	Certification Value
KF01	Quadrafire 2100	No	3	8.93 ± 1.80	3.6
KF02	Pacific Energy Super 27	No	3	5.23 ± 0.25	3.4
KF03	Haughs 171E	No	2	2.35	4.5
KF04	Earthstove 1003-C	Yes	2	15.45	3.7
KF05	Pacific Energy Super 27	No	3	4.40 ± 1.35	3.4
KF06	Waterford 104.MKII	No	1	4.00	2.9
KF07	Earthstove 1400HT	No	3	7.97 ± 1.57	6.6
KF08	Country T-Top	No	3	9.93 ± 2.98	5.7
P01	HES Trailblazer 2000-C	Yes	3	17.10 ± 0.99	3.1
P02	LOPI Answer Series	No	3	11.97 ± 1.25	3.3
P03	LOPI 380-96	No	3	5.97 ± 1.11	1.9
P04	LOPE Flushbay-96[b]	Yes	3	4.20 ± 0.36	5.2
P05	LOPI Flex-95	Yes	3	7.93 ± 4.52	4.1
P06	Pacific Energy Super 27	No	3	14.13 ± 3.66	3.4
P07	LOPI 520/96	No	3	31.53 ± 6.22	7.4
P08	Vermont Castings Defiant Encore[c]	Yes	2	24.10	1.6

[a] The certification threshold for phase 2 certified catalytic stoves is 4.1 g/hr and for non-catalytic stoves is 7.5 g/hr.

[b] Lopi Flush Bay-96 is now called Freedom. The certification value shown in the table is for the Freedom.

[c] The Vermont Castings Defiant Encore stove was installed when stove was EPA Phase I certified. Since the installation, the stove has been added to EPA Phase II certification list without changes to the stove's design.

[d] Values are followed by "± Standard Deviation".

3.3 Polycyclic Organic Matter Emissions

The analytical results for 40 individual organic compounds and compound categories are provided in Appendix D. The average emission factors and rates for these compounds and compound categories by stove type (catalytic, non-catalytic and both combined) for Klamath Falls stoves, for Portland stoves and for the overall study are provided in Tables 3-13, 3-14, and 3-15, respectively. Among the 40 compounds and compound categories are the seven and 16 polycyclic aromatic hydrocarbons (PAH) that make up the 7-PAH and 16-PAH POM surrogates. The seven and 16 PAH compounds' emissions are summed and their total emissions used as surrogates of POM. The average emission factors and rates for these two surrogates are included in Tables 3-13, 3-14 and 3-15.

A key finding of this study is that total particulate emissions cannot be used as a surrogate measurement for woodstove POM emissions. In comparing the average 7-PAH and 16-PAH values between Klamath Falls and Portland shown in Tables 3-13 and 3-14, it is clear that the POM emissions, as indicated by the surrogates, were higher for the Klamath Falls stoves than for the Portland stoves even though the particulate emissions were higher for the Portland stoves. This finding is significant because it has been suggested that total particulate emissions can be used as a surrogate measurement for POM emissions and for the New Source Performance Standards (NSPS) for wood heaters[4] it is noted that the same control techniques used to reduce particulate emission are known to reduce POM emissions. A possible explanation of the lack of correlation between particulate and POM emissions is that conifer cordwood was burned exclusively in Klamath Falls whereas a mixture of conifer and deciduous cordwood was burned in Portland. Cordwood from conifers has a higher resin content than cordwood from deciduous trees. Resin is chemically comprised of condensed aromatic rings, hence it is closer in structure to POM compounds then cellulose or lignin. It is generally believed that, if all else is equal, the higher the aromatic compound content in a fuel the more POM emissions will be produced upon its combustion. In any event, this study finds that total particulate emissions cannot be used as a surrogate for POM emissions in woodstoves although control techniques for PM may, in fact, reduce POM.

A comparison of overall average emission factors measured in this study for the 7-PAH and 16-PAH surrogates emitted from catalytic and non-catalytic stoves with the 7-PAH and 16-PAH emission factors listed for them in AP-42 (14) is provided in Table 3-16. The 7-PAH and 16-PAH data for catalytic and non-catalytic stoves in AP-42 are based on laboratory (not inhome) tests with a limited number of stoves. The AP-42 7-PAH and 16-PAH values for catalytic stoves are based on laboratory tests on seven stoves of which only one became a phase 2 certified model. The AP-42 values for non-catalytic stoves are based on laboratory tests on five stoves none of which became phase 2 certified. (The AP-42 7-PAH and 16-PAH values for conventional stoves, shown in Table 3-16 for completeness, were based on laboratory tests on one stove [40].) Residential wood combustion has been identified, based on the AP-42 emission factors, as the single, largest source of POM nationwide (2). As can be seen in Table 3-16, the

Table 3-13

Organic Compound Emission Factors and Rates For Stoves in Klamath Falls Homes

	All Stoves Average Emission Rate 8 Stoves 20 Runs µg/hr	All Stoves Average Emission Factor 8 Stoves 20 Runs µg/kg (Dry)	Non-Catalytic Average Emission Rate 7 Stoves 18 Runs µg/hr	Non-Catalytic Average Emission Factor 7 Stoves 18 Runs µg/kg (Dry)	Catalytic Average Emission Rate 1 Stove 2 Runs µg/hr	Catalytic Average Emission Factor 1 Stove 2 Runs µg/kg (Dry)
Toluene	159,922	158,134	146,381	144,568	281,792	280,228
m,p-Xylene	28,460	28,394	23,284	23,134	75,044	75,735
o-Xylene	9,702	9,613	7,761	7,680	27,175	27,014
Phenol	170,260	168,964	160,703	158,889	256,278	259,643
Benzofuran	37,900	37,708	34,891	34,597	64,987	65,710
C3-alkylbenzenes	42,070	41,994	33,527	33,537	118,957	118,102
Decane	164	120	182	134	0	0
o-Cresol	45,957	46,396	36,579	36,852	130,353	132,295
m,p-Cresol	80,541	81,517	68,023	68,792	193,204	196,043
C4-alkylbenzenes	161,273	156,220	121,448	116,622	519,699	512,599
Undecane	0	0	0	0	0	0
2-Ethylphenol	2,987	3,017	2,545	2,558	6,967	7,155
2,3-Dimethylphenol	4,970	5,039	4,271	4,306	11,267	11,628
Naphthalene †	81,892	80,967	81,767	80,769	83,021	82,750
2-Methylnaphthalene	13,813	13,763	11,540	11,523	34,266	33,918
1-Methylnaphthalene	10,739	10,722	9,703	9,691	20,066	20,001
Biphenyl	6,292	6,259	5,757	5,720	11,104	11,110
Tetradecane	13,441	13,403	12,070	12,030	25,775	25,760
C2-alkylnaphthalenes	11,825	11,819	9,417	9,449	33,498	33,152
Acenaphthylene †	21,069	21,160	20,895	21,028	22,634	22,347
Pentadecane	0	0	0	0	0	0
Acenaphthene †	1,216	1,219	1,022	1,027	2,969	2,944
Dibenzofuran	9,535	9,521	8,626	8,602	17,710	17,793
C3-alkylnaphthalenes	6,153	6,334	6,836	7,038	0	0
Fluorene †	6,011	6,049	5,703	5,755	8,778	8,695
Heptadecane	0	0	0	0	0	0
Octadecane	0	0	0	0	0	0

(Continued)

Table 3-13

(Continued)

	All Stoves Average Emission Rate 8 Stoves 20 Runs µg/hr	All Stoves Average Emission Factor 8 Stoves 20 Runs µg/kg (Dry)	Non-Catalytic Average Emission Rate 7 Stoves 18 Runs µg/hr	Non-Catalytic Average Emission Factor 7 Stoves 18 Runs µg/kg (Dry)	Catalytic Average Emission Rate 1 Stove 2 Runs µg/hr	Catalytic Average Emission Factor 1 Stove 2 Runs µg/kg (Dry)
Phenanthrene †	26,201	26,466	26,086	26,413	27,227	26,940
Anthracene †	4,648	4,744	4,532	4,649	5,692	5,595
Carbazole	0	0	0	0	0	0
Fluoranthene †	9,185	9,339	9,357	9,533	7,643	7,588
Pyrene †	6,482	6,608	6,534	6,675	6,015	6,006
Benzo(a)anthracene*†	1,592	1,624	1,685	1,723	753	736
Chrysene*†	1,739	1,783	1,832	1,884	897	877
Benzo(b)fluoranthene*†	977	1,028	974	1,030	1,004	1,013
Benzo(k)fluoranthene*†	142	153	141	154	152	143
Benzo(a)pyrene*†	432	460	440	474	361	340
Indeno(1,2,3-cd)pyrene*†	0	0	0	0	0	0
Dibenzo(a,h)anthracene*†	0	0	0	0	0	0
Benzo(g,h,i)perylene †	0	0	0	0	0	0
7-PAH	4,882	5,049	5,073	5,264	3,168	3,109
16-PAH	161,587	161,600	160,969	161,115	167,148	165,973

* 7-PAH
† 16-PAH

Table 3-14

Organic Compound Emission Factors and Rates for Stoves in Portland Homes

	All Stoves Average Emission Rate 8 Stoves 23 Runs µg/hr	All Stoves Average Emission Factor 8 Stoves 23 Runs µg/kg (Dry)	Non-Catalytic Average Emission Rate 4 Stoves 12 Runs µg/hr	Non-Catalytic Average Emission Factor 4 Stoves 12 Runs µg/kg (Dry)	Catalytic Average Emission Rate 4 Stoves 11 Runs µg/hr	Catalytic Average Emission Factor 4 Stoves 11 Runs µg/kg (Dry)
Toluene	161,197	129,649	153,252	130,978	169,864	128,199
m,p-Xylene	43,433	33,818	42,412	34,146	44,547	33,460
o-Xylene	15,008	11,813	14,463	11,933	15,602	11,681
Phenol	288,925	228,837	246,889	209,798	334,783	249,607
Benzofuran	58,355	46,327	55,553	46,037	61,413	46,644
C3-alkylbenzenes	36,454	26,559	42,873	34,265	29,452	18,152
Decane	0	0	0	0	0	0
o-Cresol	100,976	79,142	93,721	77,008	108,890	81,469
m,p-Cresol	148,328	116,373	134,439	111,970	163,480	121,177
C4-alkylbenzenes	42,786	28,971	61,377	42,469	22,505	14,245
Undecane	0	0	0	0	0	0
2-Ethylphenol	5,948	4,575	6,515	5,298	5,329	3,786
2,3-Dimethylphenol	7,749	6,068	7,969	6,584	7,509	5,504
Naphthalene †	92,300	76,911	83,124	75,044	102,310	78,947
2-Methylnaphthalene	16,167	12,566	17,788	14,619	14,398	10,327
1-Methylnaphthalene	10,446	8,625	10,770	9,322	10,092	7,865
Biphenyl	7,340	6,043	7,332	6,408	7,349	5,646
Tetradecane	14,066	11,449	12,659	11,057	15,602	11,875
C2-alkylnaphthalenes	7,225	5,433	8,793	7,143	5,515	3,568
Acenaphthylene †	17,432	14,950	16,577	15,233	18,365	14,643
Pentadecane	0	0	0	0	0	0
Acenaphthene †	541	423	215	146	896	725
Dibenzofuran	11,553	9,348	11,317	9,775	11,810	8,882
C3-alkylnaphthalenes	2,333	1,545	1,854	1,358	2,855	1,748
Fluorene †	5,520	4,433	5,053	4,379	6,030	4,492
Heptadecane	0	0	0	0	0	0
Octadecane	0	0	0	0	0	0
Phenanthrene †	16,323	13,556	15,219	13,378	17,528	13,751

Table 3-14

(Continued)

	All Stoves Average Emission Rate 8 Stoves 23 Runs µg/hr	All Stoves Average Emission Factor 8 Stoves 23 Runs µg/kg (Dry)	Non-Catalytic Average Emission Rate 4 Stoves 12 Runs µg/hr	Non-Catalytic Average Emission Factor 4 Stoves 12 Runs µg/kg (Dry)	Catalytic Average Emission Rate 4 Stoves 11 Runs µg/hr	Catalytic Average Emission Factor 4 Stoves 11 Runs µg/kg (Dry)

(Continued)

Table 3-14

(Continued)

	All Stoves Average Emission Rate 8 Stoves 23 Runs µg/hr	All Stoves Average Emission Factor 8 Stoves 23 Runs µg/kg (Dry)	Non-Catalytic Average Emission Rate 4 Stoves 12 Runs µg/hr	Non-Catalytic Average Emission Factor 4 Stoves 12 Runs µg/kg (Dry)	Catalytic Average Emission Rate 4 Stoves 11 Runs µg/hr	Catalytic Average Emission Factor 4 Stoves 11 Runs µg/kg (Dry)
Anthracene †	3,201	2,563	2,903	2,494	3,526	2,639
Carbazole	0	0	0	0	0	0
Fluoranthene †	5,752	4,693	5,530	4,904	5,993	4,463
Pyrene †	5,230	4,321	5,159	4,602	5,307	4,015
Benzo(a)anthracene*†	599	480	553	438	648	525
Chrysene*†	659	520	606	465	717	580
Benzo(b)fluoranthene*†	839	677	999	805	665	536
Benzo(k)fluoranthene*†	166	136	168	138	165	133
Benzo(a)pyrene*†	384	335	395	367	373	300
Indeno(1,2,3-cd)pyrene*†	0	0	0	0	0	0
Dibenzo(a,h)anthracene*†	0	0	0	0	0	0
Benzo(g,h,i)perylene †	0	0	0	0	0	0
7-PAH	2,648	2,148	2,722	2,214	2,567	2,075
16-PAH	148,946	123,998	136,501	122,393	162,523	125,750

* 7-PAH
† 16-PAH

Table 3-15

Organic Compound Emission Factors and Rates for Overall Study

	All Stoves Average Emission Rate 16 Stoves 43 Runs µg/hr	All Stoves Average Emission Factor 16 Stoves 43 Runs µg/kg (Dry)	Non-Catalytic Average Emission Rate 11 Stoves 30 Runs µg/hr	Non-Catalytic Average Emission Factor 11 Stoves 30 Runs µg/kg (Dry)	Catalytic Average Emission Rate 5 Stoves 13 Runs µg/hr	Catalytic Average Emission Factor 5 Stoves 13 Runs µg/kg (Dry)
Toluene	160,559	143,891	149,816	137,773	225,828	204,213
m,p-Xylene	35,946	31,106	32,848	28,640	59,796	54,598
o-Xylene	12,355	10,713	11,112	9,807	21,389	19,347
Phenol	229,593	198,901	203,796	184,343	295,530	254,625
Benzofuran	48,128	42,018	45,222	40,317	63,200	56,177
C3-alkylbenzenes	39,262	34,276	38,200	33,901	74,205	68,127
Decane	82	60	91	67	0	0
o-Cresol	73,466	62,769	65,150	56,930	119,622	106,882
m,p-Cresol	114,435	98,945	101,231	90,381	178,342	158,610
C4-alkylbenzenes	102,030	92,595	91,413	79,545	271,102	263,422
Undecane	0	0	0	0	0	0
2-Ethylphenol	4,468	3,796	4,530	3,928	6,148	5,471
2,3-Dimethylphenol	6,360	5,553	6,120	5,445	9,388	8,566
Naphthalene †	87,096	78,939	82,445	77,907	92,666	80,849
2-Methylnaphthalene	14,990	13,165	14,664	13,071	24,332	22,123
1-Methylnaphthalene	10,593	9,673	10,237	9,506	15,079	13,933
Biphenyl	6,816	6,151	6,544	6,064	9,227	8,378
Tetradecane	13,754	12,426	12,364	11,544	20,689	18,818
C2-alkylnaphthalenes	9,525	8,626	9,105	8,296	19,507	18,360
Acenaphthylene †	19,251	18,055	18,736	18,130	20,500	18,495
Pentadecane	0	0	0	0	0	0
Acenaphthene †	879	821	618	587	1,933	1,834
Dibenzofuran	10,544	9,435	9,972	9,189	14,760	13,338
C3-alkylnaphthalenes	4,243	3,939	4,345	4,198	1,428	874
Fluorene †	5,766	5,241	5,378	5,067	7,404	6,594
Heptadecane	0	0	0	0	0	0
Octadecane	0	0	0	0	0	0
Phenanthrene †	21,262	20,011	20,653	19,895	22,378	20,345

Table 3-15

(Continued)

	All Stoves Average Emission Rate 16 Stoves 43 Runs µg/hr	All Stoves Average Emission Factor 16 Stoves 43 Runs µg/kg (Dry)	Non-Catalytic Average Emission Rate 11 Stoves 30 Runs µg/hr	Non-Catalytic Average Emission Factor 11 Stoves 30 Runs µg/kg (Dry)	Catalytic Average Emission Rate 5 Stoves 13 Runs µg/hr	Catalytic Average Emission Factor 5 Stoves 13 Runs µg/kg (Dry)

(Continued)

Table 3-15

(Continued)

	All Stoves Average Emission Rate 16 Stoves 43 Runs µg/hr	All Stoves Average Emission Factor 16 Stoves 43 Runs µg/kg (Dry)	Non-Catalytic Average Emission Rate 11 Stoves 30 Runs µg/hr	Non-Catalytic Average Emission Factor 11 Stoves 30 Runs µg/kg (Dry)	Catalytic Average Emission Rate 5 Stoves 13 Runs µg/hr	Catalytic Average Emission Factor 5 Stoves 13 Runs µg/kg (Dry)
Anthracene †	3,924	3,654	3,717	3,572	4,609	4,117
Carbazole	0	0	0	0	0	0
Fluoranthene †	7,468	7,016	7,443	7,218	6,818	6,025
Pyrene †	5,856	5,465	5,847	5,639	5,661	5,010
Benzo(a)anthracene*†	1,095	1,052	1,119	1,080	701	631
Chrysene*†	1,199	1,152	1,219	1,175	807	729
Benzo(b)fluoranthene*†	908	852	987	918	835	774
Benzo(k)fluoranthene*†	154	144	155	146	158	138
Benzo(a)pyrene*†	408	398	418	421	367	320
Indeno(1,2,3-cd)pyrene*†	0	0	0	0	0	0
Dibenzo(a,h)anthracene*†	0	0	0	0	0	0
Benzo(g,h,i)perylene †	0	0	0	0	0	0
7-PAH	3,765	3,598	3,897	3,739	2,868	2,592
16-PAH	155,267	142,799	148,735	141,754	164,835	145,861

* 7-PAH
† 16-PAH

Table 3-16

Comparison of POM Emission Factors for Stoves in Current Study to AP-42 POM Emission Factors

	Catalytic Stoves		**Non-Catalytic Stoves**		**Conventional Stoves**	
PAH Compound	**Current Study g/kg (Dry)**	**AP-42 g/kg (Dry)**	**Current Study g/kg (Dry)**	**AP-42 g/kg (Dry)**	**Current Study g/kg (Dry)**	**AP-42 g/kg (Dry)**
Acenaphthene	0.002	0.003	0.001	0.005	nd	0.005
Acenaphthylene	0.018	0.034	0.018	0.016	nd	0.106
Anthracene	0.004	0.004	0.004	0.004	nd	0.007
Benzo(a)anthracene*	0.001	0.012	0.001	<0.001	nd	0.010
Benzo(a)pyrene*	0.000	0.002	0.000	0.003	nd	0.002
Benzo(b)fluoranthene*	0.001	0.002	0.001	0.002	nd	0.003
Benzo(g,h,i)perylene	0.000	0.001	0.000	0.010	nd	0.002
Benzo(k)fluoranthene*	0.000	0.001	0.000	<0.001	nd	0.001
Chrysene*	0.001	0.005	0.001	0.005	nd	0.006
Dibenzo(a,h)anthracene*	0.000	0.001	0.000	0.002	nd	0.000
Fluoranthene	0.006	0.006	0.007	0.004	nd	0.010
Fluorene	0.007	0.007	0.005	0.007	nd	0.012
Indeno(1,2,3-cd)pyrene*	0.000	0.002	0.000	0.010	nd	0.000
Naphthalene	0.081	0.093	0.078	0.072	nd	0.144
Phenanthrene	0.020	0.024	0.020	0.059	nd	0.039
Pyrene	0.005	0.005	0.006	0.004	nd	0.012
7-PAH Total	0.003	0.025	0.003	0.024	nd	0.022
16-PAH Total	0.146	0.202	0.142	0.205	nd	0.359

nd – No Data

* 7-PAH Subset Compounds

average 7-PAH and 16-PAH emission factors for a total of 16 older phase 2 certified stoves tested for a total of approximately 43 weeks under actual in-home usage were lower than corresponding AP-42 values. This suggests that estimates of national emissions of 7-PAH and 16-PAH from woodstoves are too high and new emission factors for AP-42 should be developed.

Section 4.0

Conclusions

Out of the 16 stoves inspected all showed the effects of use. However, only six were degraded to the point that it was speculated that their condition would significantly affect air emissions. Routine maintenance or minor repairs could have kept all units in good operating condition if they had been done.

An extensive data base was developed from the 43 week-long test runs on 16 homes in the two cities of Klamath Falls and Portland. No direct statistical correlation between emissions and wood moisture, burn rate or stove condition could be made due to the number of variables associated with real-world in-home use of woodstoves.

The particulate emissions for stoves in Portland homes were on the average higher than for stoves in Klamath Falls homes. This result is consistent with the average higher fuel moisture content and burn rate characteristics of the Portland portion of the study as compared with the Klamath Falls portion of the study.

The particulate emission factors of the certified phase 2 stoves evaluated in this study appear to have become higher with use, but after about seven years, on the average, they still have lower emissions than uncertified conventional stoves.

The emission rates for phase 2 stove models reported as part of the NSPS certification process do not represent emission levels of the same stove models in-homes after extended use.

Particulate emissions can not be used as a surrogate measure of POM emissions for woodstoves. POM emission factors, as based on the 7-PAH and 16-PAH surrogates, determined from the in-home use of woodstoves in this study, were lower than the POM emission factors tabulated in AP-42**.**

Section 5.0

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Section 6.0

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