Conventional Heater Baseline Study
(Volume I)

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July 31, 2006

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1. Introduction

OMNI Environmental Services, Inc. (OMNI) was contracted by the Hearth, Patio & Barbecue Association (HPBA) to measure air emissions from five conventional cordwood heaters sold prior to the Environmental Protection Agency's (EPA's) certification requirement. Environment Canada (EC) provided sponsorship for the program. The primary objective of the project was to provide emission data that could be used to support emission reduction benefits associated with the replacement of older uncertified cordwood heaters with new technology heaters. To achieve this objective, the pre-EPA certification cordwood heaters used in the study were operated in normal fashion characteristic of in-home use. Additionally, to maximize the credibility of the data, standardized testing and analytical protocols were used.

The cordwood heaters used in this study represented key pre-EPA certification heater types which included examples of (1) cast iron and steel plate construction, (2) various firebox sizes, (3) thermostatically controlled units, (4) direct fire and under fire air designs and (5) freestanding and fireplace insert models. As hardwood, specifically, oak is the most common cordwood used nationwide, typically cut and split; seasoned oak cordwood was used in this study. Because burn rates and burn durations are highly variable and are in large part reflective of individual heater design, size, and efficiency, as well as, being subject to the heat demand for a given house in a given climate it is difficult to establish a single burn rate that would be applicable to all heaters. Consequently, rather than establishing and using single burn rate for all heaters, a "middle-range" burning target scenario was selected to allow all heaters to be operated in a fashion representative of typical normal in-home use. The target burning protocol consisted of filling the firebox nearly full of cordwood after the fire, started by the kindling and starter logs, was well established and then maintaining the fire with the air controls for a target of six hours. Even this approach required some modification among the different heater models to insure that the air emissions that were produced would be representative of a home occupant's typical "mid-range" use of each model.

Particulate, carbon monoxide, nitrogen oxides, benzene, formaldehyde, polycyclic aromatic hydrocarbons, phenol, methane, non-methane volatile organic compounds, organic carbon, elemental carbon, methanol, metals, and sulfur dioxide were measured. Emissions were reported as emission factors and emission rates. Wood heater efficiencies were also measured.

2. Heaters Description and Operation

2.1 Atlanta Homesteader

Type/Size: Freestanding, under draft circulator cabinet heater, medium (2.1 ft^3)(59 liters) firebox.

Construction: The unit is constructed primarily of mild gauge steel. The firebox is lined with firebrick. The firebox dimensions are: W 11 in x L 17.5 in x H 19.5 in (W 28 cm x L 45 cm x H 50 cm). There is an outer steel shell, with vents, enclosing the unit. The feed door and ash door have 7/8 in (2.2 cm) fiberglass rope gaskets.

Air Introduction System and Combustion Control Mechanisms: Combustion air enters the firebox through an opening located at the side of the heater and is controlled by metal door attached to a bimetallic coil thermostatic draft which is connected to a dial setting by a chain. The air goes through the ash box and circulates to the underside of the fire.

Internal Baffles: No internal baffles.

Other Features: Ash dumping grate with ash storage area.

Flue Outlet: The 6 in (15.4 cm) diameter flue outlet is located in the side of the unit.

Repairs: The unit had leaks at its seams, which were cemented closed. Missing firebricks and door gaskets were also replaced.

Operation During Testing:
The stove operated hot and showed little response to a low draft setting. The door of the air introduction system was kept at its lowest position after start up. A hinged piece of metal stopping the air inlet door limited the lowest setting possible for the heater. The air inlet was set to low, with the control dial, directly after start-up and left at that setting throughout the test.

2.2 Blaze King Princess

Type/Size: Freestanding, non-catalytic wood stove; medium (2.0 ft^3) (59.5 liters) firebox.

Construction: The unit is constructed primarily of mild steel. The firebox is lined with firebrick. The firebox dimensions are: W 16 in x L 13.5 in x H 15.75 in (W 40.6 cm x L 34.3 cm x H 40.0 cm). The feed door has 1.5 in (3.8 cm) braided fiberglass rope gasket.

Air Introduction System and Combustion Control Mechanisms: Combustion air enters the firebox through an opening located at the bottom/rear of the heater and is controlled by a door connected to a bimetallic coil thermostatic draft.

Internal Baffles: No flame baffle.

Flue Outlet: The 6 in (15.4 cm) diameter flue outlet is located in the top of the unit.

Repairs: A crack in rear of the firebox was welded closed. A missing brick retainer and missing firebricks were replaced. The door gasket was replaced and cemented with stove cement.

Operation During Testing:
The Blaze King had significant response to small adjustments to the thermostatic draft. The air inlet was fully open to start the fire. It was turned down to a medium setting after start up. It was then adjusted to a low setting after 30 minutes and maintained at that setting until the second fuel load. The "low" air inlet was set by closing the air inlet door with the thermostatic control dial, as much as possible. Due to the small firebox size two fuel loads were added to meet the six-hour burn target.

2.3 Jotul Elg Model No. 121

Type/Size: Freestanding, cast iron wood stove; medium (2.5 ft^3) (70.8 liters) firebox.

Construction: The unit is constructed primarily of cast iron. The unit has a separate cast iron firebox lining. The firebox dimensions are: W 11 in x L 25.5 in x H 15.25 in (W 27.9 cm x L 64.8 cm x H 38.7 cm). The feed door is cast iron with ¼ in (0.625 cm) braided rope gasket.

Air Introduction System and Combustion Control Mechanisms: Combustion air enters the firebox and is controlled by a manual draft, through an opening, located at the front of the heater in the middle of the fuel-loading door.

Internal Baffles: A refractory baffle is mounted in the upper portion of the firebox. The flame path is forced to the front of the firebox where it travels up through the opening between the baffle and primary air manifold.

Other Notes: The heater is called the Elg (Norwegian for moose), it is the larger version of model No. 118. The space heating capacity was listed as 7,500-13,000 cubic feet (212-368 cubic meters) in the manufacturer's literature.

Flue Outlet: The 6.9 in (7 in nominal) (17.5 cm) diameter flue outlet is located in the top of the unit.

Repairs: The door gasket was replaced and cemented with stove cement.

Operation During Testing:
The air inlet was fully open to start the fire. It was turned down to a medium setting after start up. It was then adjusted to a low setting after 30 minutes, for the duration of the test. The "low" air control was set with a ¼ inch (0.64 cm) open space on the air inlet control.

Acknowledgement:
The Jotul stove was loaned to OMNI for the test program by Mr. Robert "Buck" Froman of Buck's Stove Palace.

2.4 National Stove Crafters, Craft Insert

Type/Size: Fireplace insert; large (3.2 ft^3) (90.6 liters) firebox.

Construction: The unit is constructed primarily of heavy gauge steel. The firebox has a cement base. The firebox dimensions are: W 22 in x L 14.9 in x H 17.5 in (W 50.8 cm x L 37.8 cm x H 47.0 cm). The firebox in surrounded by an air circulation area. The feed doors are cast iron and have two ½ in (1.3 cm) flat braided fiberglass gaskets.

Air Introduction System and Combustion Control Mechanisms: Combustion air enters the firebox and is controlled by spin type manual drafts, through two openings, located at the front of the heater in the fuel-loading doors.

Other Features: Hot air convection system.

Flue Outlet: The flue outlet is 18 in (45.7 cm) in length and 3.5 in (8.9 cm) width, has a damper and is located on the top of the unit. There was no connecting union between the insert flue outlet and fireplace flue.

Repairs: Door gaskets were replaced and cemented with stove cement. The unit was flashed into fireplace with steel flashing. A fan set on low (100 ft^3/min) (2.8 m^3/min), with 4 in (10.2 cm) flex pipe, was mounted on the side of fireplace and attached to the heater.

Operation During Testing:
The insert was placed and flashed into a 48 in (121.9 cm) Heatilator fireplace with 10 in (20.5 cm) stack. The Craft air inlet was fully open to start the fire. It was then adjusted to a low setting after 30 minutes. The "low" air inlet was set by opening the spin controls 3/4 of a turn. The combustion air was increased slightly after 5 hours to use up the remaining fuel and achieve the target burn time. Internal chimney temperatures were lower than the other heaters as measured 1 foot (30.5 cm) above the heater due to the fireplace acting as a heat sink. There was also dilution air supplied to the flue outlet due to air being pulled in around the flashing. Flue temperatures are, therefore, not comparable to the other heaters. A zero scale weight (all fuel consumed) was used to define the fire duration end point instead of using a center of the chimney temperature of 200 ^oF (93.3 ºC) at 1 foot (30.5 cm) above the heater, as was done for the other heaters.

2.5 Schrader (unknown model)

Type/Size: Freestanding, wood stove, large (5.4 ft^3) (153 liters) firebox.

Construction: The unit is constructed primarily of steel. The firebox is lined with firebricks. The firebox dimensions are: W 19 in x L 22.5 in H x22 in (W 48.3 cm x L 57.2 cm x 55.9 cm). The doors are aluminum.

Air Introduction System and Combustion Control Mechanisms: Combustion air enters the firebox and is controlled by two manual spin drafts, located at the front of the heater on fuel-loading doors.

Internal Baffles: No flame baffle.

Flue Outlet: The 8 in (20.3 cm) diameter flue outlet is located on the top of the unit.

Repairs: The fuel loading doors did not seal well due to lack of gaskets and warping. In order to reduce the amount of air introduced, two ½ in (1.3 cm) flat braided fiberglass gaskets were added, and cemented with stove cement.

Operation During Testing:
Due to warped fuel loading doors, which did not completely seal even with new gasket material, combustion air was not well controlled by the spin drafts. The Schrader had the largest firebox of the five heaters and had the largest fuel load. The draft was wide open initially to start the fire. The spin drafts were then set at 1 turn from fully closed for 40 minutes and then lowered to ½ turn for the majority of the test. The air controls were opened slightly near the end of the test to increase burn rate and to achieve the target burn time.

3. Testing Program

3.1 General Overview of Testing Program

Air emissions from five uncertified conventional heaters burning locally purchased white oak cordwood were measured. The air emissions tests included measurements of: total particles (PM), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), non-methane volatile organic compounds (NMVOC), methane, polycyclic aromatic hydrocarbons (7-PAH and 16-PAH), phenol, benzene, methanol, formaldehyde, metals, organic carbon, and elemental carbon.

In addition to the emissions testing, the heaters were tested for efficiency. To calculate efficiency the tests included measurements of: indoor temperature in front of the heater, internal chimney temperature 8 feet (2.4 m) above the floor, the concentration of combustion gases (O_2, CO_2, CH_4, NMVOC) in the chimney, fuel weight and moisture, and combustion residue weight. Proximate/ultimate and heat analyses of the cordwood and combustion residue were also conducted to provide data for the efficiency calculations.

3.2 Testing Setup

All tests were performed at OMNI Environmental Service's testing facilities. Each heater, with its attached chimney, was placed on a scale. A 14 in (36 cm) diameter dilution tunnel was used to cool and dilute the heater emissions prior to sample collection. The heater chimney was located under the collection hood of the dilution tunnel and the entire exhaust stream was captured and mixed with room air and outdoor air. Dilution tunnels are used for source tests because they permit the sampling of air pollutants in a chemical and physical form similar to that which they will have once they exit the chimney and mix with ambient air. Photographs of the test setup can be found in Appendix A.

3.3 Test Burn Protocol

The burn protocol consisted of targeting a six-hour fire using seasoned oak cordwood with 20±5% moisture (dry basis). Practice burns were preformed to determine the mass of wood needed for a six-hour fire. The fire was started with four pieces of black and white newspaper, Douglas fir kindling and two small oak starter logs. Douglas fir was used as the kindling, as softwood is frequently used by home occupants as kindling due to it easier starting characteristics. Thirty minutes were allowed for the starter logs to adequately start. The oak cordwood was weighed and moisture was measured before adding it to the heater, nominally filling the firebox full. Each heater had a different firebox size, therefore the wood loads varied from heater to heater. Air controls and/or the addition of more wood were then used to achieve an approximate six-hour burn duration as defined in Section 3.4. The cordwood burning protocol can be found in Appendix B

3.4 Fire Duration

The calculation of emission rates requires fire duration to be defined by a reproducible metric because there are numerous potential ways to quantify it. There are two considerations relating to fire duration. First, the fire duration is needed to provide a measure of the time when combustion process is active and consequently air emissions are being produced. This number is divided into the total mass of pollutant captured by sampling or measured by monitoring to provide the emission rate, i.e., mass of pollutant per unit time. The second consideration is the length of time necessary for sampling or monitoring to continue to measure all emissions. We defined the end of the fire duration for a wood heater as the time when the temperature cooled to 200 ºF (93.3 ºC) as measured at the center of the chimney at 1 foot (30.5 cm) above the heater. At 200 ºF (93.3 ºC) as measured at that point, the majority of combustion process is complete and a home user would no longer consider the heater to be producing useful heat. In summary, the fire duration and sampling period used in this study were the same value. Both were defined as the time from when the kindling was lit to when the flue temperature at 1 foot (30 cm) above the heater dropped to 200 ºF (93.3 ºC).

4. Sampling and Analytical Methods

4.1 Air Emissions

Total particulate material, carbon monoxide, polycyclic aromatic hydrocarbons, phenol, formaldehyde, benzene, methane, non-methane volatile organic compounds, organic and elemental carbon, and methanol air emission samples were collected from a dilution tunnel. Carbon monoxide, sulfur dioxide and nitrogen oxides were collected from the chimney at 8 feet (2.4 m) above the floor. The testing was conducted at OMNI's EPA accredited wood heater testing laboratory (certified under 40 CFR Subpart AAA, Pt. 60). The samples were analyzed following standard sampling and analytical methods. Sample run numbers and labeling conventions can be found in Appendix C. Calculations of air emissions and test data summaries are in Appendix D. Temperatures and stack gas concentrations can be found in Appendix E.

Total Particulate Material samples were collected out of the dilution tunnel onto Pall Corporation type A/E glass filters and processed following the protocols specified for wood heaters (40 CFR Pt. 60, App. A, Method 5G). Outdoor ambient and laboratory room background particulate samples were collected during each test run using similar sampling rates as used for emission sampling. Appendix A contains photographs of the Method 5G front filters.

Metals were sampled with an EPA Method 29 sampling train. Samples were collected from the dilution tunnel. Laboratory analyses were conducted using procedures specified in Method 29. Appendix F contains the laboratory data.

Formaldehyde samples were collected from the dilution tunnel. Samples were collected and analyzed by EPA Method 0011/8315A. Appendix G contains the laboratory data.

Methane samples were collected in evacuated stainless steel canisters. Samples were collected from the dilution tunnel. Samples were analyzed by modified ASTM Method D-1946. which used a GC/FID. Laboratory data can be found in Appendix H.

Benzene samples were collected in evacuated stainless steel canisters. Samples were collected from the dilution tunnel. Samples were analyzed by modified method EPA TO-14A using GC/MS in the full-scale mode. The benzene data are provided in Appendix I.

Non-methane Volatile Organic Compounds (NMVOC) samples were collected in evacuated stainless steel canisters from the dilution tunnel. Samples were analyzed by modified method EPA TO-14A using a GC/MS. NMVOC data can be found in Appendix I.

Methanol samples were collected with an EPA Method 308 sampling train from the dilution tunnel. Samples were analyzed by modified EPA Method 308 using a GC/FID. Methanol data are provided in Appendix J

Phenol and Polycyclic Aromatic Hydrocarbons (PAH) were sampled with an EPA Method 23 sampling train (often referred to as modified Method 5 or MM5). Samples were collected from the dilution tunnel. The samples were analyzed by EPA Method 8270C. The laboratory reported values for the 0010/8270 semivolatile full list, with additional non-target compounds. Phenol and the 16 individual polycyclic aromatic hydrocarbons making-up the 16-PAH list are reported. (The compounds making up the 7-PAH list are a subset of the 16-PAH list.) The phenol and PAH laboratory data are provided in Appendix K.

Organic and Elemental Carbon were collected onto quartz filters and analyzed following method (NIOSH 5040). The laboratory results are provided in Appendix L

Carbon Monoxide (CO) was measured with a gas filter correlation analyzer following EPA Method 10. Carbon monoxide was measured both in the dilution tunnel and the chimney to allow for the dilution ratio and chimney flow to be calculated. Carbon monoxide data can be found in Appendix D.

Nitrogen Oxides (NO_x) concentrations were measured with a chemiluminescent gas analyzer by EPA Method 6C. Measurements were made in the chimney so that values would be within the operating range of the instrument. Nitrogen oxide (NO) was used as a calibration gas. The instrument converted NO_2 to NO and recorded a total NO_x value (ppm_v). Final NO_x values are reported as NO_2. Moisture was constantly removed from the gas clean-up line in order not to lose NO_2 from the sample stream. Analyzer data can be found in Appendix D.

Sulfur Dioxide (SO_2) concentrations were measured with a pulsed florescence analyzer by EPA Method 6C. Measurements were made in the chimney so that values would be within the operating range of the instrument. A sulfur dioxide permeation calibrator was used to calibrate the instrument. The sample train included a continuous moisture removal system, a heated filter and a heated sample line to prevent the loss of SO_2 from the sample stream.

Oxygen and Carbon Dioxide (O_2 and CO_2) concentrations were measured with a Servomex 1400 series general purpose gas analyzer by EPA Method 3A. Measurements were made in the chimney in order to measure values within the operating range of the instrument and to obtain chimney data needed for efficiency calculations. Oxygen and CO_2 data can be found in appendix E.

Miscellaneous Measurements

Gas flow within the dilution tunnel was measured with a P-type pitot tube. Chimney gas flow was calculated by using carbon monoxide as a tracer gas. All gas analyzers, with the exception of SO_2 for which a permeation tube system was used to calibrate the instrument, were calibrated with standard calibration gas tanks. All gas analyzers were data logged every minute. Chimney, dilution tunnel, laboratory and outside temperatures were measured with type-K thermocouples and data logged every minute. Laboratory barometric pressure was measured each testing day with a mercury barometer.

4.2 Fuel and Combustion Residue Heat Content and Composition Tests

Cordwood sawdust samples were collected using a handsaw. A representative composite sample was obtained by cutting across the grain. The combustion residue was collected from the bottom of the firebox after the test was completed and this residue was weighed. Both fuel and combustion residue samples underwent proximate/ultimate and heat content analyses. The analyses include heat content (ASTM D5865), loss on drying (ASTM D3173), carbon, hydrogen, and nitrogen (ASTM D5373), oxygen (ASTM D5622), and sulfur contents (ASTM D4239). Additionally, ash (ASTM D3174), volatile matter (ASTM D3175), and fixed carbon (ASTM D3175) measurements were performed. Laboratory results are in Appendix M.

4.3 Heater Efficiencies

Heater efficiencies were calculated using lower heating values (LHV) rather than higher heating values (HHV), as the energy associated with water condensation is not available for heating because the water is carried up and out of the stack in the vapor phase. Total energy available for heating from the fuel was calculated by multiplying the dry LHV for both oak fuel and Douglas fir kindling by their respective dry masses for each test run, then accounting for fuel moisture by subtracting the latent heat of vaporization for fuel moisture from the dry LHV, since that heat is used to change the fuel moisture from liquid to vapor. Temperatures were recorded 4 feet (1.2 m) in front of each stove, and 8 feet (2.4 m) above the floor in the center of the stack, which is assumed to be the height at which heat in the stack is no longer available for heating a household. The sensible heat loss up the stack was calculated using the heat capacities and concentrations for each stack gas (O_2, CO_2, CO, H_2O, N_2, Ar, CH_4, NMVOC) and particles. Nitrogen and argon concentrations were calculated from the other gas measurements. Water vapor emissions were calculated from the fuel hydrogen and free moisture contents of the fuel. Unused heat (heat not released during combustion) was calculated using the LHV for particles, CO, CH_4, NMVOC, and the combustion residue. These values represent energy that could have been released if complete combustion occurred. Total efficiency was calculated by dividing (1) the difference of the total available energy (kJ), sensible heat loss (kJ), latent heat of vaporization for fuel moisture (kJ), and unused heat (kJ) by (2) the total available energy (kJ). Efficiency calculations can be found in Appendix N.

5. Results

5.1 Reporting

Data tabulations provide the individual results for each heater to permit comparisons among models. Means and the standard deviations are also provided so that single values representative of conventional pre-EPA certification heaters are available and so that the range in values among models can be easily assessed.

5.2 Test Conditions and Heater Operation

Table 1 contains wood heater operational characteristics, including efficiencies, during the air emission tests. The burn rate is reported with three different end points in Table 1 to allow for comparison with results from other studies. These end points are defined as: (1) when the scale tare weight equals zero, i.e., when all the mass of the fuel is consumed, (2) when the temperature in the center of the chimney at one foot above the heater reached 200 ºF (93.3 ºC), and (3) when the temperature in the center of chimney at 1 ft above heater reached 100 ºF (37.8 ºC). The values for this last convention of reporting burn duration were approximated as the tests were terminated prior to the temperature falling to 100 °F (37.8°C). As previously, noted the 200°F (93.3°C) end point was used here.

The average and maximum interior chimney temperatures measured at 1 ft (30 cm) above the heater and 8 ft (2.4 m) above the floor are shown in Table 2. The average dilution tunnel temperature, the laboratory room air temperature measured at 4 ft (1.2 m) in front of the heater, and the outside temperature measured on the roof of the testing laboratory are also shown in Table 2.

5.3 Fuel and Combustion Residue Composition

Table 3 contains proximate/ultimate analysis results and heating values for the oak cordwood, the Douglas fir kindling, and the combustion residue.

5.4 Air Emissions

Table 4 contains air emission factors, reported as a mass of pollutant/mass fuel on a dry basis for all five heaters. The 16-PAH and 7-PAH emission factors, which are the sum of 16 and 7 individual compounds, respectively, are reported in three different ways. These are: (1) using zero, (2) using one-half of the detection limit, and (3) using the full detection limit for individual compounds when their levels are below detection limits.

Particulate data have been reported both as directly measured with the Method 5G-like sampler and as converted to a Method 5H-equivalent value. The Method 5G to 5H-equvalent conversions were accomplished using the conversions formulas provided as part of the emission factor documentation for AP-42. For all tests, the outdoor ambient and indoor laboratory background particulate levels were insignificant as compared to particulate emissions.

Table 5 contains results for air emission rates as mass of pollutant/hour of wood heater operation for all five heaters. As with the emission factors, the 16-PAH and 7-PAH emission rates are reported in three different ways; (1) zero, (2) one-half the detection limit, and the full detection limit, for the value of compounds at levels below detection limits.

Table 6 and 7 contain emission factors and emission rates for each of the individual PAH compounds that make up the 16-PAH list. For compounds at levels below their detection limits, one-half of the detection limits are provided in Tables 6 and 7.

Tables 8 and 9 contain emission factors and emission rates for metals for all five wood heaters. For metals below detection limits one-half of the detection limits are provided in Tables 8 and 9.

6. Summary

The emission and efficiency values obtained with this study compare favorably with literature values. A comparison of mean emission factors and efficiencies, along with their associated standard deviations, for the five representative conventional pre-EPA certification wood heaters tested in this study is provided in Table 10. Two compilations of literature values are used for the comparisons. These are the U.S. EPA AP-42 document and a report to the Mid-Atlantic Air Management Association (MARMA) prepared by OMNI, which includes a comprehensive review of current literature. In addition, data from two specific studies published in Environmental Science and Technology are listed in Table 10 for pollutants not adequately covered in the two compilations.

The means with associated standard deviations for the key pollutants of particles, carbon monoxide, nitrogen oxides, benzene, formaldehyde, naphthalene, phenanthrene, 16-PAH and methanol, as well as, efficiency overlap with the literature values. The average values for acenapthylene, methane, and non-methane volatile organic compounds (NMVOC) range between ¼ to ½ the literature values. It needs to be remembered that the literature compilations are based on only a few measurements themselves and with the range of emissions seen among different models of wood heaters in this study; even differences at the ¼ and ½ level are reasonable and probably represent the same population of data. The average sulfur dioxide value with its standard deviation overlaps the only current sulfur dioxide measurement for conventional wood heaters identified by OMNI. (See footnote to Table 10.) Naphthalene, phenanthrene and acenapthylene are listed as key pollutants as they occur at highest concentrations in wood smoke among the 16-PAH compounds.

Not surprisingly, the results of this study confirmed that the emissions of metals from residential wood combustion are very low with most being below detection limits. In many cases, they were at or below background levels of laboratory and outdoor air measured on a day when sampling was not conducted. Comparison of literature values is not provided as there is a paucity of literature data and those values that have been reported are dependent, in large part, on the sampling, digestion and analyses techniques used. Importantly, the testing performed here, confirms that metal emissions are not of environmental significance.

In summary, the emissions from the five conventional pre-EPA certification wood heaters studied here were variable but the averages with their associated standard deviations were in the same range as previously reported values. The data provided from this study, used in conjunction with previously reported values, provide a solid basis for calculating emission inventories and provide the baseline needed for determining the emission benefits of replacing older pre-EPA certification cordwood heaters with new technology heaters.

Table 1
Wood Heater Operational Characteristics and Efficiencies

Characteristic	Units	Atlanta Homesteader	Blaze King Princess	Jotul Elg, Model No. 121	National Stove Crafters Craft Insert	Schrader (Unknown Model)	Mean	Standard Deviation
Burn Rate[1]	kg/hr, db	3.78	2.05	2.38	2.11	2.70	2.60	0.70
Burn Rate[2]	kg/hr, db	2.90	1.85	2.38	2.11	2.70	2.39	0.43
Burn Rate[3]	kg/hr, db	2.08	1.44	1.76	1.69	2.07	1.81	0.27
Total Efficiency[4]	Percent	62.4	63.4	46.8	34.0	65.6	54.4	13.6
Total Mass of Fuel[5]	kg, db	15.1	13.4	14.1	17.4	18.5	15.7	2.2
Mass of Kindling and Starter Logs	kg, db	3.6	3.6	3.6	3.8	3.6	3.6	0.1
Mass of Main Load	kg, db	11.5	9.7	10.4	13.7	14.8	12.0	2.2
Moisture of Fuel[6]	%, db	18.8	17.0	19.6	17.6	19.7	18.5	1.2
Length of Test[7]	hours	5.0	7.0	5.7	8.0	6.6	6.5	1.2
Average Chimney Flow[8]	dscfm	18.6	10.8	24.9	113.1	16.9	36.9	42.9
	dscmm	0.527	0.306	0.705	3.20	0.479	1.04	1.21

[1]End of burn defined when scale showed no fuel remaining
[2]End of burn defined when center of chimney at 1 ft (30.5 cm) above heater was less than 200 ºF (93.3 ºC), which is also the end of the test period
[3]End of burn defined when center of chimney at 1ft (30.5 cm) above heater was less than 100 ºF (37.8 ºC)
[4]Calculated using lower heating values (LHV) under the assumption that the energy associated with water condensation is not available for heating because the water is carried up and out of the stack in the vapor phase.
[5]Includes kindling, starter logs and main fuel load.
[6]Average percent moisture (dry basis) as measured from each piece of fuel with a Delmhorst moisture meter.
[7]Test time started when the newspaper was lit and ended when the center of chimney at 1 ft above heater was less than 200 ºF (93.3 ºC)
[8]Average chimney flow is reported in units of dry standard cubic feet per minute (dscfm) and dry standard cubic meters per minute (dscmm). Standard conditions are defined as 1 atmosphere pressure and 0° C.

Table 2
Temperatures During Tests

Thermocouple Location and Temperature Value	Units	Atlanta Homesteader	Blaze King Princess	Jotul Elg, Model No.121	National Stove Crafters Craft Insert	Schrader (Unknown Model)	Mean	Standard Deviation
One foot above heater in chimney, average	ºF	718	547	577	199	538	516	191
	ºC	381	286	303	93	281	269	106
One foot above heater in chimney, maximum	ºF	1341	1417	1281	432	1275	1149	405
	ºC	727	769	694	222	691	621	225
Eight foot above floor in chimney, average	ºF	718	377	477	190	413	435	191
	ºC	381	192	247	88	212	224	106
Eight foot above floor in, chimney maximum	ºF	1042	1267	1109	353	1004	955	351
	ºC	561	686	598	178	540	513	195
Laboratory, average*	ºF	80	77	74	81	80	78	3
	ºC	27	25	23	27	27	26	2
Dilution Tunnel, average	ºF	75	75	74	71	79	75	3
	ºC	24	24	23	21	26	24	2
Outside (ambient), average	ºF	53	54	45	57	56	53	5
	ºC	12	12	7	14	13	12	3

*Measured at 4 feet (1.2 m) in front of the heater

Table 3
Fuel and Combustion Residue Characterization

Analysis	Units	White Oak Cordwood	Douglas Fir Kindling	Combustion Residue
Moisture*	percent dry basis	18.5	16.1	0
Carbon	percent dry basis	49.35	50.91	63.59
Hydrogen	percent dry basis	5.46	5.38	1.15
Nitrogen	percent dry basis	0.25	0.02	0.23
Sulfur	percent dry basis	0.04	0.02	0.26
Oxygen	percent dry basis	43.67	36.60	15.23
Ash	percent dry basis	2.68	0.08	24.73
Heat content (HHV)	Btu/lb, dry basis	8253	8514	9261
	Mj/kg, dry basis	19.2	19.8	21.5
Heat content (LHV)	Btu/lb, dry basis	7212	7478	9039
	Mj/kg, dry basis	18.1	18.7	21.3

*Average percent moisture (dry basis) as measured with a Delmhorst moisture meter on each piece of fuel

Table 4
Air Emission Factors (g/kg dry fuel)

Pollutant	Atlanta Homesteader	Blaze King Princess	Jotul Elg, Model No. 121	National Stove Crafters Craft Insert	Schrader (Unknown Model)	Mean	Standard Deviation
Total Particulate (PM) M5G	7.1	4.5	1.2	22.5	2.2	7.5	8.7
Total Particulate (PM) M5H-equivalent	8.6	6.0	1.8	25.2	2.9	8.9	9.5
Carbon Monoxide (CO)	112.2	135.0	49.5	128.1	87.5	102.4	34.8
Nitrogen Oxides* (NOx)	1.1	1.0	1.8	0.8	0.8	1.1	0.4
Benzene	0.70	1.2	0.029	0.87	1.4	0.83	0.52
Formaldehyde	1.6	1.13	0.26	0.83	0.98	0.97	0.50
7-PAH**	0, 0.083, 0.17	0, 0.23, 0.46	0, 0.0046, 0.0092	0, 0.56, 1.1	0, 0.16, 0.33	0, 0.21, 0.42	0, 0.21, 0.43
16-PAH**	0.18, 0.31, 0.44	0.28, 0.73, 1.20	0.013, 0.020, 0.027	0.13, 1.3, 2.5	0.29, 0.59, 0.90	0.18, 0.60, 1.02	0.11, 0.49, 0.95
Phenol	0.10	0.22	0.010	0.28	0.19	0.16	0.10

The 7-PAH (polycyclic aromatic hydrocarbon) value is the sum of: benz(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoanthene, benzo(a)fluoranthene, benzo(a)pyrene, dibenz(a,h)anthracene, indeno(1,2,3-cd)pyrene.
The 16-PAH (polycyclic aromatic hydrocarbon) value is the sum of: naphthalene, acenaphthene, acenaphthylene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(ghi)perylene, benz(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenz(a,h)anthracene, and indeno(1,2,3-cd)pyrene.
*Reported as nitrogen dioxide
**Values reported three ways: zero, 50%, and 100% of the laboratory detection limit were used for the calculation of 7-PAH and 16-PAH levels for compounds below detection limits.

Table 4
Air Emission Factors (g/kg dry fuel)
(continued)

Pollutant	Atlanta Homesteader	Blaze King Princess	Jotul Elg, Model No. 121	National Stove Crafters Craft Insert	Schrader (Unknown Model)	Mean	Standard Deviation
Methane	5.5	8.7	2.6	12.2	8.3	7.5	3.6
Non-Methane Volatile Organic Compounds (NMVOC)	5.5	4.8	4.5	14.7	3.9	6.7	4.5
Organic Carbon	3.4	2.1	4.5	11.5	nd*	5.4	4.2
Elemental Carbon	0.2	0.2	0.04	0.1	nd*	0.1	0.1
Methanol	0.4**	1.8	0.9**	6.9	0.7	2.1	2.7
Sulfur Dioxide (SO_2)	0.008	0.089	0.006	0.015	0.007	0.010	0.004

* Data not available due to a torn filter
** ½ the laboratory detection limit used in the calculations

Table 5
Air Emission Rates (g/hr)

Pollutant	Atlanta Homesteader	Blaze King Princess	Jotul Elg, Model No. 121	National Stove Crafters Craft Insert	Schrader (Unknown Model)	Mean	Standard Deviation
Total Particulate (PM) M5G	21.3	8.6	3.1	49.1	6.1	17.6	18.9
Total Particulate (PM) M5H-equivalent	25.8	11.4	4.5	54.9	8.3	21.0	20.6
Carbon Monoxide (CO)	337.2	257.2	122.6	278.9	246.4	248.5	78.6
Nitrogen Oxides* (NOx)	3.5	2.1	4.4	1.6	2.2	2.8	1.1
Benzene	2.1	2.2	0.1	1.9	3.8	2.0	1.3
Formaldehyde	4.9	2.1	0.6	1.8	2.8	2.5	1.6
7-PAH**	0, 0.25, 0.50	0, 0.44, 0.88	0, 0.011, 0.023	0, 1.2, 2.4	0, 0.46, 0.93	0, 0.47, 0.95	0, 0.45, 0.90
16-PAH**	0.55, 0.95, 1.3	0.53, 1.4, 2.3	0.031, 0.049, 0.067	0.28, 2.9, 5.5	0.81, 1.7, 2.5	0.44, 1.4, 2.3	0.30, 1.0, 2.0
Phenol	0.31	0.43	0.026	0.60	0.53	0.38	0.23

* Reported as nitrogen dioxide
**Values reported three ways: zero, 50%, and 100% of the laboratory detection limit were used for the calculation of 7-PAH and 16-PAH levels for compounds below detection limits.

Table 5
Air Emission Rates (g/hr)
(continued)

Pollutant	Atlanta Homesteader	Blaze King Princess	Jotul Elg, Model No. 121	National Stove Crafters Craft Insert	Schrader (Unknown Model)	Mean	Standard Deviation
Methane	16.6	16.7	6.4	26.6	23.3	17.9	7.7
Non-methane Volatile Organic Compounds (NMVOC)	16.5	9.2	11.1	32.0	10.9	15.9	9.4
Organic Carbon	10.2	4.0	1.9	25.0	nd*	10.3	10.5
Elemental Carbon	0.5	0.3	0.1	0.3	nd*	0.2	0.2
Methanol	1.1**	3.4	1.0**	14.9	2.0	4.5	5.9
Sulfur Dioxide (SO_2)	0.024	0.026	0.014	0.032	0.019	0.023	0.007

*Data not available due to a torn filter
**1/2 the laboratory detection limit used in the calculations

Table 6
Polycyclic Aromatic Hydrocarbon Emission Factors (mg/kg dry fuel)

Pollutant	Atlanta Homesteader	Blaze King Princess	Jotul Elg, Model No. 121	National Stove Crafters Craft Insert	Schrader (Unknown Model)	Mean	Standard Deviation
Naphthalene	99.3	224.6	8.1	127.1	207.4	133.3	87.6
Acenaphthene	11.8*	33.0*	0.7*	79.5*	23.6*	29.7	30.4
Acenaphthylene	21.3	52.8	1.4	79.5*	46.2	40.2	30.0
Fluorine	11.8*	33.0*	0.7*	79.5*	23.6*	29.7	30.4
Phenanthrene	28.4	33.0*	2.1	79.5*	33.0	35.2	27.9
Anthracene	11.8*	33.0*	0.7*	79.5*	23.6*	29.7	30.4
Fluoranthene	20.1	33.0*	0.6	79.5*	23.6*	31.3	29.4
Pyrene	15.4	33.0*	0.3	79.5*	23.6*	30.4	30.0
Benzo(ghi)perylene	11.8*	33.0*	0.7*	79.5*	23.6*	29.7	30.4

*1/2 the laboratory detection limit used in the calculations

Table 6
Polycyclic Aromatic Hydrocarbon Emission Factors (mg/kg dry fuel)
(continued)

PAH Compound	Atlanta Homesteader	Blaze King Princess	Jotul Elg, Model No. 121	National Stove Crafters Craft Insert	Schrader (Unknown Model)	Mean	Standard Deviation
Benzo(a)anthracene	11.8*	33.0*	0.7*	79.5*	23.6*	29.7	30.4
Chrysene	11.8*	33.0*	0.7*	79.5*	23.6*	29.7	30.4
Benzo(b)fluoranthene	11.8*	33.0*	0.7*	79.5*	23.6*	29.7	30.4
Benzo(k)fluoranthene	11.8*	33.0*	0.7*	79.5*	23.6*	29.7	30.4
Benzo(a)pyrene	11.8*	33.0*	0.7*	79.5*	23.6*	29.7	30.4
Dibenzo(a,h)anthracene	11.8*	33.0*	0.7*	79.5*	23.6*	29.7	30.4
Indeno(1,2,3-c,d)pyrene	11.8*	33.0*	0.7*	79.5*	23.6*	29.7	30.4

*1/2 the laboratory detection limit used in the calculations

Table 7
Polycyclic Aromatic Hydrocarbon Emission Rates (mg/hr)

PAH Compound	Atlanta Homesteader	Blaze King Princess	Jotul Elg, Model No. 121	National Stove Crafters Craft Insert	Schrader (Unknown Model)	Mean	Standard Deviation
Naphthalene	298.5	428.1	20.1	276.8	584.1	321.5	208.4
Acenaphthene	35.5*	62.9*	1.6*	173.0*	66.4*	67.9	64.3
Acenaphthylene	64.0	100.7	3.6	173.0*	130.3	94.3	64.6
Fluorine	35.5*	62.9*	1.6*	173.0*	66.4*	67.9	64.3
Phenanthrene	85.3	62.9*	5.2	173.0*	93.1	73.9	64.2
Anthracene	35.5*	62.9*	1.6*	173.0*	66.4*	67.9	64.3
Fluoranthene	60.4	62.9*	1.5	173.0*	66.4*	67.9	64.3
Pyrene	46.2	62.9*	0.8	173.0*	66.4*	67.7	64.5
Benzo(ghi)perylene	35.5*	62.9*	1.6*	173.0*	66.4*	67.9	64.3
Benzo(a)anthracene	35.5*	62.9*	1.6*	173.0*	66.4*	67.9	64.3
Chrysene	35.5*	62.9*	1.6*	173.0*	66.4*	67.9	64.3
Benzo(b)fluoranthene	35.5*	62.9*	1.6*	173.0*	66.4*	67.9	64.3
Benzo(k)fluoranthene	35.5*	62.9*	1.6*	173.0*	66.4*	67.9	64.3
Benzo(a)pyrene	35.5*	62.9*	1.6*	173.0*	66.4*	67.9	64.3
Dibenzo(a,h)anthracene	35.5*	62.9*	1.6*	173.0*	66.4*	67.9	64.3
Indeno(1,2,3-c,d)pyrene	35.5*	62.9*	1.6*	173.0*	66.4*	67.9	64.3

*1/2 the laboratory detection limit used in the calculations

Table 8
Metals Emission Factors (mg/kg dry fuel)

Metal	Atlanta Homesteader	Blaze King Princess	Jotul Elg, Model No. 121	National Stove Crafters Craft Insert	Schrader (Unknown Model)	Mean	Standard Deviation
Antimony	0.01*	0.03	0.01*	0.01*	0.03	0.02	0.01
Arsenic	0.13*	0.15*	0.15*	0.32	0.28	0.21	0.09
Barium	2.89	4.26	4.72	2.44	1.5	3.2	1.3
Beryllium	0.01*	0.01*	0.01*	0.01*	0.01*	0.01	0.001
Cadmium	0.01*	0.02	0.01*	0.01*	0.05	0.02	0.02
Chromium	1.51	1.46	1.37	1.23	1.50	1.41	0.11
Cobalt	0.27	0.29	0.37	0.20	0.25	0.27	0.06
Copper	1.33	1.56	1.28	1.99	1.6	1.6	0.3
Lead	0.48	0.68	0.54	0.22	0.54	0.49	0.17
Manganese	0.82	0.98	0.92	0.66	0.57	0.79	0.17
Nickel	0.59	0.67	0.67	0.23	0.22	0.48	0.23
Selenium	0.33*	0.37*	0.37*	0.30*	0.26*	0.33	0.05
Silver	0.08	0.07	0.06	0.06	0.07	0.07	0.01
Thallium	0.01*	0.01*	0.01*	0.01*	0.01*	0.01	0.001
Zinc	9.50	11.64	12.31	5.06	3.77	8.46	3.86

*Metal was below reporting limit, ½ the laboratory detection limit was used to calculate the value shown, and ½ the detection limit was used for the calculation of the mean and standard deviation

Table 9
Metals Emission Rates (mg/hr)

Metal	Atlanta Homesteader	Blaze King Princess	Jotul Elg, Model No. 121	National Stove Crafters Craft Insert	Schrader (Unknown Model)	Mean	Standard Deviation
Antimony	0.04*	0.06	0.04*	0.03*	0.09	0.05	0.02
Arsenic	0.4*	0.3*	0.4*	0.7	0.8	0.5	0.2
Barium	8.7	8.1	11.7	5.3	4.3	7.6	2.9
Beryllium	0.02*	0.01*	0.02*	0.01*	0.01*	0.02	0.003
Cadmium	0.02*	0.03	0.02*	0.01*	0.15	0.05	0.06
Chromium	4.5	2.8	3.4	2.7	4.2	3.5	0.8
Cobalt	0.8	0.5	0.9	0.4	0.7	0.7	0.2
Copper	4.0	3.0	3.2	4.3	4.6	3.8	0.7
Lead	1.4	1.3	1.3	0.5	1.5	1.2	0.4
Manganese	2.5	1.9	2.3	1.4	1.6	1.9	0.4
Nickel	1.8	1.3	1.7	0.5	0.6	1.2	0.6
Selenium	1.0*	0.7*	0.9*	0.6*	0.7*	0.8	0.1
Silver	0.2	0.1	0.1	0.1	0.2	0.2	0.0
Thallium	0.02*	0.01*	0.02*	0.01*	0.01*	0.02	0.003
Zinc	28.6	22.2	30.5	11.0	10.6	20.6	9.4

*Metal was below reporting limit, ½ the laboratory detection limit was used in the calculations and is shown, and ½ the detection limit was used for the calculation of the mean and standard deviation.

Table 10
Comparison of Air Emission Factors and Efficiency
(Unless otherwise noted all units are g/kg dry fuel)

Pollutant	This Study, Mean ± Standard Deviation	U.S. EPA, AP-42	MARAMA[4]	Other References
Particles[1]	8.9 ± 9.5	15.3	16.9	
Carbon Monoxide	102.4 ± 34.8	115.4	78.4	
Nitrogen Oxides[2]	1.1 ± 0.4	1.4	1.28	
Benzene	0.83 ± 0.52	0.969	1.08	
Formaldehyde	0.97 ± 0.50	-	0.73	
Naphthalene (mg/kg dry fuel)	133.3 ± 87.6	144	91	
Acenapthylene (mg/kg dry fuel)	40.2 ± 30.0	106	-	
Phenanthrene (mg/kg dry fuel)	35.2 ± 27.9	39	-	
16-PAH[3]	0.60 ± 0.49	0.359	0.32	
Phenol	0.16 ± 0.10	-	0.15	
Methane	7.5 ± 3.6	15	32.0	
Non-methane Volatile Organic Compounds	6.7 ± 4.5	26.5	18.3	
Methanol	2.1 ± 2.7	-	-	3.24[5]
Sulfur Dioxide[3]	0.010 ± 0.004	0.2[6]	0.10[6]	0.008[6]
Efficiency (%)	54.4 ± 13.6	54	-	-

[1]Method 5H equivalent
[2]Reported as nitrogen dioxide
[3]½ the laboratory detection limit for compounds below their detection limit was used to determine total values, means and standard deviations.
[4]Technical Memorandum 2 (Emission Inventory), Control Analysis and Documentation for Residential Wood Combustion in the MANE-VU Region, prepared for the Mid-Atlantic Air Management Association (MARMA) by OMNI Environmental Services, June 9, 2006.
[5]McDonald, J.D., Zielinska, B., Fujita, E.M., Sagebiel, J.C., Chow, J.C., and Watson, J.G., 2000, Fine Particle and Gaseous Emission Rates from Residential Wood Combustion, Environmental Science and Technology, v. 34, no. 11, pp. 2080-2091.
[6]The sulfur dioxide value shown in AP-42, and included in the MARAMA review is based on only two measurements near the detection limit of the method and were made prior to 1980. It is speculated, based on mass balance considerations (i.e., the sulfur in typical wood fuel, in bottom ash, and in particulate air emissions) that the value is too high. The direct measurement value of 0.008 shown in Table 10 is believed to be more accurate. It was calculated after data provided in: Hedman,B, Naslund, M. and Marklund, S., in press, Emission of PCDD/F, PCB and HCB from Combustion of Firewood and Pellets in Residential Stoves and Boilers, Environmental Science and Technology.