Conventional Woodstove Emission Factor Study

Victor S. Li, Environment Canada, Ontario, Environmental Protection Operations Division,
4905 Dufferin St., Toronto, Ontario, Canada, M3H 5T4
Email: victor.li@ec.gc.ca Ph: (416) 739-5801

Abstract: Environment Canada (EC) and Hearth, Patio and Barbecue Association (HPBA) partnered to conduct a study 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. OMNI Environmental Services, Inc. (OMNI) was hired to conduct this study[1] and measure air emissions from five conventional cordwood heaters sold prior to the Environmental Protection Agency's (EPA's) certification requirement. To achieve this objective, the pre-EPA certification cordwood heaters used in the study were operated in a normal fashion characteristic of in-home use. Additionally, to maximize the credibility of the data, standardized testing and analytical protocols were used.

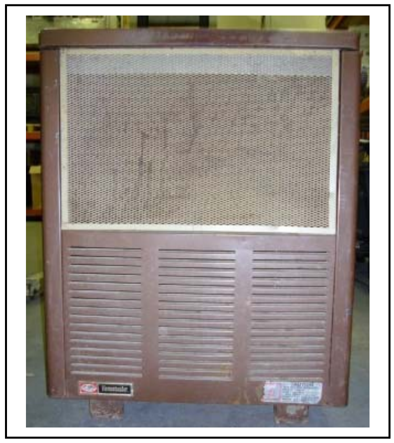
The emissions from these five conventional pre-EPA certification wood heaters were variable but the averages with their associated standard deviations were in the same range as previously reported values. The data from this study, used in conjunction with previously reported values, provide a solid basis for calculating emission inventories and provide the baseline needed for determining the emission benefits of replacing the older pre-EPA certification cordwood heaters with new technology heaters. Comparison to a study in New Zealand showed similar results[2].

Introduction: OMNI Environmental Services was hired to conduct a study on 5 conventional wood heaters. These were used heaters collected from a number of locations throughout the United States by Heath, Patio and Barbecue Association. Some of the heaters were repaired to good working order. The heaters chosen, represented the popular types used at the time (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. Since there is so much variation in the design and burning capacity of the heaters, it was a challenge to establish a protocol to ensure consistent and accurate burning measurements. A normal home usage method was developed which set a target burn of 6 hours meaning that the heaters were operated in such a manner to obtain six hours of continual burning at the home owner's "mid-range" use of each model. "Mid-range" defined as avoiding burning techniques where the heater is subjected to extreme operating parameters such a fully open of fully closed burning cycles. Various emission parameters were measured during the burning cycles. They were 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. The emissions were reported as emission factors and emission rates. Wood heater efficiencies were also measured.

2. Heaters Description and Operation[3]

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) fibreglass 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) (56.6 litres) 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 fibreglass 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 litres) 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 litres) 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 fibreglass 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 litres) 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 aluminium.

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 fibreglass 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[4]

The five stoves were set up to burn locally purchased White Oak cordwood and emissions collected for the parameters mentioned in the Introduction.
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.
The tests were conducted at OMNI Environmental Service's testing facilities in Beaverton, OR. Each stove was placed on a scale equipped with its chimney.
A 14 inch (36 cm) diameter dilution tunnel placed above the chimney was used for cooling and dilution of the chimney emissions prior to sample collection.
The burn protocol was developed to produce a six-hour fire using oak cordwood with 15-25% moisture content (dry basis). Douglas fir was used as the kindling to start the fire as softwood was frequently used by homeowners due to its ease of starting the fire. The cordwood was weighed and moisture measured before adding to the heater. Due to the differences in firebox size, the wood loads varied from heater to heater. The operation of the heater depended on the combination of air controls and/or wood addition to achieve the six hour burn cycle. The fire duration protocol was an important decision making process. There are two considerations in determining the fire duration. First, the time is needed to establish when the combustion process is producing emissions to gather the data. Secondly, the period of time to ensure all the emissions are collected until the combustion is completed. The completion of the combustion was defined when the temperature cooled to 93.3 ^{0}C (200 ^{0}F) as measured at the center of the chimney at 30.5 cm. (1 foot) above the heater. At 93.3 ^{0}C (200 ^{0}F) the combustion process is essentially complete and the heater would no longer be considered as producing useful heat by the home owner.

All sampling and testing were conducted at the EPA accredited wood heater testing laboratory operated by OMNI. All sampling and analysis was done by certified test methods and outside labs if required.

4. Results[5]: Tables 1-10 provide the test results for the various parameters which were measured for this study.
Table 1 has operational characteristics including the efficiencies during the tests.
Table 2 describes the flue temperature in the chimney during various stages of the test.
Table 3 characterizes the contents in the residue after the testing has been completed.
Table 4 contains the emission factors based on the amount of pollutants per mass of fuel on a dry basis.
Table 5 contains emission rates based on the amount of pollutant released per hour of operation.
Tables 6 and 7 contain emission factors and rates for each PAH compound and for compounds where the levels are blow the detection limit, one-half the detection limit is provided.
Tables 8 and 9 contain emission factors and rates for metals and the same goes for those levels below the detection limit as above. The one-half the detection limit was used.
Table 10 shows a comparison of the results of this study against some other references.

5. Conclusions[6]: The efficiency and emission results were comparable with the documented figures from previous studies and research. This was a pleasant surprise as there were some feelings that the literature values were not representative of actual burning conditions. The two references cited in Table 10, EPA reference AP-42 document and the Mid-Atlantic Air Management Association (MARMA) prepared by OMNI provide information which is frequently noted in other research studies. In addition, data from two specific studies published in Environmental Science and Technology are listed for pollutants not adequately covered in the two compilations.

In another study conducted in New Zealand[4], 12 wood burning wood heaters of similar age were tested for emissions. Interestingly, the test results yielded very similar numbers for the emissions collected from the burners after operating on a daily basis. The study results indicated that the average emissions from the New Zealand stoves produced 10.0 g/kg or 18.5 g/hr as compared to 8.9 g/kg or 21.0 g/hr for the stoves tested in our study. The large variation in the standard deviation in our study and 95% confidence limits in the New Zealand study, show how much difference can be seen from the data. As you can see, the average results are very similar. This kind of correlation of the average results supports the data that we have attained in our study.

One must understand that these results are from a small sampling of the many kinds of woodstoves in the marketplace. However, they reflect the emissions observed from two independent studies of the older woodstoves and demonstrate that the emissions from these older woodstove are still about 2-3 times the emissions permitted by the EPA certified types. This difference has and will increase as the design and technology improves for these types of stoves due to the pressure from government and environmental concerns in the wood burning sector.

The results of this study and the New Zealand study suggests that the emission factors defined in the AP-42 document can be used to establish emission values emanating from these older woodstoves.

References:

1. Houck, J.E., Pitzman, L., Eagle, B., Smith, R., Conventional Heater Baseline Study, Omni Environmental Services, Inc., July 31, 2006.
2. Wilton, E., Smith, J., Real Life Emissions Testing of Pre 1994 Woodburners in New Zealand, for Environment Waikato, ISSN: 1172-4006, Document #1052491v2, May 2006.
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Acknowledgements:

I would like to thank the Hearth, Patio and Barbeque Association for their in-kind support under John Crouch and assistance in managing this study and working with OMNI to get these stoves to the lab and make them operational. This was a good example of cooperation and collaboration between government and industry to achieve a common goal.

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.