Verification of Emission Factors
U.S. EPA Certified Wood Heaters
(Volume I)

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1. Introduction

OMNI Environmental Services, Inc. (OMNI) was contracted by Environment Canada to measure air emissions and efficiencies for wood stoves that have been certified by the U.S. Environmental Protection Agency for low emissions. The objective of the study was to determine real-world emissions and efficiencies and to verify the applicability of certification values to real-world usage. To that end, two typical certified wood stoves were selected and operated in a normal fashion during testing. This included: (1) tests with both hardwood and softwood cordwood, (2) both cold-start and hot-start burning scenarios, and (3) tests with both lower and higher burn rates. To provide insight into the possible range of emissions and efficiencies among U.S. EPA certified stoves, both a stove with a lower particulate certification value (2.1 g/h) and a stove with a higher particulate certification value (5.9 g/h) were selected for the study. Duplicate tests were performed for each test parameter.

Emissions of total particles (PM), particles with aerodynamic diameters of less than 2.5 microns ($PM_{2.5}$), nitrogen oxides (NO_x), carbon monoxide (CO), total volatile organic compounds (VOC), methane (CH_4), selected EPA listed hazardous air pollutants (HAP) aldehydes and ketone (formaldehyde, acetaldehyde, propionaldehyde, and acrolein), selected EPA listed HAP aromatic hydrocarbons (benzene, toluene, xylenes, ethyl benzene), and other selected compounds (1,3-butadiene, methylene chloride) were measured. In addition carbon dioxide, oxygen, temperatures (chimney, stove, room, meter boxes, particulate filters and dilution tunnel), fuel mass, and flows were measured to support the emission and efficiency calculations. Wood moisture, elemental composition, and energy content were also measured. Standard methods were used to the extent feasible for all testing.

In addition to the direct measurement of emissions and efficiencies, a literature review was conducted to allow for comparison of results measured in this study with the results from other studies. The literature values have been compiled in tabular format to facilitate comparisons. A complete list of source references has been included.

A detailed description of the testing program is provided as Section 2. The results of the testing are provided and discussed in Section 3. The results of the literature review are provided as Section 4. A summary is provided as Section 5. Photographic documentation, real time graphs, calculations, intermediate data, analytical laboratory reports, and testing program uncertainties are provided as appendices.

2. Testing Program

2.1 Measurements

Based on consultations as prescribed in the contract with Environment Canada staff and a Canadian wood heater expert retained for this purpose, the measurements that were deemed appropriate for this study were selected. Standard sampling methods were used to collect and monitor all parameters. Table 1 lists the methods used and the pollutants measured. Air emission samples were collected from a dilution tunnel. Supporting measurements were made in the heater chimney (stack) and in the surrounding laboratory. Background samples were collected for laboratory air. The pollutants measured included:

- Total particulate matter (PM)
- Particles less than 2.5 microns in aerodynamic diameter ($PM_{2.5}$)
- Methane
- Carbon monoxide (CO)
- Nitrogen oxides (NO_x, reported as NO_2)
- Total volatile organic compounds (VOC) – The total VOC emission factor was collected with a real time gas analyzer with a FID detector. This value includes methane and most non-methane VOCs, reported as carbon, as methane and as heptane.
- Non-methane VOCs (NMVOC) – calculated by the subtraction of methane from total VOCs, reported as carbon, as methane and as heptane.
- Carbon dioxide (CO_2) calculated from the fuel analysis and mass of fuel consumed
- HAP listed aldehydes and one ketone (formaldehyde, acetaldehyde, propionaldehyde, and acrolein) reported individually
- HAP listed aromatic hydrocarbons (benzene, toluene, xylenes and ethyl benzene) been reported individually
- Additional compounds – 1,3-butadiene and methylene chloride
- Background PM

Table 1. Compounds, Parameters, Sampling and Monitoring Methods, Collection and Monitoring Devices, Analytical Laboratories, and Analytical Methods

Compound Group	Analytical Compounds	Sampling Method	Collection Device	Analytical Laboratory	Analytical Method*
Efficiency	Stack loss (2 methods), Values reported using European (lower) and American (higher) heating value	Modified Section 13.9 and Annex D of CAN/CSA B415.1-00	various		
Particles	Total Particulate Matter (PM)	Modified EPA M-5G	47 mm Glass Fibre A/E Filter		
	Particles less than 2.5 microns in aerodynamic diameter ($PM_{2.5}$)	Other Test Method 27 (In accordance with EPA proposed changes to method 201A)	47 mm Glass Fibre A/E Filter, Teflon coated glass A/E		
Gases	Nitrogen Oxides (NO_x)	EPA M-07E	Chemiluminescent gas analyzer		
	Carbon Monoxide (CO)	EPA M-10	Gas filter correlation analyzer		
	Oxygen (O_2)	EPA Method 3A	General purpose gas analyzer		
	Carbon dioxide(CO_2)	EPA Method 3A	General purpose gas analyzer		
	Total Volatile Organic Compounds (VOC's)	EPA M-25A	Total hydrocarbon analyzer with flame ionizing detector (FID)		
	Methane	Air Toxics Ltd., guide to air sampling and analysis	Stainless Steel Summa Canister (6L, evacuated)	Air Toxics LTD.	Modified ASTM D-1946(sh)-CH_4 only
Volatile Organic Compounds	Non-Methane VOCs NMVOCs	Calculated by subtraction of methane (by Summa Canister) from total VOCs.(by continuous analyzer)			
	EPA listed hazardous air pollutant (HAP), Aldehydes: formaldehyde, acetaldehyde, and propionaldehyde	Modified EPA M-316	High purity water filled impingers	Columbia Analytical Services, Inc.	Colorimetric procedure, NCASI IM/CAN/WP-99.02
	Selected EPA listed HAPs and other compounds: benzene, toluene, xylenes, ethyl benzene, 1,3-butadiene, methylene chloride, acrolein, and propionaldehyde	Air Toxics Ltd., guide to air sampling and analysis	Stainless steel Summa canister (6 liter, Evacuated)	Air Toxics LTD.	Modified EPA TO-15 (GC/MS Full VOC scan, with additional components)

*See appropriate laboratory reports in the appendices for modifications to analytical methods

2.2 Efficiency

The efficiencies for each heater, with each associated operational condition, were determined by two stack loss methods. These have been described in CSA B415.1-00 Section 13.9 "Efficiency and Carbon Monoxide" and Annex D "Total Combustible Carbon Method." The results have been reported by using two reporting conventions, the European convention where the lower heating value (LHV) of the fuel is used in the denominator of the efficiency calculation and the North American convention where the higher heating value (HHV) of the fuel is used in the denominator of the efficiency calculation.

The following modifications to the test method were made:

- The fueling protocol specified by CSA B415.1-00 was modified in three ways: 1) cordwood was used rather than Douglas fir dimensional lumber. 2) A cold start scenario, with multiple fuel additions was used in half the evaluations rather than a hot start and single fuel addition. 3) The hot start scenario's had a hot coal bed, however the kindling and starter logs were used as pre-test fuel instead of the fueling protocol specified in the method. The coal bed resulting from the pretest fueling protocol specified in the method is larger than would be reasonable for a real-world evaluation.

- The number of tests used to calculate an average efficiency was modified. CSA B415.1-00 calls for measuring efficiency from each of the four burn rate (g/kg,db) categories (Category 1 ≤ 0.80, Category 2 = 0.81 to 1.25, Category 3 = 1.26 to 1.90, Category 4 = maximum rate), the final efficiency is then calculated from the average of these results, with exception of appliances that can operate at exceptionally high burn rates (5.3 kg/h). Results in this study are reported for each individual test and associated burn rate.

- The dilution tunnel was operated at a flow rate (~500 dscfm) higher than is recommended in the method (~150 dscfm, ratio of average mass flow rate in the dilution tunnel to the average fuel burn rate be less than 150:1). Elevated tunnel flows were needed to cool stack gases for accurate emission measurements of pollutants in partitioned (solid and liquid) and gas phases. There should be no significant difference in emissions results from an elevated tunnel flow, since all other method specifications/limitations were met (measurable particulate catch and filter temperatures below 90 °F (32 °C)).

2.3 Wood Stoves

Two U.S. EPA certified non-catalytic wood stoves were selected for use. Both were "broken in" prior to use with at least one week of normal use to burn off paints and oils. Both were inspected prior to use to insure that they were in good working order. As previously noted, one stove had a particulate certification value near the lower end of the certification range (2.1 g/h) and one stove had a particulate certification value near the higher end of heater certification range (5.9 g/h). The former stove had a listed heat output range of 11,900-43,200 BTU/h (27,620-100,267 KJ/h) with a usable firebox volume of 2.1 cubic feet (59.2 liter); the latter had a listed heat output range of 11,600-38,700 BTU/h (26,924-89,823 KJ/h) with a usable firebox volume of 2.3 cubic feet (65.1 liter). Both had a listed default efficiency of 63%. The heaters were operated and installed according to the manufacturer's specifications.

2.4 Fuels

Two fuel compositions were used: softwood (Douglas fir) and hardwood (maple). The cordwood was purchased locally from vendors who sell wood to the public. The target mass of the main fuel pieces was based on literature values for the typical mass of a cord (by species) and a study where the number of wood pieces in a cord was counted. The fuel loads and operational parameters are discussed in detail in the next section. Prior to use, the wood moisture content was measured with a hand held resistance type moisture meter to insure that wood fuel was seasoned (20 % ± 5%, db). Samples of sawdust were collected from representative pieces for submittal for fuel analyses, which provided carbon, hydrogen, oxygen, nitrogen, sulfur, ash, heat content and loss on drying. Table 2 is a summary of fuel materials used for testing.

Table 2. Summary of Fuel Materials

Ignition Source:	Butane lighter and crumpled black print newspaper
Kindling:	Softwood kindling sticks ~1.25 kg (2.75 pounds) ± 10%. 10 ± 5% moisture (dry basis)
Starter Pieces:	Hardwood (maple) cordwood 1.25 kg (2.75 pounds) wet basis ± 10%. Softwood (fir) cordwood 1.0 kg (2.2 pounds) wet basis ± 10%. 16 ± 2 inches (40.6 ± 5.1 cm) in length 20 ± 5% moisture (dry basis)
Main Pieces:	Hardwood (maple) cordwood 3.0 kg (7.7 pounds) wet basis ± 10%. Softwood (fir) cordwood 2.5 kg (5.5 pounds) wet basis ± 10%. 16 ± 2 inches (40.6 ± 5.1 cm) in length 20 ± 5% moisture (dry basis)

2.5 Burning Protocols

There were two main objectives taken into consideration in the design of the wood-burning protocols. These were: (1) to simulate real-world burn patterns representative of how a wood heater would be normally used with typical fuel and (2) to parallel standard test methods (CSA B415.1-00 and EPA Method 28), where possible, for verification of efficiency and air emissions. The fueling protocol was similar to the cordwood burning protocol used in the "Conventional Heater Baseline Study", prepared by OMNI Environmental Services, Inc. for Environment Canada and the Hearth, Patio & Barbecue Association in 2006. The protocols consist of targets for the mass of fuel, addition times, and burn durations. The fuel load was similar (number of fuel pieces) for each appliance due to similar firebox volumes. The fuel load mass for the low/cold burn tests were determined by the least number of fuel pieces which a home occupant would likely add (two). The small fuel load also allowed testing to be completed within a reasonable timeframe. The high/hot fuel loads were determined by the maximum number of pieces a homeowner would likely add (four). During each test the heater was operated as a typical homeowner would to produce heat for a home. There were no observed issues with excess air during the testing. The following details the two burning scenarios:

Low/Cold Burn Scenario

The low/cold burn scenario consisted of a low air inlet setting where the air inlet was turned down to the lowest possible setting on the heater. The burning guidelines in the manufacturer's instruction manuals were taken into consideration for the low burn settings and followed to the extent that they were consistent with real-world homeowner practice. Emissions and efficiency measurements started from a cold start. The sampling systems were started and within five seconds the newspaper was lit with a lighter. The low/cold burn scenario was a complete burn cycle from a cold start to the test end point. The primary end point for the tests was as stated in CSA B415.1-00, "The test run is completed when the remaining weight of the test fuel charge is zero. End the test run when the scale has indicated a test fuel charge weight of 0.00 kg for 30 seconds." If the scale reading did not reach 0.00 kg, then the secondary endpoint was used. OMNI used one of the operating limitations (section 12.6) of CSA B415.1-00 as a secondary endpoint. "The average of the five appliance surface temperature measurements (centrally on the top, left sidewall, right sidewall, bottom and back) at the start of the test run and at the completion of the test run shall be within 70 Celsius degrees (158 Fahrenheit degrees)." The low/cold protocol is shown in Table 3.

Table 3. Low/Cold Burn Protocol

- Prior to testing the following measurements are made on the fuel: (1) total mass of each piece of wood (2) total mass of the entire fuel charge and (3) moisture content, dry basis.
- Assemble kindling in a tee-pee formation with four full sheets of black-print newspaper crumpled beneath.
- Light newspaper, start test (sampling equipment on)
- After five minutes add three starter-logs
- After 15 to 30 minutes add two main fuel pieces. Stacking should be conducted to provide optimum air flow around fuel pieces. Photograph the main fuel charge.
- The air inlet is left completely open for 15 to 30 minutes, then reduced to the lowest possible setting until the end point is reached.
- End test (sampling equipment off)
- The residue (ash) is collected and weighed the following day after the test is completed and it has cooled to room temperature.

High/Hot Burn Scenario

The high/hot burn scenario consisted of a pre-burn for at least one hour or until a hot coal bed (as outlined in CSA B415.1-00) was established. For the high/hot burn scenario the heater air inlet settings were at the highest setting possible. The burning guidelines in the manufacturer's instruction manuals were taken into consideration for the high burn settings and followed to the extent that they were consistent with real-world homeowner practice. The sampling systems were started after the pre-burn as outlined in CSA B415.1-00, i.e., measurements were started with the fire already hot. Due to the omission of the start-up phase of the fire, high/hot burn scenario provides an incomplete burn cycle measurement from the hot start to the test end point. The test end point determination was the CSA B415.1-00 end point, described as the primary endpoint in the low/cold scenario. The high/hot protocol is shown in Table 4.

Table 4. High/Hot Burn Protocol

- Prior to testing the following measurements are made on the fuel: (1) total mass of each piece of wood (2) total mass of the entire fuel charge (not including the mass of the pre-burn fuel), and (3) moisture content, dry basis
- Assemble kindling in a tee-pee formation with four full sheets of black-print newspaper crumpled beneath
- Set air settings to highest possible setting
- Start fire with the ignition source
- After five minutes add four starter-logs
- After spreading the coals to establish a uniform, hot coal bed, zero the scale
- Add four main fuel pieces filling the firebox full (stacking should be conducted to provide optimum air flow around fuel pieces).
- Photograph the main fuel charge
- Start test (sampling equipment on)
- Make appropriate adjustments to settings to avoid over firing if excessive flue gas temperatures are reached
- End test (sampling equipment off)
- Collect and weigh the residue (ash) the following day after the test is completed and it has cooled to room temperature

To enhance the statistical reliability all eight test conditions for each heater were duplicated for a total of 16 test runs. Table 5 is a summary of the testing matrix.

Table 5. Testing Matrix

Test Run	Replication Identification	Heater	Cordwood Fuel	Heater Setting/Starting Option	Date
1	1	Heater 1	Softwood (fir)	Low/Cold	3/13/09
2	1-duplicate	Heater 1	Softwood (fir)	Low/Cold	3/14/09
3	2	Heater 1	Hardwood (maple)	Low/Cold	3/16/09
4	2-duplicate	Heater 1	Hardwood (maple)	Low/Cold	3/17/09
5	3	Heater 1	Softwood (fir)	High/Hot	3/18/09
6	3-duplicate	Heater 1	Softwood (fir)	High/Hot	3/19/09
7	4	Heater 1	Hardwood (maple)	High/Hot	3/19/09
8	4-duplicate	Heater 1	Hardwood (maple)	High/Hot	3/20/09
9	5	Heater 2	Softwood (fir)	Low/Cold	3/21/09
10	5-duplicate	Heater 2	Softwood (fir)	Low/Cold	3/23/09
11	6	Heater 2	Hardwood (maple)	Low/Cold	3/24/09
12	6-duplicate	Heater 2	Hardwood (maple)	Low/Cold	3/25/09
13	7	Heater 2	Softwood (fir)	High/Hot	3/26/09
14	7-duplicate	Heater 2	Softwood (fir)	High/Hot	3/26/09
15	8	Heater 2	Hardwood (maple)	High/Hot	3/27/09
16	8-duplicate	Heater 2	Hardwood (maple)	High/Hot	3/27/09

Heater 1 – Higher Emissions Heater – U.S. EPA certified non-catalytic stove with a particulate certification value of 5.9 g/h, a heat output listing of 11,600-38,700 BTU/h (27,620-100,267 KJ/h), a usable firebox volume of 2.3 cubic feet (65.1 liters) and a default efficiency of 63%.

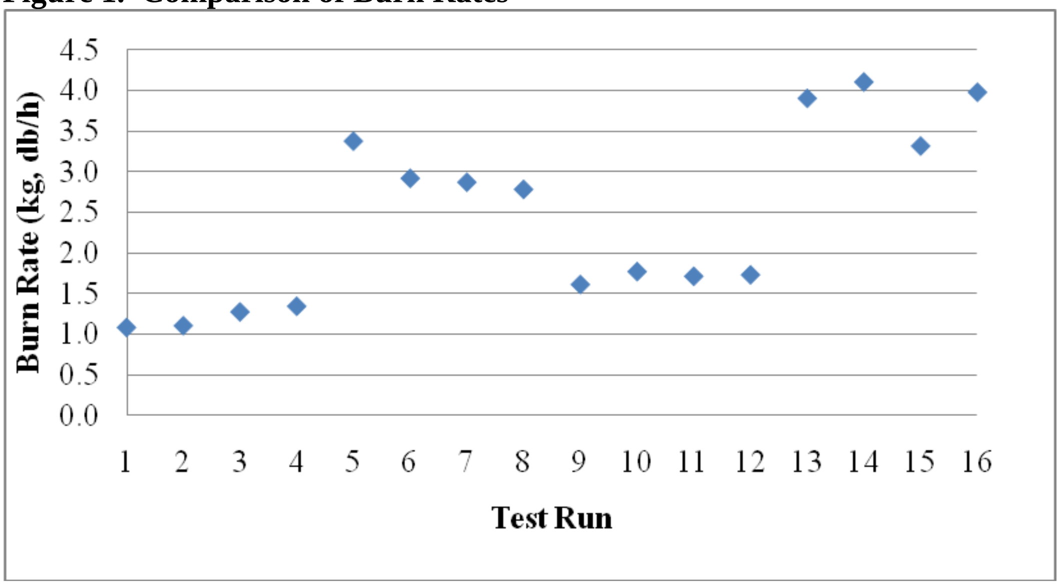
Heater 2 – Lower Emissions Heater – U.S. EPA certified non-catalytic stove with a particulate certification value of 2.1 g/h, a heat output listing of 11,900-43,200 BTU/h (26,924-89,823 KJ/h), a usable firebox volume of 2.1 cubic feet (59.2 liters) and a default efficiency of 63%.

3. Testing Results and Discussion

3.1 Operational Characteristics

Tables 6 and 7 contain wood heater operational characteristics. The parameter that best describes the operational characteristics (in terms of dry mass of fuel and time) is the burn rate, see Figure 1. For all test scenarios there was a difference in burn rates between the higher and lower emissions heaters (the lower emissions heater tests had higher burn rates than the higher emissions heater tests) due to variations in stove design (primary/secondary air, flame baffles, firebox insulation and ash removal components). Also, as expected, the burn rates for the low/cold burn scenarios were lower than the high/hot burn rates.

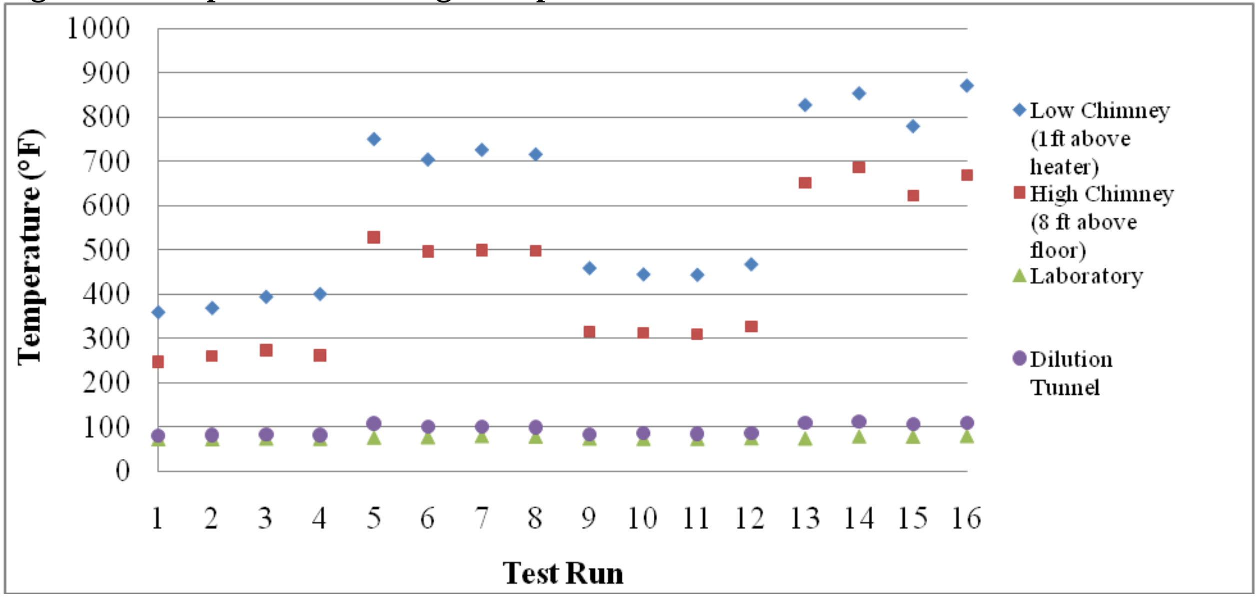
Figure 1. Comparison of Burn Rates



3.2 Temperature Measurements

Tables 8 and 9 contain wood heater temperature measurements. See Appendix C for real time temperature graphs. See Figure 2 for a summary of average temperatures. In general the higher emissions heater had lower flue temperatures than the lower emissions heater. The laboratory and dilution tunnel temperatures were similar between test runs of each burn scenario and between heaters. As would be expected, dilution tunnel temperatures were higher for the high/hot burn scenarios.

Figure 2. Comparison of Average Temperatures



3.3 Efficiencies

Tables 10 and 11 contain wood heater efficiency measurements. Results for each test run are reported by two test methods (both methods are published in CSA B415.1-00: Section 13.9 and Annex D Total Combustible Carbon), two reporting conventions (LHV and HHV) and two fuel properties (default from the method and as measured). Generally, efficiency is a comparison of the actual energy output to the theoretically possible energy output. Both methods calculate overall efficiency by subtracting the measured losses (sensible, latent and chemical) from the energy input (theoretical energy available in the fuel) and dividing by the energy input. The difference in the two conventions is how the energy input, in the denominator (not the numerator) of the efficiency calculation, is calculated. For the HHV efficiency, the energy input is calculated by using the higher heating value for the wood fuel. The use of HHV assumes that the energy associated with water condensation is available for heating. For the LHV efficiency the energy input in the denominator is calculated by subtracting the calculated latent energy losses from the HHV energy input. It should be noted that the method used here to calculate the LHV efficiency is not stated in B415.1-00 and is not the only way to calculate LHV energy input. The use of LHV assumes 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. In both conventions the higher heating values for the fuel and combustion gases, in essence, were used in the numerator of the efficiency calculation. See Appendix D and E for supporting and underlying data. See Appendix J for efficiency uncertainties.

Figure 3 and 4 compare overall efficiencies by each reporting convention (LHV and HHV). One test run (12), the Annex D, TCC results are not reported due to results that did not pass quality control checks as specified in the method. There was little difference between efficiencies for the higher and lower emissions heaters. In addition, there was little difference between the two methods used to measure efficiencies, when the default fuel properties are used. However, there was a large difference between the two methods of measuring efficiencies when the measured fuel properties were used instead of the default values specified in the method. Little difference was found when using the measured or default fuel properties in the Annex D, TCC method. Finally, there was little difference in efficiencies between wood species or burn scenarios, see Figure 4 and 5.

Tables 16-17 contain average efficiencies by the various components: i.e. burn scenario, fuel type and heater model.

Table 21 contains average efficiency results compared to stated efficiency values.

Figure 3. Comparison of Overall Efficiencies (LHV) by Two Methods (Section 13.9 and Annex D, TCC) and Two Fuel Properties (Default from the Method and as Measured).

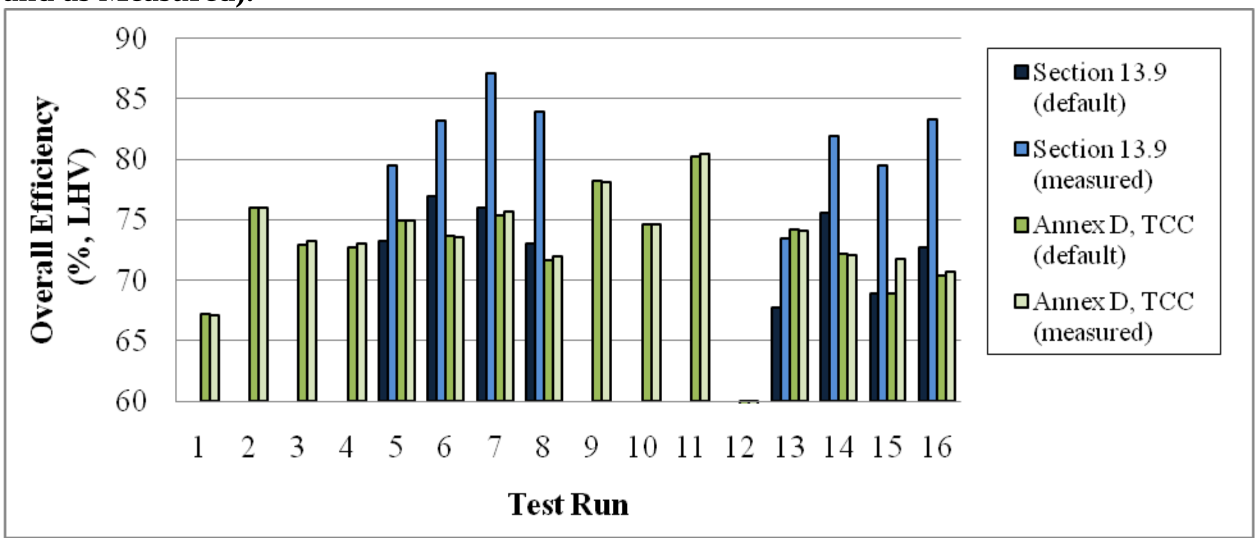


Figure 4. Comparison of Overall Efficiencies (HHV) by Two Methods (Section 13.9 and Annex D, TCC) and Two Fuel Properties (Default from the Method and as Measured).

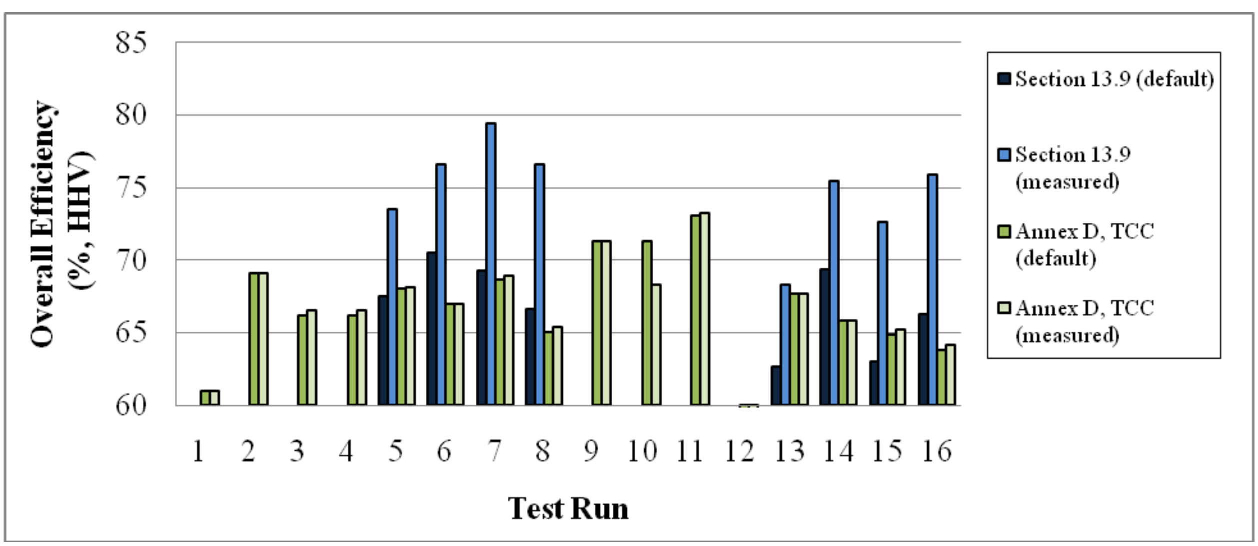


Figure 5. Comparison of Overall Efficiencies (LHV, as measured by Annex D, TCC) as Related to Wood Species and Burn Scenarios.

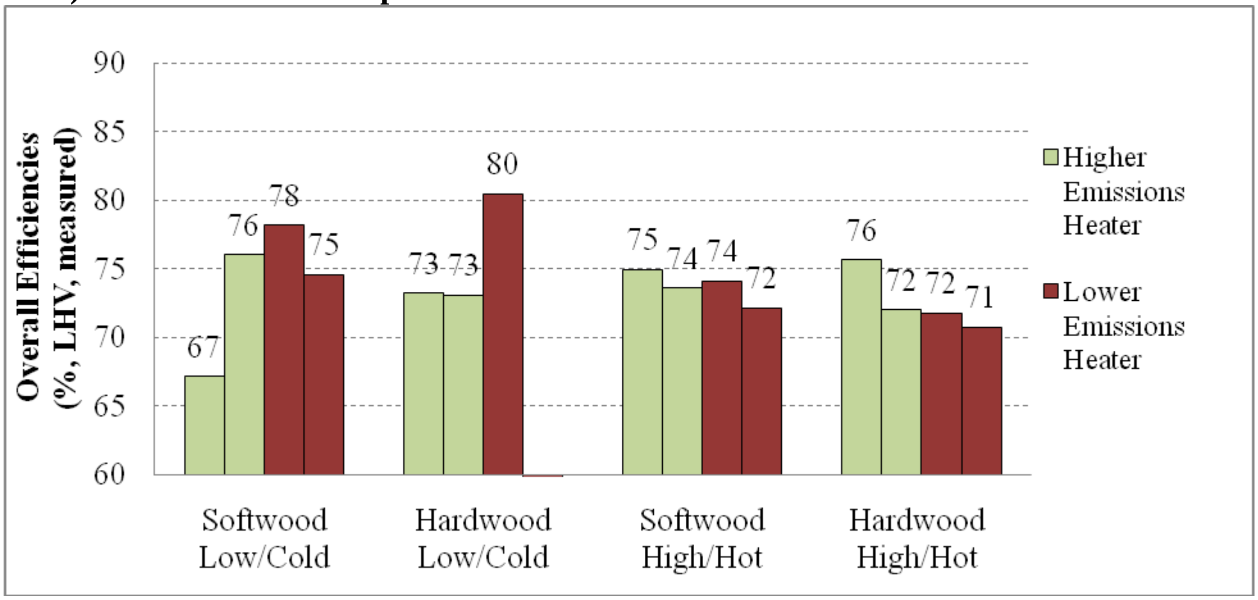
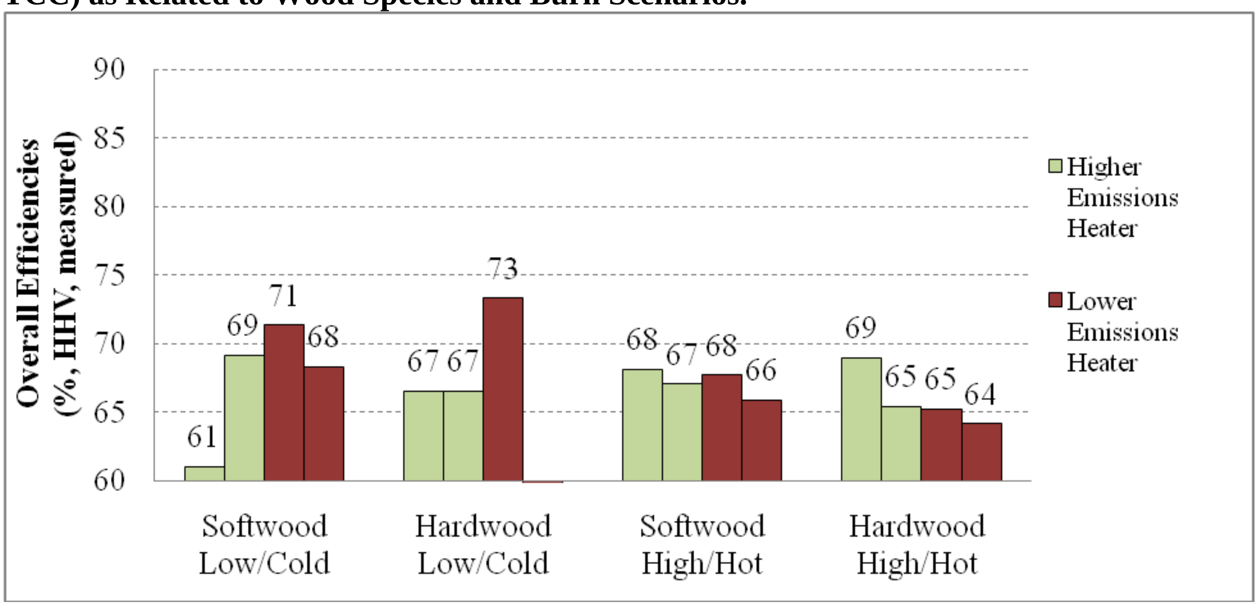


Figure 6. Comparison of Overall Efficiencies (HHV, as measured by Annex D, TCC) as Related to Wood Species and Burn Scenarios.



3.4 Air Emissions

Tables 12, 13, 14 and 15 contain wood heater air emissions measurements. Particulate data have been reported both as directly measured with the Method 5G-like sampler and as converted to Method 5H-equivalent values. The Method 5G to 5H-equvalent conversions were accomplished using both the conversions formulas provided as part of the emission factor documentation for AP-42 and the NSPS. There are a number of compounds "reported as", which means there is a different molecular weight used in the emissions calculation. VOCs have been reported as carbon, as methane, and as heptane. Nitrogen oxides (NO_x) are reported as NO_2. These reporting conventions were chosen based on how the pollutant is typically reported in the literature. VOCs were reported using three conventions to aid in comparisons to other reports and literature values. See Appendix C for real time gas analyzer graphs of stack and tunnel measurements. See Appendix J for air emission uncertainties.

As expected, the higher emissions heater had higher air emissions than the lower emissions heater, see Figures 7-10. When comparing the difference between hardwood and softwood in terms of particulate emissions there was no trend, however there were differences measured, see Figure 11. The higher emission heater had greater particulate emissions during the softwood tests and the lower emission heater had greater particulate emissions during the hardwood tests. In terms of burn scenarios, the high/hot had much lower emissions than the low/cold in both heaters, see Figure 11.

For each $PM_{2.5}$ test result, the tables include a ratio of fine particulate to total particulate (reported as M5G), expressed as a percentage. The average ratio of $PM_{2.5}$/PM (for all tests with data) was 89% ± 14%. The results show variability in the $PM_{2.5}$/PM ratio between tests, with some results showing slightly more $PM_{2.5}$ than total PM. This variability can be attributed to a number of factors including: separate sampling trains with different sampling probes and filter assemblies (the $PM_{2.5}$ sampling train incorporated a size selective cyclone/nozzle designed to meet EPA requirements for in-stack measurements of particulate matter equal to or less than 2.5 microns, where as the PM sampling train had no size selective inlets prior to the filter assembly), slightly different sampling rates, and single as opposed to duplicate sampling trains. Overall the results are within typical uncertainties of particulate measurements from combustion sources, which is in the range of ± 20%.

Tables 16-17 compare average air emissions by various components: i.e. burn scenario, fuel type and heater model.

Table 19 contains particulate emission factors compared to other studies.

Figure 7. Comparison of PM (M5G), $PM_{2.5}$, and PM (M5H-equivalent, NSPS) Emission Factors

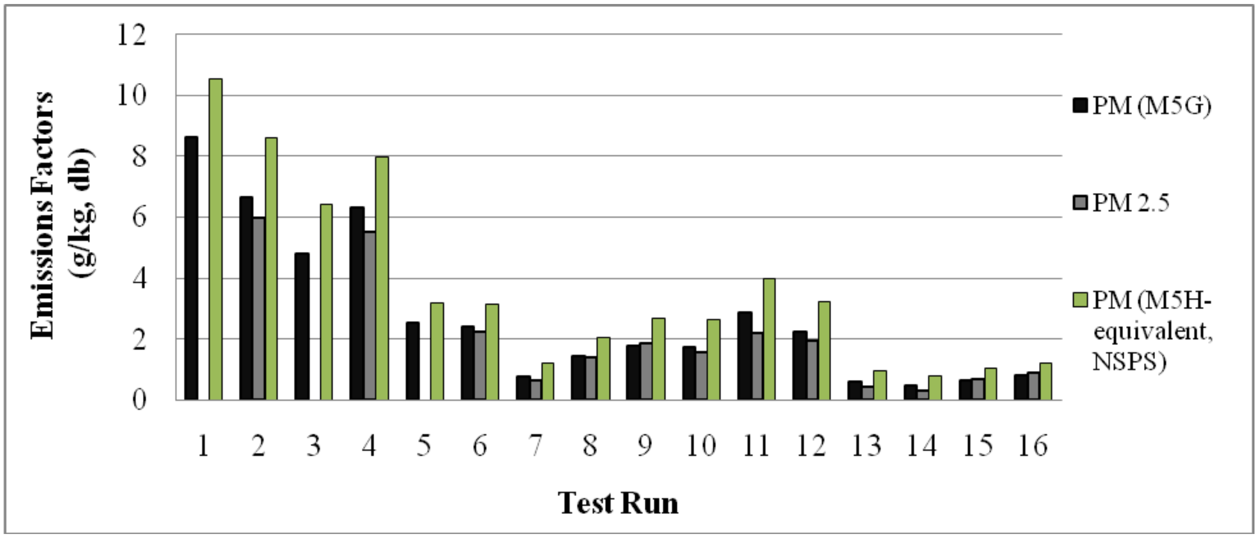


Figure 8. Comparasion of Selected Emission Factors (High Scale)

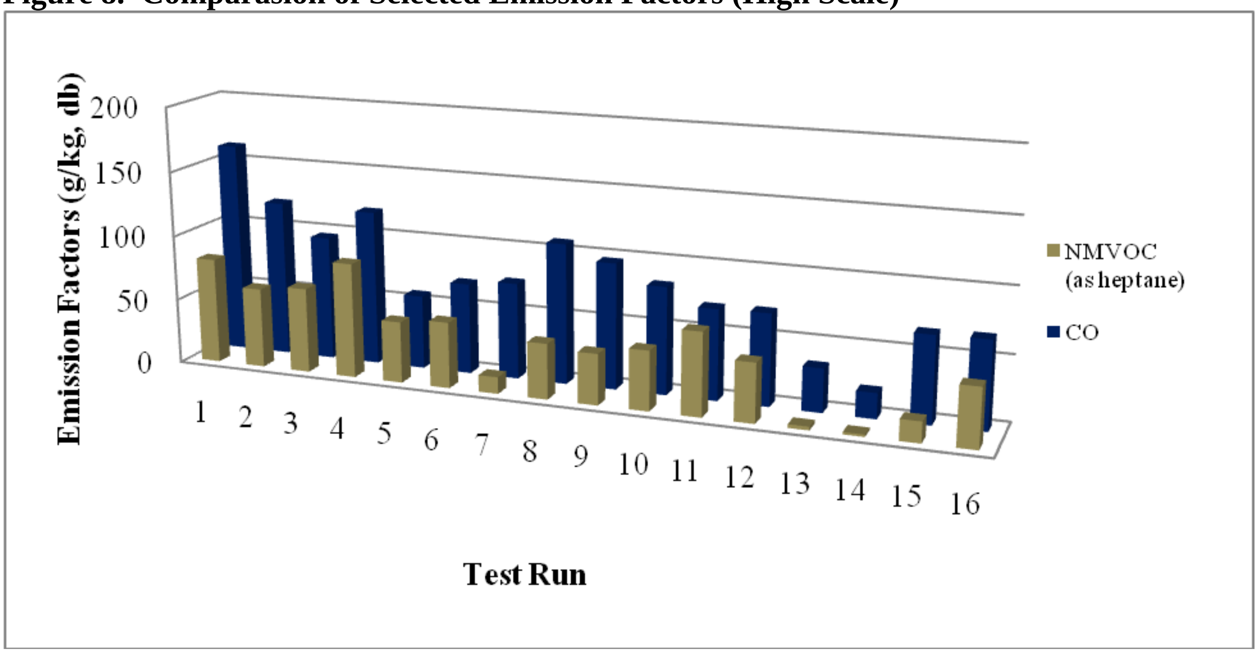


Figure 9. Comparison of Selected Air Emissions (Medium Scale)

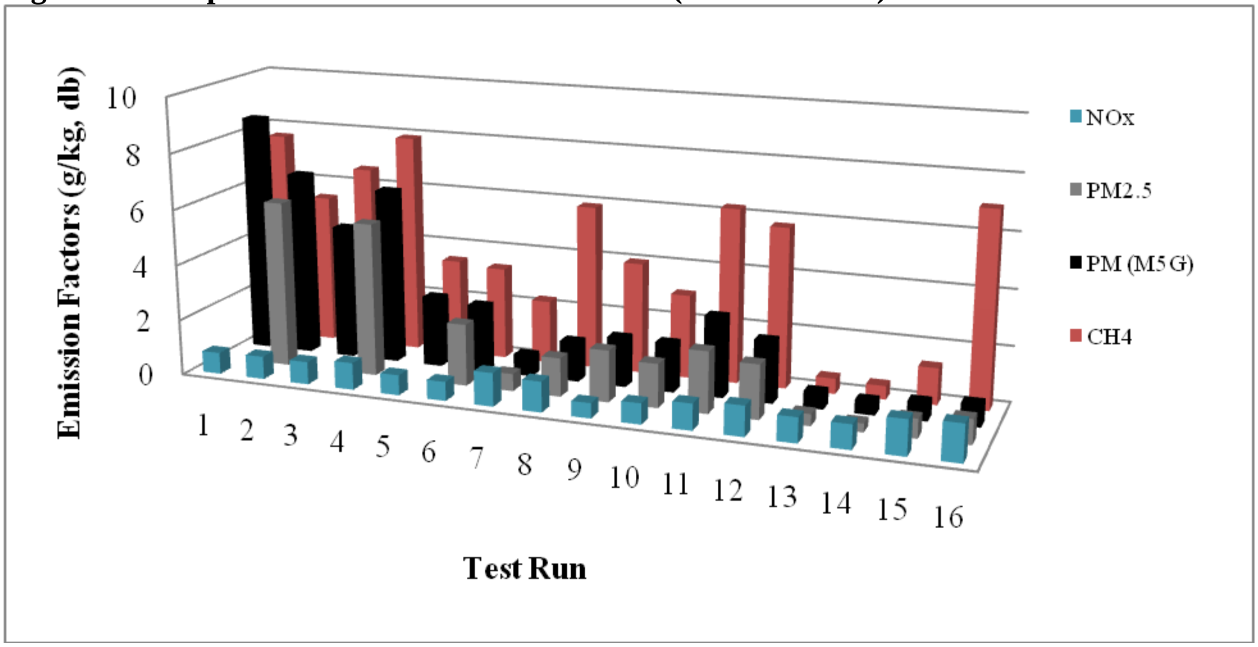
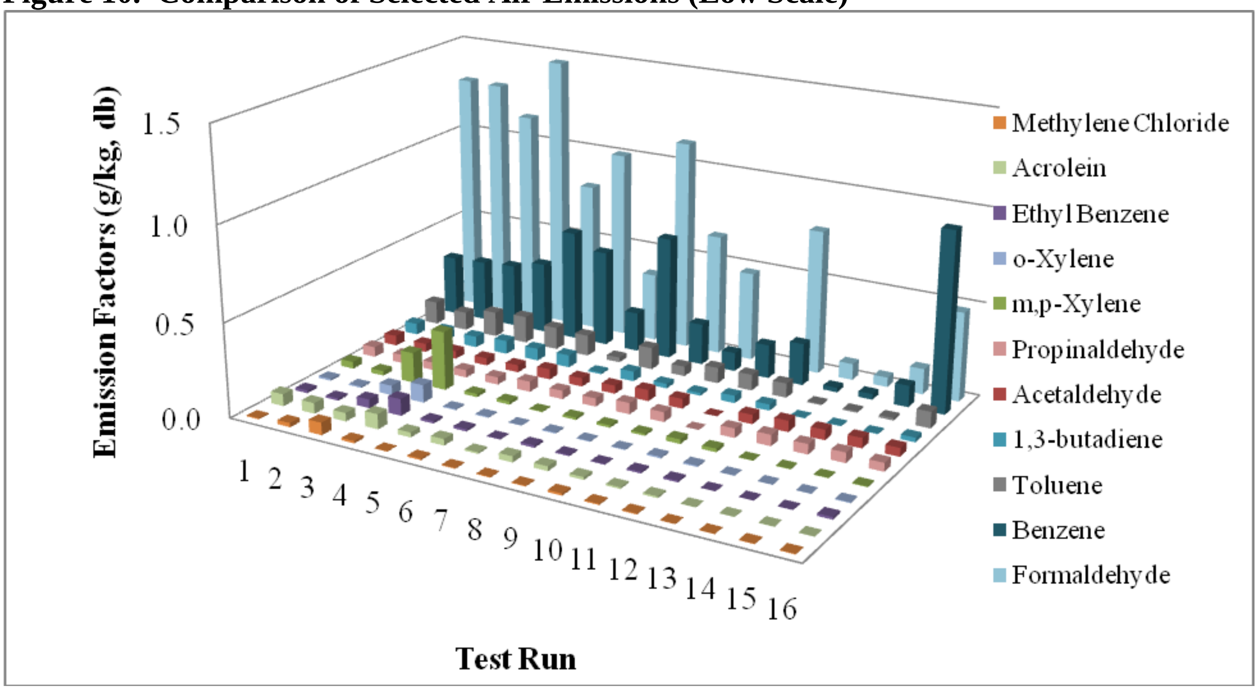
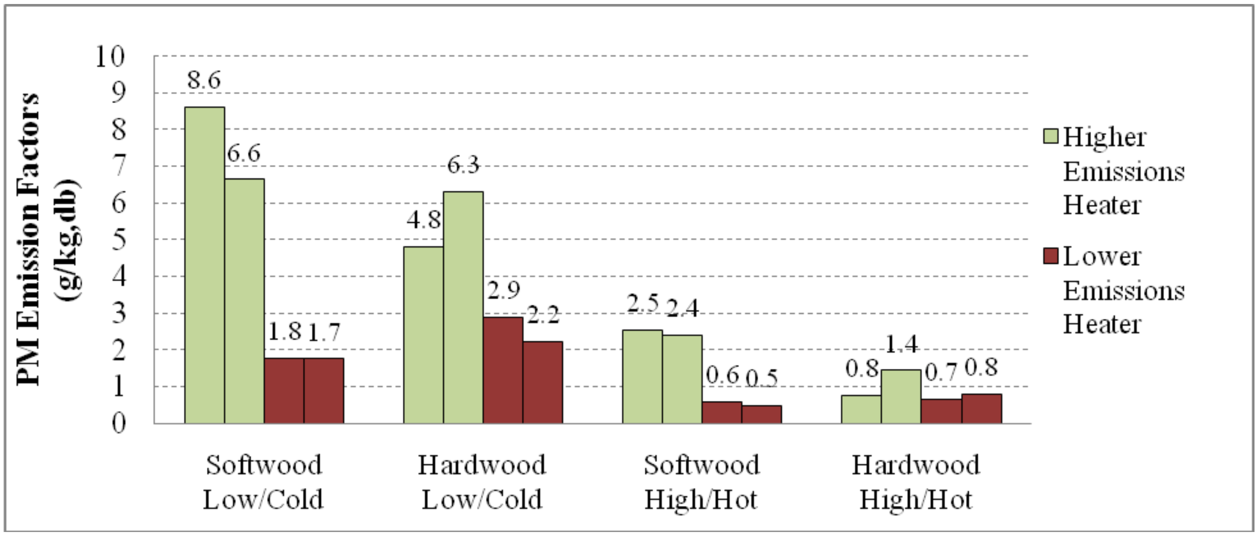


Figure 10. Comparison of Selected Air Emissions (Low Scale)*



*Pollutants listed in order, figure front to back corresponds with list top to bottom

Figure 11. Comparison of PM (M5G) Emission Factors as Related to Tree Species and Burn Scenarios.



3.5 Fuel and Combustion Residue Composition

Table 18 contains fuel analysis results and heating values for the softwood and hardwood cordwood, in addition to the combustion residue. Default fuel properties from each efficiency method are also provided. For all tests the fuel charge was consumed by the end of the test.

Table 6. Wood Heater Operational Characteristics, Higher Emissions Heater

Characteristic	Units	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Burn Rate[1]	kg/hr, db	1.08	1.10	1.27	1.34	3.37	2.92	2.87	2.78
Total Mass of Fuel[2]	kg, db	7.92	7.90	8.79	9.39	8.71	8.02	9.56	9.73
Mass of Kindling	kg, db	1.11	1.14	1.10	1.07	na	na	na	na
Mass of Starter Logs	kg, db	2.70	2.58	3.10	3.74	na	na	na	na
Mass of Main Fuel Load	kg, db	4.12	4.19	4.60	4.59	8.71	8.02	9.56	9.73
Moisture of Fuel[3]	%, db	19.83	20.92	22.10	20.12	17.98	18.04	21.80	23.15
Moisture of Fuel	%, wb	16.55	17.30	18.10	16.75	15.24	15.28	17.90	18.80
Length of Test	Hours	7.33	7.17	6.92	7.00	2.58	2.75	3.33	3.50

[1]End points: Low/Cold start tests: As stated in CSA B415.1-00, "The average of the five appliance surface temperature measurements (centrally on the top, left sidewall, right sidewall, bottom and back) at the start of the test run and at the completion of the test run shall be within 70 Celsius degrees (158 Fahrenheit degrees)." A separate endpoint was needed for the Low/Cold tests because the remaining mass did not ever equal 0.00 kg. Hot start tests: as stated in CSA B415.1-00 "The test run is completed when the remaining weight of the test fuel charge is zero. End the test run when the scale has indicated a test fuel charge weight of 0.00 kg for 30 s."

[2]Includes kindling, starter logs and main fuel load.

[3]Average percent moisture (dry basis) as measured from each piece of fuel with a Delmhorst moisture meter.

na = not applicable

db = dry basis

wb = wet basis

Table 7. Wood Heater Operational Characteristics, Lower Emissions Heater

Characteristic	Units	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run		**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Burn Rate[1]	kg/hr, db	1.61	1.77	1.71	1.73	3.90	4.10	3.31	3.97
Total Mass of Fuel[2]	kg, db	8.04	7.66	9.83	9.65	8.45	8.54	8.83	9.61
Mass of Kindling	kg, db	1.10	1.09	1.06	1.16	na	na	na	na
Mass of Starter Logs	kg, db	2.64	2.67	3.80	3.82	na	na	na	na
Mass of Main Fuel Load	kg, db	4.32	3.90	4.99	4.68	8.45	8.54	8.83	9.61
Moisture of Fuel[3]	%, db	16.71	16.66	22.29	21.71	18.19	17.06	24.20	23.66
Moisture of Fuel	%, wb	14.32	14.28	18.23	17.84	15.39	14.57	19.48	19.13
Length of Test	Hours	5.00	4.33	5.75	5.58	2.17	2.08	2.67	2.42

[1]End points: Low/Cold start tests: As stated in CSA B415.1-00, "The average of the five appliance surface temperature measurements (centrally on the top, left sidewall, right sidewall, bottom and back) at the start of the test run and at the completion of the test run shall be within 70 Celsius degrees (158 Fahrenheit degrees)." A separate endpoint was needed for the Low/Cold tests because the remaining mass did not ever equal 0.00 kg. Hot start tests: as stated in CSA B415.1-00 "The test run is completed when the remaining weight of the test fuel charge is zero. End the test run when the scale has indicated a test fuel charge weight of 0.00 kg for 30 s."
[2]Includes kindling, starter logs and main fuel load.
[3]Average percent moisture (dry basis) as measured from each piece of fuel with a Delmhorst moisture meter.
na = not applicable

Table 8. Temperatures During Tests*, Higher Emissions Heater

Characteristic	Units	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
One foot (30 cm) above heater in chimney, average	ºF	360	369	394	401	750	704	726	716
	ºC	182	187	201	205	399	373	386	380
One foot (30 cm) above heater in chimney, maximum	ºF	708	689	899	847	984	915	1101	1049
	ºC	376	365	482	453	529	491	594	565
Eight feet (2.4 m) above floor in chimney, average	ºF	248	260	273	262	528	497	499	498
	ºC	120	127	134	128	276	258	260	259
Eight feet (2.4 m) above floor in, chimney maximum	ºF	708	515	652	602	675	640	759	754
	ºC	376	269	344	317	357	338	404	401
Laboratory, average	ºF	72	72	73	73	76	77	79	78
	ºC	22	22	23	23	24	25	26	25
Dilution tunnel, average	ºF	81	82	83	83	108	101	101	100
	ºC	27	28	28	28	42	38	38	38

*From start of test to end point

Table 9. Temperatures During Tests*, Lower Emissions Heater

Characteristic	Units	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run		**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
One foot (30 cm) above heater in chimney, average	ºF	459	445	444	468	827	854	779	871
	ºC	237	229	229	242	442	456	415	466
One feet (30 cm) above heater in chimney, maximum	ºF	956	997	1060	1144	1110	1159	1149	1095
	ºC	513	536	571	618	599	626	620	590
Eight feet (2.4 m) above floor in chimney, average	ºF	316	312	310	327	653	686	624	670
	ºC	158	156	154	164	345	363	329	354
Eight foot (2.4 m) above floor in, chimney maximum	ºF	705	742	780	834	849	896	887	802
	ºC	374	395	416	446	454	480	475	428
Laboratory, average	ºF	73	73	73	74	74	78	78	79
	ºC	23	23	23	23	23	26	25	26
Dilution tunnel, average	ºF	83	86	85	86	110	114	107	110
	ºC	28	30	30	30	43	45	42	43

*From start of test to end point

Table 10. Wood Heater Efficiencies (%), Higher Emissions Heater

Overall Efficiency per CSA B415.1-00	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Section 13.9 (HHV, default fuel properties)	na[1]	na[1]	na[1]	na[1]	67.50*	70.47*	69.25*	66.68*
Section 13.9 (LHV, default fuel properties)	na[1]	na[1]	na[1]	na[1]	73.30*	76.97*	75.98*	73.06*
Section 13.9 (HHV, measured fuel properties)	na[1]	na[1]	na[1]	na[1]	73.55*	76.58*	79.42*	76.62*
Section 13.9 (LHV, measured fuel properties)	na[1]	na[1]	na[1]	na[1]	79.49*	83.25*	87.14*	83.95*
Annex D, Total Combustible Carbon (HHV, default fuel properties)	61.01	69.12	66.21†	66.18†	68.09	67.02	68.66†	65.09†
Annex D, Total Combustible Carbon (LHV, default fuel properties)	67.18	76.04	72.91†	72.75†	74.95	73.64	75.37†	71.66†
Annex D, Total Combustible Carbon (HHV, measured fuel properties)	61.00	69.14	66.54	66.51	68.10	67.02	68.95	65.42
Annex D, Total Combustible Carbon (LHV, measured fuel properties)	67.12	76.01	73.22	73.07	74.92	73.59	75.66	71.99

*Includes negative "hydrocarbon" and fuel moisture values, see Appendix J of this report.

HHV-Higher Heating Value of the fuel used in the denominator of the efficiency calculation, assumes that the energy associated with water condensation is available for heating. Higher heating values for the fuel and combustion gases were used in the numerator of the efficiency calculation.

LHV-Lower Heating Values of the fuel was used in the denominator of the efficiency calculation, assumes 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. Higher heating values for the fuel and combustion gases were used in the numerator of the efficiency calculation.

[1]na- not applicable, due to modifications in to the fueling protocol some of the interval calculations of Section 13.9 do not apply to the cold start scenarios with multiple fuel additions and therefore are not reported.

† Default fuel properties for Douglas Fir used in calculations

Table 11. Wood Heater Efficiencies (%), Lower Emissions Heater

Overall Efficiency per CSA B415.1-00	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run	**9**	**8**	**11**	**12**	**13**	**14**	**15**	**16**
Section 13.9 (HHV, default fuel properties)	na[1]	na[1]	na[1]	na[1]	62.67*	69.35*	62.99*	66.31*
Section 13.9 (LHV, default fuel properties)	na[1]	na[1]	na[1]	na[1]	67.79*	75.63*	68.93*	72.71*
Section 13.9 (HHV, measured fuel properties)	na[1]	na[1]	na[1]	na[1]	68.28*	75.42*	72.64*	75.93*
Section 13.9 (LHV, measured fuel properties)	na[1]	na[1]	na[1]	na[1]	73.51*	81.90*	79.48*	83.26*
Annex D, Total Combustible Carbon (HHV, default fuel properties)	71.33	71.33	73.05†	nd	67.71	65.86	64.91†	63.78†
Annex D, Total Combustible Carbon (LHV, default fuel properties)	78.20	74.64	80.25†	nd	74.17	72.16	68.93†	70.37†
Annex D, Total Combustible Carbon (HHV, measured fuel properties)	71.33	68.31	73.29	nd	67.70	65.85	65.24	64.12
Annex D, Total Combustible Carbon (LHV, measured fuel properties)	78.16	74.59	80.47	nd	74.12	72.11	71.78	70.72

*Includes negative "hydrocarbon" and fuel moisture values, see Appendix J of this report.
HHV-Higher Heating Value of the fuel was used in the denominator of the efficiency calculation, assumes that the energy associated with water condensation is available for heating. Higher heating values for the fuel and combustion gases were used in the numerator of the efficiency calculation.
LHV-Lower Heating Value of the fuel was used in the denominator of the efficiency calculation, assumes 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. Higher heating values for the fuel and combustion gases were used in the numerator of the efficiency calculation.
[1]na- not applicable, due to modifications in to the fueling protocol, some of the interval calculations of Section 13.9 do not apply to the cold start scenarios with multiple fuel additions and therefore are not reported.
† Default fuel properties for Douglas Fir used in calculations
nd-no data due to results that did not pass quality control checks as specified in the method.

Table 12. Air Emission Rates (g/h), Higher Emissions Heater

Compound	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Total Particulate (PM) M5G	9.12	7.32	6.11	8.47	8.54	7.00	2.17	3.99
Total Particulate (PM) M5H-equivalent*	11.97	9.81	8.33	11.19	11.28†	9.41†	3.26	5.66
Total Particulate (PM) M5H-equivalent**	11.40	9.50	8.17	10.72	10.79†	9.15†	3.46	5.74
Fine Particulate ($PM_{2.5}$)	nd	6.59	nd	7.39	nd	6.47	1.78	3.83
Percent of Total PM (5G)		90%		87%		92%	82%	96%
Methane (CH_4, as methane)	8.24	5.96	8.41	10.60	11.66	9.70	6.52	16.39
Carbon Monoxide (CO)	171.98	130.67	121.74	156.61	191.31	203.64	211.74	299.52
Nitrogen Oxides (NOx, as NO_2)	0.82	0.89	1.03	1.27	2.45	1.99	3.43	3.03
Total Volatile Organic Compounds (VOC, as carbon, as methane, as heptane)	16.72	12.68	16.73	22.37	28.43	25.53	9.22	25.30
	22.29	16.91	22.30	29.83	37.90	34.03	12.30	33.72
	139.54	105.84	139.58	186.69	237.21	213.03	76.96	211.06
Non-Methane VOCs (NMVOC, as carbon, as methane, as heptane)	10.51	8.10	9.93	14.19	19.00	17.68	4.40	14.18
	14.01	10.80	13.24	18.91	25.33	23.57	5.86	18.90
	87.69	67.61	82.88	118.39	158.57	147.52	36.67	118.31
Carbon Dioxide (CO_2)	2060	2102	2338	2468	6434	5560	5274	5113

*AP-42 conversion: $5H = (1.619) \times (5G)^{0.905}$

**NSPS conversion: $5H = (1.82) \times (5G)^{0.83}$

nd = no data due to torn filter

†NSPS certification value of 5.9 g/h (certification emission rates are weighted averages of emissions from four burn rates with a specific softwood dimensional lumber fueling protocol)

Table 12 (cont). Air Emission Rates (g/h), Higher Emissions Heater

Compound	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Formaldehyde	1.39	1.42	1.44	1.96	2.69	2.92	1.05	3.12
Acetaldehyde	<0.06*	<0.05*	<0.05*	<0.05*	<0.13*	<0.16*	<0.13*	<0.12*
Propinaldehyde	<0.06*	<0.05*	<0.05*	<0.05*	<0.13*	<0.16*	<0.13*	<0.12*
Acrolein	0.069	0.063	0.057	0.107	0.086	0.100	0.025	0.088
Benzene	0.348	0.363	0.433	0.516	1.999	1.505	0.606	1.824
Toluene	0.133	0.108	0.170	0.195	0.402	0.327	0.075	0.326
m,p-Xylene	0.040	0.027	0.206	0.421	0.059	0.048	0.011	0.034
o-Xylene	0.011	0.009	0.065	0.126	0.020	0.016	0.004	0.015
Ethyl Benzene	0.017	0.013	0.059	0.119	0.043	0.036	0.008	0.034
1,3-butadiene	0.065	0.065	0.075	0.097	0.220	0.194	0.026	0.146
Methylene Chloride	0.006	0.024	0.084	0.016	0.008	0.024	0.012	0.011

***** Sample concentrations were below detection, less than values reported with the laboratory detection limit

Table 13. Air Emission Rates (g/h), Lower Emissions Heater

Compound	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Total Particulate (PM) M5G	2.83	3.09	4.92	3.83	2.31	1.99	2.17	3.17
Total Particulate (PM) M5H-equivalent*	4.15	4.49	6.84	5.46	3.45†	3.02†	3.26	4.60
Total Particulate (PM) M5H-equivalent**	4.32	4.64	6.83	5.55	3.64†	3.23†	3.46	4.75
Fine Particulate ($PM_{2.5}$),	2.97	2.77	3.76	3.34	1.63	1.26	2.26	3.52
Percent of Total PM (5G)	105%	90%	76%	87%	71%	63%	104%	111%
Methane (CH_4, as methane)	6.43	5.32	10.72	9.94	2.14	1.98	4.36	27.75
Carbon Monoxide (CO)	152.01	143.69	115.10	116.95	130.64	80.29	220.12	266.68
Nitrogen Oxides (NOx, as NO_2)	0.85	1.29	1.56	1.79	3.48	0.87	4.16	5.28
Total Volatile Organic Compounds (VOC, as carbon,	12.37	13.97	21.94	17.08	3.01	2.53	9.90	46.06
as methane,	16.50	18.62	29.25	22.77	4.01	3.37	13.19	61.39
as heptane)	103.25	116.54	183.08	142.53	25.13	21.08	82.57	384.28
Non-Methane VOCs (NMVOC, as carbon,	7.54	9.68	13.06	9.37	1.29	0.88	6.35	21.56
as methane,	10.05	12.90	17.41	12.49	1.73	1.17	8.47	28.74
as heptane)	62.89	80.77	109.00	78.21	10.80	7.35	53.00	179.89
Carbon Dioxide (CO_2)	3069	3373	3146	3180	7439	7822	6094	7312

*AP-42 conversion: $5H = (1.619) \times (5G)^{0.905}$
**NSPS conversion: $5H = (1.82) \times (5G)^{0.83}$
†NSPS certification value of 2.1 g/h (certification emission rates are weighted averages of emissions from four burn rates with a specific softwood dimensional lumber fueling protocol)

Table 13 (cont). Air Emission Rates (g/h), Lower Emissions Heater

Compound	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Formaldehyde	1.04	0.84	nd	1.33	0.34	0.21	0.45	1.89
Acetaldehyde	<0.10*	<0.09*	nd	<0.09*	<0.23*	<0.22*	<0.18*	<0.18*
Propinaldehyde	<0.10*	<0.09*	nd	<0.09*	<0.23*	<0.22*	<0.18*	<0.18*
Acrolein	0.039	0.026	<0.014*	0.015	<0.006*	<0.006*	<0.006*	<0.005*
Benzene	0.355	0.176	0.307	0.387	0.094	0.125	0.380	3.818
Toluene	0.084	0.148	0.145	0.133	0.025	0.031	0.041	0.346
m,p-Xylene	0.021	0.020	0.041	0.032	0.007	0.014	0.007	0.016
o-Xylene	0.006	0.006	0.014	0.011	0.005	0.005	0.004	0.015
Ethyl Benzene	0.010	0.007	0.015	0.014	0.005	0.005	0.006	0.052
1,3-butadiene	0.040	0.027	0.068	0.058	0.009	0.009	0.012	0.098
Methylene Chloride	0.007	0.020	0.010	0.008	0.007	0.006	0.009	0.012

nd – no data due to sampling problem

***** Sample concentrations were below detection, less than values reported with the laboratory detection limit

Table 14. Air Emission Factors (g/kg, dry fuel), Higher Emissions Heater

Compound	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Total Particulate (PM) M5G	8.61	6.64	4.81	6.31	2.53	2.40	0.76	1.44
Total Particulate (PM) M5H-equivalent*	11.08	8.90	6.55	8.34	3.34	3.23	1.14	2.04
Total Particulate (PM) M5H-equivalent**	10.55	8.62	6.43	7.99	3.20	3.14	1.21	2.06
Fine Particulate ($PM_{2.5}$)	nd	5.98	nd	5.51	nd	2.22	0.62	1.38
Percent of Total PM		90%		87%		92%	82%	96%
Methane (CH_4, as methane)	7.63	5.41	6.62	7.90	3.46	3.33	2.27	5.90
Carbon Monoxide (CO)	162.30	120.04	95.79	119.09	56.72	69.86	73.86	107.77
Nitrogen Oxides (NOx, as NO_2)	0.77	0.82	0.81	0.97	0.73	0.68	1.20	1.09
Total Volatile Organic Compounds (VOC, as carbon,	15.78	11.65	13.16	17.01	8.43	8.76	3.22	9.10
as methane,	21.04	15.53	17.55	22.68	11.24	11.68	4.29	12.13
as heptane)	131.68	97.23	109.82	141.96	70.33	73.08	26.85	75.94
Non-Methane VOCs (NMVOC, as carbon,	9.73	7.35	7.82	10.58	5.63	6.06	1.53	5.10
as methane,	12.97	9.80	10.42	14.10	7.51	8.08	2.04	6.80
as heptane)	81.19	61.35	65.21	88.24	47.01	50.61	12.79	42.57
Carbon Dioxide (CO_2)	1907	1907	1840	1840	1907	1907	1840	1840

*AP-42 conversion: $5H = (1.619) \times (5G)^{0.905}$
**NSPS conversion: $5H = (1.82) \times (5G)^{0.83}$
nd = no data due to torn filter

Table 14 (cont.). Air Emission Factors (g/kg, dry fuel), Higher Emissions Heater

Compound	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Formaldehyde	1.29	1.28	1.13	1.46	0.80	1.00	0.37	1.12
Acetaldehyde	<0.05*	<0.05*	<0.04*	<0.04*	<0.04*	<0.06*	<0.05*	<0.04*
Propinaldehyde	<0.05*	<0.05*	<0.04*	<0.04*	<0.04*	<0.06*	<0.05*	<0.04*
Acrolein	0.064	0.057	0.045	0.080	0.026	0.034	0.009	0.032
Benzene	0.322	0.329	0.341	0.385	0.593	0.516	0.211	0.656
Toluene	0.123	0.098	0.134	0.145	0.119	0.112	0.026	0.117
m,p-Xylene	0.037	0.024	0.162	0.314	0.017	0.017	0.004	0.012
o-Xylene	0.010	0.008	0.052	0.094	0.006	0.006	0.002	0.006
Ethyl Benzene	0.016	0.012	0.046	0.089	0.013	0.012	0.003	0.012
1,3-butadiene	0.060	0.059	0.059	0.072	0.065	0.067	0.009	0.053
Methylene Chloride	0.006	0.022	0.066	0.012	0.002	0.008	0.004	0.004

***** Sample concentrations were below detection, less than values reported with the laboratory detection limit

Table 15. Air Emission Factors (g/kg, dry fuel), Lower Emissions Heater

Compound	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Total Particulate (PM) M5G	1.76	1.75	2.88	2.22	0.59	0.49	0.65	0.80
Total Particulate (PM) M5H-equivalent*	2.58	2.54	4.00	3.16	0.89	0.74	0.98	1.16
Total Particulate (PM) M5H-equivalent**	2.68	2.62	3.99	3.21	0.93	0.79	1.04	1.19
Fine Particulate ($PM_{2.5}$)	1.85	1.57	2.20	1.93	0.42	0.31	0.68	0.88
Percent of Total PM	105%	90%	76%	87%	71%	63%	104%	111%
Methane (CH_4, as methane)	4.00	3.01	6.27	5.75	0.55	0.48	1.32	6.98
Carbon Monoxide (CO)	96.64	82.54	69.65	70.31	33.50	19.58	66.45	67.09
Nitrogen Oxides (NOx, as NO_2)	0.54	0.74	0.94	1.08	0.89	0.87	1.25	1.33
Total Volatile Organic Compounds (VOC, as carbon, as methane, as heptane)	7.87	8.02	13.28	10.27	0.77	0.62	2.99	11.59
	10.49	10.69	17.70	13.69	1.03	0.82	3.98	15.45
	65.65	66.94	110.78	85.69	6.44	5.14	24.93	96.68
Non-Methane VOCs (NMVOC, as carbon, as methane, as heptane)	4.68	5.47	7.64	5.42	0.33	0.21	1.92	5.42
	6.25	7.30	10.18	7.23	0.44	0.29	2.56	7.23
	39.09	45.68	63.74	45.25	2.77	1.79	16.00	45.26
Carbon Dioxide (CO_2)	1907	1907	1840	1840	1907	1907	1840	1840

*AP-42 conversion: $5H = (1.619) \times (5G)^{0.905}$
**NSPS conversion: $5H = (1.82) \times (5G)^{0.83}$

Table 15 (cont.). Air Emission Factors (g/kg, dry fuel), Lower Emissions Heater

Compound	Softwood Low/Cold	Softwood Low/Cold Duplicate	Hardwood Low/Cold	Hardwood Low/Cold Duplicate	Softwood High/Hot	Softwood High/Hot Duplicate	Hardwood High/Hot	Hardwood High/Hot Duplicate
Test Run	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Formaldehyde	0.64	0.47	nd	0.77	0.09	0.05	0.14	0.48
Acetaldehyde	<0.06*	<0.05*	nd	<0.05*	<0.06*	<0.05*	<0.05*	<0.05*
Propinaldehyde	0.06	0.05	nd	0.05	0.06	0.05	0.05	0.05
Acrolein	0.024	0.015	<0.008*	0.009	<0.002*	<0.001*	<0.002*	<0.001*
Benzene	0.221	0.099	0.180	0.224	0.024	0.030	0.115	0.961
Toluene	0.052	0.083	0.085	0.077	0.006	0.008	0.012	0.087
m,p-Xylene	0.013	0.011	0.024	0.019	0.002	0.003	0.002	0.004
o-Xylene	0.004	0.003	0.008	0.007	0.001	0.001	0.001	0.004
Ethyl Benzene	0.006	0.004	0.009	0.008	0.001	0.001	0.002	0.013
1,3-butadiene	0.025	0.015	0.040	0.034	0.002	0.002	0.004	0.025
Methylene Chloride	0.004	0.011	0.006	0.005	0.002	0.001	0.003	0.003

nd – no data due to sampling problem
***** Sample concentrations were below detection, less than values reported with the laboratory detection limit

Table 16. Comparisons of Averages* (with Associated Standard Deviations) for Air Emission Rates (g/h) and Efficiencies (%)

Compound	High/Hot	Std. Dev.	Low/Cold	Std. Dev.	Softwood	Std. Dev.	Hardwood	Std. Dev.	Higher Emissions Heater	Std. Dev.	Lower Emissions Heater	Std. Dev.
PM, M5G	3.92	2.50	5.71	2.43	5.27	3.00	4.35	2.13	6.59	2.42	3.04	0.97
PM, M5H**	5.49	3.16	7.78	3.02	7.20	3.76	6.08	2.68	8.86†	3.02	4.41†	1.27
PM, M5H ***	5.53	2.90	7.64	2.74	7.08	3.44	6.08	2.46	8.61†	2.75	4.55†	1.20
$PM_{2.5}$	3.34	1.99	4.70	2.03	4.37	2.46	3.67	1.67	5.35	2.07	2.69	0.90
CH_4	10.06	8.69	8.20	2.13	6.43	3.40	11.84	7.33	9.69	3.32	8.58	8.38
CO	200.49	69.82	138.59	20.74	150.53	39.13	188.56	71.67	185.90	56.24	153.18	60.99
NOx, (as NO_2)	3.09	1.35	1.19	0.35	1.58	0.98	2.69	1.53	1.86	1.02	2.41	1.67
VOC (as C, as CH_4, as heptane)	18.75	15.16	16.73	3.82	14.41	9.29	21.07	11.62	19.62	6.82	15.86	13.86
	24.99	20.21	22.31	5.09	19.20	12.38	28.09	15.48	26.16	9.09	21.14	18.47
	156.42	126.47	139.63	31.87	120.20	77.51	175.85	96.92	163.74	56.88	132.31	115.63
NMVOC (as C, as CH_4, as heptane)	10.67	8.38	10.30	2.29	9.34	6.61	11.63	5.37	12.25	4.93	8.72	6.64
	14.22	11.17	13.73	3.05	12.45	8.81	15.50	7.16	16.33	6.57	11.62	8.85
	89.01	69.90	85.93	19.09	77.90	55.12	97.04	44.81	102.20	41.10	72.74	55.41
CO_2	6381	1046	2717	530	4732	2364	4366	1838	3919	1838	5179	2182

* Burn scenario averages across all fuel types and heater type, fuel type averages across all burn scenarios and heater types, heater type averages across all burn scenarios and fuel types

** AP-42 conversion: $5H = (1.619) \times (5G)^{0.905}$

*** NSPS conversion: $5H = (1.82) \times (5G)^{0.83}$

†NSPS certification value of 5.9 g/h for the higher emissions heater and 2.1 g/h for the lower emission heater (certification emission rates are weighted averages of emissions from four burn rates with a specific softwood dimensional lumber fueling protocol)

Table 16 (cont). Comparisons of Averages* (with Associated Standard Deviation) Air Emission Rates (g/h) and Efficiencies (%)

Compound	High/Hot	Std. Dev.	Low/Cold	Std. Dev.	Softwood	Std. Dev.	Hardwood	Std. Dev.	Higher Emissions Heater	Std. Dev.	Lower Emissions Heater	Std. Dev.
Formaldehyde	1.58	1.22	1.18	0.58	1.36	1.00	1.40	0.96	2.00	0.80	0.76	0.64
Acetaldehyde**	<0.170	0.042	<0.061	0.031	<0.131	0.070	<0.101	0.064	<0.095	0.046	<0.136	0.080
Propinaldehyde**	<0.170	0.042	<0.061	0.031	<0.131	0.070	<0.101	0.064	<0.095	0.046	<0.136	0.080
Acrolein	0.040	0.043	0.049	0.032	0.049	0.036	0.040	0.040	0.074	0.027	0.015	0.012
Benzene	1.294	1.271	0.361	0.098	0.621	0.719	1.034	1.228	0.949	0.702	0.705	1.263
Toluene	0.197	0.167	0.139	0.034	0.157	0.137	0.179	0.109	0.217	0.120	0.119	0.105
m,p-Xylene	0.024	0.020	0.101	0.143	0.029	0.018	0.096	0.146	0.106	0.141	0.020	0.012
o-Xylene	0.011	0.007	0.031	0.043	0.010	0.006	0.032	0.043	0.033	0.042	0.008	0.005
Ethyl Benzene	0.024	0.020	0.032	0.039	0.017	0.015	0.039	0.038	0.041	0.036	0.014	0.016
1,3-butadiene	0.089	0.088	0.062	0.021	0.079	0.082	0.072	0.043	0.111	0.069	0.040	0.032
Methylene Chloride	0.011	0.006	0.022	0.026	0.013	0.008	0.020	0.026	0.023	0.025	0.010	0.004
Overall Efficiency by Annex D, TCC (HHV, measured fuel properties)	66.55	1.65	68.02	3.95	67.31	3.01	67.15	3.10	66.58	2.60	67.98	3.33
Overall Efficiency by Annex D, TCC (LHV, measured fuel properties)	73.11	1.72	74.66	4.27	73.83	3.24	73.84	3.31	73.20	2.82	74.56	3.57

* Burn scenario averages across all fuel types and heater type, fuel type averages across all burn scenarios and heater types, heater type averages across all burn scenarios and fuel types

** Sample concentrations were below detection, less than values reported with the laboratory detection limit

Table 17. Comparisons of Averages* (with Associated Standard Deviations) Air Emission Factors (g/kg) and Efficiencies (%)

Compound	Average High/Hot	Std. Dev.	Average Low/Cold	Std. Dev.	Average Softwood	Std. Dev.	Average Hardwood	Std. Dev.	Higher Emissions Heater	Std. Dev.	Lower Emissions Heater	Std. Dev.
PM, M5G	1.21	0.83	4.37	2.61	3.10	2.94	2.48	2.09	4.19	2.82	1.39	0.89
PM, M5H[1,2]	1.69	1.06	5.89	3.29	4.16	3.77	3.42	2.74	5.58	3.64	2.01	1.23
PM, M5H [3]	1.70	0.99	5.76	3.06	4.07	3.56	3.39	2.61	5.40	3.45	2.06	1.22
$PM_{2.5}$	0.93	0.67	3.17	2.01	2.06	2.07	1.89	1.71	3.14	2.45	1.23	0.74
CH_4	3.04	2.40	5.82	1.68	3.48	2.36	5.38	2.32	5.31	2.10	3.54	2.62
CO	61.85	26.68	102.04	31.05	80.15	46.47	83.75	20.79	100.68	34.20	63.22	25.06
NOx, (as NO_2)	1.01	0.25	0.83	0.16	0.76	0.11	1.08	0.17	0.88	0.18	0.96	0.26
VOC (as C, as CH_4, as heptane)	5.68	4.25	12.13	3.34	7.74	5.08	10.08	4.91	10.89	4.47	6.92	4.91
	7.58	5.67	16.17	4.46	10.31	6.78	13.43	6.54	14.52	5.96	9.23	6.54
	47.42	35.49	101.22	27.91	64.56	42.42	84.08	40.93	90.86	37.30	57.78	40.94
NMVOC (as C, as CH_4, as heptane)	3.28	2.51	7.34	2.09	4.94	3.26	5.68	3.03	6.73	2.85	3.89	2.72
	4.37	3.35	9.78	2.79	6.58	4.35	7.57	4.04	8.97	3.79	5.18	3.63
	27.35	20.97	61.22	17.48	41.19	27.21	47.38	25.27	56.12	23.74	32.45	22.73
CO_2	1,873	36	1,873	36	1,907	0	1,840	0	1873	36	1873	36

* Burn scenario averages across all fuel types and heater type, fuel type averages across all burn scenarios and heater types, heater type averages across all burn scenarios and fuel types

[1]AP-42 conversion: $5H = (1.619) \times (5G)^{0.905}$

[2]AP-42 Emission factor for residential wood heaters (phase II non-catalytic) is 7.3 g/kg

[3]NSPS conversion: $5H = (1.82) \times (5G)^{0.83}$

Table 17 (cont.). Comparisons of Averages* (with Associated Standard Deviations) Air Emission Factors (g/kg) and Efficiencies (%)

Compound	Average High/Hot	Std. Dev.	Average Low/Cold	Std. Dev.	Average Softwood	Std. Dev.	Average Hardwood	Std. Dev.	Higher Emissions Heater	Std. Dev.	Lower Emissions Heater	Std. Dev.
Formaldehyde	0.505	0.422	1.008	0.376	0.704	0.484	0.780	0.479	1.06	0.34	0.38	0.29
Acetaldehyde**	0.050	0.007	0.043	0.019	0.053	0.007	0.040	0.017	0.046	0.006	0.047	0.020
Propinaldehyde**	0.050	0.007	0.043	0.019	0.053	0.007	0.040	0.017	0.046	0.006	0.047	0.020
Acrolein	0.013	0.015	0.038	0.028	0.028	0.023	0.023	0.028	0.043	0.023	0.008	0.008
Benzene	0.388	0.343	0.263	0.097	0.267	0.214	0.384	0.287	0.419	0.153	0.232	0.304
Toluene	0.061	0.052	0.100	0.032	0.075	0.048	0.086	0.048	0.109	0.036	0.051	0.037
m,p-Xylene	0.008	0.007	0.076	0.108	0.016	0.011	0.068	0.113	0.073	0.110	0.010	0.008
o-Xylene	0.003	0.002	0.023	0.033	0.005	0.003	0.022	0.034	0.023	0.033	0.004	0.003
Ethyl Benzene	0.007	0.006	0.024	0.030	0.008	0.006	0.023	0.030	0.025	0.029	0.006	0.004
1,3-butadiene	0.028	0.029	0.045	0.020	0.037	0.029	0.037	0.024	0.055	0.020	0.018	0.015
Methylene Chloride	0.003	0.002	0.017	0.021	0.007	0.007	0.013	0.022	0.016	0.021	0.004	0.003
Overall Efficiency by Annex D, TCC (HHV, measured fuel properties)	66.55	1.65	68.02	3.95	67.31	3.01	67.15	3.10	66.58	2.60	67.98	3.33
Overall Efficiency by Annex D, TCC (LHV, measured fuel properties)	73.11	1.72	74.66	4.27	73.83	3.24	73.84	3.31	73.20	2.82	74.56	3.57

* Burn scenario averages across all fuel types and heater type, fuel type averages across all burn scenarios and heater types, heater type averages across all burn scenarios and fuel types

** Sample concentrations were below detection, less than values reported with the laboratory detection limit

Table 18. Default Fuel Properties from CSA B415.1-00, Measured Fuel and Combustion Residue Characterization

Analysis	Units	Default Fuel Properties from CSA B415.1-00 Section 13.9	Default Fuel Properties from CSA B415.1-00 Annex D, TCC	Softwood Cordwood (Douglas Fir)	Hardwood Cordwood (Maple)	Softwood Combustion Residue[1]	Hardwood Combustion Residue[1]
Moisture	percent, dry basis	-	-	18.17*	22.38*	na	na
Moisture	percent, wet basis	-	-	15.37	18.28	na	na
Loss on Drying	percent, as received	-	-	9.38	10.00	4.84	2.91
Carbon	percent, dry basis	48.73	50.8	52.02	50.17	70.87	63.02
Hydrogen	percent, dry basis	6.87	5.83	5.95	5.79	1.34	1.24
Nitrogen	percent, dry basis	-	-	0.04	0.13	0.44	0.32
Sulfur	percent, dry basis	-	-	<0.05	<0.05	0.05	0.11
Oxygen	percent, dry basis	43.90	-	31.50	32.40	16.18	16.08
Ash	percent, dry basis	0.50	-	0.13	0.50	7.58	21.03
Energy content (HHV)	Btu/lb, dry basis	8517	8517	8693	8512	10612	9699
	KJ/kg, dry basis	19,810	19,810	20,246	19,825	24,716	22,589
Energy content (LHV)[2]	Btu/lb, dry basis	7694[†]	7694[†]	7983	7787	10,438	9554
	KJ/kg, dry basis	17,898[†]	17,898[†]	18,593	18,136	24,310	22,252

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

[1]Softwood combustion residue from test run 1 low/cold, higher emission heater. Hardwood combustion residue from test run 3 low/cold, higher emissions heater

[2] LHV of fuel was calculated using the equation LHV (BTU/lb) = HHV (BTU/lb) – 10.3(%Moisture, wet basis + (9 x %Hydrogen, dry basis))

[†] 18 percent wet basis moisture was used in the calculation of LHV energy content

4. Literature Review

Three literature review compilations have been provided here to permit comparison with the values obtained in this study. The first consists of comparing emission factors for all key pollutants (Section 4.1). The second compares total PM values for both hot and cold starts (Section 4.2). The third compares efficiencies (Section 4.3). All sources of the data are provided in the references.

4.1 Comparison of Pollutant Emission Factors

Emission factors for certified non-catalytic cordwood heaters were obtained from: (1) units that are certified under the NSPS program, and (2) high-technology units sold outside of the United States that are equivalent to modern certified units sold in the U.S. Table 19 provides a comparison of average emission factors obtained from the literature review with the average and standard deviation values obtained from this study. The particulate values are reported as "5H equivalent" values as that is the convention used for reporting certification values. In the literature PM and $PM_{2.5}$ values are treated as equivalent as in most cases only total PM was measured. However, to more accurately report emission factors we estimated $PM_{2.5}$ emissions by multiplying the PM value by the average $PM_{2.5}$ fraction reported in this study (89%). Our findings fell within the range of other (limited) research[16] into size distribution of particles from a certified wood stove of ~70% at high burn rates and >90% at low burn rates.

Literature values of emissions from EPA-certified wood heaters were not available for a number of pollutants therefore their values were estimated from literature values on uncertified heaters. Benzene, 1,3-Butadiene, Acrolein, Methane, and VOC emission factors estimated by multiplying the respective emission factors for uncertified conventional cordwood heaters by the ratio of the certified non-catalytic cordwood heater PM emission factor to the uncertified conventional cordwood heater PM emission factor. The reasoning behind using this technique for estimations is that other air pollutants, all being products of incomplete combustion, should follow the trend of particulate emissions.

Table 19. Certified Non-Catalytic Cordwood Heater Emission Factors

Pollutant	Average This Study ± Standard Deviation	Average Literature Value.	References
PM (g/kg)[1]	3.73 ± 3.04	7.51	1-10
$PM_{2.5}$ (g/kg)[1]	2.16 ± 1.86	6.68[*]	1-10
NO_x (g/kg)[2]	0.92 ± 0.22	1.14	Average of cat. and conv. see reference 11
CO (g/kg)	81.9 ± 34.8	70.4	2-9
SO_2 (g/kg)	nd	0.20	2-9
NH_3 (g/kg)	nd	0.45	12
Benzene (g/kg)	0.33 ± 0.25	0.48[†]	13,14 (AP-42)
Phenol (g/kg)	nd	0.24	1,15,16
7-PAH (g/kg)	nd	0.014	1,17-20
16-PAH (g/kg)	nd	0.16	1,16-20
Benzo(a)pyrene (mg/kg)	nd	1.09	1,15,17-23
Naphthalene (g/kg)	nd	0.069	1,15-20
1,3-Butadiene (g/kg)	0.04 ± 0.03	0.087[†]	13
Formaldehyde (g/kg)	0.74 ± 0.47	1.11	16
Acetaldehyde (g/kg)	<0.046 ± 0.01	0.32	16
Acrolein (g/kg)	0.03 ± 0.02	0.020[†]	13
Cresols (g/kg)[3]	nd	0.23	1,15
PCB_{TEQ} (pg/kg)	nd	1.40	21-23
$Dioxin_{TEQ}$ (ng/kg)	nd	0.40	21-25
Methane (g/kg)	4.4 ± 2.5	14.2[†]	14
NMVOC (g/kg, as carbon, as methane)	5.3 ± 3.1, 7.08 ± 4.1	10.1[**†]	13

[1] Reported as EPA Method 5H equivalent (NSPS conversion: $5H = (1.82) \times (5G)^{0.83}$)
[2]Reported as NO_2
[3]Sum of o, m, and p isomers
[*]Estimated by multiplying the PM value by the average $PM_{2.5}$ fraction, reported in this study (89%).
[**]as "reported", which could be a number of VOC reporting factors (It is assumed the values are carbon or methane, based on magnitude)
nd = no data
[†]Benzene, 1,3-Butadiene, Acrolein, Methane, and NMVOC emission factors estimated by multiplying the respective emission factors for uncertified conventional cordwood heaters by the ratio of the certified non-catalytic cordwood heater PM emission factor to the uncertified conventional cordwood heater PM emission factor.

4.2 Comparison of Particulate Emission Factors (5G basis) between Cold- and Hot- Start Scenarios

There has been considerable interest in the difference in particulate emissions from cold-start and hot-start scenarios. Table 20 is a compilation of literature data for certified stoves averaged separately for both cold- and hot-starts and the average and standard deviation of cold- and hot-start tests conducted for this study. In each study, the measurements were made with a Method 5G type approach which provides some consistency and results that more closely simulate actual emission factors, albeit dilution tunnel temperatures were variable among studies and were warmer than would be typical of ambient heating season temperatures. Unfortunately, little data are available for other pollutants other than total PM allowing comparisons between cold- and hot-starts and therefore the hot- and cold-start comparisons here focused on using total PM. The previous studies reviewed for the literature survey used both modern certified catalyst and non-catalyst heaters, both dimensional lumber and cordwood, both hardwood and softwood, and various burn rates. The average emission factor values for the different sets of conditions spanned nearly two orders of magnitude from a low of 0.64 g/kg to a high of 35.7 g/kg. The magnitude of these emission factors are probably lower than they are in reality due to the fact that the diluted air in the 5G dilution tunnels was warmer than typical heating season ambient temperature and hence fewer semi-volatile organic compounds in the vapor phase condensed into particles. Conversely, due to the size distribution of particles emitted from wood heaters the magnitude of the emission factors would need to be reduced somewhat to apply to $PM_{2.5}$ and PM_{10}.

While the results of this study clearly showed cold-starts/low burn rates produced higher emissions than hot-starts/high burn rates, literature values do not contribute to documenting this trend due to the variability in the stove operational parameters from study to study.

Table 20. Particulate (5G) Emission Factors for Modern Certified Wood Heaters Tested with Cold- and Hot-Starts

Start scenario	Burn rate (kg/h)* Avg. ± S.D.	Fuel†	n	Description	5G emission factor (g/kg) Avg. ± S.D.	Reference
Cold	1.39 ± 0.35	Doug. Fir cw	4	2 certified non-cat stoves	4.69 ± 3.48	This Study
	1.51 ± 0.24	Maple cw	4		4.05 ± 1.86	
Hot	3.57 ± 0.53	Doug. Fir cw	4	2 certified non-cat stoves	1.50 ± 1.11	This Study
	3.23 ± 0.55	Maple cw	4		0.91 ± 0.35	
Hot	2.05 ± 1.35	Doug. fir dl	12	certified non-cat	3.41 ± 2.38	26
Hot	0.75 ± 0.03	Doug. fir dl	3	certification tests on 26 non-cat. models	2.32 ± 0.50	27
	0.99 ± 0.13		49		3.23 ± 2.32	
	1.50 ± 0.17		33		1.86 ± 1.19	
	2.51 ± 0.44		26		1.55 ± 0.84	
Cold	range provided, 1.82 to 2.41	one run oak cw	1	certified cat.	2.2 ± 0.4	28
		one run Doug. fir cw	1		1.2 ± 0.2	
Hot	3.52 ± 0.71	white gum cw	5	high tech. Australian stove similar in design to a U.S. certified non-cat. heater	2.86 ± 1.60	29
	2.15 ± 0.22		3		12.9 ± 7.3	
	1.42 ± 0.44		5		35.7 ± 9.6	
Hot	not provided, estimated as 2.4	3 runs spruce cw	3	certified non-cat	0.68 ± 0.17	24
		3 runs maple cw	3		0.64 ± 0.23	
Cold	not provided, estimated as 2.3	oak cw	3	certified non-cat	8.2 (avg. estimated from data in publication)	21-23
Cold (one run was hot-start)	1.97 ± 0.68	oak cw	11	certified cat.	7.73 ± 5.95	16
	1.94 ± 0.99		7	certified non-cat	22.9 ± 10.7	

*S.D. = standard deviation
†dl = dimensional lumber
cw = cordwood

4.3 Comparison of Efficiencies to Stated and Default Values

Methods for measuring efficiencies from wood heaters are currently and have historically been the subjects of considerable debate. In Table 21 the efficiencies measured in this study are compared to wood heater efficiency values as stated in by the U.S. EPA in AP-42 and the default values in the U.S EPA Code of Federal Regulations. Although two methods were used to measure efficiency, given the multiple uncertainties outlined in Appendix J (negative values associated with some of the interval calculations being the most significant) and only half of the tests being applicable, the averages from CSA B415.1-00 Section 13.9 are not included in the summary table. The authors agree the most "realistic" and least problematic efficiency test method is the Annex D, TCC method. Therefore, the average overall efficiency (HHV and LHV) including both heaters, both burn scenarios and both fuel types is reported.

Table 21. Wood Heater Efficiencies Compared to Stated and Default Values

Wood Heater Type	This Study Average and Standard Deviation CSA B415.1-00 Annex D, TCC (%)*	Stated Efficiency U.S. EPA AP-42 (%)	Default Efficiency for Certified Heaters US EPA 40 CFR (%)
Conventional Uncertified Wood Stove	–	54	–
Non-catalytic Wood Stove	67.2 ± 2.94 (HHV) 73.8 ± 3.15 (LHV)	68	63
Catalytic Wood Stove	–	68	72
Certified Pellet Stove	–	68	78
Exempt (Uncertified) Pellet Stove	–	56	–
Masonry Heater	–	58	–

*Includes 15 cordwood tests with two heater types (higher and lower emissions), with two burn scenarios (high/hot and low/cold) and two fuel types (hardwood and softwood) with measured fuel properties.

5. Summary

5.1 Efficiency

Efficiency measurements were made on two U.S. EPA certified non-catalytic wood stove models, burning both hardwood and softwood cordwood fuel and under hot-start/high burn and cold-start/low burn operational conditions. One wood stove was referred to as the "lower emission heater" as its EPA particulate certification value is 2.1 g/h. The other wood stove was referred to as the "higher emission heater" as its EPA particulate certification value is 5.9 g/h. Efficiency was determined by using CAN/CSA B415.1-00 as a framework, however since the B415 method specifies Douglas fir dimensional lumber, a hot start with a substantial existing coal bed, and a single subsequent fuel load, the method was not directly applicable to the real-world testing conducted here. It is the authors' opinion that the modified alternative procedure in Annex D (Total Combustible Carbon) as described in CSA B415.1-00, with actual measured fuel parameters (in lieu of default values), provided the most realistic efficiency values. It should be noted that further adjustments and modifications to CSA B415.1-00, beyond what was done in this study, are also possible and the best method for determining efficiency remains contentious.

The efficiency values determined for the lower emission heater by the application of the Annex D procedure with actual measured fuel parameters averaged across all tests (hardwood, softwood, hot-start/high burn, and cold-start/low burn) was 67.98% reported in the higher heating value (HHV) convention and 74.56% reported in the lower heating value (LHV) convention. The analogous average efficiency values for the higher emission wood stove were 66.58% (HHV) and 73.11% (LHV). These numbers compare reasonably with the efficiency value (with an unspecified reporting format) listed in U.S. EPA AP-42 of 68% for Phase 2 certified non-catalytic wood stoves and with the default certification value of 63% (also with an unspecified reporting format) published in 40 CFR as part of the NSPS certification regulations for wood heaters. When comparing these values it should be noted that both the AP-42 and the NSPS values are based on older stove models and it is generally accepted that wood stove models have improved since the earliest certified models. Furthermore, the NSPS values were developed from apparently limited actual measurements which were conducted by undescribed methods.

5.2 Air Emissions

The key objective of this study is the verification of emission factors of U.S. EPA Certified Wood Heaters. To this end, there are three comparisons that best provide this verification. They are: (1) comparison of the real-world particulate emission rates measured in this study for the two certified wood stoves with their respective certification values, (2) comparison of real-world particulate emission factors measured in this study with emission factors published for phase 2 certified non-catalytic wood heaters in U.S. EPA AP-42, and (3) comparison of air pollutant emission factors determined in this study with those reported from previous studies. (Note: all particulate data used in the following comparisons are on a 5H equivalent basis)

The real-world particulate emission rates for both stoves used in this study were higher than their certification values. While there are a number of differences between the certification protocol and real-world practices, it is clear from the data that the cold-start/low burn conditions caused the overall averages to be higher than the certification values which are determined with hot-start conditions. The average emission rate (averaged across all test conditions) for the lower emission stove was 4.55 g/h as compared to its certification value of 2.1 g/h. The average emission rate (averaged across all test conditions) for the higher emission stove was 8.61 g/h as compared to its certification value of 5.9 g/h.

The real-world particulate emission factors for both stoves used in this study were lower than the average emission factor for phase 2 certification non-catalytic heaters published in U.S. EPA AP-42. This is reasonable in light of the fact that the database used to develop the emission factor in AP-42 is derived from the testing of wood heater models that are approximately two decades old and it is generally accepted that wood heater performance has improved since the earliest models used in the studies cited AP-42. The average particulate emission factor (averaged across all test conditions) for the lower emission stove was 2.01 g/kg and for the higher emission stove it was 5.58 g/kg as compared to the average emission factor of 7.3 g/kg published in AP-42 for phase 2 certified non-catalytic wood heaters.

Depending on the pollutant, the average real-world emission factors determined in this study were either comparable to the average literature values or were less than the average literature values. In no case were the real-world emission factors determined in this study more than the average literature values. This is consistent with the fact that the two stoves tested were modern certified stoves whereas some of the literature data were for older, ostensibly higher emitting stoves. More specifically, a comparison of average emission factors from this study (overall average of both heaters, both burn scenarios, and both fuel species) with values reported in previous studies of certified non-catalytic heaters reveals that for a number of pollutants (PM, CO, NOx, benzene, formaldehyde, and acrolein) the literature values are within the standard deviation around the mean of the value measured in this study. For $PM_{2.5}$, methane, VOCs, 1, 3 butadiene, and acetaldehyde the average emission factors determined in this study are less than the average literature values. In summary, this study provides real-world emissions from modern certified non-catalytic wood stoves and the emission values reported are similar, if not less than, the literature values.

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