Residential Wood Burning Appliances Pollutant Emissions Testing

Summary of Study Purpose, Design and Results

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Environment and Climate Change Canada

May, 2023

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The author would like to thank the following individuals for their very helpful feedback in the drafting of this paper:

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ABSTRACT

Environment and Climate Change Canada (ECCC) commissioned a study of air pollutant emissions from seven residential wood burning appliances, including an open fireplace, different types of wood stove with varying types of emission controls, a fireplace heater and a pellet stove. Study parameters emulated what are considered to be typical Canadian operating conditions of ambient temperature (-20°C, -10°C and 0°C), wood type (hardwood, softwood, mixed hardwood/softwood) and wood moisture content (varied on a dry basis from 10% to 40%). The goal of the study was to determine the relationship between these parameters and emissions of 48 pollutants, including particulates, organic and elemental carbon, greenhouse gases (CO_2, CH_4 and N_2O), carbon monoxide (CO), sulphur dioxide (SO_2), Nitrogen Oxides (NOx), volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs). A multivariate model showing the impact of the simultaneous variation of all three parameters on emissions could not be produced due to what appears to be a wide range of additional variables that affect emissions. However, univariate analysis was able to determine some significant correlations between pollutants and the three variables of interest. Moisture content was determined to be the variable of interest with significant correlations with a number of pollutants. Of the various appliances tested, open fireplaces and U.S. Environmental Protection Agency (EPA) pre-2020 certified wood stoves have the largest number of positive correlations between wood moisture content and emissions (32 and 31 of 48 pollutants, respectively). Conventional wood stoves and EPA 2020 certified catalytic wood stoves had no significant correlations between any of the variables of interest and emissions. Although there were no significant correlations evident for these two appliances, it is important to note that open fireplaces have comparatively high emissions levels of many pollutants and EPA 2020 certified catalytic wood stoves have comparatively low emissions of many pollutants.

INTRODUCTION

In 2019, Environment and Climate Change Canada (ECCC) commissioned a study of air pollutant emissions from residential wood burning appliances. Physical testing of appliances was conducted by PFS Corporation (PFS TECO), with study design and statistical analyses of the results conducted by the University of Sherbrooke. Two final reports, one from PFS TECO and the other from the University of Sherbrooke were produced in the Fall of 2022. Both documents provide detailed results from the study[1]. Below is a summary of the findings contained in those two documents. This summary does not provide any additional findings from further study of the appliance testing data, but rather is meant to serve as a concise introduction to the work completed, as the two studies combined are several hundred pages in length. The studies themselves and the test data are available in English only.

STUDY CONTEXT AND PURPOSE

Woody biomass is a commonly used renewable resource for energy production in Canada. Residential firewood is the third-largest energy source for home heating energy in Canada. In regions of the country that do not have access to natural gas, firewood can be a cost-competitive source of energy and can provide a degree of self-sufficiency.

[1] Both studies are available upon request. Please see references section of this paper for details.

At the same time, burning firewood is a major contributor to air quality problems. In Canada, estimates suggest that it contributes approximately 13% of VOCs, 9% of PM2.5, 21% of CO, 11% of Dioxins/Furans and 91% of PAHs along with other pollutants. In terms of greenhouse gases (GHGs), its contribution is smaller (3% of CH_4 emissions and 1% of N_2O emissions). However, woody biomass burning is a significant source of black carbon (or soot), a short-lived climate forcer associated with both climate warming and adverse health effects. The 2023 edition of *Canada's Black Carbon Inventory Report* identified residential wood combustion as the second-largest source of black carbon emissions after transportation, with 25% of total emissions in 2021. Concerns over the air quality and the health impacts of residential wood combustion have caused some jurisdictions to take measures such as restricting the use of wood stoves, introducing strict emission limits or offering wood stove exchange incentives. For example, the City of Montreal passed a by-law in 2015 restricting the use of wood-burning appliances. This law now only allows the use of appliances that meet the United States Environmental Protection Agency's (USEPA's) 2020 emissions standards within municipal boundaries.

Current methodology employed in Canadian inventories of greenhouse gases (GHGs) and air pollutants by Environment and Climate Change Canada uses emission factors that may not accurately reflect the Canadian situation, either because they are outdated or because they are default values developed for international use. These emission factors also do not take into account significant advancements made in stove designs and control strategies over the last several years, as well as Canadian practices in firewood burning.

Fuel moisture content, appliance design, burning practices, operational conditions and controls influence the quantity and composition of emissions. Inefficient combustion leads to the formation of emissions containing particulates (including black carbon), VOCs and PAHs. Canada has limited data on the emission profiles of pollutants from wood-burning appliances, and no national emission standards for residential wood combustion appliances. The purpose of this study is to quantify emissions from Canadian residential wood burning using typical in-use appliances representing a range of combustion technologies that influence efficiency and emission controls, and representative of users' typical burning practices.

STUDY OBJECTIVES

The objective of this study was to improve the accuracy of quantified emissions from residential wood stove burning in order to improve Canada's greenhouse gas, air pollutant and black carbon inventories. This new knowledge will allow Canadian policy makers to better understand the potential for GHG, air pollutant and short-lived climate pollutant (SLCP) emission mitigation and assess it against potential negative impacts to air quality. The study also satisfies one of the key commitments under ECCC's Strategy on SLCPs, which is to continue refining the black carbon inventory to support the development of priority mitigation measures.

STUDY SCOPE AND GENERAL APPROACH

Environment and Climate Change Canada retained PFS TECO's lab in Clackamas, Oregon to test a set of residential wood burning appliances considered representative of those found in Canadian households. ECCC also retained statisticians from the University of Sherbrooke to determine an effective experimental design for testing the appliances. The statisticians created a Design of Experiments (DoE), from which they developed statistical models. The purpose of the models is to determine as accurately as possible emission factors for the different appliances given a range of operating conditions.

Variables Modeled

The specific variables of interest for operating conditions included ambient outdoor temperature (with induced draft serving as a proxy), fuel type (softwood, hardwood or a mix of the two) and fuel moisture content.

Outdoor Ambient Temperature/Flue Draft

Outdoor temperature could not be simulated in laboratory conditions *per se*; however, relative differences in indoor and outdoor atmospheric pressure caused by changes in outdoor temperature could be simulated by changing the flue draft. While other factors such as chimney height and wind speed affect natural draft, in general as outdoor ambient temperature decreases, natural draft increases. In this study, measurements of pollutants took place within a high flow dilution tunnel. Three discrete outdoor ambient temperature points were selected to represent the range of typical Canadian operating conditions for residential wood burning appliances: -20°C, -10°C, and 0°C[2]. The relationship between outdoor ambient temperature and chimney draft is provided in the Table 1[3]. The relationship between outdoor temperature and flue draft does not apply to pellet stoves, as a fan mechanically controls flow through the appliance. As such, fuel type (hardwood pellets, softwood pellets, mixed hardwood/softwood pellets) was the only variable tested for this appliance. It is worth noting that the softwood pellets had significantly higher moisture content (7.1% moisture content by weight) than the hardwood or mixed pellets (4.9% and 4.8% moisture content by weight, respectively).

Table 1: Outdoor Temperatures Related to Flue Draft

Targeted Outdoor Temperature	Flue Draft (Pa)	Flue Draft (in H_20)	Corresponding velocity (m^3/m)	Corresponding velocity (cfm)
-20°C	14.90	0.06	3.60	135
-10°C	10.7	0.04	3.10	115
0°C	6.9	0.03	2.50	92

Fuel Type

The species selected to represent hardwoods was oak, while the species selected to represent softwoods was Douglas fir. Oak, maple and birch are typical hardwood fuels consumed in Canada, while Douglas fir and cedar along with various species of spruce and pine are typical of softwood fuels. Hardwoods are more commonly burned in the southern regions of Eastern Canada. Douglas fir is native to British Columbia but is similar in terms of fuel properties to other softwood species found elsewhere in the country.

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[2] Two other temperature points were added for the purposes of modeling, as explained in the section "Experimental Design" below. The full range of chimney draft utilized for modeling outdoor ambient temperature was 2.5-37 Pa for a 7 metre, 15 cm diameter chimney pipe. Indoor temperature was assumed to be 20°C

[3] Calculations were developed using the engineering toolbox per equations available at : https://www.engineeringtoolbox.com/natural-draught-ventilation-d_122.html

Fuel Moisture Content

Fuel moisture content (MC) varied on a dry basis from 10% to 40%, at increments of 10%, 15%, 25%, 35% and 40%. Moisture content measurements taken by PFS TECO in this study and in others showed that oak hardwood fuel could be stored inside or outside for extended periods of time (months to years) and still maintain elevated (30-40%) moisture content levels, depending on the piece size and presence of bark. Conversely, fir softwood dried to “seasoned” levels (19-25% MC) within a few weeks of being split when stored outside. If stored indoors or during months of low relative humidity (summer) softwood rapidly dropped to fuel moisture contents of 10-15%. Typical values for fuel moisture content were therefore assumed to be 30-40% for hardwood and 15-25% for softwoods. Hardwood with a moisture content of 15% was not tested, as it is unlikely it would be used under actual operating conditions.

Appliances Tested

The appliances selected for testing were intended to reflect the range of products currently in use in Canada, along with two appliances that meet the most recent iteration of the USEPA’s emissions standard, which came into effect in 2020. Canada does not currently regulate emissions from wood burning appliances given that the integrated North American market has meant that manufacturers in both the U.S. and Canada will comply with USEPA standards regardless of where the appliance is sold[4].

Different types of wood burning appliance, including an open fireplace, various models of freestanding wood stoves, a fireplace heater and a pellet stove were tested. These appliances collectively reflect the different EPA emission benchmarks that have come into effect since the EPA began regulating emissions from wood burning appliances in 1990. Therefore, two appliances had no emission controls, representing open fireplaces (which have remained unregulated) and wood stoves installed prior to EPA certification requirements. Other appliances represent “high emissions appliances” reflecting EPA standards in place from 1990 to 2014, “medium emissions appliances” reflecting EPA standards in place from 2015 to 2019 and finally newer appliances sold in 2020 or later that represent “low emissions” appliances. While the appliances selected cannot fully represent the wide range of appliance types and emission control technologies that are currently in use in Canada, they are considered a reasonable facsimile for the purposes of emission testing. Table 2 below presents the appliance types and representative appliances selected to represent each type.

Table 2: Appliance Type, Manufactured Reference Year and Selected Representative Model Tested

Appliance Type with Reference Year	**Appliance Tested (with manufacturer’s specifications)**
1) Conventional factory built open fireplace (with bi-fold doors open, metal screen closed). Represents all masonry and factory built open fireplaces	**Hearth & Home Technologies, Model: Heatilator EL36** Bi-fold glass doors with metal screen Factory supplied grate
2) Conventional free standing wood stove (pre-1988 - medium size). Represents all conventional stoves made prior to 1988	**Fisher, Model: “Bear Series” Mama Bear** Heating capacity: 1250 to 1750 sq. ft. (116 to 162 sq. m.)

[4] Although as noted in the introduction above, some municipalities regulate the use of wood burning appliances based on their emissions output.

	Log size: 24 inch (61 cm) Firebox volume: 3.1 cu ft. (88 litres)
3) Certified **non-catalytic** freestanding wood stove, **EPA 1990-2015** Emissions Range (~ 4 g/hr). **Represents large percentage of wood stoves sold between 1995-2019.**	**Pacific Energy, Model Super 27 (1993)** Ave. PM emission rate: 3.4 g/hr Firebox volume: 2.2 cu ft (62 litres)
4) Non-catalytic fireplace heater – Not EPA Certified - medium emissions appliance.	**ICC RSF, Model: Opel 2 (Canada Only)** Ave. PM emission rate: 2.8 g/hr Firebox volume: 3.6 cu ft (102 litres)
5) Certified **catalytic** freestanding wood stove, meets **EPA 2020** emissions (~1 g/hr). Represents **catalytic** heaters sold after May 15, 2020.	**Blaze King, Model: PE32** Ave. PM emission rate: 0.4 g/hr Firebox volume: 2.9 cu. ft. (82 litres)
6) Certified **non-catalytic** freestanding wood stove, meets **EPA 2020** emissions (~1 g/hr). Represents **non-catalytic** heaters sold after May 15, 2020.	**Stove Builders International (SBI), Model: Drolet Escape 1800** Ave. PM emission rate: 1.54 g/hr Firebox volume: 2.4 cu ft (68 litres)
7) Certified pellet stove (~1.5 g/h) Represents modern pellet stoves manufactured 2000 to present.	**Harman, Model: P61** Ave. PM emission rate: 1.5 g/hr Fuel feed type: Bottom

Note: "Fireplace insert" emissions factors are assumed to be the same as wood stoves (as are similarly engineered).

EXPERIMENTAL DESIGN

The high cost of conducting tests on wood burning appliances necessitated an efficient experimental design, such that the minimum number of tests would provide the required data needed to draw meaningful conclusions regarding the impact of outdoor ambient temperature, fuel type and fuel moisture content on pollutant emissions.

In this study, a statistical model known as a Central Composite Design (CCD) was used. CCD is composed of three distinct sets of experimental conditions (factorial, center points and axial points). They can give more information on the effects of the different parameters with fewer tests than would be required by a "full factorial" design[5]. Figure 1 shows an example of a CCD with center point design with 3 parameters and three levels. The center point is a test commonly added in a Design of Experiments (DoE) to detect non-linearities on the response surface. So-called axial points are the ones situated in the middle of the cube's faces, but in this case, outside the box (e.g. the end points of the range of the levels is extended beyond the specifications for the experiment). The number of experimental conditions is considerably reduced from full factorial to CCD. Center point replicates (three identical tests) were included for all appliances, to estimate the experimental error. All tests were completed for each of the 6 cordwood appliances and broken into two phases. The first phase consisted of completing

[5] A full factorial consists of evaluating all combinations of levels (e.g. for ambient temperature, the levels are -20° C, -10° C and 0° C) across all parameters (ambient temperature, fuel moisture content, fuel type).

center point and factorial points. The second phase consisted of axial points only. As an example, 9 tests (each of the factorial points and the central point) are required to determine the statistical relationships with emissions for ambient temperature, fuel moisture content and fuel type as ambient temperature conditions are changed. The outside the box axial points represent ambient temperatures beyond the temperature range of interest (i.e. a test point using -30°C would be used rather than -20°C, which is the lower end of the range of temperatures of interest).

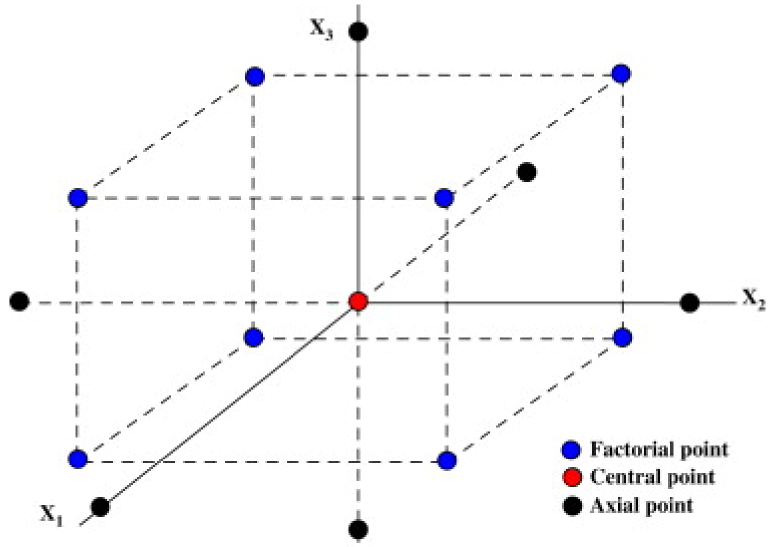

Figure 1: Representation of central composite design with axial points outside of box

POLLUTANTS STUDIED

Emission factors for 46 pollutants and two pollutant categories (Total VOC, Sum of PAHs) were developed. The specific pollutants studied are presented in Table 3 below.

Table 3: List of Pollutants Studied

N	Pollutant	N	Pollutant
1	Total Particulate Matter (TPM)	25	Cyclopentene
2	Fine Particulate Matter (PM2.5)	26	1-methylcyclopentene
3	Organic Carbon (OC)	27	Isopropyl benzene (Cumene)
4	Elemental Carbon (EC)	28	1,3-butadiene
5	Total Carbon (TC)	29	Naphthalene
6	Carbon Monoxide (CO)	30	2-Methyl-naphthalene
7	Nitrogen Oxides (NOx)	31	Acenaphthylene
8	Sulfur Dioxide (SO2)	32	Acenaphthene
9	Formaldehyde (CH2O)	33	Fluorene
10	Methane (CH4)	34	Phenanthrene
11	NMVOC (as propane)	35	Anthracene
12	Total VOC (as propane)	36	Fluoranthene
13	Nitrous Oxide (N2O)	37	Pyrene
14	Carbon Dioxide (CO2)	38	Benzo(a)Anthracene

15	Benzene	39	Chrysene
16	Propene	40	Benzo(b)Fluoranthene
17	Xylenes	41	Benzo(k)Fluoranthene
18	1-butene/2-methylpropene	42	Benzo(e)Pyrene
19	Toluene	43	Benzo(a)Pyrene
20	Propane	44	Perylene
21	1,2-butadiene	45	Indeno(123-cd)Pyrene
22	2-methylbutane	46	Benzo(ghi)Perylene
23	Ethylbenzene	47	Dibenzo(a,h)Anthracene
24	Styrene	48	19-PAHs (sum of all 19)

TEST METHODS

Fueling Protocol

A key project objective was to test appliances under typical operating conditions in the Canadian context. In all matters concerning fueling protocol, the guiding principle was "what would the operator typically do in these circumstances?". Wherever there was some doubt, the assumption was that the operator would consult the manual provided with the appliance. As with all tests, the fueling protocol required standardization in order to eliminate (to the extent possible) any extraneous variables from influencing the test results. The fueling protocol utilized was adapted from a study conducted in Italy[6]. It was used as a starting point, but it had to be adapted to Canadian operating patterns, where wood burning appliances tend to be significantly larger (with larger fuel load capacity) and are fueled less frequently. In addition, in the parameters of this study, the spectrum of wood moisture content is greater (including wet, difficult to burn fuel), and draft conditions were increased. The adaptations made were based on expert judgment of typical Canadian operating conditions.

The adapted protocol used in this study is as follows:

1. Ten crumpled sheets of newspaper and a butane lighter were used for ignition. One of the manufacturer's user manuals indicated 10 pieces of newspaper were needed;
2. Start up: 1 kg softwood kindling, with two 1kg "starter logs". The air inlet was fully open. Softwood was used as kindling in all tests, as softwood kindling dries and burns quickly. Wood type of the starter and subsequently added logs were then varied depending on the fuel characteristics to be tested;
3. The fuel loading door was opened as needed to ignite the fuel load (typically requiring 3-5 minutes but longer for some of the appliances and some of the higher moisture content fuel loads). Manufacturers' instructions also specified this step;
4. Unusually irregular pieces of knotted or rotten wood were avoided. Bark was not intentionally removed;
5. Fifteen minutes after startup, nominal fuel load #1 (per manufacturer's instructions) was loaded in, with the air inlet setting left fully open (on "high");

[6] Senem Ozgen et. al., *Emission factors from small scale appliances burning wood and pellets*, Atmospheric Environment, 2014. Ozgen's Cycle P was the protocol adapted for this study.

6. One hour after startup (45 min from fuel addition), air inlets were partially closed for a "medium" setting;
7. Two hours after startup (1 hour after step 6), the second fuel load was added and air inlet settings were fully closed to the low setting. The appliance air setting was "totally closed" as is common with an overnight burn cycle where a homeowner wants to have a low heat output and still have remaining coals in the morning (to ignite another fuel load).
8. Fuel was stacked with adequate spacing (2.2 cm (1 inch)) between pieces and alternating orientations (first layer placed, second layer placed perpendicular to allow airflow) on high and medium settings, while the low overnight burn was tightly compact parallel pieces (all with the same orientation).
9. The end of the test was defined as being when the flue temperature (measured in the center of the flue 30.5 cm (1ft) above the appliance) reaches 93.3°C (200°F). At this thermal endpoint, the majority of combustion has ceased along with the majority of pollutant emissions (with the exception of a small amount of carbon monoxide). The open fireplace, not being a closed combustion system, is subject to excess air flow and therefore had a reduced endpoint temperature of 37.7°C (100°F).
10. Fuel piece size and tolerances used are found in Table 4 below. No fuel piece specifications were defined in the Italian study.

Table 4: Fuel Piece Targets with (+/-) Tolerances

Fuel Addition	Target Mass Hardwood, kg (pounds)	Target Mass Softwood, kg (pounds)	Tolerances +/-	Width cm (in)	Tolerances +/-
Kindling (all softwood)	N/A	1 (2.2)	+/- 0.05 (0.11)	0.25-2 (0.6 – 5)	+/- 1.25 (0.5)
Starter Logs	1.5 (3.3)	1.0 (2.2)	+/- 0.25 (0.5)	7.6 (3)	+/- 1.25 (0.5)
Fuel Addition #1 (High and Medium Heat Settings)	2.5 (6.35)	2 (4.4)	+/- 0.25 (0.5)	10.1 (4)	+/- 1.25 (0.5)
Fuel Addition #2 (50% increase, Low Heat Setting)	3.75 (9.5)	3 (6.6)	+/- 0.5 (1.1)	15.2 (6)	+/- 2.5 (1)

All fuel pieces were 35.5-40.6 cm (14-16 inches) long. Target of 38.1 cm (15 in) +/- 2.5 cm (1 in)

Note: The tolerance for the 50% increase from nominal fuel load was (+/- 5%). The "increase" is an increase by wet mass as opposed to an increase in piece number or volume.

After experiencing fires prematurely extinguishing, the protocol was modified to include two additional dry (<10% MC) starter logs for 35% and 40% moisture content tests. Further, the 40% moisture content tests included splitting the larger overnight pieces in half. Both adding more startup fuel (allowing for more of a coal bed) and splitting larger high moisture pieces are thought to be typical of in-home use of wet fuel.

Two of the appliances (the conventional stove and the EPA 2020 catalytic wood stove) had air controls that if totally closed per the original protocol, under certain conditions (low draft or high moisture wood) the fire would go out (or dip below the endpoint criteria). The fueling protocol was modified for these appliances and instead of “totally closed” a minimum setting was used to allow for approximately an 8-hour “overnight” burn and maintain temperatures over 93.3°C (200°F). The catalytic appliance was unique in allowing for extended low temperature operation where tests typically lasted ~18 hours.

The open fireplace test used the same fuel loads as the other cordwood appliances. The first main fuel load was added 5 minutes sooner (at 10 minutes), as startup fuel was consumed at a faster rate. Fuel adjustments / “aesthetic pokes” were performed as needed to maintain the fire (as is typical with an open fireplace).

The Pellet stove emissions were measured for approximately 10 hours (similar target to other appliances) by adding the appropriate amount of fuel to the hopper. The pellet stove tests included emissions from the start-up cycle (the appliance had an auto-start feature that ignited the pellets after a few minutes) and a shut-down cycle (when the appliance runs out of fuel and automatically shuts off).

Dilution Tunnel Measurements and Standard Temperature and Pressure (STP)

Dilution tunnels allow the emissions from solid fuel combustion to be cooled, diluted, mixed, and kept at a relatively constant flow rate. While the temperature in the dilution tunnel is elevated above Canadian ambient heating season temperatures, dilution tunnels are important to allow the chemical / physical reactions of wood burning emissions mixing with air to occur. Of particular importance to realistic emission factors, is the gas to particle transition occurring for volatile organic compounds as they mix with cold ambient air. All emission measurements were made from a 30.5 cm (12 inch) dilution tunnel at various flow rates. The dilution tunnel included a 1.22 m (4 ft) diameter cone shaped capture hood with manual draft control baffles (which acted as fine-tune control of the simulated appliance draft). To aid in emissions mixing with laboratory air, a cross and tee were placed at the first two turns prior to the sampling ports. Two dilution tunnels were utilized over the project. Standard Temperature and Pressure (STP) corrections for all volumetric flows (sample flow and dilution tunnel flow) are reported using 0°C (32°F) and 1 ATM (29.92 in Hg).

Additional details regarding test methods can be found in the PFS TECO final report.

TEST RESULTS

Test results are categorized as follows:

1) Test Characteristics (Test time, Tunnel Flow, Draft, Fuel Mass, and Fuel Moisture)
2) Temperatures
3) Burn Characteristics (Includes Efficiency)
4) General Emissions 3 Ways: Emissions Totals (ET), Emission Factors (EF), Emission Rates (ER)
5) General EFs

6) General EFs (by appliance)
7) PAH EFs (mg)
8) Speciated VOC EFs (g)
9) Speciated VOC EFs (mg)

Detailed results across all variables can be found in an Excel spreadsheet (available upon request). Average overall efficiencies are presented in Table 5, while average emission factors across variables are provided in Table 6.

Appliance Efficiency

Appliance efficiency is a key determining factor regarding an appliance's overall emissions. Generally, the higher the appliance efficiency the lower the emissions produced per unit of useful heat emitted to the indoor area. High efficiency implies less wood is burned by the homeowner over the heating season, all other factors being equal. As shown in Table 5 below, the EPA 2020 catalytic wood stove is significantly more efficient than the other wood stoves tested, and all wood stoves are significantly more efficient than uncontrolled burning in an open fireplace. Pellet stove efficiency is similar to non-catalytic wood stoves.

Table 5: Comparison of Average Overall Efficiencies During Low Burn Cycle, Across All Variables (moisture, fuel type, draft)

	Open Fireplace	Convent-ional Wood Stove	EPA 2020 Catalytic	EPA 2020 Non-Catalytic	Pre EPA 2020	Fireplace Heater	EPA Pellet Stove
	Heatilator EL36	Fisher Mama Bear	Blaze King PE32	SBI Drolet Escape 1800	1993 Pacific Energy/ Super 27	ICC/RSF Opel 2 (Not EPA Certified)	Harman P61
Low-Overall Efficiency, HHV	14.5%	66.0%	80.3%	63.6%	63.5%	64.6%	61.4%
Low-Overall Efficiency, LHV	15.7%	72.0%	87.6%	69.4%	69.4%	70.5%	67.2%

Note: As tested by the Stack Loss Method CSA B415.1 over the low burn cycle only

Average Emission Factors Across all Variables

For most of the pollutants studied, the appliances with the highest emissions (measured in grams of pollutant per kilogram of wood burned) are the open fireplace and conventional wood stove which have no emissions controls, along with the fireplace heater[7]. The pre-EPA 2020 and EPA 2020 non-catalytic wood stoves improve upon the aforementioned appliances and the best performers are the EPA 2020

[7] The fireplace heater has some emissions control.

catalytic wood stove and the EPA pellet stove. The wood burning appliances tested that featured more advanced emission controls reduced emissions of many, but not all pollutants. The EPA 2020 catalytic stove and the pellet stove perform particularly well for emissions of total particulates, $PM_{2.5}$, organic carbon and total carbon, reducing emissions by 85-86% and 88-90%, respectively for these pollutants over the conventional wood stove. These appliances also perform well for emissions of carbon monoxide (83% and 86% reduction), formaldehyde (77% and 78% reduction), non-methane VOCs (67% and 74% reduction) and total PAHs (56% and 91% reduction) over the conventional wood stove. The EPA 2020 catalytic stove performs well on benzene emissions[8] (63% reduction over a conventional wood stove). The pellet stove performs well on methane emissions (78% reduction over a conventional wood stove). However, both the pellet stove and EPA 2020 catalytic wood stove have significantly increased emissions for NOx (261% and 169% increase over a conventional wood stove) the EPA 2020 catalytic stove has increased nitrous oxide (N_2O) emissions (9% over a conventional wood stove) and methane (CH_4) (7% over a conventional wood stove), the pellet stove has increased emissions of carbon dioxide (22% over a conventional wood stove) and both appliances provide less significant advantages when compared to the uncontrolled appliances with respect to sulfur dioxide (32% and 18% reduction over a conventional wood stove) (See Table 6).

Table 6: Comparison of Average Emission Factors (grams pollutant/kg of dry fuel) Across All Variables (moisture, fuel type and draft)

	Open Fireplace	**Convent-ional Wood Stove**	**EPA 2020 Catalytic**	**EPA 2020 Non-Catalytic**	**Pre EPA 2020**	**Fireplace Heater**	**EPA Pellet Stove**
	Heatilator EL36	**Fisher Mama Bear**	**Blaze King PE32**	**SBI Drolet Escape 1800**	**1993 Pacific Energy/ Super 27**	**ICC/RSF Opel 2 (Not EPA Certified)**	**Harman P61**
Total Particulate Matter (TPM)	14.4	15.6	2.29	6.99	6.4	11.4	1.91
Fine Particulate Matter ($PM_{2.5}$)	14.5	15.3	2.16	6.86	6.27	11.3	1.74
Organic Carbon (OC)	9.93	10.3	1.52	4.31	4.24	7.12	0.992
Elemental Carbon (EC)	0.256	0.175	0.129	0.105	0.107	0.156	0.028
Total Carbon (TC)	10.2	10.4	1.64	4.41	4.35	7.28	1.02
Carbon Monoxide(CO)	108	149	26.0	107	116	117	21.5

[8] Not reported in Table 6.

	Open Fireplace	Convent-ional Wood Stove	EPA 2020 Catalytic	EPA 2020 Non-Catalytic	Pre EPA 2020	Fireplace Heater	EPA Pellet Stove
	Heatilator EL36	Fisher Mama Bear	Blaze King PE32	SBI Drolet Escape 1800	1993 Pacific Energy/ Super 27	ICC/RSF Opel 2 (Not EPA Certified)	Harman P61
Nitrogen Oxides (NOx)	1.16	0.587	1.58	0.828	0.846	0.671	2.12
Sulfur Dioxide (SO_2)	0.032	0.038	0.026	0.024	0.026	0.027	0.031
Formaldehyde (CH_2O)	1.64	2.01	0.47	1.26	1.16	1.70	0.44
Methane (CH_4)	6.88	9.83	10.5	5.14	5.63	7.64	2.19
NMVOC (as propane)	5.45	9.63	3.22	6.29	11.328	5.34	2.46
Total VOC (as propane)	11.0	18.2	12.4	10.37	16.3	12.3	3.28
Nitrous Oxide (N_2O)	0.083	0.091	0.099	0.066	0.076	0.062	0.073
Carbon Dioxide (CO_2)	1705	1580	1570	1902	1742	2056	1922
Total 19-PAHs	0.088	0.118	0.052	0.077	0.080	0.063	0.010

The impact of moisture, fuel type and draft (ambient outdoor temperature) on emissions

Determining the relationship between wood moisture content, fuel type, draft (proxy for outdoor ambient temperature) and emissions was a key goal of this research project. The original intent was to construct a multivariate model that would produce an emission coefficient based on any change of one of the three principal variables. Rather than producing discrete coefficients for specific moisture, fuel type or temperature points, the central composite design of the testing phase was meant to produce a "surface" model that would allow any variable within a range (for example, any temperature between 0°C and -20°C, rather than simply 0°C, -10°C or -20°C) to be plugged into the model and a unique emission coefficient would be provided. With the exception of a few appliance/pollutant coefficients[9], no significant statistical relationship could be established. Univariate analysis, where the influence of only one variable was considered, provided better results in identifying trends.

[9] For the pellet stove for predicting formaldehyde and anthracene, and for the fireplace heater for predicting methane.

Coefficients from the univariate models made from data centered and reduced were developed in order to measure the degree of variation of pollutant concentrations explained by the dependant variables (moisture, fuel type and draft). Dependant variables with a coefficient greater than 0.5 or less than -0.5 for emissions of a pollutant were considered to have a strong correlation with pollutant concentrations, while dependant variables with coefficients below 0.5 or above -0.5 for emissions of a pollutant were considered to have an insignificant influence on pollutant concentrations. The statistical analysis conducted by the University of Sherbrooke showed that there were few statistically significant correlations between changes in wood moisture content, fuel type (hardwood, softwood, mix) or draft (ambient outdoor temperature proxy) on emissions. Additional tests confirmed these results. Rather, the test results indicated a significant amount of variability in emissions across the emissions tests. This would seem to indicate that there are a number of factors ("noise") other than moisture, fuel type and draft that are in many cases equally as important as the variables being tested with respect to influencing emissions levels. Although a concerted attempt was made to control for variables such as the size and shape of wood, loading methods and appliance operation, the variability of the wood and the random nature of the burn cycle[10] makes it impossible to create consistent test parameters across the number of tests conducted. It is possible that with a much larger sample size, correlations between the variables selected could be determined.

However, there did appear to be a strong correlation between wood moisture content and emissions for most appliance types and many pollutants (see Table 7). The majority of the significant correlations are positive (i.e. as moisture increases, emissions increase), although three appliances show both positive and negative correlations with different pollutants. Positive correlations are highlighted in pink in Table 7, while negative correlations are highlighted in blue. The appliances with the largest number of significant correlations between moisture content and pollutant emissions were open fireplaces and the EPA pre-2020 stove, with the EPA 2020 non-catalytic stove showing fewer significant correlations (in particular, particulates, CO, formaldehyde, N_2O and CO_2). The fireplace heater also showed some significant correlations for formaldehyde, methane, benzene, propene, styrene and 1-methylcyclopentene. The pellet stove showed some of the strongest wood moisture content-pollutant correlations (TPM, formaldehyde, propene, xylenes, all negative). The higher moisture content in the softwood pellets as compared to the hardwood or mixed pellets makes it possible that the correlation may not be between moisture content and pollutant, but rather fuel type and pollutant (i.e. softwood pellets produce lower emissions than hardwood or mixed pellets).

There was no correlation between wood moisture content and emissions of any pollutant for the conventional wood stove and the EPA 2020 catalytic stove. Why this is the case is unclear, but for the EPA 2020 catalytic stove, the ability of the catalyst to improve combustion efficiency, even in potentially unfavorable conditions (high moisture/low draft), seems a possible cause. The EPA 2020 catalytic stove also has a thermostatically controlled air supply which automatically regulates the air supply based on appliance temperature, potentially contributing to consistently low emissions across a wide range of conditions. The conventional stove may have a similar but opposite condition where the lack of emission controls and technological advances simply produce elevated emissions across a wide range of conditions.

[10] For example, wood will shift inside the firebox as it burns down, creating changes in air flow that can increase or decrease smoldering, affecting emissions.

Table 7: Coefficients from univariate models linking moisture content to pollutant emissions (made from data centered and reduced)

	Open fireplace	Conventional wood stove	EPA 2020 catalytic stove	EPA 2020 non-catalytic stove	EPA pre-2020 stove	Fireplace heater	Pellet stove
Total Particulate Matter (TPM)	**0.58**	NS	NS	**0.57**	**0.72**	NS	**-0.87**
Fine Particulate Matter (PM2.5)	**0.56**	NS	NS	**0.57**	**0.7**	NS	**-0.79**
Organic Carbon (OC)	**0.54**	NS	NS	NS	**0.65**	NS	**-0.53**
Elemental Carbon (EC)	NS	NS	NS	NS	NS	NS	NS
Total Carbon (TC)	**0.56**	NS	NS	NS	**0.64**	NS	**-0.53**
Carbon Monoxide (CO)	**0.55**	NS	NS	**0.52**	NS	NS	NS
Nitrogen Oxides (NOx)	NS	NS	NS	NS	NS	NS	**-0.63**
Sulfur Dioxide (SO2)	NS	NS	NS	NS	NS	NS	NS
Formaldehyde (CH2O)	**0.93**	NS	NS	**0.75**	**0.83**	**0.52**	**-0.99**
Methane (CH4)	NS	NS	NS	NS	**0.64**	**0.55**	NS
NMVOC (as propane)	NS	NS	NS	NS	NS	NS	**0.67**
Total VOC (as propane)	NS	NS	NS	NS	**0.55**	NS	NS
Nitrous Oxide (N2O)	NS	NS	NS	**-0.61**	NS	NS	NS
Carbon Dioxide (CO2)	NS	NS	NS	**-0.57**	NS	NS	NS
Benzene	**0.7**	NS	NS	NS	**0.51**	**0.6**	NS
propene	**0.65**	NS	NS	NS	**0.62**	**0.53**	**-0.93**
xylenes	NS	NS	NS	NS	NS	NS	**-0.82**
1-butene/2-methylpropene	NS	NS	NS	NS	NS	NS	NS
toluene	**0.51**	NS	NS	NS	NS	NS	NS
propane	NS	NS	NS	NS	NS	NS	NS
1,2-butadiene	NS	NS	NS	NS	NS	NS	NS
2-methylbutane	NS	NS	NS	NS	NS	NS	NS
ethylbenzene	NS	NS	NS	NS	NS	NS	NS
styrene	**0.62**	NS	NS	NS	**0.6**	**0.54**	NS
cyclopentene	**0.55**	NS	NS	NS	**0.57**	NS	NS
1-methylcyclopentene	NS	NS	NS	NS	**0.56**	**-0.51**	NS
isopropyl benzene (Cumene)	NS	NS	NS	NS	NS	NS	NS
1,3-butadiene	**0.62**	NS	NS	NS	**0.63**	**0.5**	NS
Naphthalene	**0.59**	NS	NS	NS	NS	NS	**-0.65**
2-Methyl-naphthalene	**0.57**	NS	NS	NS	**0.77**	NS	**-0.65**
Acenaphthylene	**0.62**	NS	NS	NS	**0.75**	NS	NS
Acenaphthene	**0.76**	NS	NS	NS	**0.73**	NS	NS
Fluorene	**0.57**	NS	NS	NS	**0.76**	NS	NS
Phenanthrene	**0.62**	NS	NS	NS	**0.65**	NS	**-0.56**
Anthracene	**0.73**	NS	NS	NS	**0.77**	NS	**-0.76**
Fluoranthene	**0.66**	NS	NS	NS	**0.75**	NS	NS
Pyrene	**0.65**	NS	NS	NS	NS	NS	NS
Benzo(a)Anthracene	**0.81**	NS	NS	NS	**0.72**	NS	NS

Chrysene	**0.91**	NS	NS	NS	**0.71**	NS	NS
Benzo(b)Fluoranthene	**0.86**	NS	NS	NS	**0.66**	NS	NS
Benzo(k)Fluoranthene	**0.74**	NS	NS	NS	**0.69**	NS	**0.69**
Benzo(e)Pyrene	**0.67**	NS	NS	NS	**0.73**	NS	NS
Benzo(a)Pyrene	**0.81**	NS	NS	NS	**0.71**	NS	**0.53**
Perylene	**0.61**	NS	NS	NS	**0.69**	NS	NS
Indeno(123-cd)Pyrene	**0.77**	NS	NS	NS	**0.67**	NS	NS
Benzo(ghi)Perylene	**0.77**	NS	NS	NS	**0.66**	NS	NS
Dibenzo(a,h)Anthracene	**0.71**	NS	NS	NS	**0.66**	NS	**0.52**
19-PAHs (sum of all 19)	**0.66**	NS	NS	NS	**0.69**	NS	**-0.61**

Note: Coefficients between 0.5 and -0.5 are indicated in the table with an "NS" (not significant); positive correlations that are considered significant are highlighted in pink and negative correlations that are considered significant are highlighted in blue.

CONCLUSIONS AND FUTURE RESEARCH

Given that the purpose of this project was to determine causal relationships between three variables (ambient temperature, wood moisture content and wood type) and emissions of a wide variety of pollutants, the results are mixed. A multivariate model could not be produced due to what appears to be a wide range of variables that affect emissions. However, univariate analysis was able to determine some significant correlations between variables of interest and pollutants. Wood moisture content was determined to be the only variable of interest with a significant impact on emissions for some appliances. Of the various appliances tested, open fireplaces and EPA pre-2020 wood stoves have a large number of positive correlations between wood moisture content and emissions of various pollutants. For open fireplaces, this phenomenon could be explained by the uncontrolled nature of the burn cycle (no control over combustion air and no emissions controls). However, the large number of positive moisture content/pollutant correlations in EPA pre-2020 wood stoves cannot be explained.

Conventional wood stoves and EPA 2020 catalytic wood stoves have no significant correlations between wood moisture content and emissions (or either of the other two variables of interest). Although this is the case, it is important to note that open fireplaces have comparatively high emissions levels of many pollutants and EPA 2020 catalytic stoves have comparatively low emissions of many pollutants when compared across the range of the appliances tested. Other appliances fall between these two in terms of emissions intensity.

From the perspective of developing emission factors for the use of wood burning appliances, the conditions under which these appliances are operating appears to matter less than the type of appliance being used. Tracking changes in the types of appliances in use within a population of appliances may yield more accurate results in determining emission factors than would factoring in the conditions under which the wood is being burned. The only possible exception to this is wood moisture content. Establishing estimates of wood moisture content that are as accurate as possible should help improve these estimates. Broadly speaking, it is worth noting that the inherently chaotic nature of the process of burning round wood in an appliance results in many random factors that can affect emissions, making it difficult to establish these conclusions with a high degree of certainty.

Be that as it may, the results of this study indicate that some of the average emission factors shown in Table 6 are similar to emission factors that have been used by ECCC in the past, indicating that they can still be considered valid. However, this study is the first to measure nitrous oxide emissions, and in the case of the open fireplace, the emissions were half those previously estimated. Also important is that the emission factors for U.S. EPA certified 2020 catalytic wood stoves are substantially lower than other, earlier models of wood stove. In future, as this type of emission control technology penetrates the population of in-use wood burning appliances, its influence will begin to be seen in emissions estimates.

Additional research would be of high value in order to confirm or refute these findings. Other agencies, notably the USEPA and Northeast States for Coordinated Air Use Management (NESCAUM) continue to conduct studies that examine the relationship between similar appliances and conditions of use to pollutant emissions. A concerted effort to link the results of various studies may yield more certainty in the conclusions that can be drawn from this research effort.

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1) Pitzman, Lyrik, *Task 4 – Final Report for "Impact of Various Parameters on Woodstove Emission Factors"*, Environment Canada Contract No. 3000698945, PFS Corporation (dba PFS TECO), November 1, 2022.
2) Robert, G., Gosselin, R., *Final Report for "Impact of Various Parameters on Solid Fuel Burning Appliances Emission Factors"*, Environment Canada Contract No. 3000698945, Université de Sherbrooke, October 25, 2022.

NOTE: Both of these documents are unpublished, but can be obtained by sending a request to: Lindsay.Pratt@ec.gc.ca