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Results of the 2018 Wood Stove Design Challenge

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Abstract

The 2018 Wood Stove Design Challenge was an international design competition which sought to identify top performing residential wood stoves based on automation. To prepare for the event, the Northeast States for Coordinated Air Use Management (NESCAUM) developed a testing protocol that challenged the stoves by testing them in more field-like conditions—capturing emissions from start-up, reloading a stove, and the use of larger piece sizes. Flue gas emissions were measured using a combination of in-stack and novel dilution sampling methods, as the event occurred on the National Mall in Washington D.C. in a non-laboratory setting. Particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4) were measured from three stoves in real-time. A combustion efficiency was also calculated for each stove in real-time.

Measured PM emission rates ranged between 1.8 and 8.0 g/hr for all stoves and operating conditions, with the highest emissions being measured during cold start in all cases. The test average PM emission rates were 2.4, 4.0, and 2.4 g/hr for stoves A, B, and C, respectively. Results showed emissions measured during transient operations, which are often excluded in current certification methods, can be significantly higher than steady-state periods—echoing other studies and highlighting the importance of testing in various operational modes for more realistic emission estimates. Additionally, the stoves had overall CO emission rates of 48.8, 284.8, and 100.8 g/hr, for stoves A, B and C, respectively. Calculated PM and CO emission factors overall were low considering the testing protocol sought to follow more challenging yet realistic practices in terms of fuel loading and operating procedures. The overall estimated combustion efficiency for stoves A, B, and C was 85%, 78%, 76%, respectively and in all cases was lowest during the cold start period.

This report details the successfully proposed and assembled instrumentation that was relatively portable for field-site testing and the results of the emissions measurements for the 2018 Wood Stove Design Challenge competition. Overall, the repeatability of each stove was favorable with coefficients of variation (COV) ranging from 7 to 15% for measured PM concentrations.

Contents

Table of Figures

Table of Tables

Introduction

The Wood Stove Design Challenge (WSDC) events were started by the Alliance for Green Heat to highlight innovations leading to cleaner, more efficient wood space heaters. Cosponsors of this event include the U.S. Department of Energy's Bioenergy Technology Office (BETO), the New York State Energy Research and Development Authority (NYSERDA), and the Osprey Foundation (www.forgreenheat.org/2018-stovedesign/stovedesign.html). As a follow up to the 2013, 2014, and 2016 Wood Stove Design Challenges (WSDC), the 2018 WSDC asked stove manufacturers to develop a stove that was automated with sensors and perhaps WIFI-enabled controls that helped reduce emissions and improve combustion efficiency—all while being easy to use.

In order to test the stoves ability to reduce emissions using its sensor and control system, the Northeast States for Coordinated Air Use Management (NESCAUM) developed a testing protocol for all the automated stoves in the competition as part of their ongoing work on advanced test method development (https://www.nescaum.org/topics/test-methods). The proposed 2018 WSDC field protocol was novel in the sense that it incorporated real-life scenarios encountered in the field such as cold start and reload periods with an operator using very few but very large pieces of firewood as opposed to many small pieces or a full firebox of fuel being forced into a low-load operation.

Standard test methods currently do not consider real-life practices and are hot-to-hot tests only; such that a hot coal bed is established prior to the fuel charge being added and emission measurement beginning. Additionally, fuel charges are added at a specified loading volume of 160 kg/m^3. This often will overlook the high emissions associated with cold starts and overloading the firebox that were captured in this testing protocol and found in literature [1, 2, 3, 4, 5]. Current test methods *do* test the stove in high, medium, and low burn periods (or four burn rate categories) but, high emissions associated with loading the fuel charge or lower burn rates can be masked with long burn out periods. Manufacturers have been criticized for lengthening the burn time of the stove (hr) to shrink the emission rate (g/hr)—as the denominator is increased, the emission rate decreases. Due to the inclusion of cold starts and non-optimal loading densities, it was expected that the emission rates calculated from the three stoves tested to the 2018 WSDC field protocol would be greater than certifiable rates.

Testing of wood stoves for certification purposes is routinely done in a controlled lab environment with a dilution tunnel for conditioning of particulates and accurate determination of emission rates. Stoves are mounted on weigh scales to determine real-time burn rates. In this event, testing was done in a much less controlled environment, on the National Mall in Washington D.C., without the benefit of weigh scales and the dilution tunnel. Therefore, a novel dilution sampling system was developed to measure PM and gaseous emissions throughout the testing protocol.

Brookhaven National Laboratory (BNL) was tasked with proposing and operating the instrumentation for emission measurements during the event, displaying the results in real-time and evaluating the stoves' performance. The 2018 WSDC field protocol was run on three stoves in triplicates over the course a week with each stove tested only once per day. Figure 1 and Figure 2 provide an image of the tent and stove layout for testing. The stoves were free standing in a tent and emissions sampling was performed using a dilution sampling system. Particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4) were measured from each stove in real-time. Emission rate (g/hr) results were calculated for CO and PM, and a combustion efficiency was calculated when applicable. The results are shown in this report with details and discussions of the tests.

Figure 1: Outdoor view of 2018 WSDC tent

Figure 2: Inside the 2018 WSDC test tent

Experimental Methods

The instrumentation needed to be relatively portable because of the nature of the Mall and yet robust enough to handle the challenging testing protocol. In the past design competitions, portable emission measurement devices were used and sampled directly from the stack during steady state conditions. However, the protocol for this event sought to challenge the automation of the stove by requiring a cold start and multiple reloads. It was anticipated the emissions could be very high and PM mass loadings to be high causing some concern for the sensitivity and loading of these instruments. Therefore, it was proposed to use a portable dilutor.

The portable dilutor designed and described below mixed the hot exhaust flue gas with room air and emission samples were then taken from the diluted stream. Gaseous emissions sampled included CO, CO_2, CH_4 and oxygen (O_2). PM, stack, and ambient temperatures were also measured. From the measured gaseous concentrations and temperatures, a combustion efficiency was calculated. Measurements were provided in real-time on a large screen during the event for participants to view. This allowed participants to understand how their stoves were performing over the course of the protocol and what phase(s) their stove had difficulty operating in.

Operational Protocol

The protocol developed by NESCAUM for use in the 2018 WSDC was a major innovation over previous efforts because it included start-up and reloading of fuel in addition to high and low load periods of operation (Table 1). Information about each stove was gathered ahead of time so appropriate fuel loads could be prepared and any needed adjustments to the protocol could be made. The detailed protocols for each of the stoves may be found in Appendix II.

Table 1: Generalized Fueling and Test Protocol for 2018 WSDC

Burn Phase	Load Parameters	Air Settings	Operational Parameters	Phase duration
Start-up	☐ Stove is empty—no ashes ☐ Crumple up to 6 full sheets of newspaper ☐ Fuel loading pattern is defined by the manufacturer's instructions. If no instructions are provided, a top-down burn protocol will be used. For the competition, the manufacturer can build the fuel charge in the stove but cannot light off and will be hands off during the stove testing. For startup phase – fuel can be loaded in multiple batches, but all fuel must be loaded within the first ten minutes of the phase. ☐ Kindling Loading density: up to 16.02 kg/m^3 for dry kindling (8-10 pieces of kindling recommended) ☐ Fuel loading density must be 64.07 kg/m^3. ☐ Minimum weight determined by fueling calculator	☐ Air settings will be determined by the manufacturer. Up to 2 changes in air settings can be used during the start-up phase.	☐ Start fire according to manufacturer's instructions. Use of a torch is acceptable for up to 30 seconds. ☐ Door may be in any position for up to 5 minutes ☐ Manufacturer will set time and door position prior to competition. ☐ For the first 15 minutes, the door can be opened, and fuel adjustments made. A maximum of four fuel adjustments can be made. Door can remain open for no more than 30 seconds per fuel adjustment. Door must be closed as soon as fuel adjustment is complete.	☐ 30 minutes after match light or loss of yellow flame.
First reload	☐ Loading density: 80.09 kg/m^3 (+/- 5%) ☐ Size: Small pieces as determined by the fuel calculator ☐ Four pieces of wood for load ☐ Fuel loading direction – manufacturer's instructions – ○ East/west ○ North/south ○ Criss-cross	☐ Low air setting or lowest heat demand	☐ Open door ☐ Chop existing wood with a fuel piece to achieve smooth coal bed ☐ Load first load ☐ Door closed immediately. Maximum reload time of 60 seconds ☐ Allow one fuel adjustment during burn period (door can be open for only 30 seconds) ☐ No air adjustment allowed	☐ 45 minutes
Second reload	☐ Loading density: 2 large pieces as defined by the fuel calculator ☐ Fuel loading direction – manufacturer's instructions – ○ East/west ○ North/south ○ Criss-cross	☐ Highest air setting or highest heat demand	☐ Open door ☐ Break up/chop/reposition remaining fuel to the extent possible. ☐ Load second load. Maximum reload time of 60 seconds ☐ Door closed immediately ☐ No fuel or air adjustment allowed	☐ 30 minutes

Third reload	☐ Loading density: as much as can be reasonably loaded, determine weight after starting low load portion must be greater than 106.19 kg/m^3. ☐ Size: at least 50% of the pieces loaded should be large pieces by number of pieces, additional space should be filled with small pieces. ☐ 5-8 pieces of wood should be used ☐ Loading direction: all pieces are loaded either east/west or north/south	☐ Low air setting or lowest heat demand	☐ Open door ☐ Mandatory chop and raking of the coal bed after second load phase ends ☐ Load third fuel charge. Maximum reload time is 90 seconds. ☐ Fuel may be adjusted once during initial 10-minute period. Door can only be open for 30 seconds	☐ 75 minutes

Dilution Sampling System

A dilution sampling system was designed to dilute the flue gas concentrations with ambient air in order to measure both gaseous and PM emissions without the risk of overloading sensors. The purpose of the dilution sampling system was to condition the hot, particulate laden, flue gas for measurement. This step was necessary to cool the semi volatile gases, and to protect the particulate sampling equipment from the high temperature, and high concentrations of particulates present in the flue gas. The dilution system consisted of three parts: 1) the sample probe, 2) the dilution air source, and 3) the diluter. This system was designed to provide 30 liters per minute of 11:1 diluted flue gas sample for particulate matter measurements. The dilutor tapped into the stack at 0.61 meters from the stove base.

Construction

The purpose of the sample probe was to facilitate sampling of flue gas for PM measurement. The sample probe was affixed inside the flue stack along the centerline, with the inlet facing directly into the incoming gas stream; the outlet of the sample probe extended outside of the flue stack to facilitate connection to the diluter. The sample probe was manufactured from 1” OD stainless steel tubing, bent an L shape with 4” straight sections. The inlet side of the sample probe was ground down to a sharp opening, such that the ID is 1”. A ¼ “compression fitting was braised to the outlet side of the sample probe to allow connection to the diluter using ¼” flexible heated tubing.

The heated sampling line was connected with compression fittings to 3 LPM critical flow orifice with differential pressure taps. The purpose of the critical flow orifice was to 1) ensure constant flow into the diluter, 2) provide a metric, in the form of differential pressure, to monitor the flow rate, and 3) to protect the diluter from occlusion. During an experiment, periodic evaluation of the differential pressure across the critical flow orifice allowed the team to identify when occlusion of the system was occurring. Upon this identification, subsequent inlet flow measurements were made. When inlet flow was sufficiently impacted, a replacement of the critical flow orifice was performed, reinstating the proper inlet flow rate and dilution ratio.

The critical flow orifice was connected to a Dekati® Diluter DI-1000, which was chosen to dilute the flue gas as it was a readily available highly portable pre-fabricated unit, with a proven track record in flue gas sampling. This dilutor features two inlets, one for flue gas sample and one for dry particle free dilution air. For these experiments 5 psig dilution air was added through the dilution air inlet at a flow rate of approximately 15 LPM. The dilution air flow rate was continuously monitored throughout the experiment. The inlet and dilution air streams were mixed by the dilutor and exhausted into a sampling chamber, consisting of a 1’ x 4” ID stainless steel tube, with ports for instrument sampling. The dilution air source used at the 2018 WSDC was an oil-less compressor with an internal air dryer, and a particulate filter connected in series.

Operation

Of primary importance to the accuracy and repeatability of the PM measurements, is the ability of the dilution system to maintain a relatively constant dilution ratio. the function of the dilutor was characterized at multiple levels continuously during each test. The first check for proper function of the dilution system was to directly measure the dilution ratio each time fuel was loaded into the appliance. The flue gas sample flow rate and the dilution air flowrate into the dilutor were simultaneously measured using a TSI flowmeter, and an Alicat flowmeter respectively. The dilution ratio was then calculated as the ratio of the sum of the two flow values over the flue gas sample flow rate as shown in Equation 1.

Equation 1: Direct dilution ratio calculation

$$DR_{direct} = \frac{\dot{V}_{sample} + \dot{V}_{dilution}}{\dot{V}_{sample}}$$

During testing, two additional “checks” were used to monitor dilution system integrity. First, the orifice pressure drop was monitored continuously for a decrease in magnitude, from previous experiments we determined that a change greater than 20% of the pre-test value likely indicated occlusion of the orifice, which would require cleaning. Second, the dilution ratio was measured indirectly using the ratio of CO concentration measurements in the flue stack and the dilution system. The equation used for this purpose is given Equation 2.

Equation 2: Indirect dilution ratio calculation

$$DR_{indirect} = \frac{[CO]_{Stack}}{[C\dot{O}]_{DS}}$$

The indirect dilution ratio calculation was performed intermittently throughout each test. An indirect dilution ratio calculation larger than the pre-test direct dilution ratio measurement by 20% likely indicated occlusion of the orifice.

When either diagnostic check indicated occlusion, the time was recorded and the dilutor was taken offline for maintenance. A direct measurement of dilution ratio was made to verify and measure the extent of the occlusion. If the direct dilution ratio measurement varied from the pretest value by more than 20% the orifice was replaced and a second direct dilution ratio was made to verify the original dilution ratio had been recovered. After a positive result the dilution system was put back online and sampling resumed. This verification and cleaning process typically lasted for 5 minutes; resulting in short gaps in the dataset.

PM Measurements

Particulate matter measurements were sampled post dilutor using a Testo 380 and were reported in PM concentration (mg/m^3) at 5 second increments. The Testo 380 is a PM measurement device that also combines the gas analyzer from the Testo 330-2 LL. This analyzer is contained in a box (0.48 x 0.36 x 0.18

m) and allows the user to sample PM, CO, and O_2 parallel in real-time. PM sampling was continuous over the entire test period; however, the data can be isolated by period to provide PM concentrations during the start-up, first reload, second reload, and the third reload burn periods. Leak checks were conducted at the beginning of each test in compliance with the Testo's operation manual.

Flue Gas Analysis

Flue gas and particulate samples were sampled either from the stack directly, or through a dilution sampling system. Excess hot flue gases were exhausted outside the tent through a vertical flue stack. Analysis of samples from the flue gas included: CO, CO_2, hydrocarbons (HC— measured as a methane (CH_4) equivalent only) and were sampled at 0.91 meters from the floor. All gases were measured using an infrared analyzer (California Analytics, Model ZRE). Each gas analyzer was calibrated prior to each test with both nitrogen and the specified calibration gas. All calibration gases were certification grade from Matheson Tri-Gas Co. and provide an accuracy of 2%.

Type K thermocouples (Omega Engineering Inc.) were also logged at a five second interval for all temperature measurements which included: stack temperature (0.76 meters from stove base), ambient air, and post dilution temperature. The thermocouples had an associated error of 2.2° or 0.75%. Thermocouples were logged on a separate computer via LabView software.

Due to equipment limitations, two test trains were used and their set-up is seen in Figure 3 and Figure 4. One train, Train I, followed all the above testing methods—using the aforementioned dilution sampling system to dilute the flue gas for PM sampling with the Testo 380 (this analyzer also measured CO), gas measurements (CO, CO_2, CH_4) from the stack using the ZRE gas analyzer, thermocouples (stack, ambient, and post dilution), and a Höntzsch ZS25 anemometer with a vane wheel flow sensor measured the flue gas velocity at 76.2 cm from the floor. Train II, however, did not use an anemometer or the single ZRE gas analyzer to measure CO, CO_2, and CH_4. Periodically, the CO concentration was checked using a Testo 350 but to avoid polluting the sensor with PM or too high of CO, the analyzer was not logged continuously and only served as a quick check. A second dilution system and Testo 380 were still used to determine the PM and CO concentrations, post dilution. Thermocouples were still used to log the stack, ambient, and post dilution temperatures for Train II. The differences between Train I and Train II may be seen in Figure 3 and Figure 4. Both trains were also portable due to the nature of this event.

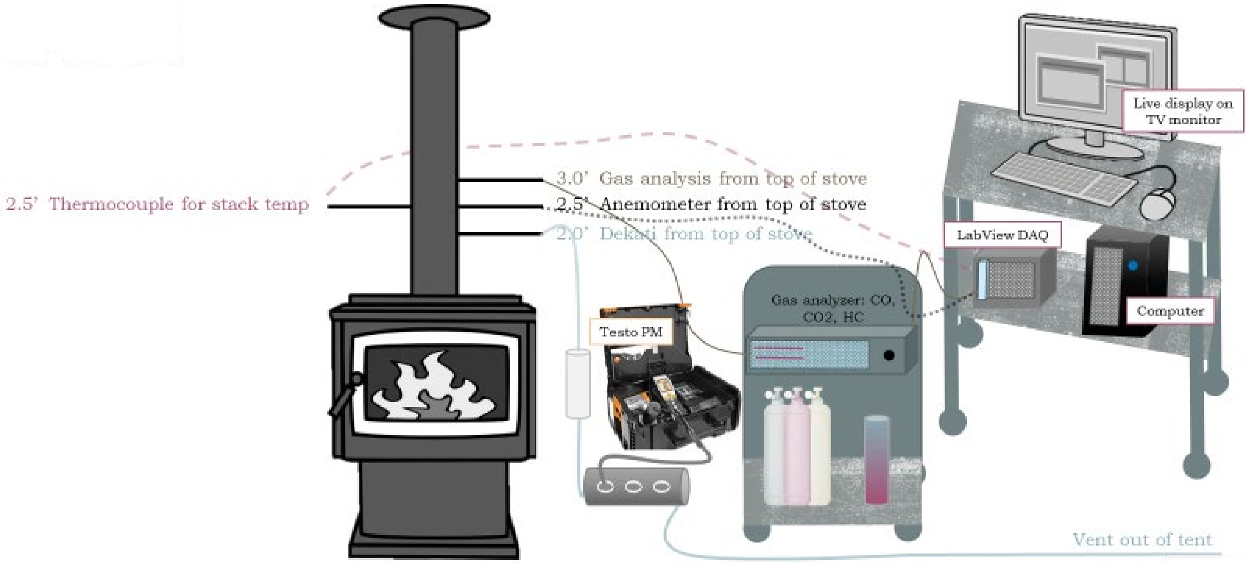

Figure 3: Train I emission sampling in-field set-up

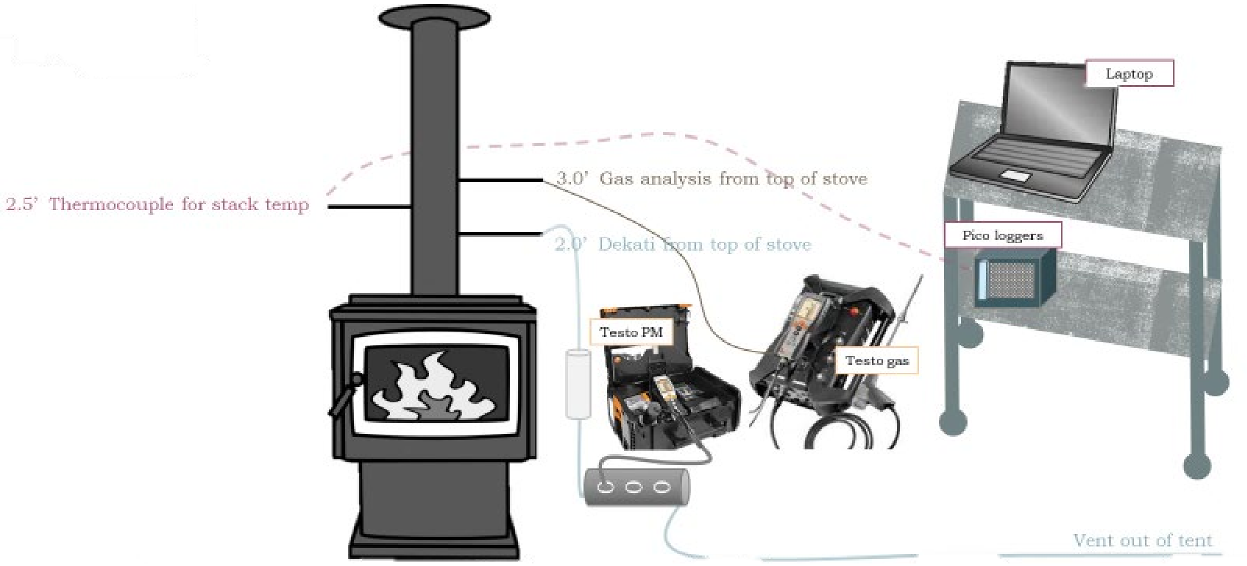

Figure 4: Train II emission sampling in-field set-up

Efficiency Calculations using a Stack Loss Method Approach

To estimate the combustion efficiency for each of the burn periods, a stack loss method was applied. This method considers the stack temperature, ambient temperature, CO concentration (ppm), and CO_2 (%) present in the stack. Inputs such as the moisture content of the fuel (mass of water per mass of dry fuel), the ambient humidity ratio, (mass of water per unit of mass of dry air) and the ultimate analysis of the dry fuel (% by weight) are required. A fuel moisture content of 22% was used for all calculations as detailed moisture data was not provided. A calculator program was built for the purpose of this test; details regarding the calculations may be found in Appendix I.

Stoves

The first stove, Stove A, was a single burn rate stove that provided a source of heat, electricity, and hot water. The stove featured down draft gasification and secondary air inlet controls. The second stove, Stove B, was a catalytic stove with a manual bypass that operated with no electricity. The air injection into the stove was valve controlled by the chimney draft generated by the stove and flue when burning. The valve controls the amount of air that enters the stove in response to the static pressure change at any given time. To prevent excessive smoke and high emissions, if an operator switches the stove into its low burn setting too quickly after reloading the stove, the valve will not cut off air flow to the stove until the static pressure is deemed safe enough.

The third unit in the competition, Stove C, was integrated with both a temperature and static pressure sensor to control combustion and optimize the stove's performance. While the user could define a burn rate of high, medium, or low, the stove would automatically control the air inlet. If the stove were deemed to not be burning cleanly, the stove would automate itself to first achieve a clean burn before achieving the burn rate set by the operator. Table 1 below summarizes the three stoves and their unique features; none of the stoves were catalytic.

Table 2: Summary of Stove Descriptions

	Stove A	**Stove B**	**Stove C**
Combustion chamber volume (m^3)	0.051	0.061	0.035
Output control	Single burn rate	Manual lever	High, medium, low setting via digital interface
Catalytic	No	Yes	No
Features	Pressure sensor and down draft gasification	Valve controlled air injection based on static pressure change	Temperature and static pressure sensor to control air inlet

Test Fuel

The fuel test charge was a mix of Beech and Maple cordwood (supplied by the Alliance for Green Heat) with an average moisture content of 18 to 25% on a dry basis. Fueling procedures were defined by the 'fueling calculator' provided with the 2018 WSDC field protocol. The calculator required the user to define the species, the firebox dimension (m^3), and the piece length (80% of the longest firebox dimension). Using these measurements and the loading densities specified for each phase (seen in Table 1), the calculator provided a range of piece size and weight for each phase. Table 2 below summarizes the piece size of the fuel, size, and weight for each stove and load. Piece size and load weights seen in Table 2 were only target ranges for each test and do not represent exact values. The kindling charge was made-up of half smaller pieces and half larger. The actual piece sizes and weights were not recorded during the event.

Table 3: Target Piece Size and Weight for Each Phase of Test Protocol for Each Stove

	Stove A	Stove B	Stove C
Fuel Length (cm)	35.6	40.6	40.6
Kindling Load			
Total Load Weight (kg)	0.8	1.0	0.7
Target # of Pieces	14 – 18	18 – 22	12 – 15
Starter Fuel			
Total Load Weight (kg)	2.5	2.9	2.0
Weight per Piece of Fuel (kg)	0.3 – 0.6	0.4 – 1.0	0.4 – 0.8
Target # of Pieces	4 – 5	4 – 5	3 – 4
First Reload			
Total Load Weight (kg)	4.1	5.0	3.4
Weight per Piece of Fuel (kg)	0.6 – 1.3	1.0 – 1.8	0.8 – 1.6
Target # of Pieces	4	4	3
Second Reload			
Total Load Weight (kg)	No target	No target	No target
Weight per Piece of Fuel (kg)	1.2 – 1.3	1.9 – 2.2	1.5 – 1.7
Target # of Pieces	2	2	2
Third Reload			
Total Load Weight (kg)	8.2	10.0	6.8
Weight per Piece of Fuel (kg)	0.6 – 2.3	1.0 – 2.7	0.8 – 2.7
Target # of Pieces and Weights	3 pc @ 0.6 – 1.3 & 3 pc @ > 1.3 kg	3 pc @ 1.0 – 1.8 & 3 pc @ > 1.9 kg	3 pc @ 0.8 – 1.6 & 3 pc @ > 1.6 kg

Wood Moisture Measurements

Moisture measurements were taken using a Delmhorst J-2000 meter that uses resistance technology to measure the moisture content of the wood. The average moisture of the test fuel load was determined by averaging three moisture readings measured parallel to the wood grain and on one side of the fuel piece. Measurements were taken at the center and a few inches in from either end of the piece. Measurements were taken only to check that the fuel pieces fell within the range of 18 to 25%, but details of each measurement point and piece were not recorded. Measurements were made one-week prior to the event and bundles for each stove and load were preassembled. The bundle was weighed the morning of each test to determine if any significant weight loss had occurred which may be owed to additional drying. No such situation occurred.

Efficiency Error Analysis

Exact piece size, weight, and moisture content were not recorded for the 2018 WSDC in detail. The fuel was conditioned by the AGH in identical conditions over the course of one year and as discussed above, moisture measurements and piece weight were tracked over time. One week prior to the event, the moisture content of the fuel was checked to assure it fell between 18 and 25% MC on a dry basis, for each measurement point with the handheld moisture meter. The pre-bundled loads (determined by the fueling calculator) were also weighed daily up until the testing day to assure no weight loss occurred. However, without exact moisture data and piece weight, errors in the combustion efficiency calculation exist and is discussed below.

The combustion efficiency calculated for the purpose of the WSDC was to provide real-time comparative data for the teams. The developed real-time calculator was novel in the sense it required no mass measurement and used inputs of flue gas concentrations. However, the calculated combustion efficiency is based on an iterative approach and accounts for both the moisture of the fuel and calorific value of the fuel, both assumed values for the purpose of this report.

Because the exact calorific value, fuel mass, and fuel moisture are unknowns, an explicit error analysis would be irresponsible. In its stead an analysis the relative uncertainties of the unknown quantities will be reasonably estimated and presented with the calculated results, in order to generate an estimate with a representative range. Only the uncertainty of the unknown quantities will be estimated, as the potential variability in these quantities is much larger than the measurement errors. In brief: the assumed average moisture content of the fuel and value used for all calculations was 22%; an average value of the allowable range between 18 and 25%. The exact amount of Beech and Maple pieces were also unknown in each bundle, contributing an uncertainty of 14% of the value. Beech and Maple fuel have different higher heating values (HHV); roughly 18 MJ/kg for Beech and 19 MJ/kg for Maple. Thus, the calorific value of wood fuel used in the efficiency calculation was 18.5 MJ/kg, and the uncertainty 9%. Additionally, the moisture content of the fuel affects the HHV, specifically lowering the value as the fuel moisture increases, representing an additional 4% uncertainty within the acceptable range. Considering an uncertainty of 14% for moisture content and 9% for calorific value, and 4% for the additional synergistic effects, the uncertainty in the calculated combustion efficiency is ±14%.

Results and Discussion

The average dilution ratio calculated from the flow rate measurements and COV of the dilution ratio for each test and stove are given in Table 4. The dilution ratios during testing of Stove A range from 12 – 18x, with maximum variations of approximately 12% throughout a given test. Intermediate dilution ratios, calculated from the stack and dilution system CO measurements, showed good agreement throughout the experiment, indicating little occlusion occurred throughout each test section, which was then verified by the flow rate-based dilution measurements. As such, there was little variation in dilution ratio within a given test and across the triplicate tests. Therefore, notable differences in individual tests of Stove A are likely due to changes in the stove's emission characteristics, shown in the raw measurement results.

The calculated dilution ratios during testing of Stove B range from 22 – 29x with maximum variations of approximately 33% throughout Tests 1 and 2, and < 10% in Test 3. Notably, the dilution ratios for Stove B were higher compared to Stove A and C, with considerably more variability. The initial dilution ratio settings for Stove B tests were also slightly higher than for Stove A and C. This choice was made to protect the Testo 380, based on the initial PM concentration data, which was well above the minimum detection limit of the instrument, and remained high throughout each test even at this higher dilution ratio. The higher variability in the dilution ratio for Stove B can be explained by higher pollutant emissions and additional issues with condensation throughout the test cycle. The extremely high stack temperatures (> 400^{o}C) during reload two caused condensation in the orifice section resulting in partial occlusion which effected the dilution ratio and requiring cleanings during the beginning and end of this section. During Test 3, the procedure was partially amended to allow for intermediate cleaning of the dilution system, which resulted in decreased variability during this test. Even given these variations, it is likely the high pollutant concentration dominates the results, such that the raw emissions measurement timeseries are representative of Stove B's performance during each test.

The calculated dilution ratios during testing of Stove C range from 12 – 17x with maximum variations of approximately 20% in Test 1, and variations of < 10% in Tests 2 and 3. The minimum initial dilution ratio was used for Stove C due to the low emissions concentrations measured throughout the test. Intermediate CO ratio measurements indicated good little variation of the dilution ratio between flow measurements at each reload, indicating little to no occlusion throughout individual test sections. The repeatability and lack of variation of the dilution ratio, in individual tests of Stove C, and throughout each test, indicate that the raw PM concentration results are well representative of trends in pollutant emission.

Stove A

Stove A was run with Train I twice (Test 1 and 2) and Train II once (Test 3).

The fueling and testing protocol was followed with a modification for Stove A because it only had one burn rate. Therefore, during the first and third reload, the stove was not put into a low fire but just run at its full output rate. The reloads occurred nominally at 30 minutes (first reload), 75 minutes (second reload), and 105 (third reload).

Table 4: Calculated Dilution Ratios for Each Stove and Test

	Stove A			**Stove B**			**Stove C**		
Test #	*Calculated Dilution Ratio*	*Stdv*	*COV*	*Calculated Dilution Ratio*	*Stdv*	*COV*	*Calculated Dilution Ratio*	*Stdv*	*COV*
1	17.8	2.0	12%	28.3	16.4	58%	16.9	4.2	25%
2	14.6	2.0	13%	29.0	13.3	46%	12.9	0.8	6%
3	12.0	1.4	12%	22.1	2.1	10%	12.2	1.6	13%

Figure 5 details the PM concentration (mg/m^3) over the entire burn for all three tests for Stove A (Test 1: top in red, Test 2: middle in blue, and Test 3: bottom in yellow) including all reloads and phases. The dilution ratios for each test are also provided in the upper righthand corner of the figure. The PM concentration was measured post dilution using the Testo 380 and in Figure 5 is not corrected for dilution. Remarkably, only Test 3 shows a spike in PM during the start-up period; start-up is typically the shortest period but represented by high levels of PM. The start-up period concluded at 30 minutes from time zero for all three tests. Only a small spike is seen during the third reload phase for this stove. However, since this stove only had a single burn rate, all periods were principally the same air flow setting with only fuel pieces and size varying.

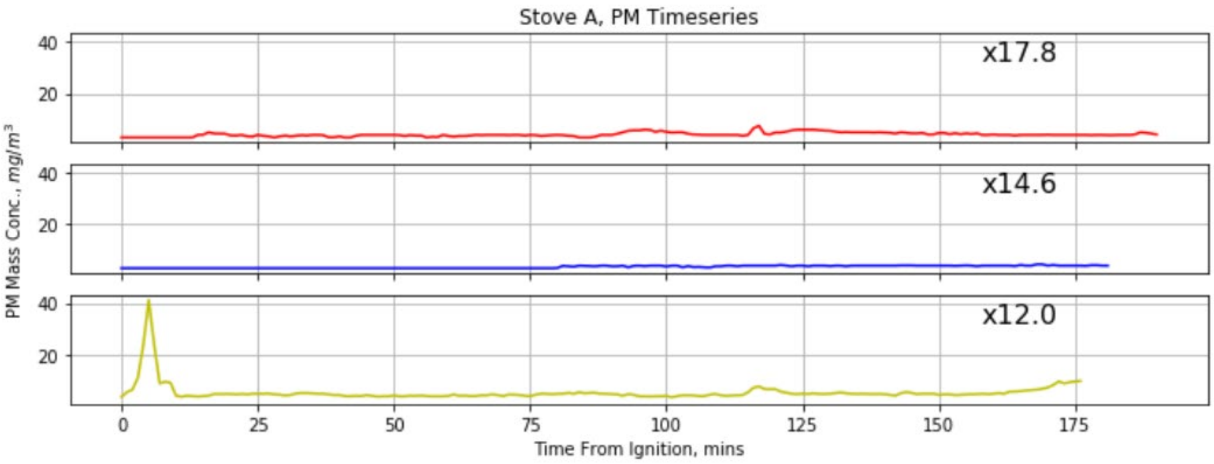

Figure 5: Stove A PM concentrations in diluted gas sample (mg/m^3) for all tests. Test 1: top plot in red, Test 2: middle plot in blue, Test 3: bottom plot in yellow

The first reload occurred at 30 minutes after starting the stove but is not evident in terms of PM concentration. After reloading a stove with more wood and or stoking the fire, typically an increase in emissions is observed, as seen in the work by Traynor et al. [6]. Similarly, the second reload in all three tests is not represented by a spike in PM near or slightly after the 105-minute mark in each of the tests. Roughly 120 minutes into the test, after the third and final load was added to the combustion chamber, Tests 1 and 3 show there was only a slight increase in PM concentration. The highest PM concentration (raw value) for Test 1 was measured as 7.5 mg/m^3 at 117 minutes into the test. Test 2's high was not much higher than the average but occurred near 120 minutes and towards the end of the entire test (at 169 minutes) measuring as 4.5 mg/m^3. Test 3 had the highest of all three tests, 41.2 mg/m^3, within the first 5 minutes (during the start-up phase). For all three tests, the lowest observed values were near or at 3.0 mg/m^3 and the lowest measurable value in the analyzers range.

For a true comparison of the average PM concentration amongst each test and phase, the dilution ratio has been applied to the raw PM concentration results. Table 5 below provides a summary of the averages of undiluted PM concentrations measured post dilution and then the dilution ratio (DR) applied $(raw\ PM\ conc.\left(\frac{mg}{m^3}\right) \times DR)$. Following the trends mentioned above, the highest average concentrations for Stove A during Test 1 and 2, were observed right after the third reload, and during start up for Test 3. the PM for each for each test and reload period are in good agreement (Table 4). Overall, the COV was highest during the start-up; noticing that only Test 3 showed a spike in PM while Tests 1 and 2 remained flat, the COV calculation is adequately supported. The overall COV for all 3 tests was 15%.

Table 5: Stove A PM Concentrations Corrected for Dilution and Coefficient of Variation Across all Tests

	PM Averages (mg/m^3)				
Test #	**Start-up**	**First Reload**	**Second Reload**	**Third Reload**	**Overall Test**
1	63	66	80	82	74
2	44	44	54	58	52
3	95	56	67	67	66
Stdv	21	9	10	10	9
Mean	67	55	67	67	64
COV	31%	17%	16%	14%	15%

Figure 6 shows the measured CO_2 values from Test 1 and Test 2 only. Only Train I measured CO_2 directly from the stack; Train II was used during Test 3 therefore CO_2 values are absent. Unlike the flat PM concentration trends, CO_2 values spike more often and are typically associated with reload periods. In both tests, there are gaps of missing data, specifically during the first phase minutes 45 to 65 for Test 1 and 57 to 68 for Test 2 and again during the third phase from minutes 139 to 166 for Test 1 and 157 and 162 for Test 2. During this time, the gas concentrations from the ZRE analyzer were recalibrated. Periodically during testing, if the testing team noticed the gas concentrations were no longer within an accurate range or in other instances to avoid saturation from an earlier event in the test (such an example would include a high spike of CO concentrations during the cold start and then concentrations drop to 0 ppm or negative values), the gas probe was removed from the stack and the analyzers were recalibrated. Data during these periods were also excluded from any analysis. For this specific stove, CO and HC (CH_4 equivalent) values were dramatically lower after the initial spike during a reload period so the analyzers needed to be recalibrated often to ensure an accurate value for the remainder of the measurement period.

Dips in the CO_2 concentration correspond to the door opening for a reload period (at 30 minutes, around 75 minutes, and around 110 minutes). The highest observed values of CO_2 for Test 1 were observed after the third reload and measured near 16%. For Test 2, a high of 16% CO_2 was also observed during the beginning of the final phase, as well as start-up.

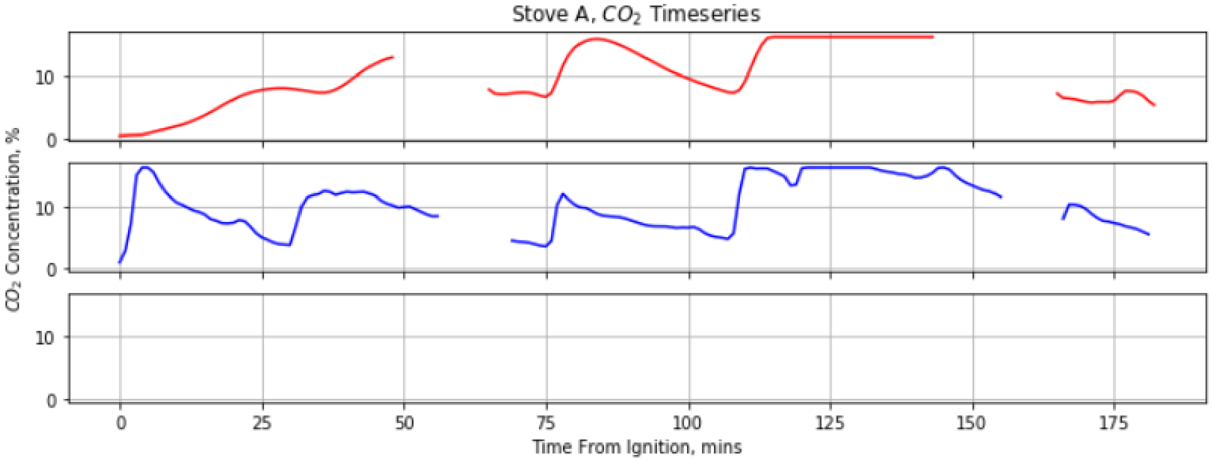

Figure 6: Stove A CO_2 (%) concentrations for all tests. Test 1: top plot in red, Test 2: middle plot in blue, Test 3: N/A

Figure 7 shows the gaseous emissions measured in both the stack and post dilution for Stove A and all three tests. Since Train II was used for Test 3, only CO post dilution is shown Test 3. Similar to Figure 6, Test 1 and 2 have 2 periods of data removed during the re-calibration of the gas analyzer. The gaseous trends observed in Figure 7 are much more similar to the CO_2 trends, with periodic spikes seen during reload events and a slow rise in CO towards the end of a phase as the fuel burns out. The highest CO values of 7530 and 8140 were measured in the stack at 112 minutes and 179 minutes for Tests 1 and 2, respectively. Values less than 10 ppm of CO measured directly in the stack, were also recorded for an extended duration throughout Test 1 and 2. While all three tests have a spike in CO and CH_4 during start-up, Test 2 and Test 3 show much higher CO spikes during the start-up period than Test 1. When CH_4 measurements were made, highs of 346 and 522 were recorded during start up, for Test 1 and 2, respectively. However, CH_4 values leveled off shortly after and recorded near 0 values for the remainder. In all cases, near the end of the test CO values rose, which is typical for the burn out period.

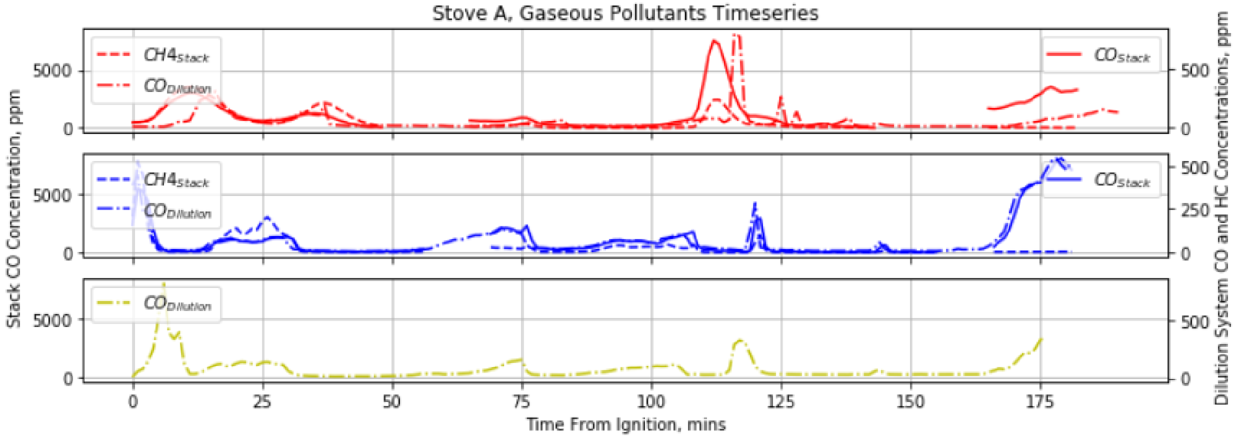

Figure 7: Stove A CO and HC (methane equivalent) concentrations (PPM) for all tests. Test 1: top plot in red, Test 2: middle plot in blue, Test 3: bottom plot in yellow

CO emissions from all three tests are compared in Table 6 below. Specifically, Table 6 provides a summary of the averages of CO concentrations measured post dilution for all three of the tests with the dilution ratio (DR) applied $(raw\ CO\ conc.post\ dilution\ (ppm) \times DR)$. The highest CO emissions were observed in Test 1 shortly after the final reload and during the start-up for Test 2 and 3. The COV was very reasonable for all phases despite the variable nature of CO measurements. An overall COV (based on the average CO for each test overall) was 3%, indicating the test and stove's behavior was quite repeatable. The reader should note, COV has only been calculated for PM and CO (measured post dilution and with the dilution ratio applied) since these values were measured in triplicate regardless of using Train I or Train II.

Table 6: Stove A Average CO Concentrations Corrected for Dilution and Coefficient of Variation Across all Tests

	CO Averages (*ppm*)				
Test #	**Start-up**	**First Reload**	**Second Reload**	**Third Reload**	**Overall Test**
1	1677	415	552	1216	1007
2	1249	588	717	1355	1033
3	2062	490	769	884	967
Stdv	332	71	92	198	27
Mean	1662	498	679	1152	1002
COV	20%	14%	14%	17%	3%

Figure 8 below shows the stack, ambient, and dilution temperatures (°C) for all three tests. All three tests follow nearly identical temperature trends with sharp decreases associated with a refuel. Test 2 was the only test that showed more variation in stack temperature during the third and final reload with the stack temperature dipping near 120 minutes, rising again and then finally leveling out.

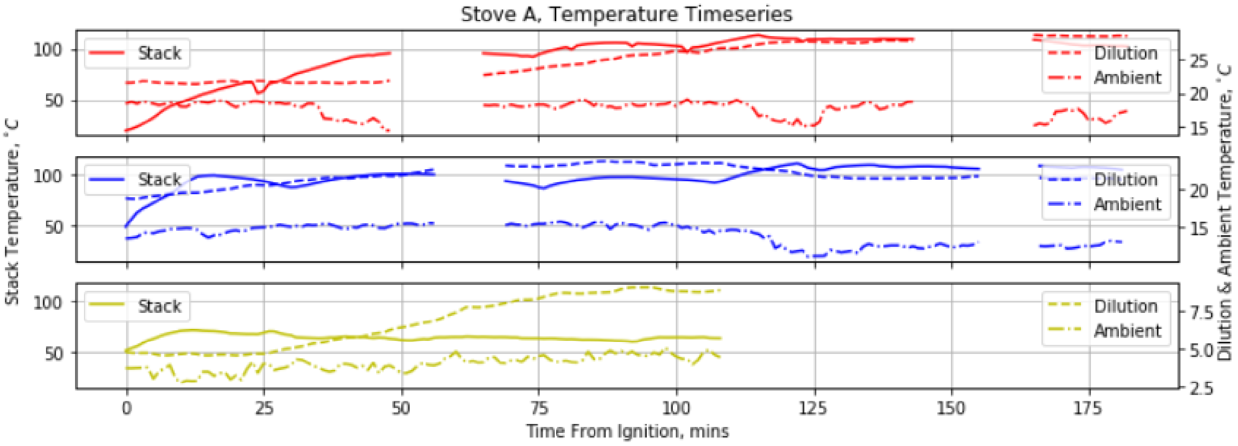

Figure 8: Stove A temperature plots (stack and dilution) for all tests. Test 1: top plot in red, Test 2: middle plot in blue, Test 3: bottom plot in yellow

As detailed above, the combustion efficiency of each stove was calculated via a stack loss method (SLM)—using temperatures, CO and CO_2 values, and assumed or known inputs regarding the fuel and moisture content. The combustion efficiency of the stove was only able to be calculated when Train I was used for sampling as it measured CO and CO_2 values directly from the stack. Figure 9 shows the calculated combustion efficiency for Test's 1 and 2 and includes the uncertainty range of ± 14%. The lowest efficiencies are seen near the start of the test with lows of 76% and 67% for Test 1 and 2, respectively. Shortly after match-lite, a very steady trend occurs throughout the remainder before decreasing slightly near the tail end when CO values increase. High combustion efficiency values of 87% and 88% for Test 1 and 2, respectively were logged. Again, periods where the analyzers were taken out for recalibration have been removed.

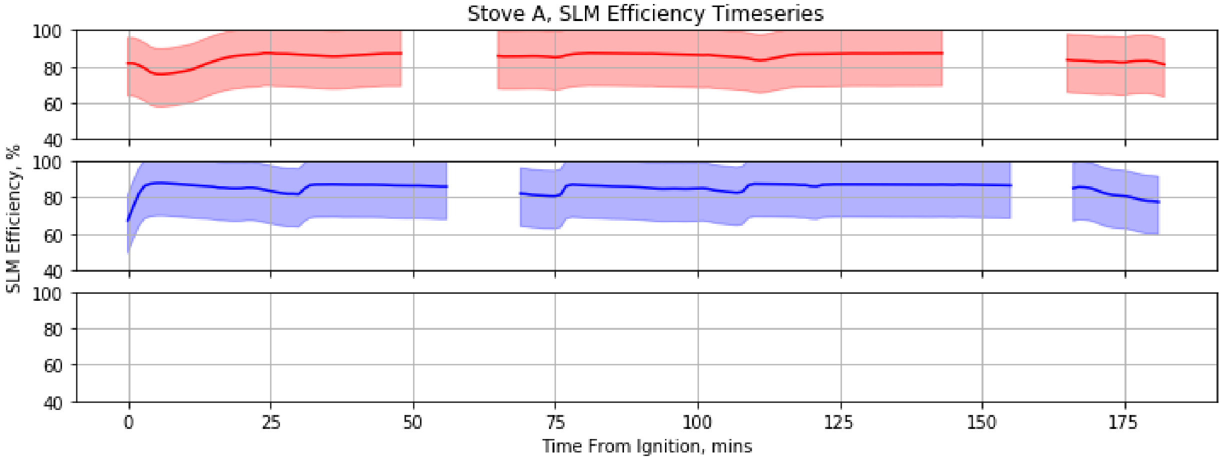

Figure 9: Stove A calculated combustion efficiency (%) for all tests. Test 1: top plot in red, Test 2: middle plot in blue, Test 3: N/A

Table 7 provides an average value for each measured (raw value) parameter for each phase of the test. PM and CO concentrations that were measured post dilution are also provided with the applied DR. Overall, the average PM concentrations for each phase were very close. The measured CO in the stack vs the CO measured post dilution but with the applied DR were only slightly different. The small difference may be owed to the lag in sampling post dilution, and combined variability in the dilution ratio and raw CO measurement. The average overall lowest CH_4 emissions were observed during the second reload period but the highest during the start-up consistent with poorer combustion. The calculated combustion efficiency based on the stack loss method was rather consistent for each period—not unexpected given the single burn rate for this stove. However, startup did have the lowest value combustion efficiency which is corroborated by high CO and CH_4 values and low CO_2 and temperature trends.

Table 7: Stove A Average Values for all Three Tests

	PM conc. (raw)	**PM conc. (DR applied)**	**CO-stack***	**CO-dilution (raw)**	**CO-dilution (DR applied)**	**CO_2-stack**	**CH_4-stack***	**Stack temperature**	**Combustion Eff.***	**Flue gas velocity***
	mg/m3	*mg/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*°C*	*%*	*m/s*
Start up	4.8	71	1319	117	1733	6.23	132	68.1	83	0.77
First Reload	3.7	54	571	35	515	8.92	42	83.4	86	0.82
Second Reload	4.3	63	467	48	711	9.97	10	87.1	86	0.94
Third Reload	4.7	70	1618	78	1158	12.69	16	92.7	85	0.87
Overall	4.4	65	1109	69	1025	10.00	43	82.8	85	0.85

** Based on an average from Tests 1 and 2 only, when Train I was used*

Test by test details regarding the averages for each phase may be seen in Appendix III.

Stove B

Stove B was run with Train I once (Test 2), Train II twice (Test 1 and 3). It's important to note for this particular stove, the operating manual states the kindling fuel pieces shall include shaved pieces. Manufacturers were allowed to set the kindling load for their stoves during the event with oversight from the judges and testing team. The use of shaved kindling pieces was allowed for the event as a best practice scenario and since it was detailed in the manual.

The PM concentration (mg/m^3) over the entire burn for all three tests (Test 1: top in red, Test 2: middle in blue, and Test 3: bottom in yellow) including all reloads and phases for Stove B is shown in Figure 10. As mentioned earlier, these plots are of the raw measured value only and are not corrected for a dilution factor, however the dilution ratio is shown on each graph in the upper right-hand corner. For each test, there is a small increase in emissions during the start-up period, seen between minute 0 and 15. Small spikes in PM concentration are also observed around 30 minutes, during the first reload period. Another set of small spikes are seen after 75 minutes (the second reload) but Test 3 is the only test that seemed to have trouble optimizing the combustion as the spike was rather large and extended for the entire second phase (two larger logs in high burn).

Consistent with the trends shown in Figure 10, the highest PM concentrations (raw value) for Test 1 and 2 occurred during start-up and measured 13.5 and 11.4 mg/m^3, respectively. Test 3 had the highest PM concentration recorded at 91 minutes and nearly double Test 2, with a value of 20.3 mg/m^3. Despite high PM concentration peaks, lows were observed near the analyzers lower limit of 3.0 mg/m^3 near the end of the second reload for Test 1 and 2, and during the tail end of the first reload for Test 3.

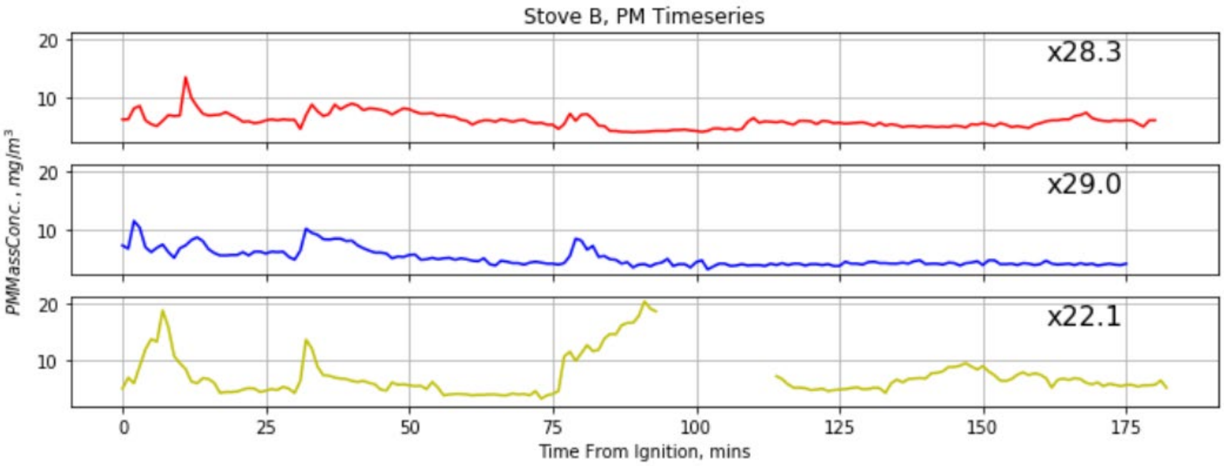

Figure 10: Stove B PM concentrations (mg/m3) for all tests. Test 1: top plot in red, Test 2: middle plot in blue, Test 3: bottom plot in yellow

Table 8 below provides a summary of the averages of PM concentrations measured post dilution for all three of the tests with the dilution ratio applied. As with the trends observed in Figure 10, the highest concentrations are found during the start-up, with the exception of Test 3, during the second reload.

Following the trends mentioned above, the highest average concentrations for Stove B during Test 1 and 2, were observed during right after the third reload, and during start up for Test 3. However, the averages for each period were relatively close to each other. Also calculated in Table 8 is the COV showing the extent of variability for the phase averages in the data set. Overall, the COV was lowest during the final period and highest during the start-up; noticing that only Test 3 showed a spike in PM while Tests 1 and 2 remained flat, the COV calculation is adequately supported. The overall COV was 7%, which is still more than good.

Table 8: Stove B Average PM Concentrations Corrected for Dilution and Coefficient of Variation Across all Tests

	PM Averages (m*g/m*^{3})				
Test #	**Start-up**	**First Reload**	**Second Reload**	**Third Reload**	**Overall Test**
1	194	194	134	155	168
2	192	164	132	115	144
3	166	123	277	143	164
Stdv	13	29	68	17	10
Mean	184	160	181	138	158
COV	7%	18%	37%	12%	7%

Figure 11 below shows the measured CO_2 values from Test 2 for stove B only, as Train I was only used for one of the three tests. Similar to Stove A above, dips followed by spikes in CO_2 values are observed typical after reloads (30 minutes, 75 minutes, and 105 minutes). A gap of data before the second reload has been removed while the analyzers were recalibrated. The highest observed values of CO_2 for Test 2 were observed after the second reload and measured near 16% with a low near 2% at minute 31.

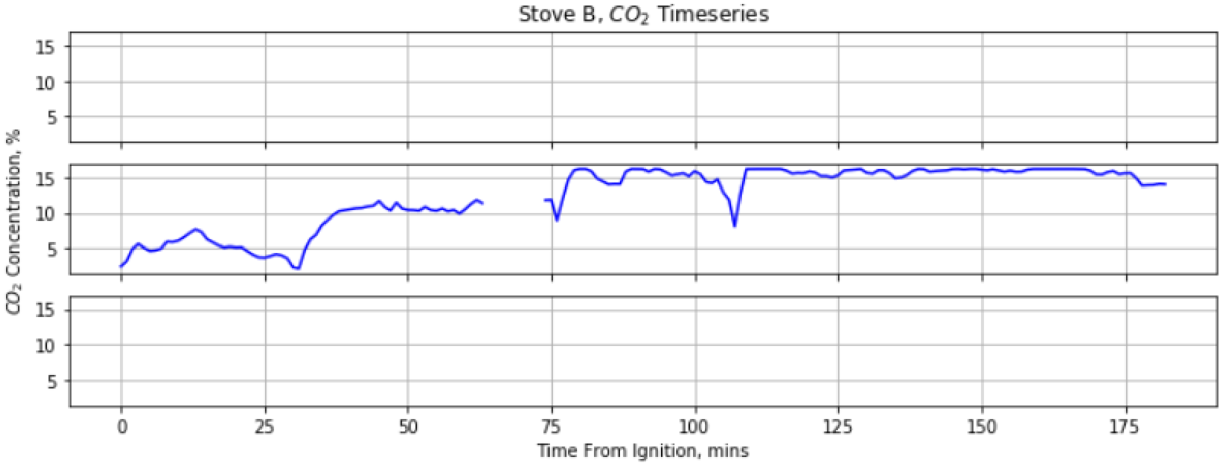

Figure 11: Stove B CO2 (%) concentrations for all tests. Test 1: top plot N/A, Test 2: middle plot in blue, Test 3: bottom plot N/A

Figure 12 shows the CO and CH_4 emissions measured in both the stack and post dilution for Stove B. The center graph in Figure 12 is the only graph that shows all three as the other two tests used Train II and only CO post dilution was measured. In all cases, a strong CO peak is observed after the third and final reload. Weaker peaks of CO measured post dilution are seen following the first and second reload during Test 1 and 3, but larger peaks for Test 2. From the gaseous trends shown in Figure 12 during the third reload period, where the firebox was overloaded and forced into a low burn operation, it is obvious the stove had a difficult time controlling the burn. Stove B used a venturi device that controls the amount of air provided to the combustion chamber based on the chimney draft—which perhaps did not allow for a smooth transition from too much air to too little causing the hunting pattern observed.

During Test 2 with Train I measuring CO in the stack, the CO analyzer reached 24,998 ppm at 109 minutes, right after the second reload. Maximum values of CO measured by Train II post dilution were found during the second reload period as well for Tests 1 and 3. CH_4 values for Test 2 were often out of the analyzers range, spiking near 500 ppm as seen in Figure 12 on the second graph. All three tests followed similar trends during the third reload presenting transient and high CO values. CO values were also increased with each reload (at 30, 75, and 105 minutes). Figure 12 does show a gap in CO and CH_4 data near 65 minutes while the analyzers were recalibrated.

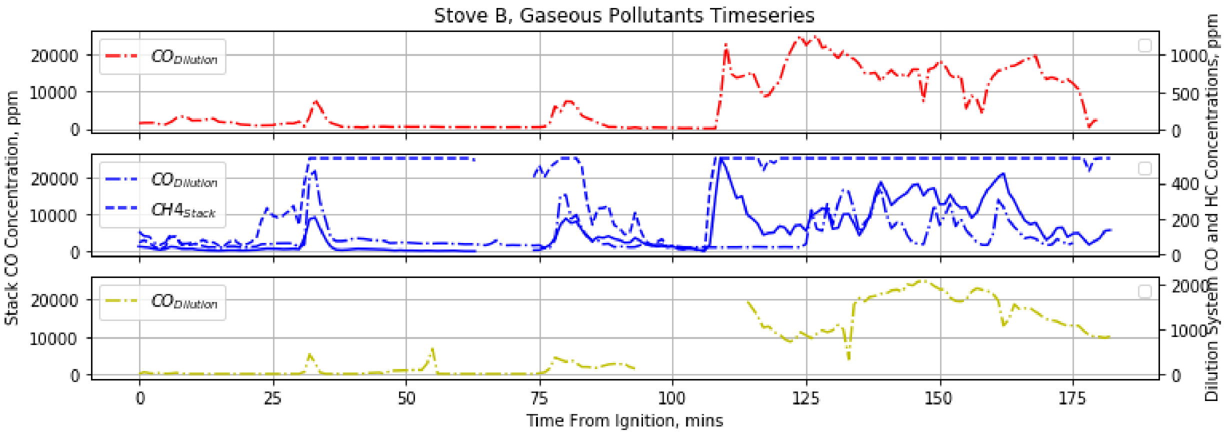

Figure 12: Stove B CO and HC (methane equivalent) concentrations (PPM) for all tests. Test 1: top plot in red, Test 2: middle plot in blue, Test 3: bottom plot in yellow

CO emissions from all three tests are compared in Table 10 below. Similar to Table 6, Table 9 provides a summary of the averages of CO concentrations measured post dilution for all three of the tests with the dilution ratio applied. The highest CO emissions were observed during the third reload for all tests. As mentioned above, this may be owed to the course venturi adjustment of the air flow based on the flue draft during a completely loaded fuel box and low burn rate setting. There are some notable points in Figure 12, primarily, lack of a startup peak during Test 3 and an inconsistency between the dilution and stack CO measurements during the beginning of the third reload. In the first case it is likely that variations in loading and lighting produced a cleaner start than was typical for the unit. In the second case, it is clear that between ~110 minutes and 125 minutes the two CO measurements diverge. During that period all other measurements are reasonable including the dilution PM measurement also made using the Testo, therefore it is likely the Testo CO sensor was temporarily not responding to CO due, possibly due to the concurrent sharp increase in CO. These factors 1) considerably affect the overall test average CO concentration for Test 2 and 2) the overall COV for the startup and third reload sections. The results being: 1) a low Test 2 CO concentration average, and 2) high COV during the startup and third reload test sections, which contribute to the high overall test COV. The main explanation for the high variability in CO emission rate is the large variability in the CO measurement.

Table 9: Stove B Average CO Concentrations Corrected for Dilution and Coefficient of Variation Across all Tests

	CO Averages (*ppm*)				
Test #	**Start-up**	**First Reload**	**Second Reload**	**Third Reload**	**Overall Test**
1	2640	1557	2506	20227	9633
2	1742	2576	2394	3775	2840
3	109	1057	2681	29320	12754
Stdv	1048	632	118	10572	4139
Mean	1497	1730	2527	17774	8409
COV	70%	37%	5%	59%	49%

Figure 13 below shows the ambient, stack and dilution temperatures (°C) for all three tests. All three tests followed similar trends in regard to temperature profiles, with the highest peaks occurring during the second reload period. Stove B's stack temperature was the highest of all three stoves tested, reaching above 400 °C at times. For

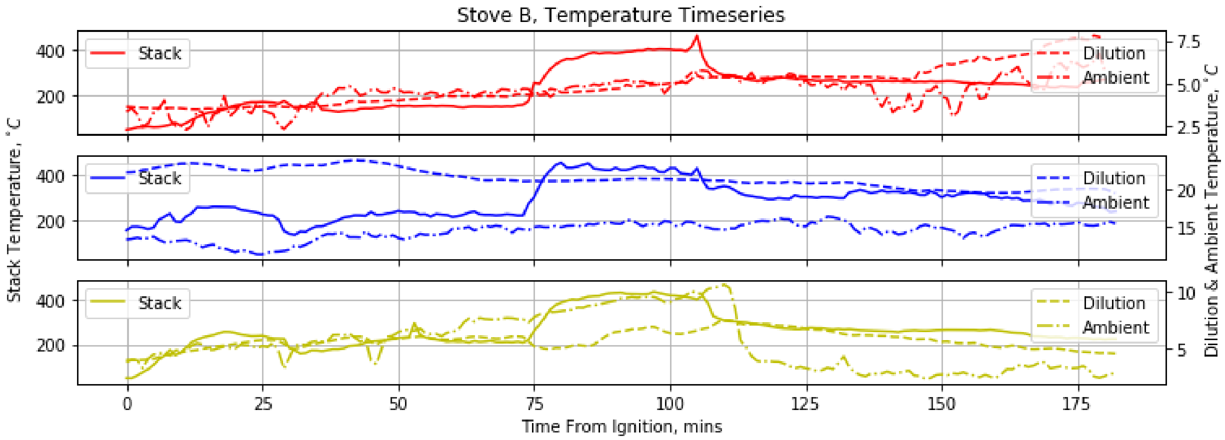

Figure 13: Stove B temperature plots (stack and dilution) for all tests. Test 1: top plot in red, Test 2: middle plot in blue, Test 3: bottom plot in yellow

Figure 14 below shows the calculated efficiency over time. The highest efficiency Stove B achieved was 83% after 38 minutes. However, during that same period, the lowest efficiency was also observed with a value of 65%.

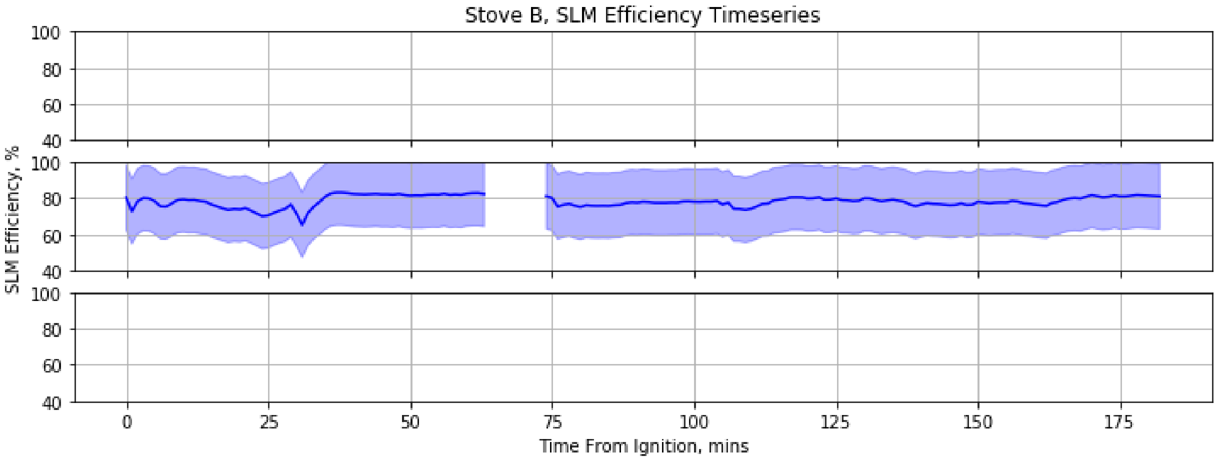

Figure 14: Stove B efficiency (%) calculate via stack loss method for all tests. Test 1: top plot N/A, Test 2: middle plot in blue, Test 3: bottom plot N/A

Table 10 provides an average value for each measured (raw value) parameter for each phase of the test. PM and CO concentrations that were measured post dilution are also provided with the applied DR. The average PM concentrations for each phase were very close. The measured CO in the stack vs the CO measured post dilution with the applied DR had a noticeable difference. This discrepancy is largely explained by the sensor error during the third reload section of Test 2, which is amplified by the fact that Test 2 was the only experiment with stack CO measurements. CH_4 emissions were only measured for Test 2 but lowest during the start-up and similar to the CO trends, highest during the third reload. The calculated combustion efficiency for Test 2 across all periods was fairly consistent, with a low during the start-up period as the stove came up to temperature and established better combustion.

Table 10: Stove B Average Values for all Three Tests

	PM conc. (raw)	PM conc. (DR applied)	CO-stack*	CO-dilution (raw)	CO-dilution (DR applied)	CO_2-stack	CH_4-stack*	Stack temperature	Combustion Eff.*	Flue gas velocity*
	mg/m3	*mg/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*°C*	*%*	*m/s*
Start up	7.0	190	607	53	1396	5.04	102	171.6	76	1.53
First Reload	6.0	160	1187	64	1691	9.93	531	189.9	81	0.39
Second Reload	7.3	190	3050	98	2580	15.03	210	401.9	77	0.26
Third Reload	5.3	140	10545	725	19176	15.68	537	275.7	79	0.87
Overall	6.1	160	5465	339	8965	12.40	400	259.8	78	0.78

** Based on Test 2 only, when Train I was used*

Test by test details regarding the averages for each phase may be seen in Appendix III.

Stove C

Stove C was run with Train I twice (Test 1 and 3) and Train II once (Test 2). The protocol detailed in Appendix III was followed for Stove C with no deviations.

Figure 15 details the PM concentration (mg/m^3) over the entire burn for all three tests (Test 1: top in red, Test 2: middle in blue, and Test 3: bottom in yellow) including all reloads and phases. The PM concentration was measured post dilution using the Testo 380 and in Figure 15 is not corrected for dilution, just the raw measured value is shown but dilution ratios are given in the upper right hand corner. Oddly, only Test 3 shows a spike in PM during the start-up period; start-up is typically the shortest period but represented by high levels of PM. The start-up period concluded at 30 minutes from time zero for all three tests.

The first reload is apparent for both Tests 1 and 3, occurring at 30 minutes after match lite. The second reload in all three tests is represented by a large spike in PM near or slightly after the 100-minute mark in each of the tests. After 30 minutes, the last fuel charge was added and filled the entire combustion chamber. In only Test 2 was there a spike in PM after the third reload (near 125 minutes) while Test 1 remained very level in terms of PM and Test 3 had periodic dips. The highest PM concentration (raw value) for Test 1 was measured 109 minutes in just after the third reload phase and was 7.5 mg/m^3. Test 2's high was measured 102 minutes in, just before the third reload and 6.3 mg/m^3. Test 3 had the highest of all three tests at 9.8 mg/m^3 just 5 minutes in, during the start-up. Each of the stoves observed the lowest PM during the tail end of the burn out phase of the third reload as seen from Figure 15. Similar to Stove A, Stove C PM measurements approached the low range of the Testo 380 capabilities, measuring near or at 3.0 mg/m^3.

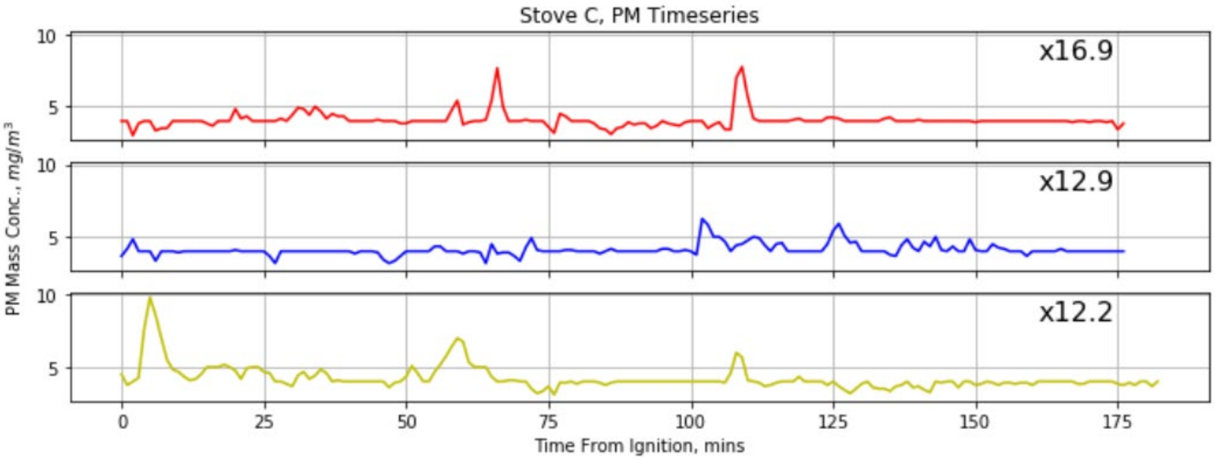

Figure 15: Stove C PM concentrations (mg/m^3) for all tests. Test 1: top plot in red, Test 2: middle plot in blue, Test 3: bottom plot in yellow

Table 11 below provides a summary of the averages of PM concentrations measured post dilution for all three of the tests with the dilution ratio (DR) applied. Following the trends mentioned above, the highest average concentrations for Test 1, 2, and 3 for Stove C was observed during the first reload phase, just after the third reload, and during start-up, respectively. Also calculated in Table 15 is the coefficient of variation (COV) showing the extent of variability in the data set. Overall, the COV was lowest during the start-up period and highest during the first reload. The overall COV was 13%, which is more than good given the nature of cordwood burning and having a non-laboratory setting.

Table 11: Stove C Average PM Concentrations Corrected for Dilution and Coefficient of Variation Across all Tests

	PM Averages (mg/m^3)				
Test #	**Start-up**	**First Reload**	**Second Reload**	**Third Reload**	**Overall Test**
1	67	73	64	69	69
2	51	50	52	55	53
3	62	54	48	48	52
Stdv	7	10	7	9	8
Mean	60	59	55	57	58
COV	11%	17%	12%	15%	13%

Figure 16 below shows the measured CO_2 values from Test 1 and Test 3 only. Only Train I measured CO_2 directly from the stack; Train II was used during Test 2, so CO_2 values are absent. As with the PM concentration trends, spikes in CO_2 are clear during the first reload (near 30 minutes), again at the second reload (near 75 minutes), and the final third reload slightly after 100 minutes into the test. In Figure 16, for Test 1 (top plot), there is a gap of missing data from minute 17 to 20. During this time, the gas concentrations from the ZRE analyzer were recalibrated and data during this period was removed from all analysis. Dips in the CO_2 correspond to the door opening for a reload period (at 30 minutes, around 75 minutes, and around 110 minutes). The highest observed values of CO_2 were 12.7% and 12.6% for Test 1 and 3, respectively. Both incidents happened after the third reload period.

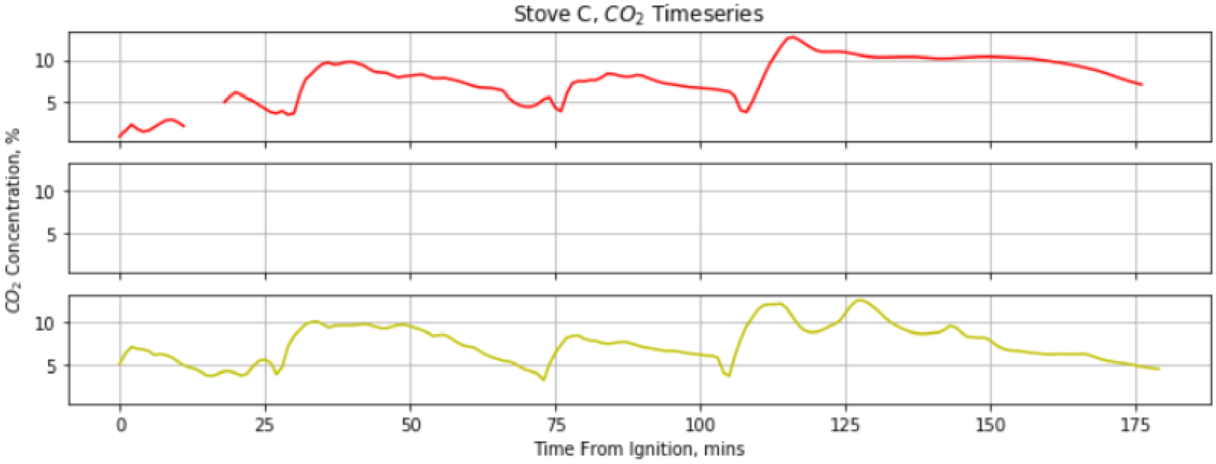

Figure 16: Stove C CO_2 (%) concentrations for all tests. Test 1: top plot in red, Test 2: middle plot N/A, Test 3: bottom plot in yellow

Figure 17 shows the gaseous emissions measured in both the stack and post dilution for Stove C and all three tests. Since Train II was used for Test 2, only CO post dilution is shown Test 2. In Test 1, data is not included from 17 to 20 minutes because of the analyzer re-calibration. As with PM concentrations and CO_2 emissions shown in the above figures, CO and HC (CH_4 equivalent) show a similar trend. Spikes in concentrations are seen following every reload, with the smallest spikes seen during the second reload at roughly 75 minutes. The highest observed values of CO and HC (CH_4 equivalent) recorded in the stack were 7539 ppm and 539 ppm for Test 1, respectively; noting the recorded CH_4 value is the analyzer's upper limit. For Test 3, the highest values for CO and HC measured in the stack were 6570 ppm and 503 ppm, respectively. It's important to note while CH_4 values did approach the analyzer's upper limits at times, lows of 16 ppm and 0 ppm were observed during Test 1 and 3, respectively. In addition, the lowest CO values measured directly in the stack were 215 ppm and 195 ppm for Test 1 and 3, respectively. During the third reload and final phase of the burn cycle, emissions overall average the highest. Both incidents happened after the third reload period. This may be owed to poorer combustion from an overloaded chamber and the stove trying to maintain a low output setting.

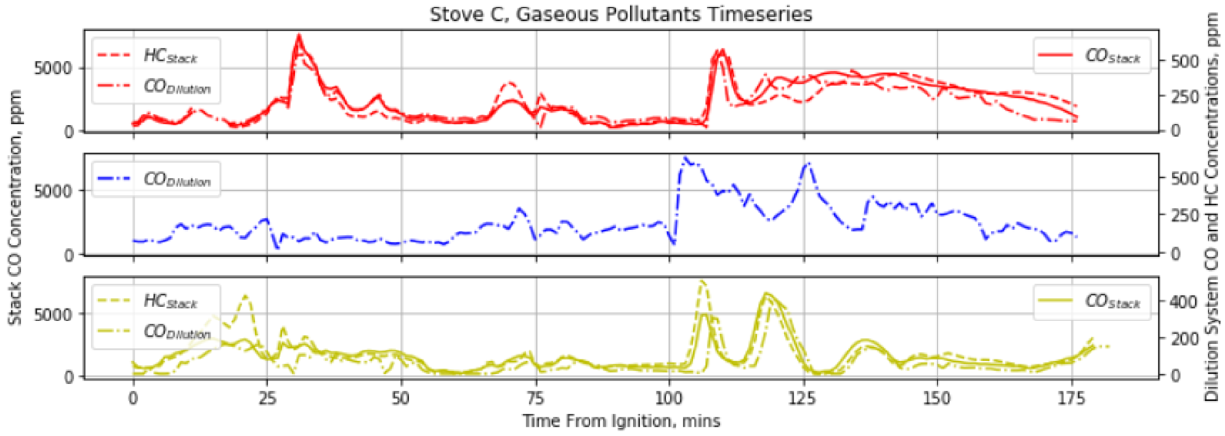

Figure 17: Stove C CO and HC (methane equivalent) concentrations (PPM) for all tests. Test 1: top plot in red, Test 2: middle plot in blue, Test 3: bottom plot in yellow

To compare CO gaseous emissions from all three tests, Table 12 below provides a summary of the averages of CO concentrations measured post dilution for all three of the tests with the dilution ratio applied. The highest CO emissions were observed in Test 1, 2, and 3 during the first reload, third reload, and again third reload, respectively. The COV was rather high for all phases, but that is expected given the fluctuation amongst CO measurements. As mentioned above, COV has only been calculated for PM and CO (measured post dilution and with the dilution ratio applied) since these values were the only measured in triplicate regardless of using Train I or Train II.

Table 12: Stove C Average CO Concentrations Corrected for Dilution and Coefficient of Variation Across all Tests

	CO Averages (*ppm*)				
Test #	**Start-up**	**First Reload**	**Second Reload**	**Third Reload**	**Overall Test**
1	1642	3072	1743	4101	3053
2	1712	1196	2039	3650	2453
3	944	562	303	1057	779
Stdv	347	1066	758	1342	962
Mean	1433	1610	1362	2936	2095
COV	24%	66%	56%	46%	46%

Figure 18 below shows the stack and dilution temperatures (°C) for all three tests. All three tests follow nearly identical temperature trends with sharp decreases associated with a refuel. Test 2 was the only test that showed more variation in stack temperature during the third and final reload with the stack temperature dipping near 120 minutes, rising again and then finally leveling out.

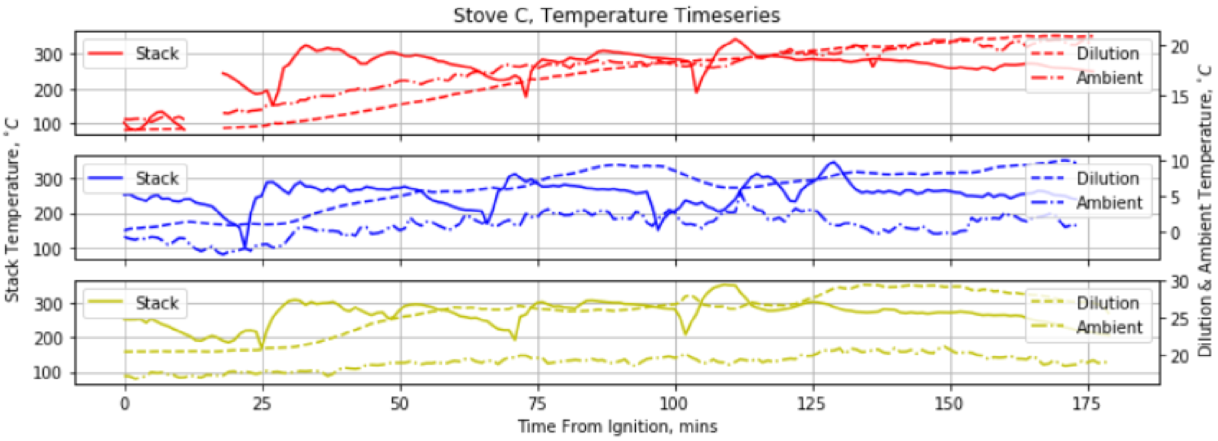

Figure 18: Stove C temperature plots (stack and dilution) for all tests. Test 1: top plot in red, Test 2: middle plot in blue, Test 3: bottom plot in yellow

Figure 19 shows the efficiency (calculated via the stack loss method) for Tests 1 and 3 only. Test 2 used Train II for measurements so CO_2, velocity, and pressure data was unavailable to calculate the efficiency. Overall, Tests 1 and 3 follow very similar trends with the exception of the being of Test 1. Again, minutes 17 to 20 have been removed due to an analyzer re-calibration. Visible dips in the efficiency specifically around minute 30, 75, and 105 correlates with the door open and a fuel charge added. The highest efficiency for Test 1 was observed during the second reload, seconds before the third fuel charge was added (104 minutes) and had a calculated value of 80%. Test 3 had a high of 81% and this was observed 129 minutes into the test after the last reload. Lows of 59% and 62% were also calculated for Test 1 and 3, respectively.

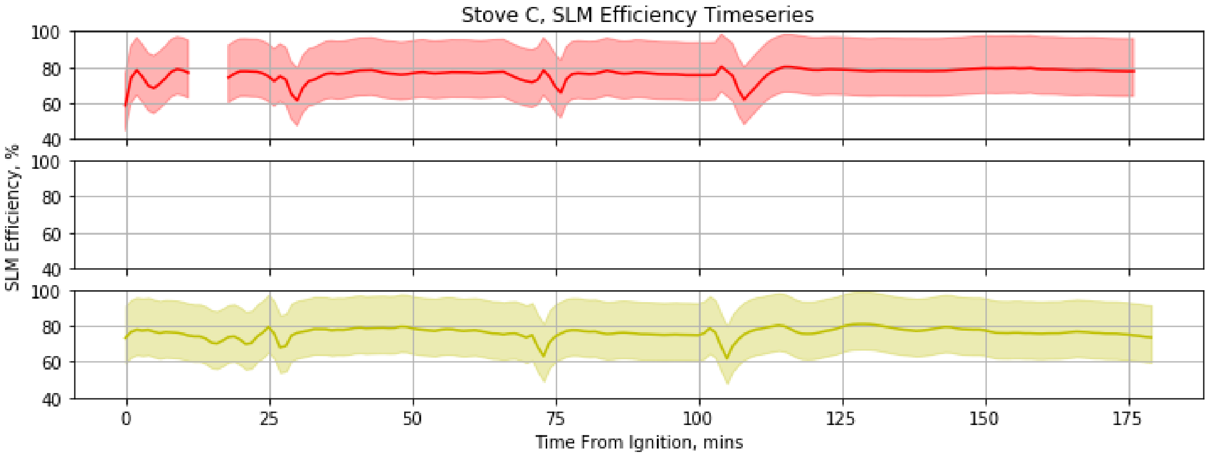

Figure 19: Stove C efficiency (%) calculated via stack loss method for all tests. Test 1: top plot in red, Test 2: middle plot N/A, Test 3: bottom plot in yellow

Table 13 provides an average value for each measured parameter for each phase of the test. PM and CO concentrations that were measured post dilution are also provided with the applied DR. Overall, the average PM concentrations for each phase were very close. A comparison of the measured CO in the stack against the CO measured post dilution with the applied DR shows good agreement considering the high COV in the period averages. The average overall lowest CH_4 emissions were observed during the second reload period but the highest during the third reload phase. As mentioned above, this is not unexpected as the firebox was overfilled with fuel with the lowest output set on the stove. The calculated efficiency based on the for Stove C had the lowest value during start up and highest on the third reload, with an overall average for the test of 76%.

Table 13: Stove C Average Values for all Three Tests

	PM conc. (raw)	PM conc. (DR applied)	CO-stack*	CO-dilution (raw)	CO-dilution (DR applied)	CO_2-stack	CH_4-stack*	Stack temperature	Combustion Eff.*	Flue gas velocity*
	g/m3	*g/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*°C*	*%*	*m/s*
Start up	4.3	61	1461	103	1435	4.2	127	196.1	75	1.49
First Reload	4.2	59	1782	107	1495	7.9	121	271.4	77	1.54
Second Reload	3.9	55	974	95	1336	6.9	83	276.5	76	1.80
Third Reload	4.1	57	2539	204	2858	8.9	198	270.6	77	1.31
Overall	4.1	58	1921	145	2029	7.6	150	253.7	76	1.48

** Based on an average from Tests 1 and 3 only, when Train I was used*

Test by test details regarding the averages for each phase may be seen in Appendix III.

Calculated Emission Rates

Emission rates for have been calculated for PM and CO only as these two parameters were the only two measured in triplicate regardless of using Train I or Train II. All calculated PM and CO emission rates are based on the PM and CO values measured using the Testo 380, post dilution and have the respective dilution ratio applied. Additionally, to calculate the rate, a flow rate is used which is taken from the anemometer data. The anemometer data however was only available when using Train I, therefore some tests had no measured flow rate. For these tests the average flow rate from the other test runs on that particular stove were used, and are marked with an Asterix (*) in Figure 20 through Figure 22 below.

The emission rates calculated knowing the velocity of the flue gas (V, measured by the anemometer) and the diameter of the stack (D_S), the actual stack flow rate $\left(Q_{wet,acfm}\right)$, and using an assumed value of 20% moisture content for the fuel. The average velocity measured from the stack center was used for all calculations and not corrected for a profile factor since the flue stacks were of such small diameter (~10 cm) and for air flowing through a long, straight duct the centerline velocity approximates the average velocity [7]. The stack flow was corrected to standard conditions to calculate a dry, flow rate at standard conditions. The high-level calculations are shown below.

$$Q_{wet,acfm} = V \times \frac{\pi}{4}(D_s)^2$$

$$Q_{wet,scfm} = Q_{wet,acfm} \times \left[\frac{T_{std} \times P_s}{T_s \times P_{std}}\right]$$

$$Q_{dry,scfm} = Q_{wet,scfm} \times B_d$$

Where is B_d the water volume dry fraction in gas stream. Finally, the emission rate (E_{PM}) is calculated from the PM concentration (PM_{conc}) and dry flow rate at standard conditions ($Q_{dry,scfm}$) as shown below.

$$E_{PM} = PM_{conc} \times Q_{dry,scfm} \times 60$$

PM Emission Rate

Figure 20 below shows the PM emission rates for Stove A, broken down by test period and over entire test. Overall, the lowest PM emission rates were observed during the first reload period (four pieces of fuel, lowest air setting, 45-minute duration). The next two periods (made up of either 2 very large pieces of fuel and a high burn setting or overloading the chamber with fuel and having the lowest burn setting) show very similar trends. It's important to recall this particular stove had only one high burn setting. Therefore, its understandable little difference exists between each reload. The most notable point across phases and tests was the cold start for Test 3, which had nearly double the emission rate, and high variability compared to the other test sections. The cause being the startup peak which was captured during this test, and absent during cold start of Test 1 and Test 2. This startup peak is therefore likely for much of the variability in the PM emission rate for Stove A. This finding foreshadows the importance of including cold starts in wood combustion testing, as this period can be highly variable and highly polluting. Overall Stove A had an average emission rate of 2.4 g/hr, certainly meeting the 2020 emission limits.

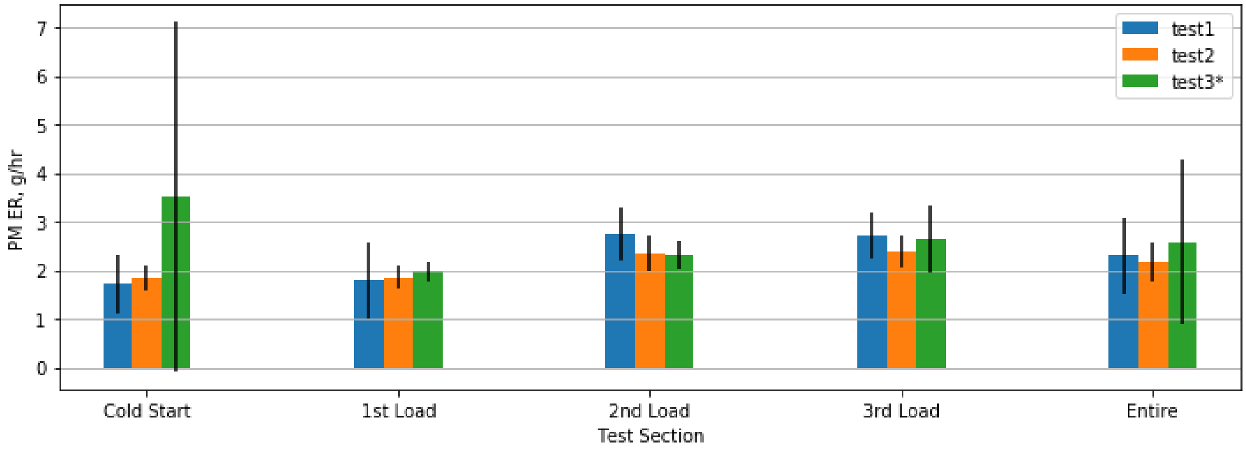

Figure 20: Stove A calculated PM emission rate (g/hr) for each test, by period

Calculated PM emission rates for Stove B are seen in Figure 21. Similar to Stove A, Stove B also had the lowest PM emission rates during the first reload—a low burn period with 4 pieces of fuel. Stove B is perhaps a perfect example of how emissions could be deceived by hot-to-hot testing protocols. During the first reload, a coal bed is established, fuel is loaded on-top of the coals, and the firebox is not overloaded causing emissions to be relatively low as the stove is able to manage its air flow settings appropriately. As the protocol moves along into more challenging periods with oversized pieces of fuel and overloaded fireboxes forced into low burn output conditions, emission rates increase. The cold start period had the highest emissions. This is important to note as startup periods are also the shortest time frame but often contribute to the most emissions [7, 8, 9].

Stove B also showed more variation in PM emission rate during each operating condition and between tests than the other stoves. This finding underscores the need for repeat testing of an appliance and a strict laboratory protocol, so as to not favor or misrepresent emissions from devices that have more variability in their emissions rate. The PM emission rate of Stove B during start-up is nearly four times that of the first reload. Over the entire test, Stove B had an average PM emission rate of 4.0 g/hr.

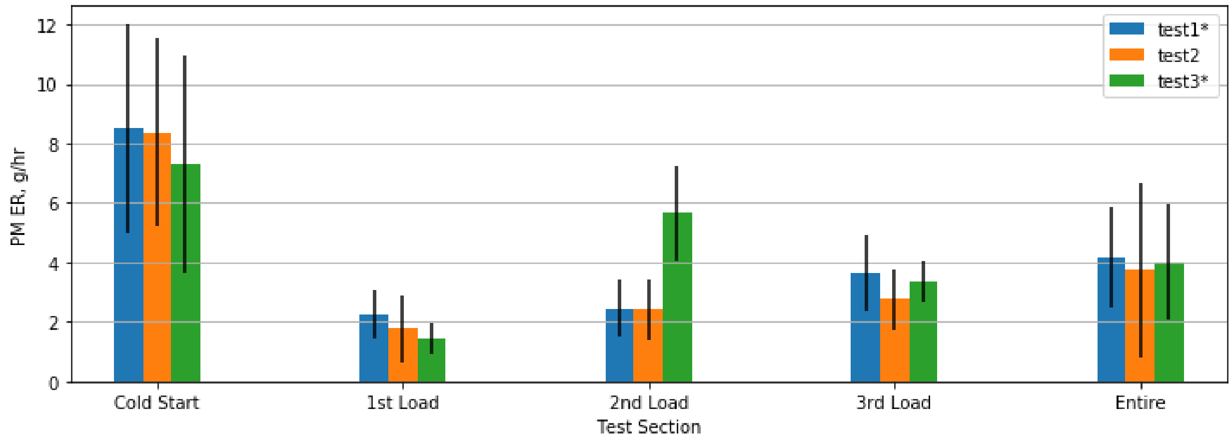

Figure 21: Stove B calculated PM emission rate (g/hr) for each test, by period

Figure 22 shows the calculated PM emission rates for Stove C, all relatively consistent as well. Unlike the other two stoves, Stove C has the lowest emission rates observed during the third and final reload when the firebox is overloaded and the stove is forced into a low burn, something representative of what happens when a homeowner fuels their stove before going to bed. Stove C is the most consistent of all three stoves over all periods of the testing protocol. Further, Stove C listed its primary feature as its low-cost control system, shows that stove automation is possible at low cost. The overall PM emission rate for Stove C was 2.4 g/hr,

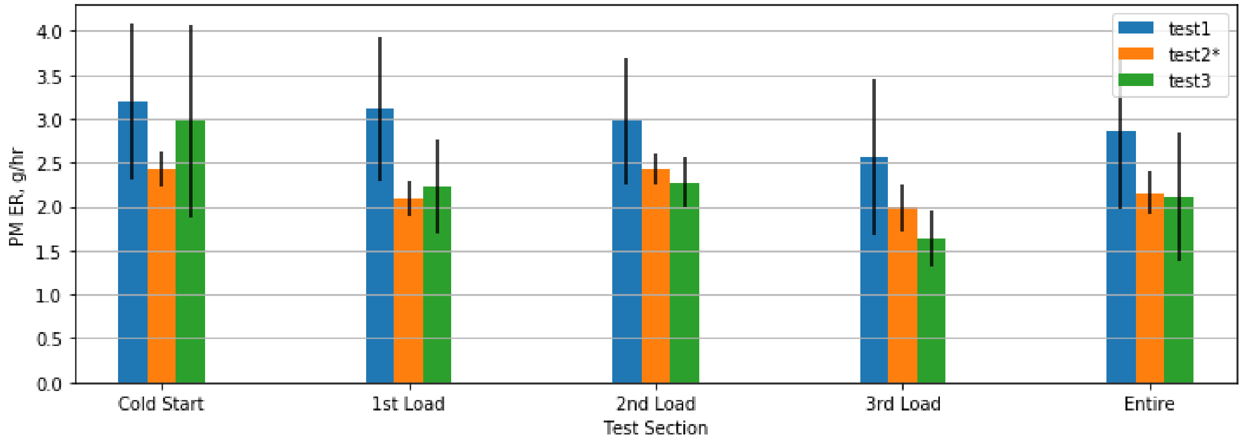

Figure 22: Stove C calculated PM emission rate (g/hr) for each test, by period

CO Emission Rate

The CO emissions rates for Stove A, B, and C were also calculated and are discussed in detail below. The major findings regarding CO emission rates were: 1) overall the range in CO emission rates were between 10 and 1000 g/hr, 2) the third reload, where the firebox was loaded to its maximum density, typically resulted in the highest CO emission rates, with some elevated results also measured during cold start, 3) to a lesser extent the lowest CO emission rates were measured during the first reload. To give some context to the following results: the average CO emission rate of EPA certified stoves is 74.1 g/hr, with a high of 162.8 g/hr and low of 4.2 g/hr.

The CO emission rate for Stove A is shown in Figure 23 below. The mean CO emission rate for Stove A was fairly constant across test conditions and repetitions, ranging between 19 and 95 g/hr. The highest emission rate was measured during the cold start condition of Test 3. The lowest emission rate was measured during the first reload of Test 1. Notably, the first reload had the lowest emission rate for every test. The third reload had the highest emission rates and variability in emission rate overall. Stove A had an entire test triplicate average CO emission rate of 48.8 g/hr, which is well within the range of reported values for other EPA certified stoves, despite the difficult test method.

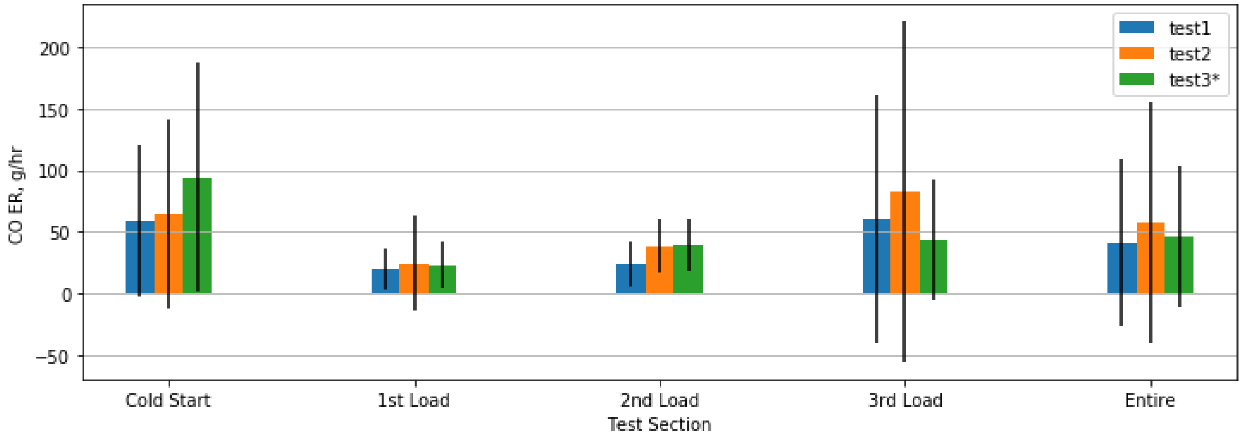

Figure 23: Stove A calculated CO emission rate (g/hr) for each test, by period

The CO emission rate for Stove B is shown in Figure 24 below. The CO emission rate for Stove B was substantially higher than for Stove A, with considerably more variability. The emission rate values ranged between 5 and 875 g/hr. The highest rate was measured during the third reload during all three tests, with the highest rate overall during Test 3. Similarly, the lowest emission rates were consistently measured during the first reload, except for test Test 3 where the lowest value was measured during cold start. Stove B therefore shows the same general trend as Stove A, in terms of highest and lowest emission periods. The entire test triplicate average CO emission rate for Stove B was 284.8 g/hr, more than five times the value for Stove A, and is outside the range of values reported during EPA certification. It should be noted that the third reload CO emission rate value during Test 1 and 3 was significantly larger than other operating conditions; so much so, that it dominates the entire test average CO emission rate value. Further during Test 2, the only test with Train I, the value was much more moderate. Given these factors it is difficult to ascertain which results are more representative of the operation of the appliance.

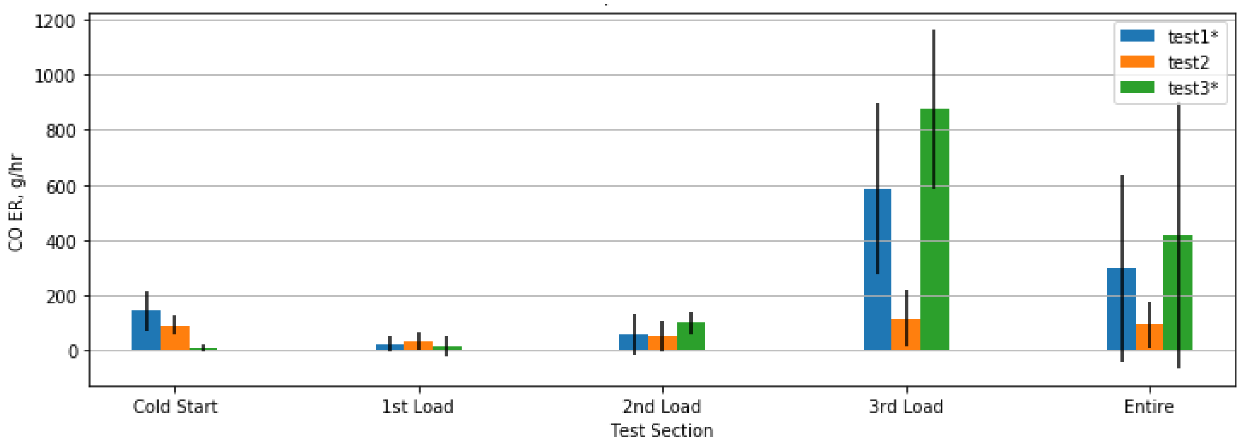

Figure 24: Stove B calculated CO emission rate (g/hr) for each test, by period

Bar graphs of the CO emission rate measured during testing of Stove C are shown in Figure 25. Stove C was between Stove A and Stove B in terms of emission rate magnitude, with a range of 17-185 g/hr. Stove C was inconsistent across tests, where Test 3 had significantly lower CO emission rates than the previous two tests. Overall, the highest emission rate was measured during the third load of Test 1, the second highest rate was measured in the same period during Test 2. The lowest emission rates were measured in different operating conditions during each test, Test 1: cold start, Test 2: first reload, Test 3: second reload. The entire test triplicate average CO emission rate for Stove C was 100.8 g/hr, towards the upper end of the values reported to the EPA during certification testing.

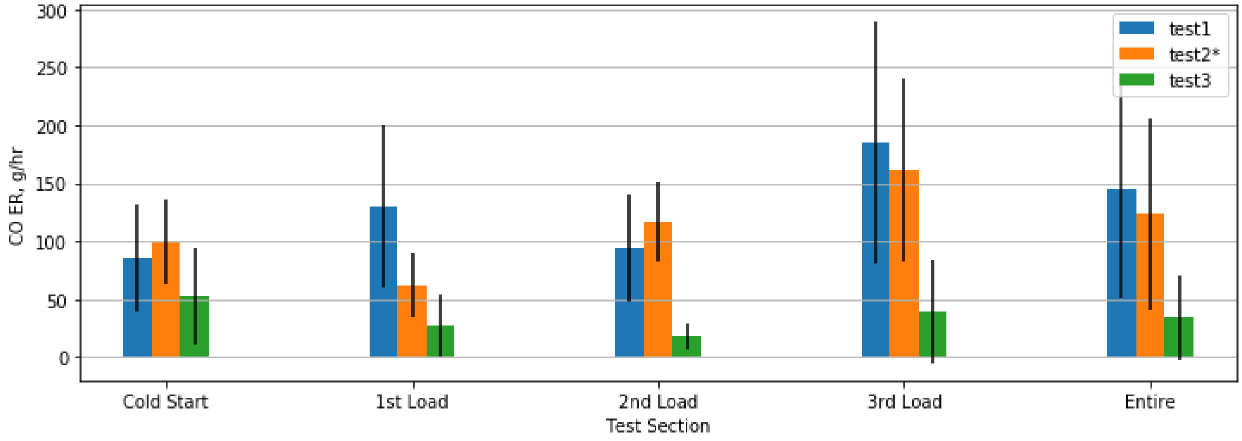

Figure 25: Stove C calculated CO emission rate (g/hr) for each test, by period

Comparison of Stoves A, B, and C

Ranking the three stoves based on PM and CO emission rate shows: Stove A < Stove C < Stove B.

Surprisingly, even though much more difficult testing periods were carried out, the stoves did remarkably well in terms of achieving near or in some cases better than emission rate limits as shown in Table 14 below. Overall, the average PM emission rates for each stove were almost always the highest during the cold start and lowest during the first reload period—a period with a small loading density of 80.1 kg/m^3 and low air settings. A boxplot summary of the triplicate average PM emission rate for each stove is also shown in Figure 26.

All three stoves outperformed the 2015 NSPS Certification Limit of 4.5 g/hr, despite the much more difficult test method. Stove A and C which also performed better than the 2020 NSPS Limit of 2.5 g/hr, and further performed well according to EPA's Burnwise list. Of 73 certified stoves tested with cordwood, the average PM emission rate is 1.5 g/hr, with a high of 2.5 g/hr and low of 0.55 g/hr.

Table 14. PM emission rate (g/hr) by stove and operating condition

Stove	Cold Start	First Load	Second Load	Third Load	Overall
A	2.4	1.9	2.5	2.6	2.4
B	8.0	1.8	3.6	3.3	4.0
C	2.8	2.4	2.6	2.1	2.4

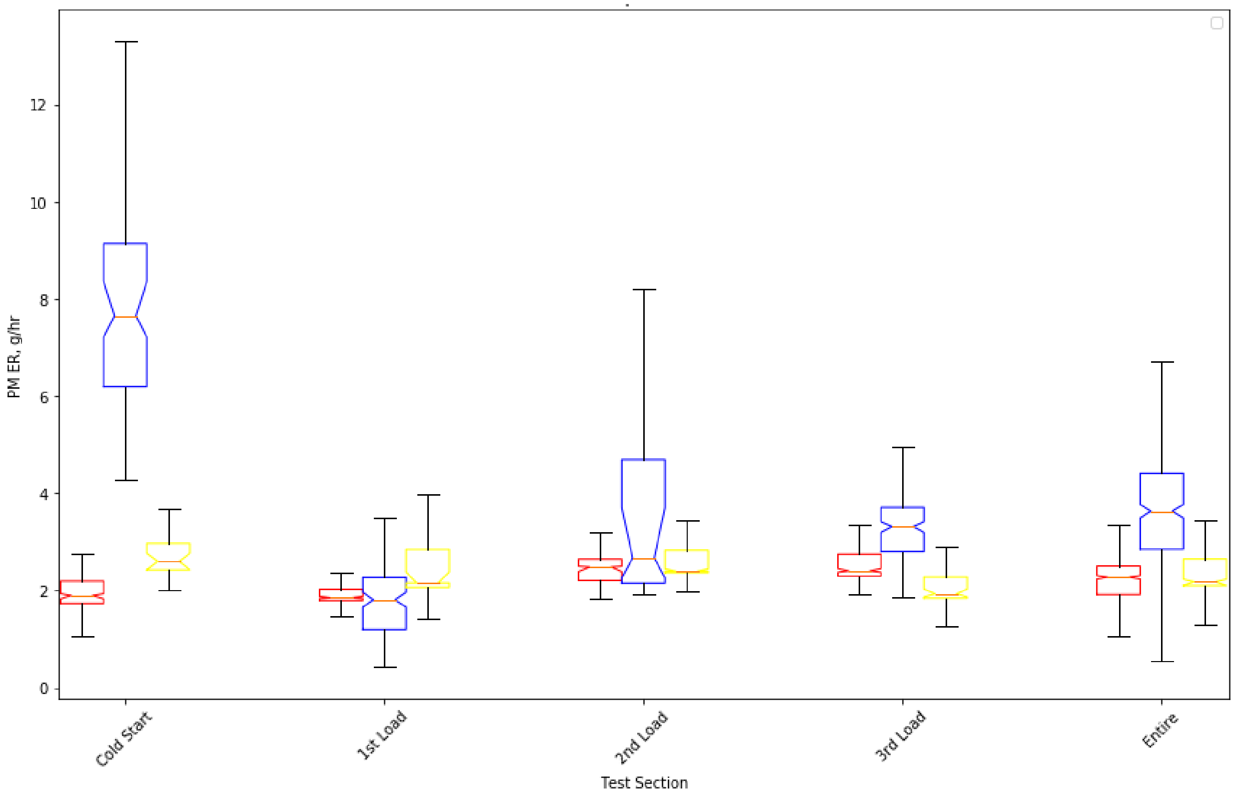

Figure 26. Boxplots of triplicate average PM emission rate for each stove by operating condition. Stove A is the left-most box in each set, followed by Stove B in the center, and Stove C. The mean of each test series for each stove during the given test section is represented by an orange bar, the cutouts on each box extend to one standard deviation around the mean. The boxes extend between the 25th and 75th percentiles, and the whiskers extend from the 5th to 95th percentiles.

A boxplot summary of the triplicate average CO emission rate is shown in Figure 27, the mean values are given explicitly in Table 15. The CO emission rate ranking was much clearer than the PM emission rate ranking. The entire test triplicate average CO emission rate of Stove A was half that of Stove C, and one-fifth that of Stove B. EPA’s Burnwise list of certified stoves, contains 73 certified stoves tested with cordwood, the average CO emission rate among them is 74.1 g/hr, with a high of 162.8 g/hr and low of 4.2 g/hr. The three stoves tested here performed well in comparison, considering the differences in test method. Stove A below the average. Stove C fell between the maximum and the average. Stove B exceeded the maximum reported value but showed below average results for some test periods.

Table 15. CO emission rate (g/hr) by stove and operating condition

Stove	Cold Start	First Load	Second Load	Third Load	Overall
A	72.3	22.2	33.8	61.3	48.8
B	78.8	22.1	74.9	529.3	284.8
C	78.5	69.5	79.2	130.6	100.8

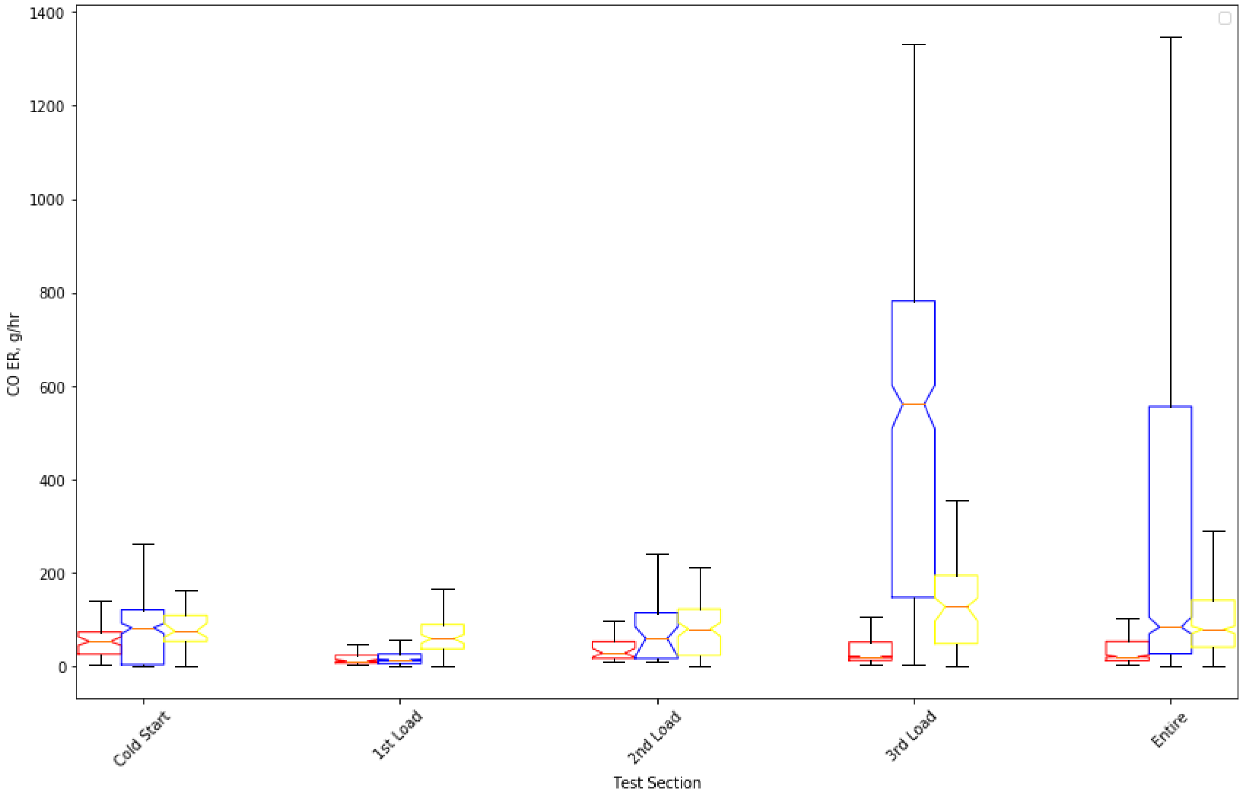

Figure 27. Boxplots of triplicate average CO emission rate for each stove by operating condition. Stove A is the left-most box in each set, followed by Stove B in the center, and Stove C. The mean of each test series for each stove during the given test section is represented by an orange bar, the cutouts on each box extend to one standard deviation around the mean. The boxes extend between the 25th and 75th percentiles, and the whiskers extend from the 5th to 95th percentiles.

The test method developed for the 2018 WSDC was successful in challenging the competition stoves automation level; resulting in varied performance throughout the test and in marked variations in performance between the stoves. Quantitively, it is clear that in particular the cold start and the third reload periods, where the operators "stuffed the firebox", stand out from the rest of the test. The cold start period featured the highest PM emission rate for 7 out of 9 experiments overall and was the highest

PM emission period for 2 out of 3 stoves. Only Stove A had, on average a relatively clean cold start period, however this is due primarily to the fact that no characteristic startup spike was observed for 2 out of 3 tests of this unit. In the third test, the startup peak was much larger than all other emissions measurements for that test by an order of magnitude. These findings suggest technologies exist that can mitigate the startup peak, however even well-designed stoves experience hiccups during difficult combustion conditions. Therefore, the authors encourage repeated testing as it is essential to measure these transient periods, as the high emissions during these periods are large and should not be ignored.

Similarly, "stuffing the firebox" in the third reload period clearly led to an increased CO emission rate relative to the other test sections. The third reload period featured the highest CO emission rate for 5 out of 9 experiments overall and was the highest CO emission period for 2 out of 3 stoves. For Stove B the emissions during the third reload were more than 5x, and for Stove C nearly 2x the emissions during the other test periods. For Stove A, emissions during cold start and the third reload were comparable, however the CO emission rate during those periods were again nearly 2x the emissions rate during the first and second reload. These findings further relay the importance of repeated testing, even with only a slight majority of tests showing the trend of highest emission during the third reload, the average emissions during this period are significantly impacted for all stoves.

Concluding Remarks

The 2018 WSCD showcased three stoves that utilized different automation technologies to override poor user behavior to reduce emissions and increase efficiency—some more effective than others. The, 2018 WSDC field protocol, a duty-cycle type test, challenged the automation of stoves as it included more than steady state testing. Cold starts, multiple reloads, overloading the firebox and forcing the stove into a low burn immediately, and piece size variations were included in the developed testing protocol. A combination of in-stack and novel dilution measurement methods were explored to successfully measure both PM and gaseous emissions throughout the protocol, without overloading filters or analyzer sensors; which was a cause of concern given the inclusion of high-emission and poor operational practices in the protocol. Additionally, a combustion efficiency was calculated without the use of a scale to account for fuel consumption given the field layout of the event. All measurements were given in real-time to 1) create a suspenseful competition environment and 2) provide feedback to teams regarding different periods as opposed to an integrated value over the entire test.

The utility and repeatability of the dilution sampling system developed for the 2018 WSDC was also successfully demonstrated at the event. Specifically, in this report we show that our dilution sampling system was capable of accurately measuring PM concentrations between 36-494 mg/m^3 in real-time. Further these bounds could be easily extended by changing the initial dilution ratio. Following this positive demonstration, future efforts will be leveraged to improve the dilution system, specifically to incorporate CO or CO_2 measurement capabilities into the system to allow for continuous real-time dilution ratio measurements, which would improve the accuracy of the device. Overall, the repeatability across each stove was favorable with COVs for measured PM concentrations of 15%, 7%, and 13%, for Stoves A, B, and C, respectively. The overall COV for CO varied more strongly but was expected due to spikes of CO concentration throughout the test with values of 3%, (with variations within a given period as high as 20%), 49%, and 46% for Stove A, B, and C, respectively.

Considering a more rigorous testing protocol was followed, the calculated PM and CO emission rates for each of the stoves rivaled stoves on the EPA BurnWise list at the time. The average PM emission rate for certified stoves in 2018 was 1.5 g/hr and the three stoves tested during this event had values of 2.4, 4.0 and 2.4 g/hr for Stove A, B, and C, respectively. Further, the average CO emission rate for certified stoves in 2018 was 74.1 g/hr and Stoves A, B, and C, had calculated values of 48.8, 100.8, and 248.8 g/hr, respectively. The minute-by-minute calculated combustion efficiency values ranged between 65-88% over all tests and results indicated the lowest combustion efficiency during cold start. The calculation was informative as it was sensitive to changes in combustion conditions however, the lack of velocity measurements during four experiments, and the unknown parameters of exact fuel charge weights, fuel type, and moisture content hindered the analysis. In future work, these deficiencies will be addressed, thus expanding the dataset and improving the accuracy of the efficiency calculation.

Key outcomes from the 2018 WSDC, reiterate the importance of measuring a stove's performance in transient states during certification testing to adequately determine the performance of a stove in real world condition. Specifically, startup yields a drastic increase in PM and CO emission rates as well as covariance. Also testing stoves under conditions of poor operator practices often carried out in the field, such as the third reload period of overloading a firebox and decreasing the heat demand is suggested to provide more realistic efficiency values for homeowners.

Acknowledgments

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Appendix I

Method to Calculate Combustion Efficiency of a Wood Appliance using Stack Loss

Basis – 100 kg of dry fuel

Inputs:

- Ultimate Analysis of dry fuel (% by weight)
    - Carbon – CA
    - Hydrogen – HY
    - Oxygen – OX
- Moisture Content – mass of water per mass of dry fuel – Mcdb
- Ambient Humidity Ratio – mass of water per unit mass of dry air – ω
- Flue gas temperature (F) – Ts
- Room temperature (F)-Tr
- CO in the dry flue gas (ppm) – PPMco
- CO_2 in the dry flue gas (%) – PCTCO2
- Higher heating value of the dry fuel (lb/MMBtu) – HHV

<u>Combustion Balance Equation:</u>

$$C_xH_yO_z + (1 + \alpha)\bullet\gamma(O_2 + 3.76N_2) + \left[\omega\bullet\left(\frac{(1+\alpha)\bullet\gamma\bullet(32 + 3.76\bullet 28)}{18}\right)+\frac{Mcdb}{18}\right] H_2O$$

$$\rightarrow (x-\beta)\,CO_2 + \beta CO + (\alpha\bullet\gamma+\frac{\beta}{2})\,O_2 + (1+\alpha)\bullet\gamma\bullet 3.76\,N_2 + \left[\frac{y}{2}+\omega\bullet\left(\frac{(1+\alpha)\bullet\gamma\bullet(32+3.76\bullet 28)}{18}\right)+\frac{Mcdb}{18}\right]H_2O$$

Where:

$x = CA/12$

$y = HY$

$z = OX/16$

$\gamma = (x+\frac{y}{4}-\frac{z}{2})$

$\alpha =$ excess air parameter, e.g. if $\alpha =$ 0.5 there is 50 % excess air

From this:

$$PPMco = \frac{1E6\cdot\beta}{x+\left(\alpha\cdot\gamma+\frac{\beta}{2}\right)+(1+\alpha)\cdot\gamma\cdot 3.76}$$

$$PCTCO2=\frac{100\cdot(x-\beta)}{x+\left(\alpha\cdot\gamma+\frac{\beta}{2}\right)+\left(1+\alpha\right)\cdot\gamma\cdot 3.76}$$

With flue gas CO and CO_2 measured, these two equations can be solved simultaneously for β and α.

$$\beta=\frac{100\cdot x\cdot PPMco}{1E6\cdot PCTCO2\cdot+100\cdot PPMco}$$

$$\alpha=\frac{\frac{100\cdot\left(x-\beta\right)}{PCTCO2}-x-\frac{\beta}{2}-3.76\cdot\gamma}{4.76\cdot\gamma}$$

Calculation of the Molar Coefficient for Each of the Products

For the assumption of 100 kg of dry fuel, this is the number of mols of each product for the input conditions

$MFCO=\beta$ Molar Coefficient for CO

$MFCO2=x-\beta$ Molar Coefficient for CO_2

$MFH2O=\frac{\gamma}{2}+\frac{Mcdb}{18}+\frac{\omega\cdot\left(1+\alpha\right)\cdot\gamma\cdot\left(32+3.76\cdot 28\right)}{18}$ Molar Coefficient for H_2O

$MFO2=\alpha\cdot\gamma+\frac{\beta}{2}$ Molar Coefficient for O_2

$MFN2=\left(1+\alpha\right)\cdot\gamma\cdot 3.76$ Molar Coefficient for N_2

Conversion of Molar Coefficients to Mass of Products per Unit Mass of Dry Fuel

$MCO=MFCO\cdot 28/100$	kg CO in flue products per kg dry fuel fired
$MCO2=MFCO2\cdot 44/100$	kg CO_2 in flue products per kg dry fuel fired
$MH2O=MFH2O\cdot 18/100$	kg H_2O in flue products per kg dry fuel fired
$MO2=MFO2\cdot 32/100$	kg O_2 in flue products per kg dry fuel fired
$MN2=MFN2\cdot 28/100$	kg N_2 in flue products per kg dry fuel fired

Heat Capacity of Exhaust Products

The general equation for representing how the heat capacity of the exhaust products varies with temperature is:

$$C = A \cdot Tk + B$$

Where:

C = heat capacity J/mol K or kJ/kgmol K
A and B are constants
Tk = Temperature in °K

The values for A and B for the exhaust components are provided in the table below

Component	A	B
CO	.0056	27.162
CO2	.029	29.54
H2O	.0057	32.859
O2	.009	26.782
N2	.0062	26.626

For each component, heat capacity is calculated at the stack temperature and at room temperature. The average of these is used to calculate sensible heat loss.

Calculation of Heat Losses for Efficiency Determination

$HHVJ = HHV \cdot 2.326$ Higher heating value in kJ/kg (conversion from Btu/lb)
$LHWV = 43969$ Latent heat of water vapor in kJ/kgmol

$Llat = MFH2O \cdot LHWV \;/\; HHVJ$ Heat loss in latent heat of water vapor, % of input energy
$Lco = MFCO \cdot 282993 / HHVJ$ Heat loss in chemical energy in CO, % of input energy
$Lsens = (MFCO \cdot C\_COm + MFCO2 \cdot C\_CO2m + MFH2O \cdot C\_H2Om + MFO2 \cdot C\_O2m$
$+ MFN2 \cdot C\_N2) \;/\; HHVJ$ Heat loss in sensible heat in flue gas, % of input energy

$Efficiency = 100 - Llat - Lco - Lsens$ Stack loss efficiency, %

Appendix II

Stove A Protocol

Wood Stove Design Challenge Protocol – Automated Stove Competition

Stove:	A
Dimensions:	none given
Volume:	1.79 ft^3

Proposed Fuel Length – 14" – *Note that piece weights will change if length is changed*
Fuel species – beech or maple
Fuel moisture – 18% - 25%
For all portions of the protocol, the excessive smoke protocol will be applied, if deemed appropriate.

Start-up

Fuel load density 4 lb/ft^3
Amount of kindling: not to exceed 1.8 lbs. piece size in sticks and must resemble typical kindling, typically 8-10 pieces of kindling weighs 1 lb.
Amount of starter fuel: 5.4 lbs. +/- 5%
Minimum weight for starter fuel pieces = 0.70 lbs.

1. Stove is empty – no ashes
2. Amount of paper for starter – 6 full sheets
3. Amount of kindling is 1.8 lbs..
4. Amount of starter fuel is 5.4 lbs..
5. Fuel loading pattern is defined by the manufacturer's instructions. If no instructions are provided, a top-down burn protocol will be used. For the competition, the manufacturer can build the fuel charge in the stove but cannot light off and will be hands off during the stove testing. For startup phase – fuel can be loaded in multiple batches but all fuel must be loaded within the first ten minutes of the phase.
6. Air settings will be determined by the manufacturer. Up to 2 changes in air settings can be used during the start-up phase.
7. Fire will be started with a torch. Torch can be used for up to 30 seconds
8. Door can remain open for up to 5 minutes. Manufacturer will set time and door position prior to competition.
9. For the first 15 minutes, the door can be opened and fuel adjustments made. A maximum of four fuel adjustments can be made. Door can remain open for no more than 30 seconds per fuel adjustment. Door must be closed as soon as fuel adjustment is complete.
10. Phase ends after 30 minutes or when there is loss of yellow flame, whichever comes first. If Start-up ends before 30 minutes, it should be noted in the testing comments but no loss of points will occur.

First Reload

Fuel load density 5 lb/ft^3
Allowable Fuel piece weight: 1.40 – 2.80 lbs.
Target pieces for load: 4
Fuel load weight: 9.0 lbs. +/- 5%

1. Immediately after the end of Start-up Phase, open stove door.
2. Chop existing wood with a fuel piece and to the extent possible smooth coalbed.
3. Load first Reload charge following the specifications for this phase provided above.
4. Fuel loading pattern defined by the manufacturer's instructions. Options are:
    a. East/west
    b. North/south
    c. Criss-cross
5. Close door immediately after loading fuel. Maximum time to reload 60 seconds.
6. Air settings/thermostat immediately turned to low demand
7. During first reload phase one (1) fuel adjustment is allowed. Additional fuel adjustments can be requested but the total score deduct 2 points for each additional fuel adjustment. Door can remain open for no more than 30 seconds for a fuel adjustment. Door must be closed as soon as fuel adjustment complete.
    a. Teams can make recommendations about when and how to make fuel adjustments.
    b. Additional fuel adjustments interventions can be made at the request of the stove team. Each additional fuel adjustment results in a loss of 1 points from scoring.
8. Air Adjustments - During the first Reload phase no air adjustments can be made unless judge(s) determine an intervention is required. Each intervention results in a loss of 2 points from scoring for every x minutes the air settings differ from the protocol. Interventions that result in point loss, will be completed upon request by the stove team.
9. First Reload Phase ends after 45 minutes.

Second Reload

Fuel load – 2 pieces

Allowable Fuel piece weight: 2.8 lbs. +/- 5%

1. Immediately after the end of First Reload Phase, open stove door.
2. Break up/chop/reposition remaining fuel to the extent possible.
3. Load second Reload charge following the specifications for this phase provided above.
4. Fuel loading pattern defined by the manufacturer's instructions. Options are:
    a. East/west
    b. North/south
    c. Criss cross
5. Close door immediately after loading fuel. Maximum time to reload 60 seconds.
6. Air settings/thermostat immediately turned to high demand
7. During Second Reload phase no fuel adjustments are allowed.

    a. Fuel adjustments can be requested but the total score deduct 1 point for each additional fuel adjustment. Door can remain open for no more than 30 seconds for a fuel adjustment. Door must be closed as soon as fuel adjustment complete.
8. Air Adjustments - During the Second Reload phase no air adjustments can be made unless judges determine an intervention is required. Each intervention results in a loss of 2 points from scoring for every x minutes the air settings differ from the protocol.
9. Second Reload Phase ends after 30 minutes.

Third Reload

Allowable Fuel piece weight: 1.40 – 5.00 lbs.
Target pieces for load: 5-8 - load should be a 50/50 mix of small and large pieces
Fuel load weight: 17.80 lbs. +/- 5%

1. Immediately after the end of Second Reload Phase, open stove door.
2. Break up/chop/reposition remaining fuel to the extent possible.
3. Load Third Reload charge following the specifications for this phase provided above.
    a. Load large piece first, then small piece, large piece, small piece, etc until no more wood fits in the stove. Likely that 2/3 of load may not fit in but as much as possible should be loaded with a mix of small and large pieces.
4. Fuel loading pattern defined by the manufacturer's instructions. Options are:
    a. East/west
    b. North/south
5. Close door immediately after loading fuel. Maximum time to reload 90 seconds.
6. Air settings/thermostat immediately turned to low demand
7. During Third Reload phase one (1) fuel adjustment is allowed within the first 10 minutes of the phase.
    a. Additional fuel adjustments interventions can be made at the request of the stove team. Each additional fuel adjustment results in a loss of 1 points from scoring. Door can remain open for no more than 30 seconds for a fuel adjustment. Door must be closed as soon as fuel adjustment complete.
8. Air Adjustments - During the Second Reload phase no air adjustments can be made unless judges determine an intervention is required. Each intervention results in a loss of 2 points from scoring for every x minutes the air settings differ from the protocol.
9. Third Reload Phase ends after 75 minutes.

Disruption Phase:

Optional Phase TBD by organizing committee

1. No wood is loaded.
2. Unit is placed in disruption mode, this could be: eliminating power, disengaging catalyst, etc.
3. Disruption phase lasts 15 minutes.
4. Visible emissions may be the only measurement.

Stove B Protocol

Wood Stove Design Challenge Protocol – Automated Stove Competition

Stove:	B
Dimensions:	16L x 11H x 21W
Volume:	2.16 ft^3

- **Fuel species – beech or maple**
- **Fuel length proposed – 16" –** *Note that piece weights will change, if length is changed*
- **Fuel moisture – 18% - 25%**
- **For all portions of the protocol, the excessive smoke protocol will be applied, if deemed appropriate.**

Start-up

Fuel load density 4 lb/ft^3
Amount of kindling: not to exceed 2.2 lbs. piece size in sticks and must resemble typical kindling, typically 8-10 pieces of kindling weighs 1 lb.
Amount of starter fuel: 6.5 lbs. +/- 5% -
Minimum weight for each starter fuel piece = 0.80 lbs.

11. Stove is empty – no ashes
12. Amount of paper for starter – 6 full sheets
13. Amount of kindling is 2.2 lbs..
14. Amount of starter fuel is 6.3 lbs..
15. Fuel loading pattern is defined by the manufacturer's instructions. If no instructions are provided, a top-down burn protocol will be used. For the competition, the manufacturer can build the fuel charge in the stove but cannot light off and will be hands off during the stove testing. For startup phase – fuel can be loaded in multiple batches but all fuel must be loaded within the first ten minutes of the phase.
16. Air settings will be determined by the manufacturer. Up to 2 changes in air settings can be used during the start-up phase.
17. Fire will be started with a torch. Torch can be used for up to 30 seconds
18. Door can remain open for up to 5 minutes. Manufacturer will set time and door position prior to competition.
19. For the first 15 minutes, the door can be opened and fuel adjustments made. A maximum of four fuel adjustments can be made. Door can remain open for no more than 30 seconds per fuel adjustment. Door must be closed as soon as fuel adjustment is complete.
20. Phase ends after 30 minutes or when there is loss of yellow flame, whichever comes first. If Start-up ends before 30 minutes, it should be noted in the testing comments but no loss of points will occur.

First Reload

Fuel load density 5 lb/ft^3
Allowable Fuel piece weight: 2.30 – 4.00 lbs.
Target pieces for load: 4
Fuel load weight: 11.0 lbs. +/- 5% -

10. Immediately after the end of Start-up Phase, open stove door.
11. Chop existing wood with a fuel piece and to the extent possible smooth coalbed.
12. Load First Reload charge following the specifications for this phase provided above.
13. Fuel loading pattern defined by the manufacturer's instructions. Options are:
    a. East/west
    b. North/south
    c. Criss-cross
14. Close door immediately after loading fuel. Maximum time to reload 60 seconds.
15. Air settings/thermostat immediately turned to low demand
16. During First reload phase one (1) fuel adjustment is allowed. Additional fuel adjustments can be requested but the total score deduct 2 points for each additional fuel adjustment. Door can remain open for no more than 30 seconds for a fuel adjustment. Door must be closed as soon as fuel adjustment complete.
    a. Teams can make recommendations about when and how to make fuel adjustments.
    b. Additional fuel adjustments interventions can be made at the request of the stove team. Each additional fuel adjustment results in a loss of 1 points from scoring.
17. Air Adjustments - During the First Reload phase no air adjustments can be made unless judge(s) determine an intervention is required. Each intervention results in a loss of 2 points from scoring for every x minutes the air settings differ from the protocol. Interventions that result in point loss, will be completed upon request by the stove team.
18. First Reload Phase ends after 45 minutes.

Second Reload

Fuel load – 2 pieces

Allowable Fuel piece weight: 4.5 lbs. +/- 5%

10. Immediately after the end of first Reload Phase, open stove door.
11. Break up/chop/reposition remaining fuel to the extent possible.
12. Load Second Reload charge following the specifications for this phase provided above.
13. Fuel loading pattern defined by the manufacturer's instructions. Options are:
    a. East/west
    b. North/south
    c. Criss cross
14. Close door immediately after loading fuel. Maximum time to reload 60 seconds.
15. Air settings/thermostat immediately turned to high demand
16. During Second Reload phase no fuel adjustments are allowed.
    a. Fuel adjustments can be requested but the total score deduct 1 point for each additional fuel adjustment. Door can remain open for no more than 30 seconds for a fuel adjustment. Door must be closed as soon as fuel adjustment complete.
17. Air Adjustments - During the Second Reload phase no air adjustments can be made unless judges determine an intervention is required. Each intervention results in a loss of 2 points from scoring for every x minutes the air settings differ from the protocol.
18. Second Reload Phase ends after 30 minutes.

Third Reload

Allowable Fuel piece weight: 2.30 – 6.00 lbs.

Target pieces for load: 5-8 - load should be a 50/50 mix of small and large pieces

Fuel load weight: 21.6 lbs. +/- 5%

10. Immediately after the end of Second Reload Phase, open stove door.

11. Break up/chop/reposition remaining fuel to the extent possible.
12. Load Third Reload charge following the specifications for this phase provided above.
    a. Load large piece first, then small piece, large piece, small piece, etc until no more wood fits in the stove. Likely that 2/3 of load may not fit in but as much as possible should be loaded with a mix of small and large pieces.
13. Fuel loading pattern defined by the manufacturer's instructions. Options are:
    a. East/west
    b. North/south
14. Close door immediately after loading fuel. Maximum time to reload 90 seconds.
15. Air settings/thermostat immediately turned to low demand
16. During Third Reload phase one (1) fuel adjustment is allowed within the first 10 minutes of the phase.
    a. Additional fuel adjustments interventions can be made at the request of the stove team. Each additional fuel adjustment results in a loss of 1 points from scoring. Door can remain open for no more than 30 seconds for a fuel adjustment. Door must be closed as soon as fuel adjustment complete.
17. Air Adjustments - During the Second Reload phase no air adjustments can be made unless judges determine an intervention is required. Each intervention results in a loss of 2 points from scoring for every x minutes the air settings differ from the protocol.
18. Third Reload Phase ends after 75 minutes.

<u>Disruption Phase:</u>

Optional Phase TBD by organizing committee

5. No wood is loaded.
6. Unit is placed in disruption mode, this could be: eliminating power, disengaging catalyst, etc.
7. Disruption phase lasts 15 minutes.
8. Visible emissions may be the only measurement.

Stove C Protocol

Wood Stove Design Challenge Protocol – Automated Stove Competition

Stove:	C
Dimensions:	none given
Volume:	~1.25 ft^3

- **Proposed Fuel Length – 16" - –** ***Note that piece weights will change if length is changed***
- **Fuel species – beech or maple**
- **Fuel moisture – 18% - 25%**
- **For all portions of the protocol, the excessive smoke protocol will be applied, if deemed appropriate.**

Start-up

Fuel load density 4 lb/ft^3
Amount of kindling: not to exceed 1.25 lb piece size in sticks and must resemble typical kindling, typically 8-10 pieces of kindling weighs 1 lb.
Amount of starter fuel: 3.75 lbs. +/- 5% -
Minimum weight for starter fuel pieces = 0.70 lbs.

21. Stove is empty – no ashes
22. Amount of paper for starter – 6 full sheets
23. Amount of kindling is 1.25 lb.
24. Amount of starter fuel is 3.75 lbs.. Minimum weight for each piece is 0.70 lbs..
25. Fuel loading pattern is defined by the manufacturer's instructions. If no instructions are provided, a top-down burn protocol will be used. For the competition, the manufacturer can build the fuel charge in the stove but cannot light off and will be hands off during the stove testing. For startup phase – fuel can be loaded in multiple batches but all fuel must be loaded within the first ten minutes of the phase.
26. Air settings will be determined by the manufacturer. Up to 2 changes in air settings can be used during the start-up phase.
27. Fire will be started with a torch. Torch can be used for up to 30 seconds
28. Door can remain open for up to 5 minutes. Manufacturer will set time and door position prior to competition.
29. For the first 15 minutes, the door can be opened and fuel adjustments made. A maximum of four fuel adjustments can be made. Door can remain open for no more than 30 seconds per fuel adjustment. Door must be closed as soon as fuel adjustment is complete.
30. Phase ends after 30 minutes or when there is loss of yellow flame, whichever comes first. If Start-up ends before 30 minutes, it should be noted in the testing comments but no loss of points will occur.

First Reload

Fuel load density 5 lb/ft^3
Allowable Fuel piece weight: 1.2 – 2.50 lbs.
Target pieces for load: 4
Fuel load weight: 6.25 lbs. +/- 5% -

19. Immediately after the end of Start-up Phase, open stove door.

20. Chop existing wood with a fuel piece and to the extent possible smooth coalbed.
21. Load First Reload charge following the specifications for this phase provided above.
22. Fuel loading pattern defined by the manufacturer's instructions. Options are:
    a. East/west
    b. North/south
    c. Criss-cross
23. Close door immediately after loading fuel. Maximum time to reload 60 seconds.
24. Air settings/thermostat immediately turned to low demand
25. During First reload phase one (1) fuel adjustment is allowed. Additional fuel adjustments can be requested but the total score deduct 2 points for each additional fuel adjustment. Door can remain open for no more than 30 seconds for a fuel adjustment. Door must be closed as soon as fuel adjustment complete.
    a. Teams can make recommendations about when and how to make fuel adjustments.
    b. Additional fuel adjustments interventions can be made at the request of the stove team. Each additional fuel adjustment results in a loss of 1 points from scoring.
26. Air Adjustments - During the First Reload phase no air adjustments can be made unless judge(s) determine an intervention is required. Each intervention results in a loss of 2 points from scoring for every x minutes the air settings differ from the protocol. Interventions that result in point loss, will be completed upon request by the stove team.
27. First Reload Phase ends after 45 minutes.

Second Reload

Fuel load – 2 pieces
Allowable Fuel piece weight: 2.7lbs. +/- 5%

19. Immediately after the end of First Reload Phase, open stove door.
20. Break up/chop/reposition remaining fuel to the extent possible.
21. Load Second Reload charge following the specifications for this phase provided above.
22. Fuel loading pattern defined by the manufacturer's instructions. Options are:
    a. East/west
    b. North/south
    c. Criss cross
23. Close door immediately after loading fuel. Maximum time to reload 60 seconds.
24. Air settings/thermostat immediately turned to high demand
25. During Second Reload phase no fuel adjustments are allowed.
    a. Fuel adjustments can be requested but the total score deduct 1 point for each additional fuel adjustment. Door can remain open for no more than 30 seconds for a fuel adjustment. Door must be closed as soon as fuel adjustment complete.
26. Air Adjustments - During the Second Reload phase no air adjustments can be made unless judges determine an intervention is required. Each intervention results in a loss of 2 points from scoring for every x minutes the air settings differ from the protocol.
27. Second Reload Phase ends after 30 minutes.

Third Reload

Allowable Fuel piece weight: 1.20 – 5.00 lbs.
Target pieces for load: 5-8 - load should be a 50/50 mix of small and large pieces
Fuel load weight: 12.5 lbs. +/- 5%

19. Immediately after the end of Second Reload Phase, open stove door.
20. Break up/chop/reposition remaining fuel to the extent possible.

21. Load Third Reload charge following the specifications for this phase provided above.
    a. Load large piece first, then small piece, large piece, small piece, etc until no more wood fits in the stove. Likely that 2/3 of load may not fit in but as much as possible should be loaded with a mix of small and large pieces.
22. Fuel loading pattern defined by the manufacturer's instructions. Options are:
    a. East/west
    b. North/south
23. Close door immediately after loading fuel. Maximum time to reload 90 seconds.
24. Air settings/thermostat immediately turned to low demand
25. During Third Reload phase one (1) fuel adjustment is allowed within the first 10 minutes of the phase.
    a. Additional fuel adjustments interventions can be made at the request of the stove team. Each additional fuel adjustment results in a loss of 1 points from scoring. Door can remain open for no more than 30 seconds for a fuel adjustment. Door must be closed as soon as fuel adjustment complete.
26. Air Adjustments - During the Second Reload phase no air adjustments can be made unless judges determine an intervention is required. Each intervention results in a loss of 2 points from scoring for every x minutes the air settings differ from the protocol.
27. Third Reload Phase ends after 75 minutes.

Disruption Phase:

Optional Phase TBD by organizing committee

9. No wood is loaded.
10. Unit is placed in disruption mode, this could be: eliminating power, disengaging catalyst, etc.
11. Disruption phase lasts 15 minutes.
12. Visible emissions may be the only measurement.

Appendix III

Detailed Stove Results from 2018 WSDC

Details regarding the average value of each measured (and some calculated) parameters are shown in Table 35 through Table 43 below for Tests 1, 2 and 3 for Stoves A, B and C. Data is reported also averaged by the individual burn phase. Both the measured values and those corrected based on the calculated dilution ratios are provided. In cases where Train II was used so no stack data (CO, CH_4, CO_2, stack velocity and efficiency) was collected the section is filled with 'N/A'. Averages of the three tests for each stove and by phase, as well as the COV are provided above in the respective Results and Discussion section for each stove.

Stove A

Table 16: Stove A Test 1 Averages

	PM conc. (raw)	PM conc. (DR applied)	CO-stack	CO-dilution (raw)	CO-dilution (DR applied)	CO_2-stack	CH_4-stack	Stack temperature	Combustion Eff.	Flue gas velocity
	g/m3	*g/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*°C*	*%*	*m/s*
Start up	0.0035	0.0630	1439	94	1677	3.94	158	50.8	82.3	0.56
First Reload	0.0037	0.0664	642	23	415	8.55	76	90.0	86.1	0.64
Second Reload	0.0045	0.0799	223	31	552	12.19	2	102.9	86.8	0.84
Third Reload	0.0046	0.0821	1808	68	1216	12.27	29	107.9	85.2	0.73
Overall	0.0042	0.0739	1154	57	1007	9.71	60	87.9	85.1	0.70

Table 17: Stove A Test 2 Averages

	PM conc. (raw)	PM conc. (DR applied)	CO-stack	CO-dilution (raw)	CO-dilution (DR applied)	CO_2-stack	CH_4-stack	Stack temperature	Combustion Eff.	Flue gas velocity
	g/m3	*g/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*°C*	*%*	*m/s*
Start up	0.0030	0.0439	1199	85	1249	8.52	106	86.8	84.4	0.98
First Reload	0.0030	0.0439	501	40	588	9.29	7	96.1	85.5	1.01
Second Reload	0.0037	0.0542	712	49	717	7.75	18	95.5	85.3	1.03
Third Reload	0.0040	0.0584	1427	93	1355	13.10	3	106.4	85.6	1.00
Overall	0.0035	0.0515	1065	71	1033	10.29	27	96.2	85.2	1.00

Table 18: Stove A Test 3 Averages

	PM conc. (raw)	PM conc. (DR applied)	CO-stack	CO-dilution (raw)	CO-dilution (DR applied)	CO_2-stack	CH_4-stack	Stack temperature	Combustion Eff.	Flue gas velocity
	g/m3	*g/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*°C*	*%*	*m/s*
Start up	0.0079	0.0947	N/A	171	2062	N/A	N/A	66.7	N/A	N/A
First Reload	0.0044	0.0528		41	490			64.1		
Second Reload	0.0046	0.0558		64	769			62.8		
Third Reload	0.0056	0.0673		73	884			63.8		
Overall	0.0055	0.0662		80	967			64.3		

Stove B

Table 19: Stove B Test 1 Averages

	PM conc. (raw)	PM conc. (DR applied)	CO-stack	CO-dilution (raw)	CO-dilution (DR applied)	CO2-stack	CH4-stack	Stack temperature	Combustion Eff.	Flue gas velocity
	g/m3	*g/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*°C*	*%*	*m/s*
Start up	0.0069	0.1942	N/A	93	2640	N/A		110.5	N/A	
First Reload	0.0069	0.1940		55	1557			148.6		
Second Reload	0.0047	0.1337		89	2506			376.2		
Third Reload	0.0055	0.1554		716	20227			264.0		
Overall	0.0059	0.1676		341	9633			224.8		

Table 20: Stove B Test 2 Averages

	PM conc. (raw)	PM conc. (DR applied)	CO-stack	CO-dilution (raw)	CO-dilution (DR applied)	CO2-stack	CH4-stack	Stack temperature	Combustion Eff.	Flue gas velocity
	g/m3	*g/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*°C*	*%*	*m/s*
Start up	0.0066	0.1922	607	60	1742	5.04	102	215.9	75.8	1.53
First Reload	0.0056	0.1639	1187	89	2576	9.93	531	213.1	81.0	0.39
Second Reload	0.0046	0.1323	3050	82	2394	15.03	210	424.4	77.1	0.26
Third Reload	0.0040	0.1154	10545	130	3775	15.68	537	301.9	78.5	0.87
Overall	0.0050	0.1438	5465	98	2840	12.40	400	288.8	78.2	0.78

Table 21: Stove B Test 3 Averages

	PM conc. (raw)	PM conc. (DR applied)	CO-stack	CO-dilution (raw)	CO-dilution (DR applied)	CO2-stack	CH4-stack	Stack temperature	Combustion Eff.	Flue gas velocity
	g/m3	*g/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*°C*	*%*	*m/s*
Start up	0.0075	0.1664	N/A	5	109	N/A		188.5	N/A	
First Reload	0.0056	0.1232		48	1057			208.1		
Second Reload	0.0125	0.2767		122	2681			405.1		
Third Reload	0.0065	0.1425		1329	29320			261.3		
Overall	0.0074	0.1640		578	12754			265.7		

Stove C

Table 22: Stove C Test 1 Averages

	PM conc. (raw)	PM conc. (DR applied)	CO-stack	CO-dilution (raw)	CO-dilution (DR applied)	CO_2-stack	CH_4-stack	Stack temperature	Combustion Eff.	Flue gas velocity
	g/m3	*g/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*℃*	*%*	*m/s*
Start up	0.0039	0.0667	982	97	1642	3.37	81	150.1	74.4	1.44
First Reload	0.0043	0.0733	2136	181	3072	7.83	160	285.2	76.0	1.59
Second Reload	0.0038	0.0645	1045	103	1743	6.84	111	279.8	75.4	1.74
Third Reload	0.0041	0.0693	3216	242	4101	9.51	281	276.1	77.6	1.37
Overall	0.0041	0.0689	2245	180	3053	7.73	194	247.8	76.3	1.50

Table 23: Stove C Test 2 Averages

	PM conc. (raw)	PM conc. (DR applied)	CO-stack	CO-dilution (raw)	CO-dilution (DR applied)	CO_2-stack	CH_4-stack	Stack temperature	Combustion Eff.	Flue gas velocity
	g/m3	*g/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*℃*	*%*	*m/s*
Start up	0.0040	0.0514	N/A	133	1712	N/A		220.7	N/A	
First Reload	0.0039	0.0501		93	1196			255.6		
Second Reload	0.0041	0.0522		159	2039			261.7		
Third Reload	0.0043	0.0554		284	3650			262.1		
Overall	0.0041	0.0529		191	2453			250.0		

Table 24: Stove C Test 3 Averages

	PM conc. (raw)	PM conc. (DR applied)	CO-stack	CO-dilution (raw)	CO-dilution (DR applied)	CO_2-stack	CH_4-stack	Stack temperature	Combustion Eff.	Flue gas velocity
	g/m3	*g/m3*	*ppm*	*ppm*	*ppm*	*%*	*ppm*	*℃*	*%*	*m/s*
Start up	0.0051	0.0617	1941	77	944	5.1	174	217.6	74.6	1.54
First Reload	0.0044	0.0539	1428	46	562	8.0	81	273.5	77.0	1.48
Second Reload	0.0040	0.0484	903	25	303	7.0	56	288.2	75.7	1.87
Third Reload	0.0039	0.0476	1862	87	1057	8.2	115	273.2	76.9	1.25
Overall	0.0042	0.0516	1597	64	779	7.4	105	263.2	76.2	1.47