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# Performance of a Biomass Boiler in a Load Profile Test

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# *Performance of a Biomass Boiler in a Load Profile Test*

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## Abstract

In this report, results are presented of the performance evaluation of a modern residential cordwood-fired hydronic heater. This unit was tested under a specific load and operating profile that includes cold start, four load levels, reload, and cycling in response to an emulated thermostat. The protocol can be completed in a single day, which allows for replicate runs in about a week of testing. This can characterize variability with greater confidence than current methods used in certification testing, reduces time to conduct certification tests, and moves toward greater representative operations as the test includes start-up and requires boilers to respond to a variety of heat loads in a manner that better reflects day-to-day operations. Detailed in the report are the results of triplicate testing of one U.S. Environmental Protection Agency-certified cordwood-fired outdoor wood boiler. Cold start emissions were the greatest among all testing periods. In triplicate testing, emission output values for the cold start tests were 9.52, 4.74, and 6.63 lb/MMBtu of output for Test 1, 2, and 3, respectively. The overall emission output values for Test 1, 2, and 3 were 0.44, 0.34, and 0.19 lb/MMBtu of output, respectively. Additionally, the work in this project found significant differences in filter sampling methods with different integrated time periods. The use of real-time particulate matter emission measurement devices was explored. Specifically, sampling with one filter over a long test with various phases (cold starts, reloads, high and low burns) yielded lower particulate mass than sampling phase by phase (one filter for high burns, one filter for low burns, etc.). Perhaps the use of a real-time particulate matter emission measurement device can be used to distinguish different burn phases without having to change filters multiple times throughout a varied load test method.

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## Introduction

The focus of this work was an evaluation of the efficiency and air pollutant emissions of a modern, residential, cordwood hydronic heater under representative field conditions. The hydronic heater selected for these tests can be characterized as high mass with a large internal water volume that would typically be installed outdoors. The unit has advanced technical features including a flue gas oxygen sensor, internal combustion zone temperature sensors, a catalytic exhaust emission reduction system, and a microprocessor controller.

For certification approval, this type of unit is typically tested in the United States using U.S. Environmental Protection Agency (EPA) Method 28 Wood Hydronic Heaters (M28 WHH) [1]. Under this test method, a hydronic heater is tested under four load categories, listed below in Table 1. The loads listed here are a percentage of the maximum or nominal output.

**Table 1: Burn Rate Categories Based on EPA M28 WHH**

| | **Category I** | **Category II** | **Category III** | **Category IV** |
|---|---|---|---|---|
| % of maximum burn rate | < 15% of manufacturer's rated heat output | 16% to 24% of manufacturer's rated heat output | 25% to 50% of manufacturer's rated heat output | Manufacturer's rated heat output |

Each of these "Category" tests are a separate test run starting from a hot boiler with a defined coal bed and a consistent fuel load. No replicate data are required. The test is conducted at the category load until all of the weight of the appliance returns to the same weight as before the test fuel was added. The thermal load on the hydronic heater is nominally constant for the duration of each of the four tests. For larger residential boilers running under the lowest load (Category I), the duration of the test can be several days.

In the study reported here, a different approach has been explored. The hydronic heater test started with a nominally cold boiler so that measurements of emissions even during the startup period were included. During a single test the hydronic heater was operated under different load levels. This single day test also included a "burnout" phase where the loaded charge of the fuel is first burned down to coals and then a hot reload of fresh fuel is added, which is followed by a time period where the heat demand from the building thermostat is cycling. A key goal of this approach is to achieve sufficient information to understand how a hydronic heater might operate in the field under the range of conditions expected in service, with a single day test. A single day test makes it economically feasible to complete replicate runs without increasing testing costs.

In EPA M28 WHH, particulate emissions are measured using filters with integrated mass values over the entire category test. In the test developed in this work, the particulate emissions were parsed over different phases of the operation using one sampling train as discussed later in the report and another sampling train for the entire testing protocol. Real-time particulate measurement

methods were also deployed and are discussed below. Sampling in this approach allows the contribution of different parts of the operating cycle to total particulate emissions to be evaluated as opposed to the entire burn period only.

## Experimental

Boiler Description

The boiler used during the experiments was a residential outdoor wood-fired hydronic heater with a nominal rated output capacity of 102,400 Btu/hr (30 kW), with the nominal ability to fully modulate to completely avoid cycling and meet any heat demand. This boiler has an on-board 55-gallon (gal) water capacity that is heated and circulated to the home or space to be heated. Unlike many outdoor wood-fired boilers, this boiler boasts advanced features including a secondary combustion chamber, a lambda sensor to measure residual oxygen and adjust the burn rate, internal combustion zone temperature sensors, a microprocessor control, and a catalyst in the exhaust stream. Technical specifications include a primary and secondary air duct equipped with two dampers and a dry fire chamber made of 8-gauge steel to prevent creosote build-up.

Brookhaven National Laboratory (BNL) Lab Facilities

The boiler was installed on a weigh scale so that the fuel burn rate could be directly determined from the mass change. The weigh scale under the boiler has a rated capacity of 6,000 pounds (lb) and a resolution of 0.2 lb. The annual calibration to National Institute of Standards and Technology (NIST)-traceable standards is done by a commercial contractor as part of a BNL-wide scale calibration program. As per the manufacturer's installation instructions for the boiler's piping loop, a pump that was able to deliver 10-12 gallons per minute (GPM) and a mixing valve to ensure that water below 140°F never returns to the boiler were installed. Figure 1 shows the boiler sitting on the platform scale and Figure 2 shows the boiler flue gas entering the dilution tunnel.

**Figure 1: Boiler set up on a platform scale**

**Figure 2: Boiler exhaust entering dilution tunnel.**

Figure 3 provides a sketch of the boiler hydronic setup in the laboratory. The heat exchanger consists of two plate-type heat exchangers in parallel inside of a foam insulated box. On the other or open side of the heat exchanger, cold "city" water flows at a controlled rate to impose the target load. The flow rate of the cooling water is controlled and measured using a Belimo model epiv control module. From the heat exchanger, the cooling water is directed to a weigh scale located on the floor above for a direct mass measurement of the cooling water flow rate. The 50-gal tank on the weigh scale must be periodically emptied, and the output of the flow meter that is part of the Belimo control module is used during these brief times to determine the flow rate for energy output purposes. The flow rate from the boiler to the load heat exchanger was adjusted to provide a temperature drop across the heat exchanger of 20°F (supply return) to approximate the performance expected in the field.

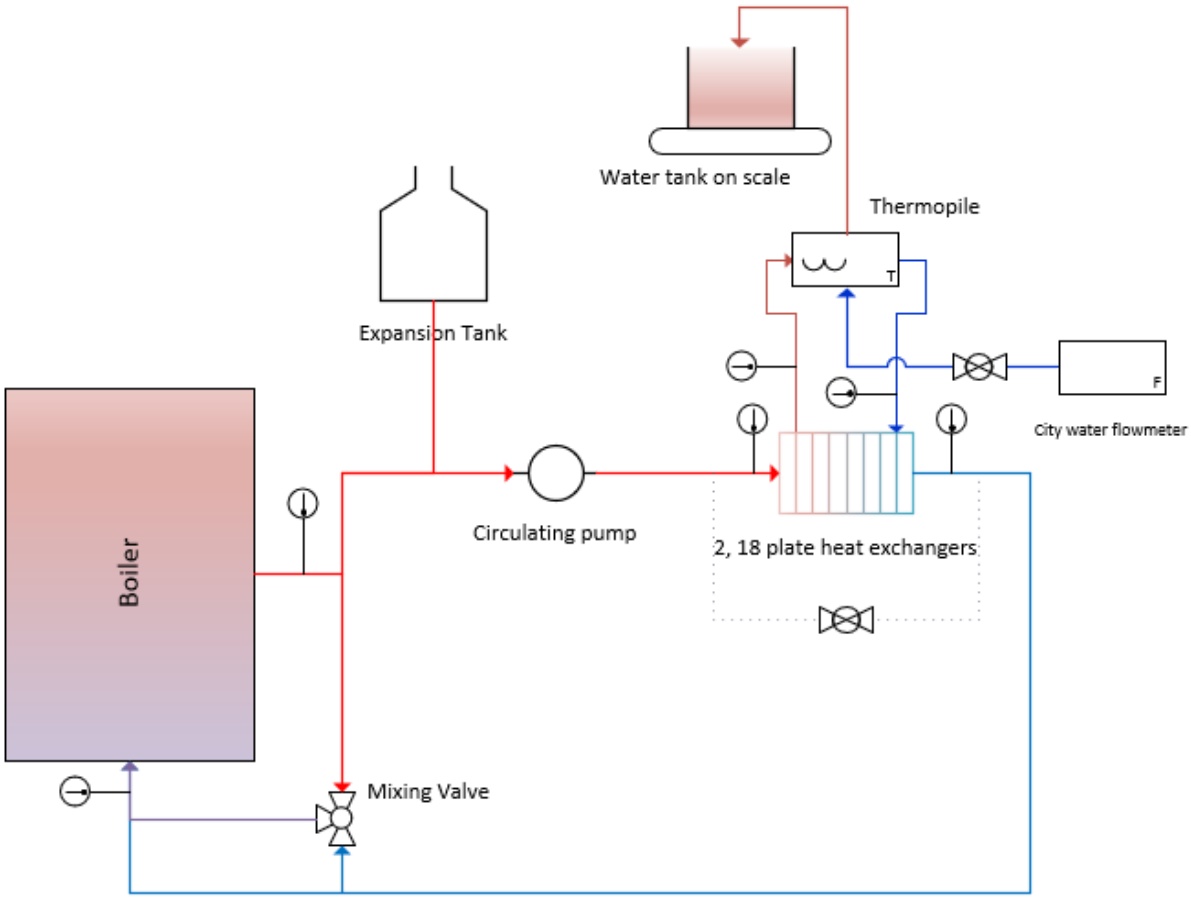


**Figure 3: Test arrangement in BNL lab.**

## Dilution Tunnel

The boiler's exhaust is connected to an 8"-diameter dilution tunnel that collects and mixes the boiler exhaust gas with the room's air. The dilution tunnel was built to specifications of the American Society for Testing and Materials (ASTM) E2515-10 *Standard Test Method for*

*Determination of Particulate Matter Emissions Collected in a Dilution Tunnel* [2]. A pitot tube probe was used to measure dilution tunnel velocity, which provides nearly a constant velocity so that the emission rate of particulates integrated over a transient operating cycle can be determined from the average concentration and tunnel flow. In the dilution tunnel, the gas is cooled, and semi-volatile organics are condensed and collected on particulate filters downstream. Figure 4 illustrates the dilution tunnel arrangement.

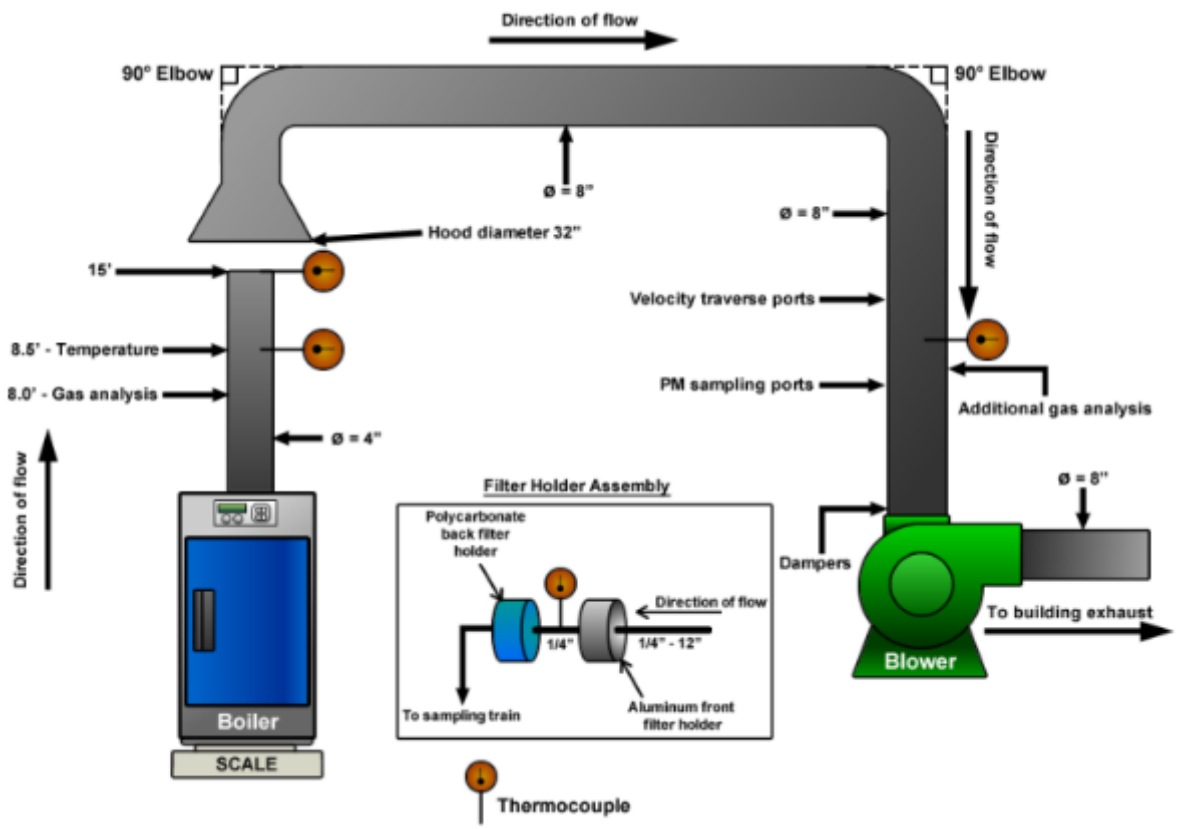


**Figure 4: Illustration of the dilution tunnel arrangement.**

## Particulate Matter Measurements

Particulate emissions were recorded from the dilution tunnel and conducted in compliance with ASTM E2515-10 [2]. The flow in the dilution tunnel is maintained constant throughout the testing and samples taken are drawn through a filter. Samples were extracted from the center of the dilution tunnel at room temperature with a preset sampling rate. This rate was typically set to 0.2 cubic feet per minute (cfm), which is within the specified range of 0.1 to 0.25 cfm as per ASTM 2515. Particulates were captured using two dual-filter EPA method 5 sampling trains operating simultaneously. Automatic sampling systems (Apex Instruments model XC-5000 AutoKinetic) were used to minimize user error by prescribing the desired sampling rate and time. Both sampling trains were comprised of two filters in a series, each 47 millimeters (mL) in diameter, in accordance with the filter holder assembly conditions in ASTM E2515.

In this study, Teflon-coated glass fiber filters (Palllflex Emfab TX 40) were used. Filters were conditioned prior to testing in a desiccator and weighed at least twice over a two-day period on a gravimetric balance, with a resolution of 0.001 milligrams (mg), prior to sampling. Post-test, filters were returned to the desiccator and weighed regularly until the weight stabilized (less than a 0.2-mg weight change was determined within a six-hour period). This mass was then used in the final determination of particulate emissions.

To remove any previous particulate matter (PM) emissions on the probes, an acetone rinse was used. Gloves and tweezers were used in all loading and measuring of filters and probes to eliminate excess weights from skin contact. Leak tests were also conducted on the sampling system to ASTM E2515.

For some of the testing done with this unit, particulate emissions in the dilution tunnel were measured using a real-time particulate concentration monitor referred to as a Tapered Element Oscillating Microbalance (TEOM). This instrument (Thermo Electron Corporation, rp series 1400AB) provides an opportunity to study particulate emissions during transients in boiler operations. The TEOM used PallFlex TX40 filters with a 13-millimeter (mm) effective diameter. The TEOM operating temperature was 30°C with an inlet flow rate of 0.5 liters per minute (lpm), establishing a filter face velocity of 6.3 cubic meters per second (cm/s). The TEOM provides a particulate concentration (milligrams per cubic meter, $mg/m^3$) and, with a known dilution tunnel flow rate ($m^3/s$), an emission rate (grams per hour, g/hr) may be calculated as the results show below.

Several changes to the instrument operational configuration were made since the default configuration is for ambient air PM sampling and will not work for this application. With this configuration, PM concentrations are reported at EPA standard temperature and pressure (STP) of 1 atmosphere and 25°C. Table 2 shows the default and new settings for the dilution tunnel TEOM.

**Table 2: TEOM Operation Parameters**

| Parameter | Original Value | New Value |
|---|---|---|
| MR/MC Avg | 1,800 | 2 |
| TM Ave | 1,800 | 30 |
| Const A | 3 | 0 |
| Const B | 1.03 | 1.00 |
| Case T | 50 | 30 |
| Air T | 50 | 30 |
| Cap T | 50 | 0 |
| Ave Temp | 25 | 25 |
| Ave Pres | 1 | 1 |
| Std Temp | 99 | 25 |
| Std Pres | 9 | 1 |
| Wait Time | 1,800 | 0 |
| Set MainF | 3 | 0.5 |

| Parameter | Original Value | New Value |
|---|---|---|
| Set AuxF | 13.7 | 0 |
| Storage Interval | 3600 | 15 |

It should be noted that when run with this fast response configuration, all data are reported regardless of the instrument's operating condition. This means that the data must be reviewed and invalid data (from events like filter changes) must be removed manually.

### *Dual Sampling Trains*

While two-dual sampling trains were used, they were not sampling PM in the same manner. One sampling train sampled PM over the entire testing period, thereby establishing one *integrated* filter (or a few filters if a single filter was plugged). The other sample train sampled each *individual* phase of operation. For example, a single filter was used to measure Phase 1, Phase 2, Phase 3, and so on (phase descriptions are detailed in the Test Profile below). Throughout the report and in the results found in the Appendix, notations of A and B refer to the train used to sample the individual phases and the integrated sampling train, respectively. When an individual phase ended, front filters only were changed between phases and this procedure was accomplished typically in less than 1 minute (min). Back filters were not changed because the mass collected was negligible and changing these filters would have slowed the filter change process, thereby resulting in a loss of sampling time and potentially PM. Any mass collected on the back filter was apportioned to the mass collected on the front filters.

After the sampling was completed, the mass of the PM on the filters was combined with any additional matter collected on the sampling probes, and measured after desiccating the filters and probes over a 24-hour period. Leak checks were also conducted at the end of the test and leakage rates were no more than the acceptable 0.01 cfm; however, leak tests were not done between sampling periods to minimize sampling time lost while changing filters.

Both sampling systems used for particulate emission rate measurements automatically adjust the flow rate to the target value and record all parameters at a time interval of 5 seconds. Both samplers use a type K thermocouple for temperature analysis which has an associated error of 2.2° or 0.75%. The sampler has flow rate measurement errors of $3.53 \times 10^{-5}$ cubic feet ($ft^3$) and ΔH measurement errors of 0.005.

### Flue Gas Analysis

Flue gas samples for analysis were taken from the dilution tunnel and directly from the stack, as seen in Figure 4. For sampling from the dilution tunnel, water vapor (7.2°C dew point) was removed using a thermoelectric cooler/drier with a backup anhydrous calcium sulfate column and a diaphragm sampling pump. Gas analysis in the dilution tunnel included oxygen ($O_2$) and carbon monoxide (CO). The analysis of samples from the flue gas included $O_2$, CO, volatile hydrocarbons (HCs as methane), and carbon dioxide ($CO_2$), and were sampled directly at the boiler's exhaust, not at the standard 8.0 feet (ft) from the top of the scale in accordance with the

Canadian Standards Association's Performance Testing of Solid-Fuel-Burning Heating Appliances (CSA B415.10) [3]. This change was the result of the boiler having a required air damper installed at the flue gas exit. 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%.

CO was measured in the dilution tunnel using a Rosemount Analytical Model 880 NDIR Carbon Monoxide analyzer. Oxygen was measured in the dilution tunnel via a Beckman model 755 paramagnetic Oxygen Analyzer. CO, $CO_2$, and HCs (methane-equivalent) were measured directly in the stack using an infrared analyzer (California Analytics, Model ZRE). The CO limit on this particular analyzer was 50,000 parts per million (ppm) and the methane limit was 1,600 ppm; above these values the analyzer is out of range and no longer provides a measured value. Nitrogen oxides ($NO_x$) were measured using a Rosemount Model 955 chemiluminescent $NO_x$ analyzer.

For cooling water flow control and logging of flue gas composition, cooling water flow, boiler scale mass, dilution tunnel velocity, and cooling water inlet and outlet temperatures, a laboratory data acquisition (DAQ) system was used with Visual Basic programming. The signals from all analyzers were logged at five-second intervals. Each gas analyzer had a resolution of 0.1%. The programming allowed for a target heat output rate, and the cooling water flow was continuously adjusted by the program to achieve the target output.

Type K thermocouples were also logged at a five-second interval for all temperature measurements. including stack temperature (8.5 ft from the stove base), top of the stack (15 ft), dilution tunnel, ambient air (laboratory), and in-between the front and back filters in each PM sample probe. The thermocouples were purchased from Omega and have an associated error of 2.2° or 0.75%. Thermocouples were logged on a separate computer via Pico Logger software. Pressure in the dilution tunnel was measured with a digital BAPI ZPS series differential pressure transmitter capable of measuring 0 to 30 pascals.

### Test Fuel

The fuel test charge was red oak cordwood, with an average moisture content of 19% to 25% on a dry basis. During the testing, two fueling procedures were followed, which were both detailed in the owner's appliance manuals. The first was as per M28 WHH [1], where a full load is considered as 10 lb/ft$^3$, which is equivalent to 125 lb of fuel. The second loading procedure, representative of common in-field practice and written in the manufacturer's manual, is to fill the combustion chamber up to within one inch (1") of the top of the door, equating to about 160 to 180 lb of fuel depending on piece size, packing, and density. To assess the impacts of different load volumes, both procedures were explored. In both cases, fuel pieces were placed in the firebox parallel to the longest firebox dimension. The manual recommends tightly packing cordwood pieces when placed on top of the established coal bed. Per M28 WHH, the fuel length was nominally 80% of the firebox's depth, which equated to 22".

The test fuel was prepared by the State University of New York, College of Environmental Science and Forestry, under the direction of Dr. William Smith in accordance with the procedures documented in a study of the partial kiln drying and moisture measurement of cordwood for combustion testing [4]. The fuel used for the tests was free of any notable decay, fungus, and loose bark.

The kindling fuel charge was loaded in two different ways, but both as per the manufacturer's specifications. The written instructions in the owner's manual suggest the kindling be loaded on top of the paper and cardboard in a *parallel* direction, whereas an online *YouTube* video posted by the manufacturer suggests a *crisscross* pattern. In both scenarios, the kindling weight is 10% of the initial fuel charge and made up of half smaller pieces and half larger pieces. Newspaper and cardboard were also used in the kindling load for the cold start or Phase 1. Whether following the owner's manual or the *YouTube* video, there was no strong indication if the direction the kindling lay had any impact on combustion performance and coal bed formation. Kindling was weighed prior to each test; however, moisture of the kindling pieces was not recorded.

Wood Moisture Measurements

The overall efficiency of the boiler provides a uniform basis for comparison of performance of different units. This is of value to the consumer and is determined through the total energy input, output, and losses. The moisture content of the wood factors into the total energy input and, therefore, moisture measurements of the fuel charge are essential. The wood moisture meter used for measurements was a Delmhorst RDM-3, which is capable of measuring test fuel moisture to within 1% moisture content (nominal). The meter also allows the user to specify the species measuring to ensure accuracy. Measurements were taken four hours prior to every test.

The moisture of the test fuel load was determined by averaging six moisture readings for each piece, measured parallel to the wood grain and on one side of the fuel piece. Moisture readings were recorded 3" from both ends of the fuel piece, one in the center at ¼"- and ¾"-depths into the fuel piece using the moisture meter's insulated electrodes. As per the procedures documented in a study of the partial kiln drying and moisture measurement of cordwood for combustion testing by Dr. William Smith [4], an acceptable criterion for the test fuel load was 18% to 28% at the individual measurement points with an overall average of 19% to 25%. While the fuel was partially kiln dried, no moisture was added to any fuel charges that registered below the acceptable range. The piece weight was dictated by CSAB415.1-10 [3] fuel loading procedures.

Test Profile

BNL completed baseline testing using M28 WHH protocols, which is the current test method to certify compliance under federal regulations for residential wood heaters. The test requires the use of red oak dimensional lumber (4x4). M28 WHH requires one test run in each of the categories specified below in Table 1. The M28 WHH test is a steady-state, hot-to-hot test. Before PM and gaseous emission sampling begins, a coal bed is established using a pre-burn fuel charge that is similar in weight and moisture content to that of the test fuel charge. Both the pre-burn fuel and

test fuel charges have a loading density of 10 lb/ft$^3$, as per the method. The pre-burn charge is ignited and then, when 80% of the charge is consumed, a coal bed is established and the test fuel charge is added to the hot coals. Gaseous and PM emission sampling begins immediately when the test fuel charge is added to the combustion chamber on top of the coal bed. The test run is a hot-to-hot test, which means that a load of fuel is placed on a hot bed of coals and ends when the scale returns to the pre-load weight.

BNL conducted two Category IV test runs per EPA M28 WHH. A full output load is also established during a Category IV load to verify the manufacturer's nominal rating. The first Category IV test used cribwood (dimensional lumber) and the second test used cordwood (as described above), which is representative of ASTM 2618. Both fuels were of the red oak species. The 4x4 cribwood was red oak cut to a 22" length and moisture measurements were taken similar to those of the cordwood described above. A comparison of the crib and cordwood testing is provided in the discussion section.

Through this project a draft test protocol was developed with project partner, Northeast States for Coordinated Air Use Management (NESCAUM), which is intended to better reflect typical field operating conditions, capturing varying emission cycles and reloading patterns not currently captured in existing test methods. The testing procedure developed does not test a full batch of wood at a single load, but rather tests a full batch of wood at various heat demands. Part way through, the boiler is reloaded with another batch of fuel and different heat loads are again placed on the boiler. The entire test procedure was divided into 10 phases: cold start, ramp-up, steady state at various high- and low-load profiles, burn-out, hot reload, and a cyclic operation that reflects different use patterns boilers experience in the field. The test method that was developed for this project went through several iterations. The test procedure followed for the triplicate tests discussed in this report can be seen in Table 3.

In contrast to the method used here, the current EPA standard method uses one test batch of wood for each load at which a test is run. The load is fixed for each of the four load category tests. In the test used here, the unit is loaded, various heat demands reflecting use patterns are placed on the boiler, the unit is reloaded (before burning the entire load), and a different cycle of operation is placed on the unit. Testing with many load levels can be accomplished in a single day. With the EPA method, tests under the lower load categories can take several days to complete.

EPA accreditation tests indicated the unit was unable to operate in a Category I load and therefore the requirement to test in the low-load category was waived. However, low loads are common in the field and so a test method that reflects field-like operations should include low-load periods. To confirm if the unit could operate at 15% or less of rated nominal output, a preliminary Category I load was placed on the boiler for a four-hour period. No formal Category I test was conducted but a small coal bed was established, 60 lb of red oak cordwood were loaded into the combustion chamber, and a 15% load was placed on the boiler. For the four-hour duration, the boiler maintained the 15% output without going into shutdown or overheat mode. From this test, it was

determined the unit would be able to operate in Phase 8 of the developed test protocol seen in Table 3.

It is important to note that during the time of this project the test method was under development and so the method discussed throughout this report is not a final approved test method but an earlier iteration of *A Test Method for Certification of Cord Wood-Fired Hydronic Heating Appliances Based on a Load Profile: Measurement of Particulate Matter (PM) and Carbon Monoxide (CO) Emissions and Heating Efficiency of Wood-Fired Hydronic Heating Appliances* [5]. Each phase started and ended based on either a time constraint or percentage of fuel burned; the constraining parameter is marked with an asterisk (*). The boiler's output and a description of the burn period are also listed for each of the phases.

**Table 3: Varied Load Operating Protocol**

| Phase | Description | Estimated Duration (hr) | Fuel Burned (% of fuel charge) | Boiler Load (Btu/hr) |
|---|---|---|---|---|
| | Add 12.5 lb of kindling | | | |
| 1 | Cold start: Includes kindling (10% of fuel charge weight) made up of 50% small pieces and 50% larger kindling pieces | 0.25 | ~ 80% until catalyst reaches 750°F[a] | 102,400 |
| | First fuel charge: Add 125 lb of fuel charge | | | |
| 2 | Fuel charge addition and ramp up to 100% burn rate (when boiler says "running") | 1 | 20[a] | 102,400 |
| 3 | Steady State Part I – 100% burn rate (Category IV) | 1.5 | 20[a] | 102,400 |
| 4 | Steady State Part II – 25% output (Category II) | 2.5[a] | 20 | 25,600 |
| 5 | Steady State Part III – 50% load operation (Category III) | 1 | 15[a] | 51,200 |
| 6 | End Phase – burn out[b] | 1.5 | 10[a] | 102,400 |
| | Second fuel charge: Add roughly 160 lb of fuel charge (filling chamber to 1" from top) | | | |
| 7 | Reload – Equivalent of a hot start | 0.5 | 10[a] | 102,400 |
| 8 | Steady State Part IV<br>Low Load Operation – Modulated 15% of maximum (Category I) | 3[a] | 20 | 15,360 |
| 9 | Steady State Part V – 100% burn rate (Category IV) | 2 | 20[a] | 102,400 |
| 10 | Cyclic operation (5 min on, 10 min off) | 1[a] | 15 | 102,400 |
| | Let remainder of fuel burn out at maximum load no sampling | N/A | **35** | 102,400 |
| | **Total duration** | **14.75+** | | |

a. Most important milestone to reach for the individual phase.

b. End burn-out phase sampling and begin reload when coal bed is 15% of fuel charge weight.

Phase 1 began once the match or torch was lit, igniting the first batch of fuel. In this case, the kindling and paper was added and the "start" button on the home screen was pressed. The boiler home screen during this period read "cold start." Once the catalyst temperature reached 750°F, roughly 80% of the kindling was burned and a small coal bed was established. The first fuel charge (following a similar loading density of M28 WHH of 10 lb/ft$^3$) was then added, as per the manufacturer's instruction manual. Once the fuel charge was added, Phase 2 sampling began. This period was characterized by the boiler working toward its steady-state period by increasing the fan speed and positioning the dampers. This period was concluded when the boiler no longer indicated it was in "cold start" and displayed "running" on its home screen with the boiler's temperature reaching 180°F. The following three phases (Phase 3, 4, and 5) were category loads that are currently used in certification testing for wood hydronic heaters under M28 WHH [1]. These load categories are listed in Table 1, above. During each of these periods, the boiler maintained its "running" readout on the home screen. These categories reflected what may happen in a home with full output, low-load requirements, and recovery from low-load operations. Following Phases 3 through 5 was burn-out. The boiler's stack and catalyst temperature at this point decreased and only a small percentage of the initial fuel charge remained.

Once the remaining fuel charge burned down to a coal bed that was 15% of the initial fuel charge, the second, larger fuel charge was loaded to 1" from the top of the door. The second fuel charge was larger than that of the first for two reasons. It is generally understood that in-field practices follow visual cues such as those highlighted in the manufacturer's instructions, loading by volume rather than the prescribed loading densities set by the EPA. This boiler's manual instructs the user to fill the combustion chamber to within 1" of the top of the door, unless using a dense fuel. The second thought is that many users wish to maximize the time between refueling their boiler and so filling the chamber with as much fuel as possible may also be a common practice. Once the fuel charge was added and the door was shut, the start button on the home screen was pressed to indicate "reload," and Phase 7 sampling began until 10% of the fuel charge had been consumed, typically a 30-min period. Once the fuel charge ignited during the reload period and the boiler indicated it was "running," a low Category I load was placed on the boiler to assess the impact of overloading the firebox chamber and imposing an immediate low load. Under certain circumstances, such as a homeowner leaving for work or during the nighttime, it is believed that the firebox chamber may be filled entirely and followed by a low heat and hot water demand. Phase 8 was followed by Phase 9, a recovery period of full output (Category IV load).

Phase 10, the final sampling period, was a cyclic operation that is common in a home where there is a demand for heat and that once the load is satisfied, there is no longer a demand. In other words, it is not often or common that boilers will fire in a full-output period for an extended amount of time. Consider an oil or gas-fired burner in a home that has a demand for heat, calling for a burner to fire, but once the thermostat is satisfied, the burner will shut off. With manually fed biomass boilers it is not possible to cease a flame and reignite the fire without manual assistance, and so

they modulate. To study the effects forced cycling has on emissions, the cooling water load was turned on for 5 min and off for 10 min until an hour had passed.

## Results

In this section, detailed results of the Category IV tests performed with both crib and cordwood and the three-final operating protocol (as per Table 3) tests are presented. Preliminary tests that helped design the final testing protocol are discussed below as well.

Preliminary tests

### Catalyst Conditioning

Prior to all PM testing, the unit's catalyst was conditioned for a minimum of 24 hours at 50% of its nominal output. Prior to the formal varied-load protocol tests, pretests were carried out to help build and establish the protocol. With these runs included, well over 50 hours of catalyst conditioning time was achieved before the triplicate testing of the varied load protocol.

### Category IV Test 1: Red oak cribwood

On October 17, 2017, the first Category IV with red oak cribwood test was performed. A summary of the testing time, output, moisture content, and overall PM emissions can be found in Table 4 below.

**Table 4: Summary of Category IV Crib Results**

| Test Date | October 17, 2017 |
|---|---|
| **Testing duration (min)** | 374 |
| **Weight of fuel burned (lb)** | 126.6 |
| **Average moisture content of fuel charge I** and **II (% dry basis)** | 22.6 |
| **Overall emission factor (lb/MMBtu)** | 0.04 |
| **Overall emission rate (g/h)** | 1.71 |
| **Overall emission index (g/kg)** | 0.19 |

### Discussion of Category IV Test 1 Results

Prior to the start of the test, the cold boiler was cleaned to remove any coal or ash. A kindling charge (10% of the fuel charge) was prepared using paper, cardboard, and both small and larger pieces of wood as described above. The cardboard and paper, as well as the kindling charge (12.6 lb), may be seen in Figures 5 and 6 below. The boiler was then ignited, and the kindling was burned down to form a coal bed. On top of the kindling coal bed, a pre-burn charge of 123.3 lb was added. Once 80% of the pre-burn charge was burned, a coal bed was established and then the cribwood test fuel charge was added. Figure 7 shows the cribwood test fuel charge addition. All PM and gas sampling began once the test crib fuel was added to the coal bed. The test was concluded when the complete addition of the cribwood test fuel charge was burned and the scale mass returned to the beginning weight (that of the 20% pre-burn coal bed).

**Figure 5: Category IV cribwood paper and cardboard addition**

**Figure 6: Kindling charage for Category IV cribwood test.**

**Figure 7: Category IV cribwood addition to kindling coal bed.**

Figure 8 through Figure 10 depict the CO (ppm), HC (ppm), and $CO_2$ (%) concentrations in the stack for the duration of the test. There was an initial spike of CO upon the addition of the fuel that was over the analyzer's range of 50,000 ppm. For unknown reasons, the CO spiked once again at 100 and 140 min into the test. For a majority of the test, the HCs were well above the 1,600 ppm limit of the analyzer, as shown in Figure 9. Besides an initial dip in $CO_2$ concentrations upon the addition of the fuel, $CO_2$ remained rather steady throughout the burn, only slightly fluctuating. The fluctuations are thought to be a result of the catalyst firing on and off throughout the burn, and this is developed in more detail in the Discussion section below. The $CO_2$ is near or at its maximum quite often in the boiler's operation, indicating there is little to no flue gas $O_2$, and so the combustion is running very fuel rich.

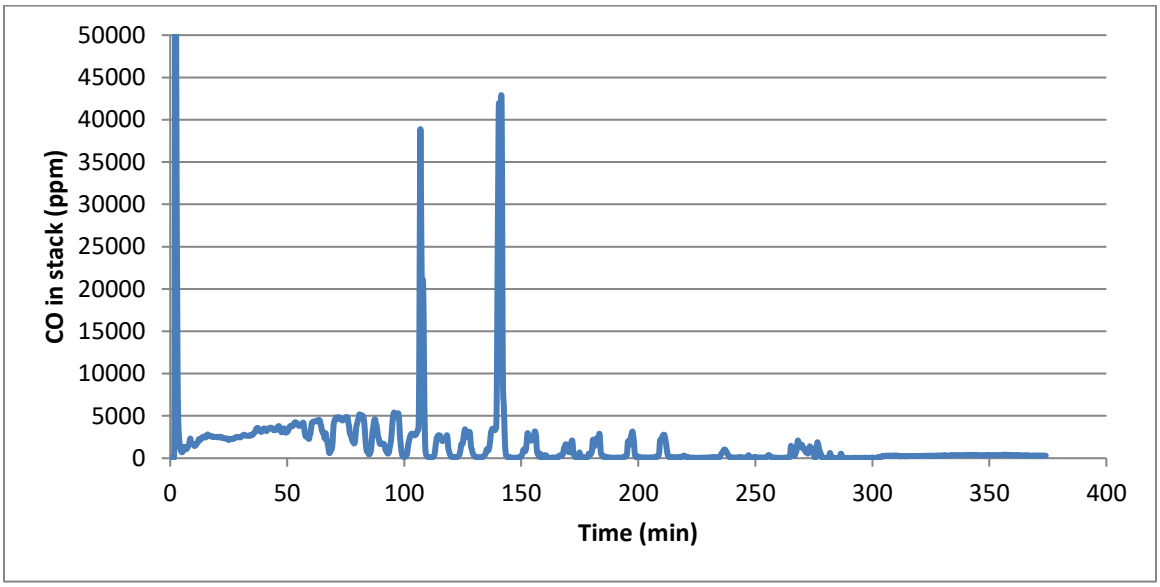


**Figure 8: CO concentration in the stack for Category IV cribwood.**

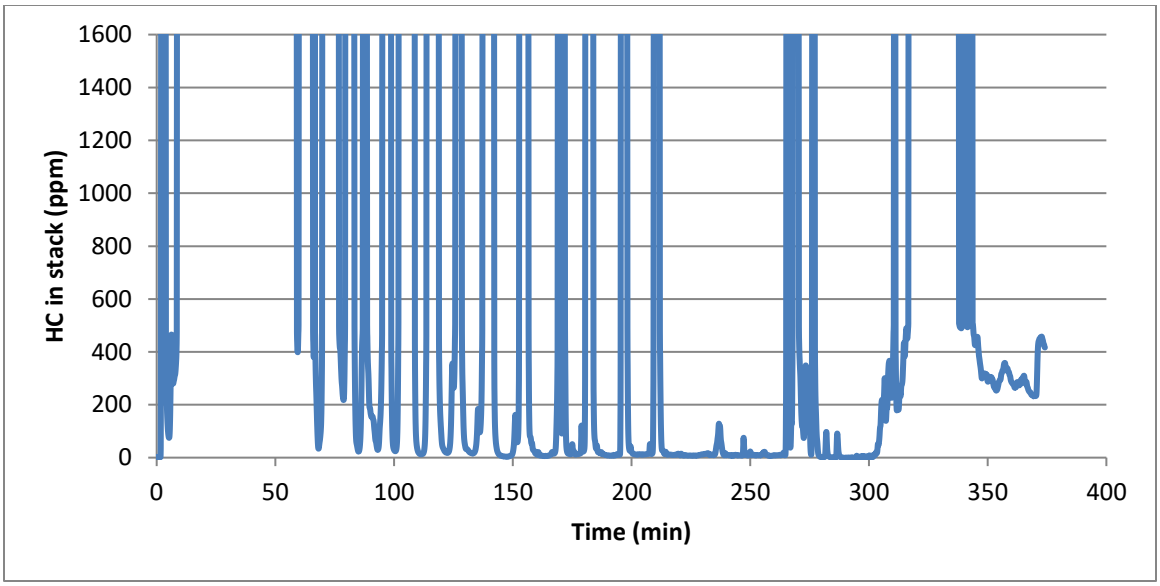


**Figure 9: HC concentration in stack for Category IV cribwood.**

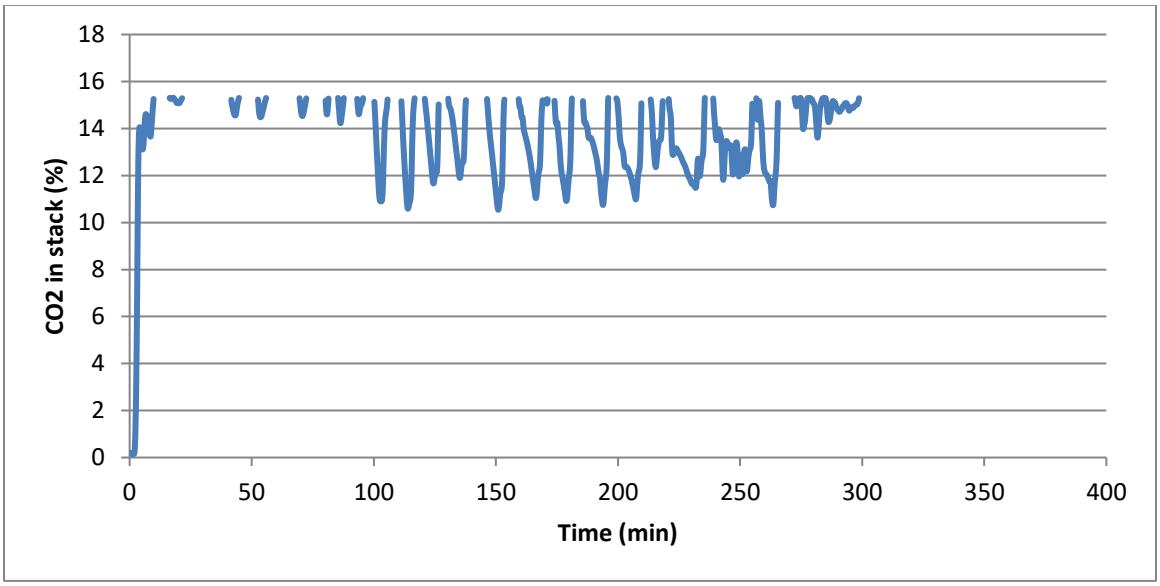


**Figure 10: $CO_2$ concentration in stack for Category IV cribwood.**

### Category IV Test 2: Red oak cordwood

On October 31, 2017, the first Category IV with red oak cordwood test was performed. A summary of the testing time, output, moisture content, and overall PM emissions may be found in Table 5 below.

**Table 5: Summary of Category IV Cord Results**

| Test Date | October 31, 2017 |
|---|---|
| **Testing duration (min)** | 420 |
| **Weight of fuel burned (lb)** | 122 |
| **Average moisture content of fuel charge I** and **II (% dry basis)** | 18.8 |
| **Overall emission factor (lb/MMBtu)** | 0.05 |
| **Overall emission rate (g/h)** | 1.95 |
| **Overall emission index (g/kg)** | 0.25 |

## Discussion of Category IV Test 2 Results

Prior to starting a test, the cold boiler was again cleaned to remove any coal or ash. Similar to Test 1, a kindling charge (10% of the fuel charge, totaling 12.2 lb) was prepared using paper, cardboard, and both small and larger pieces of wood as described above. The cardboard and paper, as well as the kindling charge, can be seen in Figure 11 and Figure 12 below. The boiler was then ignited, and the kindling was burned down to a coal bed. On top of the kindling coal bed, a pre-burn charge of 120 lb was added, as seen in Figure 13. Once 80% of the pre-burn charge was burned a coal bed was established (Figure 15), and then the cordwood test fuel charge was added. Figure 14 shows the test fuel charge and Figure 16 shows the test fuel charge placed on top of the coal bed. All PM and gas sampling began once the test fuel was added to the coal bed. The test was concluded when the complete addition of the cordwood test fuel charge was burned, and the scale mass returned to the beginning weight (that of the 20% pre-burn coal bed).

**Figure 11: Category IV cordwood paper and cardboard addition.**

**Figure 12: Kindling charge for Category IV cordwood test.**

**Figure 13: Pre-burn charge to kindling coal bed for Category IV cordwood test.**

**Figure 14: Cordwood test fuel charge.**

**Figure 15: Pre-burn coal bed.**

**Figure 16: Category IV cordwood addition to kindling coal bed.**

Figure 17 through Figure 19 depict the CO (ppm), HC (ppm), and $CO_2$ (%) concentrations in the stack for the duration of the test. Similar to the cribwood test, there was an initial spike of CO upon the addition of the fuel that was over the analyzer's range of 50,000 ppm. Small spikes of CO occurred throughout the test, which is thought to be due to the catalyst firing on and off. For a majority of the test, the HCs were well above the 1,600 ppm limit of the analyzer, as shown in Figure 18. As with the CO, $CO_2$ slightly fluctuated throughout the test as a result of the catalyst firing on and off throughout the burn, again described in more detail in the Discussion section below. Just as with the cribwood results, the $CO_2$ is approached its maximum limit quite often in the boiler's operation, indicating there is little to no excess oxygen, and so the combustion is running fuel rich.

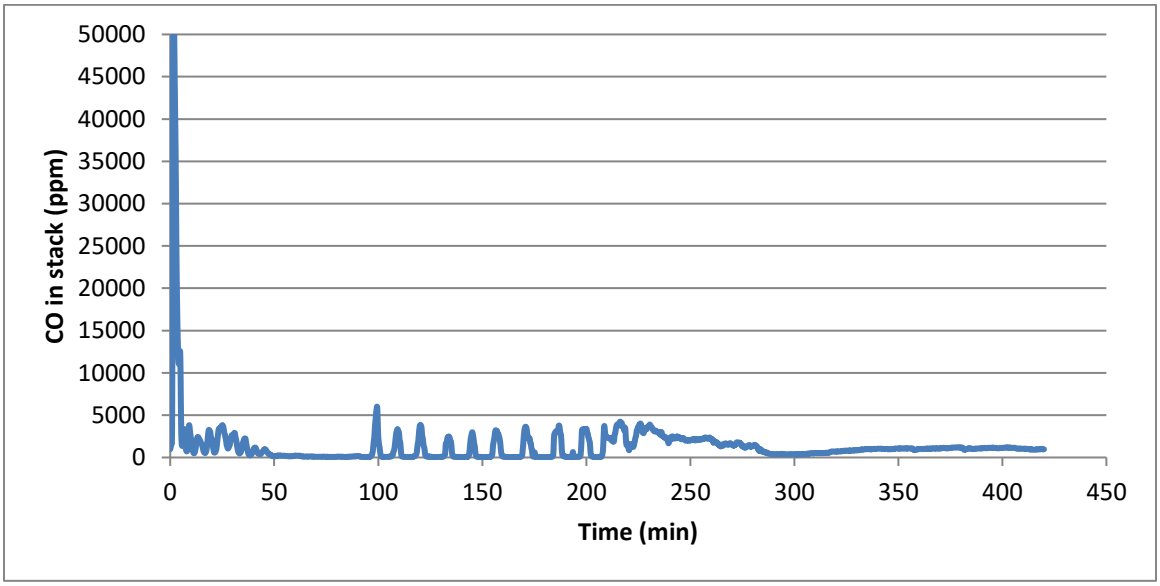


**Figure 17: CO concentration in the stack for Category IV cordwood.**

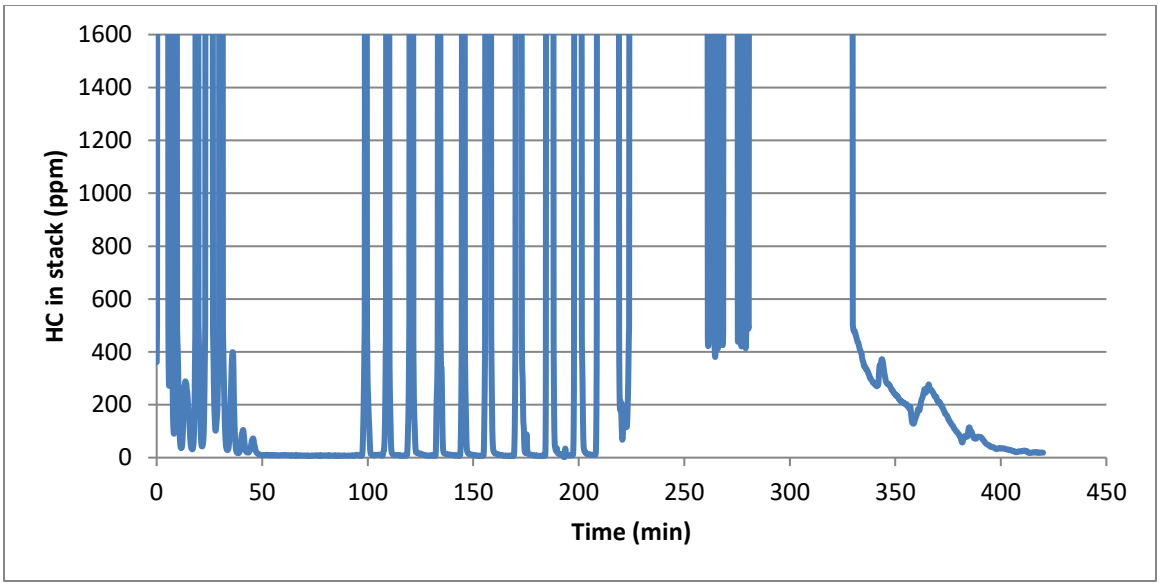


**Figure 18: HC concentration in the stack for Category IV cordwood.**

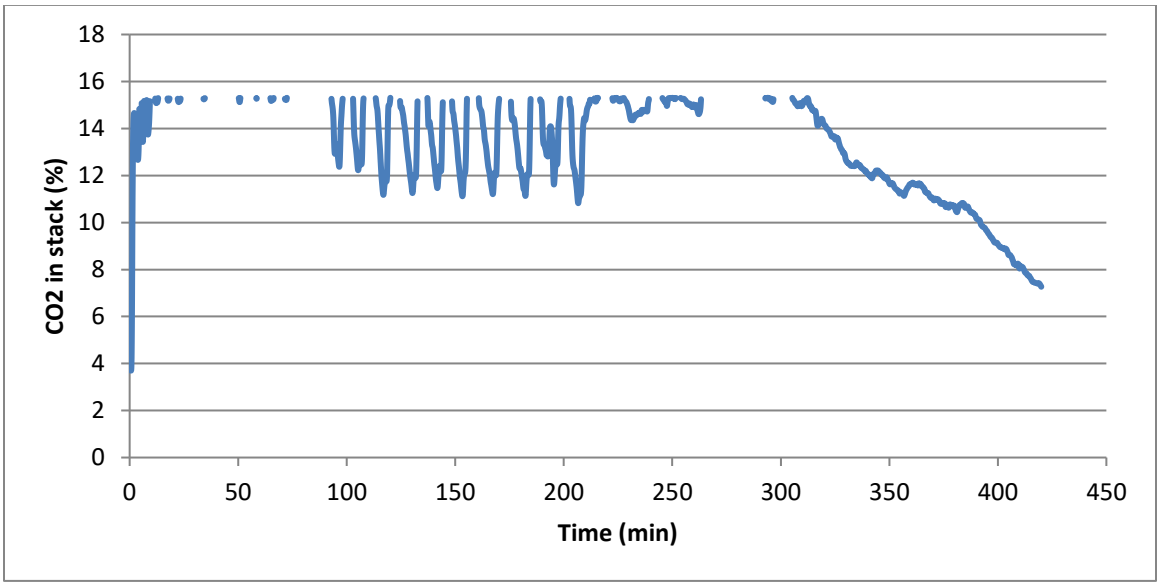


**Figure 19: $CO_2$ concentration in the stack for Category IV cordwood.**

## Early Iterations of the Varied Load Profile Test

A total of four preliminary iterations on the varied load profile test were run to yield what the team felt was the most realistic and challenging protocol. Initial trials of the test method included only the 125-lb charge of fuel followed by a smaller 60-lb charge, and did not include the cyclic operation period. It was determined that having too small of a second charge of fuel was an unlikely practice of a homeowner and the fuel charge was too quickly consumed for extensive testing.

Additional preliminary tests showed loading the second larger fuel charge and immediately going into a Category I load (avoiding a full-output reload period) caused the large fuel charge to not ignite properly and periods of heavy smoke from which the boiler could not recover. The team also looked at the impact of kindling. One preliminary test included a 20%-of -fuel-weight kindling charge to perhaps yield a larger coal bed. The kindling pieces still consisted of both smaller and larger pieces. However, with the larger charge of kindling, the boiler surprisingly had trouble igniting all the kindling and establishing a decent coal bed. Therefore, the approach was changed, and the original manufacturer's written instructions were followed using 10%-of-fuel-weight only. The fifth and final iteration yielded the protocol seen above and triplicates were run to this protocol as described below.

The protocol developed includes EPA M28 WHH Category I, II, III, and IV load levels, but unlike the traditional test, the categories are not full categories – they only include the steady-state portion of the run and not a complete hot-to-hot burn, i.e., they are much shorter. However, for comparative purposes, emission output data from the Category II, III, and IV phases in early iterations of the protocol were compared against the reported EPA certification test emission output reported values.

For certification purposes, this unit used an alternative test method (ATM), which did not require testing at Category I levels. This comparison is shown in Figure 20 below. In all cases, the category tests at BNL within the protocol were higher than those values in the certification tests. This could be expected since the certification testing is done with cribs and is a hot-to-hot test. In other words, the certification tests allow a significant coal bed to be established prior to the addition of the fuel charge and longer steady-state operation periods.

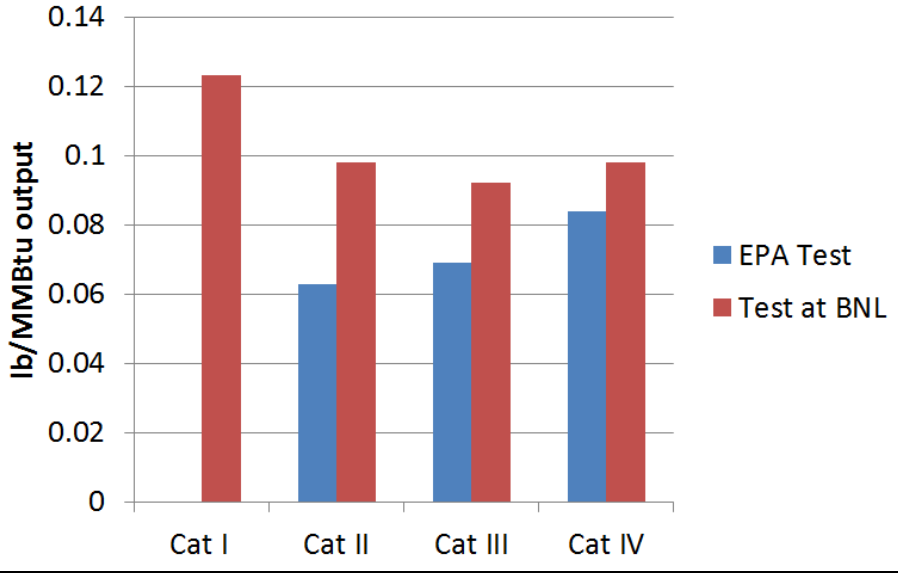


**Figure 20: Emission outputs per M28 WHH category for BNL and accreditation tests.**

Test 1 Results

On February 2, 2018, the first complete final varied load profile test (Table 3) was performed. As previously mentioned, the purpose of this test was to operate the boiler in one day in a manner that is more reflective of in-field performance as opposed to traditional category tests. A summary of the testing time, output, moisture content, and overall PM emissions may be found in Table 6 below.

**Table 6: Summary of Test 1 Results**

| Test Date | February 2, 2018 |
|---|---|
| **Testing duration (min)** | 727 |
| **Weight of fuel burned (lb)** | 185.2 |
| **Average moisture content of fuel charge I** and **II (% dry basis)** | 18.1 |
| **Overall emission factor (lb/MMBtu)** | 0.44 |
| **Overall emission rate (g/h)** | 18.52 |
| **Overall emission index (g/kg)** | 2.67 |
| **Overall stack loss efficiency (%)** | 82.8 |

### *Discussion of Test 1 Results*

Prior to starting the test, the cold boiler was cleaned to remove any coal or ash. A kindling charge was prepared using paper, cardboard, and both small and larger pieces of wood, as described above. The kindling charge and loading can be seen in Figure 21 and Figure 22 below. The boiler was then ignited, and PM and gaseous sampling began. Figure 23 shows the exit of the flue stack into the dilution tunnel during the cold start portion of the burn. Once the boiler's catalyst temperature reached 750°F after 15.7 min, the first fuel charge of 124.45 lb was added, as shown in Figure 24. Eighty-five percent of the first fuel charge was consumed within 381.64 min, leaving a bed of hot coals as shown in Figure 25. The second fuel charge of 141.95 lb was then added, and sampling resumed (Figure 26 and Figure 27).

**Figure 21: Test 1 cardboard and paper portion of kindling charge.**

**Figure 22: Test 1 kindling charge loaded in boiler.**

**Figure 23: Test 1 cold start flue exit.**

**Figure 24: Test 1 addition of first fuel charge.**

**Figure 25: Test 1 coal bed established after fuel charge 1.**

**Figure 26: Test 1 addition of second fuel charge.**

**Figure 27: Test 1 addition of second fuel charge on top of a coal bed.**

Light-off of the boiler was at 8:41:31 and sampling concluded at 21:07:43, resulting in a total testing time of 746.2 min, with only 727 min of active PM sampling. The total fuel consumed during this test was 169.8 lb. From Figure 28 and Figure 29 illustrating the CO and HC concentrations throughout the test, it can be seen that the boiler's operation is variable, as expected with the testing protocol. Specifically, Figure 29 shows the high concentration of HC emissions that very often exceed the analyzer's limit of 1,600 ppm and there are only a few instances when the CO analyzer's limit of 50,000 ppm is breached. The CO concentration on the other hand peaks during Phases 1, 2, 4, 6, 7, and 10; otherwise it remains rather low and steady. At around 600 min the boiler ended Phase 8 and transitioned into Phase 9, triggering a spike in CO; however, the explanation for the spike is undetermined.

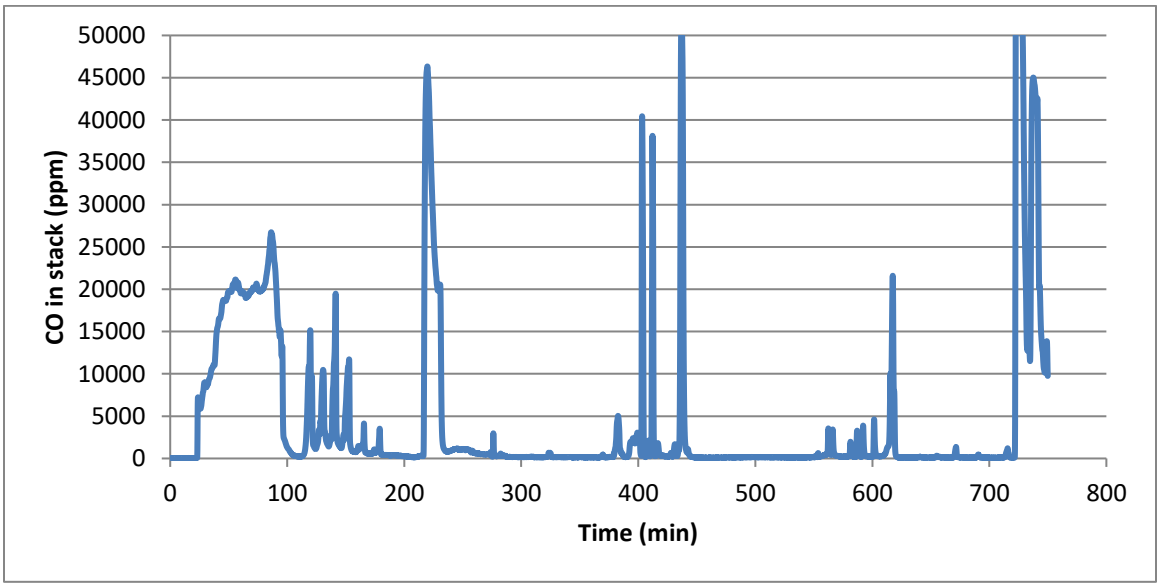


**Figure 28: Test 1 CO trends.**

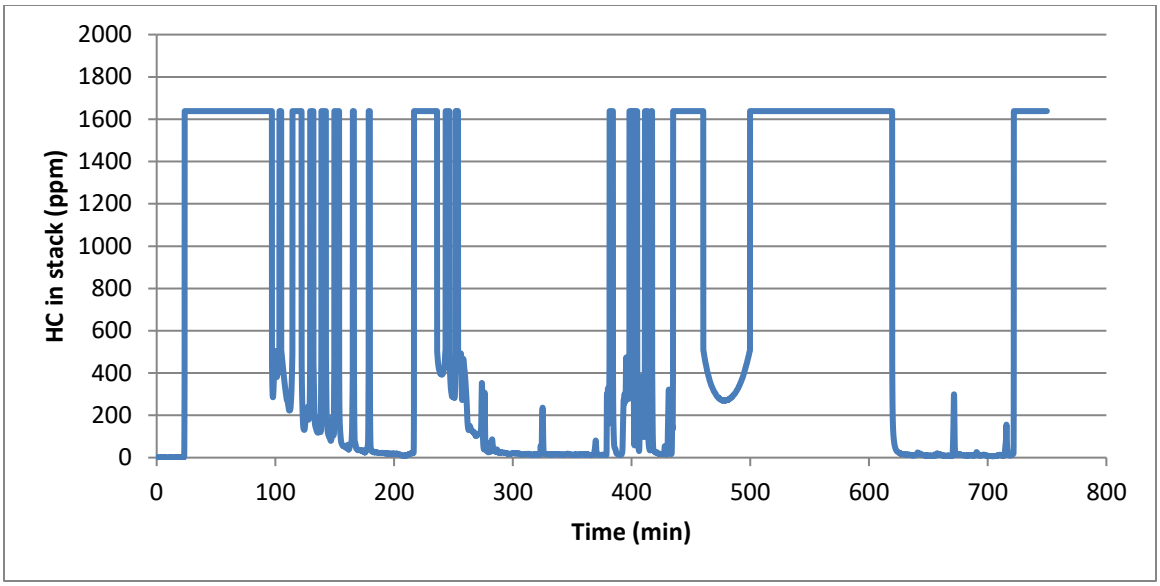


**Figure 29: Test 1 HC trends.**

Figure 30 shows the boiler's stack temperature trends over the entire sampling period. From here, it can be seen at points, specifically during Phase 3 and halfway into Phase 4 (100 to 200 min), the stack temperature frequently jumps. This behavior is owed to the catalyst and its "hunting" nature. This was discussed with the manufacturer and is uncommon in traditional, non-catalytic boilers. The boiler controls read the $O_2$ levels from the lambda sensor and then choose to adjust excess air, thereby affecting the catalyst's temperature, which is ultimately reflected in the boiler's stack temperature. The consequence of the boiler "hunting" ultimately affects the $CO_2$ and $O_2$ concentrations of the boiler's exhaust gas, as seen in Figure 31. The $CO_2$ is near the maximum level quite often in the boiler's operation, indicating there is little to no $O_2$, and so the combustion is running fuel rich.

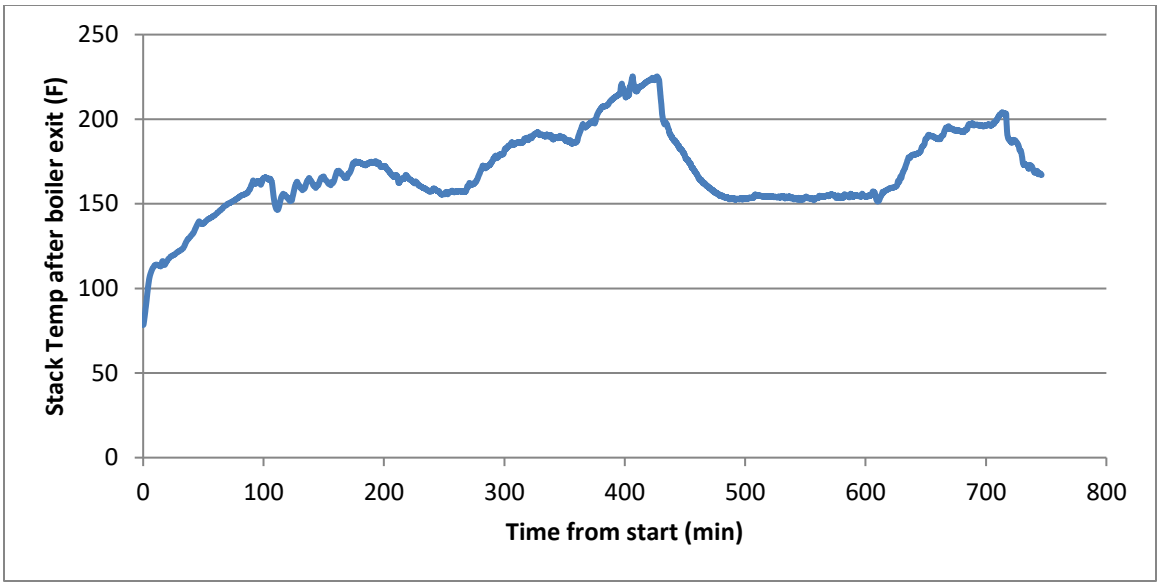


**Figure 30: Test 1 stack temperature.**

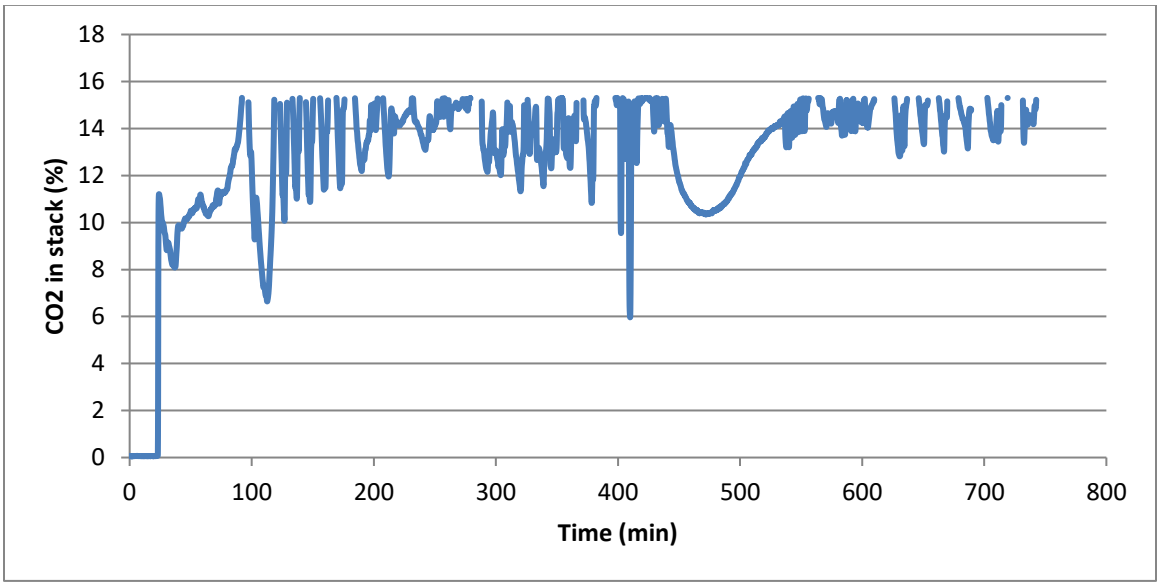


**Figure 31: Test 1 $CO_2$ trends.**

During Phase 10 (cooling water on for 5 min and off for 10 min), the boiler seemed to have some difficulty in controlling its temperature set-point. The boiler seemed to fire hard during the period when the cooling water was on to meet the set-point temperature; however, once the cooling water was turned off, it would get to temperature too quickly and had great difficulty modulating quickly enough. The boiler did not go into a slumber phase or shut-off mode. However, this led to visible smoke and ultimately a high emission period.

Overall, the boiler's stack-loss efficiency was relatively consistent throughout all the periods, achieving 74.1% as the lowest during Phase 10 and a high of 86.3% during Phase 9. Emission performance varied much more significantly, with a low of 0.01 lb/MMBtu during Phase 6 and a high of 9.52 lb/MMBtu during Phase 1. The overall particulate emission factor for the entire test period was 0.42 lb/MMBtu. Detailed emission and gaseous values for each phase can be seen in the Appendix.

Test 2 Results

On February 22, 2018, a second varied load profile test was performed. A summary of the testing time, output, moisture content, and overall PM emissions can be found in Table 7 below.

**Table 7: Summary of Test 2 Results**

| Test Date | February 22, 2018 |
|---|---|
| **Testing duration (min)** | 790 |
| **Weight of fuel burned (lb)** | 196.9 |
| **Average moisture content of fuel charge I** and **II (% dry basis)** | 19.7 |
| **Overall emission factor (lb/MMBtu)** | 0.34 |
| **Overall emission rate (g/h)** | 13.56 |
| **Overall emission index (g/kg)** | 2.00 |
| **Overall stack loss efficiency (%)** | 81.0 |

### *Discussion of Test 2 Results*

Prior to the start of the test, the cold boiler was cleaned to remove any coal or ash. A kindling charge was prepped using paper, cardboard, and both small and larger pieces of wood, as described above. However, the kindling this time was laid in a crisscross pattern as opposed to the loading in Test 1 that was all in a parallel direction; the loading can be seen in Figure 32 and Figure 33 below. The boiler was then ignited, and PM and gaseous sampling began. Figure 34 shows the exit of the flue stack into the dilution tunnel during the cold start portion of the burn. Once the boiler's catalyst temperature reached 750°F after 15.3 min, the first fuel charge of 124.04 lb was added, as shown in Figure 35 and Figure 36. Eighty-five percent of the first fuel charge was consumed within 395 min, leaving a bed of hot coals as shown in Figure 37. The second fuel charge of 163.89 lb was then added and sampling resumed (Figure 38 and Figure 39).

**Figure 32: Test 2 cardboard and paper portion of kindling charge.**

**Figure 33: Test 2 kindling charge.**

**Figure 34: Test 2 cold start flue exit.**

**Figure 35: Test 2 first fuel charge.**

**Figure 36: Test 2 loading of first fuel charge.**

**Figure 37: Test 2 coal bed from first fuel charge.**

**Figure 38: Test 2 second fuel charge.**

**Figure 39: Test 2 loading of second fuel charge.**

Light off of the boiler was at 8:22:47 and sampling concluded at 23:13:22, resulting in a total testing time of 890.6 min, with only 730 min of active PM sampling. The total fuel consumed during this test was 188.7 lb. Similar to Test 1, Figure 40 and Figure 41 illustrate the variable burn owed to the testing protocol through the CO and HC trends. Unlike Test 1, the CO concentrations peak much more, almost always with the exception of Phase 9 from 738 to 843 min; they also often exceed the analyzer's limits. No control or operating parameters were changed from Test 1 to Test 2; therefore, it is inconclusive as to why the boiler operated so differently.

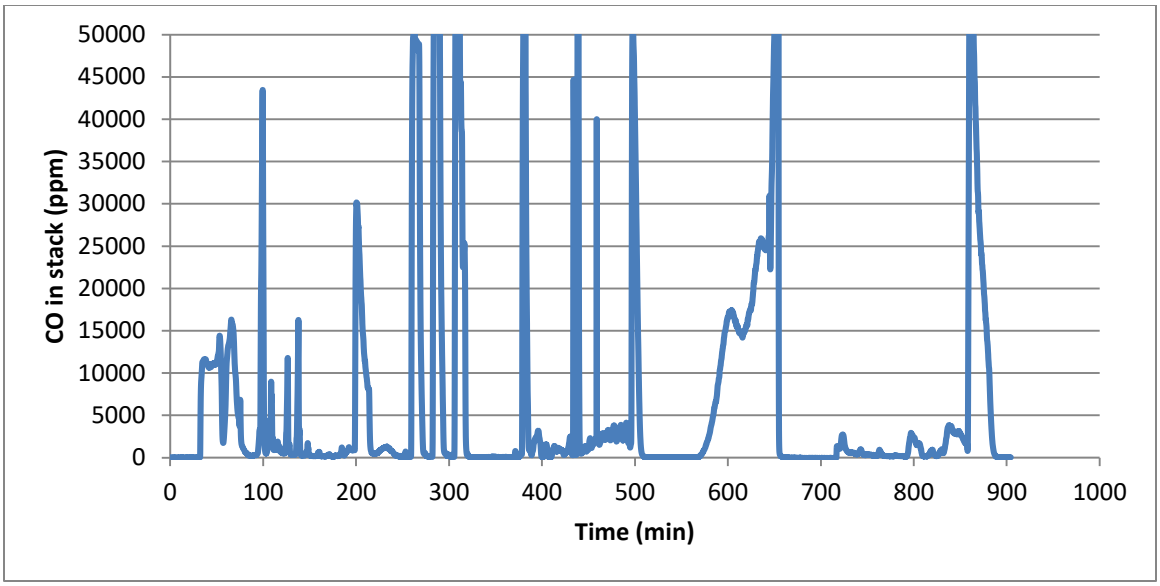


**Figure 40: Test 2 CO trends.**

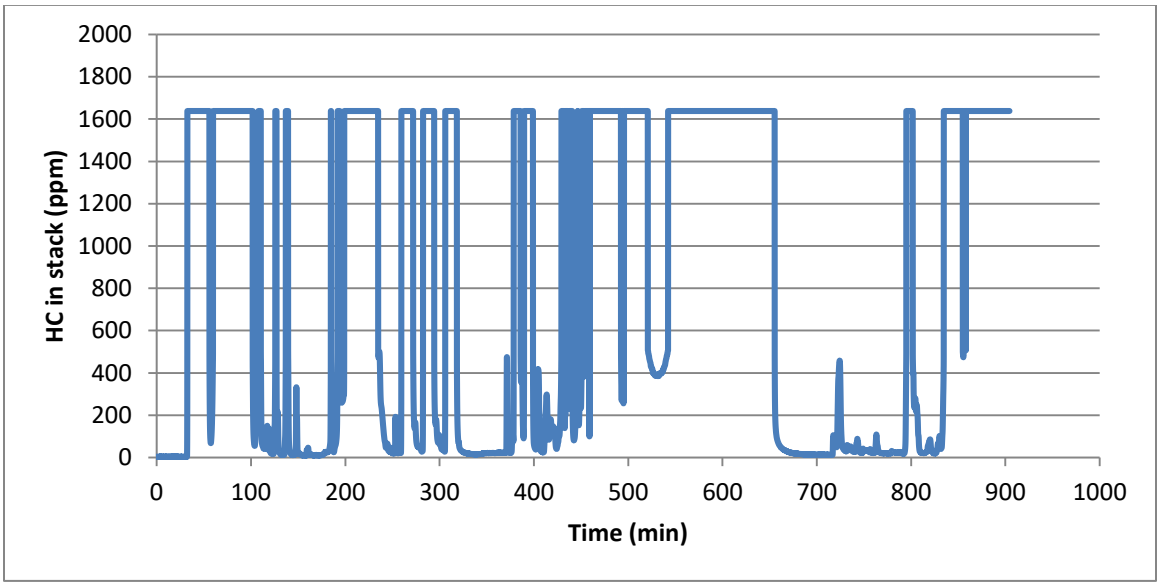


**Figure 41: Test 2 HC trends.**

At around 650 min the boiler's catalyst temperature fell below 500°F and the control display indicated the boiler was in a "cold start" operation. As seen in the figures above, CO and HC values were significantly high, over a range, and there was visible smoke (Figure 42). Figure 43 reflects the effect this had on $CO_2$ values in the stack, indicating a fuel lean situation (maximum $O_2$). While the three-hour minimum for Phase 8 testing had not been met, a decision was made to force the boiler into Phase 9 (a high-burn, Category IV load) early to avoid complete shutdown. At roughly 740 min, the boiler had resumed normal operation (indicating "running") and Phase 9 sampling began. It is important to note that during this period there were some rumbling sounds and puffs of smoke from the stack. Figure 44 shows the boiler's stack temperature trends over the entire sampling period and similar to Test 1, the stack's temperature frequently jumps.

**Figure 42: Test 2 visible smoke seen during Category I operation.**

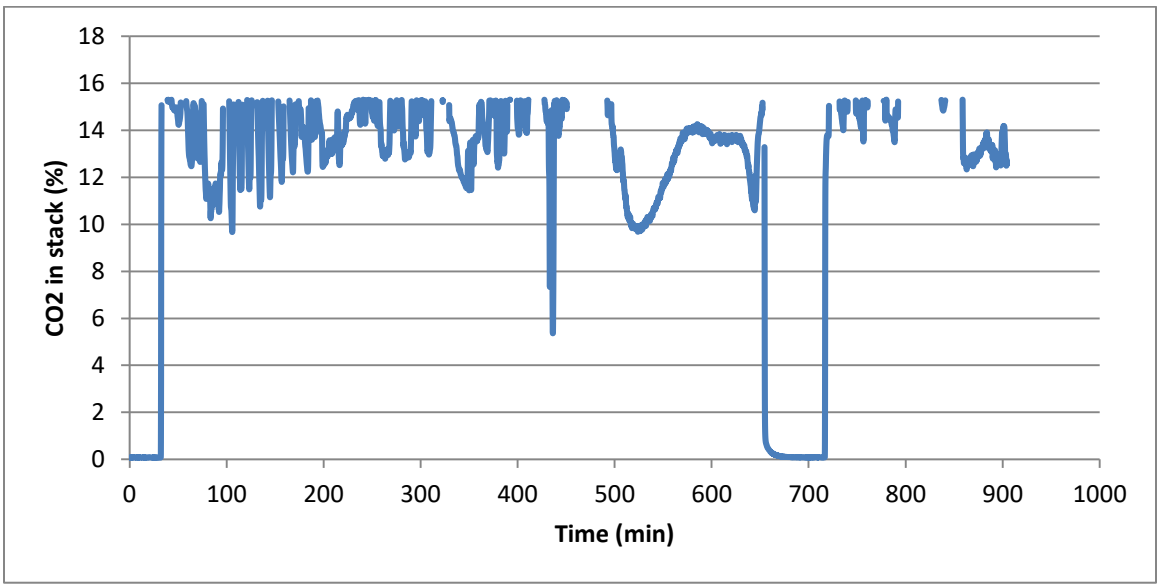


**Figure 43: Test 2 $CO_2$ trends.**

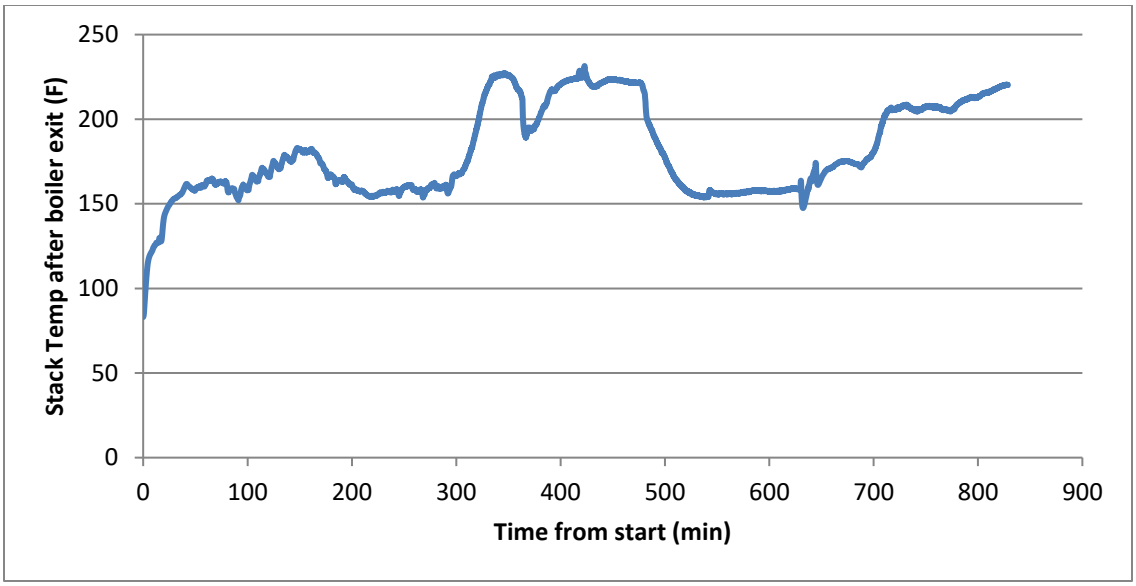


**Figure 44: Test 2 stack temperature.**

While there was a spike in CO during Phase 10, the boiler seemed to have less difficulty in controlling its temperature set-point than in Test 1, yielding better emission values. This time there was no visible smoke either. Overall, the boiler's stack loss efficiency was relatively consistent throughout all the periods, achieving 75.9% as the lowest during Phase 10 and a high of 85.7% during Phase 9. Emissions performance varied much more significantly, with a low of 0.01 lb/MMBtu during Phase 6 and a high of 4.74 lb/MMBtu during Phase 1; almost half of Test 1's values. The overall particulate emission factor for the entire test period was 0.34 lb/MMBtu. Detailed emission and gaseous values for each phase can be seen in the Appendix.

Test 3 Results

On April 2, 2018, the third and final varied load profile test was run. A summary of the testing time, output, moisture content, and overall PM emissions may be found in Table 8 below.

**Table 8: Summary of Test 3 Results**

| Test Date | April 2, 2018 |
|---|---|
| **Testing duration (min)** | 842 |
| **Weight of fuel burned (lb)** | 204.3 |
| **Average moisture content of fuel charge I** and **II (% dry basis)** | 20.0 |
| **Overall emission factor (lb/MMBtu)** | 0.19 |
| **Overall emission rate (g/h)** | 7.60 |
| **Overall emission index (g/kg)** | 1.15 |
| **Overall stack loss efficiency (%)** | 82.8 |

### *Discussion of Test 3 Results*

The kindling charge and loading were similar to that of Test 1, all laid in a parallel direction, which can be seen in Figure 45 and Figure 46 below. The boiler was then ignited, and PM and gaseous sampling began. Figure 47 shows the exit of the flue stack into the dilution tunnel during the cold start portion of the burn. Once the boiler's catalyst temperature reached 750°F after 18.3 min, the first fuel charge of 126.4 lb was added, as shown in Figure 48 and Figure 49. Eighty-five percent of the first fuel charge was consumed within 460 min, leaving a bed of hot coals as shown in Figure 50. The second fuel charge of 150.73 lb was then added, and sampling resumed (Figure 51).

**Figure 45: Test 3 cardboard and paper portion of kindling charge.**

**Figure 46: Test 3 kindling charge.**

**Figure 47: Test 3 cold start flue exit.**

**Figure 48: Test 3 first fuel charge.**

**Figure 49: Test 3 loading of first fuel charge.**

**Figure 50: Test 3 coal bed from first fuel charge.**

**Figure 51: Test 3 loading of second fuel charge.**

Light off of the boiler was at 8:12:45 and sampling concluded at 22:36:10, resulting in a total testing time of 866 min and sampling for 842 of those min. The total fuel consumed during this test was 204.3 lb. As mentioned above, the average output was 45,931 Btu/hr. Figure 52 and Figure 53 show the CO and HC concentrations, respectively, throughout the test. Similar to Test 1 the other tests, there are spikes in CO during the transition to Phase 4 (roughly 300 min), Phase 6 (470 min), and Phase 10 (roughly 850 min), but otherwise relatively steady. Comparable to the two previous tests, the HC analyzer's maximum range was exceeded multiple times.

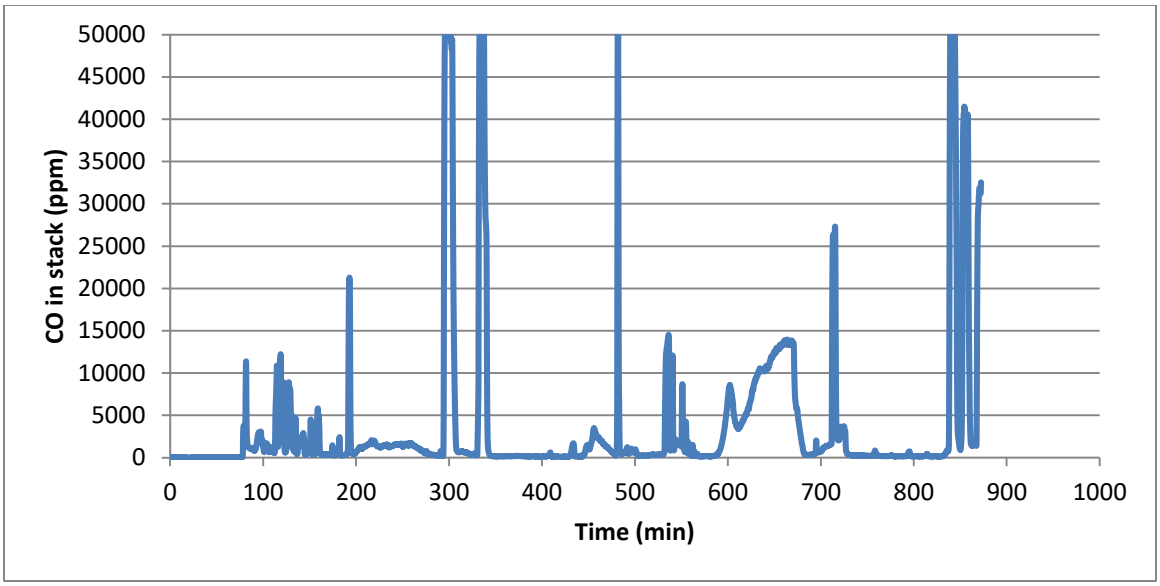


**Figure 52: Test 3 CO trends.**

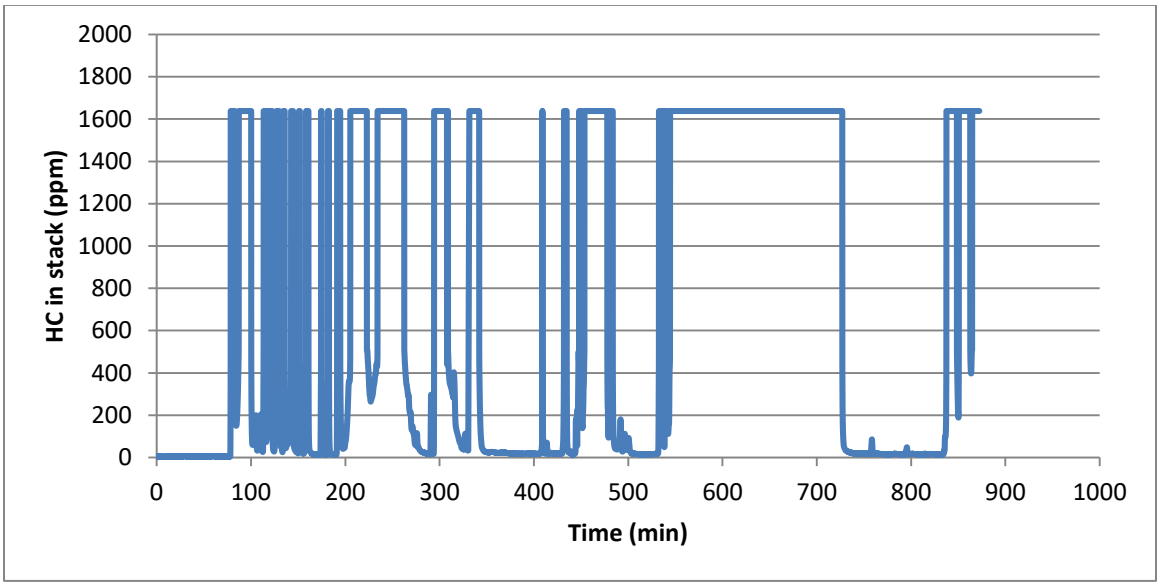


**Figure 53: Test 3 HC trends.**

Figure 54 and Figure 55 show the boiler's stack temperature and $CO_2$ trends, respectively, over the entire sampling period; and similar to Test 1 and 2, the stack temperature and $CO_2$ fluctuate frequently, operating in a fuel-rich/fuel-lean scenario.

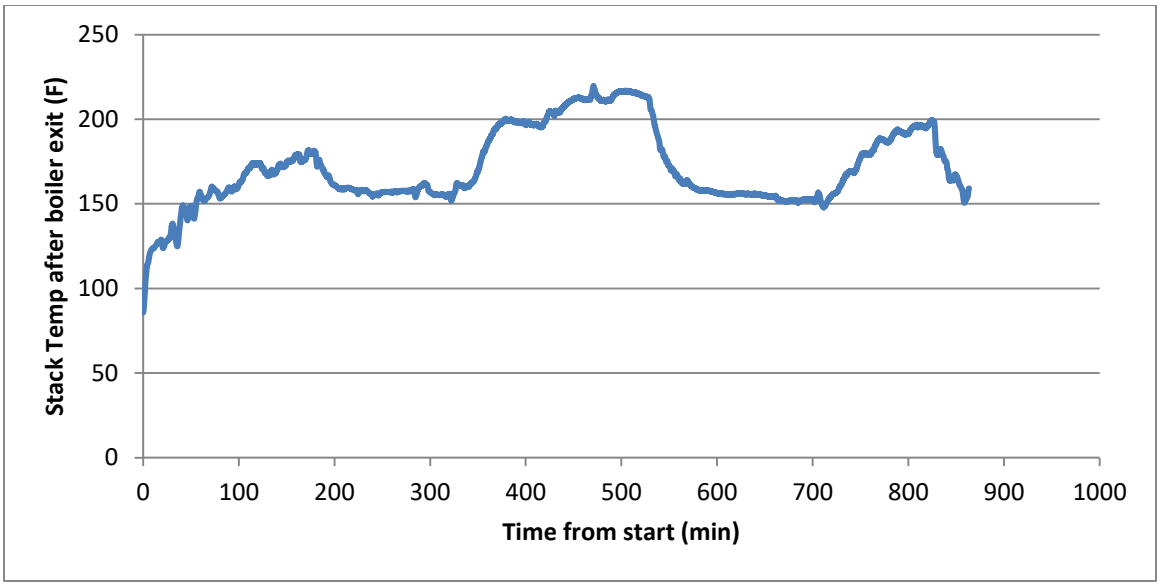


**Figure 54: Test 3 stack temperature.**

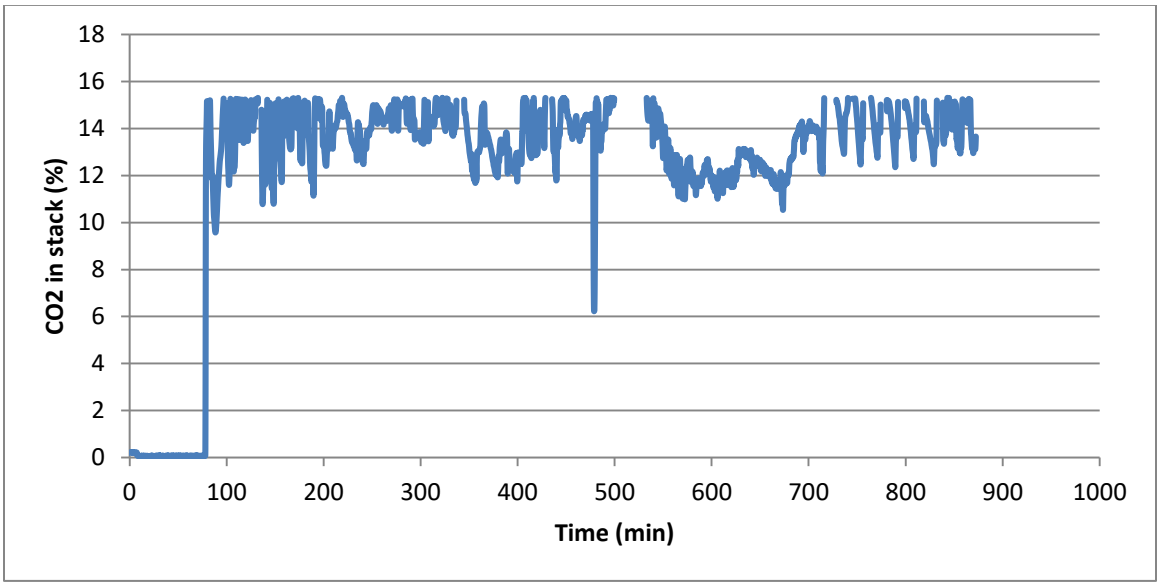


**Figure 55: Test 3 $CO_2$ trends.**

Overall, the boiler's stack loss efficiency was relatively consistent and matched well with Tests 1 and 2. The lowest efficiency was again during Phase 10, with a value of 75.9%; and the high during Phase 9, with a value of 85.7%. Emissions performance varied with a low of 0.02 lb/MMBtu during Phases 6, 7, and 9; and a high of 6.63 lb/MMBtu during Phase 10. The overall particulate emission factor for the entire test period was lower than the previous two tests at 0.19 lb/MMBtu. Detailed emission and gaseous values for each period can be seen in the Appendix.

## Discussion

Category IV Comparison

Preliminary Category IV tests were run as mentioned above to compare EPA accreditation tests with BNL lab results using red oak cribwood and cordwood. Emission output factors, rates, and indices are seen below in Table 9. As shown, EPA emission factor values are nearly double the tests conducted at BNL.

**Table 9: Emission Factors, Rates, and Indices for Category IV Tests**

| Category IV comparison | EPA Reported Value | October 17 (cribwood) | October 31 (cordwood) |
|---|---|---|---|
| Burn duration (min) | 408 | 374 | 420 |
| Emission factor (lb/MMBtu) | 0.08 | 0.04 | 0.05 |
| Emission index (g/kg) | 0.53 | 0.19 | 0.25 |
| Emission rate (g/hr) | 3.60 | 1.80 | 1.95 |

Plots of temperature and emission rates for the cribwood and cordwood testing at BNL are plotted below in Figure 56 and Figure 57. In terms of stack temperature, there is little to no difference in the trend. The cordwood stack temperature is overall slightly lower, and the burn time is longer than the cribwood. This may be due to a decreased burn surface area (cribs are uniformly spaced between pieces, leaving open surface area and air/gas flow paths). In both cases, between 100 and 230 min, the stack temperature fluctuates moderately, but frequently. As discussed above regarding CO and $CO_2$ trends, this is thought to be due to the catalyst firing and not firing, which is discussed in more detail below. Figure 57 shows the emission rate calculated from the TEOM PM concentration (mg/m$^3$) and known dilution tunnel flow (m$^3$/min) for both Category IV tests. Interestingly, the emission rates (g/hr) and factors (lb/MMBtu) are almost identical, which contradicts conventional thinking that movement from cribwood to cordwood will significantly change emission outcomes. In both cases, there is an initial spike when the fuel charges are added to the coal bed, but then remains low throughout the burn, until the tail end.

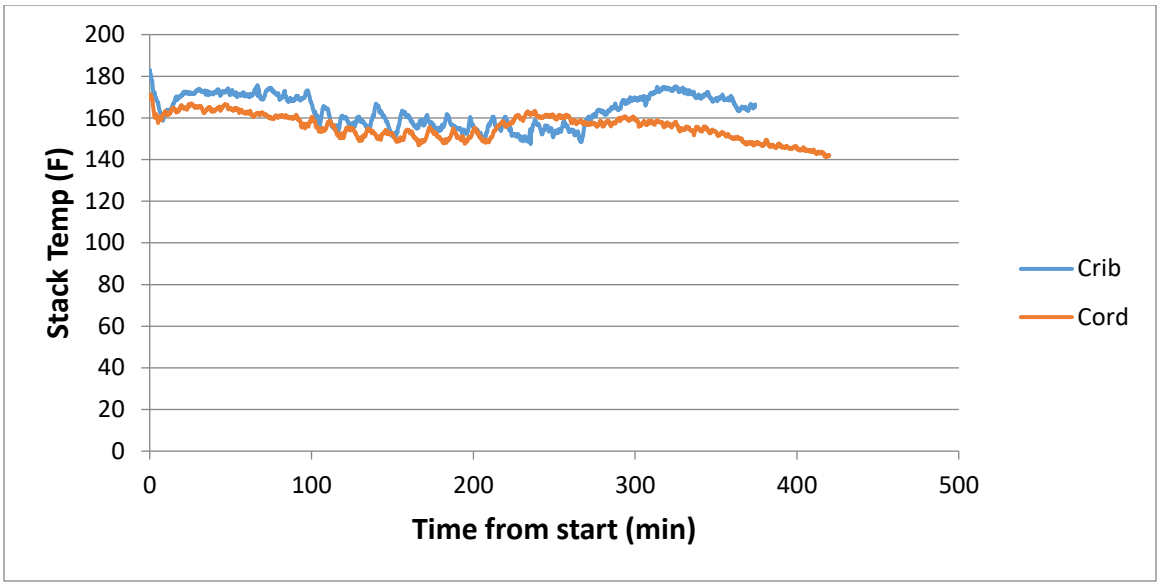


**Figure 56: Stack temperature for Category IV tests.**

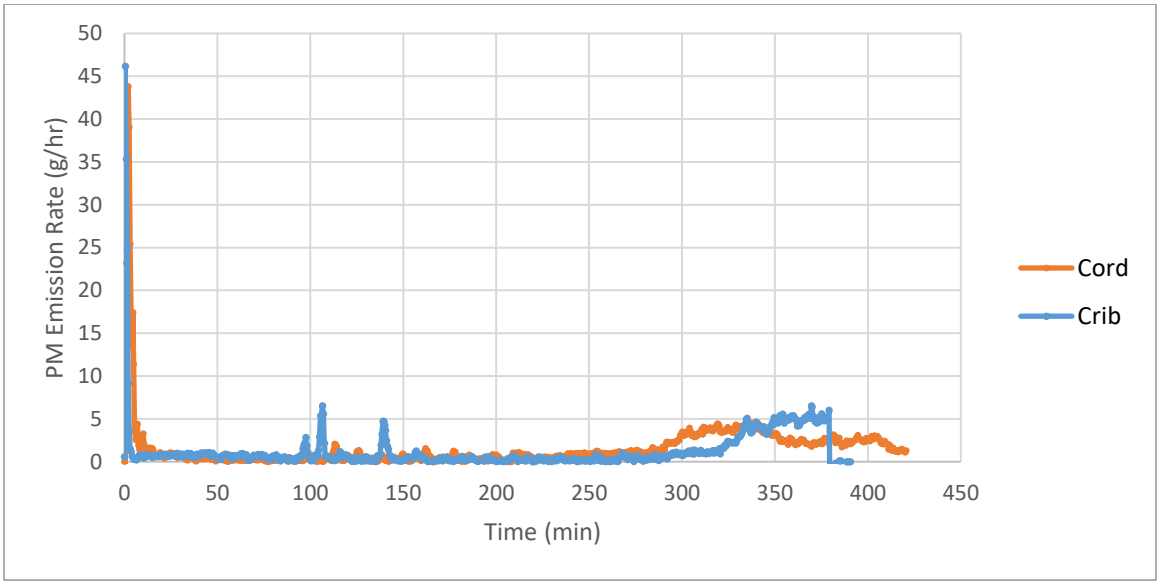


**Figure 57: Emission rates over time for Category IV tests.**

$NO_x$ data were periodically collected throughout the duration of the test as well. Overall, $NO_x$ trends remain consistent and indicate cribwood has a slightly higher $NO_x$ than cordwood. One may expect this since there is no thermal $NO_x$ associated with biomass fuel and $NO_x$ is only a result of the nitrogen and oxygen present in the fuel and combustion air.

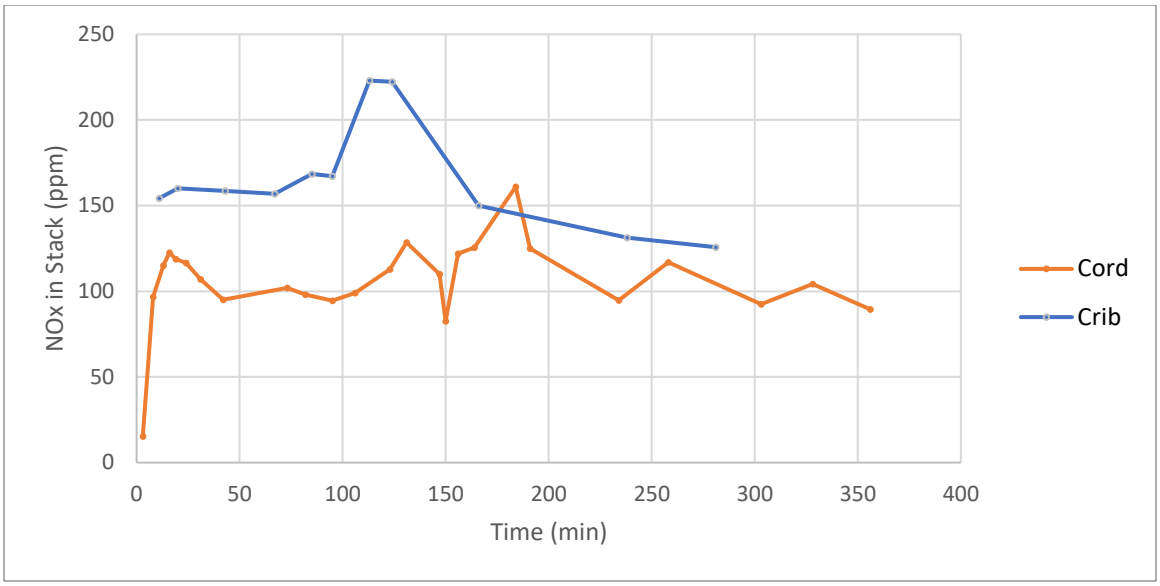


**Figure 58: $NO_x$ emissions over time for Category IV tests.**

Triplicate Tests to the Varied Load Profile Test

All three tests were run to the protocol seen in Table 3 above. The only variation between the three tests were Tests 1 and 3 used a parallel loading of the kindling charge whereas Test 2 used a crisscross pattern, as described above. The data suggest this had little impact on emissions and other parameters (outside the user's control) may be more influential. Tests 1 and 2 had much higher overall emissions than Test 3, and specifically Test 2 had a very different emission profile for Phase 8 than the other two tests. Reasons for the differences in the Phase 8 tests are unknown, other than the catalyst's temperature fell below 750°F, as detailed above. Regardless of the emission differences, all three tests had similar efficiency results. Table 10 details these results below.

**Table 10: Emission Factors and Efficiencies for All Three Tests by Period[a]**

| Phase | Test 1 | | Test 2 | | Test 3 | |
|---|---|---|---|---|---|---|
| | Fuel MC: 18.1% | | Fuel MC: 19.7 | | Fuel MC: 20.0 | |
| | Emission Factor (lb/MMBtu) | Efficiency (%) | Emission Factor (lb/MMBtu) | Efficiency (%) | Emission Factor (lb/MMBtu) | Efficiency (%) |
| Entire Burn | 0.55 | 82.8 | 0.39 | 81.0 | 0.22 | 82.6 |
| 1 | 9.52 | 80.0 | 4.74 | 80.0 | 6.63 | 80.0 |
| 2 | 3.03 | 77.2 | 0.79 | 82.2 | 0.47 | 81.8 |
| 3 | 0.22 | 84.5 | 0.07 | 84.7 | 0.05 | 85.2 |
| 4 | 0.03 | 84.2 | 0.03 | 80.0 | 0.03 | 82.8 |
| 5 | 0.02 | 85.9 | 0.03 | 77.1 | 0.03 | 80.3 |
| 6 | 0.01 | 84.8 | 0.01 | 84.4 | 0.02 | 85.2 |
| 7 | 0.07 | 83.5 | 0.03 | 82.2 | 0.02 | 83.9 |
| 8 | 0.03 | 86.2 | 1.21 | 80.0 | 0.09 | 83.7 |
| 9 | 0.06 | 86.3 | 0.09 | 85.7 | 0.02 | 85.7 |
| 10 | 0.35 | 74.1 | 0.05 | 75.9 | 0.05 | 75.9 |

a. Data are reported from Filter Train A only – filter train sampling the individual periods. The entire burn emission output is calculated by summing the mass collected from each filter during each phase, summing the fuel consumed in each phase, and considering the output of each phase, which is not the result of the cumulative filter sampling the entire duration of the burn continuously (Filter Train B).

The highest PM emission output was seen during Phase 1 and 2, periods not accounted for in current test methods. The first, second, and third tests indicated the emission output (lb/MMBtu) for the boiler during Phase 1 were 31, 14, and 34 times higher than the average emission output value for each test, respectively. Similarly, the emission output during Phase 2 was 7, 2, and 2 times higher than the average output during the first, second, and third tests, respectively. Figure 59 depicts these results (notations of A and B refer to the integrated sampling train and the train used to sample the individual phases, respectively). Table 11 below shows the percentage of mass collected for each period in comparison to the amount of time spent in the period, indicating total mass collected is not proportional to time.

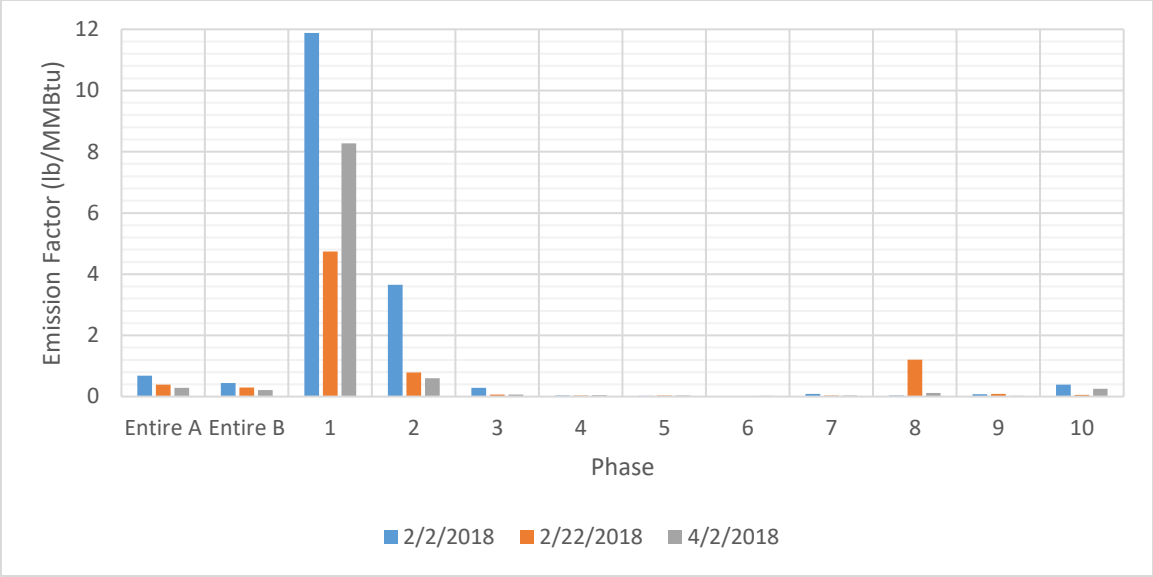


**Figure 59: Emission factors for Tests 1, 2, and 3 for each period.**

**Table 11: Percent of Mass Collected and Time Spent in Each Operation Period**

| **Test** | **1** | | **2** | | **3** | |
|---|---|---|---|---|---|---|
| **Date** | **2/2/2018** | | **2/22/2018** | | **4/2/2018** | |
| **Period** | **% of Total Mass Collected** | **% of Total Time** | **% of Total Mass Collected** | **% of Total Time** | **% of Total Mass Collected** | **% of Total Time** |
| 1 | 32% | 2% | 30% | 2% | 69% | 2% |
| 2 | 53% | 12% | 14% | 7% | 14% | 9% |
| 3 | 6% | 9% | 2% | 8% | 3% | 8% |
| 4 | 1% | 13% | 1% | 19% | 2% | 18% |
| 5 | 0% | 12% | 1% | 9% | 1% | 11% |
| 6 | 0% | 7% | 0% | 6% | 1% | 6% |
| 7 | 0% | 2% | 1% | 6% | 1% | 6% |
| 8 | 1% | 25% | 45% | 21% | 5% | 21% |
| 9 | 2% | 11% | 5% | 13% | 1% | 11% |
| 10 | 6% | 8% | 1% | 8% | 1% | 7% |

Figure 60 shows the percent of PM collected in each operation phase of the boiler in comparison to the total amount collected. The most PM was collected during Phase 2, followed by Phase 1 and Phase 10. Figure 61 on the other hand shows the amount of testing time the boiler spent in each period, illustrating very little time was actually in Phase 1 and Phase 2, yet these phases were the largest contributors to the boiler's PM mass collected.

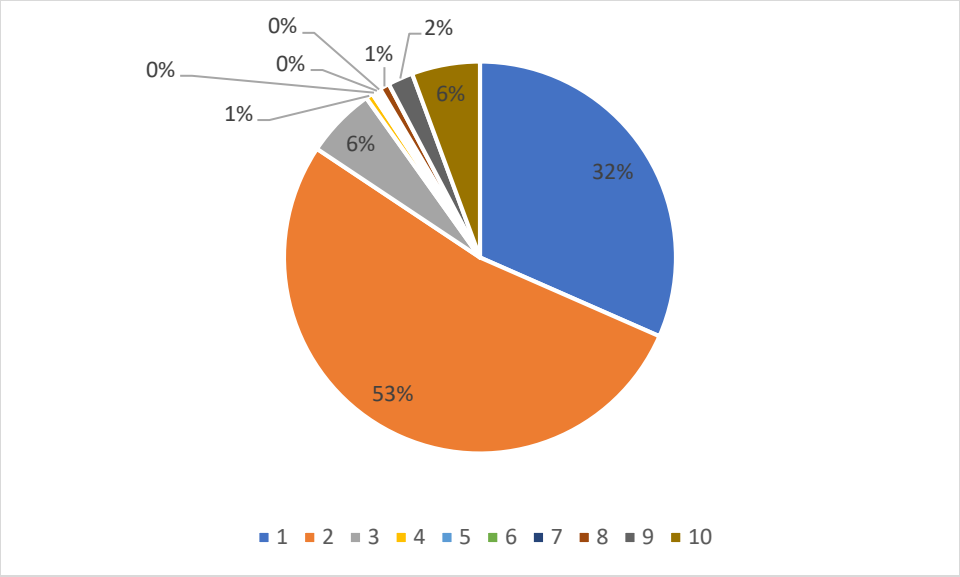


**Figure 60: Distribution by phase of total mass collected during Test 1.**

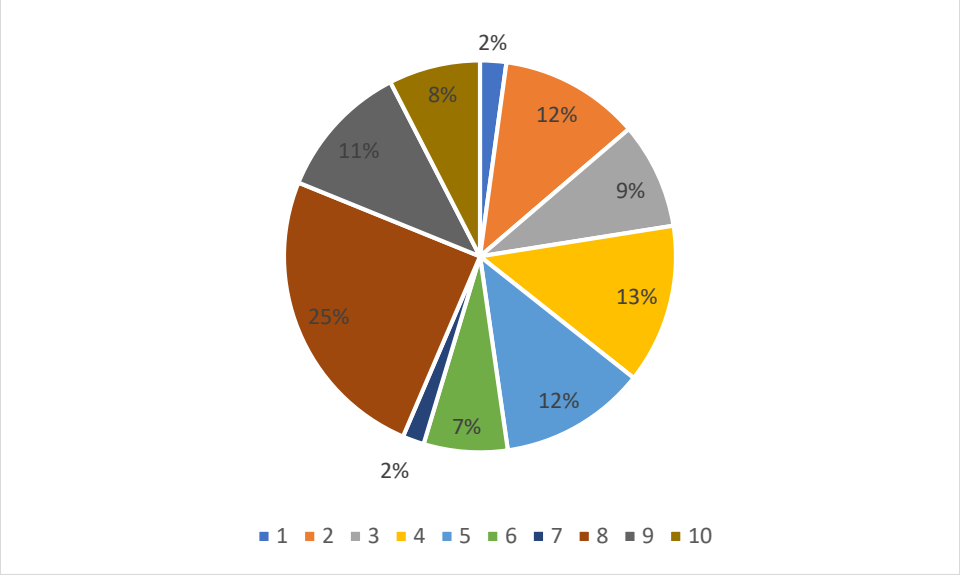


**Figure 61: Percent of time spent in each boiler operating phase during Test 1.**

Similar to Figure 60 above, the second test (Figure 62) shows a large percent of PM collected during Phase 1 and 2, but now also during Phase 8. Figure 63 looks similar to Figure 61, illustrating again very little testing time was actually in Phase 1 and 2, and while almost half of the mass collected was from Phase 8, where less than a quarter of the testing time was spent.

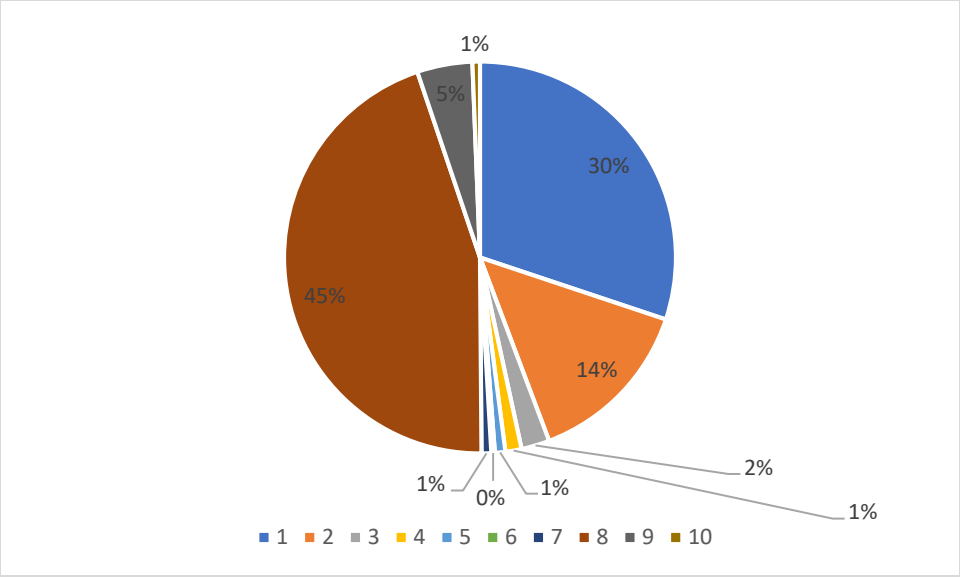


**Figure 62: Distribution by phase of total mass collected during Test 2.**

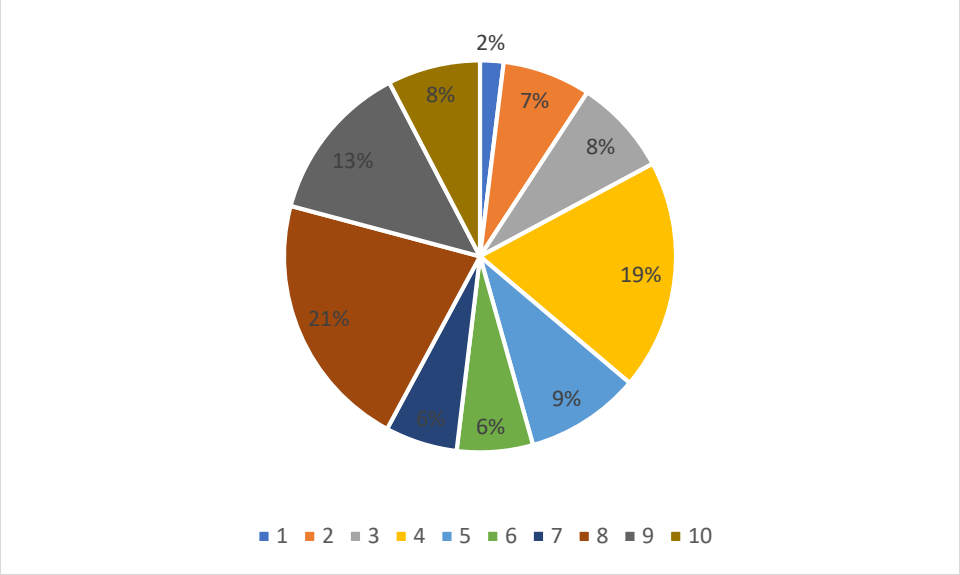


**Figure 63: Percent of time spent in each boiler operating phase during Test 2.**

Very similar to Figure 60 and Figure 62 above, the third test shows a large percent of PM collected during Phase 1 and Phase 2 (Figure 64). Figure 65 also resembles Test 1 and 2 in regard to the testing time spent in each period.

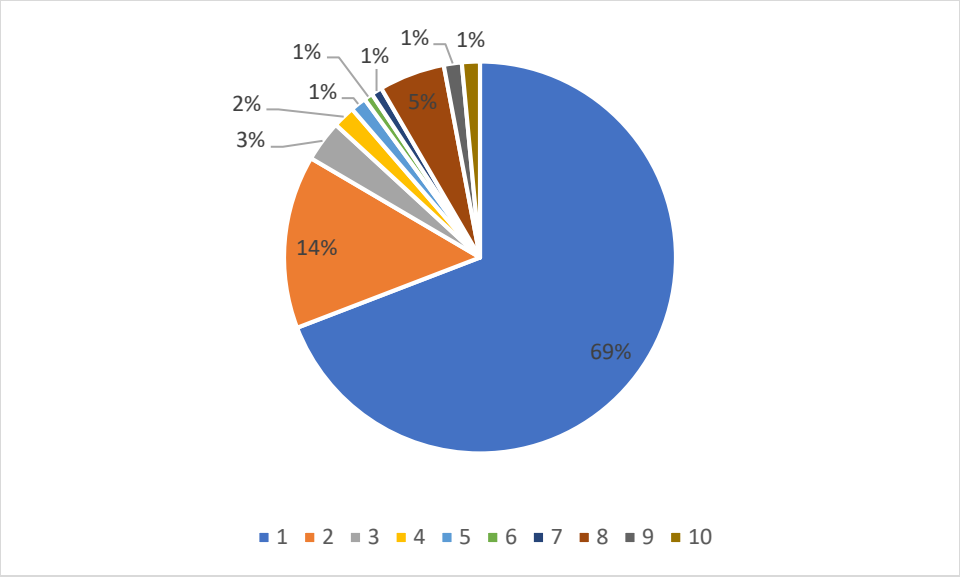


**Figure 64: Distribution by phase of total mass collected during Test 3.**

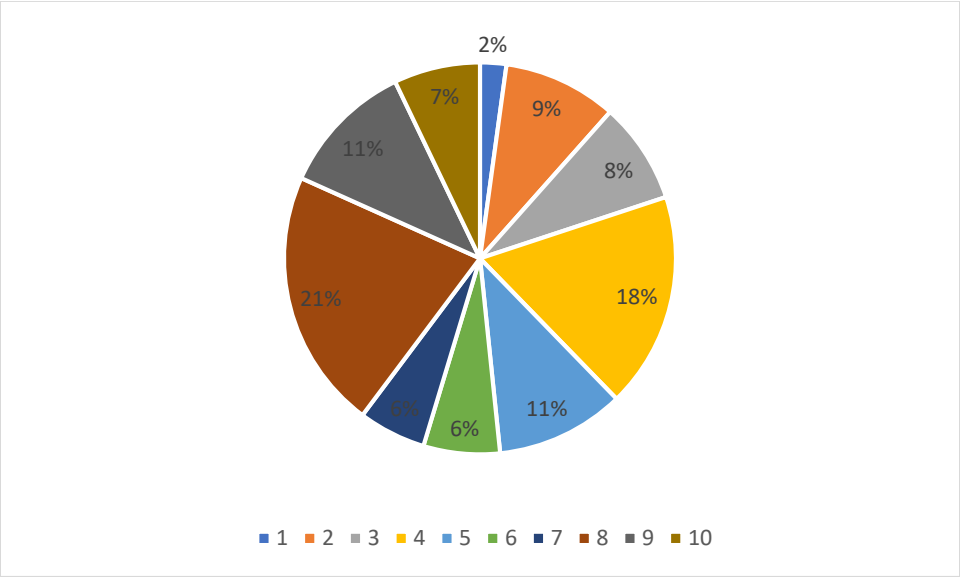


**Figure 65: Percent of time spent in each boiler operating phase during Test 3.**

In Figure 66 and Figure 67, the boilers operating temperatures (flue gas, supply, and return) also match reasonably well, with only a slight lag in time from one to the other. With this, it is obvious the varied-load testing protocol challenges the unit with a variety of different load conditions that are easily repeatable. However, as shown above in some of the figures, the boiler's emission profiles are not always as repeatable.

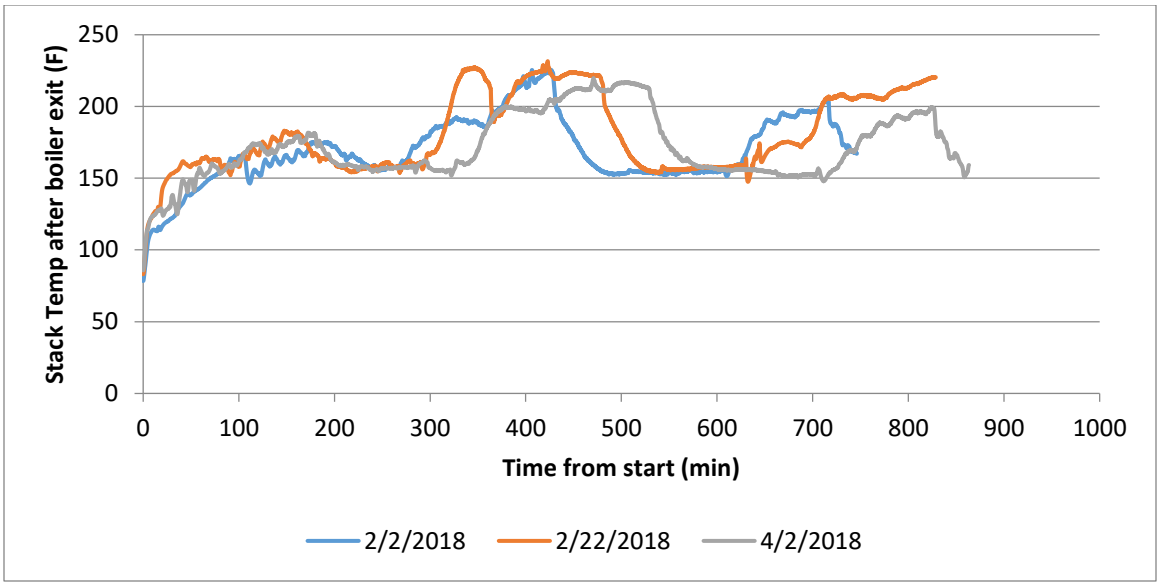


**Figure 66: Flue gas temperature comparison of all three tests.**

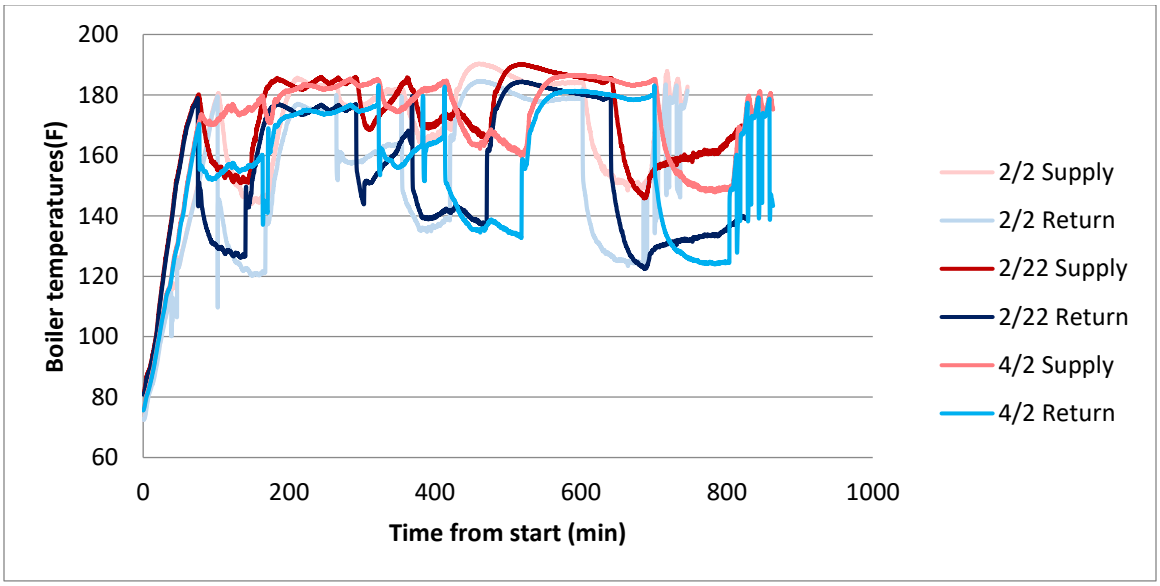


**Figure 67: Boiler supply and return temperatures for all three tests.**

Under some operating conditions, a specific hydronic heater was observed to undergo hunting (oscillating or unsteady combustion conditions represented by changes in oxygen). Periodically the air control system would drive the unit into an apparent near-zero air flow. The system would remain in this condition for a short period and then air flow would again resume. During the air shut-off periods, flue gas $CO_2$ and CO became extremely high but the flow of flue gas also essentially stopped, so there is minimal emission impact. In discussions with the manufacturer, we

learned this is an integral part of the control strategy and the catalyst temperature is the factor driving this. However, details are considered proprietary. This hunting behavior is seen for example in Figure 68.

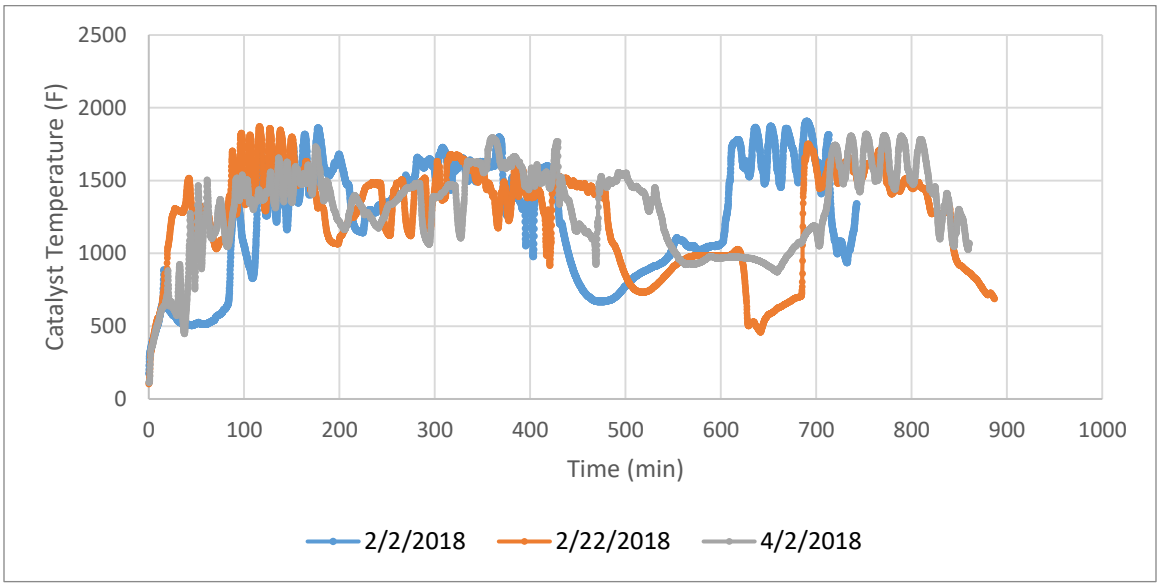


**Figure 68: Catalyst temperature comparison of all three tests.**

For all tests, the efficiency was determined using a stack-loss method instead of an output/input method. The test arrangement was planned to enable efficiency to be determined with both methods. With the stack-loss method, the energy discarded out the flue is determined based on flue gas temperature and composition measurements, fuel moisture composition, and assumed ultimate analysis of the dry fuel. The flue losses include flue gas sensible heat, latent heat in the flue gas water vapor, and chemical energy in the flue gas CO. This method is commonly used (e.g., in standards such as CSA B415.1-10) [3]. The output/input method requires direct measurement of the energy output to the heat exchanger, accounting for changes in the boiler temperature between the start and end of the test. The process, however, is very time consuming and potentially inaccurate for all the sampling periods associated with this protocol. Part of the accuracy question relates to the determination of the boiler temperature at the start and end of each test phase. Averages of the boiler return and supply temperatures are used to determine an average boiler temperature. However, with the large volume of water in the boiler, there can be a significant stratification and, depending on the temperature profile in the boiler, the average of these two temperatures may not accurately reflect the mean temperature. In long test runs the impact of this becomes small, but with short test phases it is a concern. For this reason, a decision was made to proceed with the analysis based only on the stack-loss method.

Figure 69 through Figure 74 take a further look at each of the tests by overlaying the emission rate (g/hr) calculated from the TEOM data, the stack CO concentration (ppm), and the stack

temperature (°F). Phases 1 and 2 dominate the emission rate in comparison to all other phases, muting any later emission trends. Therefore, Figure 70, Figure 72, and Figure 74 zoom in on different parts of the burn to get a closer look at any foreseeable trends in the data (emission rates are also multiplied by 10). In all cases, there is a trend between the stack CO concentrations and the PM emission rates. There also seems to be a slight trend of an increase in CO (and thereby PM) when the stack temperature increases, such as after Phase 6 (the addition of the second fuel charge, roughly 400 min in). Surprisingly, there is an increase in CO concentrations during Phase 9 (roughly at 700 min). With the exception of Test 2, the boiler seems to have its best performance in terms of PM emission rates and CO concentrations during Phase 8. During the second test, on February 22, 2018, the catalyst temperature fell below 750°F, causing a spike in emissions. No user involvement or changes to the boiler's control caused this to occur.

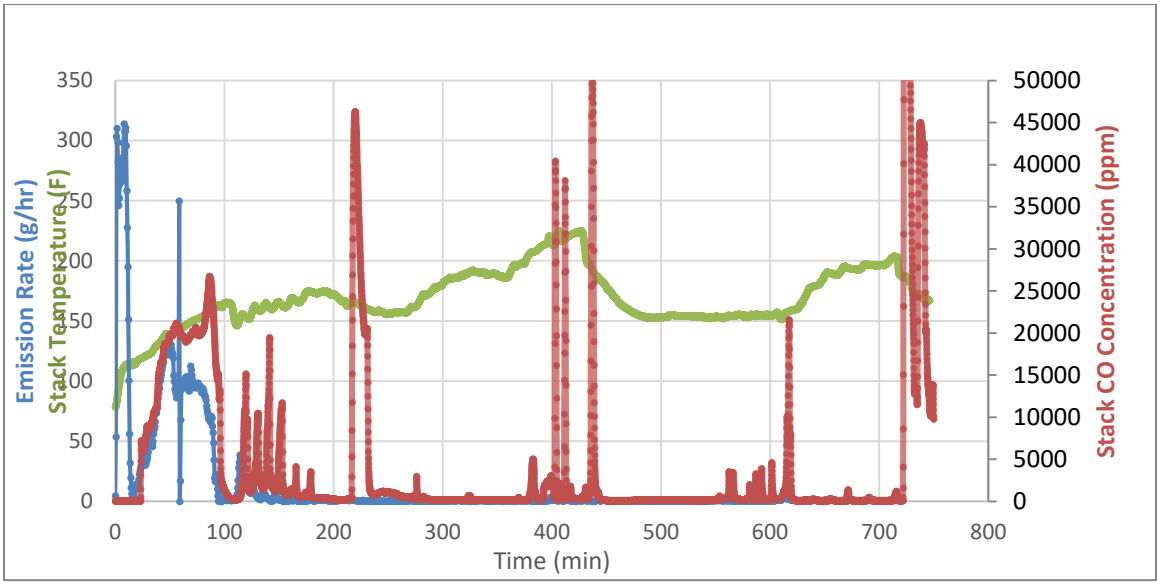


**Figure 69: Comparison of PM and CO emissions with stack temperature for the entire Test 1.**

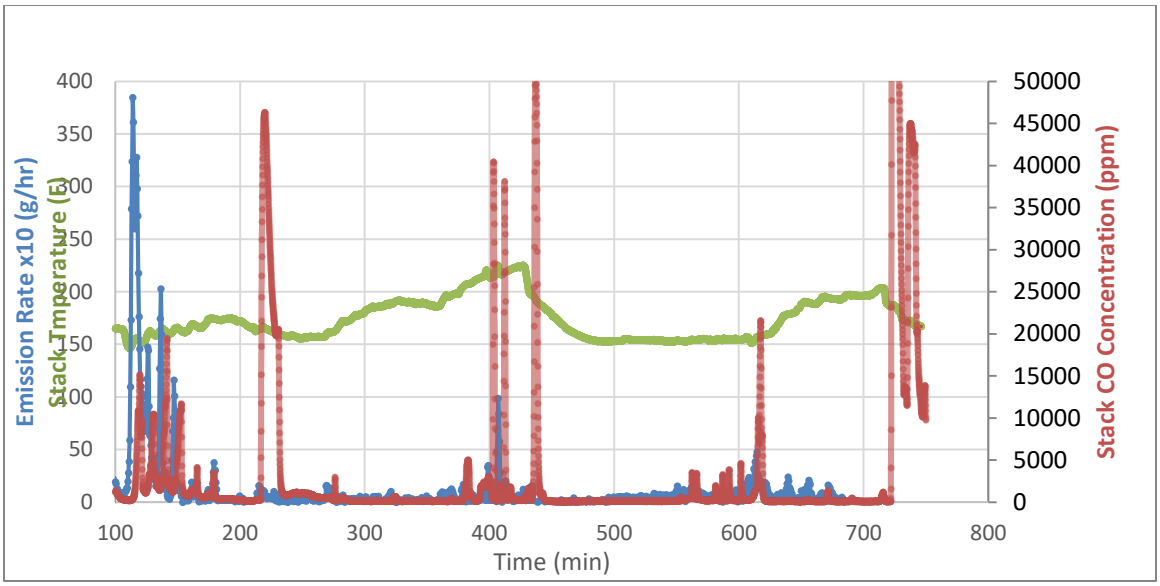


**Figure 70: Comparison of PM (x10) and CO emissions with stack temperature after cold start and ramp-up periods for Test 1.**

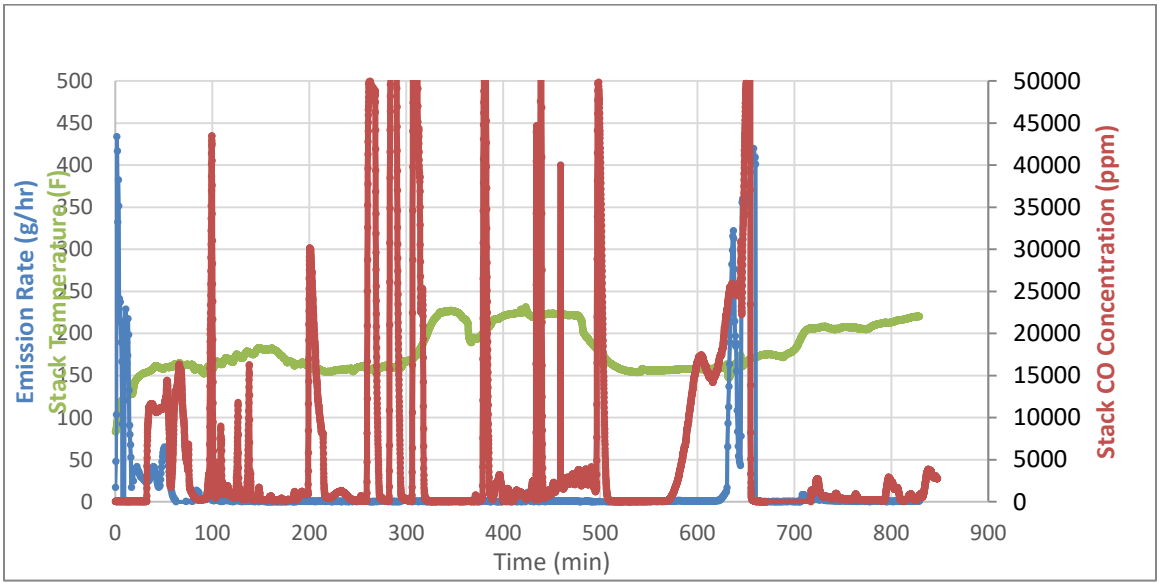


**Figure 71: Comparison of PM and CO emissions with stack temperature for the entire Test 2.**

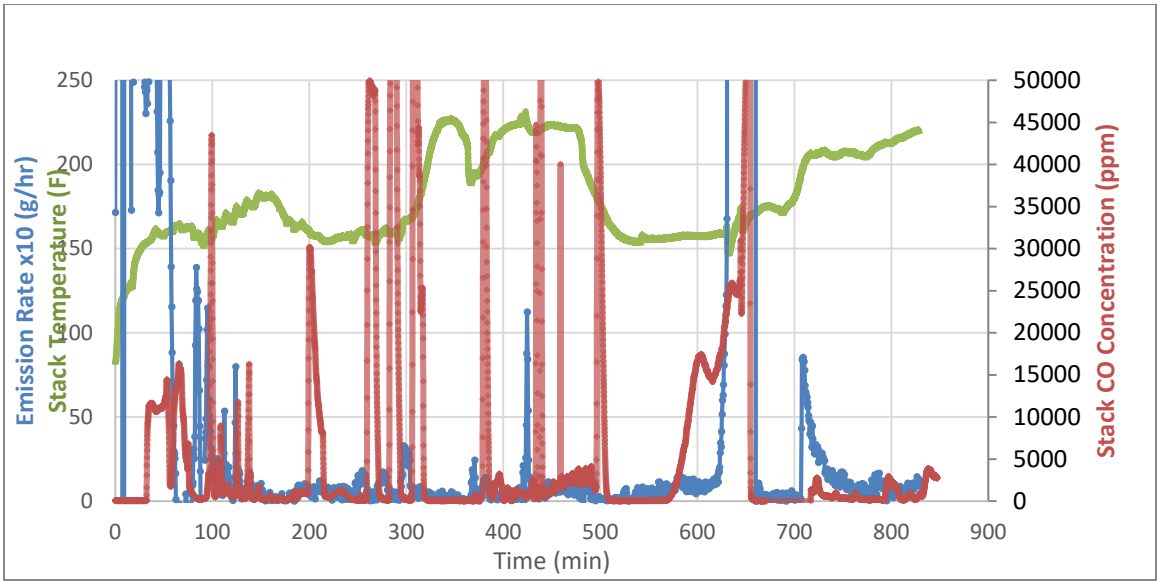


**Figure 72: Zoomed in comparison of PM (x10) and CO emissions with stack temperature for Test 2.**

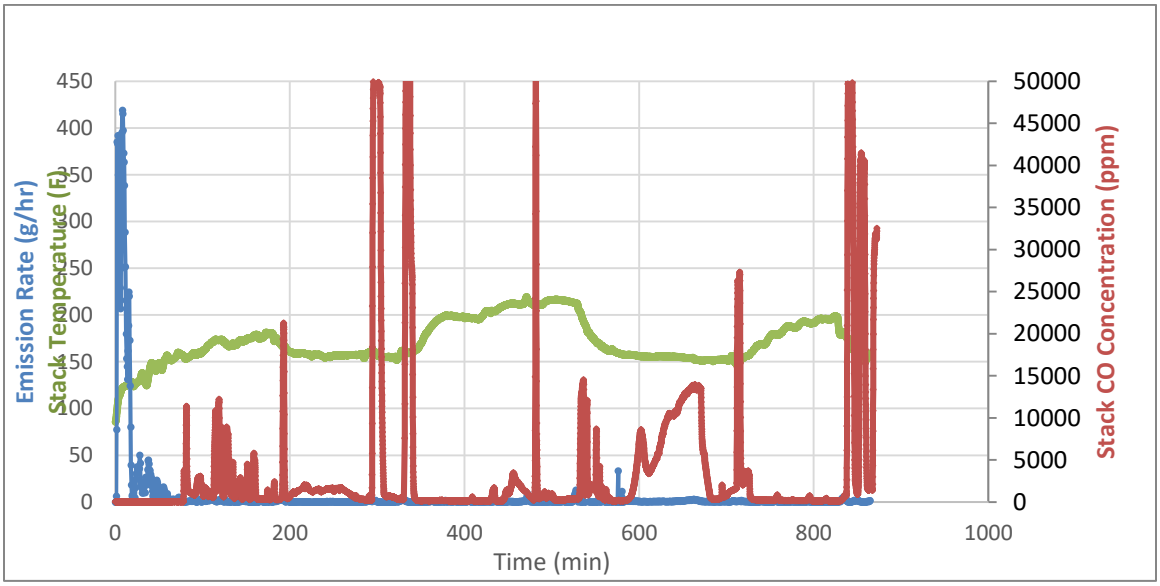


**Figure 73: Comparison of PM and CO emissions with stack temperature for the entire Test 3.**

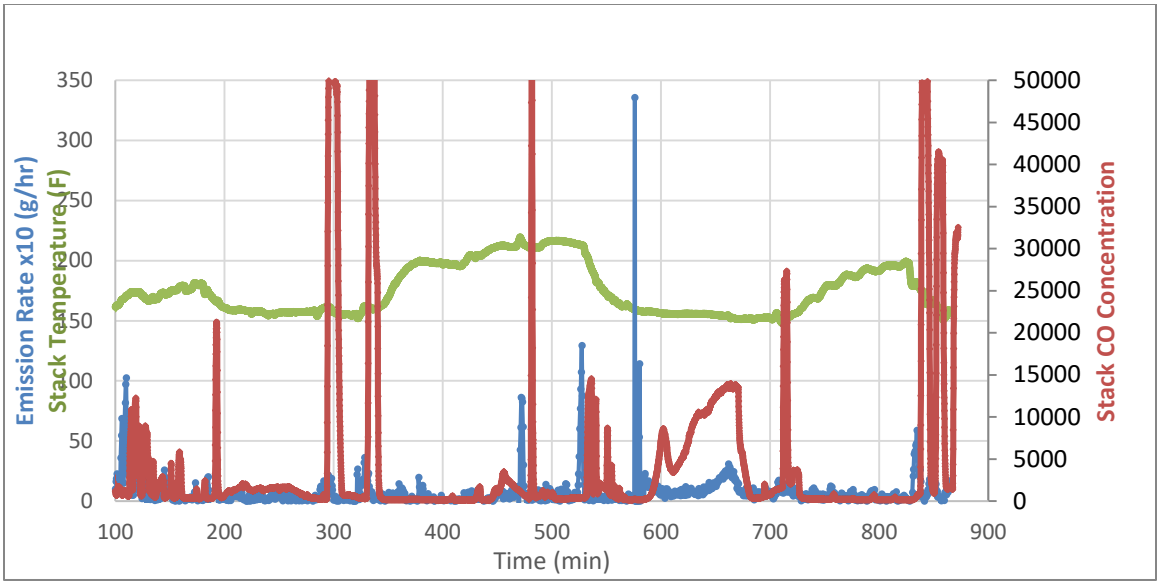


**Figure 74: Comparison of PM (x10) and CO emissions with stack temperature after cold start and ramp-up periods for Test 3.**

For real-time particulate emission rate measurements, the project team used a TEOM. With this device, particulates are captured on a TX40 filter mounted on an oscillating element and, as the mass of particles on the element increases, the natural frequency of oscillation changes and is used to determine the collected mass. TEOM-type devices allow for real-time emission profiles that can be important to states, stakeholders, and policymakers in terms of short-term emission exposure. From another point of view, the real-time information shows a detailed look as to how the unit is operating, collecting a measurement of PM concentration (mg/m$^3$) every 30 sec as opposed to a PM concentration over the entire duration of the burn, or even for the duration of individual periods as in gravimetric filter measurements. Specifically, for this project a Thermo TEOM (Model 1400AB) was used. Using the known dilution tunnel flow rate, an emission rate (g/hr) can be calculated from the PM concentration provided by the TEOM. A plot of the entire burn duration using the TEOM and calculating an emission rate may be seen in Figure 75 below. One advantage of the TEOM is the real-time data provided. Therefore, high emission periods are no longer masked by clean burn periods as is done with a cumulative filter collecting PM over a period with only a known mass difference and total volume sampled.

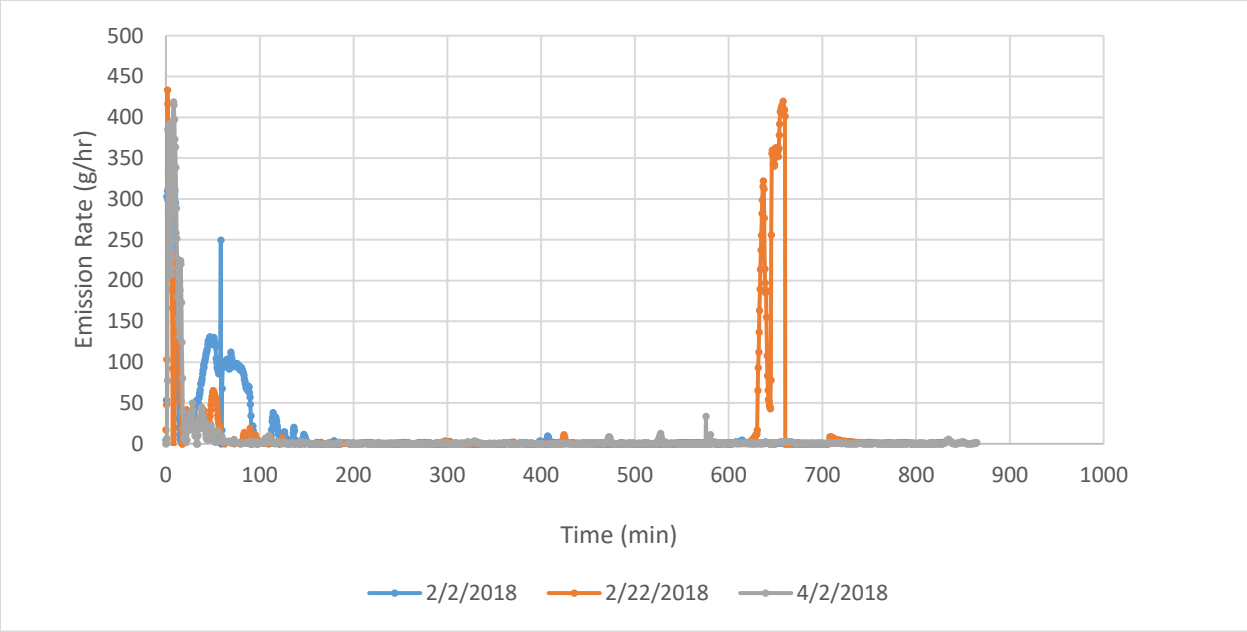


**Figure 75: Comparison of PM concentration over entire testing periods for all tests using TEOM.**

To better understand the correlation between all three tests, Figure 76 through Figure 85 show each individual period. There is good agreement in most of the periods, with peaks of high and low PM concentrations overlapping each other or following similar trends min apart. In some cases, such as Figure 77 and Figure 78, there is no obvious reason for the greater PM emission rate on the first run (February 2, 2018) vs the other two runs (at min 41.5 there was a filter change for Test 1 and the same at minute 12 for Test 3, causing for a lapse of data shown in the graph). However, during the second run on February 22, 2018, as mentioned above, there was some difficulty during Phase 8 with the catalyst temperature falling below 750°F, also as mentioned above. While there was no explanation in terms of the operating condition of the boiler, the PM emission rate trends gathered from the TEOM display a significant increase compared to the first and third tests (Figure 83), matching the CO and HC trends displayed above.

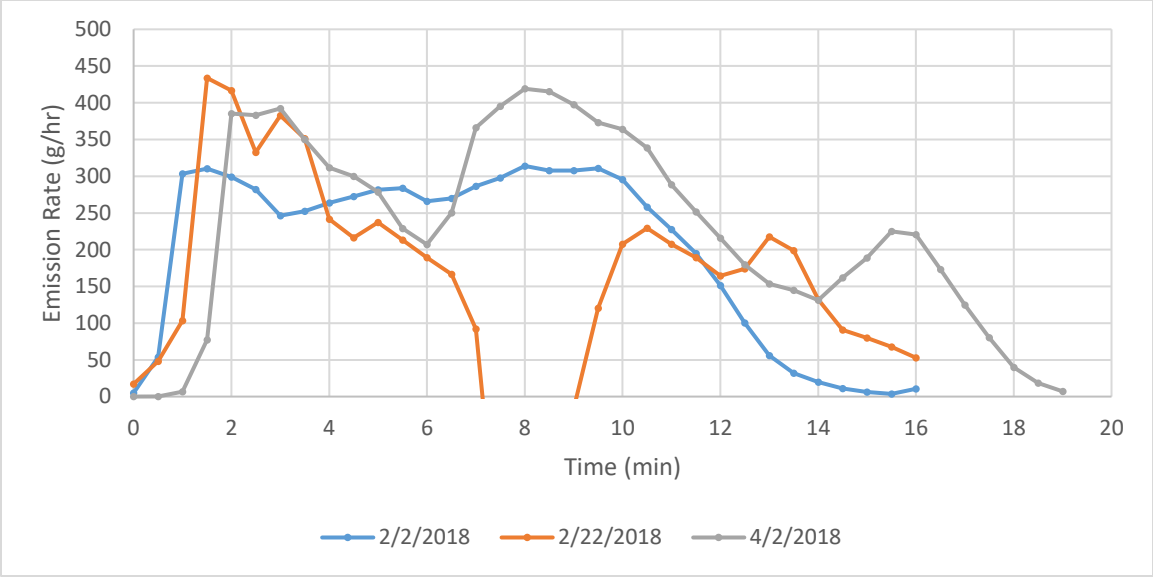


**Figure 76: Comparison of cold start PM emission rates for all tests using the TEOM.**

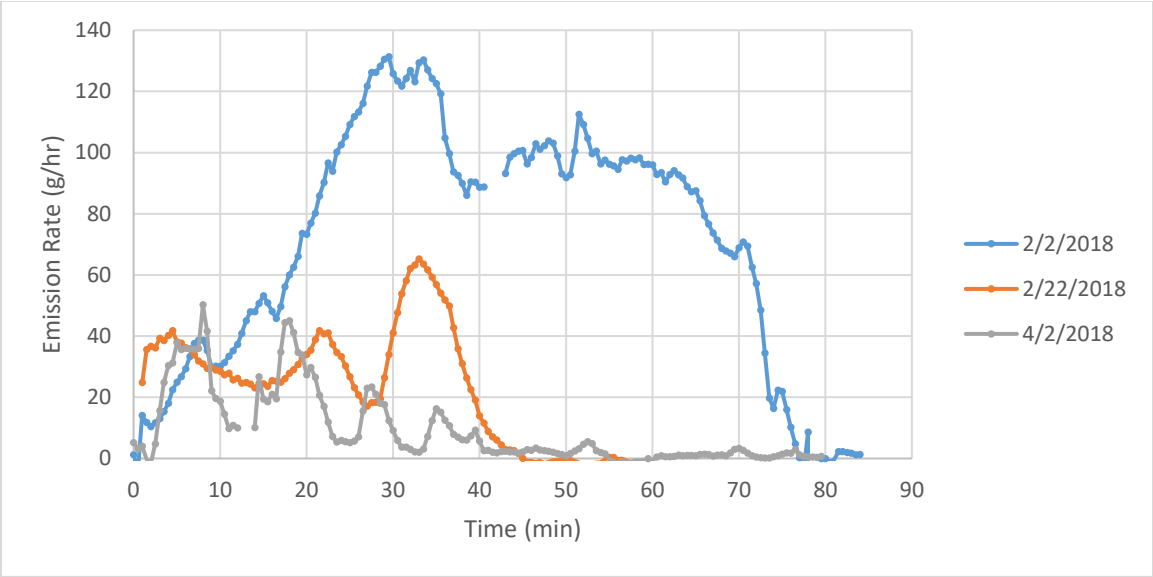


**Figure 77: Comparison of ramp-up PM emission rates for all tests using TEOM.**

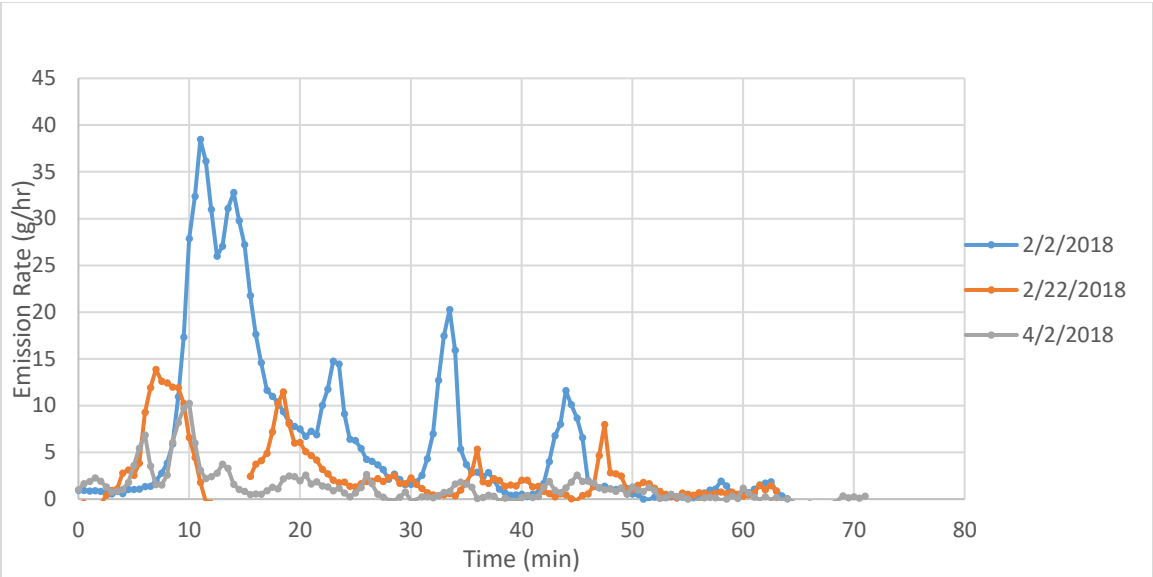


**Figure 78: Comparison of first Category IV PM emission rates for all tests using TEOM.**

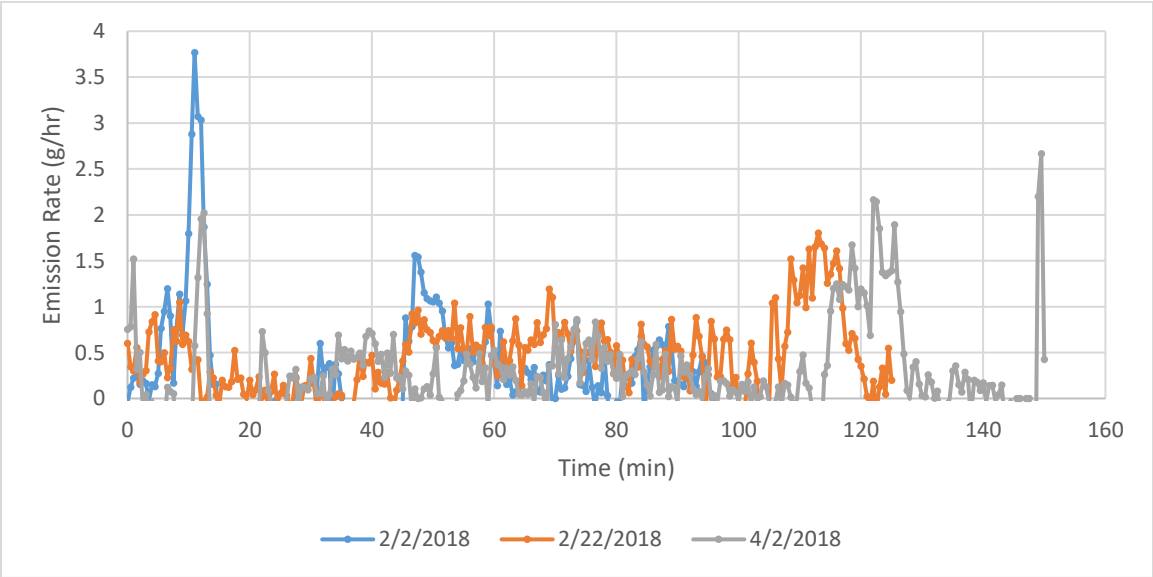


**Figure 79: Comparison of Category II PM emission rates for all tests using TEOM.**

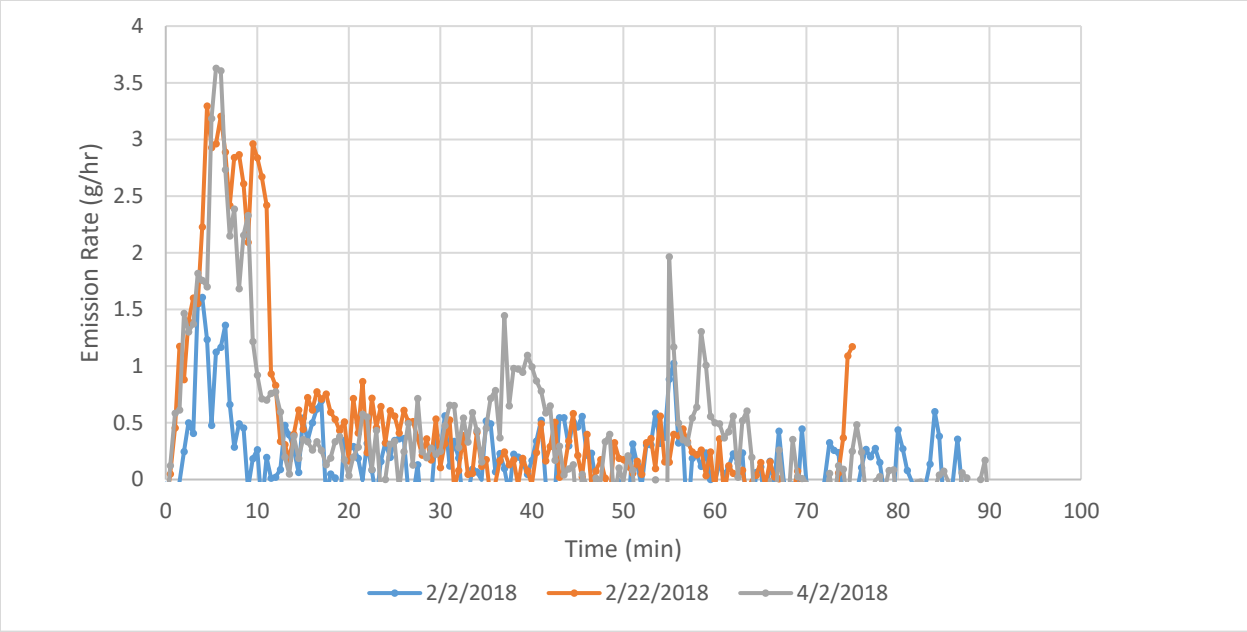


**Figure 80: Comparison of Category III PM emission rates for all tests using TEOM.**

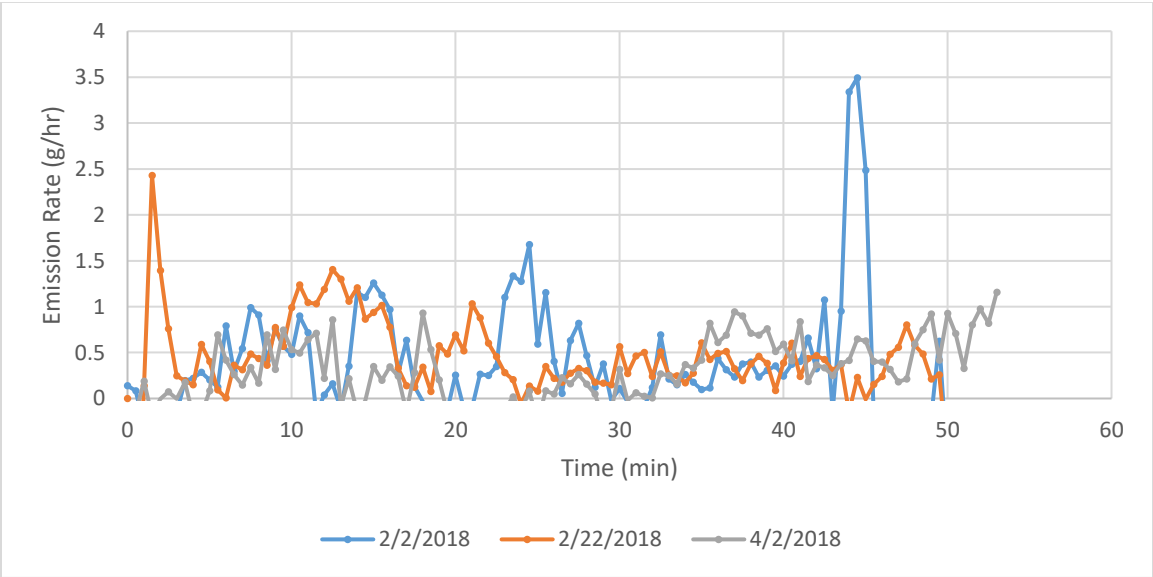


**Figure 81: Comparison of burn-out PM emission rates for all tests using TEOM.**

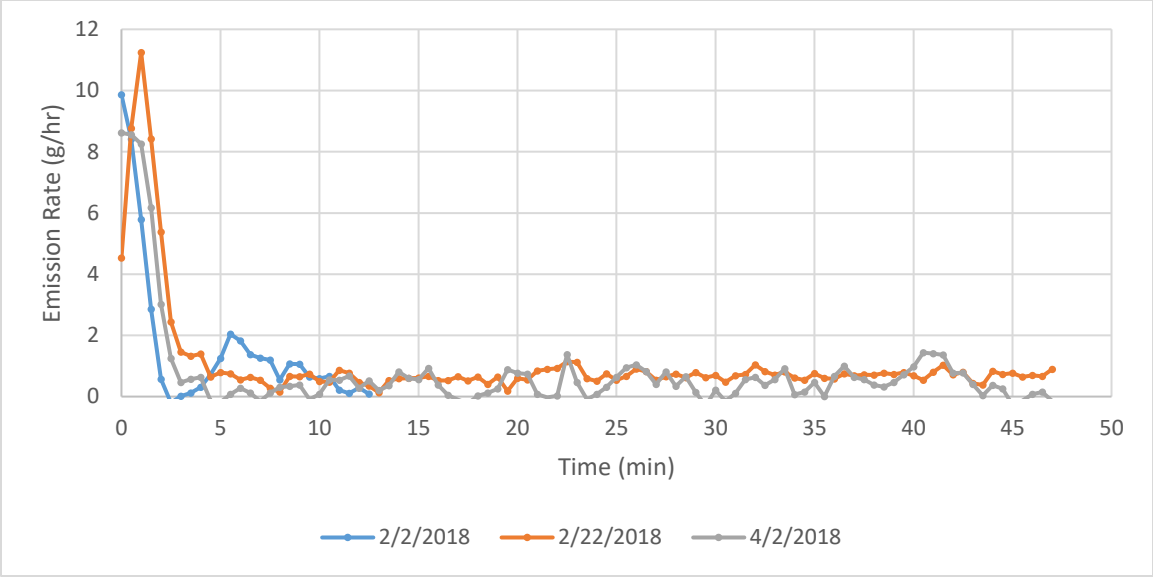


**Figure 82: Comparison of reload PM emission rates for all tests using TEOM.**

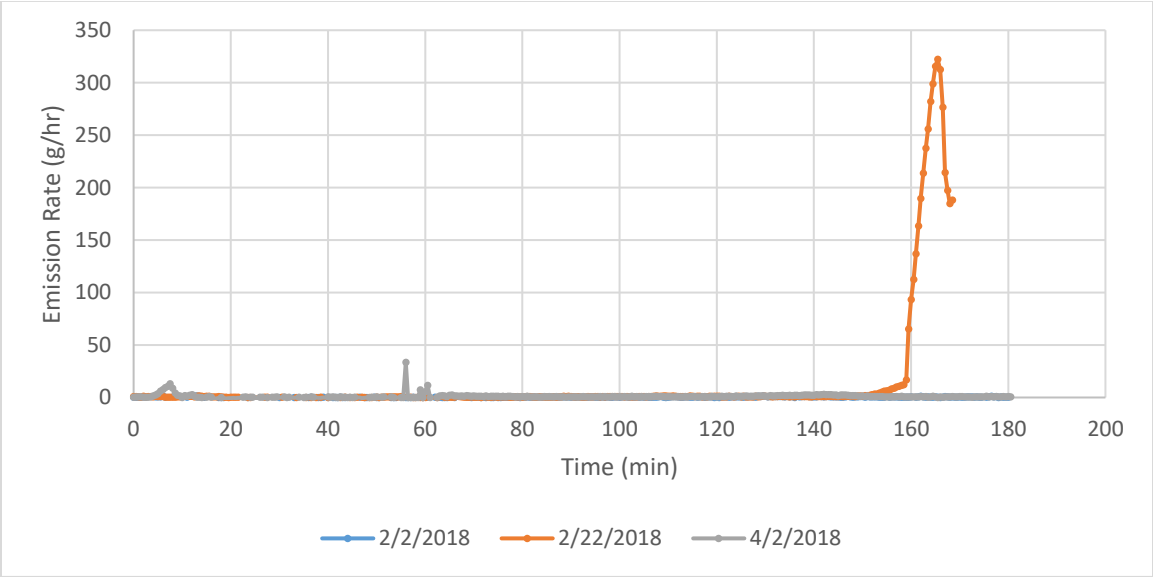


**Figure 83: Comparison of Category I PM emission rates for all tests using TEOM.**

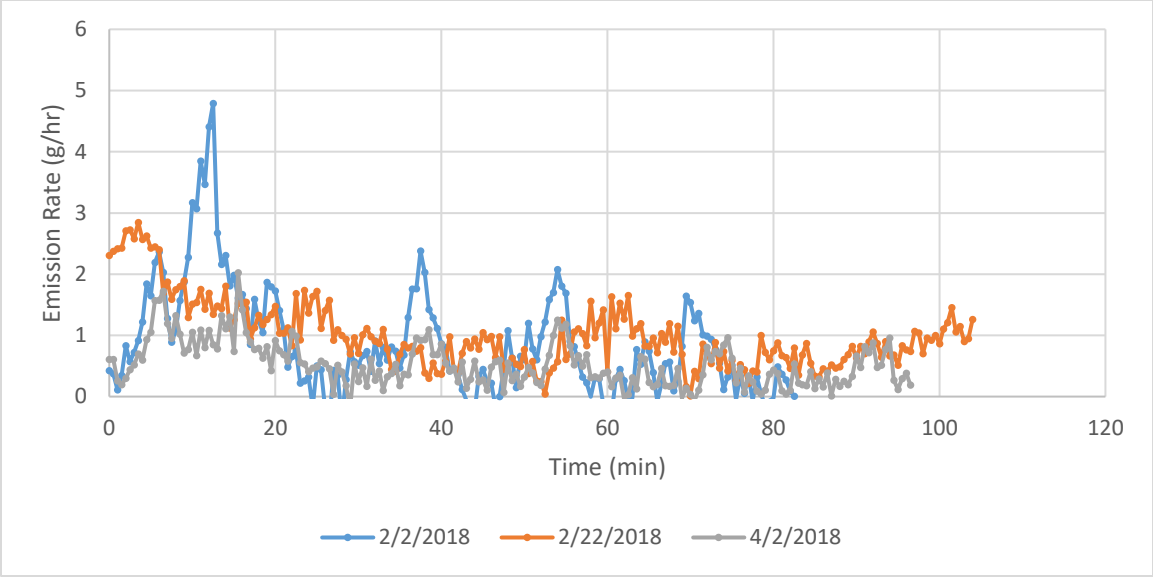


**Figure 84: Comparison of second Category IV PM emission rates for all tests using TEOM.**

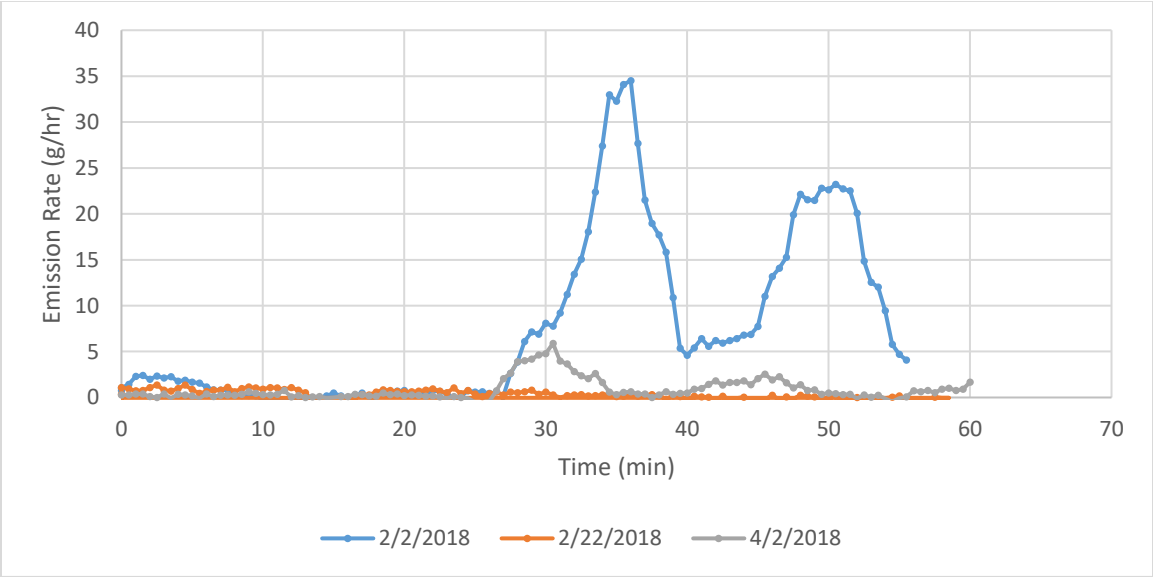


**Figure 85: Comparison of cyclic operation PM emission rates for all tests using TEOM.**

As discussed above, two sampling trains were used, but they were not sampling PM in the same manner. One sampling train measured PM over the entire testing period, thereby establishing one *integrated* filter (or a few filters if a single filter plugged). The other sample train sampled each *individual* phase of the operation. For example, a single filter was used to measure Phase 1, another single filter for Phase 2, Phase 3, and so on. In the results below, notations of A and B refer to the train used to sample individual phases and the integrated sampling train, respectively.

In Table 12 below, emission factors are shown for the two sampling trains calculated for the *entire* test protocol. Train A considers the emissions from Phases 1 through 10, while Train B was a filter sampling for the entire duration of the test and was only changed if a filter plugged.

**Table 12: Emission Factors from Two Filter Trains for Triplicate Tests**

| Test | Emission Factors (lb/MMBtu) | |
|---|---|---|
| | Sampling Train A | Sampling Train B |
| 1 | 0.55 | 0.34 |
| 2 | 0.39 | 0.30 |
| 3 | 0.22 | 0.17 |

When comparing the **total** mass collected on trains A and B, it is more than obvious in all three tests that Train A collected more mass than Train B due to the increased emission factor. This may be owed to filter blow-off or loss of volatiles over time from the cumulative filter (Train B). For example, should a very clean period follow a dirty period, as the flue gas is sampled and pulled through the filter, there is a chance for blow-off from the filter.

## Conclusions:

In this study, an outdoor wood-fired hydronic heater was run through a series of tests with a one-day variable load test profile that is mindful of time, cost, and is more representative of in-field use. In EPA accreditation testing, prior to this study, it was not possible to operate in the low load (< 15%) category and, as a result, the requirement for this test was waived. In the study reported here, it was possible to operate at this load level and so the boiler was able to operate in Phase 8 of the proposed protocol. However, a full test using the EPA M28 WHH at this load was not done. Preliminary tests included Category IV tests with both cordwood and cribwood, indicating small differences in emission output factors between the two fuel types, and species when compared to the EPA accreditation test. When comparing phases within the varied load profile test that were similar in load profiles to the M28 WHH test method, emission output factors were slightly greater. This may be due to differences in boiler temperatures as the unit changes between phases, smaller coal beds, fuel species and type, and shorter phase operation times. Real-time data from a TEOM also provided data to support the need for cold starts (Phase 1) and transition periods (Phases 2 and 6) in future test methods. Currently, these phases are not captured or their impact on emission rates and factors are masked within other phases. Short periods with high emissions have significant impacts on health and the environment, and cannot be ignored.

From the work carried out during this project, it is evident that the varied load profile test is a feasible one-day testing protocol that appropriately challenges hydronic heaters. The method used in this study is able to run in a day's time and does not require four separate category tests, where even an individual category test may take several days. In addition, the proposed method captures high emission periods such as cold-start (Phase 1) and cyclic operations (Phase 10), which are absent from current test methods. The importance of capturing these periods is evident based on the results detailed above. In each test the emission output (lb/MMBtu) from Phase 1 was the greatest contributor, ranging from 14 to 34 times higher than the average emission output. The coefficient of variation for the overall emission output was 38%, indicating some disagreement between each of the tests. The nature of burning cordwood is often variable and as mentioned above, there were some differences in the boiler's operation from run to run, even though the same protocol was followed each time.

## Acknowledgements

The authors would like to thank Lisa Rector and George Allen of the Northeast States for Coordinated Air Use Management for their help in developing the varied load testing protocol and TEOM-related operations. In addition, the authors would like to thank the New York State Research and Development Authority and Agreement 63017 for funding the project.

## Appendix

As discussed above, two sampling trains were used, but they were not sampling PM in the same manner. One sampling train measured PM over the entire testing period, thereby establishing one *integrated* filter (or a few filters if a single filter plugged). The other sample train sampled each *individual* phase of operation. For example, a single filter was used to measure Phase 1, another single filter for Phase 2, Phase 3, and so on. In the results below, notations of A and B refer to the train used to sample individual phases and the integrated sampling train, respectively. In the tables below, "Entire" refers to the entire testing period, which includes Phases 1 through 10. Tests 1 and 3 used both filter trains to capture the emissions associated with Phase 10 (detailed in the Test Profile); the notations of A and B below only indicate the train used for sampling. Only train A was used in Test 2 to capture Phase 10. Since fuel consumption, gaseous emissions, stack and ambient temperatures, and efficiency are not dependent on the filter train used, values for these parameters are the same for both trains A and B during the entire burn and Phase 10.

When comparing the **total** mass collected on trains A and B, it is more than obvious in all three tests that train A collected more mass than train B due to the larger PM concentration ($mg/m^3$) seen; and thereby yielded an increased emission rate, index, and factor. This may be owed to filter blow-off or loss of volatiles over time from the cumulative filter (train B). For example, should a very clean period follow a dirty period, as the flue gas is sampled and pulled through the filter, there is a chance for blow-off from the filter.

**Table 13: Test 1 Emission Details**

| Outdoor Wood Boiler with a Catalyst | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Friday, February 2, 2018 | | | | | | | | | | | | |
| Test 1 | | | | | | | | | | | | |
| | **Duration** | **PM Concentration** | **Emission Factor** | **Emission Rate** | **Emission Index** | **Fuel Burned** | **$CO_2$** | **CO** | **$O_2$** | **Ambient Temperature** | **Stack Temperature** | **CSA B415.1 Efficiency** |
| | **Minutes** | **mg/m3** | **lb/MMBtu** | **g/h** | **g/kg** | **lb** | **%** | **ppm** | **%** | **F** | **F** | **%** |
| Entire Train A | 727 | 25.18 | 0.55 | 23.05 | 3.32 | 185.2 | 11.9 | 5,951 | 11.29 | 64.4 | 167.4 | 82.8 |
| Entire Train B | | 15.29 | 0.34 | 14.00 | 2.02 | | | | | | | |
| 1 | 15.7 | 641.80 | 9.52 | 593.24 | 55.43 | 6.2 | 0.1 | 44 | 18.94 | 57.1 | 105.6 | 80.0 |
| 2 | 84.2 | 168.04 | 3.03 | 154.06 | 17.03 | 27.9 | 10.5 | 15,128 | 9.12 | 64.7 | 142.2 | 77.2 |
| 3 | 63.7 | 14.29 | 0.22 | 13.06 | 1.34 | 22.9 | 11.5 | 3,423 | 12.24 | 64.8 | 160.3 | 84.5 |
| 4 | 95.7 | 0.99 | 0.03 | 0.91 | 0.16 | 19.6 | 14.0 | 5,209 | 7.43 | 64.5 | 165.1 | 84.2 |
| 5 | 87.8 | 0.60 | 0.02 | 0.55 | 0.10 | 18.6 | 13.4 | 233 | 8.73 | 63.6 | 180.8 | 85.9 |
| 6 | 50.3 | 0.74 | 0.01 | 0.67 | 0.07 | 18.1 | 13.7 | 1,840 | 11.82 | 62.5 | 203.5 | 84.8 |
| 7 | 12.9 | 4.15 | 0.07 | 3.79 | 0.43 | 4.2 | 14.5 | 3,738 | 11.93 | 62.8 | 219.8 | 83.5 |
| 8 | 179.7 | 0.71 | 0.03 | 0.66 | 0.20 | 21.4 | 13.0 | 1,419 | 7.26 | 65.8 | 163.1 | 86.2 |
| 9 | 82.1 | 4.07 | 0.06 | 3.73 | 0.36 | 31.0 | 14.3 | 817 | 12.32 | 64.9 | 176.9 | 86.3 |
| 10 Train A | 55.0 | 15.68 | 0.35 | 14.40 | 1.90 | 15.3 | 14.2 | 27,660.2 | 13.1 | 64.4 | 167.4 | 74.1 |
| 10 Train B | | 14.40 | 0.32 | 13.22 | 1.74 | | | | | | | |

**Table 14: Test 2 Emission Details**

| Outdoor Wood Boiler with a Catalyst | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Thursday, February 22, 2018 | | | | | | | | | | | | |
| Test 2 | | | | | | | | | | | | |
| | **Duration** | **PM Concentration** | **Emission Factor** | **Emission Rate** | **Emission Index** | **Fuel Burned** | **$CO_2$** | **CO** | **$O_2$** | **Ambient Temperature** | **Stack Temperature** | **CSA B415.1 Efficiency** |
| | **Minutes** | **mg/m3** | **lb/MMBtu** | **g/h** | **g/kg** | **lb** | **%** | **ppm** | **%** | **F** | **F** | **%** |
| Entire Train A | 790 | 16.65 | 0.39 | 15.33 | 2.26 | 196.9 | 12.2 | 8,301 | 12.03 | 75.9 | 180.4 | 81.0 |
| Entire Train B | | 12.79 | 0.30 | 11.78 | 1.74 | | | | | | | |
| 1 | 15.3 | 380.10 | 4.74 | 353.04 | 26.97 | 7.4 | 0.1 | 28 | 18.92 | 68.4 | 116.2 | 80.0 |
| 2 | 57.6 | 47.77 | 0.79 | 44.19 | 4.63 | 20.2 | 12.9 | 7,896 | 9.71 | 72.0 | 156.8 | 82.2 |
| 3 | 62.8 | 4.30 | 0.07 | 3.97 | 0.39 | 23.1 | 12.5 | 3,136 | 13.02 | 75.2 | 165.3 | 84.7 |
| 4 | 150.2 | 1.03 | 0.03 | 0.95 | 0.18 | 28.9 | 13.9 | 13,010 | 8.57 | 76.0 | 163.7 | 80.0 |
| 5 | 74.8 | 1.34 | 0.03 | 1.23 | 0.19 | 18.2 | 13.4 | 16,282 | 9.10 | 76.5 | 201.2 | 77.1 |
| 6 | 49.6 | 0.67 | 0.01 | 0.61 | 0.07 | 15.8 | 14.4 | 2,051 | 14.10 | 77.0 | 213.0 | 84.4 |
| 7 | 47.1 | 1.97 | 0.03 | 1.80 | 0.19 | 16.7 | 14.2 | 6,503 | 15.89 | 76.4 | 222.2 | 82.2 |
| 8 | 168.2 | 31.56 | 1.21 | 29.09 | 7.01 | 25.6 | 12.6 | 12,306 | 7.27 | 76.8 | 165.2 | 80.0 |
| 9 | 104.3 | 5.09 | 0.09 | 4.66 | 0.54 | 32.8 | 14.7 | 818 | 14.54 | 77.7 | 210.5 | 85.7 |
| 10 Train A | 60.5 | 1.19 | 0.05 | 1.10 | 0.30 | 8.2 | 13.1 | 20,983.3 | 9.1 | 75.9 | 177.4 | 75.9 |

**Table 15: Test 3 Emission Details**

| Outdoor Wood Boiler with a Catalyst | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Monday, April 2, 2018 | | | | | | | | | | | | |
| Test 3 | | | | | | | | | | | | |
| | **Duration** | **PM concentration** | **Emission Factor** | **Emission Rate** | **Emission Index** | **Fuel Burned** | **$CO_2$** | **CO** | **$O_2$** | **Ambient Temperature** | **Stack Temperature** | **CSA B415.1 Efficiency** |
| | **Minutes** | **mg/m3** | **lb/MMBtu** | **g/h** | **g/kg** | **lb** | **%** | **ppm** | **%** | **F** | **F** | **%** |
| Entire Train A | 842 | 9.33 | 0.22 | 8.69 | 1.31 | 204.3 | 11.4 | 5,529 | 10.80 | 72.6 | 171.4 | 82.6 |
| Entire Train B | | 6.98 | 0.17 | 6.51 | 0.98 | | | | | | | |
| 1 | 18.3 | 566.54 | 6.63 | 527.92 | 38.04 | 9.3 | 0.1 | 27 | 18.93 | 71.1 | 118.1 | 80.0 |
| 2 | 79.1 | 23.07 | 0.47 | 21.60 | 2.75 | 22.8 | 3.7 | 774 | 15.71 | 71.3 | 147.8 | 81.8 |
| 3 | 70.4 | 3.57 | 0.05 | 3.33 | 0.32 | 27.2 | 13.5 | 2,379 | 10.62 | 69.8 | 171.9 | 85.2 |
| 4 | 149.8 | 0.91 | 0.03 | 0.85 | 0.20 | 23.5 | 14.1 | 8,047 | 6.26 | 73.9 | 160.2 | 82.8 |
| 5 | 89.5 | 1.08 | 0.03 | 1.01 | 0.16 | 20.6 | 13.2 | 10,752 | 7.44 | 73.5 | 183.7 | 80.3 |
| 6 | 53.1 | 1.01 | 0.02 | 0.94 | 0.13 | 14.5 | 14.1 | 1,091 | 6.74 | 75.0 | 206.6 | 85.2 |
| 7 | 46.9 | 1.40 | 0.02 | 1.31 | 0.15 | 15.5 | 14.4 | 3,120 | 14.28 | 73.9 | 214.3 | 83.9 |
| 8 | 180.8 | 2.24 | 0.09 | 2.09 | 0.54 | 25.5 | 12.6 | 4,928 | 6.97 | 71.6 | 163.3 | 83.7 |
| 9 | 93.9 | 1.17 | 0.02 | 1.09 | 0.12 | 30.8 | 14.0 | 1,678 | 11.04 | 72.9 | 172.4 | 85.7 |
| 10 Train A | 60.0 | 1.83 | 0.05 | 1.70 | 0.26 | 14.5 | 13.9 | 22,491.0 | 10.1 | 72.6 | 160.1 | 75.9 |
| 10 Train B | | 1.62 | 0.04 | 1.51 | 0.23 | | | | | | | |

## References


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