# RocketChar 301 Emission Test Report

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**For:**
Rowdy Yeatts
High Plains Biochar
Laramie, Wyoming

**Combustion System:** RocketChar 301 biomass furnace
**Test Location:** High Plains Biochar in Laramie, Wyoming
**Test Date:** Test 1 on February 16, 2023, Test 2 on February 17, 2023
**Fuel:** Pine woodchips fed by auger. Fire started with oil, paper, and scrap pine wood
**Burn sequence:** Full burn cycle including startup, steady state operation, and then burnout.

# Emission Test Method

A continuous exhaust sample was drawn from a port in the exhaust chimney on the outside of the building using the Possum1 portable dilution sampling system. Emission reporting metrics were calculated using two methods: the carbon balance method and the stack flow method. Measurement uncertainty was estimated and propagated to the reporting metrics. All sensors were calibrated on site before and after the measurements.

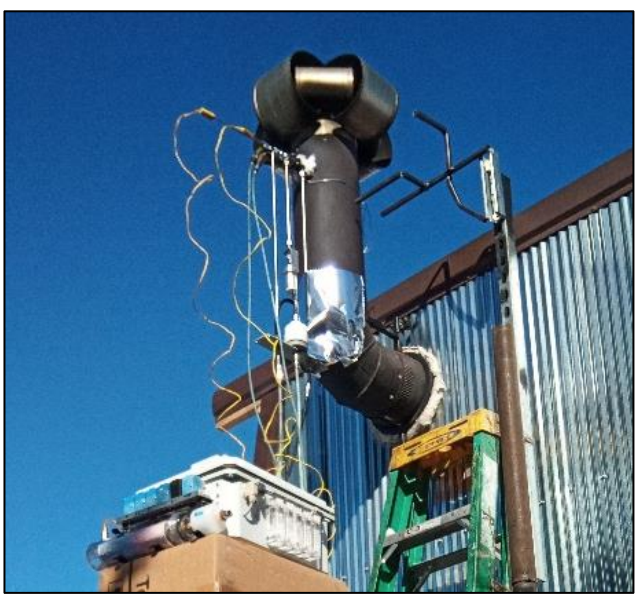

**Figure 1: a) Sampling equipment installed on the chimney. Insulation is packed around the probe nozzle to seal the port hole. b) Inside the shed before lighting the furnace.**

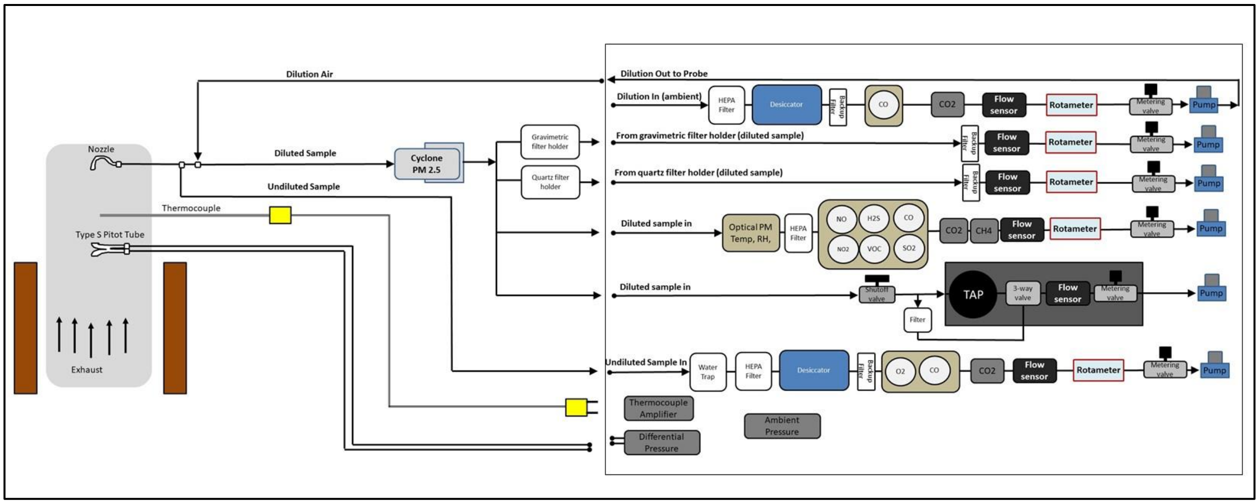


**Figure 2: Possum1 portable dilution sampling system flow diagram.**

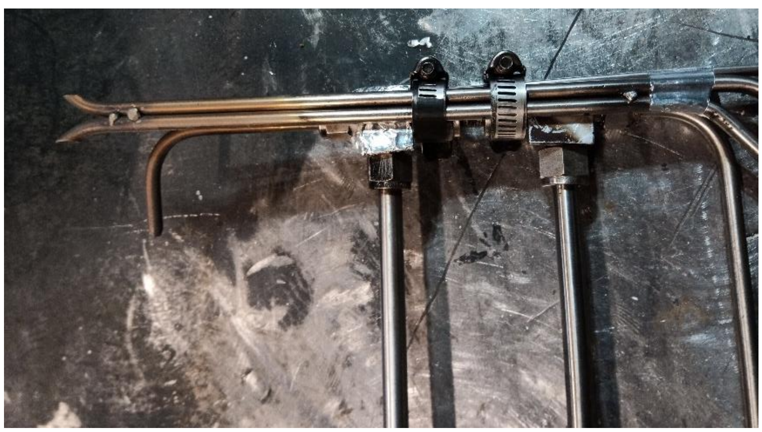

**Figure 3: Sampling nozzle head**

## Measurements:

**$CO_2$ (carbon dioxide):** Three non-dispersive infrared sensors, one in the undiluted sample train, one in the diluted sample train, and one in the dilution air train

**CO (carbon monoxide):** Three electrochemical cells, one in the undiluted sample train, one in the diluted sample train, and one in the dilution air train

**$O_2$ (oxygen):** Electrochemical cell in undiluted sample train

**NO (nitric oxide):** Electrochemical cell in diluted sample train

**$NO_2$ (nitrogen dioxide):** Electrochemical cell in diluted sample train

**$SO_2$ (sulfur dioxide):** Electrochemical cell in diluted sample train

**VOC (volatile organic compounds):** Photoionization detector ($10^6$ eV lamp) in diluted sample train

**$H_xC_y$ (hydrocarbons):** non-dispersive infrared sensor in diluted sample train

**$CH_4$ (methane):** Calculated as the difference between total hydrocarbons (measured by the NDIR hydrocarbon sensor) and non-methane hydrocarbons (measured by the photoionization detector).

**$PM_{2.5}$ (particulate matter):** The diluted sample train contains a cyclone with 2.5 micrometer cut point, 47 mm filter holders for gravimetric analysis, and an optical PM sensor. Filter flows are measured continuously with mass flow sensors. The optical (light-scattering) PM sensor shows real-time PM emissions.

**Black carbon particulate matter:** PM is collected on 47 mm quartz filter for thermal-optical analysis by Sunset OC/EC analyzer to determine the mass fractions of elemental carbon and organic carbon. A second quartz filter is placed downstream of the gravimetric filter in order to measure and correct for positive adsorption artifact on the primary quartz filter. Particle light absorption is measured in real-time using the TAP (Tri-color Absorption Photometer).

**Stack flow:** The flow rate is measured with a Type S pitot tube, and that pressure differential is measured continuously with a pressure transducer. The stack temperature is measured continuously with a thermocouple. The pitot tube is located at stack center to measure the center-line velocity during emission testing. A velocity traverse was conducted once to measure the velocity profile.

**Fuel:** The mass of fuel consumed is measured with a scale. The fuel moisture content is determined by taking a fuel sample for thermo-gravimetric analysis. The mass of char is determined by measuring the total volume of char, and drying a sample to measure the dry bulk density. Fuel samples and char samples are collected for laboratory analysis of carbon fraction and heating value.

## Emission Reporting Metrics

Reporting metrics are calculated using both the carbon balance method and the stack flow method. The test results in this report show some discrepancy between the two methods. When there is a discrepancy, the carbon balance metrics should be used for reporting stove performance, because the carbon balance metrics have lower measurement uncertainty.

### Carbon Balance Method

Emission species concentrations are measured in the exhaust stream, and used to calculate carbon emission ratios (the mass of each species over the mass of carbon). A carbon mass balance is performed to determine the mass of carbon emitted. Emission factors and emission rates can then be calculated from emission ratios. The required inputs for the carbon balance are:

1. Mass of fuel loaded
2. Moisture content of fuel loaded
3. Carbon fraction of fuel loaded
4. Mass of char/ash remaining

5. Moisture content of char/ash remaining
6. Carbon fraction of char/ash remaining

**Stack Flow Method**

Emission species concentrations are measured in the exhaust stream, as well as the exhaust flow rate using a Type S pitot tube. Emission rates are calculated from concentrations and exhaust flow rate. Emission factors are calculated from total mass of emissions and total fuel mass.

# Results

## Test 1

Fuel inputs are shown in Table 1. Measurement uncertainty is reported for each metric as 1 standard deviation. Fuel consumption metrics are in Table 2. Emission reporting metrics are in Table 3.

**Table 1: Fuel Inputs for Test 1**

| Fuel | Mass input (kg) | MC, wet basis (%) | $C_{frac}$, dry basis | LHV, as received |
|---|---|---|---|---|
| woodchips | 43.0±1.0 | 20.7 | 0.511±0.01 | 14.08±1.0 |
| pine wood | 4.15±.04 | 11.5 | 0.5±0.025 | 16.25±1.0 |
| paper | 0.28±0.0 | 10 | 0.6±0.05 | 20±5.0 |
| oil | 0.056±0.0 | 0 | 0.8±0.1 | 40±5.0 |
| total fuel load | 47.5±1.0 | 20 | 0.51±0.01 | 14.3±0.9 |
| char | 7.67±0.3 | 0 | 0.858±0.01 | 30.2±1.0 |

**Table 2: Fuel consumption metrics for Test 1**

| metric | units | value ± uncert. | description |
|---|---|---|---|
| test duration | hrs | 6.53 ± 0 | burn time |
| fuel feed rate | kg/hr | 7.27 ± 0.15 | mass of raw fuel loaded |
| dry fuel feed rate | kg/hr | 5.82 ± 0.16 | mass of dry fuel loaded |
| char production rate | kg/hr | 1.17 ± 0.05 | raw fuel moisture content, wet basis |
| char yield | $kg_{char}/kg_{dryfuel}$ | 0.201 ± 0.010 | dry char produced per dry mass of fuel loaded |
| firepower | kW | 19.1 ± 2 | firepower |

The results in Table 3 show that the stack flow method reports emission metrics that are a factor of two higher than the carbon balance method. The discrepancy can be attributed to several potential sources of measurement uncertainty, most notably the pitot tube velocity measurement and the velocity profile. The carbon balance check in Figure 4 shows that stack flow method calculated twice as much carbon emitted as the carbon balance method. The measured inputs for the carbon balance were relatively good quality compared to the stack flow method. Even if the actual measurement uncertainties for the carbon balance are greater than estimated, they could not be off by a factor of two. Therefore, we conclude that the metrics reported by the stack flow method are lower quality than the carbon balance method, and the carbon balance metrics should be used for reporting performance.

Despite the discrepancy, both methods confirm that the emissions of CO and PM from the RocketChar were extremely low compared to other common sources of biomass combustion.

**Table 3: Emission reporting metrics for Test 1**

| Test 1 | | Emission Repoting Metrics | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Carbon Balance Method | | | Stack Flow Method | | | |
| metric | units | value ± uncert. | | | value ± uncert. | | | metric description |
| MCE | mol/mol | 0.9977 | ± | 0.0002 | | | | modified combustion efficiency |
| $EF_{CO2,fuel}$ | $g/kg_{fuel}$ | 991 | ± | 52 | 1811 | ± | 40 | $CO_2$ emission factor: grams per kg raw fuel loaded |
| $EF_{CO,fuel}$ | $g/kg_{fuel}$ | 1.466 | ± | 0.125 | 2.908 | ± | 0.068 | CO emission factor: grams per kg raw fuel loaded |
| $EF_{NO,fuel}$ | $g/kg_{fuel}$ | 0.598 | ± | 0.112 | 1.161 | ± | 0.040 | NO emission factor: grams per kg raw fuel loaded |
| $EF_{PM,fuel}$ | $mg/kg_{fuel}$ | 15.46 | ± | 0.96 | 34.57 | ± | 0.96 | $PM_{2.5}$ emission factor: mg per kg raw fuel loaded |
| $EF_{CO2,dry fu}$ | $g/kg_{dry fuel}$ | 1236 | ± | 66 | 2259 | ± | 63 | $CO_2$ emission factor: grams per kg dry fuel |
| $EF_{CO,dry fue}$ | $g/kg_{dry fuel}$ | 1.829 | ± | 0.157 | 3.626 | ± | 0.104 | CO emission factor: grams per kg dry fuel |
| $EF_{NO,dry fue}$ | $g/kg_{dry fuel}$ | 0.746 | ± | 0.140 | 1.447 | ± | 0.056 | NO emission factor: grams per kg dry fuel |
| $EF_{PM,dry fue}$ | $mg/kg_{dry fuel}$ | 19.28 | ± | 1.21 | 43.10 | ± | 1.39 | $PM_{2.5}$ emission factor: mg per kg dry fuel |
| $EF_{CO2,char}$ | $g/kg_{char}$ | 6132 | ± | 373 | 11209 | ± | 446 | $CO_2$ emission factor: grams per kg char produced |
| $EF_{CO,char}$ | $g/kg_{char}$ | 9.074 | ± | 0.823 | 17.996 | ± | 0.726 | CO emission factor: grams per kg char produced |
| $EF_{NO,char}$ | $g/kg_{char}$ | 3.70 | ± | 0.70 | 7.18 | ± | 0.34 | NO emission factor: grams per kg char produced |
| $EF_{PM,char}$ | $mg/kg_{char}$ | 95.7 | ± | 6.6 | 213.9 | ± | 9.2 | $PM_{2.5}$ emission factor: mg per kg char produced |
| $ER_{CO2}$ | g/hr | 7199 | ± | 1076 | 12832 | ± | 91 | $CO_2$ emission rate: g per hour |
| $ER_{CO}$ | g/hr | 9.67 | ± | 1.72 | 19.68 | ± | 0.32 | CO emission rate: g per hour |
| $ER_{NO}$ | g/hr | 4.35 | ± | 1.01 | 8.22 | ± | 0.23 | NO emission rate: g per hour |
| $ER_{PM}$ | mg/hr | 112.3 | ± | 17.2 | 244.9 | ± | 4.4 | $PM_{2.5}$ emission rate: mg per hour |
| $EF_{CO2,energ}$ | g/MJ | 105 | ± | 11 | 192 | ± | 20 | $CO_2$ emission factor: grams per MJ |
| $EF_{CO,energy}$ | g/MJ | 0.155 | ± | 0.020 | 0.307 | ± | 0.032 | CO emission factor: grams per MJ |
| $EF_{NO,energy}$ | g/MJ | 0.063 | ± | 0.013 | 0.123 | ± | 0.013 | NO emission factor: grams per MJ |
| $EF_{PM,energy}$ | mg/MJ | 1.634 | ± | 0.182 | 3.655 | ± | 0.388 | $PM_{2.5}$ emission factor: mg per MJ |

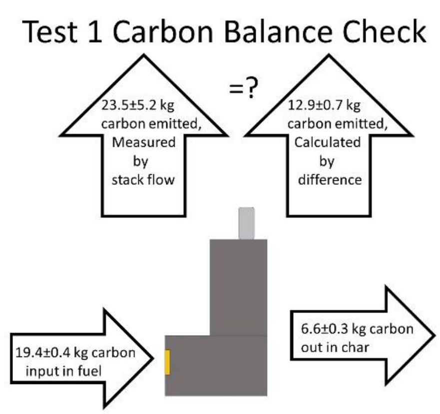


**Figure 4: Carbon balance check**

## Test 2

Fuel inputs are shown in Table 4. Measurement uncertainty is reported for each metric as 1 standard deviation. Fuel consumption metrics are in Table 5. Emission reporting metrics are in Table 6.

**Table 4: Fuel Inputs for Test 2**

| Fuel | Mass input (kg) | MC, wet basis (%) | $C_{frac}$, dry basis | LHV, as received |
|---|---|---|---|---|
| woodchips | 46.5±1.0 | 20.7 | 0.511±0.01 | 14.08±1.0 |
| pine wood | 3.15±.04 | 11.5 | 0.5±0.025 | 16.25±1.0 |
| paper | 0.20±0.0 | 10 | 0.6±0.05 | 20±5.0 |
| oil | 0.22±0.0 | 0 | 0.8±0.1 | 40±5.0 |
| total fuel load | 50.1±1.0 | 20 | 0.51±0.1 | 14.3±0.9 |
| char | 6.76±0.3 | 0 | 0.858±0.01 | 30.2±1.0 |

**Table 5: Fuel consumption metrics for Test 2**

| metric | units | value ± uncert. | | | description |
|---|---|---|---|---|---|
| test duration | hrs | 6.47 | ± | 0 | burn time |
| fuel feed rate | kg/hr | 7.75 | ± | 0.15 | mass of raw fuel loaded |
| dry fuel feed rate | kg/hr | 6.20 | ± | 0.16 | mass of dry fuel loaded |
| char production rate | kg/hr | -1.05 | ± | 0.05 | raw fuel moisture content, wet basis |
| char yield | $kg_{char}/kg_{dryfuel}$ | 0.169 | ± | 0.009 | dry char produced per dry mass of fuel loaded |
| firepower | kW | 22.1 | ± | 2.1 | firepower |

The results in Table 6 show that stack flow method reports emission metrics that are higher than the carbon balance method, although the two methods agree much better in Test 2 than in Test 1. The carbon balance check in Figure 5 shows that stack flow method calculated 27% more carbon emitted than the carbon balance method. The carbon balance metrics should be used for reporting instead of the stack flow metrics.

**Table 6: Emission Reporting Metrics for Test 2**

| Test 2 | | Emission Repoting Metrics | | |
|---|---|---|---|---|
| | | Carbon Balance Method | Stack Flow Method | |
| metric | units | value ± uncert. | value ± uncert. | metric description |
| MCE | mol/mol | 0.9991 ± 0.0001 | | modified combustion efficiency |
| $EF_{CO2,fuel}$ | $g/kg_{fuel}$ | 1076 ± 52 | 1482 ± 37 | $CO_2$ emission factor: grams per kg raw fuel loaded |
| $EF_{CO,fuel}$ | $g/kg_{fuel}$ | 0.601 ± 0.065 | 1.045 ± 0.030 | CO emission factor: grams per kg raw fuel loaded |
| $EF_{NO,fuel}$ | $g/kg_{fuel}$ | 0.555 ± 0.163 | 1.013 ± 0.056 | NO emission factor: grams per kg raw fuel loaded |
| $EF_{PM,fuel}$ | $mg/kg_{fuel}$ | 6.73 ± 0.52 | 8.09 ± 0.57 | $PM_{2.5}$ emission factor: mg per kg raw fuel loaded |
| $EF_{CO2,dry fuel}$ | $g/kg_{dry fuel}$ | 1345 ± 68 | 1852 ± 56 | $CO_2$ emission factor: grams per kg dry fuel |
| $EF_{CO,dry fuel}$ | $g/kg_{dry fuel}$ | 0.751 ± 0.081 | 1.306 ± 0.043 | CO emission factor: grams per kg dry fuel |
| $EF_{NO,dry fuel}$ | $g/kg_{dry fuel}$ | 0.694 ± 0.204 | 1.266 ± 0.074 | NO emission factor: grams per kg dry fuel |
| $EF_{PM,dry fuel}$ | $mg/kg_{dry fuel}$ | 8.41 ± 0.66 | 10.12 ± 0.73 | $PM_{2.5}$ emission factor: mg per kg dry fuel |
| $EF_{CO2,char}$ | $g/kg_{char}$ | 7976 ± 493 | 10984 ± 515 | $CO_2$ emission factor: grams per kg char produced |
| $EF_{CO,char}$ | $g/kg_{char}$ | 4.451 ± 0.508 | 7.744 ± 0.377 | CO emission factor: grams per kg char produced |
| $EF_{NO,char}$ | $g/kg_{char}$ | 4.11 ± 1.22 | 7.50 ± 0.51 | NO emission factor: grams per kg char produced |
| $EF_{PM,char}$ | $mg/kg_{char}$ | 49.9 ± 4.3 | 60.0 ± 4.8 | $PM_{2.5}$ emission factor: mg per kg char produced |
| $ER_{CO2}$ | g/hr | 8338 ± 1160 | 11481 ± 174 | $CO_2$ emission rate: g per hour |
| $ER_{CO}$ | g/hr | 4.65 ± 0.79 | 8.80 ± 0.42 | CO emission rate: g per hour |
| $ER_{NO}$ | g/hr | 4.30 ± 1.38 | 7.84 ± 0.41 | NO emission rate: g per hour |
| $ER_{PM}$ | mg/hr | 52.1 ± 7.9 | 62.7 ± 4.2 | $PM_{2.5}$ emission rate: mg per hour |
| $EF_{CO2,energy}$ | g/MJ | 105 ± 10 | 144 ± 14 | $CO_2$ emission factor: grams per MJ |
| $EF_{CO,energy}$ | g/MJ | 0.058 ± 0.008 | 0.102 ± 0.010 | CO emission factor: grams per MJ |
| $EF_{NO,energy}$ | g/MJ | 0.054 ± 0.017 | 0.099 ± 0.011 | NO emission factor: grams per MJ |
| $EF_{PM,energy}$ | mg/MJ | 0.655 ± 0.076 | 0.787 ± 0.093 | $PM_{2.5}$ emission factor: mg per MJ |

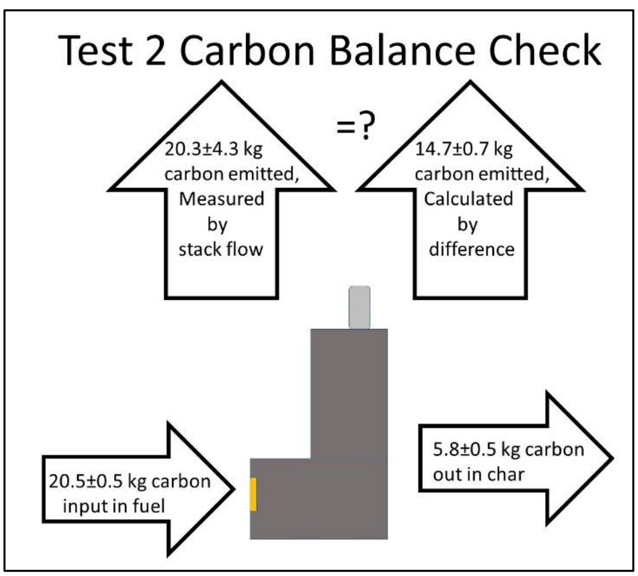


**Figure 5: Carbon balance check**

## Organic Carbon and Elemental Carbon Particulate Emissions

The composition of particulate matter was explored in Test 2 by collecting samples on quartz filters for thermal-optical analysis (TOA) to determine the mass fractions of organic carbon (OC) and elemental carbon (EC). The results are shown in Table 7. The OC/EC ratio was 0.26, indicating that the particulate carbon was mostly elemental (black) carbon. Total carbon (TC) is the sum of OC and EC. The TC/PM ratio was 0.54, indicating that only half of the total PM mass was accounted for as carbon. The remaining mass fraction of PM could be ash.

**Table 7: OC and EC reporting metrics**

| Test 2 | Emission Repoting Metrics for OC and EC | | | | |
|---|---|---|---|---|---|
| | | Carbon Balance Method | | | |
| **metric** | **units** | **value ± uncert.** | | | **metric description** |
| OC/EC | g/g | 0.263 | ± | 0.077 | OC/EC ratio |
| OC/PM | g/g | 0.113 | ± | 0.033 | OC/PM ratio |
| EC/PM | g/g | 0.431 | ± | 0.043 | EC/PM ratio |
| TC/PM | g/g | 0.545 | ± | 0.059 | TC/PM ratio |
| $EF_{OC,fuel}$ | $mg/kg_{fuel}$ | 0.763 | ± | 0.224 | OC emission factor: mg per kg raw fuel loaded |
| $EF_{EC,fuel}$ | $mg/kg_{fuel}$ | 2.90 | ± | 0.30 | EC emission factor: mg per kg raw fuel loaded |
| $EF_{OC,dry fuel}$ | $mg/kg_{dry fuel}$ | 0.954 | ± | 0.281 | OC emission factor: mg per kg dry fuel |
| $EF_{EC,dry fuel}$ | $mg/kg_{dry fuel}$ | 3.63 | ± | 0.38 | EC emission factor: mg per kg dry fuel |
| $EF_{OC,char}$ | $mg/kg_{char}$ | 5.66 | ± | 1.68 | OC emission factor: mg per kg char produced |
| $EF_{EC,char}$ | $mg/kg_{char}$ | 21.5 | ± | 2.4 | EC emission factor: mg per kg char produced |
| $ER_{OC}$ | mg/hr | 5.91 | ± | 1.90 | OC emission rate: mg per hour |
| $ER_{EC}$ | mg/hr | 22.5 | ± | 3.8 | EC emission rate: mg per hour |
| $EF_{OC,energy}$ | mg/MJ | 0.074 | ± | 0.023 | OC emission factor: mg per MJ |
| $EF_{EC,energy}$ | mg/MJ | 0.282 | ± | 0.038 | EC emission factor: mg per MJ |

# Emissions Below Detection Limit

Table 3 and Table 6 report the emissions that were above detection limit. Additional emissions were measured, but the measured concentrations were at or below detection limit. Table 8 shows the additional emissions that were measured below detection limit, along with the corresponding detection limit.

**Table 8: Emission metrics values that were below detection limits are reported as no detection (ND) along with the corresponding detection limit.**

| | | Test 1 | Test 2 | |
|---|---|---|---|---|
| **metric** | **units** | **detection limit** | **detection limit** | **metric description** |
| $EF_{NO2,fuel}$ | $g/kg_{fuel}$ | ND < 0.134 | ND < 0.219 | $NO_2$ emission factor: grams per kg raw fuel loaded |
| $EF_{SO2,fuel}$ | $g/kg_{fuel}$ | ND < 0.187 | ND < 0.305 | $SO_2$ emission factor: grams per kg raw fuel loaded |
| $EF_{HC,fuel}$ | $g/kg_{fuel}$ | ND < 14.6 | ND < 23.8 | HC emission factor: grams per kg raw fuel loaded |
| $EF_{NMHC,fuel}$ | $g/kg_{fuel}$ | ND < 0.654 | ND < 1.070 | NMHC emission factor: grams per kg raw fuel loaded |
| $EF_{CH4,fuel}$ | $g/kg_{fuel}$ | ND < 7.3 | ND < 11.9 | $CH_4$ emission factor: grams per kg raw fuel loaded |
| $EF_{NO2,dry fuel}$ | $g/kg_{dry fuel}$ | ND < 0.167 | ND < 0.274 | $NO_2$ emission factor: grams per kg dry fuel |
| $EF_{SO2,dry fuel}$ | $g/kg_{dry fuel}$ | ND < 0.233 | ND < 0.381 | $SO_2$ emission factor: grams per kg dry fuel |
| $EF_{HC,dry fuel}$ | $g/kg_{dry fuel}$ | ND < 18.2 | ND < 29.8 | HC emission factor: grams per kg dry fuel |
| $EF_{NMHC,dry fuel}$ | $g/kg_{dry fuel}$ | ND < 0.815 | ND < 1.340 | NMHC emission factor: grams per kg dry fuel |
| $EF_{CH4,dry fuel}$ | $g/kg_{dry fuel}$ | ND < 9.1 | ND < 14.9 | $CH_4$ emission factor: grams per kg dry fuel |
| $EF_{NO2,char}$ | $g/kg_{char}$ | ND < 0.83 | ND < 1.63 | $NO_2$ emission factor: grams per kg char produced |
| $EF_{SO2,char}$ | $g/kg_{char}$ | ND < 1.16 | ND < 2.26 | $SO_2$ emission factor: grams per kg char produced |
| $EF_{HC,char}$ | $g/kg_{char}$ | ND < 90 | ND < 177 | HC emission factor: grams per kg char produced |
| $EF_{NMHC,char}$ | $g/kg_{char}$ | ND < 4.1 | ND < 7.9 | NMHC emission factor: grams per kg char produced |
| $EF_{CH4,char}$ | $g/kg_{char}$ | ND < 45 | ND < 89 | $CH_4$ emission factor: grams per kg char produced |
| $EF_{NO2,energy}$ | g/MJ | ND < 0.014 | ND < 0.021 | $NO_2$ emission factor: grams per MJ |
| $EF_{SO2,energy}$ | g/MJ | ND < 0.020 | ND < 0.030 | $SO_2$ emission factor: grams per MJ |
| $EF_{HC,energy}$ | g/MJ | ND < 1.540 | ND < 2.320 | HC emission factor: grams per MJ |
| $EF_{NMHC,energy}$ | g/MJ | ND < 0.069 | ND < 0.104 | NMHC emission factor: grams per MJ |
| $EF_{CH4,energy}$ | g/MJ | ND < 0.770 | ND < 1.160 | $CH_4$ emission factor: grams per MJ |
| $ER_{NO2}$ | g/hr | ND < 0.97 | ND < 1.70 | $NO_2$ emission rate: g per hour |
| $ER_{SO2}$ | g/hr | ND < 1.36 | ND < 2.37 | $SO_2$ emission rate: g per hour |
| $ER_{HC}$ | g/hr | ND < 106 | ND < 185 | HC emission rate: g per hour |
| $ER_{NMHC}$ | g/hr | ND < 0.82 | ND < 1.34 | NMHC emission rate: g per hour |
| $ER_{CH4}$ | g/hr | ND < 53 | ND < 93 | $CH_4$ emission rate: g per hour |

# Velocity Traverse

A velocity traverse was performed during Test 1. The Reynolds number of the exhaust flow was 6800, indicating fully turbulent flow at the sample port. The velocity profile in Figure 7 shows a non-uniform profile, with higher velocity on the port side, likely due to the proximity from the elbow and the chimney cap.

The average velocity was determined from the profile to be 3.26 m/s. For the duration of both Test 1 and Test2, the pitot tube was fixed stationary at point 3, which had a velocity of 2.76 m/s during the traverse. Therefore, a correction factor of 1.18 was applied to the continuous stack velocity measurement during Test 1 and Test 2 to convert the measured velocity at point 3 to an average velocity for the flow rate calculation.

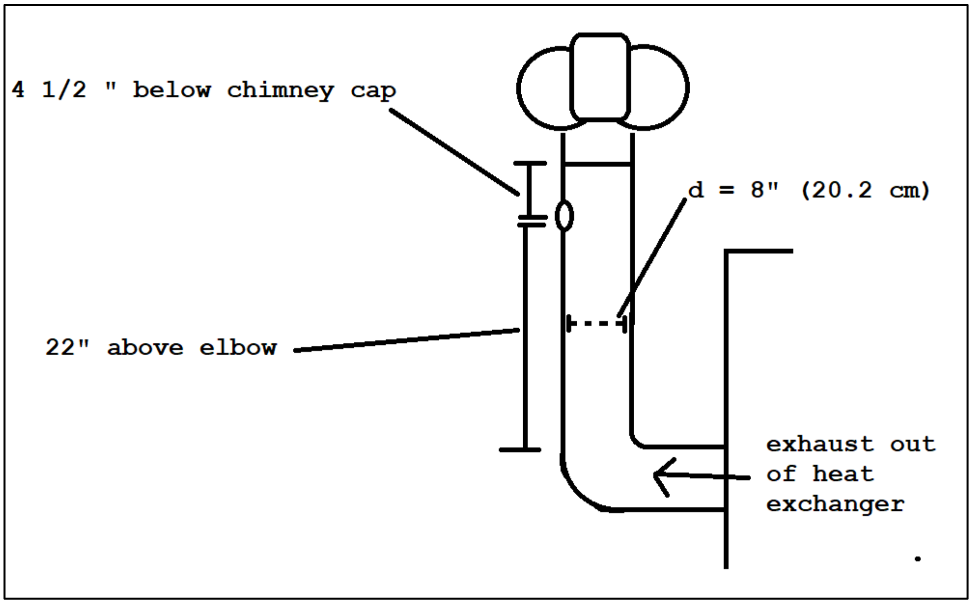


**Figure 6: Chimney diagram with port hole location.**

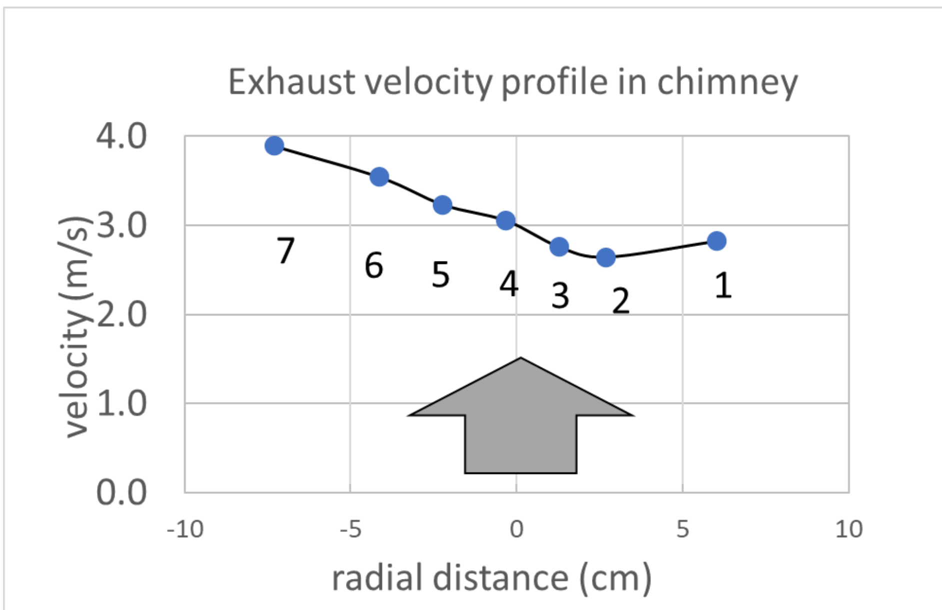


**Figure 7: Velocity profile in the chimney, looking at the chimney from the orientation in Figure 6. The port hole is on the y -axis. Point 3 (r = 1.3 cm) was the fixed location of the pitot tube throughout Test 1 and Test 2. The range of traverse points was limited by the travel of the pitot tube assembly. The traverse points only cover the center half of the cross-sectional area. The profile was measured in only one dimension, and assumed to be symmetrical along the other dimension into the page.**

# Time Series Data

The full burn sequence can be divided into three phases: warm-up, steady-state, and burn-out. The warm-up phase lasted about two hours and was responsible for nearly all emissions of incomplete combustion products (CO, PM). The steady-state phase is when the combustion chamber has reached a steady state temperature, and incomplete combustion products are near or below detection limit. The fuel feed auger cycles off and on, which causes an oscillation in the $CO_2$ concentration. The burn-out phase is after fuel feeding stops when the hot coals remaining emit CO as they slowly burn out.

# Test 1 Plots

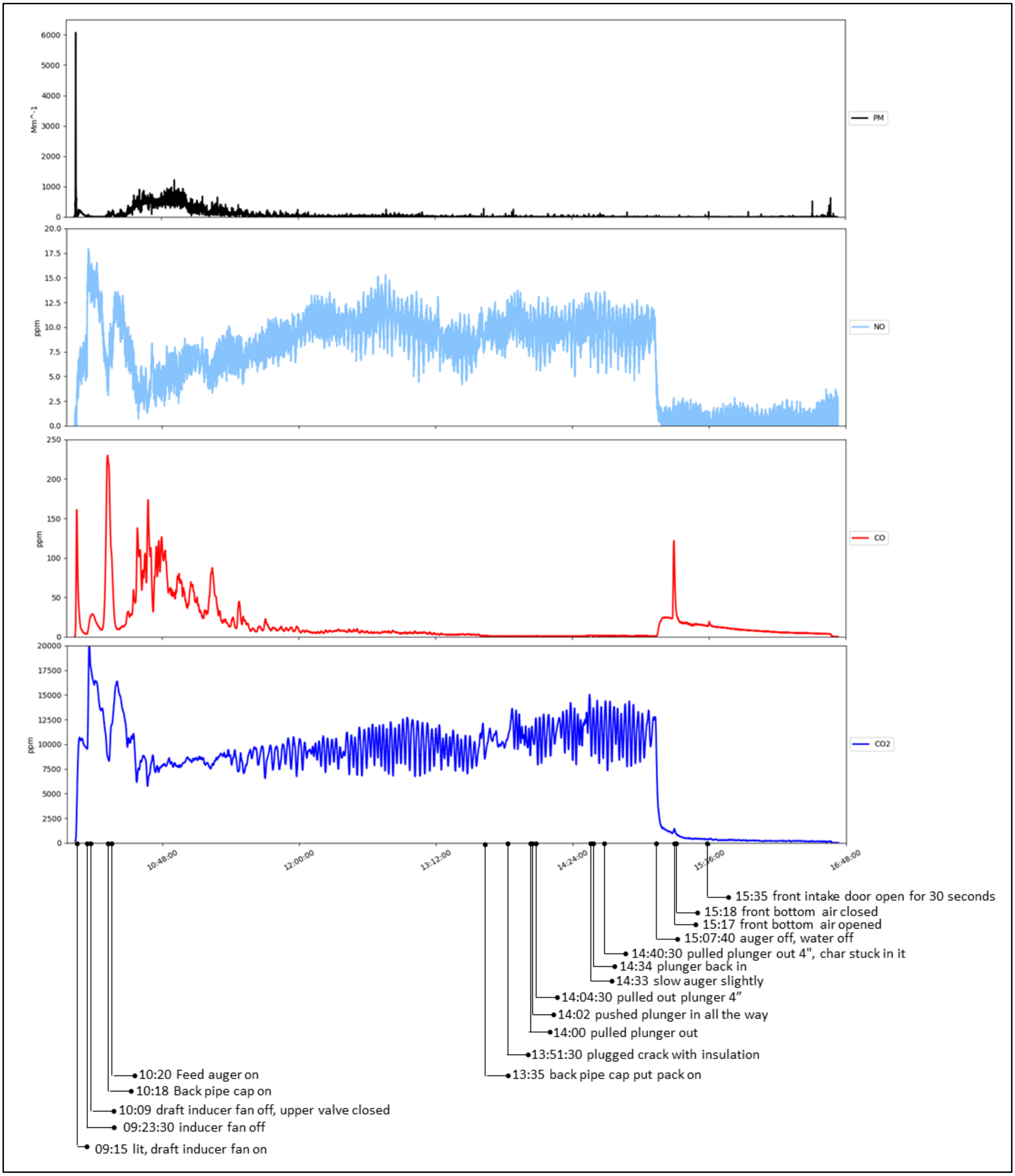


**Figure 8: Test 1 time series data of concentrations.**

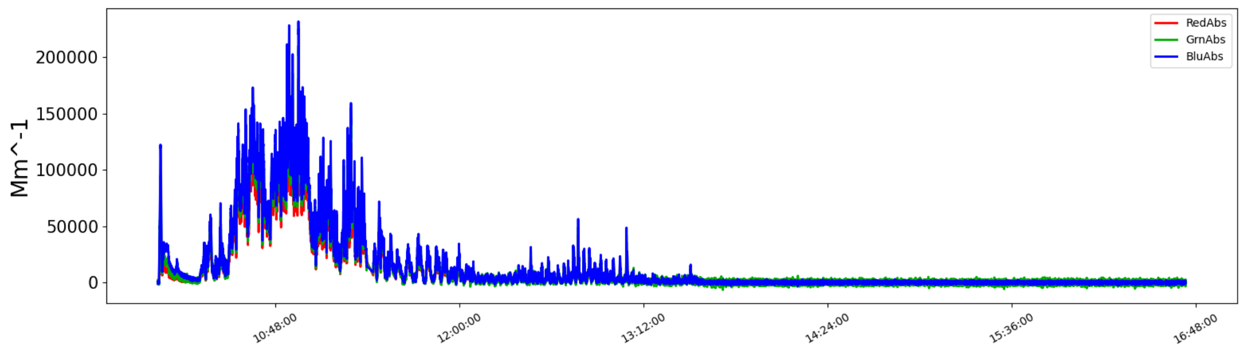


**Figure 9: Test 1 Particle light absorption from the TAP sensor. The trend matches the optical PM sensor data. The red, green, and blue absorption signals are all of similar magnitude, which indicates that the absorption is equal across all wavelengths, and the particles are black in color. This is consistent with the OC/EC analysis results that the particulate carbon is mostly elemental carbon.**

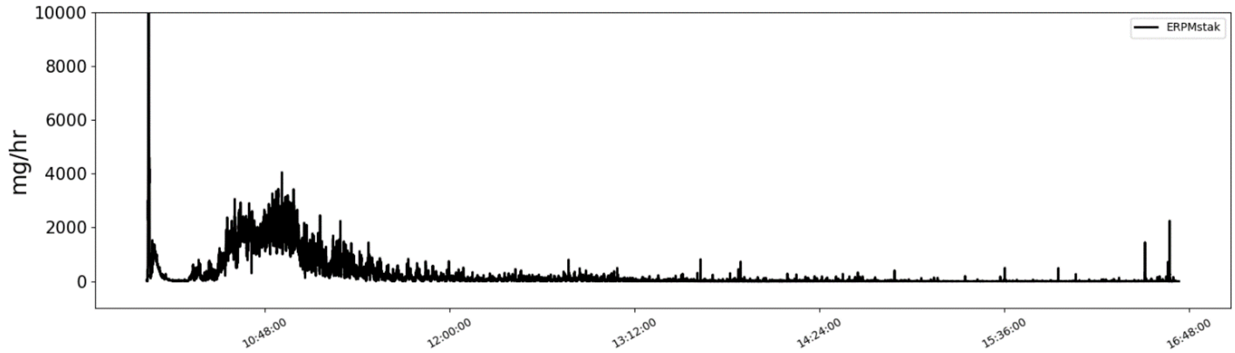


**Figure 10: Test 1 PM emission rate**

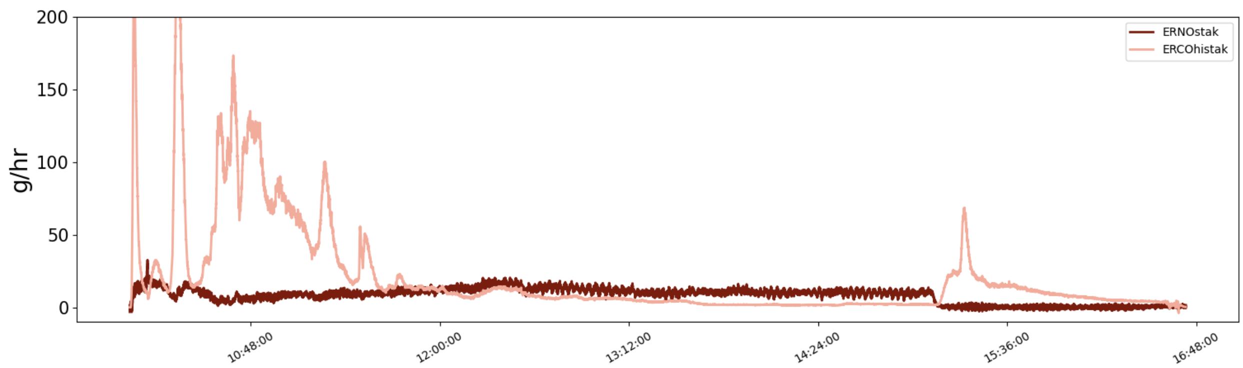


**Figure 11: Test 1 CO and NO emission rate**

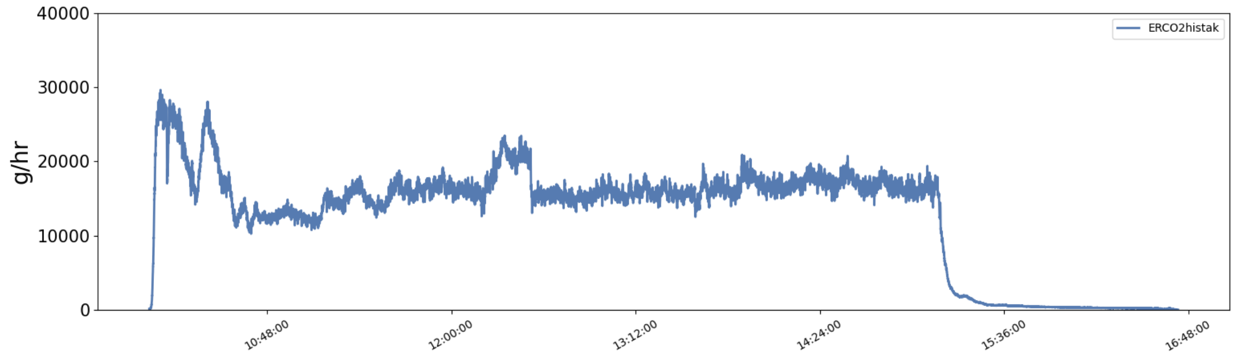


**Figure 12: Test 1 CO2 emission rate**

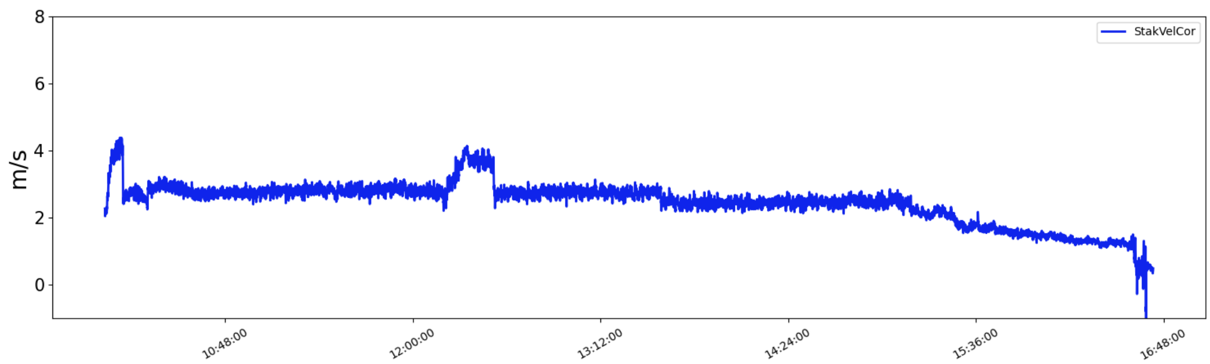


**Figure 13: Test 1 stack velocity measured by pitot tube. The high velocity at the beginning is the draft inductor fan. The high velocity in the middle is the velocity traverse.**

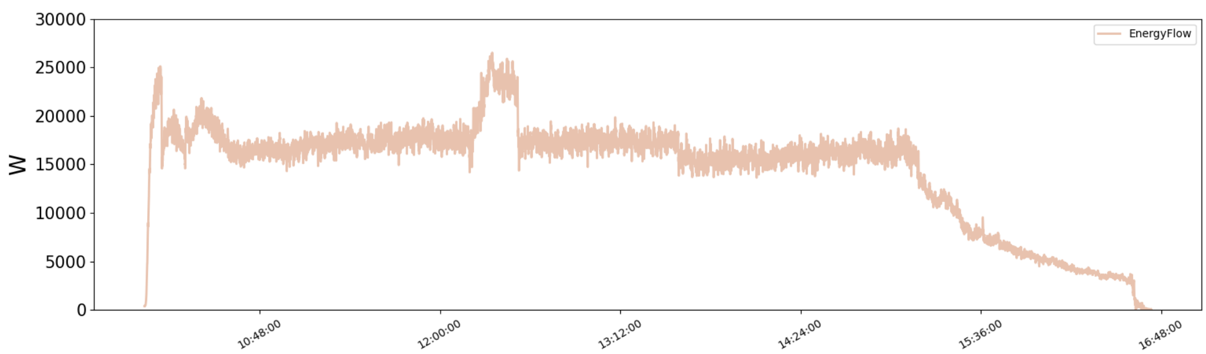


**Figure 15: Test 1 Energy Flow rate. This is the heat energy contained in the flue gas. It can be used to estimate thermal efficiency.**

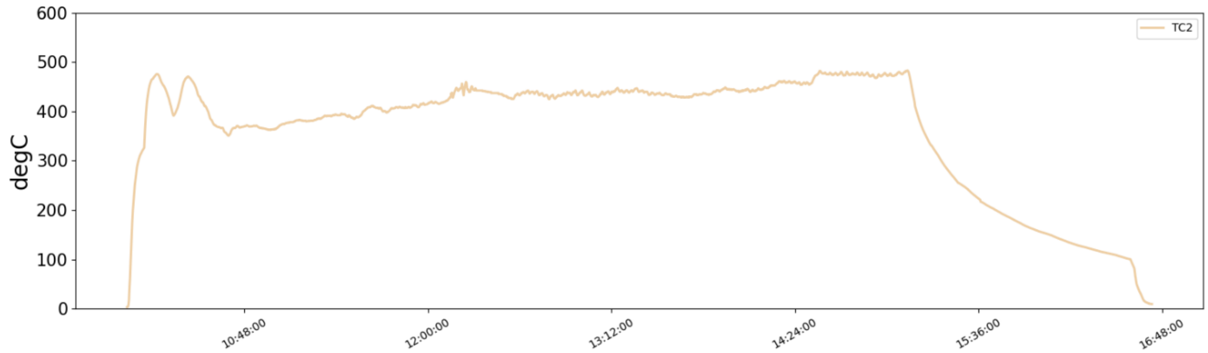


**Figure 16: Test 1 Flue gas temperature measured by the thermocouple**

# Test 2 Plots

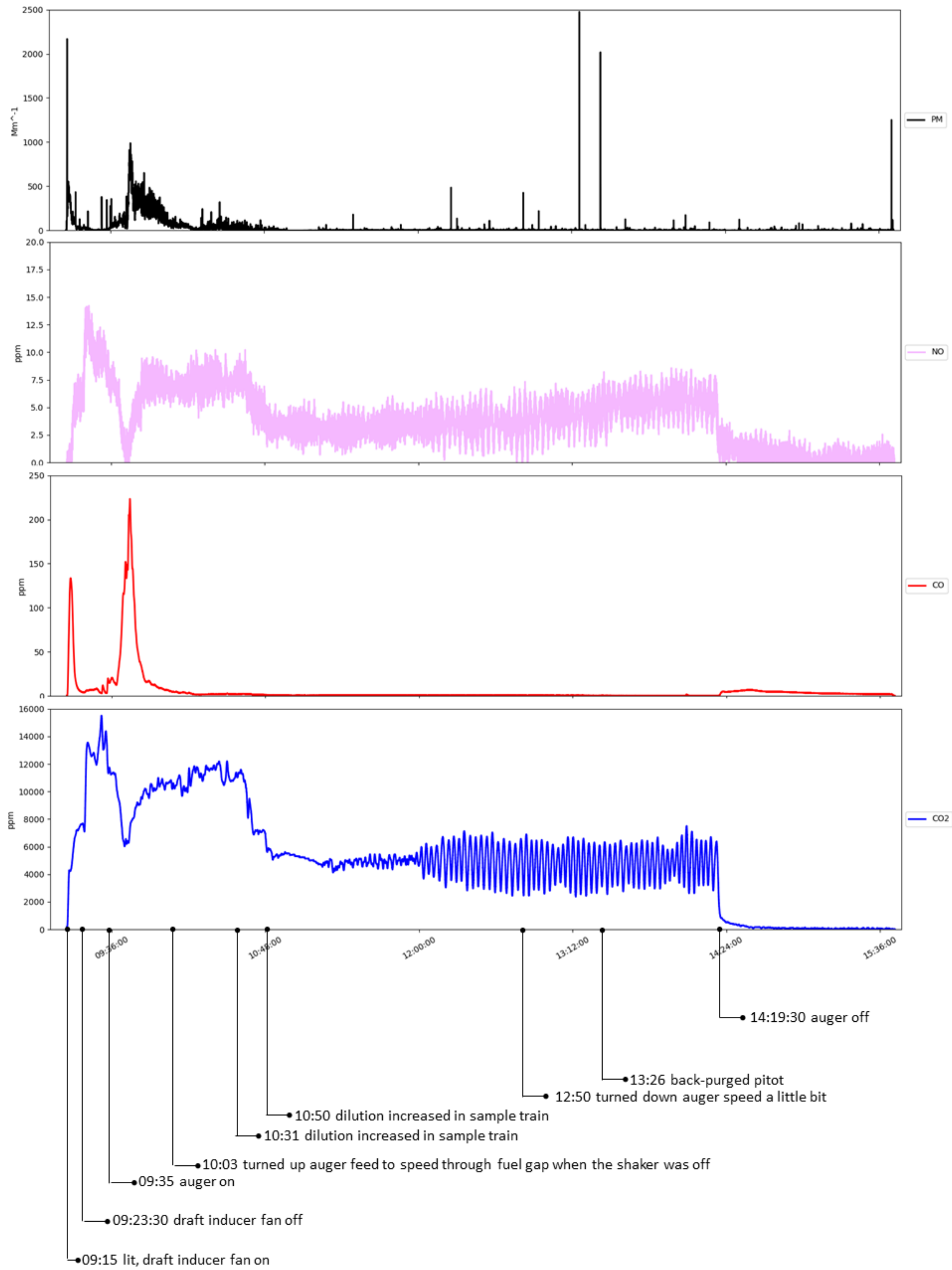


**Figure 17: Test 2 time series data of concentrations.**

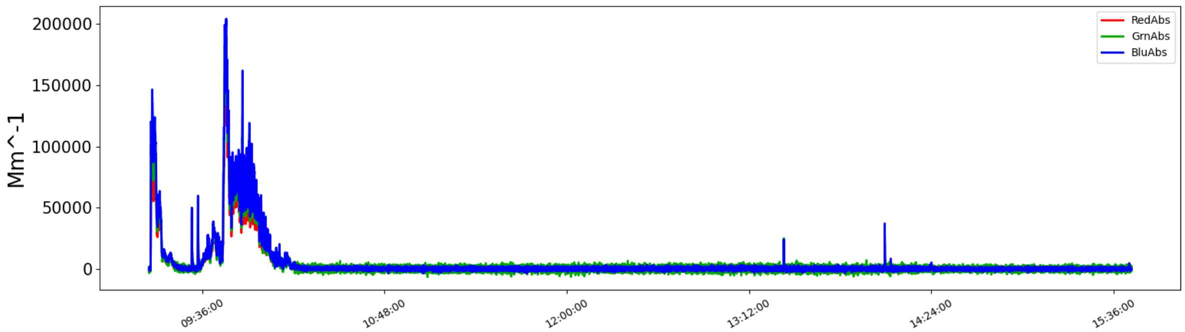


**Figure 18: Test 2 Particle light absorption from the TAP sensor. The trend matches the optical PM sensor data. The red, green, and blue absorption signals are all of similar magnitude, which indicates that the absorption is equal across all wavelengths, and the particles are black in color. This is consistent with the OC/EC analysis results that the particulate carbon is mostly elemental carbon.**

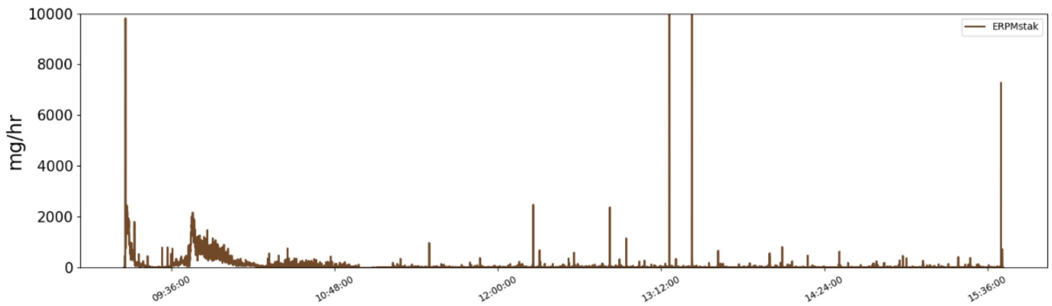


**Figure 19: Test 2 PM emission rate**

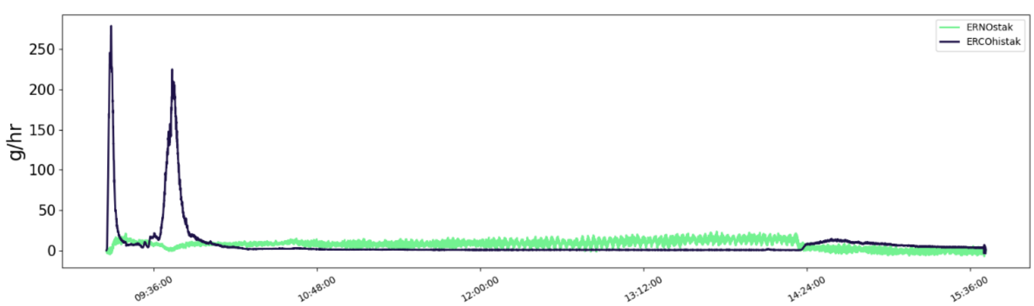


**Figure 20: Test 2 CO and NO emission rate**

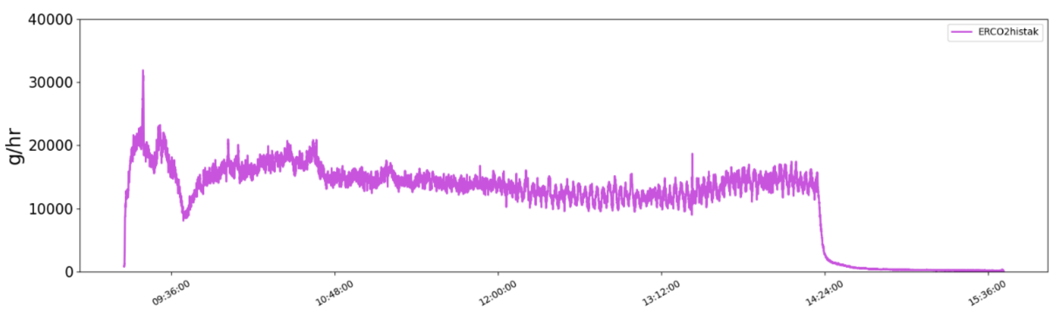

**Figure 21: Test 2 CO2 emission rate**

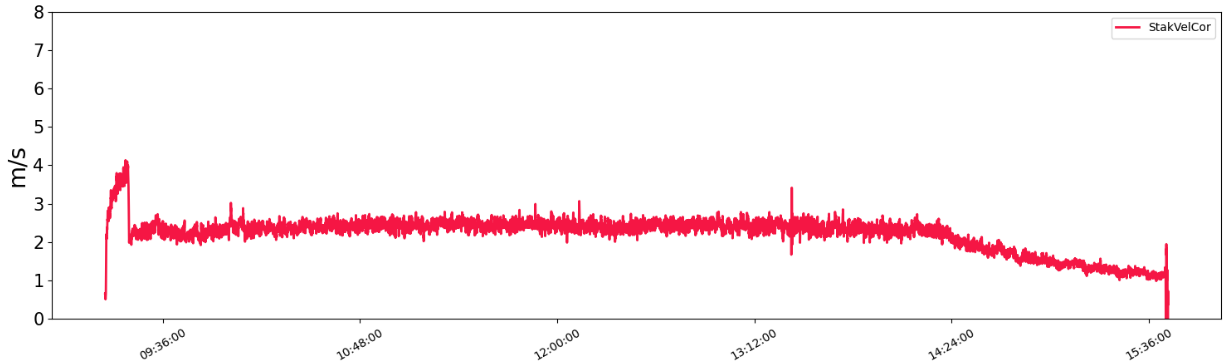


**Figure 22: Test 2 stack velocity measured by pitot tube. The spike at 13:30 is when the pitot tube was disconnected momentarily and back-purged with compressed air.**

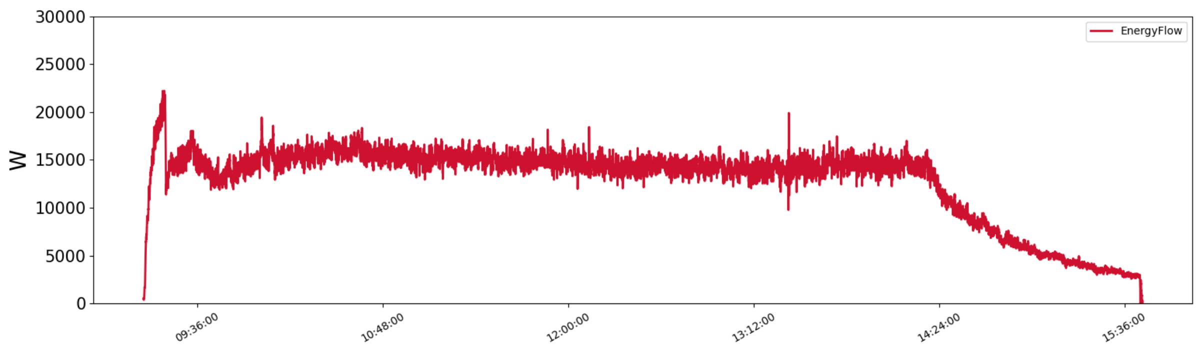


**Figure 24: Test 2 Energy Flow rate. This is the heat energy contained in the flue gas. It can be used to estimate thermal efficiency.**

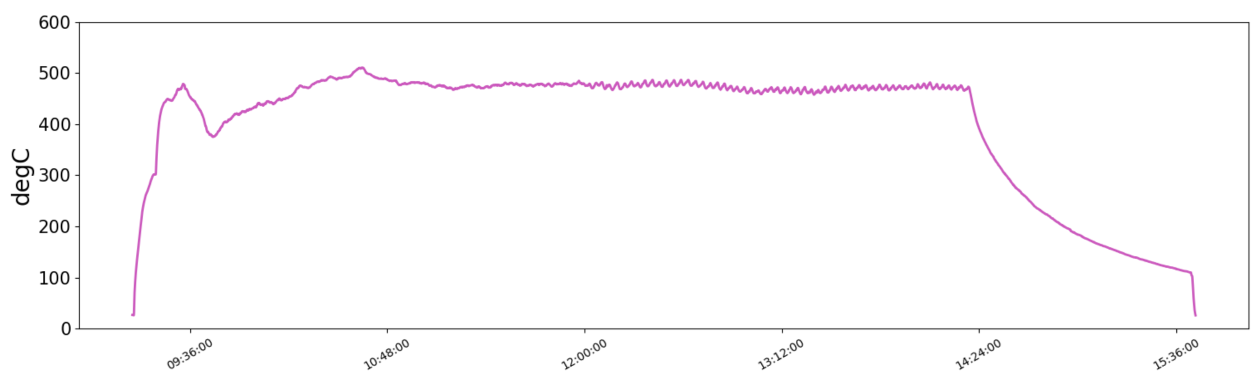


**Figure 25: Test 2 Flue gas temperature measured by the thermocouple**