Development of an Integrated Duty-Cycle Test Method for Cordwood Stoves

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Development of an Integrated Duty-Cycle Test Method for Cordwood Stoves

Final Report

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Notice

Abstract

In an effort to create an improved test method for residential wood heating devices, NESCAUM, developed the Integrated Duty-Cycle (IDC) test approach. The IDC test is designed to be accurate, representative, repeatable, and affordable; to address many of the problems identified with the US Environmental Protection Agency (EPA), ASTM, and the Canadian Standards Association (CSA) test methods; and to build on the "beReal" efforts in Europe to develop improved test methods.[1] The IDC approach incorporates emission measurements during typical operating situations, including start-up, reload, and transition from various heat output loads. The single-day test allows for replicate testing without increasing certification test costs. Unlike ASTM methods, the IDC is undergoing rigorous analysis using a variety of appliances to assess protocol performance prior to finalizing methods. A focus of this research is gathering data to characterize the precision of the IDC test methods. This report contains data from the Phase I research effort.

Keywords

Residential wood heating, wood stove, cordwood testing, test methods, certification testing, federal reference methods, particulate matter, carbon dioxide.

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Acronyms and Abbreviations

ASTM	American Society for Testing and Materials
ATM	Alternative test method
BNL	Brookhaven National Lab
CO	Carbon monoxide
CSA	Canadian Standards Association
EPA	U.S. Environmental Protection Agency
FRM	Federal reference method
g/h	grams per hour, which is an emission rate
g/kg	grams per kilogram, which is an emission factor
EN	European Nation
HHV	higher heating value, which refers to the heating value of a fuel with the water component of the fuel included.
IDC	Integrated Duty Cycle
ISO	International Organization of Standardization
kg/h	kilogram per hour, which is an appliance's burn rate
LHV	Lower heating value, which refers to the heating value of a fuel with the water component of the fuel removed.
M28	Refers to M28R, which is the federal reference method for crib wood testing that references ASTM 2780
NSPS	New Source Performance Standards
NYSERDA	New York State Energy Research Development Authority
pDR	personal data ram
PM	Particulate matter
TEOM	tapered element oscillating measurement
VOC	volatile organic compounds

Summary

Although wood burning devices provide a small portion of energy used in residences in the United States, the devices are a substantial source of air pollutant emissions. In 2017, residential wood burning devices in New York State were responsible for 51% of fine particulate matter ($PM_{2.5}$) and 69% of volatile organic compound (VOC) emissions from all stationary fuel combustion sources in the State (US EPA 2017). $PM_{2.5}$ and other wood smoke constituents are linked to a range of respiratory, cardiac, and neurological health effects, as well as increased mortality (Naeher, 2007). Nationally, residential wood smoke accounts for 20% of total stationary and mobile polycyclic organic matter (POM) emissions, 50% of all area source air toxic cancer risks, and 8% of overall noncancer (respiratory) risk (NATA 2011).

Wood stoves that perform well in the laboratory but produce much higher emissions in the field pose a risk to public health for users and nearby and downwind communities. This report documents an investigation of the factors that affect emissions from wood burning devices and the development of laboratory certification test procedures that better reflect in-field performance of these appliances than the current test methods. Improved emission certification test protocols would promote the design and manufacture of cleaner burning and more efficient residential wood burning devices.

The United States Environmental Protection Agency's (EPA) New Source Performance Standards (NSPS) for residential wood heaters limit emissions of particulate matter (PM) from new wood-fired residential heaters. A wood heater model is certified as compliant with the NSPS requirements if emissions from a prototype appliance, as measured by an EPA-qualified testing laboratory, are consistent with those limits.

The current federal reference certification method for wood stoves, EPA's Method 28R (M28) crib wood test, is a "hot to hot" steady-state test that burns a specified configuration of dimensional Douglas fir lumber with spacers. M28 builds on ASTM[2] Method 2780, which incorporated EPA's original Method 28 with some modifications. Because M28 does not replicate typical consumer fueling and operating conditions and does not record emissions during start-up periods, the certification results do not accurately represent in-use emissions.

ASTM has since developed a cordwood wood stove test method. The EPA has designated that method, ASTM 3053-17, as a Broadly Applicable Alternative Test Method (ATM) procedure for certifying compliance with the NSPS emissions standards. However, many of the problems in the M28 are not addressed in the ASTM 3053-17 procedure, which measures the stove's average performance across long steady-state burns. The ASTM 3053-17 test provides limited information about emissions that occur during cold-starts, fuel reloads, and the end phases of stove operation. In addition, those procedures do not generate replicate data that would allow for an assessment of the reproducibility of results.

Emissions from wood burning devices are far more variable than those produced by appliances that burn other fuels. Natural gas and heating oil are homogeneous fuels with consistent physical and chemical parameters. By contrast, the wood burned in residential wood heaters is highly heterogeneous, encompassing a range of species, moisture contents, piece sizes, densities, and bark and resin contents. Gas and oil fuels are mechanically fed to the heating appliances. Cordwood stoves are filled by the user, which introduces significant variability in burn characteristics. Further, operators have control over door position, airflow and other settings that affect stove performance and emissions. An effective emission certification test procedure must include elements and approaches that capture and measure this inherent variability.

It is not possible to test the full range of homeowner stove use patterns. A 2019 study found that homeowner use patterns varied widely across appliances and even within the same home over a month-to-month or year-to-year period. (Ahmadi 2019). Because achieving a "real-world" test is not feasible, a more effective approach is to assess an appliance's operation over variable conditions. To accurately represent stove performance in the field, a certification test must account for in-use variability in fueling and operating parameters while providing sufficient specificity to allow the results to be reproducible and to allow comparisons between models. The Northeast States for Coordinated Air Use Management (NESCAUM) collaborated with various partners to develop new test methods for stoves and central heating units that fulfill those criteria. Collectively, these protocols are known as the Integrated Duty Cycle (IDC) test methods.

The IDC methods are designed to be accurate, representative of in-use conditions, repeatable and affordable, and to address many of the shortcomings identified with EPA, ASTM, and Canadian Standards Association (CSA) test methods. The IDC protocol: (1) characterizes variability with greater precision than current methods; (2) captures representative operations, including start-up, reload periods, and a variety of heat loads; (3) includes simpler and more accurate PM measurement approaches; (4) better measures efficiency; and (5) reduces the time to conduct certification tests. The single-day test allows for replicate testing without appreciably increasing certification test costs. It also provides a framework that can be easily adjusted if the state of knowledge changes, requiring changes to the protocols.

This report presents the results of a series of emissions tests on eight wood burning stoves. The tests were designed to evaluate existing methods, to develop the IDC Test Method for Certification of Wood-Fired Stoves Using Cordwood, and to analyze the replicability and comparability of test results. In this paper, the term “replicable” refers to the reproducibility of results in multiple identical tests on the same unit while “comparable” refers to equivalency among different models and test procedures. The ultimate goal of this effort is to inform the development of a full suite of next generation test method protocols that will promote the design and manufacture of cleaner burning and more efficient residential wood burning devices.

The report first provides an overview of the study design and methods. The overview is followed by a detailed presentation of the results of tests performed on each stove, and then an evaluation of the parameters measured in those tests and how the results inform the development of a replicable certification test that best represents common fueling and operating conditions. The implications of the study results are then presented in Section 4: Findings and Recommendations. Those findings, along with the underlying study data and analysis, provide information that can be used by policymakers, manufacturers, test labs, and researchers seeking to reduce the impacts of wood stoves on air quality.

1 Study Design and Methodology

In an effort to evaluate emissions and emissions testing in a cross section of the market, laboratory testing was conducted on eight different models of wood stoves of various sizes and construction types. The stoves included those with catalytic, non-catalytic, and hybrid emission control systems. Table 1 provides an overview of the characteristics of the stoves used in this study.

Table 1. Study Stoves

Stove #	Construction Type	Firebox Size	Emission Control Technology	EPA 2015 NSPS Certification Value
Stove 1	High mass	3.1 ft^3 - Large	Non-catalytic tube	Step 1 cert value <3.0 g/h
Stove 2	High mass	1.3 ft^3 - Small	Catalytic	Step 2 cert value <2.0 g/h
Stove 3	Steel	3.2 ft^3 - Large	Catalytic	Step 1 cert value <2.0 g/h
Stove 4	Cast iron	0.8 ft^3 - Small	Non-catalytic tube	Step 1 cert value <4.0 g/h
Stove 5	Cast	2.1 ft^3 - Medium	Non-catalytic non-tube	Step 1 cert value <2.0 g/h
Stove 6	Steel	2.2 ft^3 - Medium	Non-catalytic tube	Step 1 cert value <4.0 g/h
Stove 7	High mass	1.9 ft^3 - Medium	Hybrid—catalytic/non-catalytic	Step 2 cert value <2.0 g/h
Stove 8	Steel	1.7 ft^3 - Medium	Non-catalytic tube	Step 1 cert value <4.0 g/h

Due to equipment malfunction, testing of Stove 3 was discontinued and the results of tests on that stove are not included in this document.

A variety of protocols were employed to enable comparisons of stove performance across currently approved federal certification test methods, the IDC alternative method, and research protocols. Testing included the following:

- Baseline runs using modified EPA Method 28 R (M28) crib wood certification testing procedures. M28 is EPA's Federal Reference Method (FRM) for testing wood heater.
- Tests using the ASTM 3053-17 cordwood wood stove test method, which has been designated by the EPA as a Broadly Applicable ATM.
- Research and development runs designed to develop and refine NYSERDA's alternative cordwood testing method, the IDC protocol.
- IDC final protocol tests.

The M28 crib wood test is a "hot to hot" steady state test that burns a specified configuration of dimensional Douglas fir lumber with spacers. The test begins after a hot coal bed has been established and continues at a specified unchanged air setting until 100% of the fuel load is burned. The method requires the completion of four separate runs at different air settings:

- Category 1 average dry-burn rate: <0.8 kilograms per hour (kg/h)
- Category 2 average dry-burn rate: 0.80 to 1.25 kg/h
- Category 3 average dry-burn rate: 1.25 to 1.90 kg/h
- Category 4 at the stove's maximum burn rate

PM emission rates (ER) measured in the four runs are then weighted according to burn rate probability factors specified in the method to calculate a weighted average ER, which is used to certify compliance with the New Source Performance Standards (NSPS) limit.

In this study, the researchers performed baseline tests on all study stoves using M28 procedures at three of the four air settings prescribed in that method: the highest air control setting (category 4), the lowest setting (generally category 1), and the manufacturer's recommended air setting for a medium burn rate (category 2 or 3). As stipulated in the M28 protocol, all baseline test runs burned dimensional Douglas fir as a test fuel. In all test runs, PM was measured using two types of measurement methods: (1) real-time PM measurements with a tapered element oscillating microbalance (TEOM) and a personal data ram (pDR) and (2) the ASTM 2515 filter measurements required in the federal certification test program. Real-time PM measurements enabled the evaluation of the changes in emissions and correlation of emissions with other parameters of interest throughout all test phases, which is not possible using only the traditional filter-based PM measurement method.

Baseline runs were used to: (1) evaluate the impact of air setting and other operating parameters on PM emissions in stoves of differing sizes, construction materials, and control technologies; (2) compare the emissions rate (ER) in grams per hour (g/h) and emissions factor (EF) in grams per kilogram of fuel burned (g/kg) measured at the end of the M28 runs (when 100% of the load had been combusted) with the ER and EF at 90% fuel consumption; and (3) compare M28 ERs and EFs, as well as temperatures and other operating parameters, with those measured using other test methods.

As a Broadly Applicable Alternative Test Method, manufacturers can choose to use the ASTM[3] 3053-17 cordwood test in place of the M28 crib wood test to certify compliance with the NSPS cordwood limits. A complete ASTM 3053-17 test consists of two runs. Each run begins with a start-up/high air setting phase.

After 90% of the high air load is consumed, a medium air setting burn is conducted in one run and a low air setting burn in the other. The medium and low setting burns are continued until 100% of the load has been consumed.

ASTM 3053-17 cordwood tests were conducted on four of the study stoves, stoves 1, 6, 7, and 8 to conduct a comparison of the two methods. In stove 6, complete ASTM 3053-17 tests were performed with three different fuel types; maple, red oak, and beech; allowing for a comparative analysis of the effect of fuel type on the stove's performance and emissions.

The IDC test measures PM and carbon monoxide (CO) emissions, heating efficiency, and operating parameters such as temperatures and air flow. Real-time PM emissions data are collected using a TEOM placed in a dilution tunnel. Use of a dilution tunnel allows the flue gas to cool and PM to condense prior to measurement.

A complete IDC test includes three replicate runs. Each run consists of four phases: start-up, high-fire, maintenance fire, and a low-fire large load burn. A fuel load calculator is used to determine the allowable sizes of the load, coal bed, and fuel pieces for each phase, based on the dimensions of the stove's firebox.

The start-up phase begins with a cold start and the air setting on high. Kindling is loaded at a density of 1 pound per cubic foot (lb/ft^3) of firebox volume and starter fuel at a density of 3 lb/ft^3. The phase ends when the coal bed reaches the weight specified by the fuel load calculator, when 75% of the start-up load has been consumed. The protocol requires use of maple (big leaf, red, or silver) cordwood with a moisture content between 22% to 27% on a dry basis.

The high-fire phase starts immediately after the end of the start-up phase and is designed to replicate operating conditions commonly employed by stove owners to quickly heat an area shortly after restarting an appliance. In this phase, small pieces of wood are loaded at a density of 7 lb/ft^3. Air settings are fully open for the first half of this phase and are changed to the lowest setting when 50% of the fuel load has been consumed. The air setting change represents common in-use practices and ensures that the stove temperatures at the end of the phase are typical of those in the field. Abnormally high temperatures would affect emissions in the following phase. The high-fire phase ends when 90% of the load has been consumed.

The maintenance phase, which begins immediately after the end of the high-fire phase, represents conditions when stoves are attended or semi-attended to maintain heat. At this point, the stove has a well-developed coal bed. Large cordwood pieces are loaded to a fuel density of 5 lb/ft^3. Airflow remains at the lowest setting throughout the phase, which ends when 90% of the load has been consumed.

The final phase, the low-burn phase, is intended to represent periods when homeowners want to sustain heat over an extended period without attending to the fire, as may occur overnight or when residents are away for several hours. A large coal bed is present at the beginning of this phase. The stove is fully loaded with a mix of small and large cordwood pieces, with large pieces, as defined by the fuel calculator, making up at least 50% of the fuel charge load, by number of pieces. Fuel is loaded in one direction with as many pieces as can be added without force, to a load density of 12 lb/ft^3. The air setting is kept on low and the test ends when 90% of this load has been combusted.

The phases of the IDC protocol runs are summarized in Table 2.

Table 2. Summary of IDC Protocol

Load	Fueling and Operating Parameters
Start-up	Cold Start, bottom-up loading; up to 6 pieces of paper; kindling density—1 lb/ft^3 max; 3 lb/ft^3 starter fuel (minimum piece weight determined by calculator). Air fully open or according to User Guide. Burn 75% of load, by weight.
Reload 1 High-fire	Load density—7 lb/ft^3; small cordwood pieces; random loading pattern. High air setting. When 50% is burned, switch to lowest air setting. Burn 90% of load, by weight.
Reload 2 Maintenance	Load density—5 lb/ft^3; random loading pattern. Lowest air setting. Burn 90% of load.
Reload 3 Overnight	Load density—12 lb/ft$^{3;}$ mix of small and large cordwood pieces; loaded in one direction to maximum volume. Lowest air setting. Burn 90% of load.

Table 3 compares the IDC Protocol with the M28 and ASTM 3053-17 methods.

Table 3. Comparison of Key Characteristics of EPA, ASTM, and IDC Test Method Approaches

Element	M28	ASTM 3053-17	IDC
Operational Parameters			
Number of loading events	1	1 in low and medium runs, 2 in start-up/high run	4
Start-up	No	Yes, combined with high fire	Yes, separate phase
High fire	Yes	Yes, combined with start up	Yes
Maintenance—semi-active attended burn	No	No	Yes
Overnight burn	Yes	Yes	Yes
Replicates	None	None	3
Long charcoal tails	Yes	Yes	No
Protocol supported by user data	No	No	Yes
Precision and variability data	No	No	Yes
Fueling Parameters			
# of different load sizes by weight	1	2	4
# different piece configurations	1	1	4
# of allowed fuel species allowed	1	Unlimited based on density	2
Impact of species data	No	No	Yes
PM Measurement			
Real-time PM measure	No	No	Yes

In this study, a total of 14 research runs were performed on stoves 1, 2, 4, 5, and 6 to refine the IDC test method. The research runs evaluated the effect of the following factors on stove performance and emissions:

- Configuration of start-up fuel (top-down versus bottom-up burn).
- Fuel density (5 lb/ft^3 in the high-fire phase and 7 lb/ft^3 in the maintenance phase versus 7 lb/ft^3 in high-fire and 5 lb/ft^3 in maintenance).
- Air setting in the high-fire phase (high setting for entire phase versus a switch from high to low when 50% of the load was combusted).
- Effect of a maintenance phase on the subsequent low-burn phase (maintenance phase included or excluded from the test).
- Air setting in the maintenance phase (medium versus low).

Complete IDC tests, consisting of three replicate tests, were performed on all stoves using seasoned red maple cordwood. To evaluate the effect of fuel species on emissions, operating parameters and replicability, IDC tests were also run with other fuel species and performed in two stoves: oak in stove 6 and oak and poplar in stove 7. As discussed above, ASTM 3053-17 tests using red oak and beech, as well as maple, were also performed on stove 6. To evaluate the impact of moisture content on those metrics, IDC tests were conducted on stoves 6 and 7 using oak cordwood before and after seasoning. The moisture content measured in the seasoned oak loads ranged from 19.7% to 22.3%, on a dry fuel basis, and was 27.2 to 29.6% in the wet oak loads.

Testing was conducted at Hearth Lab Solutions (HLS) in Randolph, Vermont. The HLS testing followed quality assurance plan procedures for documentation, records, sampling methods, sample handling procedures, chain of custody, analytical methods, testing, instrumentation, calibration, data acquisition, data management, data review, and data validation similar to those used for an EPA project that required an EPA Level 2 Quality Assurance Project Plan (QAPP). Details of the quality assurance, quality control plan can be obtained from NESCAUM.

As discussed above, a tapered element oscillating microbalance (TEOM) was used to measure dilution tunnel PM concentrations. Details about the TEOM method and the quality assurance/quality control procedures used in those measurements are included in the Standard Operation Procedures for Thermo 1405 TEOM®. Routine QC checks included TEOM inlet flow measurements before and after each test run, performed with a TSI model 4140 mass flow meter. These external checks were compared to the reported flow from the TEOM's internal mass flow meter, with a difference of more than 5% triggering corrective action. Instrument parameters needed for data validation, such as sensor temperatures and flows, were collected along with the PM concentration data and were used to screen data at the 1-minute level for proper instrument operation. The TEOM data files included with this report include all these operational parameters. Post-processing of data used standard procedures and quality assurance and quality control measures. Those procedures are attached as appendix A.

Two TEOM models were employed in this study, Thermo Scientific model 1400AB and 1405. The 1400AB TEOM was used from the start of this work in October 2017 until October 18, 2018 and the 1405 TEOM was used for the remaining period of the study. When the change from the 1400AB to the 1405 TEOMs was made, a single test day of data was collected with both instruments to assess comparability. Agreement was excellent, with a 1.5% difference in average PM and a R^2 of 0.998 for 10-minute block average PM concentration data. However, there was an observed difference between the 1400AB and the 1405 TEOM cordwood tests when compared to the manual filter samples. While both models of TEOM were well correlated with the manual filter samples and with non-significant intercepts, the 1400 slope was 0.82 (SE=0.02) and the 1405 slope was 0.98 (SE=0.02).

There are some differences in the two TEOM models that could explain some of this divergence. First, the heated down-tube in the 1400 is ~30% longer, providing more surface area and residence time for SVOC aerosol to condense on the tube surface. Second, there is an instrument software error in the 1405 caused by a database timing issue (personal communication, Maria Johncox, Thermo Fisher Scientific) that when combined with other instrument software characteristics results in an approximately 5% positive bias in the reported PM data. Additional collocation of the 1400 and 1405 TEOMs showed the 1400 to be between 8 and 13% lower than the 1405, but well correlated, with $R^2 > 0.99$. Because of this difference, the TEOM model is flagged in this report as a potential source of variability when the results of runs performed using different instruments are compared. Because the 1400AB TEOM is now obsolete and no longer supported by Thermo, the 1405 model will be used in all future tests.

The precision of TEOM measurements was evaluated using collocated 1405 TEOMs to measure emissions from high-emitting (PM concentration of 12 mg/m^3) and low-emitting (PM concentration less than 2 mg/m^3) appliances. In both cases, the collocated TEOMs showed very good correlation and numerical agreement. For the high emission test, the regression slope is 1.015 and the $R^2 = 0.998$, while for the low emission test, the regression slope was 0.972 and the $R^2 = 0.977$. More information about the precision analysis will be presented in an upcoming paper and is available from NESCAUM.

The upcoming NESCAUM TEOM paper also presents the results of several experiments designed to compare TEOM PM measurements with those obtained using the current filter-based methodology. The run-average measured PM concentrations obtained from the manual filter pulls (final equilibrated data, with catch) and the TEOM were compared using ordinary least squares linear regressions with the filter pull PM as the known variable; this is the most rigorous validation of proper operation for both systems, serving as a level 2 external consistency data validation step. Data from the 1400 model was analyzed separately from 1405 data. For the cordwood stove tests in this report, the coefficient of determination (R^2) was 0.97 for both the 1400 and 1405 data sets. The regression slope for the 1400 was 0.819 (TEOM

PM lower than filter pull); for the 1405 it was 0.976. For crib wood tests with the 1400AB TEOM, the slope was 0.885 and R^2 was 0.96. None of the regression intercepts were significantly different from 0 at a 95% confidence interval. TEOM data do not include prove "catch," which can be several percent of the total mass for filter pull samples and is one factor causing TEOM data to be lower.

In Test Results by Stove, section 2 of this document, the results of tests performed using M28, ASTM 3053-17, and IDC methodologies are presented for each stove. That section also includes an analysis of stove parameters that may explain those results, the replicability of results from multiple runs using the same method, and the comparability of results obtained using different methods. Three PM metrics are reported for each phase of each test: total PM emitted, the PM EF in grams of PM per kilogram of fuel combusted (g/kg) and the PM ER in grams of PM per hours of run time (g/h). Other parameters also provide information about the stove operation, including the surface temperature of the exhaust stack, which is indicated in this document as "stack temperature," and the average stove temperature, which is the average of the surface temperature measured by probes at five locations on the stove (top, bottom, right, left, and back).

In Comparative Analysis, section 3, test results using the above protocols, as well as the research runs performed to develop and refine the IDC test, are used to analyze the impact of the following on the PM emissions metrics listed above and other critical parameters, including thermal efficiency, expressed as higher heating value (HHV):

- Run time that corresponds to consumption of 90% versus 100% of the fuel load.
- Start-up conditions, including start-up load configuration and stove door position.
- Load density, fuel piece size and air settings.
- Fuel species and moisture content.

That section also includes an analysis of the replicability of the IDC test runs performed on each stove and an analysis of CO emission rates measured in the IDC tests.

2 Test Results by Stove

As described in Study Design and Methodology, section 1, eight stoves, identified as stoves 1-8, were tested. Testing of stove 3 was suspended, and that stove is not included in the discussion due to operational problems with that appliance. Tests were performed on the other seven stoves (stoves 1, 2, 4, 5, 6, 7, and 8) using the EPA Method 28 (M28) crib wood method and the IDC protocol cordwood method. In addition, four of the stoves (stoves 1, 6, 7, and 8) were tested using the ASTM Method 3053 cordwood test and a variety of research runs, primarily designed to refine the IDC method, were conducted. Test results by stove are presented in this section.

2.1 Stove 1

Stove 1 is a large, high-mass stove with non-catalytic emissions controls. A total of 15 tests were performed on stove 1, as listed in Table 4. Test IDs are composed of the stove number (S1) and the test date. Descriptions of the research and development (R&D) and IDC test protocols include two key parameters: the weight of fuel loaded per cubic foot of the stove firebox (lb/ft^3), represented by the symbol "#", and the air setting (high, medium, or low). Each ASTM 3053-17 run is divided into two parts (start-up + high, followed by either a medium or low load) and separate test IDs are assigned to each part of those tests. Fuel loads for the ASTM 3053-17 tests are defined as the weight of the wet wood, consistent with that protocol.

Table 4. Stove 1—Test Descriptions

Test ID	Test Method	Fuel Species	Fuel Type	Description
S1-17-10-03	M28 (baseline)	Douglas Fir	Crib	High fire, load burned 100%
S1-17-10-06	M28 (baseline)	Douglas Fir	Crib	Medium fire, load burned 100%
S1-17-10-04	M28 (baseline)	Douglas Fir	Crib	Low fire, load burned to 100%
S1-18-01-19	IDC v1 (research)	Red Maple	Cord	Cold start Reload 1 (RL1) - 5# at high RL2 - 7# at medium RL3 - 12# at low
S1-18-03-01	R&D	Red Maple	Cord	Cold start bottom-up kindling RL1 - 7# at high
S1-18-03-16	R&D	Red Maple	Cord	Cold start top-down kindling RL1 - 7# at high RL2 - 5# at medium

Table 4 continued

Test ID	Test Method	Fuel Species	Fuel Type	Description
S1-18-05-08	R&D	Red Maple	Cord	Cold start top-down kindling RL1 - 7# at high shut to low at 50% burned RL2 - 12# at low to 90% burned
S1-18-05-09	R&D	Red Maple	Cord	Cold start top-down kindling RL1 - 7# at high shut to low at 50% burned RL2 - 5# at low RL3 - 12# at low to 90% burned
S1-18-05-31-1	ASTM 3053-17	Red Maple	Cord	Start-up (15.8 lb)[b] + high fire (31.7 lb)
S1-18-05-31-2	ASTM 3053-17	Red Maple	Cord	Low fire (31.1 lb)
S1-18-06-04-1	ASTM 3053-17	Red Maple	Cord	Start-up (16.2 lb) + high fire (32.5 lb)
S1-18-06-04-2	ASTM 3053-17	Red Maple	Cord	Medium fire (35.9 lb)
S1-18-08-08 (Replicate 1)	IDC Final Protocol	Red Maple	Cord	Cold start bottom-up RL1 (High-fire phase) - 7# at high shut to low at 50% burned RL2 (Maintenance phase) - 5# at low RL3 (Overnight phase) - 12# at low
S1-18-08-09 (Replicate 2)	IDC Final Protocol	Red Maple	Cord	Same as Replicate 1
S1-18-08-10 (Replicate 3)	IDC Final Protocol	Red Maple	Cord	Same as Replicate 1

[a] Symbol # denotes fuel loading density in pounds per cubic foot of the stove firebox (lb/ft^3).

[b] In ASTM 3053-17 testing, fuel loads are defined as the weight of the wet wood.

The 1400AB TEOM was used for continuous PM measurements in all stove 1 test runs. The results of M28, ASTM 3053-17, and the IDC final protocol Stove 1 Tests are presented below. The research runs, which were used in the development of the IDC final protocol, are discussed in section 4.

2.1.1 Baseline Tests

Baseline tests were conducted using EPA Method 28 (M28) procedures at three of the four air settings prescribed in that method: the highest air control setting (Method 28 Category 4), the lowest setting (category 1), and the manufacturer's recommended air setting for a medium burn rate (category 2 or 3). As stipulated in the M28 protocol, all baseline test runs burned dimensional Douglas fir as a test fuel. Particulate matter (PM) emissions were measured continuously with a tapered element oscillating microbalance (TEOM), which enable collection of continuous PM emissions data over the course of each burn, as well as with the PM filter methodology prescribed by M28.

Table 5 summarizes the results of the baseline modified M28 testing. At the lowest air control setting, the appliance achieved a burn rate in category 3, similar to the burn rate at the medium air setting. Results are presented for combustion of 100% and 90% of the fuel load. The M28 protocol requires tests to be run until 100% of the fuel load is burned. However, because wood stove owners often refuel before the previous load has been completely burned, the parameters associated with combustion of 90% of a fuel load may more accurately reflect stove performance under actual in-use conditions. A more detailed comparison of the results of 90% and 100% combustion is presented in section 2.

Three PM emissions metrics are presented in Table 5: (1) Total PM emitted, in grams (g), (2) the PM Emission Rate (ER), in grams/hour (g/h), and (3) the PM Emission Factor (EF), in grams/kilograms fuel combusted (g/kg). Because fuel weights are similar in the three runs, EFs correlate well with the Total PM measurements. However, this is not necessarily the case with the ER, because that metric also considers the length of the run, a parameter that varies with air settings. The Higher Heating Value (HHV) thermal efficiency of each run, which is calculated from carbon monoxide and carbon dioxide measurements, are also included in Table 5.

Table 5. Stove 1—Modified M28 Test Run Metrics

	Test Time (min)		**Dry-Burn Rate (kg/h)**		**Total PM (g)**		**PM Emission Rate (g/h)**		**PM Emission Factor (g/kg)**		**HHV Efficiency (%)**
% Burn	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*100%*
High	90	123	5.21	4.20	12.14	11.71	8.09	5.67	1.55	1.35	33.4
Medium	168	262	2.64	1.88	13.02	12.76	4.65	2.92	1.76	1.55	49.7
Low	216	327	2.08	1.52	24.20	23.76	6.72	4.36	3.22	2.84	50.8

The HHV efficiency of the stove was lowest in the high burn run (33.4%) and highest in the low burn run (50.8%).

Total PM emitted and the PM EF were highest in the low burn run and lowest in the high burn run. However, because the run time was considerably shorter in the high burn run than in the others runs, that burn had the highest ER. A more detailed discussion of PM emission follows.

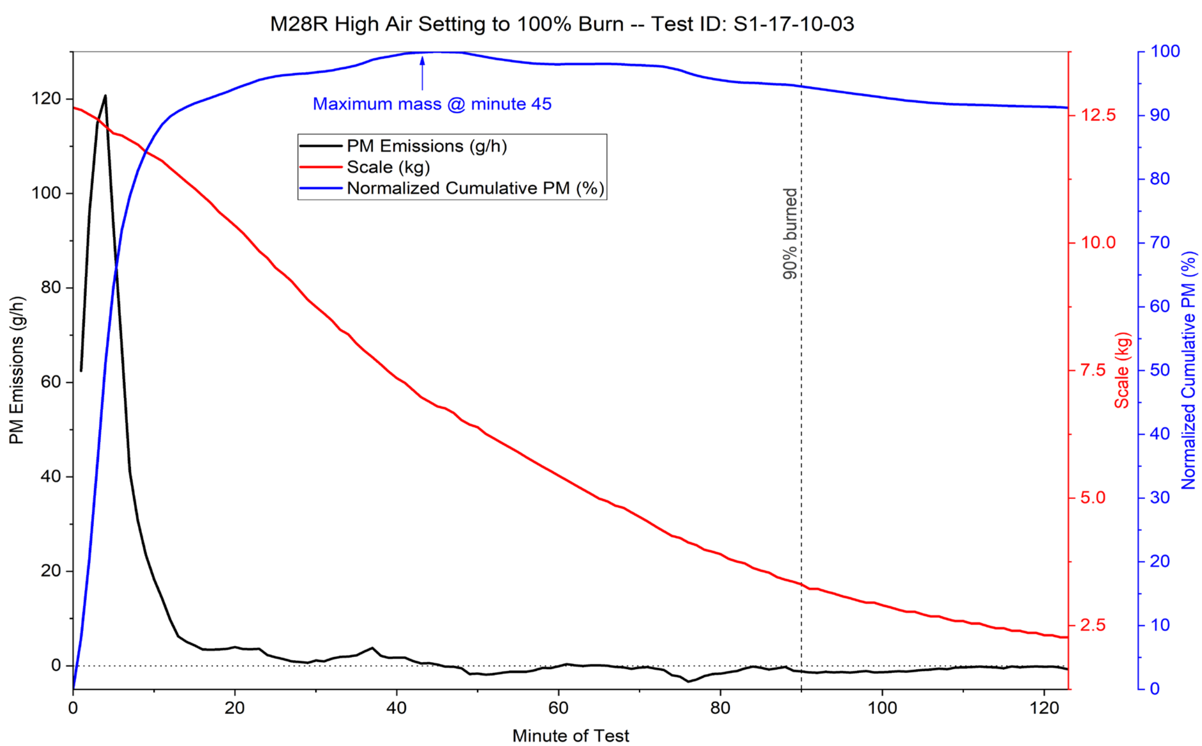
2.1.1.1 Real-Time Measurements Plots

Plots of real-time measurements for the three stove 1 M28 test runs are presented in Figure 1 below. The real-time TEOM PM emission rate profiles are shown in black in those plots. Virtually all PM was emitted early in all three runs and the latter part of the each run inlcuded an extended period of zero or negative emission measurements. The TEOM records negative emissions when clean, hot air passing through the TEOM filter volatlizes the more volatile species of the PM collected earlier in the run.

The blue line in each of the run profile plots represents the cumulative PM collected during the test run, normalized to the maximum cumulative PM measurement in that run. In all M28 stove 1 runs, the maximum cumulative PM occurred before 90% of the fuel charge weight had been consumed and well before 100% fuel consumption (the end of the test), due to the volatilization losses discussed above.

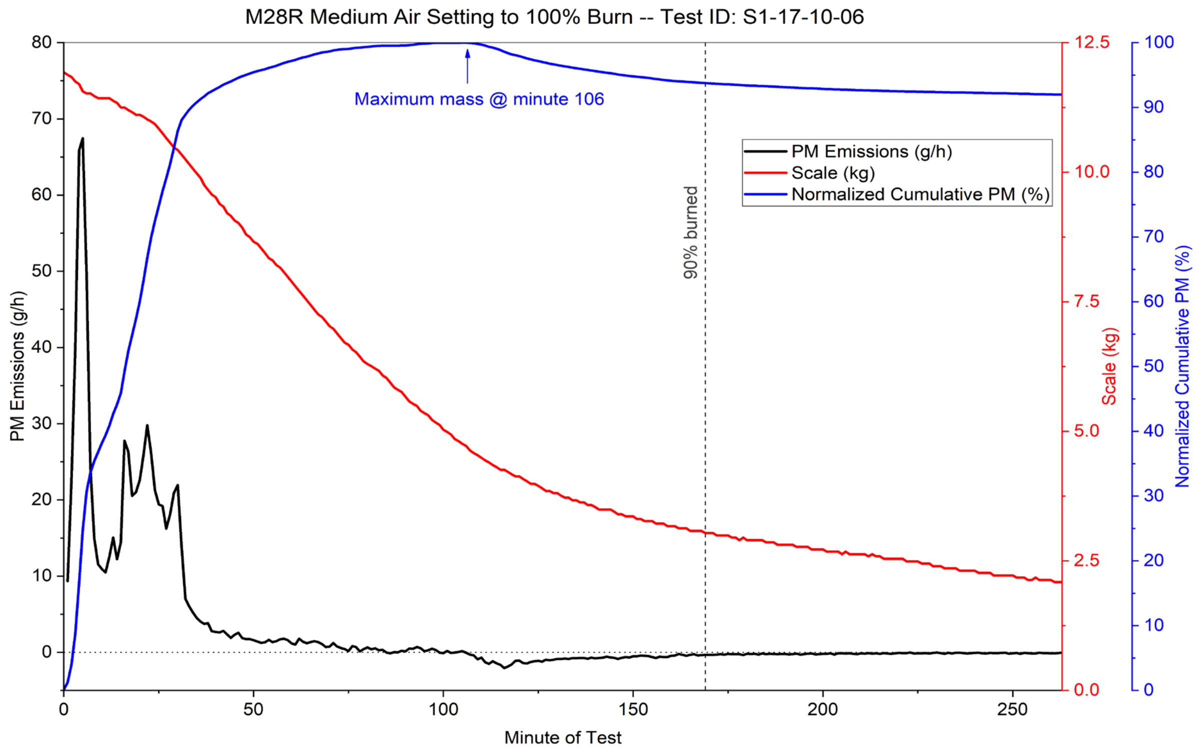
The red line in the plots shows the weight of the fuel remaining at each point of the test. The time that 90% of the fuel had been consumed is marked with a vertical line. The impact of testing to 90% versus 100% fuel consumption is discussed in more detail in section 5.1.

Figure 1. Stove 1—M28 Baseline Test Results

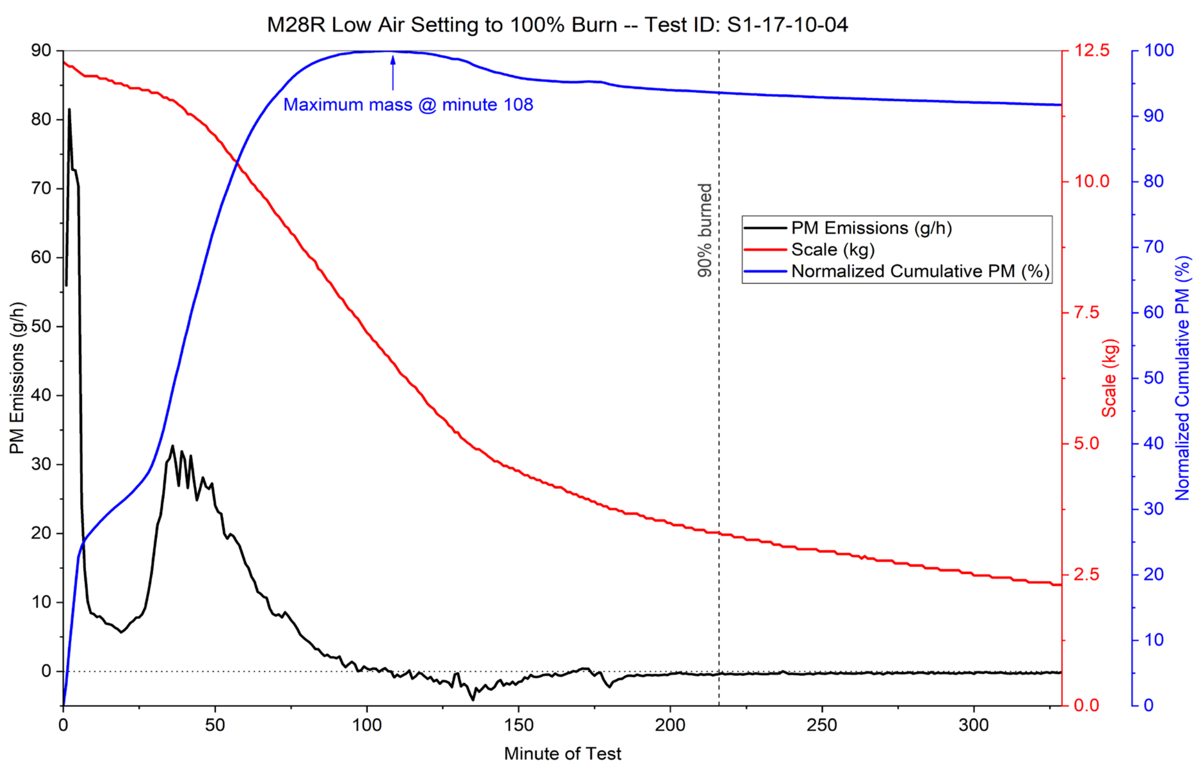


* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Figure 1 Continued



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

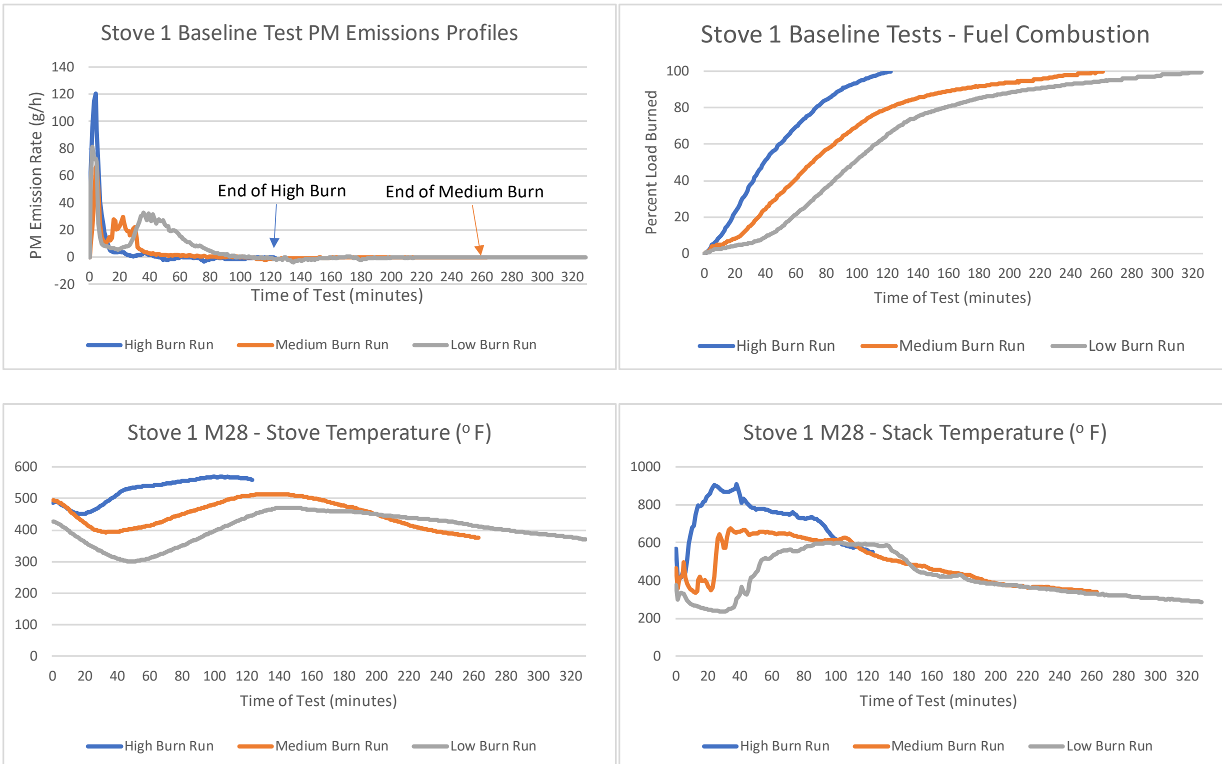
2.1.1.2 PM Emissions Profiles

As can be seen in Figure 1, almost all (92%) of PM emissions occurred in the first 15 minutes of the high-fire run. The maximum instantaneous PM ER for that run, 120.7 g/h, occurred at minute 4 and was followed by a rapid drop in emissions. PM emissions in the medium and low burns also peaked in the first few minutes of the burn, as shown in Figure 2. The peak instantaneous emission rates for those runs, 67.4 g/h at 5 minutes for the medium burn and 81.5 g/h at 2 minutes for the low burn, were lower than in the high-burn run.

Unlike the high burn, significant PM emissions continued after the initial peak in the medium- and low-burn runs. In the medium-burn run, emissions began to increase again at minute 16 and continued to be elevated during the next 15 minutes of the run. The second period of significant emissions occurred later and lasted longer in the low-burn test—in that run, emissions began to increase approximately 30 minutes into the test and remained elevated for approximately 35 minutes. Ninety percent of total PM was emitted in the first 34 minutes of the medium-burn run and the first 65 minutes of the low-burn run, as compared to the first 12 minutes of the high-burn run.

Figure 2 shows the emission profiles, fuel combustion, and temperature curves for the three stove 1 baseline runs.

Figure 2. Stove 1—M28 Runs—PM Emission, Cumulative Fuel Consumption, and Stove Temperature Profiles



The differences in the emissions profiles in the three runs may be explained by the stove and stack temperature and fuel combustion curves displayed in Figure 2. The entire fuel load ignited immediately in the high-burn run, but ignition was delayed by a few minutes in the medium burn and occurred even later in the low-burn run. Those delays occurred because early in the medium- and low-burn runs, the stove temperature was not hot enough to light off the entire fuel load. When moisture was driven off the fuel, the temperatures rose, creating favorable lighting conditions. The secondary light-off produced additional PM emissions.

2.1.1.3 Cumulative PM Emissions

As discussed above, the maximum cumulative PM measurements occurred midway through each of the three runs, due to the volatilization losses that occurred later in the burns. Volatilization losses can be clearly seen in the normalized cumulative PM curves (blue lines) in Figure 1.

In the high-burn run, the maximum cumulative PM was recorded at minute 45; this was 45 minutes before the point that 90% of the fuel was consumed and 78 minutes before the end of the run (100% fuel consumption). The cumulative PM measurement at the end of the high-burn test was 9% lower than at the peak collection point. The period after maximum PM collection, during which no significant additional PM was collected and PM loss occurred, constituted 64% of the total test period.

In the medium-burn run, the maximum cumulative PM was recorded at 106 minutes, which was 62 minutes before the time of 90% fuel consumption and 94 minutes before 100% of the fuel was consumed. The cumulative PM measurement at the end of the medium burn test was 8% lower than at the peak collection point. The period after maximum PM collection, during which no significant additional PM was collected and PM was lost from the filter, constituted 60% of the total test period.

In the low-burn run, the maximum cumulative PM was recorded at 103 minutes, which was 113 minutes before 90% fuel consumption and 224 minutes before 100% of the fuel was consumed. The cumulative PM measurement at the end of the low-burn test was 8% lower than at the peak collection point. The period after maximum PM collection, during which no significant additional PM was collected and PM loss occurred, constituted 61% of the total test period.

2.1.1.4 Ninety Percent versus 100% Fuel Combustion

As discussed above, PM emissions occurred early in all stove 1 baseline runs, with no additional emissions in the last 60–64% of the run time. Because the ER, the metric that is used in stove certifications, is the total PM (in grams) collected during the run divided by the run time (in hours), an extended run period with no additional PM emissions reduces the calculated ER. Because wood stove users often add more wood to their appliances before all of the previous load has been consumed, tests conducted to 100% combustion, as prescribed in M28, may underrepresent actual in-use ERs. To more accurately reflect actual in-use conditions, we calculated PM emission parameters at the point in the run that 90% of the fuel had been combusted, as well as at the end of the run (100% fuel combustion).

For the stove 1 high-burn run, the additional time between 90% and 100% fuel combustion was 33 minutes, 27% of the total run time. During that period, PM emissions (g) decreased by 3.5% and the PM EF (in g/kg) decreased by 13%. The PM ER, the metric used to certify stoves, decreased from 8.09 g/h at 90% fuel combustion to 5.67 g/h at 100% combustion, a reduction of 30% largely due to the lengthened averaging period.

For the medium-burn run, the time period between 90% and 100% combustion was 94 minutes, 36% of the total run time. During that period, PM emissions decreased by 1.9% and the PM EF by 12%. The PM ER decreased by 37%, from 4.65 g/h to 2.92 g/h. For the low-burn run, the additional time period was 111 minutes, 34% of the total run time. During that period, low-burn PM emissions decreased by 1.8%, the EF (g/kg) decreased by 12%, and the ER rate decreased by 35%, from 6.75 g/h to 4.36 g/h.

The average ER associated with 100% combustion in the three runs was 4.3 g/h, as compared to 6.5 g/h for 90% combustion. Therefore, the ER calculated using the current 100% combustion procedures for this stove significantly underestimates the actual ER that would be expected in the field, where loads are commonly not completely burned before additional wood is added.

2.1.1.5 Comparison of PM Emission Metrics by Air Setting

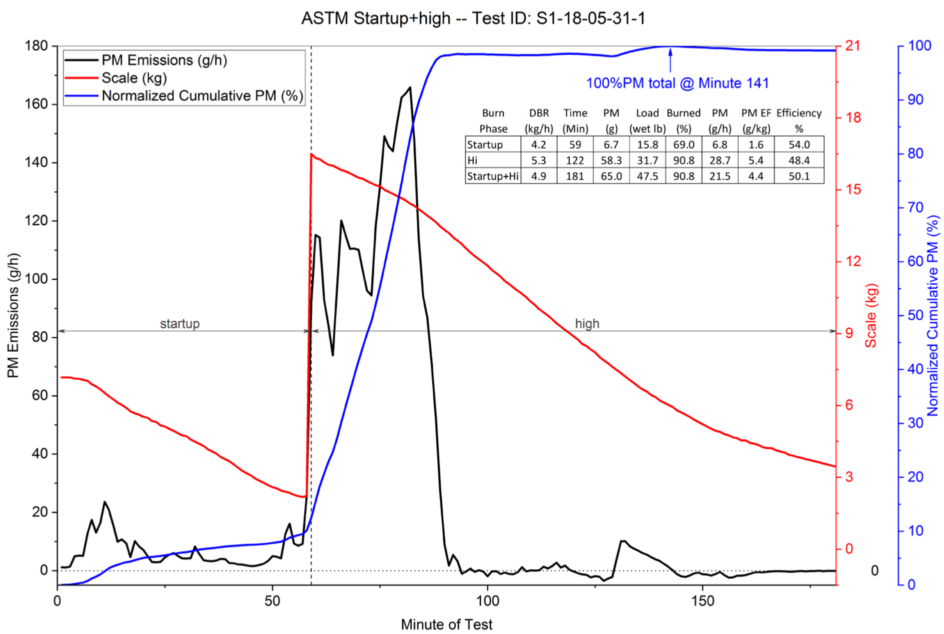
As discussed above, the initial instantaneous peak in the high-air setting run was higher than in the other runs. However, because that burst of emissions was short-lived and did not recur, the overall PM emissions for the high burn (12.14 g) were slightly lower than those in the medium burn (13.02 g) and about half of the PM emitted in the low burn (24.20 g). A similar relationship was seen in the PM EFs because those factors are calculated as the PM emissions per kg fuel burned and the fuel loads were similar for the three runs. The relationship is different for the ER, however, because that metric is dependent on both emissions and the time required to reach 100% combustion. Although the total PM emitted in the high-burn run was approximately twice that in the low-burn run, the ER calculations average those emissions across the test time, which was almost three times longer in duration in the low burn than in the high burn. As a result, the high-burn emissions rate (5.67 g/h) was higher than that for the low burn (4.36 g/h). The medium burn—which had emissions similar to and a burn period twice as long as that of the high burn—had the lowest ER.

2.1.2 ASTM 3053-17 Tests

A complete ASTM 3053-17 cordwood stove test includes two runs. Each run begins with a start-up + high-air setting phase, and then, after 90% of the initial load is consumed, a medium-air setting burn is conducted in one run and a low-air setting burn in the other. The start-up procedures for the ASTM 3053-17 method are similar to those in the final IDC protocol. However, the ATSM method allows twice as much kindling (2 lb/ft^3 loading density) as prescribed in the IDC protocol.

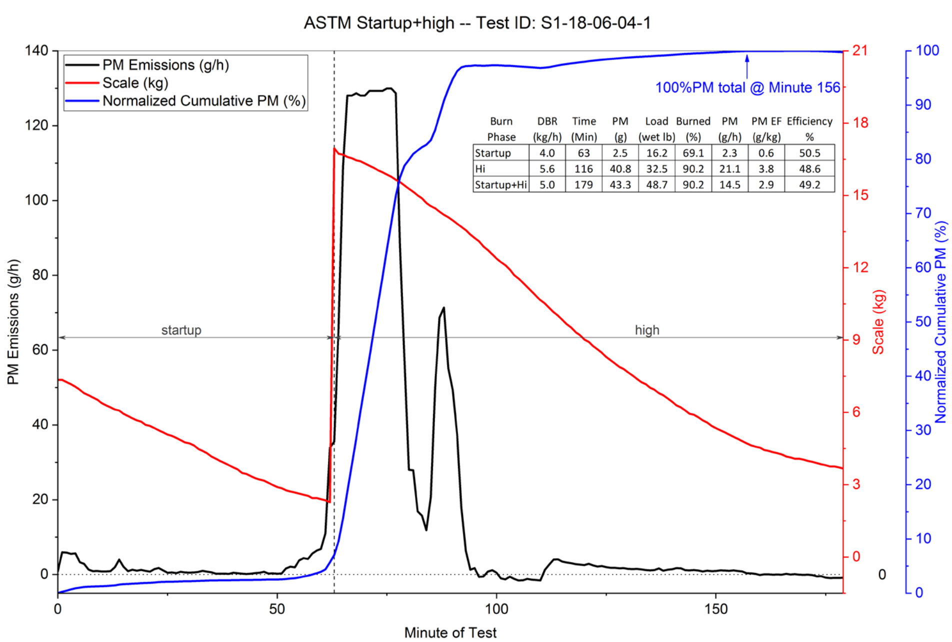
Two ASTM 3053-17 runs (one complete test) were performed on stove 1 with red maple cordwood as a fuel. The initial start-up + high-air setting phase in run S1-18-05-31 was followed by a low-air burn and, in run S1-18-06-04, by a medium-air burn. The profiles of the ASTM 3053-17 runs are presented below in two parts; the start-up + high-fire phases of the runs (S1-18-05-31-1 and S18-06-04-1) are shown in Figure 3 and the low (S1-18-05-31-2) and medium burn (S1-18-06-04-2) phases in Figure 4.

Figure 3. Stove 1—ASTM 3053-17 Runs—Start-Up and High-Fire Phases



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency %
Startup	4.2	59	6.7	15.8	69.0	6.8	1.6	54.0
Hi	5.3	122	58.3	31.7	90.8	28.7	5.4	48.4
Startup+Hi	4.9	181	65.0	47.5	90.8	21.5	4.4	50.1

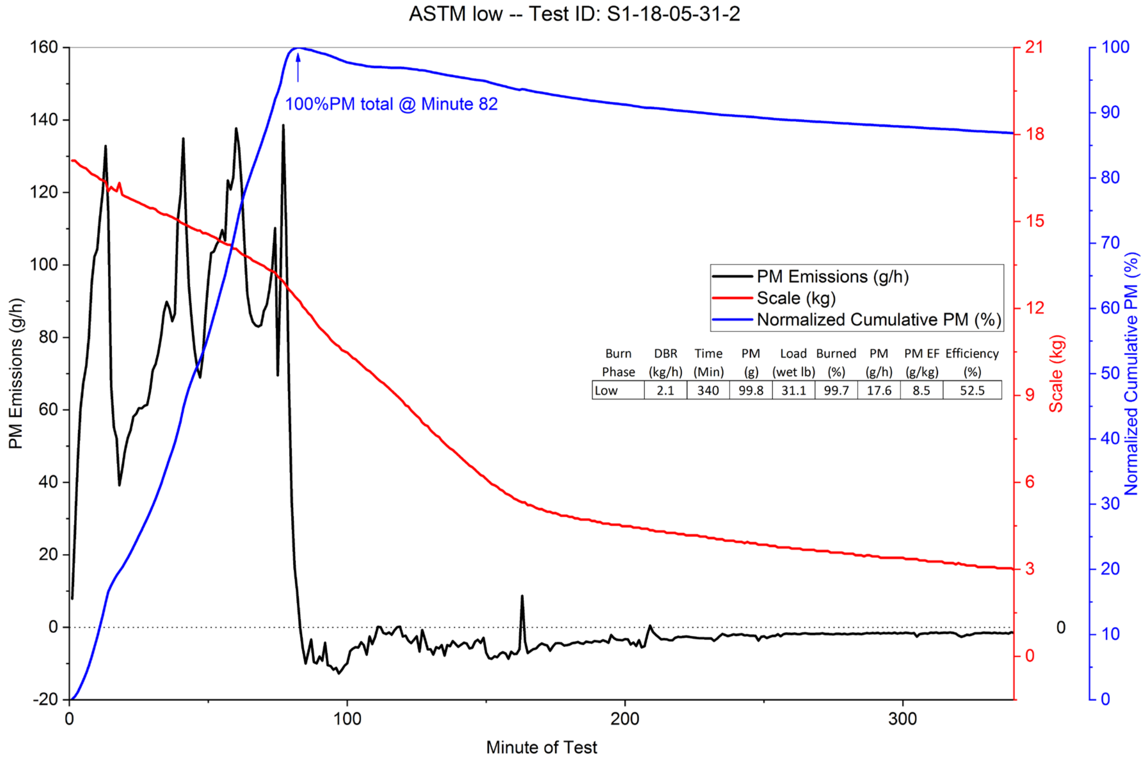
* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



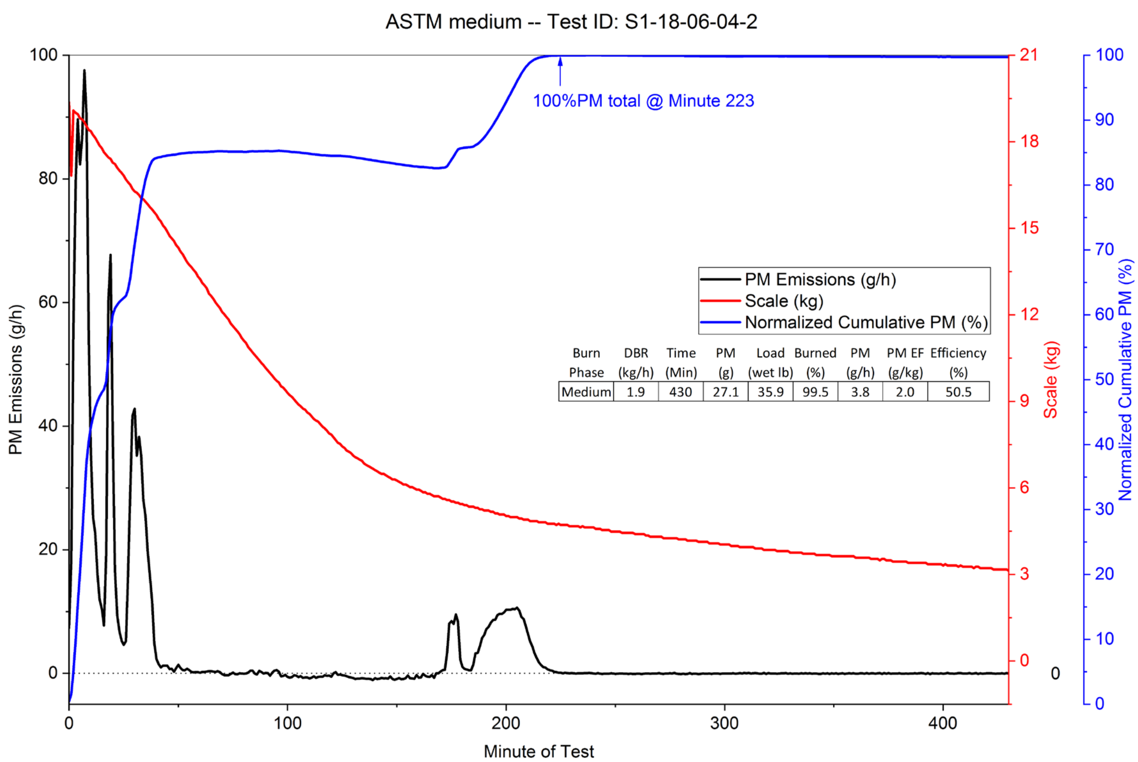
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency %
Startup	4.0	63	2.5	16.2	69.1	2.3	0.6	50.5
Hi	5.6	116	40.8	32.5	90.2	21.1	3.8	48.6
Startup+Hi	5.0	179	43.3	48.7	90.2	14.5	2.9	49.2

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Figure 4. Stove 1—ASTM 3053-17 Low and Medium Loads



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

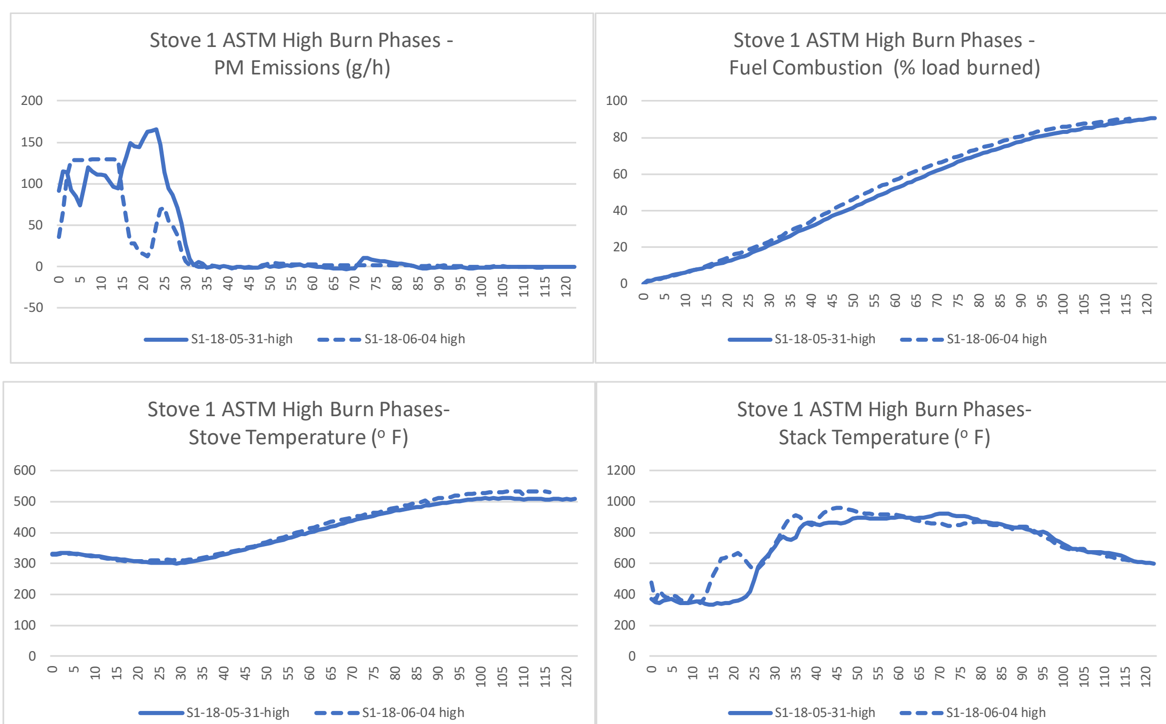
The ASTM 3053-17 run test metrics for the start-up and high-air phases are shown in Table 6.

Table 6. Stove 1—ASTM 3053-17 Start-Up and High-Air Phase Metrics

	Start-up		High Air	
Test ID #	S1-18-05-31-1	S1-18-06-04-1	S1-18-05-31-1	S1-18-06-04-1
Dry-Burn Rate (kg/h)	4.17	3.97	5.29	5.60
Time (min)	59	63	122	116
Total PM (g)	6.66	2.46	58.33	40.79
PM Emission Rate (g/h)	6.77	2.35	28.69	21.10
PM Emission Factor (g/kg)	1.62	0.59	5.43	3.77
HHV Efficiency (%)	54.0	50.5	48.4	48.6

The two ASTM 3053-17 runs had similar dry-burn rates and test times in the start-up and high-air phases. However, PM emissions, ERs, and EFs in the first run (S1-18-5-31-01) were nearly three times higher in the start-up phase and 40% higher in the high-air phase than those measured in the second run (S1-18-06-04-1). Figure 5 compares the emissions, temperature, and fuel combustion profiles in the high-burn phase of the two stove 1 ASTM 3053-17 runs.

Figure 5. Stove 1—ASTM 3053-17 High-Burn Phases—PM Emission, Cumulative Fuel Consumption and Stove Temperature Profiles



As shown in that figure, the PM emissions in the high-burn phase of both runs occurred primarily in the first 30 to 33 minutes of the burn. However, in minutes 15 to 33, the ER was higher in the 18-05-31 run than in the 18-06-04 run. Fuel combustion rates and stove temperatures were not substantially different in the two runs during that period, but the stove temperature in the higher emitting run during that time were substantially lower than in the lower emitting run.

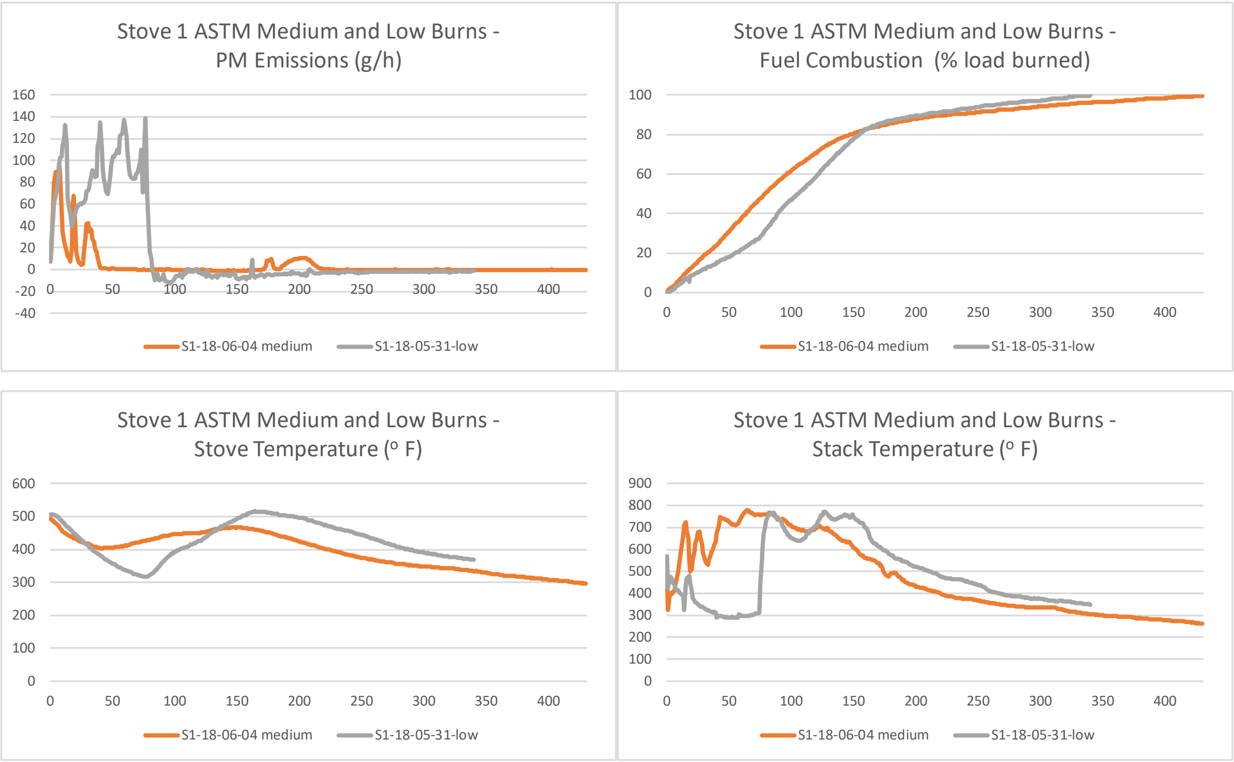
As shown in Figure 5, all significant PM emissions occurred during the first quarter of the test time in the low-air phase of the first ASTM 3053-17 run (S1-18-05-31-2) and, in the medium-air phase of the second run (S1-18-06-04-2), emissions dropped close to zero after about 10% of the test time. The test metrics for the low-air burn and medium-air burn phases are shown in Table 7.

Table 7. Stove 1—ASTM 3053-17 Low- and Medium-Phase Metrics

Test ID #	S1-18-05-31-2 Low	S1-18-06-04-2 Medium
Dry-Burn Rate (kg/h)	2.1	1.9
Time (min)	340	430
Total PM (g)	99.8	27.1
PM Emission Rate (g/h)	17.6	3.8
PM Emission Factor (g/kg)	8.5	2.0
HHV Efficiency (%)	52.5	50.5

The dry mass of the fuel load burned in the medium burn run was 14% larger than in the low run, which may partially explain the longer test time of the medium run. The PM ER and EF were more than four times higher in the low-air than the medium-air run, although the burn rates in the two runs were similar. The reason for the emission differences is illuminated by the comparative run profiles shown in Figure 6.

Figure 6. Stove 1—ASTM 3053-17 Medium and Low Phases—PM Emission, Cumulative Fuel Consumption and Stove Temperature Profiles



Significant PM emissions occurred in the beginning of both the low and medium burns. However, emissions were higher and continued for approximately twice as long (81 versus 40 minutes) in the low-burn than in the medium-burn run. In minutes 41to 81, when emissions continued in the low-burn but not the medium-burn run, the low-burn run recorded lower stove and stack temperatures and a lower fuel combustion rate than those of the medium burn. The drop in PM emissions in the low-burn run at the end of that period corresponded to a sharp increase in the stack temperature and increased stove and fuel combustion rates.

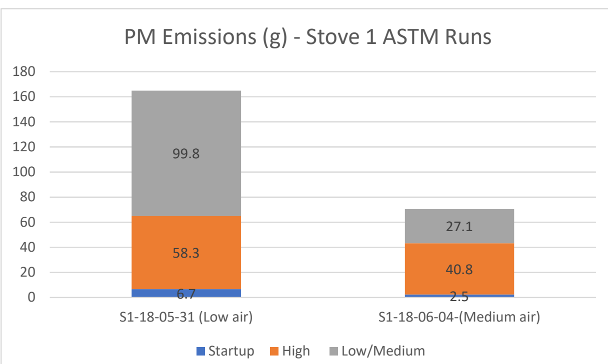
The metrics for the entire S1-18-05-31 (start-up, high-fire, and low-fire phases) and S1-18-06-04 (start-up, high-fire, and medium-fire phases) runs are shown in Table 8.

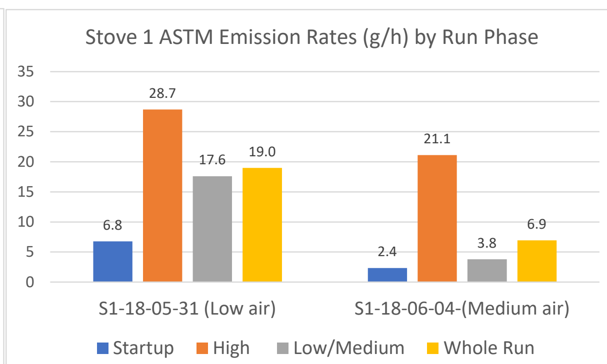
Table 8. Stove 1—Metrics for Entire ASTM 3053-17 Runs

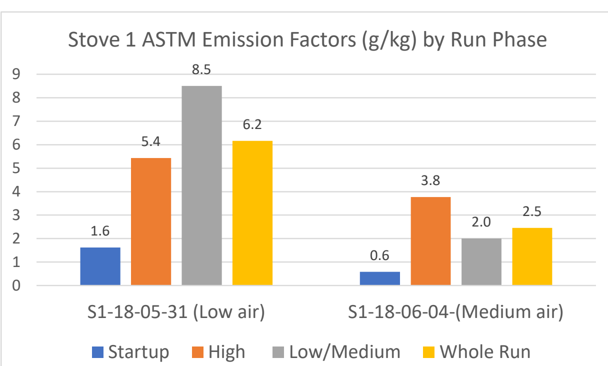
Test ID #	S1-18-05-31	S1-18-06-04
Dry-Burn Rate (kg/h)	3.1	2.8
Time (min)	521	609
Total PM (g)	164.8	70.4
PM Emission Rate (g/h)	19.0	6.9
PM Emission Factor (g/kg)	6.2	2.5

Total PM emissions in run S1-18-05-31, the low-air run, were 2.3 times higher than those in run S1-18-06-04, and the ER and EF in that run were similarly elevated. Figure 7 shows the Stove 1 ASTM 3053-17 run PM emission metrics graphically. As discussed above, even though the start-up + high-burn protocols were the same in the two runs, PM emissions were higher in those phases of S1-18-05-31 than in S1-18-06-04. Emissions in the low-burn phase of S1-18-05-31 were considerably higher than in any of the other phases in either run. ERs were highest in the high-air phase of both runs. However, the PM EF in the low-burn phase of S1-18-05-31 was higher than in any of the other phases in either run.

Figure 7. Stove 1—ASTM 3053-17 Runs—Comparison of PM Metrics



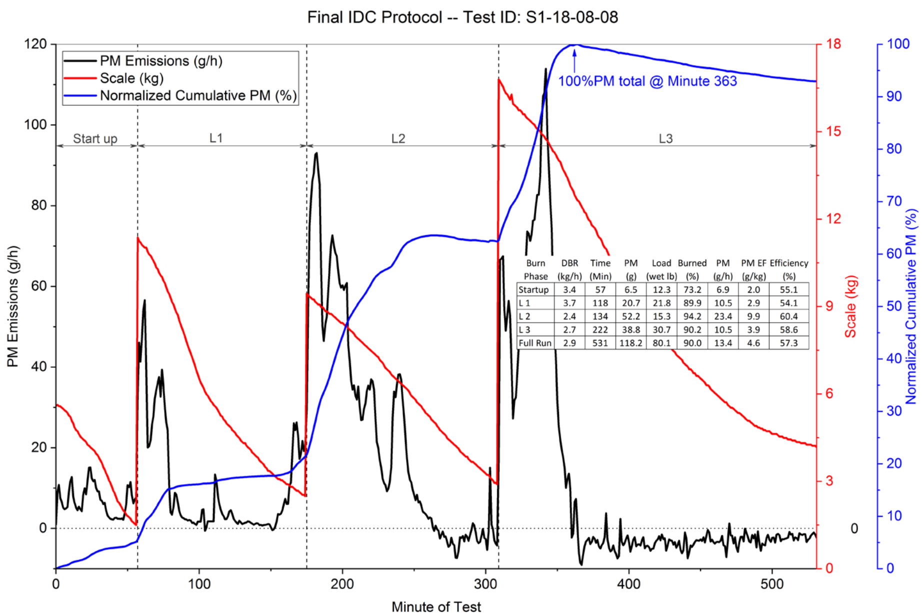




2.1.3 IDC Tests

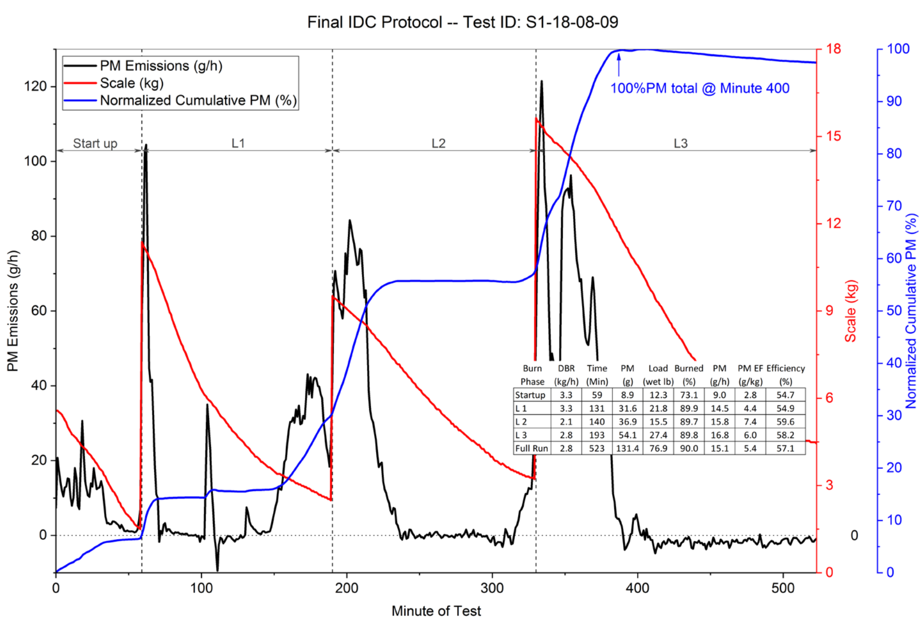
As discussed above, all stoves were tested using IDC protocol procedures. The protocol calls for three replicate runs, each consisting of a start-up, high-fire, maintenance, and overnight phase, as summarized in Table 2. Red maple cordwood was used for all stove 1 IDC final protocol runs. Figure 8 shows the results of the three IDC stove 1 tests, which were run on consecutive days.

Figure 8. Stove 1—IDC Final Protocol Replicate Runs



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.4	57	6.5	12.3	73.2	6.9	2.0	55.1
L 1	3.7	118	20.7	21.8	89.9	10.5	2.9	54.1
L 2	2.4	134	52.2	15.3	94.2	23.4	9.9	60.4
L 3	2.7	222	38.8	30.7	90.2	10.5	3.9	58.6
Full Run	2.9	531	118.2	80.1	90.0	13.4	4.6	57.3

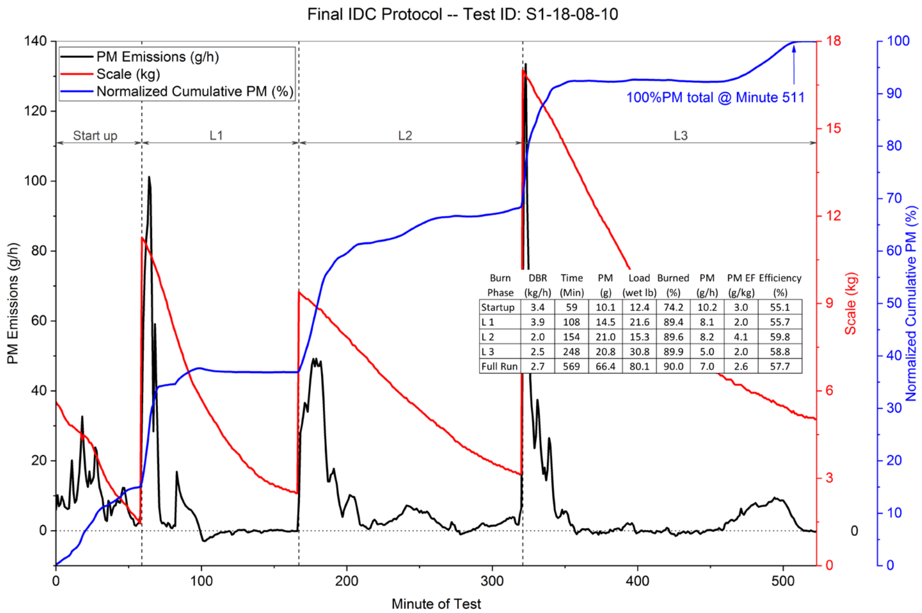
* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.3	59	8.9	12.3	73.1	9.0	2.8	54.7
L 1	3.3	131	31.6	21.8	89.9	14.5	4.4	54.9
L 2	2.1	140	36.9	15.5	89.7	15.8	7.4	59.6
L 3	2.8	193	54.1	27.4	89.8	16.8	6.0	58.2
Full Run	2.8	523	131.4	76.9	90.0	15.1	5.4	57.1

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Figure 8 Continued



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

The metrics for the start-up phase of the three replicate IDC stove 1 IDC runs are shown in Table 9.

Table 9. Stove 1—Metrics for Start-Up Phase of the IDC Replicate Runs

Run ID #	S1-18-08-08 Replicate 1	S1-18-08-09 Replicate 2	S1-18-08-10 Replicate 3
Dry-Burn Rate (kg/h)	3.40	3.27	3.36
Time (min)	57	59	59
Total PM (g)	6.5	8.9	10.1
PM Emission Rate (g/h)	6.87	9.03	10.23
PM Emission Factor (g/kg)	2.02	2.76	3.04

The dry-burn rates and test times for the start-up phase of the three IDC runs were similar. However, total PM start-up emissions varied significantly, ranging from 6.5–10.1 g. Due to the difference in PM mass, the start-up PM ERs and EFs also varied widely between runs. The start-up ER and EF in the third (highest emitting) replicate run were approximately 50% higher than those in the first (lowest emitting) run.

The metrics for the high-fire phase (Reload 1) of the IDC runs are shown in Table 10. During this phase, a fuel load of 7 lb/ft^3 comprised of small cordwood pieces is burned at the highest air control setting. When 50% of the load is consumed, the air control is switched to the lowest setting and the load is burned to 90% consumption, by weight.

Table 10. Stove 1—Comparison of Metrics for Reload 1—High-Fire Phases for IDC Replicate Runs

Run ID #	S1-18-08-08 Replicate 1	S1-18-08-09 Replicate 2	S1-18-08-10 Replicate 3
Dry-Burn Rate (kg/h)	3.68	3.30	3.94
Time (min)	118	131	108
Total PM (g)	20.7	31.6	14.5
PM Emission Rate (g/h)	10.52	14.48	8.07
PM Emission Factor (g/kg)	2.86	4.39	2.05

Dry-burn rates in the high-fire phase exhibited slightly greater variability than in the start-up phase, ranging from 3.3–3.9 kg/h. As discussed above, in the start-up phase, PM emissions were highest in the Replicate 3 run. However, in the high-fire phase, PM emissions were highest in Replicate 2. Total high-fire PM emissions in Replicate 2, which had the lowest burn rate, were more than twice those in that phase of the third run, the replicate with the highest burn rate. The high-fire phase ER and EF in Replicate 2 were approximately twice those in the third run.

As can be seen in the emission profiles in Figure 8, PM emissions peaked in the first few minutes of the high-fire phase in all three replicate runs, with small additional peaks shortly after the air control was moved to the low setting, when 50% of the load had been combusted. That peak was most pronounced in Replicate 2. There were virtually no additional PM emissions in the Replicate 3 run after that point, but significant PM emissions occurred late in Replicate 2, and, to a lesser extent, the Replicate 1 high-fire phase burns.

In the Reload 2-maintenance phase, air controls are kept at the lowest setting and two large pieces of wood are loaded into the stove. At this point in the run, the coal bed is well developed. This phase simulates operating conditions that would be present when a stove is in a semi-attended maintenance mode. The metrics measured in the maintenance phases of the three replicate runs are shown in Table 11.

Table 11. Stove 1—Test Metrics for Reload 2—Maintenance Phase Replicate Burns

Test ID #	S1-18-08-08 Replicate 1	S1-18-08-09 Replicate 2	S1-18-08-10 Replicate 3
Dry-Burn Rate (kg/h)	2.37	2.13	1.99
Time (min)	134	140	154
Total PM (g)	52.2	36.9	21.0
PM Emission Rate (g/h)	23.37	15.79	8.20
PM Emission Factor (g/kg)	9.86	7.40	4.12

As shown in Table 11, the maintenance phase burn rate for Replicate 1 (2.37 kg/h) was higher than those for the Replicates 2 and 3 (2.1 and 1.99 kg/h, respectively), and the combustion time for that run (134 minutes) was lower than for the other two runs (140 and 154 minutes). In the previous phase, the run with the lowest burn rates had the highest PM emissions. However, in this phase, the opposite was true— Replicate 1 produced 2.5 times more PM than the third run. The load 3 ER and EF for Replicate 1 were 2.8 and 2.4 times higher than in Replicate 3, the lowest emitting run, respectively.

The final phase in the IDC protocol simulates conditions associated with a long burn, such as would be employed for an overnight burn or when the fire is unattended for a significant amount of time (>6 hours) during the day. For this phase, the coal bed is raked, and the user loads as much wood as possible, using large and small pieces. The air control is set at its lowest setting.

Table 12 presents the results of the reload 3 phase.

Table 12. Stove 1—Comparison of IDC Run Metrics for Reload 3—Overnight Burn Phase

Test ID #	S1-18-08-08 Replicate 1	S1-18-08-09 Replicate 2	S1-18-08-10 Replicate 3
Dry-Burn Rate (kg/h)	2.72	2.82	2.46
Time (min)	222	193	248
Total PM (g)	38.8	54.1	20.8
PM Emission Rate (g/h)	10.49	16.81	5.03
PM Emission Factor (g/kg)	3.86	5.96	2.04

The stove 1 overnight phase lasted 3.2 to 4.1 hours. As with the maintenance phase, higher burn rates in this phase were associated with higher PM emissions. In this phase, the highest burn run (Replicate 2) emitted 2.6 times as much PM as in the lowest burn run (Replicate 3). The PM ERs and EFs showed the same pattern, with the ER 3.2 higher and the EF 2.9 times higher in Replicate 2 than in Replicate 3.

Table 13 shows the test metrics for the entire run of each of the IDC replicates.

Table 13. Stove 1—Comparison of Test Metrics for the Entire IDC Protocol

Test ID #	S1-18-08-08	S1-18-08-09	S1-18-08-10
Dry-Burn Rate (kg/h)	2.92	2.81	2.71
Time (min)	531	523	569
Total PM (g)	118.2	131.4	66.4
PM Emission Rate (g/h)	13.36	15.08	7.00
PM Emission Factor (g/kg)	4.58	5.37	2.59
HHV Efficiency (%)	57.3	57.1	57.7

The total time to complete the runs ranged from 523 to 569 minutes (8.7 to 9.5 hours). Because stove 1 is a large firebox stove, it is likely that this test time is at the upper range of those that would be expected, an indication that the IDC protocol can be completed in less than 10 hours, making a single day test run feasible.

Average burn rates for the entire protocol were similar in the three runs (2.71 to 2.92 kg/h) and the HHV thermal efficiency measured did not vary significantly among the replicate tests. However, the PM metrics in the replicates did vary substantially. All of the PM metrics (total PM, PM ER, and PM EF) were approximately twice as high in Replicate 2, the highest emitting run, than in the Replicate 3, the lowest emitting. The variability in the ERs measured in the three runs, despite the use of identical protocols, supports the need for performing three replicate runs.

Figure 9 shows the test metrics by test phase for each of the stove 1 IDC runs graphically.

Figure 9. Stove 1—Comparison of Metrics for IDC Replicate Runs: S1-18-08-08 (Replicate 1), S1-18-08-09 (Replicate 2), and S1-18-08-10 (Replicate 3)

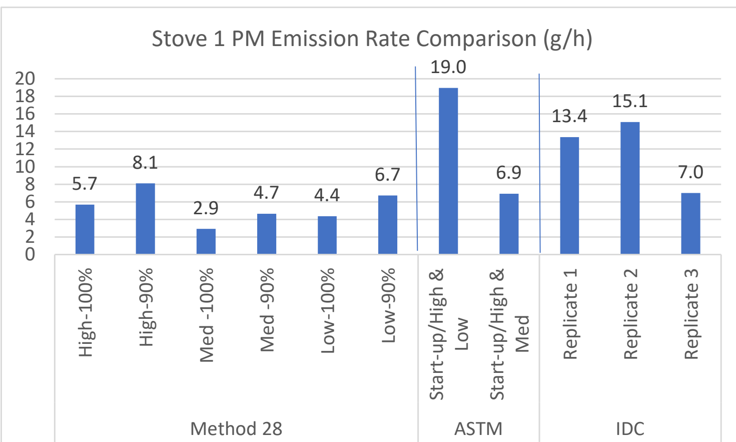
As can be seen in that figure, the burn rates were highest in the high-fire (Reload 1) phase and lowest in the maintenance (Reload 2) phase in all IDC runs. The difference in burn rates between phases was most pronounced in the Replicate 3 run (S1-18-01-10), which had the highest high-fire burn rate and the lowest maintenance burn rate of the three runs.

The overnight phase in Replicate 2 and the maintenance run in Replicate 1 produced the most PM emissions. The highest ER and EF were observed in the Replicate 1 maintenance phase. Total PM, PM ER, and PM EF were lower in Replicate 3 than in the other runs for all phases except for the start-up phase. See Section 4: Findings and Recommendations for a more detailed analysis of the differences between IDC replicate runs.

2.1.4 Comparison of Stove 1 Emission Rate Measurements

Figure 10 compares the emissions rates measured in each of the Stove 1 M28, ASTM 3053-17, and IDC final protocol runs.

Figure 10. Stove 1—Comparison of M28, ASTM 3053-17, and IDC Emission Rate Measurements



The ERs displayed in Figure 10 for the M28 and ASTM 3053-17 runs should not be compared to regulatory values, which are calculated using weighting factors. However, as shown in that figure, the ERs measured using M28, the current EPA protocol, were considerably lower than those measured using the IDC protocol. This is of concern because the IDC protocol is designed to replicate real-life use parameters. The Method 28 ERs associated with combustion of 90% of the fuel load were 43% to 59% higher than the 100% combustion ERs, but still tend to be lower than those measured with IDC. Section 4 presents a more detailed analysis of the differences between the results for different test methods, including a comparison of the operating parameters measured in the high-fire phases of runs using different methods and a similar comparison of low-fire phase parameters.

2.2 Stove 2

Stove 2 is a small fire box, high-mass stove with catalytic controls. A total of 15 test runs were performed on stove 2, as listed in Table 14. M28 baseline tests were conducted with Douglas fir crib wood, and all other tests used red maple cordwood.

Table 14. Stove 2—Test Run Descriptions

Test ID	Test Method	Fuel Species	Fuel Type	Description
S2-18-02-06	M28 (baseline)	Douglas Fir	Crib	High fire, load burned 100%
S2-18-02-12	M28 (baseline)	Douglas Fir	Crib	Medium fire, load burned 100%
S2-18-02-09	M28 (baseline)	Douglas Fir	Crib	Low fire, load burned to 100%
S2-18-01-24	IDC v1 (research)	Red Maple	Cordwood	Cold start-up RL 1 - 5# at high RL 2 - 7# at medium RL 3 - 12# at low
S2-18-02-27	R&D	Red Maple	Cordwood	Cold start bottom-up kindling RL 1 - 5# at high
S2-18-02-28	R&D	Red Maple	Cordwood	Cold start top-down kindling RL 1 - 5# at high (test aborted)
S2-18-03-29	IDC v2 (research)	Red Maple	Cordwood	Cold start bottom-up kindling RL 1 - 7# at high RL 2 - 5# at medium RL 3 - 12# at low
S2-18-05-12	R&D	Red Maple	Cordwood	Cold start top-down kindling RL 1 - 7# at high shut to low at 50% burned No RL 2 RL 3 - 12# at low to 90% burned
S2-18-05-17	R&D	Red Maple	Cordwood	Cold start top-down kindling RL 1 - 7# at high shut to low at 50% burned RL 2 - 5# at low RL 3 - 12# at low to 90% burned
S2-18-10-23	IDC Final Protocol	Red Maple	Cordwood	Door cracked open in first 5 minutes of start-up
S2-18-10-24	IDC Final Protocol	Red Maple	Cordwood	Door cracked open in first 5 minutes of start-up
S2-19-01-09	IDC Final Protocol	Red Maple	Cordwood	Door cracked open in first 5 minutes of start-up
S2-19-01-07	IDC Final Protocol	Red Maple	Cordwood	Door wide open in first 5 minutes of start-up
S2-19-01-08	IDC Final Protocol	Red Maple	Cordwood	Door wide open in first 5 minutes of start-up
S2-18-10-25	IDC Final Protocol	Red Maple	Cordwood	Door cracked open in first 5 minutes of start-up

[a] Symbol # denotes fuel loading density in pounds per cubic foot of the stove firebox (lb/ft^3).

[b] In ASTM 3053-17 testing, fuel loads are defined as the weight of the wet wood.

In the baseline and research runs in stove 2, continuous PM was measured with the1400AB TEOM, while the IDC final protocol runs used the 1405 TEOM for those measurements. The results of the stove 2 baseline and IDC final protocol run results are presented in this section. Research runs were used to develop the IDC final protocol and are summarized in section 4.

2.2.1 Baseline Tests

As with Stove 1, baseline tests for stove 2 were conducted using modified EPA Method 28 (M28) procedures at three of the four air control settings prescribed in that method: the highest air control setting (category 4), the lowest setting (category 1), and the manufacturer's recommended air setting for a medium burn rate (category 2 or 3). Table 15 summarizes the results of the stove 2 baseline modified M28 testing. At the low- and medium-air settings, stove 2 achieved burn rates that were essentially equivalent and fall into EPA's category 2.

Table 15. Stove 2—Summary of the Modified M28 Baseline Test Results

	Test Time (min)		Dry-Burn Rate (kg/h)		Total PM (g)		PM Emission Rate (g/h)		PM Emission Factor (g/kg)		HHV Efficiency (%)
% Burn Completed	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*100%*
High	112	157	1.83	1.45	5.21	5.15	2.79	1.97	1.53	1.36	31.6
Medium	135	199	1.52	1.15	3.64	3.60	1.61	1.09	1.06	0.94	28.5
Low	138	200	1.51	1.15	2.61	2.58	1.13	0.77	0.75	0.67	43.0

The HHV thermal efficiency of stove 2 was lowest (28.5%) in the medium-air run and highest (43.0%) in the low-air run.

Unlike stove 1, total PM emissions and EF in the stove 2 baseline runs were highest at the high-air setting. Both PM emissions and the PM EF were twice as high in the high-air run than in the low-air run. Because the test time for the high-air run was considerably shorter than in the others runs, the ratio of ERs was even higher; the high-air ER was 2.6 times higher than in the low-fire run. A more detailed discussion of PM emissions follows.

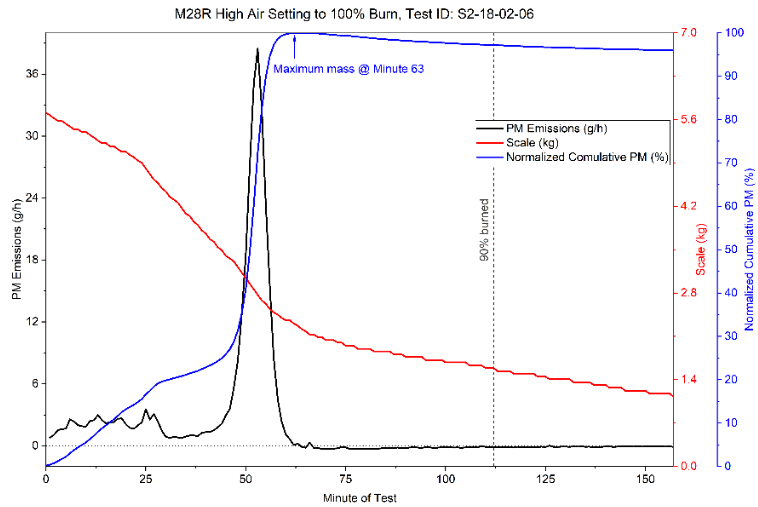
2.2.1.1 Real-Time Measurements

Real-time plots of the three stove 2 M28 test runs are presented in Figure 11. The real-time TEOM PM emission rate profiles are shown in black in those figures. Unlike the stove 1 PM emission rates, which peaked in the first few minutes of the baseline runs, stove 2 emission rates peaked 53 to 60 minutes into the runs. However, as with the stove 1, the latter section of all three stove 2 baslines runs run included an extended period of zero or negative emission measurements. As discussed above, the TEOM records negative emissions when clean, hot air passing through the TEOM filter carries off the more volatile species of the PM collected earlier in the run.

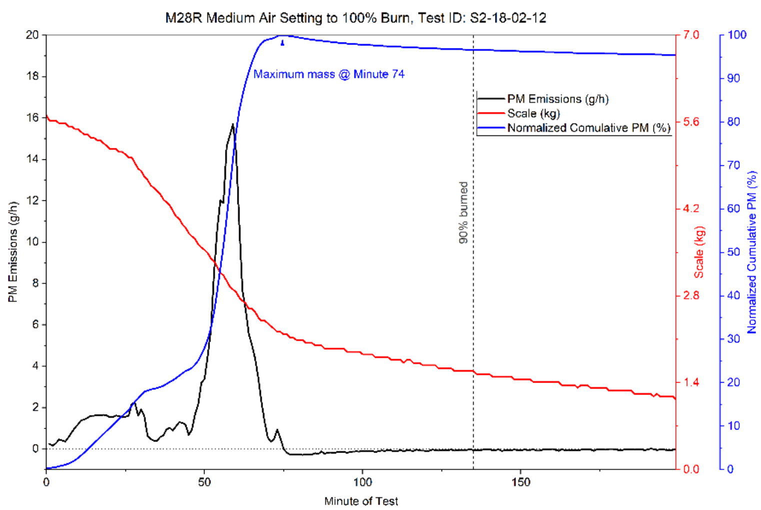
The blue line in each figure represents the cumulative PM collected during the test run, normalized to the maximum cumulative PM measurement in that run. Because of the volatilization loss effect discussed above, the maximum cumulative PM measurement, which is marked in the plots, occurred midway through the runs. In all stove 2 M28 tests, the maximum cumulative PM occurred before 90% of the fuel charge weight had been consumed and well before 100% fuel consumption (the end of the test).

The red line in the plots shows the weight of the fuel remaining at each point of the test. The 90% fuel consumption time is marked with a vertical line. The impact of testing to 90% versus 100% fuel consumption is discussed in more detail in section 5.1.

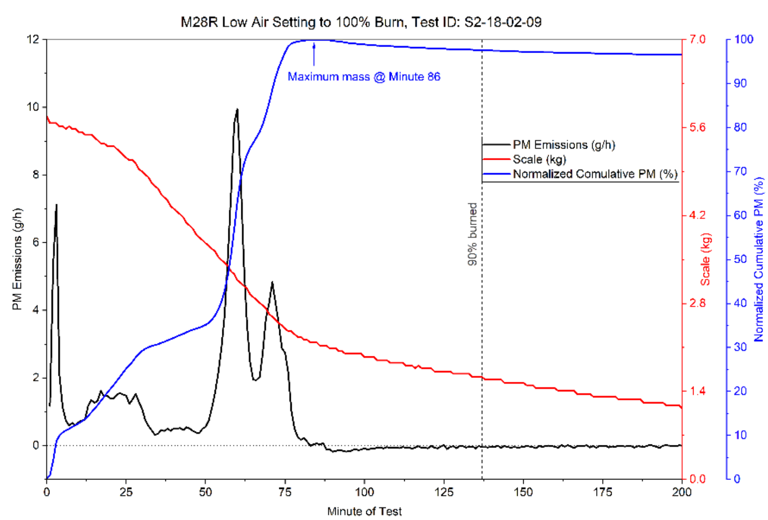
Figure 11. Stove 2—M28 Baseline Test Results



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



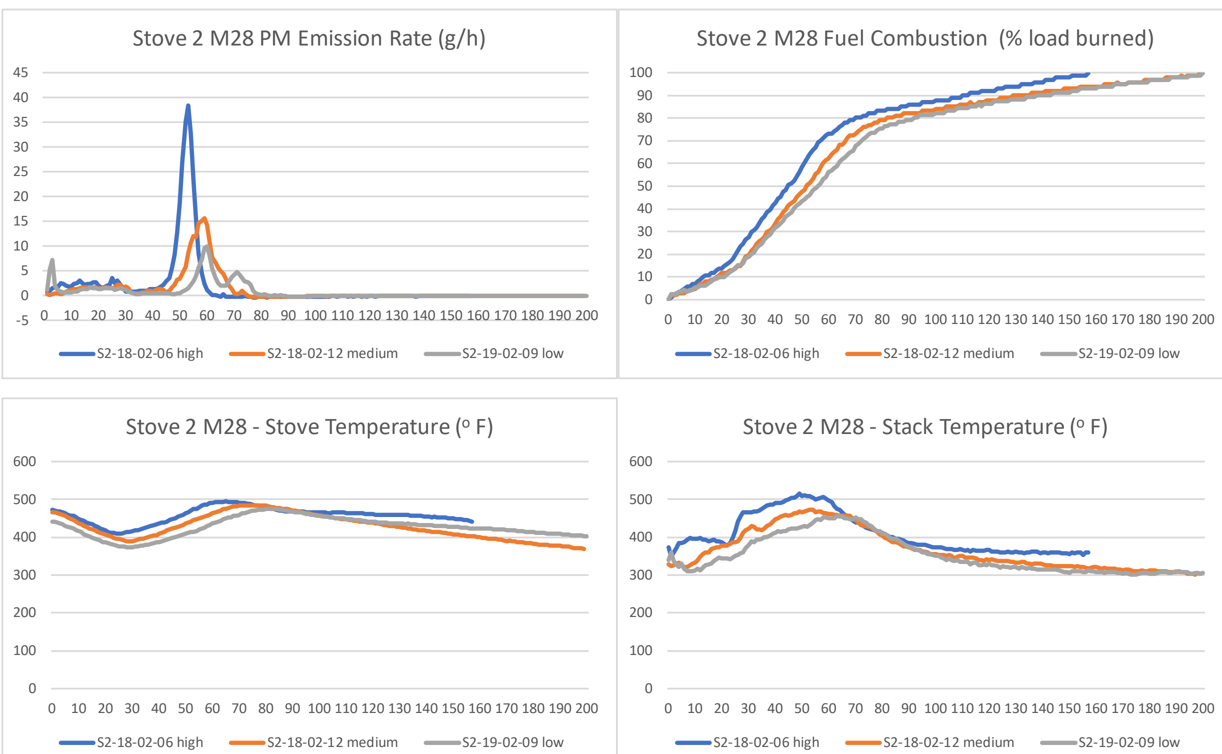
* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

2.2.1.2 PM Emissions Profiles

As discussed above, the maximum instantaneous PM ER recorded for the three stove 2 baseline runs occurred 53 to 60 minutes into the burns, considerably later than in the stove 1 runs. The peak instantaneous ER in the stove 2 high-air run was considerably higher and occurred earlier (38.5 g/h at 53 minutes) than the peaks in the medium- and low-air runs (15.7 g/h at 59 minutes and 9.9 g/h at 60 minutes, respectively). Two additional secondary peaks were recorded in the low-air run; the first early in the run (7.1 g/h at 3 minutes) and the other a peak of 4.8 g/h at 71 minutes. Ninety percent of PM was emitted in the first 55 minutes of the 157-minute high-burn run, the first 64 minutes of the 199-minute medium-burn run and the first 72 minutes of the 200-minute low-burn run.

Figure 12 shows the emission profiles and fuel combustion and stack temperature curves for the three stove 2 baseline runs.

Figure 12. Stove 2—Baseline Runs—PM Emissions, Cumulative Fuel Consumption, and Stove and Stack Temperature Profiles



As shown in Figure 12, the delay in the PM emission peaks can partially be explained by a delay in the fuel light-off; the combustion rate increased 21 to 28 minutes into the runs, consistent with a light-off of the fuel load at that point, with the inflection point occurring earliest in the high-burn run. However, PM emissions did not increase until approximately 20 minutes after the light-off and peaked about 30 minutes after light-off. This is different from the patterns seen in stove 1; in that stove, PM emissions increased immediately after light-off. In addition, peak emissions occurred in all stove 2 baseline runs during the period when the stove and stack temperatures were at their highest, while in stove 1 higher temperatures were associated with reduced emissions. The difference between the stove 1 and stove 2 profiles may be influenced by the fact that stove 1 has non-catalytic controls and stove 2 catalytic.

2.2.1.3 Cumulative PM Emissions

As discussed above, the maximum cumulative PM measurements occurred midway through each of the three stove 2 M28 runs, due to volatilization losses later in the burns. Volatilization losses can be clearly seen in the normalized cumulative PM curves (blue lines) in Figure 11.

Cumulative PM was at its maximum at minute 63 of the high-burn run, which was 49 minutes before 90% of the fuel was consumed and 94 minutes before the end of the run (100% fuel consumption). The cumulative PM measurement at the end of the high-burn test was 4% lower than at the peak collection point. The period after maximum PM collection, during which no significant additional PM was collected and PM filter loss occurred, constituted 60% of the total test period.

In the medium burn run, the maximum cumulative PM was recorded at minute 74, which was 61 minutes before the point of 90% fuel consumption and 125 minutes before 100% of the fuel was consumed. The cumulative PM measurement at the end of the medium burn test was 5% lower than at the peak collection point. The period after maximum PM collection, during which no significant additional PM was collected and PM loss occurred, constituted 63% of the total test period.

In the low-burn run, the maximum cumulative PM was recorded at 86 minutes, which was 49 minutes before 90% fuel consumption and 114 minutes before 100% of the fuel was consumed. The cumulative PM measurement at the end of the low-burn test was 3% lower than at the peak collection point. The period after maximum PM collection, during which no significant additional PM was collected and PM loss occurred, constituted 57% of the total test period.

2.2.1.4 Ninety Percent versus 100% Fuel Combustion

As discussed above, virtually all PM emissions occurred in the first 40% of the stove 2 baseline test runs. Because minimal or no additional emissions occurred later in the burns, the ERs for the M28 runs were highly influenced by the length of the run. As with stove 1, PM emission parameters were calculated at the point in the run that 90% of the fuel had been combusted, as well as at the end of the run (100%fuel combustion).

For the stove 2 high-burn run, the time period between 90% and 100% fuel combustion was 45 minutes, which was 29% of the total run time. During that period, PM emissions decreased by 1.2% and the PM EF (in g/kg) decreased by 11%. The PM ER, the metric used to certify stoves, was 2.79 g/h at the point of 90% fuel combustion and 1.97 g/h at 100% combustion, a reduction of 29% that is largely due to the lengthened averaging period.

For the medium burn run, the time period between 90% and 100% combustion was 64 minutes, 32% of the total run time. During that period, PM emissions decreased by 1.1% and the PM EF by 11%. The PM ER decreased by 32%, from 1.61 g/h to 1.09 g/h. For the low-burn run, the time from 90% to 100% combustion was 63 minutes, 31% of the total run time. During that period, low-burn PM emissions decreased by 1.2%, the EF (g/kg) decreased by 11%, and the ER rate decreased by 32%, from 1.13 g/h to 0.77 g/h.

The average ER associated with 100% combustion for the three runs was 1.3 g/h, as compared to 1.8 g/h for 90% combustion.

2.2.1.5 Comparison of PM Emissions Metrics by Air Control Setting

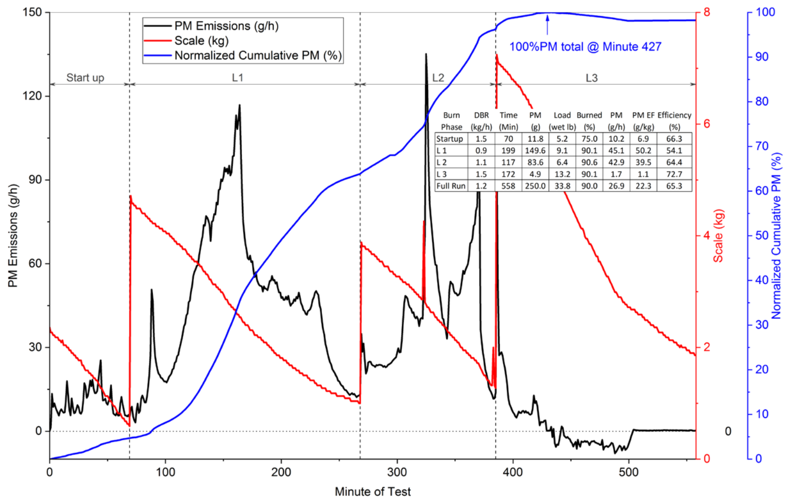
As discussed above, the instantaneous peak PM concentration in the high-air run was higher than in the other runs. Unlike stove 1, the high-air run also emitted substantially more PM (5.15 g at 100% combustion) than was emitted in the medium (3.60 g) or low (2.58 g) runs. PM emissions were approximately twice as high in the high-air setting run than in the low-air (lowest emitting) run. A similar relationship was seen in the PM EFs because those factors are calculated as the PM emissions per kg fuel burned and the fuel loads were similar for the three runs. The ratio of the high-air run to low-air run ERs was even greater because that metric is dependent on both emissions and the time required to reach 100% combustion. The high-burn emission rate (1.97 g/h) was 2.6 higher than that for the low-air run (0.77 g/h).

2.2.2 IDC Tests

Two sets of three replicates, a total of six test runs, were performed on stove 2. The first set of runs was performed on consecutive days in October 2018. In the first two of those runs, the stove door was cracked open during the five minutes of the start-up period and, in the third run of that set, the door was wide open during that period. The second set of runs were performed on consecutive days in January 2019; in that set, the door was wide open for the first five minutes of start-up for the first two runs and cracked open for that period for the third run. This enabled an investigation of the impact of the door position at the beginning of start-up. Test profiles of the stove 2 IDC runs are shown in Figures 13 and 14. The month of the tests is used here only to distinguish between the two sets of tests, and not to imply that differences between the sets of tests are linked to the specific month of testing.

Figure 13. Stove 2—IDC Final Protocol Runs—October 2018

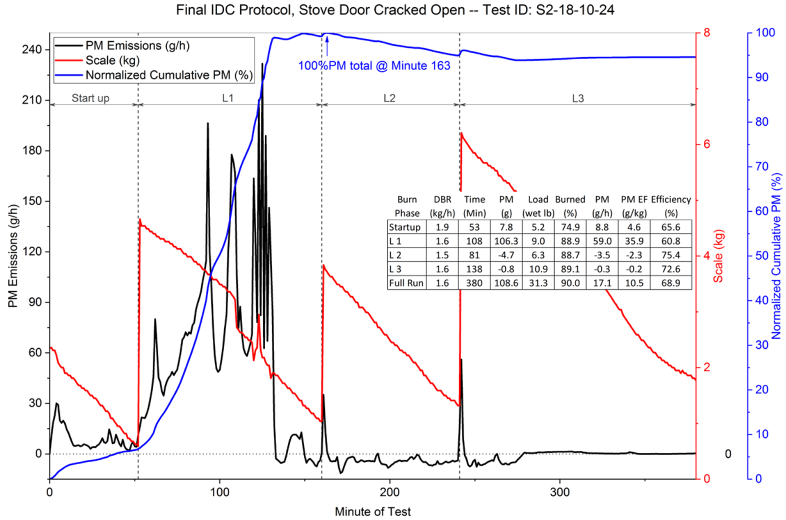
Final IDC Protocol, Stove Door Cracked Open -- Test ID: S2-18-10-23



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	1.5	70	11.8	5.2	75.0	10.2	6.9	66.3
L 1	0.9	199	149.6	9.1	90.1	45.1	50.2	54.1
L 2	1.1	117	83.6	6.4	90.6	42.9	39.5	64.4
L 3	1.5	172	4.9	13.2	90.1	1.7	1.1	72.7
Full Run	1.2	558	250.0	33.8	90.0	26.9	22.3	65.3

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

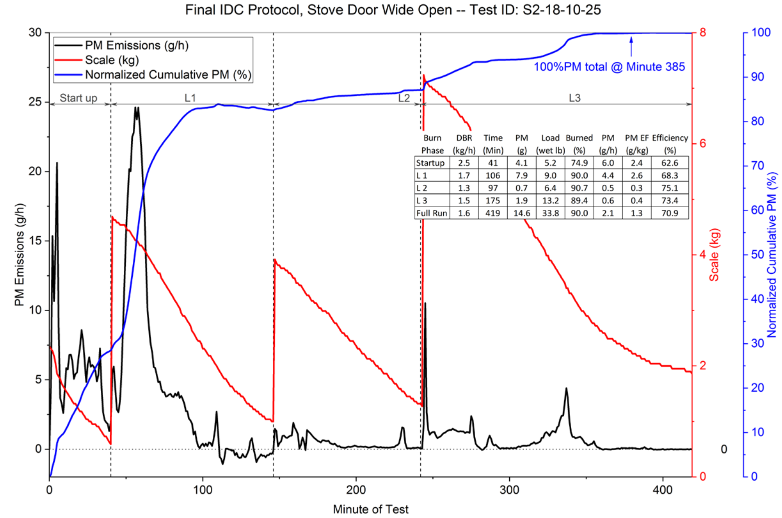
Final IDC Protocol, Stove Door Cracked Open -- Test ID: S2-18-10-24



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	1.9	53	7.8	5.2	74.9	8.8	4.6	65.6
L 1	1.6	108	106.3	9.0	88.9	59.0	35.9	60.8
L 2	1.5	81	-4.7	6.3	88.7	-3.5	-2.3	75.4
L 3	1.6	138	-0.8	10.9	89.1	-0.3	-0.2	72.6
Full Run	1.6	380	108.6	31.3	90.0	17.1	10.5	68.9

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Final IDC Protocol, Stove Door Wide Open -- Test ID: S2-18-10-25

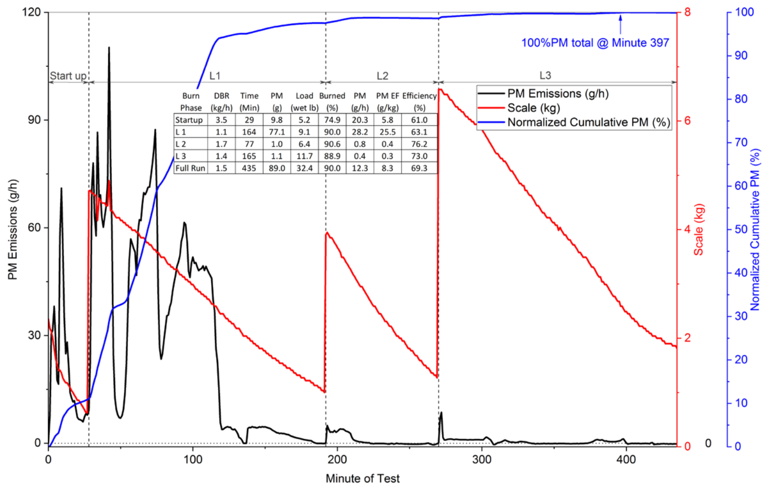


Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.5	41	4.1	5.2	74.9	6.0	2.4	62.6
L 1	1.7	106	7.9	9.0	90.0	4.4	2.6	68.3
L 2	1.3	97	0.7	6.4	90.7	0.5	0.3	75.1
L 3	1.5	175	1.9	13.2	89.4	0.6	0.4	73.4
Full Run	1.6	419	14.6	33.8	90.0	2.1	1.3	70.9

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Figure 14. Stove 2—IDC Final Protocol Runs—January 2019

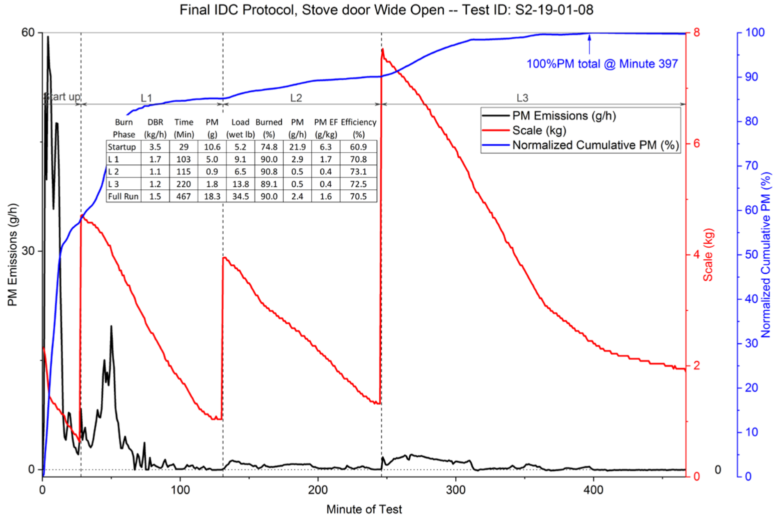
Final IDC Protocol, Stove Door Wide Open -- Test ID: S2-19-01-07



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.5	29	9.8	5.2	74.9	20.3	5.8	61.0
L 1	1.1	164	77.1	9.1	90.0	28.2	25.5	63.1
L 2	1.7	77	1.0	6.4	90.6	0.8	0.4	76.2
L 3	1.4	165	1.1	11.7	88.9	0.4	0.3	73.0
Full Run	1.5	435	89.0	32.4	90.0	12.3	8.3	69.3

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

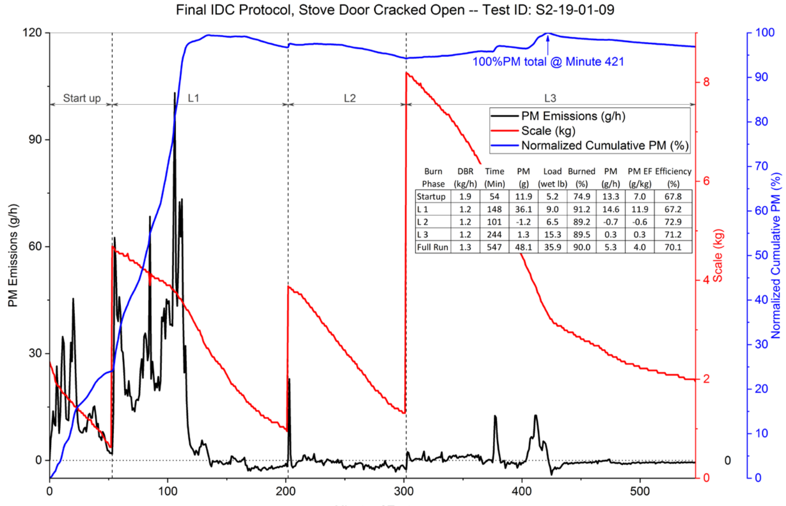
Final IDC Protocol, Stove door Wide Open -- Test ID: S2-19-01-08



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.5	29	10.6	5.2	74.8	21.9	6.3	60.9
L 1	1.7	103	5.0	9.1	90.0	2.9	1.7	70.8
L 2	1.1	115	0.9	6.5	90.8	0.5	0.4	73.1
L 3	1.2	220	1.8	13.8	89.1	0.5	0.4	72.5
Full Run	1.5	467	18.3	34.5	90.0	2.4	1.6	70.5

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Final IDC Protocol, Stove Door Cracked Open -- Test ID: S2-19-01-09



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	1.9	54	11.9	5.2	74.9	13.3	7.0	67.8
L 1	1.2	148	36.1	9.0	91.2	14.6	11.9	67.2
L 2	1.2	101	-1.2	6.5	89.2	-0.7	-0.6	72.9
L 3	1.2	244	1.3	15.3	89.5	0.3	0.3	71.2
Full Run	1.3	547	48.1	35.9	90.0	5.3	4.0	70.1

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

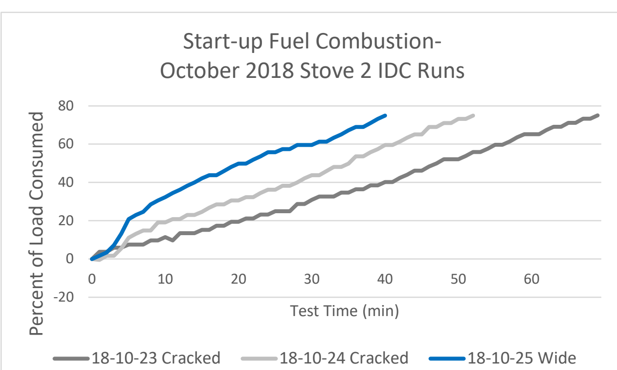
The test metrics for the start-up phase of the two sets of three replicate runs are shown in Table 16.

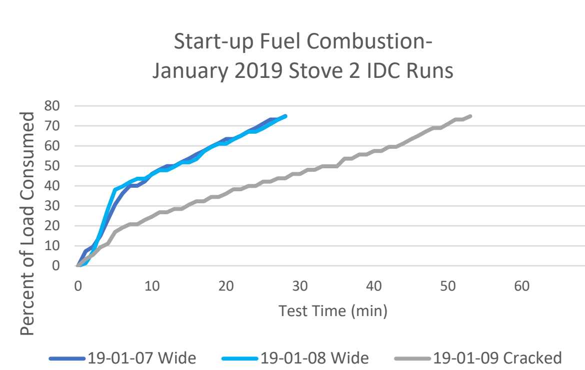
Table 16. Stove 2—Comparison of Test Metrics in Start-Up Phase of IDC runs

Test ID #	Door Position (5 min at startup)	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
S2-18-10-23	cracked open	1.47	70	11.85	10.15	6.92
S2-18-10-24	cracked open	1.93	53	7.77	8.80	4.57
S2-18-10-25	wide open	2.49	41	4.13	6.05	2.43
S2-19-01-07	wide open	3.53	29	9.83	20.33	5.76
S2-19-01-08	wide open	3.50	29	10.60	21.94	6.26
S2-19-01-09	cracked open	1.89	54	11.93	13.26	7.01

In both replicate groups, start-up loads burned faster when the door was wide open in the first five minutes, which resulted in higher burn rates and shorter run times for the start-up phase in door-wide-open burns. Cumulative burn profiles for the start-up phase of the two sets of three replicate runs are shown in Figure 15. The wide-open door start-ups are displayed in shades of blue and the cracked-open door start-ups in shades of grey in the graphs. As can be seen in that figure, in both replicate groups, the wide-open position was associated with a faster initial burn in the first five minutes, when the door was open.

Figure 15. Stove 2—Cumulative Burn Rates—Start-Up Phase of IDC Runs





The relationships were more complicated for the PM metrics. As shown in Table 16, runs with the initial wide-open door position had higher PM emission rate than EFs in the start-up phase. That difference was substantial in earlier runs (average cracked-door emissions and EF 2.4 times the wide-open door values). However, the PM emissions and EF were only slightly (17%) higher in the cracked-open door than in the average of the open door runs completed later in the test series.

The relationship is even more complex for ER. The highest start-up ERs in the six runs were in the two-door wide-open runs (S2-19-01-07 and S2-19-01-08), largely due to the short test time of those runs. However, the other door wide-open run (S2-18-10-25), achieved the lowest ER of all cracked and wide-open runs.

Table 17 shows the key metrics for the high-fire phase (Reload 1) for the stove 2 IDC runs. During this phase, a fuel load of 7 lb/ft^3 comprised of small pieces is loaded into the stove with fully open-air settings. When 50% of the fuel load, by weight, has been consumed, air settings are moved to the lowest setting.

Table 17. Stove 2—Comparison of Test Metrics for IDC Reload 1—High-Fire Phase

Test ID #	Door Position (5 min at startup)	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
S2-18-10-23	cracked open	0.90	199	149.65	45.12	50.17
S2-18-10-24	cracked open	1.65	108	106.28	59.04	35.88
S2-18-10-25	wide open	1.69	106	7.85	4.44	2.62
S2-19-01-07	wide open	1.10	164	77.08	28.20	25.52
S2-19-01-08	wide open	1.73	103	5.04	2.94	1.70
S2-19-01-09	cracked open	1.23	148	36.06	14.62	11.92

The start-up door position does not appear to have a primary influence on the high-fire phase. However, there was very wide variability in the results for this phase in both sets of replicates. Two of the runs in the first group, S2-18-10-24 (cracked open) and S2-18-10-25 (wide open), had very similar high-fire phase dry-burn rates and test times. However, all the PM parameters for S2-18-10-24 were more than 13 times those for S2-18-10-25. The other replica run in that group, S2-18-10-23 (cracked open), had a high-fire phase burn rate that was approximately one-half and a run time approximately twice that of the other two replicate runs. That replicate had the highest high-fire phase total PM and EF in either sampling period. However, due to the longer test time, the ER rate for S2-18-10-23 was lower than that for S2-18-10-24. S2-19-01-08 had the highest burn rate and shortest test period, while the reverse was true for run S2-19-01-07. As with the previous testing, the run with the lowest burn rate produced the most PM, 15 times the PM produced by the highest burn rate run. The ERs and EFs measured in the S2-19-01-08 and S2-19-01-07 runs were similarly divergent. Both of those runs had wide-open door positions in the beginning of the start-up period.

The maintenance phase (reload 2) phase metrics for the two sets of IDC replicates are shown in Table 18.

Table 18. Stove 2—Comparison of Test Metrics for Reload 2—Maintenance Phase

Test ID #	Door Position (5 min at start-up)	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
S2-18-10-23	cracked open	1.09	117	83.58	42.86	39.48
S2-18-10-24	cracked open	1.55	81	-4.72	-3.50	-2.26
S2-18-10-25	wide open	1.34	97	0.73	0.45	0.34
S2-19-01-07	wide open	1.69	77	0.97	0.76	0.45
S2-19-01-08	wide open	1.12	115	0.90	0.47	0.42
S2-19-01-09	cracked open	1.24	101	-1.25	-0.74	-0.60

During the maintenance phase, significant PM emissions occurred in only one of the six runs, S2-19-10-23. That run, the first of the six chronologically, also had the highest PM emissions in the previous phase. The dry-burn rate for that run was lower than for the other runs, but only slightly lower than the rate in one of the January runs, S2-19-01-08, which did not have significant PM emissions. All other runs either had minimal emissions (<1 g) or recorded a loss of PM from the filter during this phase.

The metrics measured in the overnight phase in the two IDC testing periods are shown in Table 19.

Table 19. Stove 2—Comparison of Test Metrics for Reload 3—Overnight Phase

Test ID #	Door Position (5 min at start-up)	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
S2-18-10-23	cracked open	1.53	172	4.92	1.72	1.13
S2-18-10-24	cracked open	1.56	138	-0.76	-0.33	-0.21
S2-18-10-25	wide open	1.50	175	1.86	0.64	0.43
S2-19-01-07	wide open	1.41	165	1.14	0.42	0.29
S2-19-01-08	wide open	1.25	220	1.76	0.48	0.39
S2-19-01-09	cracked open	1.24	244	1.32	0.33	0.26

The overnight phases of the stove 2 IDC runs lasted 138to 244 minutes (2.3 to 4.1 hours). The overnight dry-burn rates in four of the runs were similar except S2-18-10-23 and S2-19-10-24. The first run, S2-19-10-23, again emitted more PM than any of the other runs, but the amount of PM (4.9 g) emitted in this run was much lower than in the previous phases. Run S2-19-10-24 lost PM mass during this phase. All other runs produced 1–2 g of PM.

Table 20 shows the test metrics for the entire run of each of the stove 2 IDC runs.

Table 20. Stove 2—Comparison of Test Metrics for Entire IDC Runs

Test ID #	Door Position (5 min at start-up)	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	HHV Efficiency (%)
S2-18-10-23	cracked open	1.20	558	250.00	26.88	22.35	65.3
S2-18-10-24	cracked open	1.63	380	108.57	17.14	10.50	68.9
S2-18-10-25	wide open	1.61	419	14.58	2.09	1.30	70.9
S2-19-01-07	wide open	1.49	435	89.02	12.28	8.25	69.3
S2-19-01-08	wide open	1.46	467	18.30	2.35	1.61	70.5
S2-19-01-09	cracked open	1.30	547	48.07	5.27	4.05	70.1

The total time to complete the stove 2 IDC runs ranged from 380 to 558 minutes (6.3 to 9.3 hours). This again supports the premise that the IDC protocol can be completed in less than 10 hours, making a single-day test run feasible. Although the efficiencies measured in the runs did not diverge substantially, the run with the lowest efficiency (S2-18-10-23) had the highest PM emissions, ER, and EF, while those PM metrics were lowest in the run with the highest efficiency (S2-18-10-25).

Average burn rates for the entire protocol were 36% higher in the shortest run (S2-18-10-24) than in the longest run (S2-18-10-23). A wide range of total PM emissions were measured. Run S2-18-10-23 emitted 2.5 times more PM than emitted in the next highest run and 17 times the PM emitted by the lowest emitting run. Although the highest emitting run had the lowest burn rate, burn rate did not correlate with emissions. Note that the run with the second highest emissions, S2-18-10-24, had the highest burn rate. The S2-18-10-23 ER and EF for the entire run were also substantially higher than for all other runs.

Figure 16 shows the test metrics by test phase for each of the IDC runs graphically.

Figure 16. Stove 2—Comparison of Metrics for IDC Runs

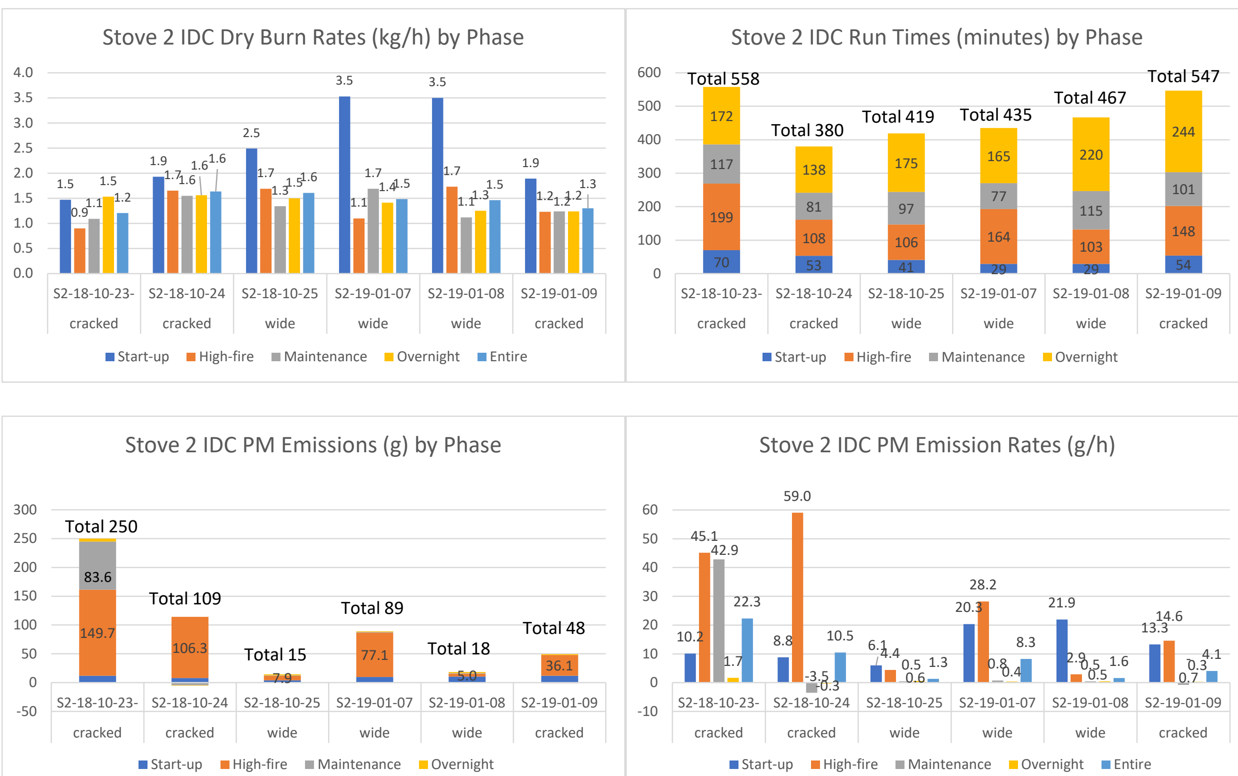
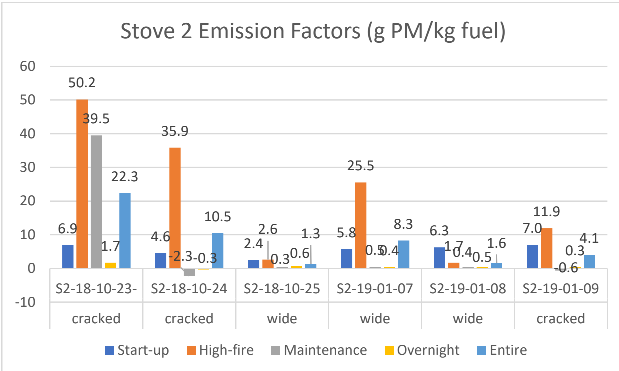


Figure 16 continued



Except for the start-up phase in the runs with wide-open door positions in the first 5 minutes of start-up, dry-burn rates in all phases of the stove 2 runs were lower than 2 kg/h.

The wide-open door position in the first five minutes of the start-up runs increased the start-up phase burn rate and appears to have increased the ER in that phase. However, the increased wide-open door start-up phase ER was mostly due to the shorter test times, rather than increased PM emissions, in those runs and did not affect the overall ER measured for the entire run. Therefore, it does not appear that initial door position is an important factor in the overall stove performance.

The PM emissions results illustrated in Figure 16 are very different from those for stove 1 discussed above. In the three stove 1 IDC runs, the high-fire, maintenance and the overnight burns all produced significant PM emissions. In stove 2, however, significant PM emissions were produced in only one of the maintenance phases and in none of the overnight phases. Two of the runs, one in each of the testing periods, produced minimal emissions throughout the entire run.

The divergence in PM emissions in the stove 2 IDC runs can be partially explained by stove temperatures. Figure 17 shows the stove temperature and PM emissions profiles for each of the six stove 2 IDC final protocol runs. In each run, substantial emissions occurred when the average stove temperature was less than 300°F. In the two lowest emitting runs, S2-18-10-25 and S2-19-01-08, the stove reached 300°F rapidly, at minutes 82 and 67, during the high-air setting portion of reload 1. In comparison, in the highest emitting run, S2-18-10-23, that temperature was not reached until minute 376, at the end of the maintenance run. The other three, intermediate-emitting runs reached 300°F at intermediate times, minute 136 for both S2-09-01-07 and S2-19-01-09 and minute 150 for S2-18-10-24, all during the second, low-air setting half of the reload 1 burn.

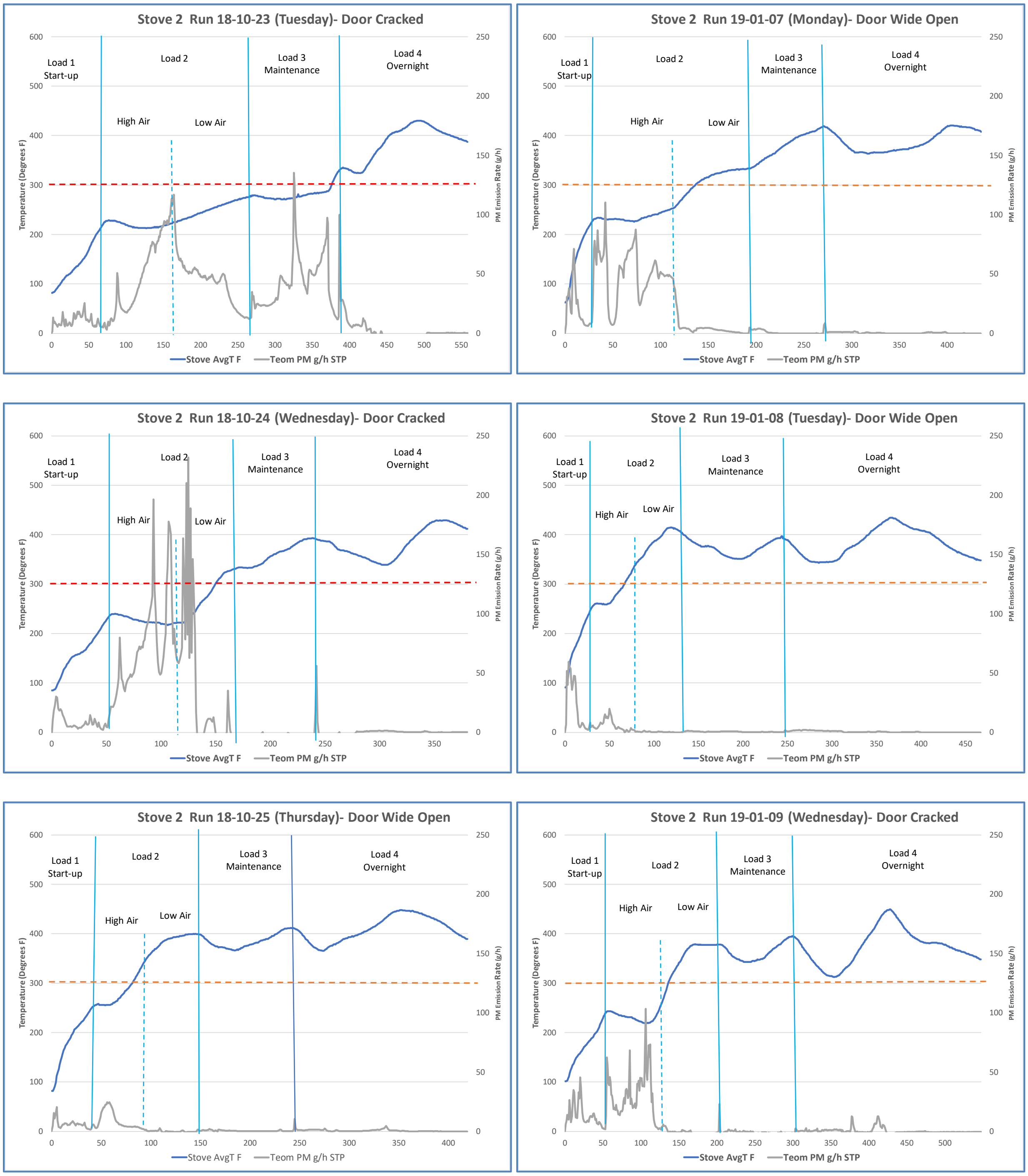
The fact that the stove temperature in run S2-18-20-23 did not reach 300ºF until the end of the maintenance run, while that temperature was achieved during the reload 1 burn in the other runs, explains why the high emissions in that run continued into the maintenance load. Stove 2 is controlled by a catalytic device that is activated with temperature. Until that device is activated, the stove is essentially running uncontrolled. The rapid drop in PM emissions in the stove 2 runs when the stove temperature reached approximately 300ºF is an indication that the catalytic converter activated at about that temperature. That activation occurred much later in run S2-18-10-23 than in the other runs.

The reason for the differences in the temperature profiles is less clear. The starting temperatures of the stove ranged from 62ºF in run S2-19-01-07 to 101ºF in run S2-19-01-09 but starting temperature did not correlate with length of the start-up phase, temperature at the end of the start-up phase, the time that the stove temperature reached 300ºF, or PM emissions. In the first five minutes of start-up, the stove door was cracked open in three of the runs and wide open in the other three runs. Although the burn rates were higher and the start-up phase run time lower in the runs that started with the door wide open, the stove temperatures at the end of the start-up phase was similar in the two groups.

While each set of IDC stove 2 tests was run on sequential days, there were approximately 12 weeks between the two sets of runs. This space of time introduces the potential for other variations in operation. However, except for the first run in the first group, which was different from all other runs in both groups, there was no clear difference between the range of temperatures or emission profiles and the first and second group of runs. What is very clear, however, is that stove 2 does not burn consistently, even with a standardized fueling protocol, and that differences in the stove temperature profile have a strong impact on the effectiveness of the catalytic control system. Replicability issues are further discussed in section 4.

Figure 17. Stove 2—IDC Runs—Emission and Temperature Profiles

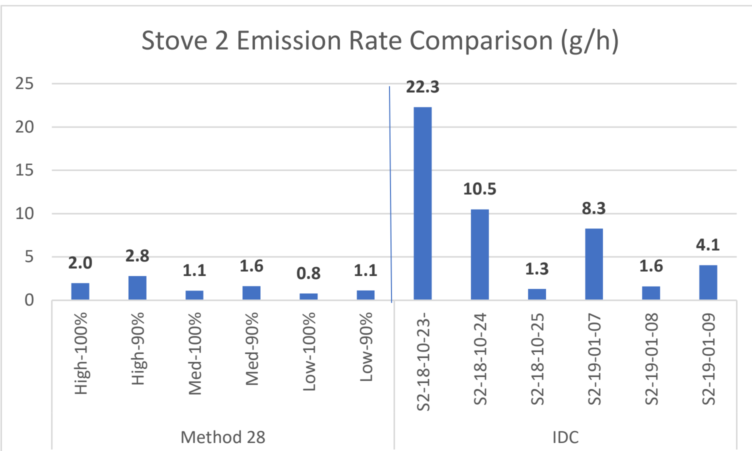
Stove 2—October 2018 IDC Runs | **Stove 2—January 2019 IDC Runs**



2.2.3 Comparison of Stove 2 Emission Rate Measurements

Figure 18 compares the emission rates measured for the M28 and IDC final protocol runs performed on Stove 2. PM was measured using the 1400AB TEOM in the baseline runs and the 1405 TEOM in the IDC runs. A previous evaluation of data from collocated 1400AB and 1405 TEOMs showed excellent correlation between the measurements with the two instruments; however, the 1400AB PM measurements were 8% to 13% lower than the levels measured with the 1405.

Figure 18. Stove 2—Comparison of Method 28 and IDC Emission Rate Measurements



The ERs displayed in Figure 18 for the M28 runs should not be compared to regulatory values, which are calculated using weighting factors. However, as shown in that figure, the ERs measured using M28, the current EPA protocol, were considerably lower than those measured in four of the six IDC runs. Because M28 is a hot-to-hot method (measurements start after a bed of hot coals has been generated), the stove temperature at the start of the M28 runs (442–472ºF) were already substantially above the 300ºF temperature that appears to be required for the catalytic control system to ignite and the stove temperature never fell below 370ºF in any of those runs.

This demonstrates that in a catalytically controlled stove like stove 2, a hot-to-hot test can substantially underestimate emissions under common field operating conditions, which include cold and warm starts. In the field, the stove essentially operates uncontrolled until the stove is hot enough for the catalytic controls to ignite, which can result in substantially higher emissions than those measured by M28. The M28 ERs associated with combustion of 90% of the fuel load were 42% to 48% higher than the 100% ERs but using those numbers did not compensate for the underestimate in emissions due to the temperature issues.

Section 4 presents a more detailed analysis of the differences between the results for different test methods, including a comparison of the operating parameters measured in the high-fire phases of runs using different methods and a similar comparison of low-fire phase parameters.

2.3 Stove 4

Stove 4 is a small fire-box, cast-iron stove with non-catalytic emission controls. Nine test runs were performed on stove 4, as listed in Table 21. M28 baseline tests burned Douglas fir crib wood, and all other tests used red maple cordwood.

Table 21. Stove 4—Test Descriptions

Test ID	Test Method	Fuel Species	Fuel Type	Description
S4-17-10-23	M28	Douglas Fir	Crib	High fire, load burned 100%
S4-17-10-25	M28	Douglas Fir	Crib	Medium fire, load burned 100%
S4-17-10-24	M28	Douglas Fir	Crib	Low fire, load burned to 100%
S4-18-01-16	IDC v1	Red Maple	Cordwood	Cold start-up RL 1 - 5# at high [a] RL 2 - 7# at medium RL 3 - 12# at low
S4-18-04-19	R&D	Red Maple	Cordwood	Cold start top-down kindling RL 1 - 7# at high shut to low at 50% burned No RL 2 RL3 - 12# at low to 90% burned
S4-18-05-10	R&D	Red Maple	Cordwood	Cold start top-down kindling RL 1 - 7# at high shut to low at 50% burned RL 2 - 5# at low RL 3 - 12# at low to 90% burned
S4-18-10-16 Replicate 1	IDC Final Protocol	Red Maple	Cordwood	
S4-18-10-17 Replicate 2	IDC Final Protocol	Red Maple	Cordwood	
S4-18-10-18 Replicate 3	IDC Final Protocol	Red Maple	Cordwood	

[a] Symbol # denotes fuel loading density in pounds per cubic foot of the stove firebox (lb/ft^3).

The 1400AB TEOM was used for continuous PM measurements in all stove 4 test runs. The results of the stove 4 baseline and IDC final protocol run results are presented in this section. The research runs, which were used to refine the IDC protocol, are discussed in section 2.

2.3.1 Baseline Tests

As with the previous stoves, baseline tests for stove 4 were conducted using modified EPA Method 28 (M28) procedures at three of the four air control settings prescribed in that method: the highest air control setting (category 4), the lowest setting (category 1), and the manufacturer's recommended air setting for a medium-burn rate (category 2/3). Table 22 summarizes the results of the baseline modified M28 testing. Note that at the medium air setting, stove 4 achieved a category 3 burn rate.

Table 22. Stove 4—Summary of the Modified M28 Baseline Test Results

	Test Time (min)		Dry-Burn Rate (kg/h)		Total PM (g)		PM Emission Rate (g/h)		PM Emission Factor (g/kg)		HHV Efficiency (%)
% Burn Completed	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*100%*
High	25	33	4.58	3.85	0.90	0.90	2.16	1.64	0.48	0.42	CBD
Medium	49	70	2.24	1.73	4.69	4.87	5.74	4.17	2.56	2.41	52.0
Low	112	157	0.99	0.79	4.83	5.04	2.59	1.93	2.62	2.43	67.5

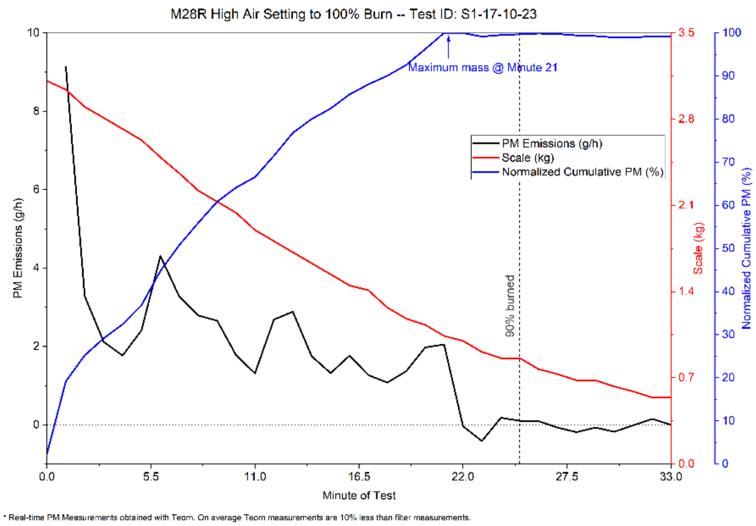
The HHV thermal efficiency of stove 4 was higher in the low-air than the medium-air run and could not be determined because of problems with CO and CO_2 measurement data in the high-air run.

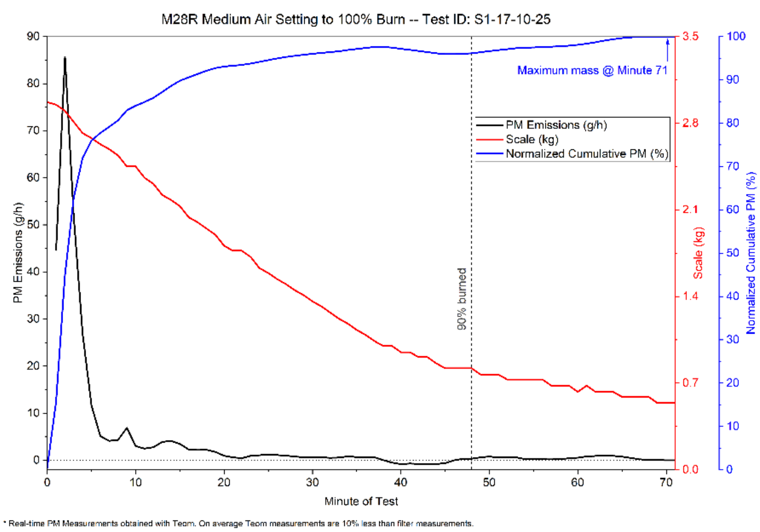
Total PM emissions and EF in the stove 4 medium- and low-air setting baseline runs were 5 to 6 times higher than those measured in the high-air setting run. The combustion test time in the medium- and low-air runs were 2.1 and 4.8 times higher than in the high-air run, respectively. The ER for the medium run was 2.5 times that for the high-air run. However, due to the much longer test time, the ER measured in the low-air run was only 18% greater than that in the high-air run. A more detailed discussion of PM emissions follows.

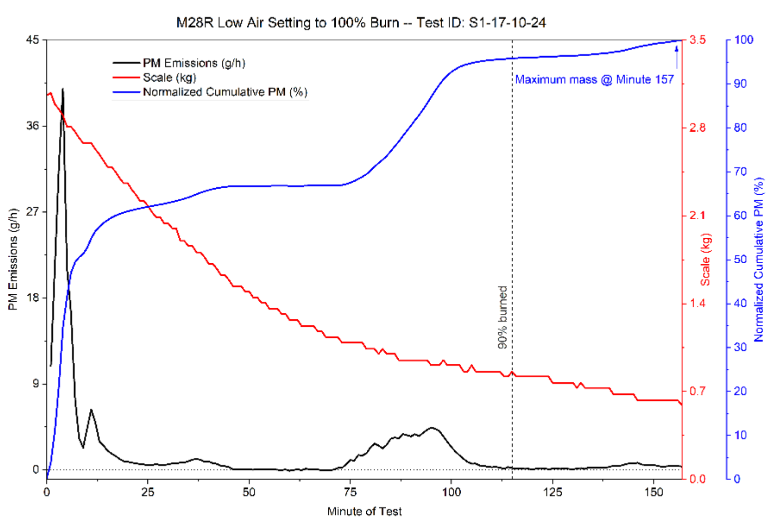
2.3.1.1 PM Emission Profiles

Real-time plots of the three stove 4 M28 test runs are presented in Figure 19 below. As in the plots for the previous stoves, the TEOM PM emission rate profiles are shown in black, cumulative PM in blue, and remaining fuel load in red.

Figure 19. Stove 4—M28 Baseline Test Results





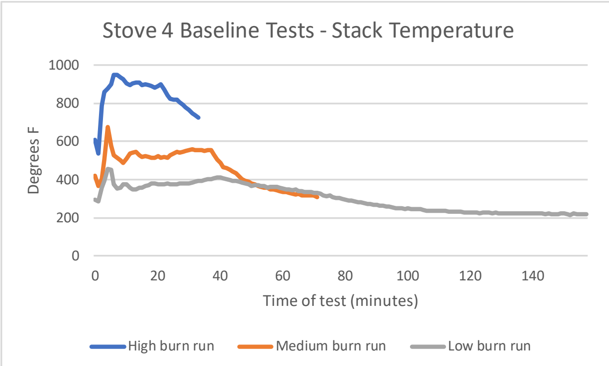


The maximum instantaneous PM ER for all three of the stove 4 baseline runs occurred within the first few minutes of the burns. The medium air run produced a higher instantaneous peak ER, 85.7 g/h at 2 minutes, than the peaks produced in the low-air (39.9 g/h at 4 minutes) and high-air (9.1 g/h at 1 minute) runs. Ninety percent of total PM emissions occurred in the first 18 minutes of the 33-minute high-burn run, the first 15 minutes of the 70-minute medium-burn run and the first 97 minutes of the 157-minute low-burn run.

Figure 20 shows the PM emissions profiles, cumulative PM, fuel combustion, and stove and stack temperature profiles for the three stove 4 baseline runs.

Figure 20. Stove 4—Baseline Runs—PM Emission Profiles, Cumulative PM Emissions, Cumulative Fuel Consumption, and Stack Temperatures

Figure 20 continued



As discussed above and shown in Figure 20, the PM emission profiles for all three runs show a sharp emission peak in the first few minutes of the test run, with the maximum instantaneous ER highest in the medium burn and lowest in the high-burn run. Minimal total PM were generated in the high-burn run. This may be at least partly explained by the stove and stack temperature, which were much higher throughout the high burn than in the other runs. The starting stove temperature for the high run was 589ºF, approximately 200 degrees higher than the starting temperatures in the medium- (399ºF) and low- (361ºF) fire runs and may have triggered the immediate activation of the non-catalytic control system on stove 4.

The initial emissions peak occurred slightly later in the low burn than in the other runs, probably due to a slight delay in the light-off of the fuel load, as seen in the fuel combustion plot in Figure 20. However, due to the small firebox size in this stove, that delay was minimal. The low burn also emitted a small but significant amount of PM during the period approximately 80 to 100 minutes into the run, resulting in total PM emissions for that run that were slightly higher than for the medium burn, despite the higher initial PM peak in the medium-burn run.

2.3.1.2 Cumulative PM Emissions

As discussed above, maximum cumulative PM often occurs midway through baseline runs, due to volatilization filter losses that occur later in the burns. However, volatilization losses were not seen in the stove 4 baseline runs, likely due to the relatively short burns associated with the small fuel load. As discussed above, total PM emissions were similar in the medium- and low-fire runs and were more than five times higher in those runs than in the high-fire run.

2.3.1.3 Ninety Percent versus 100% Fuel Combustion

As discussed above, measuring the ER for an entire test run generally underestimates the rate that would occur in the field, because most emissions occur early in the burns and wood stove owners often refuel before the previous load has been completely consumed. For stove 4, 90% of total PM emissions were generated in the first 55%, 21%, and 62% of the high-, medium-, and low-fire baseline runs, respectively.

To more accurately reflect actual in-use conditions, we calculated PM emission parameters at the point in the run that 90% of the fuel had been combusted, as well as at the end of the run (100% fuel combustion). For the stove 4 high-burn run, the time period between 90% and 100% fuel combustion was 8 minutes, which is 24% of the total run time. Total PM emissions did not change during that period, but because at 90% those emissions are associated with combustion of 10% less fuel, the EF (in g/kg) at 100% combustion was 12% lower than at 90% combustion. The PM ER, the metric used to certify stoves, was 2.16 g/h at 90% fuel combustion and 1.64 g/h at 100% combustion, a reduction of 24% that is due to the lengthened averaging period.

For the medium-burn run, the time period between 90% and 100% combustion was 21 minutes, 30% of the total run time. During that period, total PM emissions increased by 4%, but the PM EF decreased by 6%. The PM ER decreased by 27%, from 5.74 g/h to 4.17 g/h.

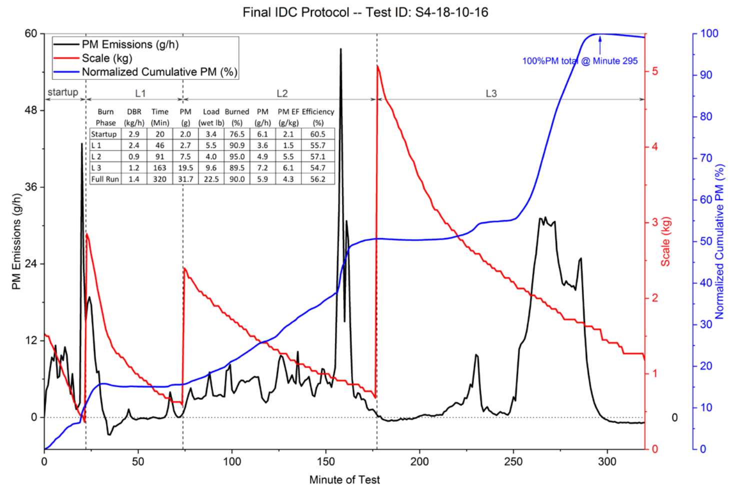
For the low-burn run, the time from 90% to 100% combustion was 45 minutes, 29% of the total run time. During that period, low-burn PM emissions increased by 4%, the EF (g/kg) decreased by 7%, and the ER rate decreased by 25%, from 2.59 g/h to 1.93 g/h.

The average ER associated with 100% combustion in the three runs was 2.6 g/h, as compared to 3.5 g/h for 90% combustion.

2.3.2 IDC Tests

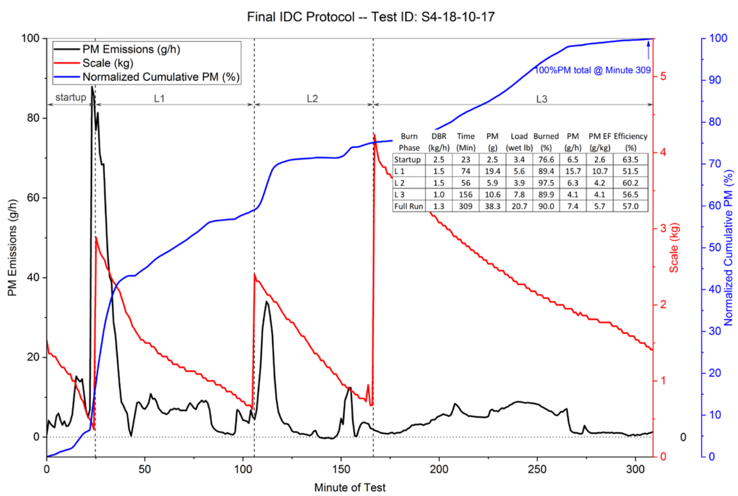
Three replicate IDC final protocol runs were performed on stove 4. Profiles of the stove 4 IDC final protocol runs are shown in Figure 21.

Figure 21. Stove 4—IDC Final Protocol Runs



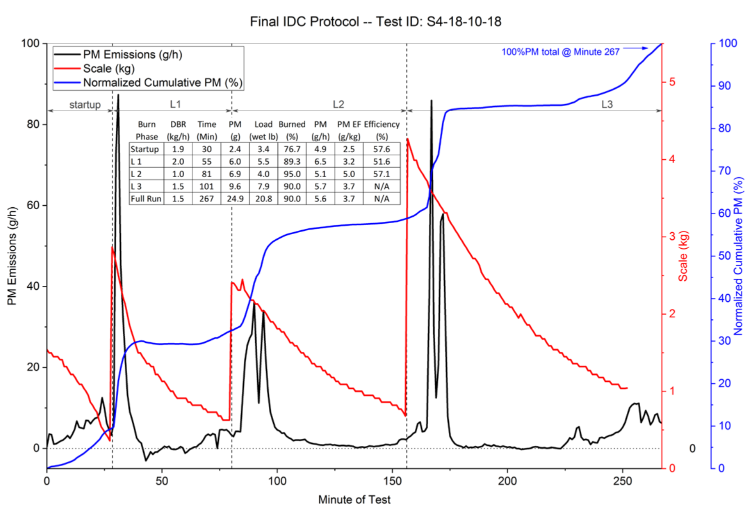
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.9	20	2.0	3.4	76.5	6.1	2.1	60.5
L 1	2.4	46	2.7	5.5	90.9	3.6	1.5	55.7
L 2	0.9	91	7.5	4.0	95.0	4.9	5.5	57.1
L 3	1.2	163	19.5	9.6	89.5	7.2	6.1	54.7
Full Run	1.4	320	31.7	22.5	90.0	5.9	4.3	56.2

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.5	23	2.5	3.4	76.6	6.5	2.6	63.5
L 1	1.5	74	19.4	5.6	89.4	15.7	10.7	51.5
L 2	1.5	56	5.9	3.9	97.5	6.3	4.2	60.2
L 3	1.0	156	10.6	7.8	89.9	4.1	4.1	56.5
Full Run	1.3	309	38.3	20.7	90.0	7.4	5.7	57.0

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	1.9	30	2.4	3.4	76.7	4.9	2.5	57.6
L 1	2.0	55	6.0	5.5	89.3	6.5	3.2	51.6
L 2	1.0	81	6.9	4.0	95.0	5.1	5.0	57.1
L 3	1.5	101	9.6	7.9	90.0	5.7	3.7	N/A
Full Run	1.5	267	24.9	20.8	90.0	5.6	3.7	N/A

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

The metrics for the start-up phase of the three replicate IDC stove 4 IDC runs are shown in Table 23.

Table 23. Stove 4—Metrics for Start-Up Phase of the IDC Replicate Runs

Run ID #	S4-18-10-16 Run 1	S4-18-10-17 Run 2	S4-18-10-18 Run 3
Dry-Burn Rate (kg/h)	2.90	2.52	1.94
Time (min)	20	23	30
Total PM (g)	2.0	2.5	2.4
PM Emission Rate (g/h)	6.14	6.49	4.88
PM Emission Factor (g/kg)	2.12	2.57	2.52

The start-up phase dry-burn rate was highest and the test time lowest in run 1, and the reverse was true for run 3. PM emissions and the PM EF were about 20% higher in runs 2 and 3 than in the first run. Due to the longer time period, the start-up PM ER for run 3 was about 20% lower than in the other runs.

The metrics for the high-fire phase (reload 1) of the IDC runs are shown in Table 24. During this phase, a fuel load of 7 lb/ft^3 comprised of small cordwood pieces is burned at the highest air control setting. When 50% of the load is consumed, the air control is switched to the lowest setting and the load is burned to 90% consumption, by weight.

Table 24. Stove 4—Metrics for Reload 1—High-Fire Phase of the IDC Replicate Runs

Run ID #	S4-18-10-16 Run 1	S4-18-10-17 Run 2	S4-18-10-18 Run 3
Dry-Burn Rate (kg/h)	2.41	1.46	2.01
Time (min)	46	74	55
Total PM (g)	2.7	19.4	6.0
PM Emission Rate (g/h)	3.55	15.72	6.49
PM Emission Factor (g/kg)	1.47	10.74	3.23

Reload 1 (high-fire) phase PM emissions were much higher in run 2 than in the other runs. The high-fire phase run 2 Total PM and EF were 7 times and 3 times higher than those in run 1 and 3, respectively. The run 2 high-fire phase ER was 4 times higher than the run 1 ER and twice that of the run 3 rate. The run 2 dry-burn rate for this phase was 39% of the run 1 and 27% of the run 3 burn rates. As will be discussed further below, the run 2 high-fire phase stove temperature was also considerably lower than in the other runs, which may have increased PM emissions.

In the reload 2 burn, the maintenance phase, air controls are kept at the lowest setting and two large pieces of wood are loaded into the stove. At this point, the coal bed is well developed. The metrics measured in the phase in stove 4 IDC runs are shown in Table 25.

Table 25. Stove 4—Metrics for Reload 2—Maintenance Phase of the IDC Replicate Runs

Test ID #	S4-18-10-16 Run 1	S4-18-10-17 Run 2	S4-18-10-18 Run 3
Dry-Burn Rate (kg/h)	0.90	1.51	1.04
Time (min)	91	56	81
Total PM (g)	7.5	5.9	6.9
PM Emission Rate (g/h)	4.92	6.31	5.15
PM Emission Factor (g/kg)	5.49	4.19	4.96

The maintenance phase dry-burn rate for run 2 was similar to the burn rate in the previous phase. However, the dry-burn rates in the other two runs were considerably lower in the maintenance phase than in the previous phase. As a result, although the high-fire phase burn rate was lower in run 2 than in the other runs, in the maintenance phase, run 2 had the highest burn rate, 68% higher than the run 1 rate and 45% higher than the run 3 burn rate. PM emissions parameters were similar in the maintenance phase of the three runs.

The final phase in the IDC protocol (reload 3, the overnight phase) reflects conditions required to obtain a long burn, such as those needed for overnight burns or during the day when the fire will be unattended for a significant amount of time (>6 hours). During this phase, the coal bed is raked, and the user loads as much wood as possible, using large and small pieces. The metrics measured in the overnight phase in the two IDC testing periods are shown in Table 26.

Table 26. Stove 4—Metrics for Reload 3—Overnight Phase of the IDC Replicate Runs

Test ID #	S4-18-10-16 Run 1	S4-18-10-17 Run 2	S4-18-10-18 Run 3
Dry-Burn Rate (kg/h)	1.18	0.98	1.55
Time (min)	163	156	101
Total PM (g)	19.5	10.6	9.6
PM Emission Rate (g/h)	7.17	4.06	5.69
PM Emission Factor (g/kg)	6.08	4.12	3.68

The overnight phases of the stove 4 IDC runs were 101 to 163 minutes (1.7 to 2.7 hours) long. In this phase, the run 3 dry-burn rate was higher and the run time lower than in the other runs. Run 1 produced about twice as much PM as the other runs. However, because the fuel load in run 1 was 23% to 25% higher than in the other runs, the run 1 EF was only 48% and 65% higher than in runs 2 and 3, respectively. The run 1 ER was 76% higher than that of run 2 and 26% higher than in run 3.

Table 27 shows the test metrics for the entire run of each of the stove 4 IDC replicates.

Table 27. Stove 4—Comparison of Test Metrics for the Entire IDC Protocol

Test ID #	S4-18-10-16 Run 1	S4-18-10-17 Run 2	S4-18-10-18 Run 3
Dry-Burn Rate (kg/h)	1.38	1.31	1.53
Time (min)	320	309	267
Total PM (g)	31.7	38.3	24.9
PM Emission Rate (g/h)	5.94	7.44	5.60
PM Emission Factor (g/kg)	4.30	5.69	3.66
HHV Efficiency (%)	56.2	57.0	---

The total time to complete the stove 4 IDC runs ranged from 267 to 320 minutes (4.5 to 5.3 hours), clearly feasible for completion in a single day. The HHV efficiencies were similar in the first two runs and could not be determined in the third run, due to issues with the carbon monoxide and carbon dioxide data.

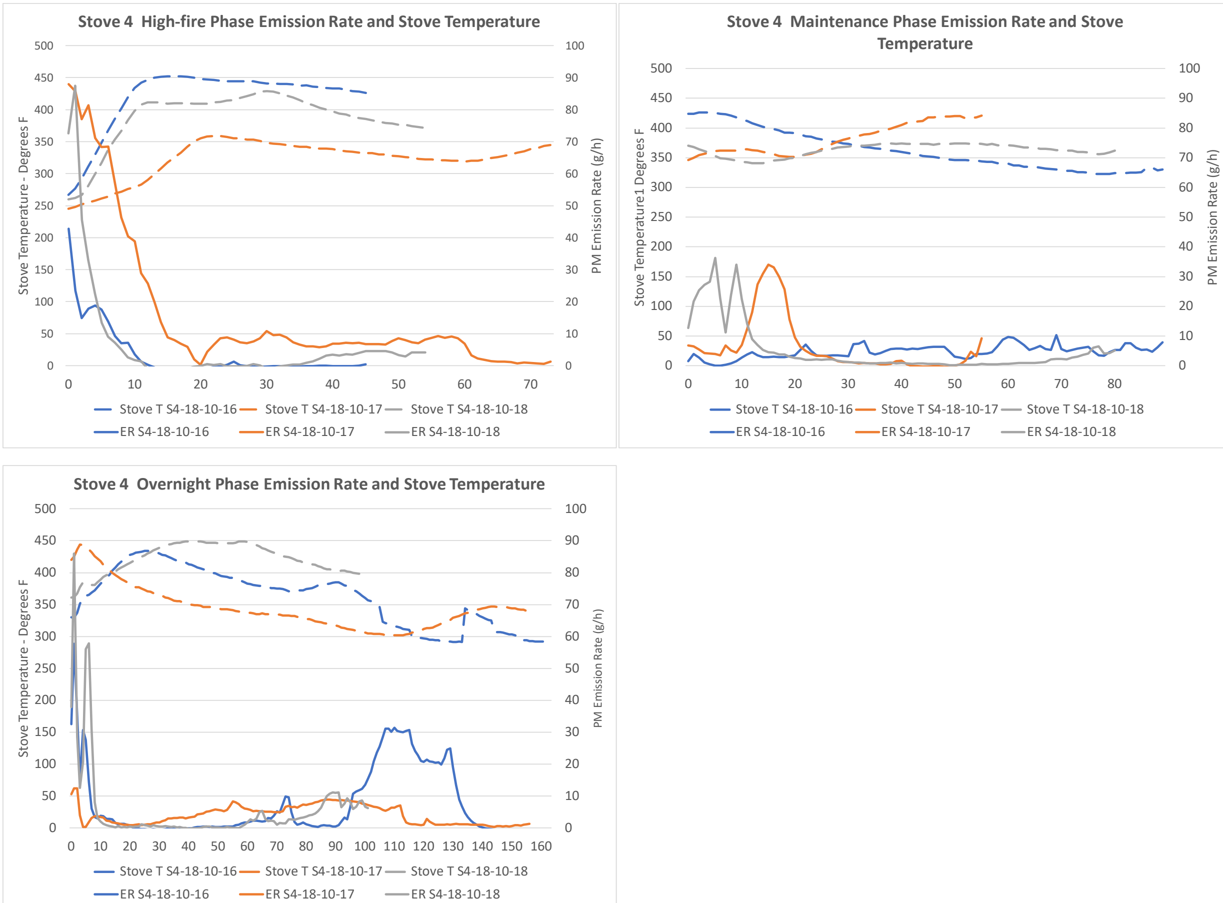
Variability in metrics between runs were lower in stove 4 than in some of the other stoves. For the entire run, the run 3 average dry-burn rate was 11-% to 17% higher and the test time 14% to 17% shorter than those of the other runs. The PM parameters were highest in run 2 and lowest in run 3. Total PM, the PM EF and the PM ER were 54%, 55%, and 33% higher in run 2 than in run 3. A detailed analysis of the reproducibility of the replicate tests is presented in section 4.

Figure 22 shows the test metrics by test phase for each of the IDC runs graphically.

Figure 22. Stove 4—Comparison of Metrics for IDC Replicate Runs S4-18-10-16, S4-18-10-17, and S4-18-10-18

As can be seen in that figure, dry-burn rates did not show a consistent pattern from run to run. The results of the PM metrics, by phase, were similar in the three runs with two exceptions: PM emissions were elevated relative to the other runs in run 2 in the high-fire phase and in run 1 in the overnight phase. These differences can be at least partially explained by the stove temperatures in those phases, as shown in Figure 23. In that figure, emission rate profiles for the phase in the three runs are shown with solid lines and the stove temperatures for those runs are shown with dashed lines in the corresponding colors.

Figure 23. Stove 4—PM Emission Rates and Stove Temperatures



In the high-fire phase, the ERs of all three runs peaked immediately after the fuel was loaded and stove temperatures were low (245267ºF) at that time. At the beginning of that phase, the stove temperature was higher and the ER lower in Run 1 than in the other runs. The run 1 stove temperature increased rapidly in the first few minutes of the high-fire phase and reached 450ºF by minute 13, when the ER in that run had dropped to zero. Run 3 showed a similar pattern at the beginning of the high-fire phase; by minute 12, the run 3 PM emissions were zero and the stove temperature 411ºF. At the end of the run 3 high-fire phase, the temperature began to decrease to a final temperature of 371ºF and a small amount of additional emissions were recorded at that time.

The high-fire phase pattern was different in run 2, however. In that run, the temperature started slightly lower than in the other runs and remained an average of 67ºF lower than run 3 and 99ºF lower than run 1 for the remainder of the run. Run 2 high-fire phase PM emissions were highest in the beginning of the run, when the stove temperature was below 300ºF, but significant emissions continued throughout most of the phase. The maximum stove temperature in that run was 358ºF.

In the maintenance phases of runs 2 and 3, PM emissions were highest at the beginning of the burns, when the stove temperatures were lowest (<380ºF). The PM peak occurred later in run 2 (max at 15 minutes) than in run 3 (twin peaks at 5 and 9 minutes). That difference cannot be explained by temperature or burn rate. The maintenance phase stove temperature started out higher in run 1 (424ºF) than in the other runs but decreased slowly but steadily throughout the phase. At minute 33, the run 1 stove temperature was 370ºF, lower than the other runs, and decreased to 330ºF by the end of the phase. Unlike the other runs, run 1 did not have significant emissions at the beginning of the run, probably because of the elevated temperature at that time. However, small but significant emissions were measured throughout the run, particularly when the temperatures dropped below about 390ºF. As shown above, although the shapes of the emission profiles in the three maintenance runs differed, total emissions in that phase were similar in the three runs.

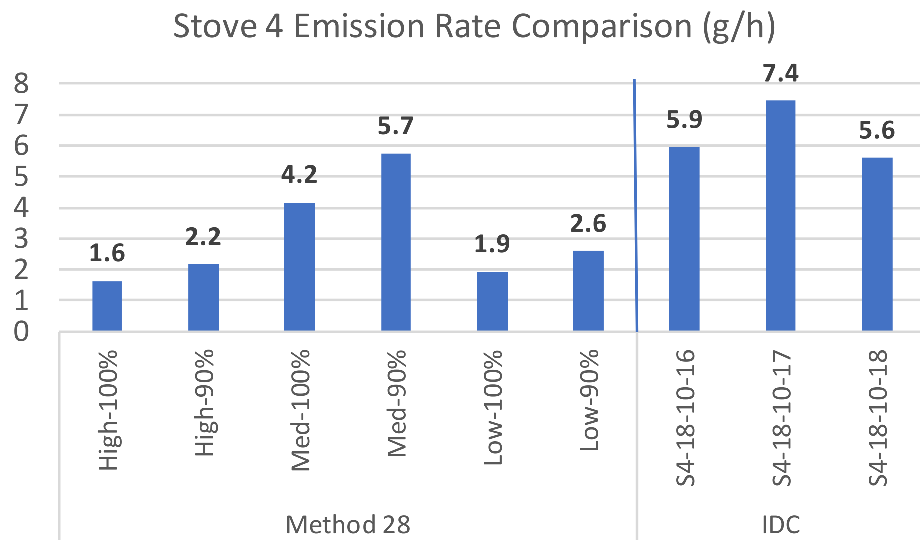
As discussed above, overnight phase emissions were considerably higher in run 1 than in the other runs. Most of those emissions occurred in the first few minutes of the burn, when the stove temperature was less than 370ºF, and in an approximately 40-minute period beginning at about minute 95, when the temperature had dropped to 299–376ºF. Run 2, which had the highest initial stove temperature in the maintenance phase, did not have high peak PM emissions in the beginning of that phase. However, the stove temperature declined through most of that run, and small but significant emissions rates were recorded throughout the period when the stove temperature was below 360ºF. Run 3 had the highest instantaneous overnight phase emissions in the first few minutes of the overnight phase, when the stove temperature was 381ºF, which fell off abruptly as the stove temperature increased.

A more detailed discussion of replicability of IDC runs is included in section 4.

2.3.3 Comparison of Stove 4 Emission Rate Measurements

Figure 24 compares the emission rates for the M28 and IDC test runs performed on stove 4.

Figure 24. Stove 4—Comparison of Method 28 and IDC Emission Rate Measurements



As shown in that figure, the ERs measured by the current crib wood EPA certification method, M28, were generally lower than those measured in the IDC runs. As discussed above, these M28 ER measurements should not be compared directly to the regulatory standard, which employs weighting factors. The M28 ER associated with 90% combustion at the medium-air setting was similar to those measured with IDC.

Section 3.5 presents a more detailed analysis of the differences between the results for different test methods, including a comparison of the operating parameters measured in the high-fire phases of runs using different methods and a similar comparison of low-fire phase parameters.

2.4 Stove 5

Stove 5 is a medium sized fire-box, cast-iron stove with non-catalytic emisison controls. A total of 11 tests runs were performed on stove 5, as listed in Table 28. M28 baseline tests burned Douglas fir crib wood, and all other tests used red maple cordwood.

Table 28. Stove 5—Test Descriptions

Test ID	Test Method	Fuel Species	Fuel Type	Description
S5-17-11-29	M28	Douglas Fir	Crib	High fire, load burned 100%
S5-18-01-29	M28	Douglas Fir	Crib	Medium fire, load burned 100%
S5-18-01-31	M28	Douglas Fir	Crib	Low fire, load burned to 100%
S5-18-01-12	IDC v1	Red Maple	Cordwood	Cold start-up RL 1 - 5# at high* RL 2 - 7# at medium RL 3 - 12# at low
S5-18-03-02	R&D	Red Maple	Cordwood	Cold start bottom-up kindling RL 1 - 7# at high No RL 2 RL3 - 12# at low
S5-18-03-15	R&D	Red Maple	Cordwood	Cold start top-down kindling RL 1 - 7# at high RL 2 - 5# at medium No RL 3
S5-18-05-02	R&D	Red Maple	Cordwood	Cold start bottom-up (side) kindling RL 1 - 7# at high shut to low at 50% burned No RL 2 RL 3 - 12# at low to 90% burned
S5-18-05-04	R&D	Red Maple	Cordwood	Cold start bottom-up (side) kindling RL 1 - 7# at high shut to low at 50% burned RL 2 - 5# at low RL 3 - 12# at low to 90% burned
S5-18-08-01 Replicate 1	IDC Final Protocol	Red Maple	Cordwood	
S5-18-08-02 Replicate 2	IDC Final Protocol	Red Maple	Cordwood	
S5-18-08-03 Replicate 3	IDC Final Protocol	Red Maple	Cordwood	

The 1400AB TEOM was used for continuous PM measurements in all stove 5 test runs. The results of the stove 5 baseline and IDC final protocol run results are presented in this section. The research runs, which were used to refine the IDC method, are summarized in section 4.

2.4.1 Baseline Tests

As with the previous stoves, stove 5 baseline tests were conducted using a modified EPA Method 28 (M28) at three of the four air control settings prescribed in that method: the highest air control setting (category 4), the lowest setting (category 1), and the manufacturer's recommended air setting for a medium-burn rate (category 2/3). Table 29 summarizes the results of the baseline modified M28 testing. After completing the low- and medium-burn rate tests, a stove defect was found. The high fire was completed immediately after the repair, and retests at the medium and low setting were completed two months later due to lab scheduling issues. Note that stove 5 achieved a category 2 burn rate in both the medium- and low-air setting runs and that the medium-burn rate was actually lower than that for the low-air setting.

Table 29. Stove 5—Summary of the Modified M28 Baseline Test Results

	Test Time (min)		Dry-Burn Rate (kg/h)		Total PM (g)		PM Emission Rate (g/h)		PM Emission Factor (g/kg)		HHV Efficiency (%)
% Burn Completed	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*100%*
High	90	116	3.41	2.94	19.12	19.15	12.75	9.91	3.73	3.37	---
Medium	243	374	1.33	0.96	11.02	10.49	2.72	1.68	2.04	1.75	62.4
Low	191	298	1.69	1.20	6.31	6.46	1.98	1.30	1.17	1.08	57.8

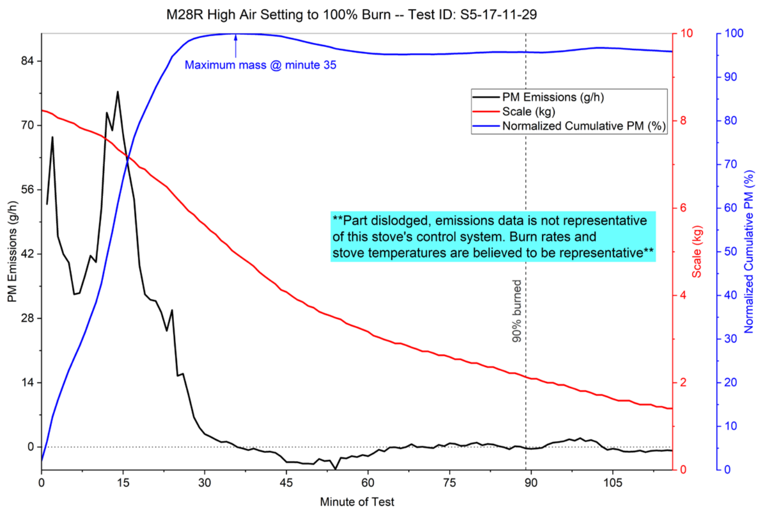
The HHV thermal efficiency of stove 5 was higher in the medium-air than the low-air run and could not be determined in the high-air run due to issues with the CO and CO_2 measurements.

Total PM emissions and the PM EF in the stove 5 high-air setting baseline run were 2 and 3 times those in the medium- and low-air setting runs, respectively. The high-air setting ER was 5.8 times the medium rate and 7.6 times the low rate, due to a combination of the higher emissions and a much shorter run time in that run. As discussed above, the average stove 5 burn rate was higher and the run time lower in the low-air setting run than at the medium-air setting. A more detailed discussion of baseline PM emissions follows.

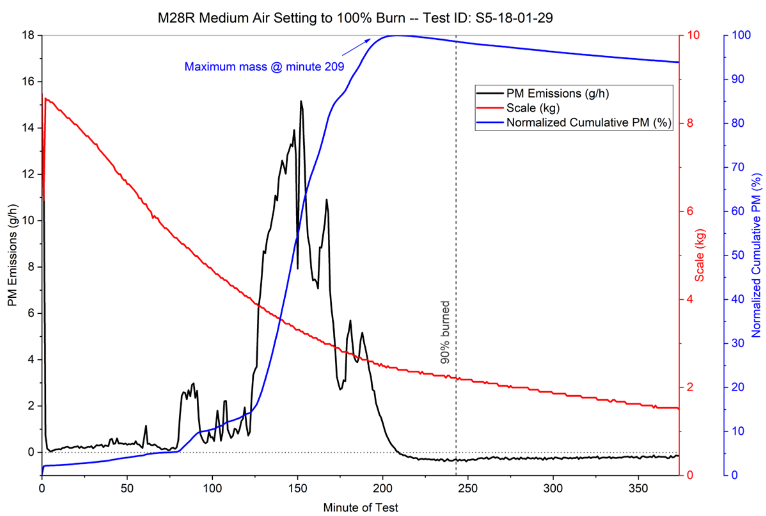
2.4.1.1 PM Emissions Profiles

Real-time plots of the three stove 5 M28 test runs are presented in Figure 25. As in the plots for the previous stoves, the TEOM PM emission rate profiles are shown in black, cumulative PM in blue, and remaining fuel load in red.

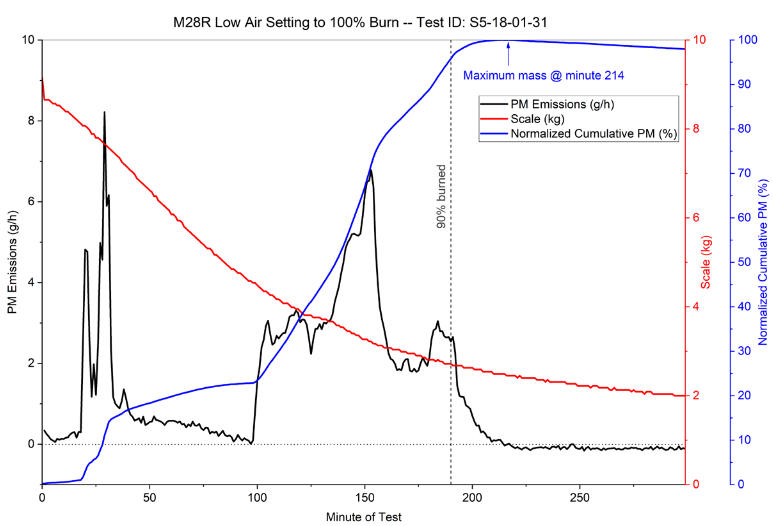
Figure 25. Stove 5—M28 Baseline Test Results



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

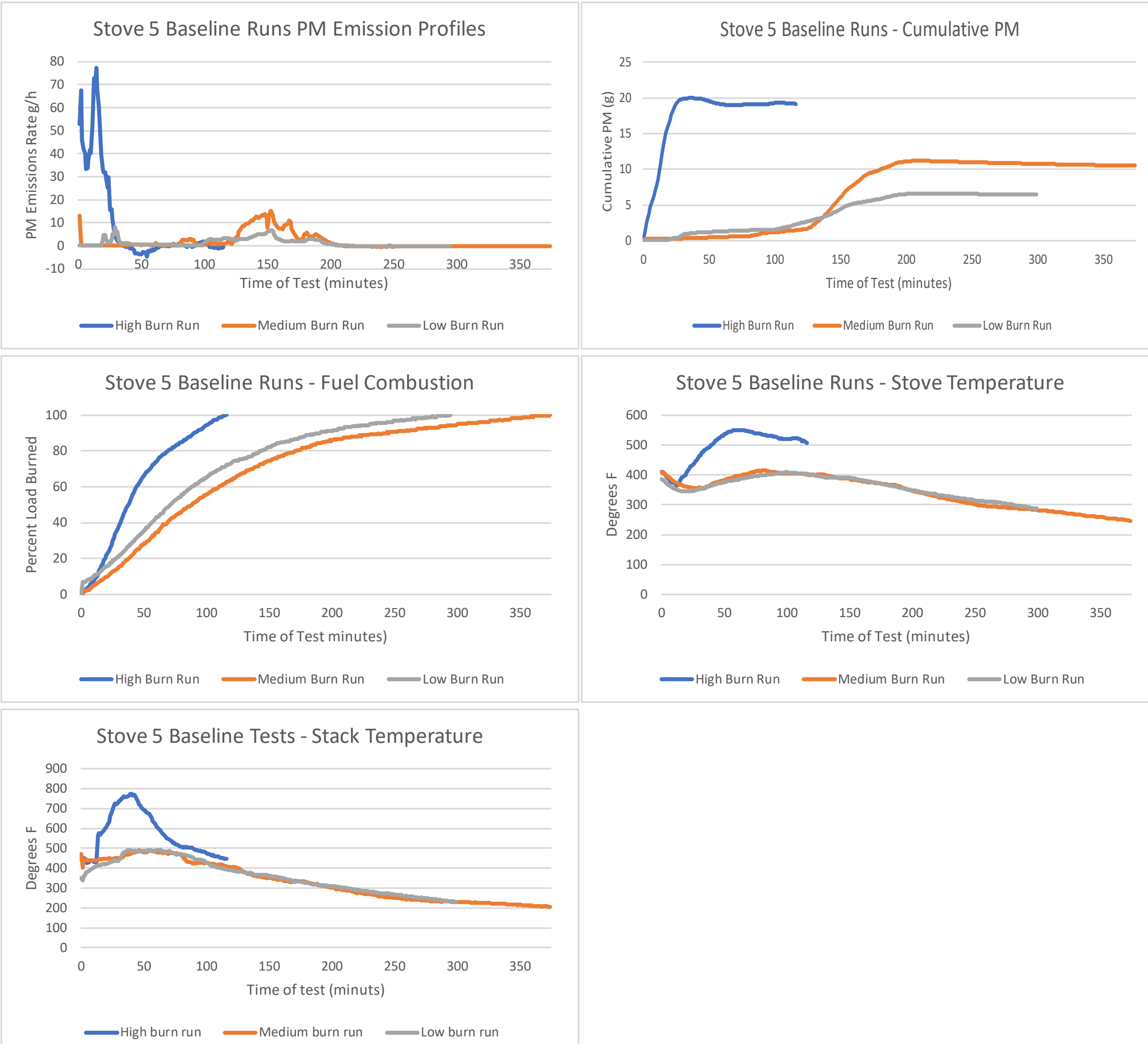


* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Instantaneous emissions were highest in the high-burn run. In that run, the emission rate peaked at minute 2 (67.5 g/h) and between minutes 12 and 15 (77.5 g/h) and were minimal after minute 32. The test operator noted that the emissions in that run may not be representative of normal stove operation. In the medium- and low-burn runs, maximum instantaneous emission rates were lower, and emissions were spread out over a longer period. In the medium run, an initial elevated emission rate peak occurred immediately (13.0 g/h at a minute 1), after which the ER immediately fell to essentially zero. Significant medium-burn emissions again began at minute 123 and continued for approximately 73 minutes, with a peak ER of 15.2 g/h at 152 minutes. Instantaneous emissions were lowest in the low-air run. Significant emissions occurred in two periods of that run, a 13-minute period beginning at minute 19 (peak 8.2 g/h at minute 29) and a 68-minute period beginning at minute 102 (peak 6.8 g/h at minute 153). Ninety percent of total PM emissions occurred in the first 22 minutes of the 116-minute high-burn run and the first 181 minutes of both the 374-minute medium-burn run and the 294-minute low-burn run.

Figure 26 shows the PM emissions rate, cumulative PM, fuel combustion, and stove and stack temperature profiles for the three stove 5 M28 baseline runs.

Figure 26. Stove 5—M28 Baseline Runs—PM Emission Profiles, Cumulative PM Emissions, Cumulative Fuel Consumption, and Stack Temperatures



As shown Figure 26, the PM emissions in the high-air run occurred in the first 33 minutes of that run. During most of that time, the high-air run stove and stack temperatures were rapidly rising and the burn rate was considerably higher than in the other runs. Emissions were much lower in the beginning of the medium- and low-air runs, and those runs did not see the increase in stove and stack temperatures recorded in the high-air run. Additional low levels of PM were emitted later in those runs, peaking at minutes 151–152 in both runs. The stove and stack temperature profiles for the medium- and low-air runs were almost the same and the burn rates in those two runs were also similar. The medium-burn run was 80 minutes shorter than the low run, primarily because of a difference in fuel consumption at the very beginning of the burns; in the first minute of the runs, 7% of the fuel was consumed in the low-air run and only 0.3% in the medium-air run. As discussed previously, the stove was repaired in between the high-run and the low- and medium-air runs, which may at least partially explain the inter-run discrepancies.

2.4.1.2 Cumulative PM Emissions

As observed with many of the other stoves, the maximum cumulative PM were measured midway through the stove 5 baseline runs. For the high- and medium-burn runs, the maximum PM occurred before 90% of the fuel was consumed. In the low-burn run, the PM maximum occurred after the point of 90% fuel consumption but before 100% of the load had been consumed.

In the high-burn run, the maximum cumulative PM was recorded at minute 35, which was 55 minutes before 90% of the fuel was consumed and 81 minutes before the end of the run (100% fuel consumption). The cumulative PM measurement at the end of the high-burn run was 4% lower than the maximum. The period after maximum PM collection, during which no significant additional PM was collected and PM filter loss occurred, constituted 70% of the total test period.

In the medium-burn run, the maximum cumulative PM was recorded at minute 209, which was 34 minutes before the point of 90% fuel consumption and 165 minutes before 100% of the fuel was consumed. The cumulative PM measurement at the end of the medium-burn test was 6% lower than the maximum. The period after maximum PM collection, during which no significant additional PM was collected and PM loss occurred, constituted 44% of the total test period.

In the low-burn run, the maximum cumulative PM was recorded at minute 214, which was 23 minutes after the point of 90% fuel consumption, but 80 minutes before 100% of the fuel was consumed. The cumulative PM measurement at the end of the low-burn test was 2% lower than the maximum. The period after maximum PM collection, during which no significant additional PM was collected and PM loss occurred, constituted 27% of the total test period.

2.4.1.3 Ninety Percent versus 100% Fuel Combustion

As discussed previously, measuring the ER for an entire test run generally underestimates the rate that would occur in the field because most emissions occur early in the burns and wood stove owners often refuel before the previous load has been completely consumed. For stove 5, 90% of total PM emissions were generated in the first 19%, 48%, and 62% of the high-, medium-, and low-fire baseline runs, respectively.

To more accurately reflect actual in-use conditions, we calculated PM emission parameters at the point in the run that 90% of the fuel had been combusted, as well as at the end of the run (100% fuel combustion). For the stove 5 high-burn run, the time period between 90% and 100% fuel combustion was 25 minutes, 22% of the total run time. Total PM emissions did not change during that period, but because at 90% those emissions are associated with combustion of 10% less fuel, the EF (in g/kg) at 100% combustion was 10% lower than at 90% combustion. The PM ER, the metric used to certify stoves, was 3.41 g/h at 90% fuel combustion and 2.94 g/h at 100% combustion, a reduction of 22% that is due to the lengthened averaging period.

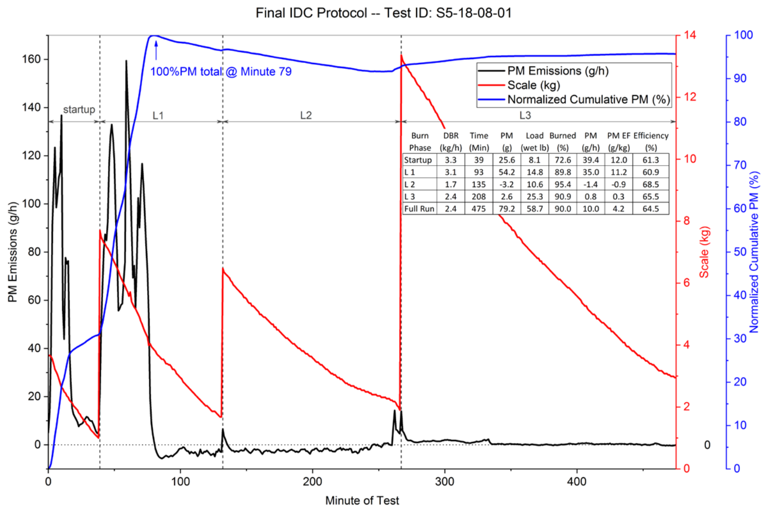
For the medium-burn run, the time period between 90% and 100% combustion was 131 minutes, 54% of the total run time. During that period, total PM emissions decreased by 5% and the PM EF decreased by 14%. The PM ER decreased by 38%, from 1.33 g/h to 0.96 g/h. For the low-burn run, the time from 90% to 100% combustion was 107 minutes, 56% of the total run time. During that period, low-burn PM emissions increased by 2%, the EF (g/kg) decreased by 8%, and the ER rate decreased by 35%, from 1.69 g/h to 1.20 g/h.

The average ER associated with 100% combustion in the three runs was 4.3 g/h, as compared to 5.8 g/h for 90% combustion.

2.4.2 IDC Tests

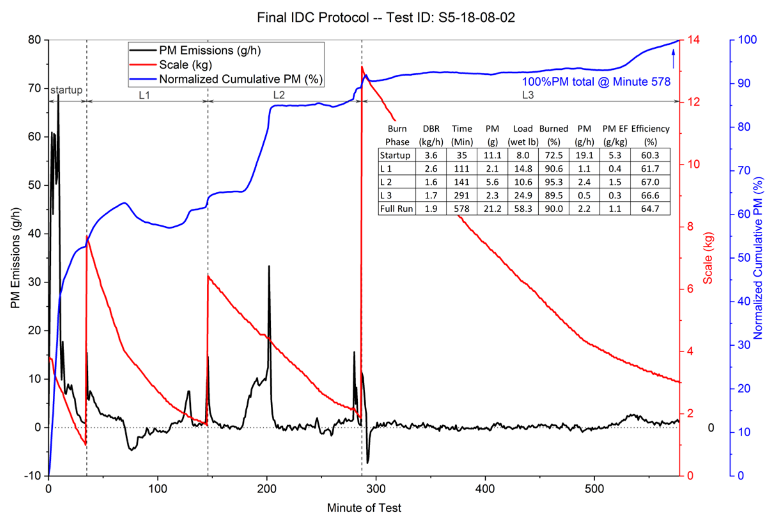
Three replicate runs using the final IDC protocol were run on stove 5. Profiles of the stove 5 IDC final protocol runs are shown in Figure 27.

Figure 27. Stove 5 – IDC Final Protocol Runs



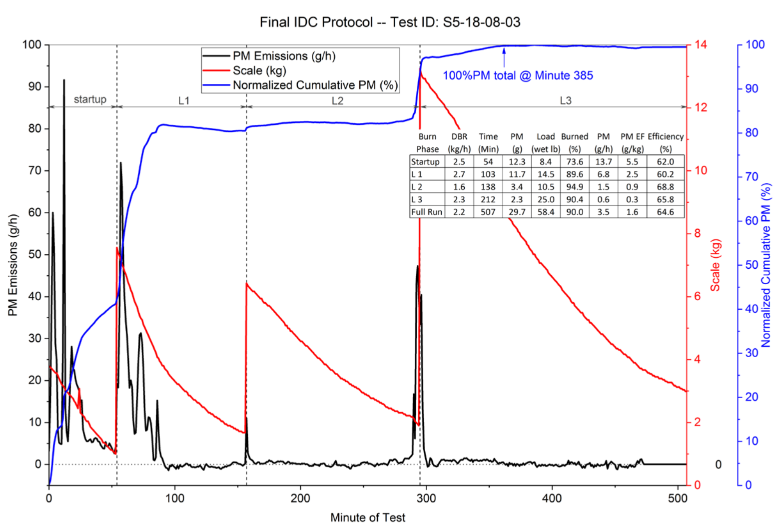
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.3	39	25.6	8.1	72.6	39.4	12.0	61.3
L 1	3.1	93	54.2	14.8	89.8	35.0	11.2	60.9
L 2	1.7	135	-3.2	10.6	95.4	-1.4	-0.9	68.5
L 3	2.4	208	2.6	25.3	90.9	0.8	0.3	65.5
Full Run	2.4	475	79.2	58.7	90.0	10.0	4.2	64.5

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.6	35	11.1	8.0	72.5	19.1	5.3	60.3
L 1	2.6	111	2.1	14.8	90.6	1.1	0.4	61.7
L 2	1.6	141	5.6	10.6	95.3	2.4	1.5	67.0
L 3	1.7	291	2.3	24.9	89.5	0.5	0.3	66.6
Full Run	1.9	578	21.2	58.3	90.0	2.2	1.1	64.7

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.5	54	12.3	8.4	73.6	13.7	5.5	62.0
L 1	2.7	103	11.7	14.5	89.6	6.8	2.5	60.2
L 2	1.6	138	3.4	10.5	94.9	1.5	0.9	68.8
L 3	2.3	212	2.3	25.0	90.4	0.6	0.3	65.8
Full Run	2.2	507	29.7	58.4	90.0	3.5	1.6	64.6

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

The metrics for the start-up phase of the three replicate IDC Stove 5 IDC runs are shown in Table 30.

Table 30. Stove 5—Comparison of Test Metrics from Start-Up Phase of IDC Runs

Test ID #	S5-18-08-01 Run1	S5-18-08-02 Run 2	S5-18-08-03 Run 3
Dry-Burn Rate (kg/h)	3.28	3.64	2.50
Time (min)	39	35	54
Total PM (g)	25.6	11.1	12.3
PM Emission Rate (g/h)	39.38	19.10	13.69
PM Emission Factor (g/kg)	12.01	5.25	5.48

In the start-up phase, the dry-burn rate was highest and the test time lowest in run 2, and the reverse was true for run 3. PM emissions and the PM EF were more than twice as high in run 1 than in runs 2 and 3. Although start-up phase PM emissions were similar in runs 2 and 3, the run 1 start-up ER was 2.1 times higher than the run 2 ER and 2.9 times the run 3 ER, due to the longer run time for that phase of run 3.

The metrics for the high-fire phase (reload 1) of the stove 5 IDC runs are shown in Table 31. During this phase, a fuel load of 7 lb/ft^3 comprised of small cordwood pieces is burned at the highest air setting. When 50% of the load is consumed, the air control is switched to the lowest setting and the load is burned to 90% consumption, by weight.

Table 31. Stove 5—Comparison of Test Metrics from Reload 1—High-Fire Phase of IDC Runs

Test ID #	S5-18-08-01 Run 1	S5-18-08-02 Run 2	S5-18-08-03 Run 3
Dry-Burn Rate (kg/h)	3.13	2.63	2.73
Time (min)	93	111	103
Total PM (g)	54.2	2.1	11.7
PM Emission Rate (g/h)	34.99	1.12	6.83
PM Emission Factor (g/kg)	11.18	0.42	2.50

As shown in Table 31, high-fire phase PM emissions were much higher in run 1 than in the other runs. Run 2 produced particularly low emissions in this phase. The run 1 high-fire phase Total PM and EF were more than four times higher than those for run 3 and more than 26 times higher than in run 2.

The run 1 ER was five times higher than the run 3 ER and 31 times higher than the run 2 rate. As will be discussed below, burn rates during much of the high-fire phase of the runs were similar, but the stove temperatures throughout the phase were very different, with the temperature consistently lowest in run 1 and highest in run 2.

In the reload 2 burn, the maintenance phase, air controls are kept at the lowest setting and two large pieces of wood are loaded into the stove. At this point, the coal bed is well developed. The metrics measured in the phase in stove 5 IDC runs are shown in Table 32.

Table 32. Stove 5—Comparison of Test Metrics from Reload 2—Maintenance Phase

Test ID #	S5-18-08-01 Run 1	S5-18-08-02 Run 2	S5-18-08-03 Run 3
Dry-Burn Rate (kg/h)	1.66	1.56	1.59
Time (min)	135	141	138
Total PM (g)	-3.2	5.6	3.4
PM Emission Rate (g/h)	-1.44	2.40	1.48
PM Emission Factor (g/kg)	-0.87	1.54	0.93

The maintenance phase dry-burn rates were similar in the three runs and were lower than in the high-fire phase. Emissions in this phase were low in all runs and were net negative in run 1. The stove temperatures remained above 358°F in all three runs throughout this phase and were particularly high in run 1, which recorded temperatures in the range 379–414°F during this phase.

The final phase in the IDC protocol (reload 3, the overnight phase) represents conditions required to obtain a long burn, such as those needed for overnight burns or during the day when the fire will be unattended for a significant amount of time (>6 hours). During this phase, the coal bed is raked, and the user loads as much wood as possible, using large and small pieces. The metrics measured in the overnight phase of the stove 5 IDC runs are shown in Table 33.

Table 33. Stove 5—Comparison of Test Metrics for Reload 3—Overnight Phase

Test ID #	S5-18-08-01 Run 1	S5-18-08-02 Run 2	S5-18-08-03 Run 3
Dry-Burn Rate (kg/h)	2.40	1.67	2.31
Time (min)	208	291	212
Total PM (g)	2.6	2.3	2.3
PM Emission Rate (g/h)	0.75	0.48	0.65
PM Emission Factor (g/kg)	0.31	0.29	0.28

The overnight phases of the stove 4 IDC runs lasted 208 to 291 minutes (3.5 to 4.9 hours). In this phase, the dry-burn rate in run 2 was lower and the run time higher than in the other runs. The stove temperature remained high throughout all runs (350-441ºF) and emissions were low and similar in all runs.

Table 34 shows the test metrics for the entire run of each of the IDC replicates.

Table 34. Stove 5—Comparison of Test Metrics for the Entire IDC Protocol

Test ID #	S5-18-08-01 Run 1	S5-18-08-02 Run 2	S5-18-08-03 Run 3
Dry-Burn Rate (kg/h)	2.40	1.95	2.22
Time (min)	475	578	507
Total PM (g)	79.2	21.2	29.7
PM Emission Rate (g/h)	10.00	2.20	3.52
PM Emission Factor (g/kg)	4.16	1.13	1.58
HHV Efficiency (%)	64.5	64.7	64.6

The total time to complete the stove 2 IDC runs ranged from 475 to 578 minutes (7.9 to 9.6 hours), a longer period than for some of the other stoves, but still less than the 10-hour period that would be feasible for completion in a single day. The HHV thermal efficiencies were similar in all three runs.

The PM parameters were significantly higher in run 1 than in the other runs, primarily due to the elevated emissions during the high-fire phase of that run. The total PM emissions and EF for the entire run 1 were both 3.7 times higher than those of run 2, the lowest emitting run. The run 1 ER (10.0 g/h) was 4.4 times higher than the run 2 ER (2.2 g/h).

Figure 28 shows the test metrics by test phase for each of the IDC runs graphically.

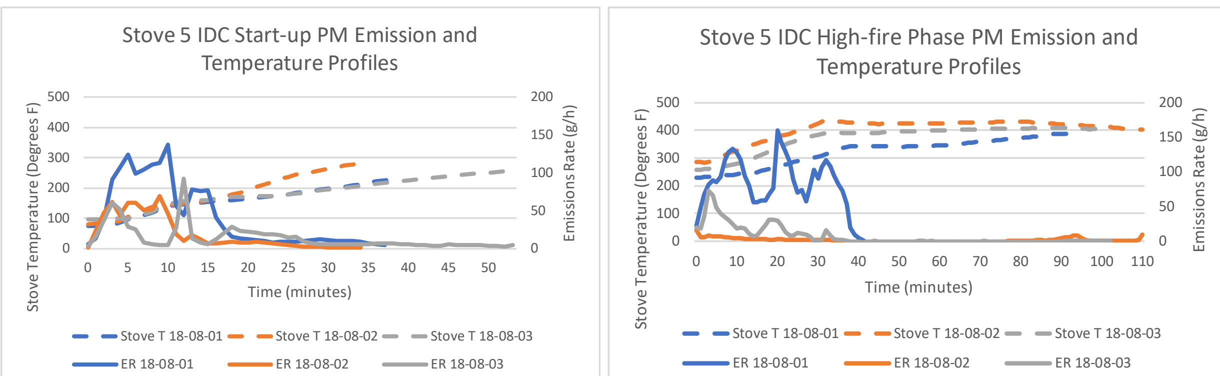
Figure 28. Stove 5—Comparison of Metrics for IDC Replicate Runs S5-18-08-01, S8-18-08-02, and S5-18-08-03

As can be seen in that figure, dry-burn rates were highest in the start-up and high-fire phases. Burn times were similar in the three runs for all phases except for the overnight burn, which was about 50% longer in run 2 than in the other runs. Unlike in the results of the previous stoves, emissions in the start-up phase were a significant portion of total PM emissions in all stove 5 runs, constituting 32%, 53%, and 41% of the total PM emissions in runs 1, 2, and 3, respectively. The start-up load is considerably smaller than the other loads and, in the stove 5 runs, represented 11–12% of fuel burned over the entire run. High-fire phase emissions were also important in runs 1 and 3, representing 68% and 39% of total PM emissions in those runs, respectively. 25–26% of total fuel is burned during the high-fire burn.

The start-up and high-fire phase PM emissions, as well as the PM EF and ER, were considerably higher in run 1 than in the other runs. Start-up emissions in both runs 2 and 3 were approximately half of those of run 1. For the high-fire phase, emissions were considerably lower in run 2 than in run 3. High-fire phase run 1 emissions were 26 and 5 times higher than the emissions for that phase in run 2 and run 3, respectively.

The reasons for the differences in emissions in the start-up and high-fire phases of the runs are not altogether clear. Figure 29 shows the PM emissions and stove temperature profiles for the two phases. In that figure, PM emissions for each run are plotted with solid lines and the stove temperatures are plotted with dashed lines in corresponding colors.

Figure 29. Stove 5—IDC Runs—PM Emission and Stove Temperature Profiles for Start-Up and High-Fire Phases



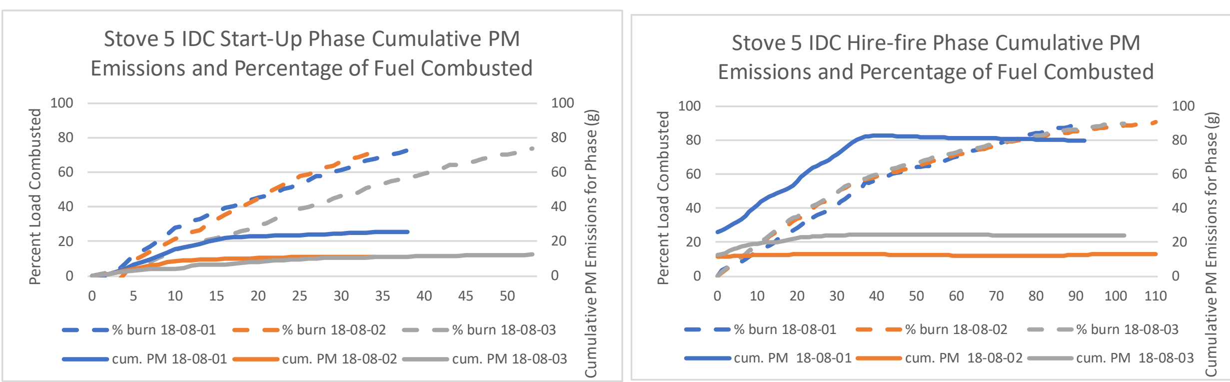
Stove temperatures were very low for most of the start-up phases of all runs. At those temperatures, the non-catalytic controls may not have been operable, so the stove would have been burning virtually uncontrolled during that period. However, because the temperatures were similar in the three runs during the early part of the start-up when most of the significant emissions occurred, that variable does not explain inter-run differences in that phase.

As shown in the second plot in Figure 29, stove temperatures were higher and more divergent among the runs in the high-fire phase. The stove temperature was lowest in run 1, the run that produced the highest PM emissions. The initial stove temperature at the start of the high-fire phase of run 1 was 229ºF, as compared to 258ºF in run 3, which had considerably lower emissions, and 286ºF in run 2, the run with minimal high-fire emissions. PM emissions dropped to near zero by minute 39 of the run 1 high-fire phase; at that point, the stove temperature was 342ºF. That temperature was reached much sooner in the other runs, at minute 13 in run 2 and minute 21 in run 3. Stove temperature differences may at least partly explain the differences in PM emissions in the three runs in the high-fire phase.

To investigate the possible effect of combustion rate on PM emissions in the start-up and high-fire phases, we compared cumulative PM emissions with the percentage of the load combusted in those phases of the three runs. As shown in Figure 30, combustion rates did not explain the higher emissions in run 1, because the run 1 combustion rates were similar to those in run 2 during the start-up phase and all runs showed similar combustion patterns in the high-fire phase.

Replicability issues are further discussed in section 4.

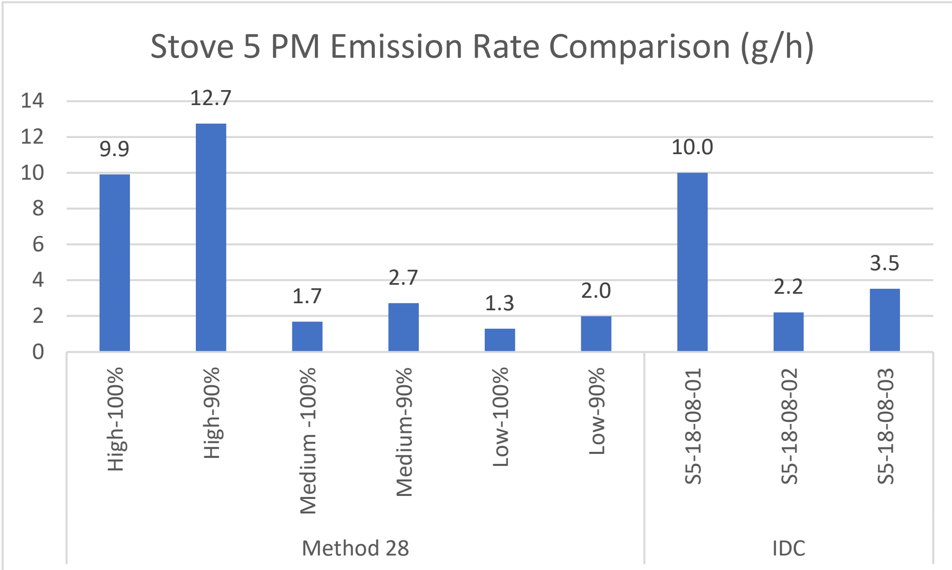
Figure 30. Stove 5—IDC Runs—Cumulative PM Emissions and Percentage of Load Combusted in Start-Up and High-Fire Phases



2.4.3 Comparison of Stove 5 Emission Rate Measurements

Figure 31 compares the stove 5 emission rates measured using M28 and the IDC final protocol.

Figure 31. Stove 5—Comparison of Method 28 and IDC Emission Rate Measurements (g/h)



For stove 5, the ERs measured by the two methods have similar ranges. In both cases, the first run measured an ER of about 10 g/h, while the ERs in subsequent runs were substantially lower. The reason for the differences between runs was not the same for the two methods, however. As discussed above, PM emissions were highest in the IDC runs when stove temperatures were low, below approximately 340°F. The stove temperature in the M28 hot-to-hot runs started out considerably higher than that level. In fact, the M28 run with the highest emissions, the high air setting run, had by far the highest stove temperatures. Note, however, that in the IDC runs, the highest ERs were seen in the phases with open air control settings (start-up and high-fire burns). This is consistent with the M28 results; in that test, the high-air setting run emitted significantly more PM than the runs at the medium- and low-air settings.

Section 4 presents a more detailed analysis of the differences between the results for different test methods, including a comparison of the operating parameters measured in the high-fire phases of runs using different methods and a similar comparison of low-fire phase parameters.

2.5 Stove 6

Stove 6 is a medium sized fire-box, cast-iron stove with non-catalytic emisison controls. A total of 34 tests runs were performed on stove 6, as listed in Table 35. M28 baseline tests burned Douglas fir crib wood. The six research runs burned red maple cordwood. ASTM 3053-17 and IDC final protocol runs were performed using several fuels, in order to evaluate the effect of fuel species on operating parameters and emissions. The ASTM 3053-17 tests burned three species of wood: red maple, seasoned oak, and beech, and the IDC final protocol tests were performed with red maple, seasoned oak, and wet oak cordwood. Because each ASTM 3053-17 run includes two parts (start-up + high, followed by either a medium or low load), separate test IDs are assigned to each part of the test.

Table 35. Stove 6—Test Descriptions

Test ID	Test Method	Fuel Species	Fuel Type	Description
S6-18-01-01	M28 (baseline)	Douglas Fir	Crib	High fire, load burned 100%
S6-18-01-03	M28 (baseline)	Douglas Fir	Crib	Medium fire, load burned 100%
S6-18-01-02	M28 (baseline)	Douglas Fir	Crib	Low fire, load burned to 100%
S6-18-01-09	IDC v1 (research)	Red Maple	Cord	Cold start-up RL 1 - 5# at high [a] RL 2 - 7# at medium RL 3 - 12# at low
S6-18-03-22	IDC v2 (research)	Red Maple	Cord	Cold start (top-down kindling) RL 1 - 7# at high RL 2 - 5# at medium RL 3 - 12# at low
S6-18-02-27	R&D	Red Maple	Cord	Cold start bottom-up kindling RL 1 - 5# at high No RL 2 or 3
S6-18-02-28	R&D	Red Maple	Cord	Cold start top-down kindling RL 1 - 5# at high No RL 2 or 3
S6-18-05-01	R&D	Red Maple	Cord	Cold start top-down kindling RL 1 - 7# at high shut to low at 50% burned RL 2 - 5# at low RL 3 - 12# at low to 90% burned
S6-18-05-05	R&D	Red Maple	Cord	Cold start top-down kindling RL 1 - 7# at high shut to low at 50% burned No RL 2 RL 3 - 12# at low to 90% burned
S6-18-06-07-1	ASTM	Red Maple	Cord	Start-up (11.1 lb) [b] + high fire (22.3 lb)
S6-18-06-07-2	ASTM	Red Maple	Cord	Low fire (23.1 lb)
S6-18-06-08-1	ASTM	Red Maple	Cord	Start-up (10.5 lb) + high fire (21.3 lb)
S6-18-06-08-2	ASTM	Red Maple	Cord	Medium fire (21.4 lb)
S6-19-01-31-1	ASTM	Red Maple	Cord	Start-up (10.9 lb) + high fire (22.1 lb)
S6-19-01-31-2	ASTM	Red Maple	Cord	Medium fire (22.3 lb)
S6-19-02-01-1	ASTM	Red Maple	Cord	Start-up (11 lb) + high fire (22.1 lb)
S6-19-02-01-2	ASTM	Red Maple	Cord	Medium fire (22.3 lb)
S6-19-02-04-1	ASTM	Beech	Cord	Start-up (10.8 lb) + high fire (21.9 lb)

Table 35 continued

S6-19-02-04-2	ASTM	Beech	Cord	Medium fire (27 lb)
S6-19-02-05-1	ASTM	Beech	Cord	Start-up (10.8 lb) + high fire (22 lb)
S6-19-02-05-2	ASTM	Beech	Cord	Low fire (25.8 lb)
S6-19-02-07-1	ASTM	Seasoned Oak	Cord	Start-up (10.8 lb) + high fire (21.9 lb)
S6-19-02-07-2	ASTM	Seasoned Oak	Cord	Medium fire (23.1 lb)
S6-19-02-08-1	ASTM	Seasoned Oak	Cord	Start-up (10.9 lb) + high fire (21.95 lb)
S6-19-02-08-2	ASTM	Seasoned Oak	Cord	Low fire (25.1 lb)
S6-18-07-18 Replicate 1-RM	IDC Final Protocol	Red Maple	Cord	
S6-18-07-19 Replicate 2-RM	IDC Final Protocol	Red Maple	Cord	Replicate 2: Same as Replicate 1
S6-18-07-20 Replicate 3-RM	IDC Final Protocol	Red Maple	Cord	Replicate 3: Same as Replicate 1
S6-19-03-13 Replicate 1-SO	IDC Final Protocol	Seasoned Oak	Cord	
S6-19-03-18 Replicate 2-SO	IDC Final Protocol	Seasoned Oak	Cord	
S6-19-03-19 Replicate 3-SO	IDC Final Protocol	Seasoned Oak	Cord	
S6-19-02-18 Replicate 1-WO	IDC Final Protocol	Wet Oak	Cord	
S6-19-03-21 Replicate 2-WO	IDC Final Protocol	Wet Oak	Cord	
S6-19-03-22 Replicate 3-WO	IDC Final Protocol	Wet Oak	Cord	

[a] Symbol # denotes fuel loading density in pounds per cubic foot of the stove firebox (lb/ft^3).

[b] In ASTM 3053-17 testing, fuel loads are defined as the weight of the wet wood.

PM was measured using the 1400AB TEOM in the stove 6 tests in the baseline runs, research runs, the complete ASTM test using maple fuel, and the IDC maple runs. The 1405 TEOM was used in two additional ASTM maple runs; the ASTM test that burned beech and oak, and the IDC runs that burned wet and seasoned oak. The results of the Stove 6 baseline and IDC final protocol run results are presented in this section. Research runs were used to develop the IDC final protocol and are summarized in section 4.

2.5.1 Baseline Tests

As discussed previously, baseline modified M28 tests were performed at three of the four air control settings prescribed in that method: the highest air control setting (category 4), the lowest setting (category 1), and the manufacturer's recommended air setting for a medium burn rate (category 2/3). Table 36 summarizes the results of the baseline modified M28 testing. Note that at both the low- and the medium-air setting, stove 6 achieved a category 3 burn rate.

Table 36. Stove 6—Summary of the Modified M28 Baseline Test Results

	Test Time (min)		Dry-Burn Rate (kg/h)		Total PM (g)		PM Emission Rate (g/h)		PM Emission Factor (g/kg)		HHV Efficiency (%)
% Burn Completed	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*100%*
High	79	123	4.20	2.99	4.25	4.26	3.23	2.08	0.77	0.69	36.8
Medium	164	247	2.01	1.48	4.03	3.99	1.47	0.97	0.73	0.65	46.0
Low	189	279	1.79	1.32	15.43	15.07	4.90	3.24	2.74	2.46	49.5

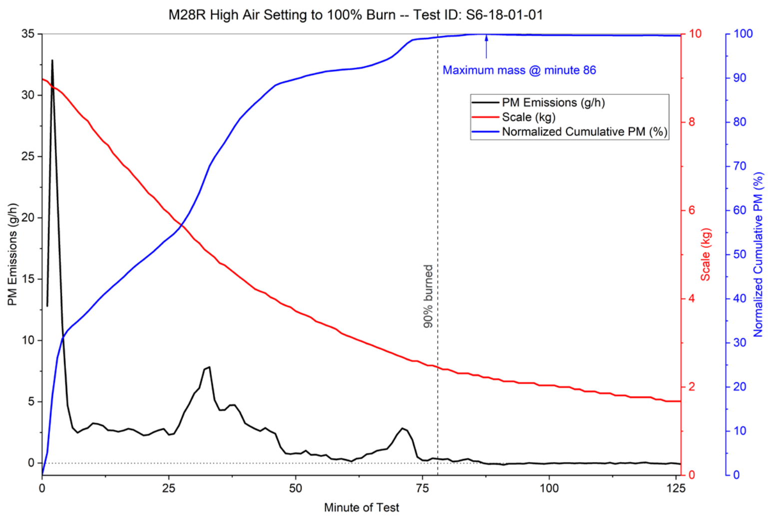
The HHV thermal efficiency of stove 6 was highest in the low-air run and lowest in the high-air run.

PM emissions were considerably higher in the low-air run than at the other two air settings. Total PM emissions and the PM EF in the stove 6 low-air run were almost 4 times those in the medium- and high- air runs. The low-air ER was 3.3 times the medium rate. The difference in ERs was smaller for the high setting, because the high-air test time was less than half that of the low and medium runs. The low-air ER was 56% higher than the high-air value. A more detailed discussion of PM emissions follows.

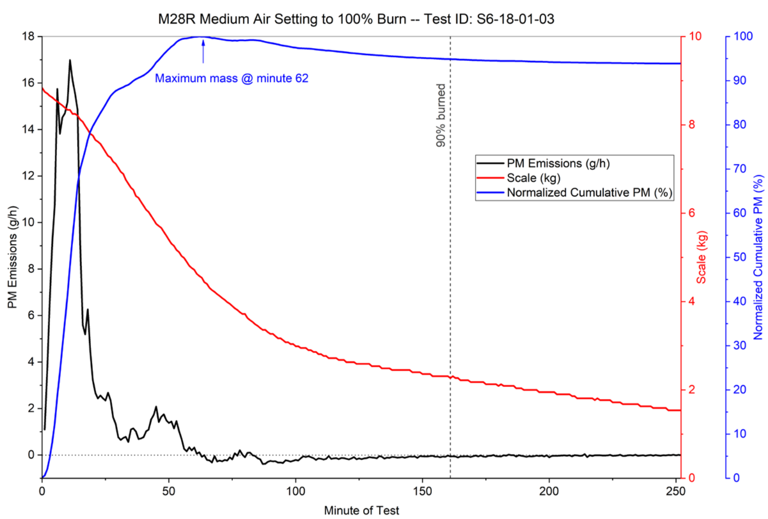
2.5.1.1 PM Emissions Profiles

Real-time plots of the three stove 6 M28 test runs are presented in Figure 32. As in the plots for the previous stoves, the TEOM PM emission rate profiles are shown in black, cumulative PM in blue. and the remaining fuel load in red.

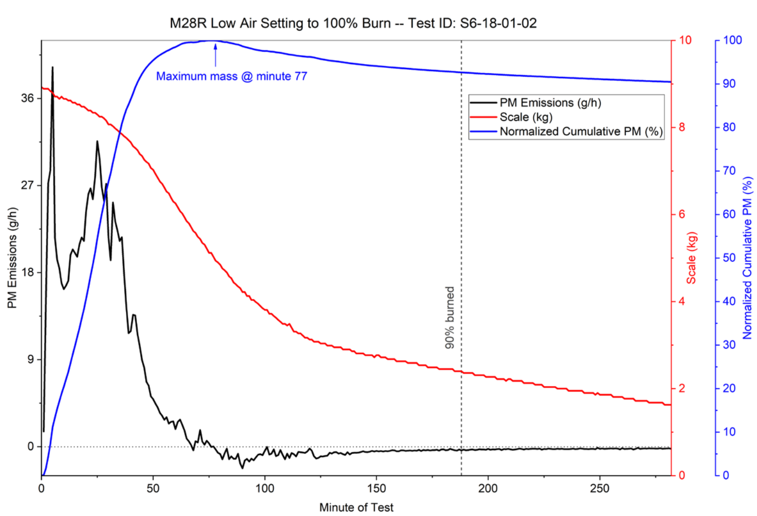
Figure 32. Stove 6—M28 Baseline Test Results



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



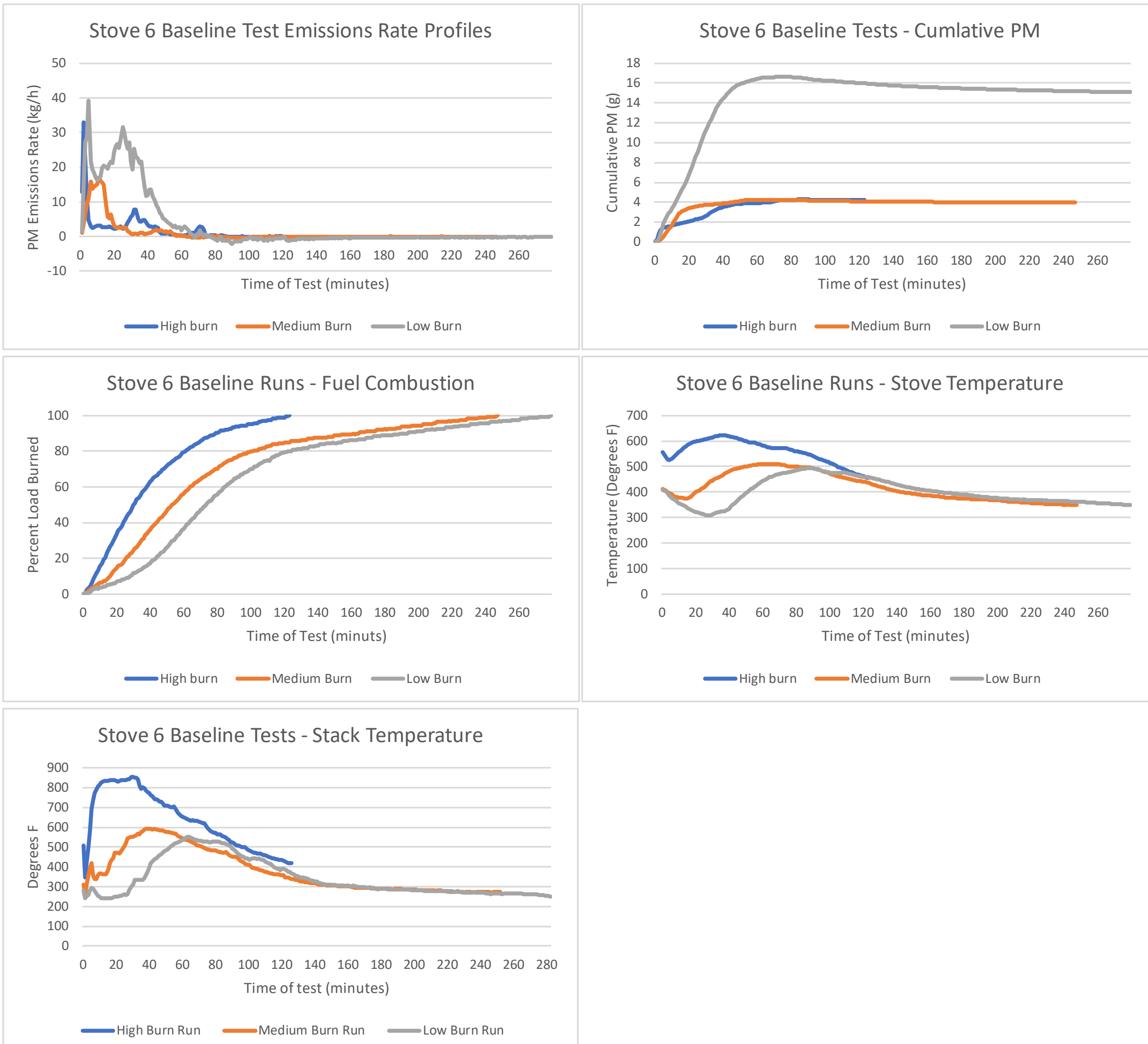
* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Instantaneous emissions were highest in the first few minutes of all three runs. The maximum instantaneous rate was 32.9 g/h at minute 2 of the high-burn run, 17.0 g/h at minute 11 of the medium run, and 39.2 g/h at minute 5 of the low run. In the high-burn run, the instantaneous PM emission rate dropped to below 4 g/h at minute 5 and were then above 4 g/h for an 11-minute period beginning at minute 38.

The initial emissions rate peak in the medium air run was lower but lasted longer than in the high run; instantaneous emission rates were above 4 g/h in minutes 3 to 19 in the medium run. The PM emission rate continued to be elevated for an even longer period in the low-air run. A second peak of 31.6 g/h occurred in that run at 25 minutes and the ER continued to be above 4 g/h through minute 52.

Figure 33 shows the PM emissions rates, cumulative PM, fuel combustion, and stove and stack temperature profiles for the three stove 6 baseline runs.

Figure 33. Stove 6—Baseline Runs—PM Emission Profiles, Cumulative PM Emissions, Cumulative Fuel Consumption, and Stove and Stack Temperatures



As shown Figure 33, the stove and stack temperatures were considerably higher and the burn rate faster in the high-burn run than the other runs. The low-air run fuel combustion curve and secondary emission peaks are consistent with a delayed light-off of the fuel load. The stove and stacks temperatures in that run were considerably lower than in the other runs throughout the period of significant PM emissions.

2.5.1.2 Cumulative PM Emissions

As observed in other stoves, the maximum cumulative PM was measured midway through the stove 6 baseline runs due to the volatilization losses that occur later in the burns. This loss was significant in the low- and medium-burn runs, in which the maximum PM occurred substantially before 90% of the fuel was consumed. In the high-burn run, minimal PM was lost after the point of maximum collection, which occurred after 90% fuel consumption but before 100% of the load had been consumed.

The maximum cumulative PM was recorded at minute 86 of the high-burn run, which was 7 minutes after 90% of the fuel was consumed and 37 minutes before the end of the run (100% fuel consumption). The cumulative PM measurement at the end of the high-burn test was essentially equal to that at the peak collection point. The period after maximum PM collection, during which no significant additional PM was collected and slight loss occurred, constituted 37% of the total test period.

In the medium-burn run, the maximum cumulative PM was recorded at minute 62, which was 102 minutes before the point of 90% fuel consumption and 185 minutes before 100% of the fuel was consumed. The cumulative PM measurement at the end of the medium-burn test was 6% lower than the maximum. The period after maximum PM collection, during which no significant additional PM was collected and PM loss occurred, constituted 75% of the total test period.

In the low-burn run, the maximum cumulative PM was recorded at minute 77, which was 112 minutes before the point of 90% fuel consumption and 202 minutes before 100% of the fuel was consumed. The cumulative PM measurement at the end of the low-burn test was 9% lower than the maximum. The period after maximum PM collection, during which no significant additional PM was collected and PM loss occurred, constituted 72% of the total test period.

2.5.1.3 Ninety Percent versus 100% Fuel Combustion

As discussed above, measuring the ER associated with 100% fuel consumption often underestimates the rate that would occur in the field because most emissions occur early in the burns and wood stove owners often refuel before the previous load has been completely consumed. For stove 6, 90% of total PM emissions were generated in the first 41% of the high-baseline run and the first 15% of the medium- and low-fire baseline runs.

To more accurately reflect actual in-use conditions, we calculated PM emission parameters at the point in the run that 90% of the fuel had been combusted, as well as at the end of the run (100% fuel combustion). For the stove 6 high-burn run, the time period between 90% and 100% fuel combustion was 44 minutes, 36% of the total run time. Total PM emissions remained essentially unchanged during that period, but because the emissions at 90% are associated with combustion of 10% less fuel, the EF (in g/kg) at 100% combustion was 10% lower than at 90% combustion. The PM ER, the metric used to certify stoves, was 3.23 g/h at 90% fuel combustion and 2.08 g/h at 100% combustion, a reduction of 34% that is due to the lengthened averaging period.

For the medium-burn run, the time period between 90% and 100% combustion was 83 minutes, 33% of the total run time. During that period, total PM emissions decreased by 1% and the PM EF decreased by 11%. The PM ER decreased by 34%, from 1.47 g/h to 0.97 g/h. For the low-burn run, the time from 90% to 100% combustion was 90 minutes, 32% of the total run time. During that period, low-burn PM emissions decreased by 2%, the EF (g/kg) decreased by 11%, and the ER rate decreased by 34%, from 4.90 g/h to 3.24 g/h.

The average ER associated with 100% combustion in the three runs was 2.1 g/h, as compared to 3.2 g/h for 90% combustion.

2.5.2 ASTM 3053-17 Tests

The ASTM 3053-17 cordwood stove test protocol (ASTM 3053-17) requires two runs for each test. Each run consists of an initial start-up + high-air setting phase and then, after 90% of the initial load is consumed, either a medium-air setting or low-air setting burn. The start-up procedures for the ASTM 3053-17 method are very similar to those in the final IDC protocol. However, the ATSM method allows twice as much kindling (2 lb/ft^3 loading density) as that prescribed in the IDC protocol.

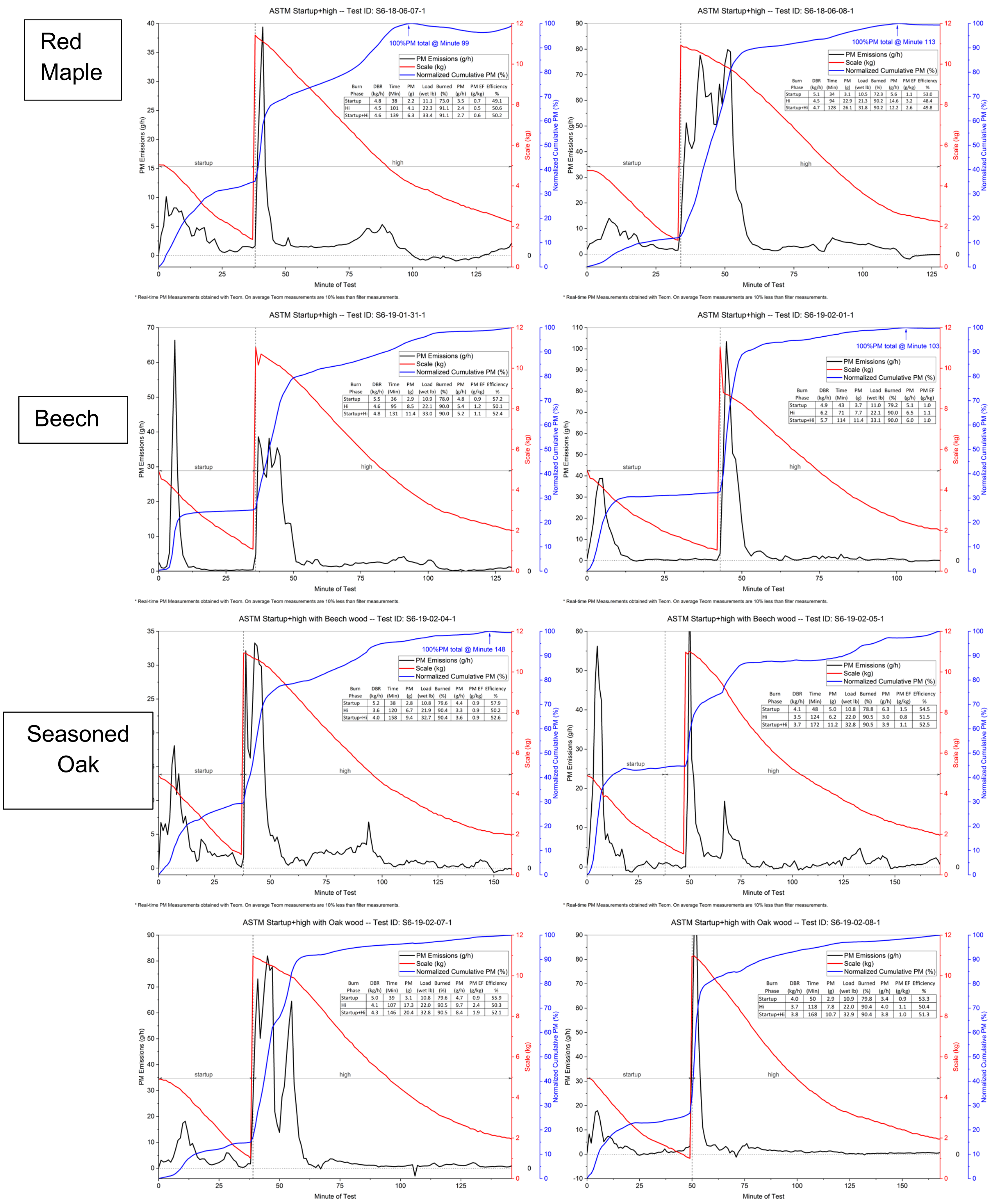
As discussed above, the impact of the wood fuel species on stove and emissions parameters was investigated in stove 6 using both the ASTM 3053-17 and the final IDC protocols. As listed in Table 35, the stove 6 ASTM 3053-17 runs are as follows:

- Four runs (one complete test and two additional medium-burn runs) with red maple cordwood as fuel.
    - The initial start-up and high-air setting phase in run S6-18-06-07 was followed by a low-air burn.

- In the other three ASTM 3053-17 red maple runs (S6-18-06-08, S6-19-01-31, and S6-19-02-01), the start-up and high-air setting phase was followed by a medium-air burn.
- Two runs (one complete test) with beech cordwood as fuel.
  - The initial start-up and high-air setting phase in run S6-19-02-04 was followed by a medium air burn.
  - The initial start-up and high-air setting phase in run S6-19-02-05 was followed by a low-air burn.
- Two runs (one complete test) with seasoned oak cordwood as fuel.
  - The initial start-up and high-air setting phase in run S6-19-02-07 was followed by a medium-air burn.
  - The initial start-up and high-air setting phase in run S6-19-02-08 was followed by a low-air burn.

PM emissions in the S6-18-06-07 and S6-18-08 ASTM 3053-17 maple runs were measured using the 1400AB TEOM, while the other stove 6 ASTM 3053-17 runs used the 1405 TEOM. The profiles of the start-up and high-fire phases of all of the stove 6 ASTM 3053-17 runs are shown in Figure 34.

Figure 34. Stove 6—ASTM 3053-17 Runs—Start-Up and High-Fire Phases



The ASTM 3053-17 run test metrics for the start-up phase are shown in Table 37.

Table 37. Stove 6—Comparison of ASTM 3053-17 Start-Up Test Metrics

Test ID #	Fuel Type	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	Efficiency (%)
S6-18-06-07-1	Maple	4.84	38	2.20	3.48	0.72	49.1
S6-18-06-08-1	Maple	5.07	34	3.15	5.55	1.10	53.0
S6-19-01-31-1	Maple	5.50	36	2.86	4.76	0.87	57.2
S6-19-02-01-1	Maple	4.94	43	3.67	5.12	1.04	58.8
S6-19-02-04-1	Beech	5.15	38	2.78	4.39	0.85	57.9
S6-19-02-05-1	Beech	4.08	48	5.03	6.28	1.54	54.5
S6-19-02-07-1	Oak	5.02	39	3.05	4.69	0.94	55.9
S6-19-02-08-1	Oak	3.96	50	2.87	3.45	0.87	53.3

The start-up phase test times were, on average, slightly higher and the dry-burn rate slightly lower in the oak and beech runs than in the maple runs. However, there was a considerable overlap in the ranges of those parameters among the species. The start-up EFs for all runs ranged from 0.85–1.10 g/kg, with the exception of one lower and one higher value; 0.72 g/kg for the first maple run and 1.54 g/kg for the second beech run, respectively. The ERs ranged from 3.45–6.28 g/h. On average, the ERs of the start-up phase tests were 4.7 g/h for the maple burns, 5.3 g/h for beech and 4.2 g/h for oak cordwood, but there was considerable overlap in the ERs of individual runs in each group. The thermal efficiency was similar for all groups.

The metrics for the high-fire phase are shown in Table 38.

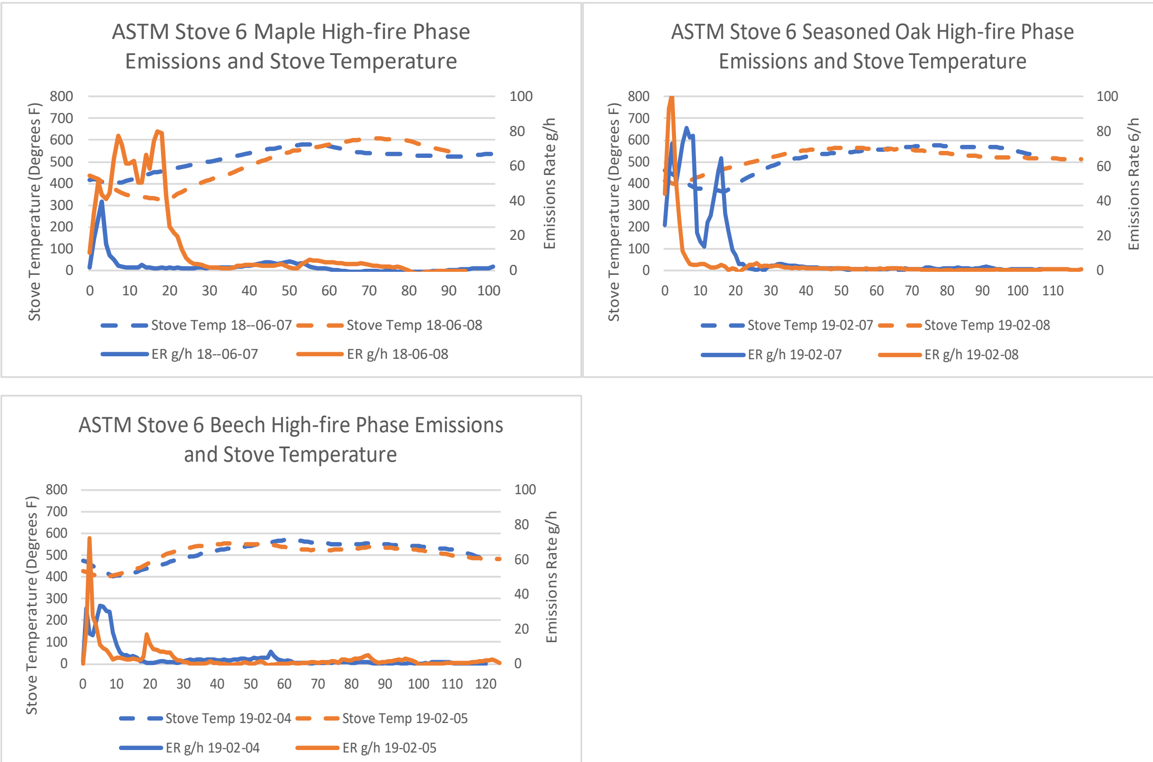
Table 38. Stove 6—Comparison of ASTM 3053-17 High-Air Setting Test Metrics

Test ID #	Fuel Type	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	Efficiency (%)
S6-18-06-07-1	Maple	4.47	101	4.06	2.41	0.54	50.6
S6-18-06-08-1	Maple	4.52	94	22.93	14.64	3.24	48.4
S6-19-01-31-1	Maple	4.55	95	8.52	5.38	1.18	50.1
S6-19-02-01-1	Maple	6.18	71	7.71	6.52	1.05	54.8
S6-19-02-04-1	Beech	3.63	120	6.66	3.33	0.92	50.2
S6-19-02-05-1	Beech	3.55	124	6.22	3.01	0.85	51.5
S6-19-02-07-1	Oak	4.05	107	17.33	9.72	2.40	50.3
S6-19-02-08-1	Oak	3.70	118	7.82	3.98	1.07	50.4

The test times in the high-fire phase were highest and the dry-burn rates lowest for the runs that burned beech and the reverse was the case for the maple burns. There was no overlap in those metrics among groups. The beech fueled runs also produced less PM and had lower EFs and ERs than all other runs except for the first maple burn. There was considerable intragroup variation in the emissions in both the maple and oak runs. The EF and ER for this phase of the highest emitting maple burn was six times higher than for the lowest maple run, which were performed on consecutive days. Similarly, the EF and ER for the higher oak burn for this phase were more than twice as high as for the other oak run. Although the high-fire phase thermal efficiency for the highest emitting maple run was lower than in the other maple runs, the thermal efficiencies were similar in the high-fire phase of the two oak runs.

It appears that the discrepancy in high-fire phase PM emissions in the maple and seasoned oak burn groups may be at least partly explained by stove temperatures. As shown in Figure 35, stove temperatures in the highest emitting maple run and the higher emitting seasoned oak burn decreased to below 400°F early in the run while stove temperatures remained above that temperature in the lowest emitting maple run and the lower emitting season oak run, as well as in both beech runs, which did not see a wide divergence in emissions.

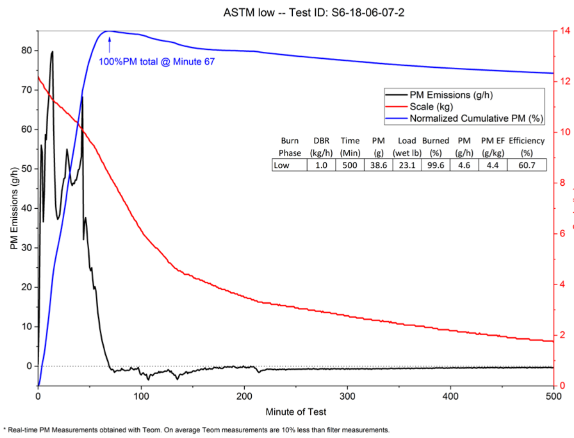
Figure 35. Stove 6—ASTM 3053-17 Runs—High-Fire Phase Emission and Temperature Profiles



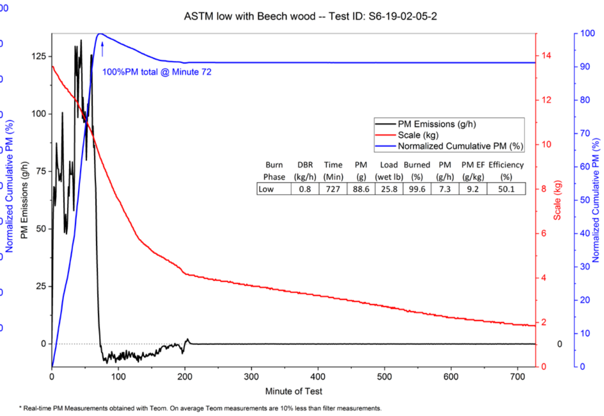
The ASTM 3053-17 high-fire phase ends when 90% of the fuel load is consumed. At that point, the stove is reloaded, and a low-fire or medium-fire burn is conducted. A complete test is composed of two runs, one with the reload burned at a low-air setting and other at a medium setting. The profiles for the three low-fire phase burns (one with each wood species) are shown in Figure 36 and the metrics for that phase are shown in Table 39.

Figure 36. Stove 6—ASTM 3053-17 Runs—Low Fire Phases

Red Maple



Beech



Seasoned

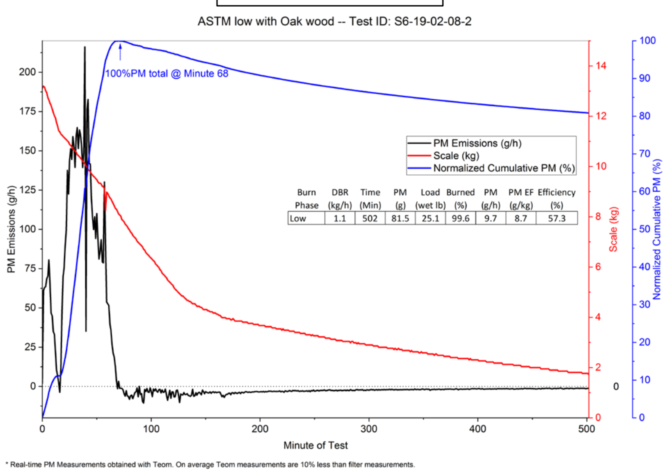


Table 39. Stove 6—Comparison of ASTM 3053-17 Low-Air Setting Test Metrics

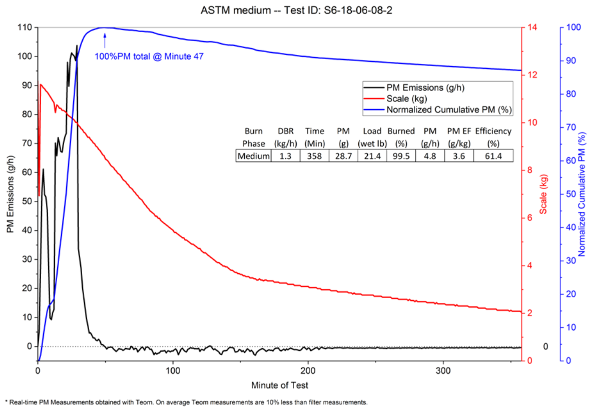
Test ID #	Fuel Type	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	Efficiency (%)
S6-18-06-07-2	Maple	1.05	500	38.57	4.63	4.43	60.7
S6-19-02-05-2	Beech	0.80	727	88.59	7.31	9.17	50.1
S6-19-02-08-2	Oak	1.12	502	81.54	9.75	8.69	57.3

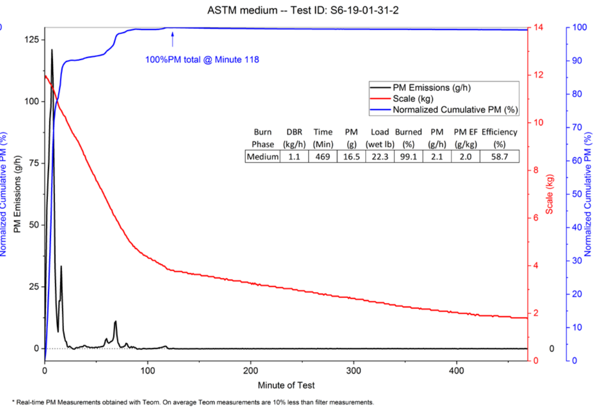
At the low-air setting, the test time was longer and the dry-burn rate lower for the beech fueled run than for the maple and oak fueled runs. The EFs in the low-burn phases of the beech and oak runs were twice that of the maple burn. The ER of the beech burn was 1.6 times higher and the oak burn 2.1 times higher than in the maple burn. The thermal efficiency in the low-burn phase of the maple run was higher than in the runs with the other fuels, particularly the beech run.

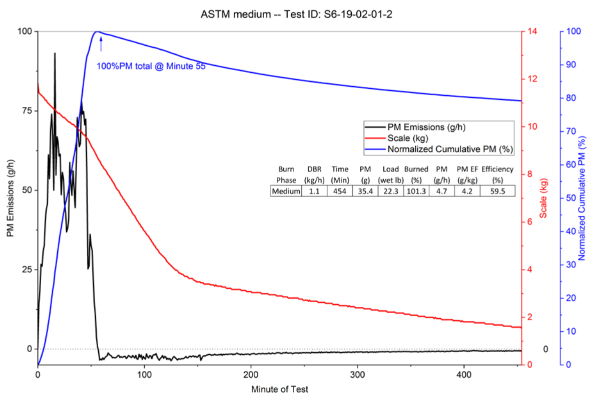
The profiles of the five medium fire phase runs (three maple, one beech, and one seasoned oak) are shown in Figure 37 and the metrics for that phase are shown in Table 40.

Figure 37. Stove 6—ASTM 3053-17 Runs—Medium-Fire Phases

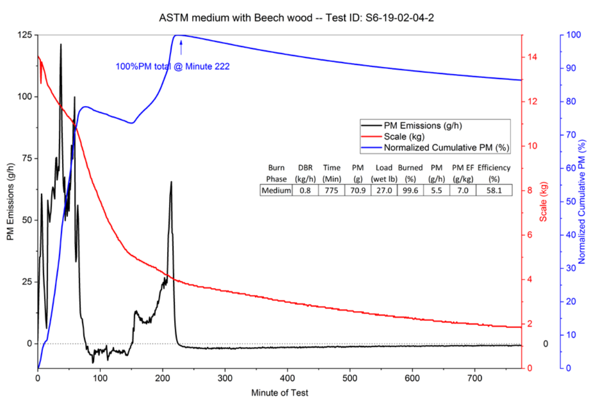
Red Maple







Beech



Seasoned

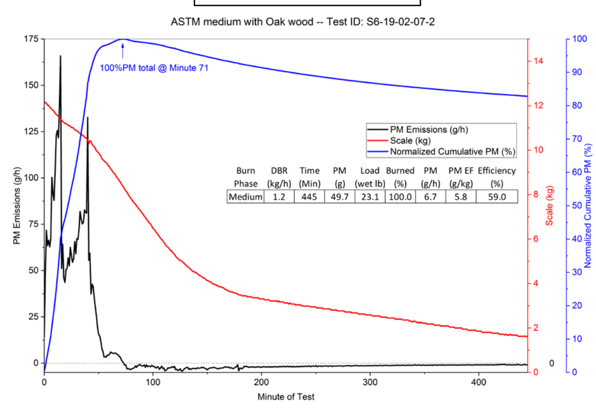


Table 40. Stove 6—Comparison of ASTM 3053-17 Medium-Air Setting Test Metrics

Test ID #	Fuel Type	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	Efficiency (%)
S6-18-06-08-2	Maple	1.33	358	28.69	4.81	3.61	61.4
S6-19-01-31-2	Maple	1.07	469	16.54	2.12	1.97	58.7
S6-19-02-01-2	Maple	1.11	454	35.44	4.68	4.23	59.5
S6-19-02-04-2	Beech	0.78	775	70.94	5.49	7.04	58.1
S6-19-02-07-2	Oak	1.16	445	49.70	6.70	5.76	59.0

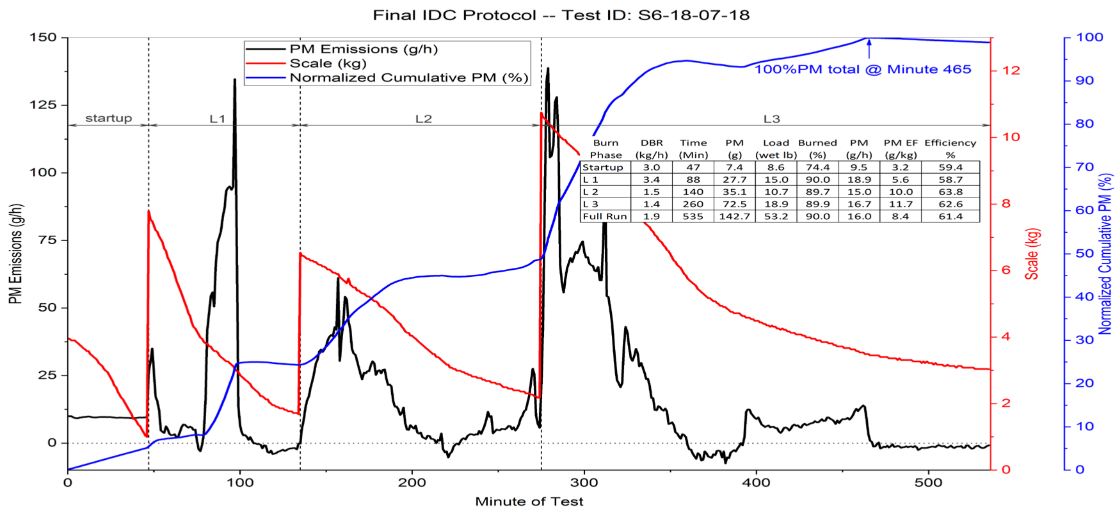
The run time and dry-burn rate for the medium-fire phase of the oak run were within the range of those of the maple runs. The beech run was longer and had a lower burn rate than the runs with the other fuels. The thermal efficiency for the beech run was also lower than for the other fuels, although that difference was not as substantial as in the low-fire phase. The PM emissions metrics were lower in all maple runs than those in either of the other fuels. The EFs for the beech and oak runs were approximately twice those of the average maple EF and the ERs for the beech and oak runs were 42% and 73% higher than the average maple ER, respectively. There was also substantial variability in the PM emissions metrics within the maple group, although the thermal efficiencies were similar in the three maple runs (relative standard deviation of 2%).

In all low and medium fire runs, most of the PM was emitted early in the run and PM was volatilized from the filters later in the run, as is the case in the M28 runs. In the three low-fire phase runs, the PM measurements at the end of the phase was 9%–19% lower than at the maximum. For the four of the five medium phase runs, 13%–21% of the maximum PM was lost. In one of the medium phases runs that burned red maple, S6-19-01-31, only 1% of total PM was lost, although the maximum occurred after 25% of the run.

2.5.3 IDC Tests

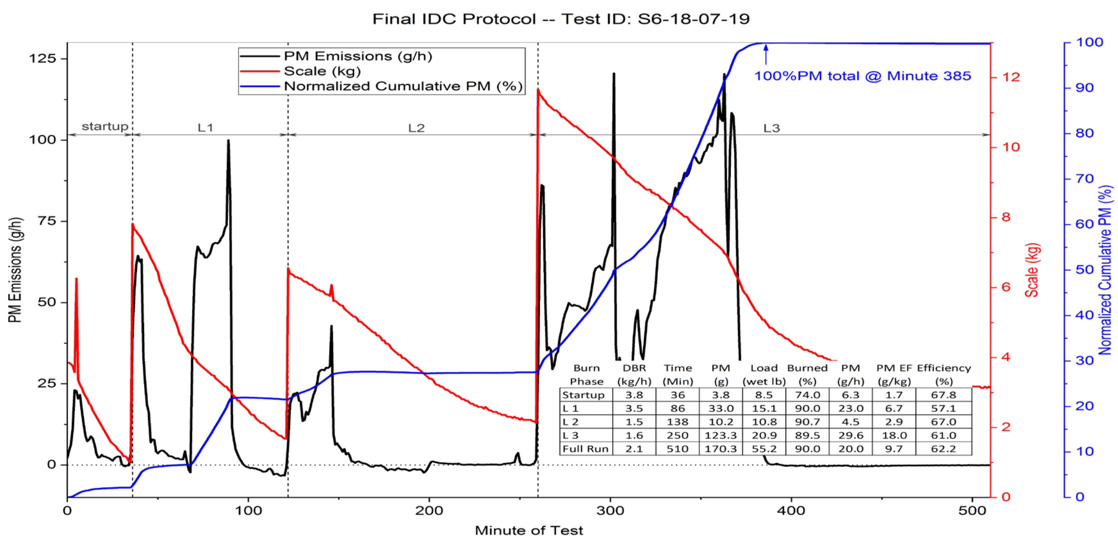
A total of nine runs using the final IDC protocol were run with stove 6, three replicate runs fueled with red maple, three with seasoned oak, and three with wet oak cordwood. During the start-up phase of all tests, the moisture (dry basis) content of the cordwood fuel for all tests was approximately 17.5%. However, in subsequent loads, the average moisture content, on a dry basis, was 21.4% in the seasoned oak and 28.1% in the wet oak cordwood. The average dry basis moisture content of the red maple cordwood in this set of IDC final protocol tests was 21.1%. PM was measured using the 1400AB TEOM in the maple runs and with the 1405 TEOM in the other IDC tests. Profiles of the stove 6 red maple, seasoned oak, and wet oak IDC replicates are shown in Figures 38 to 40, respectively.

Figure 38. Stove 6—IDC Final Protocol Replicate Runs with Red Maple Cordwood



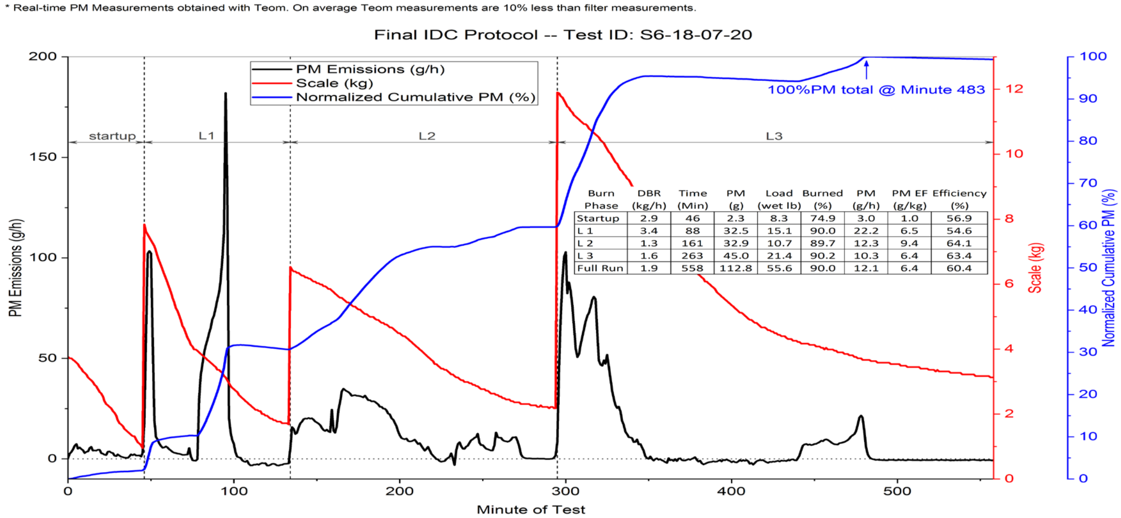
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency %
Startup	3.0	47	7.4	8.6	74.4	9.5	3.2	59.4
L 1	3.4	88	27.7	15.0	90.0	18.9	5.6	58.7
L 2	1.5	140	35.1	10.7	89.7	15.0	10.0	63.8
L 3	1.4	260	72.5	18.9	89.9	16.7	11.7	62.6
Full Run	1.9	535	142.7	53.2	90.0	16.0	8.4	61.4

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.8	36	3.8	8.5	74.0	6.3	1.7	67.8
L 1	3.5	86	33.0	15.1	90.0	23.0	6.7	57.1
L 2	1.5	138	10.2	10.8	90.7	4.5	2.9	67.0
L 3	1.6	250	123.3	20.9	89.5	29.6	18.0	61.0
Full Run	2.1	510	170.3	55.2	90.0	20.0	9.7	62.2

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

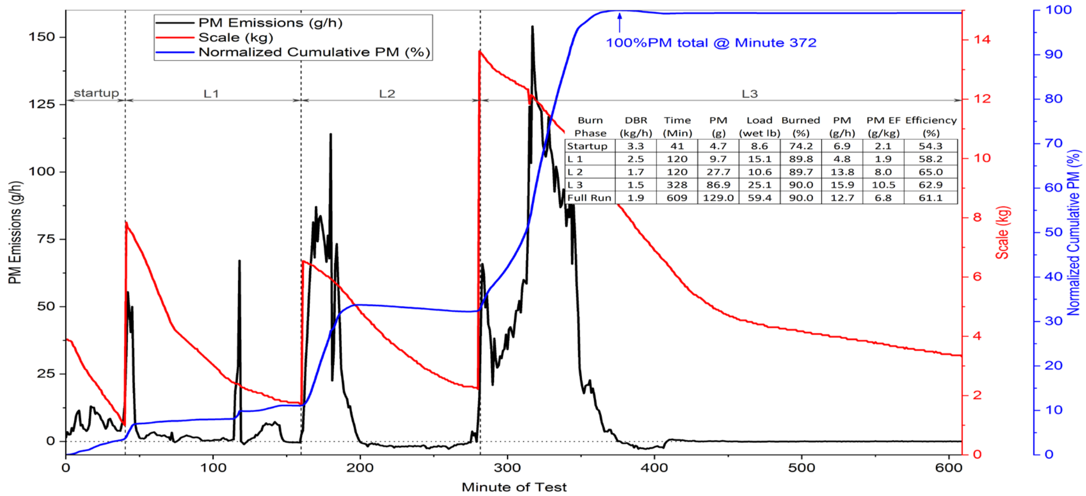


Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.9	46	2.3	8.3	74.9	3.0	1.0	56.9
L 1	3.4	88	32.5	15.1	90.0	22.2	6.5	54.6
L 2	1.3	161	32.9	10.7	89.7	12.3	9.4	64.1
L 3	1.6	263	45.0	21.4	90.2	10.3	6.4	63.4
Full Run	1.9	558	112.8	55.6	90.0	12.1	6.4	60.4

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Figure 39. Stove 6—IDC Final Protocol Replicate Runs with Seasoned Oak Cordwood

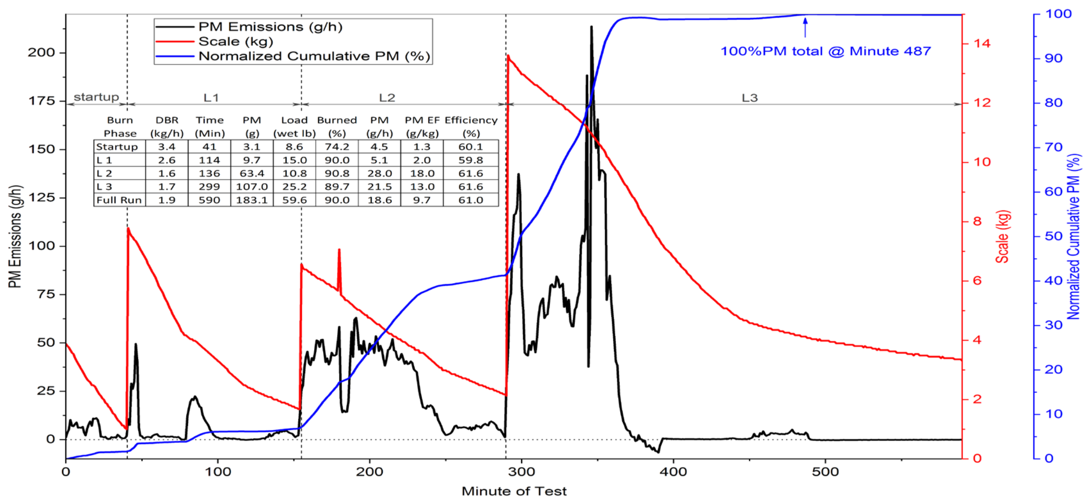
Final IDC Protocol with seasoned Oak wood -- Test ID: S6-19-03-13



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.3	41	4.7	8.6	74.2	6.9	2.1	54.3
L 1	2.5	120	9.7	15.1	89.8	4.8	1.9	58.2
L 2	1.7	120	27.7	10.6	89.7	13.8	8.0	65.0
L 3	1.5	328	86.9	25.1	90.0	15.9	10.5	62.9
Full Run	1.9	609	129.0	59.4	90.0	12.7	6.8	61.1

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

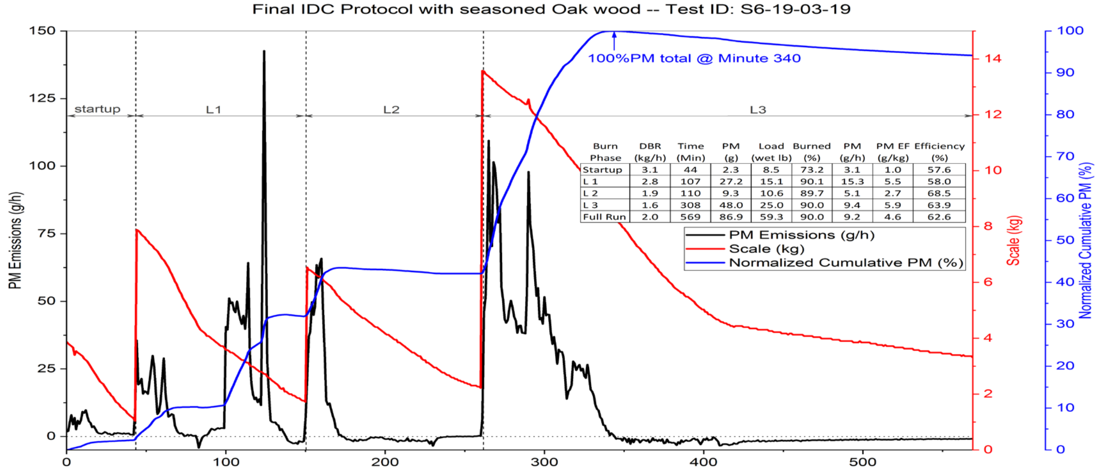
Final IDC Protocol with seasoned Oak wood -- Test ID: S6-19-03-18



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.4	41	3.1	8.6	74.2	4.5	1.3	60.1
L 1	2.6	114	9.7	15.0	90.0	5.1	2.0	59.8
L 2	1.6	136	63.4	10.8	90.8	28.0	18.0	61.6
L 3	1.7	299	107.0	25.2	89.7	21.5	13.0	61.6
Full Run	1.9	590	183.1	59.6	90.0	18.6	9.7	61.0

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Final IDC Protocol with seasoned Oak wood -- Test ID: S6-19-03-19

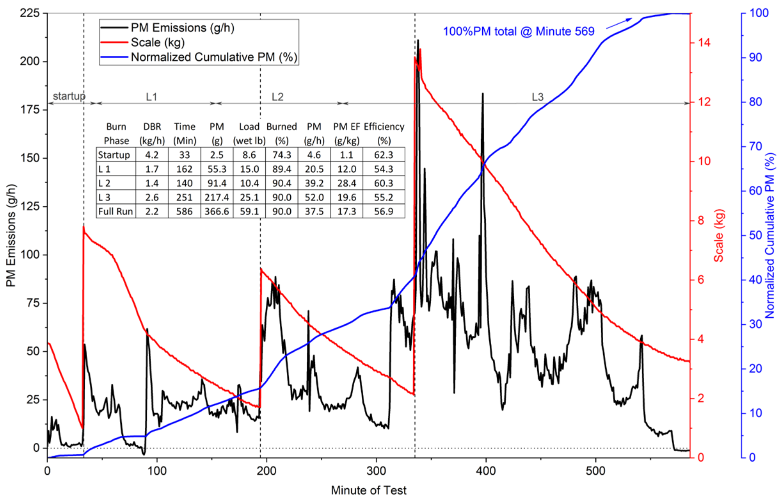


Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.1	44	2.3	8.5	73.2	3.1	1.0	57.6
L 1	2.8	107	27.2	15.1	90.1	15.3	5.5	58.0
L 2	1.9	110	9.3	10.6	89.7	5.1	2.7	68.5
L 3	1.6	308	48.0	25.0	90.0	9.4	5.9	63.9
Full Run	2.0	569	86.9	59.3	90.0	9.2	4.6	62.6

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Figure 40. Stove 6—IDC Final Protocol Replicate Runs with Wet Oak Cordwood

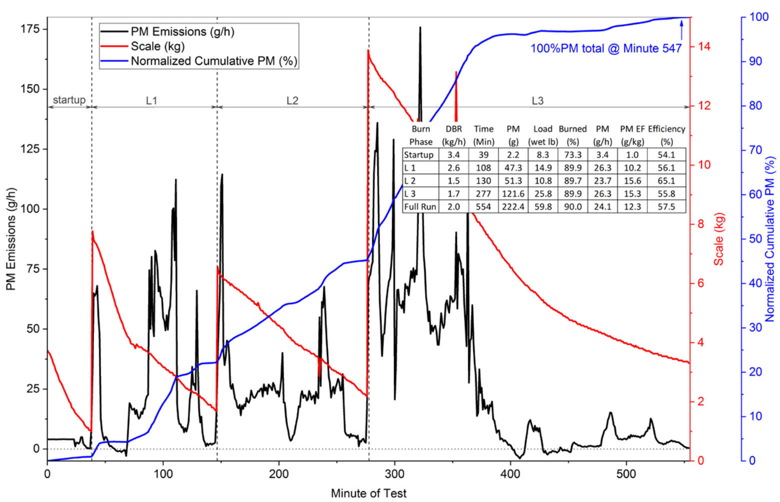
Final IDC Protocol with wet Oak wood -- Test ID: S6-19-02-18



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	4.2	33	2.5	8.6	74.3	4.6	1.1	62.3
L 1	1.7	162	55.3	15.0	89.4	20.5	12.0	54.3
L 2	1.4	140	91.4	10.4	90.4	39.2	28.4	60.3
L 3	2.6	251	217.4	25.1	90.0	52.0	19.6	55.2
Full Run	2.2	586	366.6	59.1	90.0	37.5	17.3	56.9

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

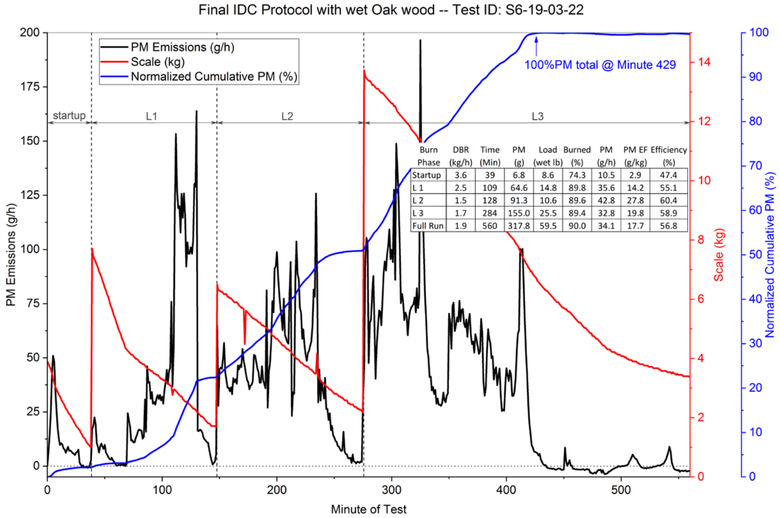
Final IDC Protocol with wet Oak wood -- Test ID: S6-19-03-21



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.4	39	2.2	8.3	73.3	3.4	1.0	54.1
L 1	2.6	108	47.3	14.9	89.9	26.3	10.2	56.1
L 2	1.5	130	51.3	10.8	89.7	23.7	15.6	65.1
L 3	1.7	277	121.6	25.8	89.9	26.3	15.3	55.8
Full Run	2.0	554	222.4	59.8	90.0	24.1	12.3	57.5

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Final IDC Protocol with wet Oak wood -- Test ID: S6-19-03-22



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.6	39	6.8	8.6	74.3	10.5	2.9	47.4
L 1	2.5	109	64.6	14.8	89.8	35.6	14.2	55.1
L 2	1.5	128	91.3	10.6	89.6	42.8	27.8	60.4
L 3	1.7	284	155.0	25.5	89.4	32.8	19.8	58.9
Full Run	1.9	560	317.8	59.5	90.0	34.1	17.7	56.8

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

The metrics for the start-up phase for the three sets of three replicate stove 6 IDC runs are shown in Table 41.

Table 41. Stove 6—Comparison of Test Metrics from Start-Up Phase of IDC Final Protocol Runs

Fuel	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	S6-18-07-18	2.96	47	7.44	9.50	3.20
	S6-18-07-19	3.79	36	3.76	6.27	1.65
	S6-18-07-20	2.90	46	2.32	3.03	1.04
Seasoned Oak	S6-19-03-13	3.34	41	4.73	6.92	2.07
	S6-19-03-18	3.38	41	3.05	4.46	1.32
	S6-19-03-19	3.07	44	2.3	3.14	1.02
Wet Oak	S6-19-02-18	4.21	33	2.51	4.57	1.09
	S6-19-03-21	3.37	39	2.24	3.45	1.02
	S6-19-03-22	3.57	39	6.83	10.51	2.95

Because the same start-up fuel and fueling procedures were used in all tests, the nine IDC runs are replicates of each other in this phase. The mean start-up ER and EF were 5.8 g/h and 1.7 g/kg, respectively. The highest ER and EF were about three times higher than the lowest.

The metrics for the high-fire phase (reload 1) of the IDC runs are shown in Table 42. During this phase, a fuel load of 7 lb/ft^3 comprised of small cordwood pieces is burned at the highest air control setting. When 50% of the load is consumed, the control is switched to the lowest setting and the load is burned to 90% consumption by weight.

Table 42. Stove 6—Comparison of Test Metrics from High-Fire Phase of IDC Final Protocol Runs

Fuel	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	**S6-18-07-18**	3.40	88	27.70	18.89	5.56
	S6-18-07-19	3.46	86	33.03	23.05	6.67
	S6-18-07-20	3.39	88	32.49	22.15	6.54
Seasoned Oak	**S6-19-03-13**	2.5	120	9.69	4.84	1.94
	S6-19-03-18	2.57	114	9.65	5.08	1.97
	S6-19-03-19	2.77	107	27.21	15.26	5.51
Wet Oak	**S6-19-02-18**	1.7	162	55.27	20.47	12.01
	S6-19-03-21	2.57	108	47.29	26.27	10.21
	S6-19-03-22	2.51	109	64.64	35.58	14.15

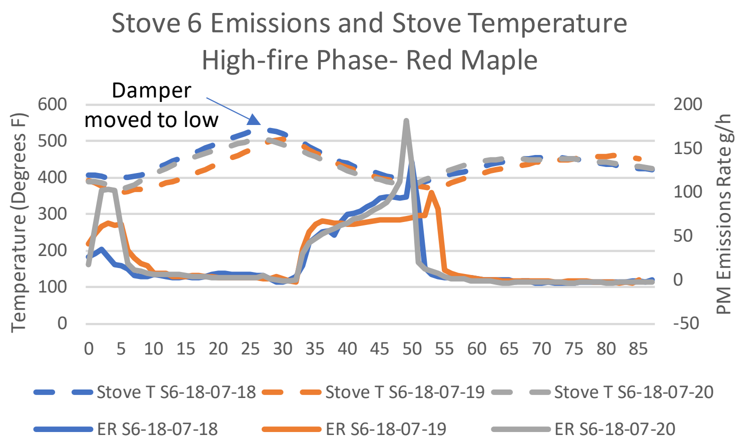
In the high-fire phase, the test times were lower and the dry-burn rates higher in all of the red maple runs than in any of the seasoned or wet oak runs. The red maple replicates and wet oak replicates had much less intragroup variability in PM emissions than in the previous phase. The PM emissions, ER, and EF for the highest emitting red maple run were only about 20% higher than for the lowest.

In the high-fire phase of the wet oak runs, total PM emissions, the PM EF and the PM ER in the highest emitting replicate were 37%, 39%, and 74% greater than the lowest emitting run, respectively. The wet oak fueled runs emitted substantially more PM than the runs that burned the other fuels. The average wet oak EF was almost twice that of the red maple runs. Due to a longer test time, the difference in ERs was less substantial; the average high-fire phase wet oak ER, 27.4 g/h, was 28% higher than that of the red maple runs, 21.4 g/h.

Two of the seasoned oak runs had essentially equal PM emissions that were approximately three times lower than in the maple runs and five-six times lower than the wet oak emissions. PM emissions in the third seasoned oak run were higher in the range of those in the maple group.

The emissions profiles in Figures 38 to 40 show that substantial PM emissions in this phase occurred after 50% of the fuel load was combusted and the air control was moved to the low setting. Figure 41 displays the temperature profile and emissions profile for the red maple IDC runs. In the 20 minutes after the air setting was moved to low, the stove temperature decreased by about 100ºF and substantial emissions occurred.

Figure 41.Stove 6—Red Maple IDC High-Fire Phase Emissions and Stove Temperature Profile



In Reload 2, the maintenance phase, the air setting is kept at the lowest setting and two large pieces of wood are loaded into the stove. At this point, the coal bed is well developed. The metrics measured in this phase of the stove 6 IDC runs are shown in Table 43.

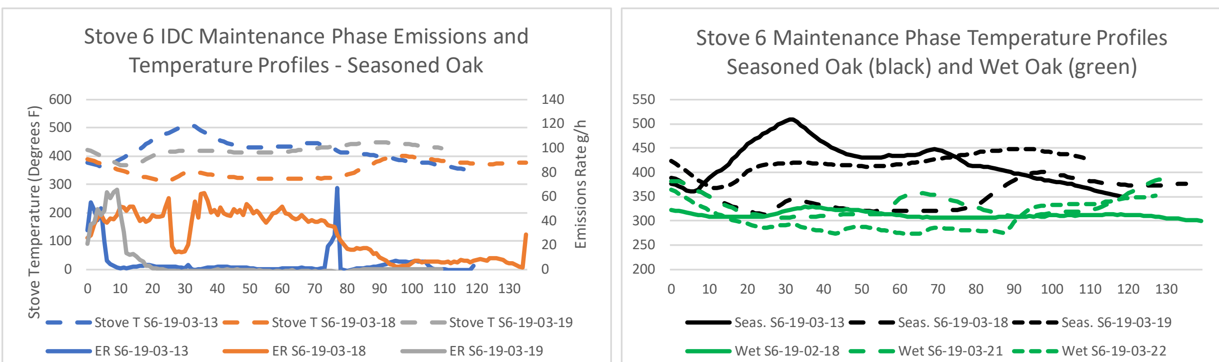
Table 43. Stove 6—Comparison of Test Metrics from Maintenance Phase of IDC Final Protocol Runs

Fuel	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	S6-18-07-18	1.50	140	35.11	15.05	10.00
	S6-18-07-19	1.55	138	10.24	4.45	2.87
	S6-18-07-20	1.30	161	32.94	12.28	9.44
Seasoned Oak	S6-19-03-13	1.74	120	27.67	13.83	7.96
	S6-19-03-18	1.56	136	63.42	27.98	17.98
	S6-19-03-19	1.90	110	9.34	5.09	2.68
Wet Oak	S6-19-02-18	1.38	140	91.38	39.16	28.39
	S6-19-03-21	1.51	130	51.29	23.67	15.63
	S6-19-03-22	1.54	128	91.33	42.81	27.79

In the maintenance phase, dry-burn rates were lower than in the previous phases and slightly higher in the seasoned oak runs than in the red maple and wet oak burns. PM emissions varied substantially within the fuel groups. On average, the maintenance phase EFs in the seasoned oak and wet oak runs were 28% and 250% (2.5 times) greater than those in the red maple runs. The average maintenance phase ERs for seasoned oak, 15.6 g/h, and wet oak, 35.2 g/h, were 48% and 230% (2.3 times), respectively, greater than the maple ER, 10.6 g/h.

It is interesting to further investigate why PM emissions in one of the seasoned oak replicates, S6-19-03-18, were substantially higher than in the other runs with that fuel, and similar to the emissions in the wet oak runs. As shown in Figure 42, this observation can be at least partly explained by stove temperatures because the stove temperatures in that run were much lower than in the other seasoned oak runs and were similar to those in the wet oak runs.

Figure 42. Stove 6—Variability in Seasoned Oak Maintenance Phase Emissions and Temperatures



The final phase (reload 3, overnight phase) in the IDC protocol represents conditions required to obtain a long burn, such as those needed for overnight burns or during the day when the fire will be unattended for a significant amount of time (>6 hours). During this phase, the coal bed is raked, and the user loads as much wood as possible, using large and small pieces. The metrics measured in the overnight phase of the stove 6 IDC runs are shown in Table 44.

Table 44. Stove 6—Comparison of Test Metrics from Overnight Phase of IDC Final Protocol Runs

Fuel	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	S6-18-07-18	1.43	260	72.48	16.70	11.70
	S6-18-07-19	1.64	250	122.77	29.47	17.93
	S6-18-07-20	1.61	263	44.85	10.23	6.35
Seasoned Oak	S6-19-03-13	1.51	328	86.91	15.9	10.51
	S6-19-03-18	1.65	299	106.96	21.46	12.98
	S6-19-03-19	1.6	308	48.01	9.35	5.86
Wet Oak	S6-19-02-18	2.65	251	217.43	51.98	19.62
	S6-19-03-21	1.72	277	121.57	26.33	15.33
	S6-19-03-22	1.65	284	155.03	32.75	19.80

The overnight phases of the stove 6 maple IDC runs lasted 250 to 263 minutes (4.2 to 4.4 hours). The time range for this phase was similar for the wet oak runs (4.2 to 4.7 hours) and somewhat higher in the seasoned oak runs (5.0 to 5.5 hours). The dry-burn rate was similar in all of the runs except for the first wet oak burn, which had a dry-burn rate more than 50% higher than all other runs. The fuel load in that run was approximately 40% larger than in the other two wet oak runs.

On average, the overnight phase EF and ER for the wet oak runs were approximately twice those of the seasoned oak runs. The average overnight red maple EF and ER were slightly higher (about 20%) than those for the seasoned oak. The average red maple, seasoned oak and wet oak ERs for this phase were 18.8, 15.6, and 37.0 g/h, respectively.

Table 45 shows the test metrics for the entire run of each of the IDC replicates.

Table 45. Stove 6—Comparison of Test Metrics for Entire Run of IDC Final Protocol Runs

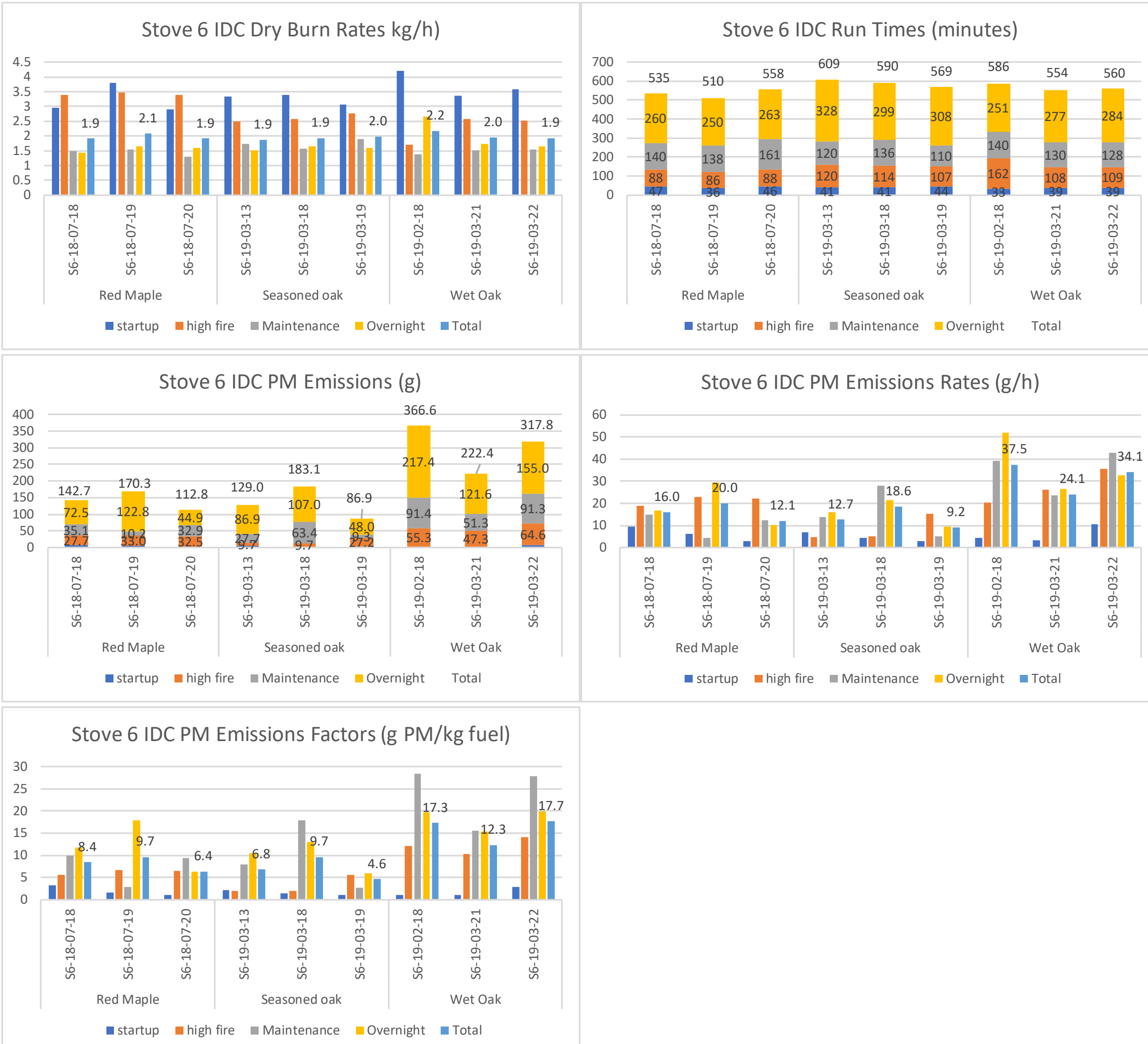
Fuel	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	HHV Efficiency (%)
Red Maple	S6-18-07-18	1.91	535	142.73	16.01	8.39	61.4
	S6-18-07-19	2.08	510	170.30	20.03	9.65	62.2
	S6-18-07-20	1.91	558	112.75	12.12	6.35	60.4
Seasoned Oak	S6-19-03-13	1.87	609	128.99	12.71	6.78	61.1
	S6-19-03-18	1.93	590	183.08	18.62	9.65	61.0
	S6-19-03-19	1.99	569	86.87	9.16	4.60	62.6
Wet Oak	S6-19-02-18	2.17	586	366.60	37.54	17.28	56.9
	S6-19-03-21	1.95	554	222.40	24.09	12.33	57.5
	S6-19-03-22	1.93	560	317.82	34.05	17.66	56.8

The total time to complete the stove 6 IDC red maple runs ranged from 510 to 558 minutes (8.5 to 9.3 hours), a longer period than for some of the other stoves, but still less than the 10 hour period that would be feasible for completion in a single day. The time range for the seasoned oak runs (9.5 to 10.2 hours) and wet oak (9.2 to 9.8 hours) were slightly higher than those of the red maple runs. The HHV thermal efficiencies were similar in all red maple and seasoned oak runs and somewhat lower in the wet oak runs.

There was somewhat more variation in the PM metrics in the seasoned oak runs than in the other fuel groups. The EF and ER in the highest emitting seasoned oak runs were 2.1 and 2.0 times higher than in the lowest emitting run in that group, respectively. The EF and ER in the highest emitting red maple run were 52% and 65% higher than the lowest. In the wet oak group, the run with the highest PM emissions had an EF and ER 43% and 56% higher than the lowest, respectively.

Figure 43 shows the test metrics by test phase for each of the IDC runs graphically.

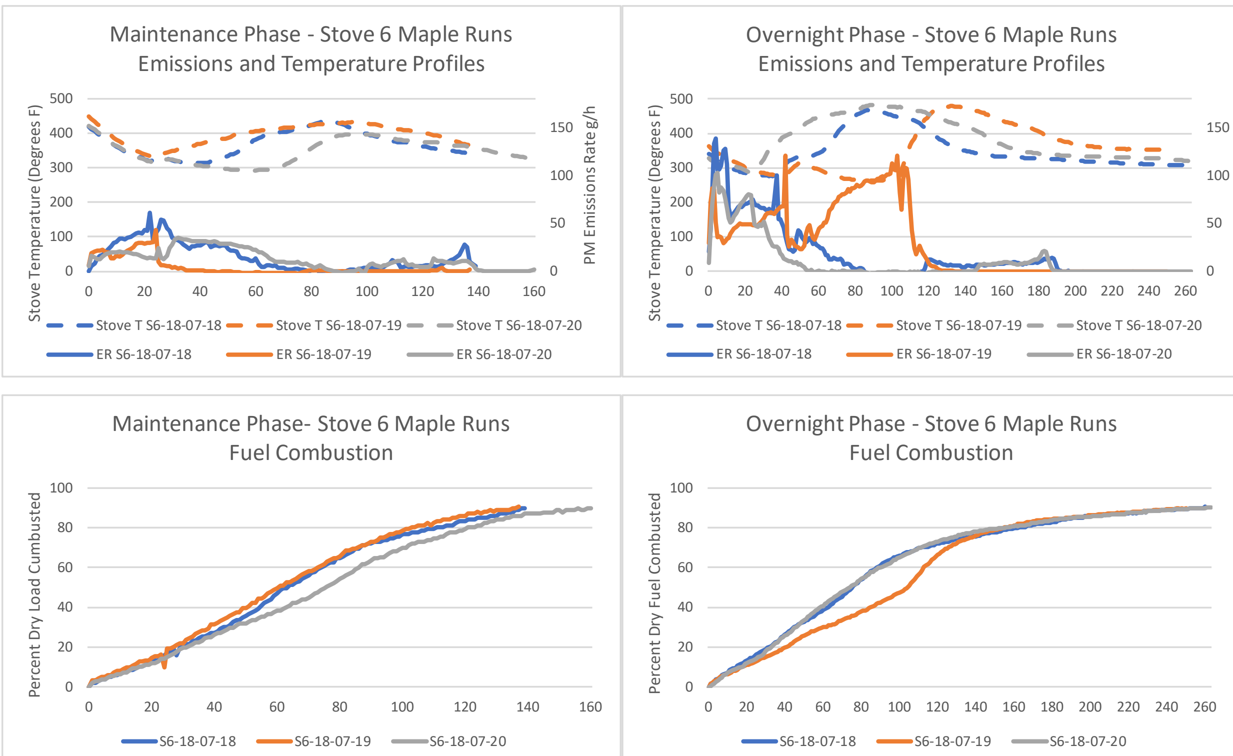
Figure 43. Stove 6—Comparison of Metrics for IDC Replicate Runs



Average dry-burn rates and test times were quite consistent among the replicates. As discussed previously, the PM emission metrics for wet oak were higher than those for other fuels in all phases except for start-up. The ER and EF for the entire second red maple run, S6-18-07-19, were higher than in the other two runs in that fuel group, largely because of the higher emissions in the overnight phase of that run. The PM emissions in the previous phase, the maintenance phase, were lower in that run than in the other two red maple runs.

This intragroup difference can be explained, at least in part, by comparing the stove temperature patterns in those two phases, as shown in Figure 44. In this figure, the PM emissions profiles for the three replicate runs are denoted with solid lines and the stove temperatures for those runs with dotted lines in corresponding colors.

Figure 44.Stove 6—Comparison of Emission and Temperature Profiles and Fuel Combustion Curves for the Maintenance and Overnight Phases of the Red Maple IDC Runs



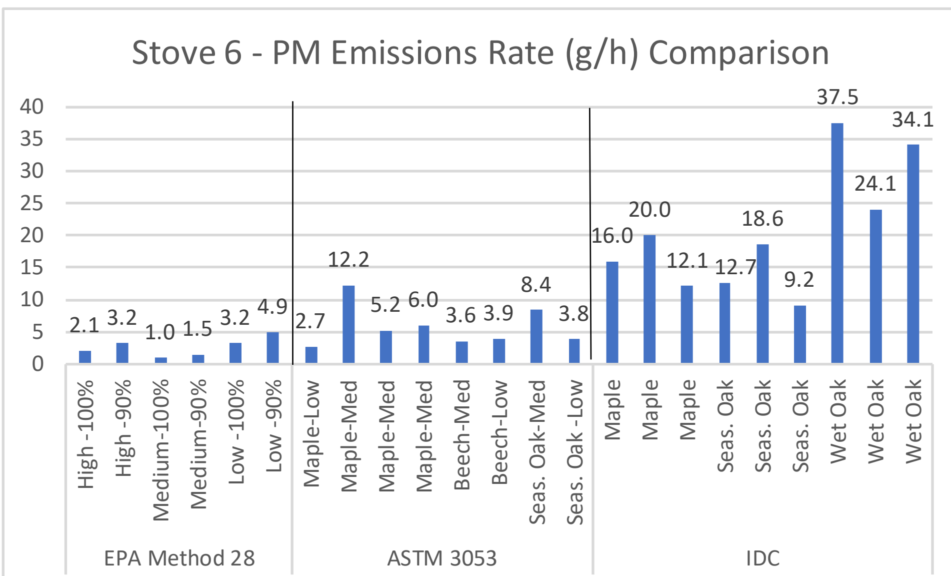
The stove temperature decreased at the beginning of the maintenance phase in all runs, coinciding with a period of significant PM emissions. However, the temperature recovered quickly in the maintenance phase of run 2 (orange in Figure 44), and emissions decreased sharply at that time. The stove temperatures decreased further and recovered more slowly in the maintenance phase of run 1 (blue), and even more so in run 3 (gray), resulting in emissions over a longer period and higher ERs and EFs for those runs than for run 2. A different pattern occurred in the overnight phase. In that phase, the stove temperature in Run 2 began to recover from the initial decrease, but then experienced a second period of decreasing temperatures during which the temperature dropped below 300°F. During that second temperature decrease, significant additional emissions occurred in run 2. The other two runs did not experience a similar secondary temperature decrease and emissions peak.

As can be seen in Figure 44, the fuel consumption rate was also lower for run 2 than for the other turns during that period of the overnight phase, and then picked up after about 100 minutes into the phase, when the temperature began to increase. This is indicative of a second fuel light-off. The run 2 overnight emissions decreased to insignificant levels soon after this second light-off occurred.

2.5.4 Comparison of Stove 6 Emission Rate Measurements

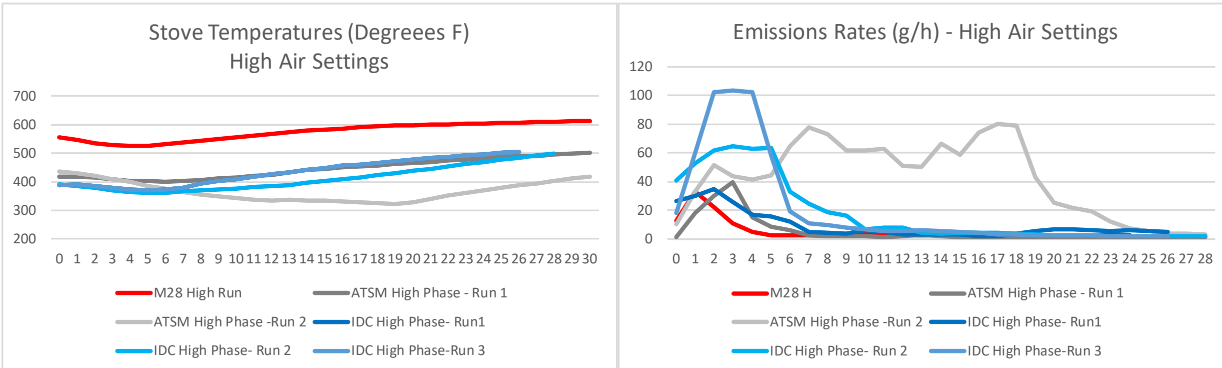
Figure 45 compares the emission rates measured in the runs performed using EPA's current crib wood protocol, Method 28, the ASTM 3053-17, and IDC final protocol cordwood test runs performed on stove 6.

Figure 45. Stove 6—Comparison of Method 28, ASTM 3053-17, and IDC Final Protocol Emission Rate Measurements



As shown in Figure 45, the stove 6 ERs measured using the IDC protocol tended to be considerably higher than those measured with the other methods. The M28 and ASTM 3053-17 ERs in this figure should not be directly compared to the regulatory standard. Figure 46 compares stove temperatures in the stove 6 tests when the air control was at its highest setting; the high-burn run M28 run, the high-fire phase of the ASTM 3053-17 runs, and the first half of load combustion in the high-fire phase of the IDC final protocol runs before the air control was moved to a low setting. In both graphs in that figure, the M28 run is shown in red, the high-fire phase of the two ASTM 3053-17 runs in shades of gray, and the high-fire phase of the IDC runs in shades of blue.

Figure 46. Stove 6—Comparison of Temperature Profiles and Emission Rates in Burns at High-Air Setting



The temperature in the M28 high-fire run started out at least 150ºF higher than the temperature at the beginning of the high-fire phases of all IDC runs and remained approximately 100ºF higher than the IDC runs at the point that the IDC air controls were switched to the low setting. This may at least partly explain the higher emissions in the IDC runs. While the temperatures in this phase of the first IDC run were similar to those in the other IDC runs, the emissions in that run were considerably lower than in the other runs and similar to the M28 emissions.

As shown in Figure 46, the temperatures at the beginning of the high-fire phase of the ASTM 3053-17 runs were slightly higher than at the start of the high-fire phase of the IDC runs. In one of the ASTM 3053-17 runs, the temperatures remained similar to the IDC temperatures during the high-air setting period, while the temperatures in the other ASTM 3053-17 run dipped after the first six minutes of that burn. PM emissions showed a similar pattern; the ERs for the ASTM 3053-17 and IDC runs were in the same range in the first few minutes of the high-fire burn, but significant emissions in the ASTM 3053-17 burn with the lower temperatures continued for approximately 15 minutes longer than in any of the other runs.

Section 2 presents a more detailed analysis of the differences between the results for different test methods, including a comparison of the operating parameters measured in the high-fire phases of runs using different methods and a similar comparison of low-fire phase parameters.

2.6 Stove 7

Stove 7 is a high-mass hybrid stove with a medium size fire box. A total of 19 tests were performed on this stove. Descriptions of the test methods are shown in Table 46. The M28 baseline tests were conducted with Douglas fir crib wood, and the ASTM 3053-17 tests and one set of IDC final tests were performed with red maple cordwood. In addition, three sets of IDC final tests were conducted with seasoned oak, wet oak, and poplar cordwood fuel. Because each ASTM 3053-17 run includes two parts (start-up + high, followed by either a medium or low load), separate test IDs are assigned to each part of the test.

Table 46. Stove 7—Test Descriptions

Test ID	Test Method	Fuel Species	Fuel Type	Description
S7-19-02-21-H	M28 (baseline)	Douglas Fir	Crib	High fire, load burned 100%
S7-19-02-22	M28 (baseline)	Douglas Fir	Crib	Medium fire, load burned 100%
S7-19-02-21-L	M28 (baseline)	Douglas Fir	Crib	Low fire, load burned to 100%
S7-19-02-25-1	ASTM 3053-17	Red Maple	Cord	Start-up (9.7 lb)** + high fire (19.9 lb)
S7-19-02-25-2	ASTM 3053-17	Red Maple	Cord	Low fire (21.14 lb)
S7-19-02-27-1	ASTM 3053-17	Red Maple	Cord	Start-up (9.31 lb) + high fire (19 lb)
S7-19-02-27-2	ASTM 3053-17	Red Maple	Cord	Medium fire (18.65 lb)
S7-18-07-25 Replicate 1-RM	IDC Final Protocol	Red Maple	Cord	
S7-18-07-26 Replicate 2-RM	IDC Final Protocol	Red Maple	Cord	
S7-18-07-27 Replicate 3-RM	IDC Final Protocol	Red Maple	Cord	
S7-19-02-20 Replicate 1-WO	IDC Final Protocol	Wet Oak	Cord	
S7-19-03-25 Replicate 2-WO	IDC Final Protocol	Wet Oak	Cord	
S7-19-03-26 Replicate 3-WO	IDC Final Protocol	Wet Oak	Cord	
S7-19-03-28 Replicate 1-Pop	IDC Final Protocol	Poplar	Cord	
S7-19-03-29 Replicate 2-Pop	IDC Final Protocol	Poplar	Cord	
S7-19-03-30 Replicate 3-Pop	IDC Final Protocol	Poplar	Cord	
S7-19-04-03 Replicate 1-SO	IDC Final Protocol	Seasoned Oak	Cord	
S7-19-04-04 Replicate 2-SO	IDC Final Protocol	Seasoned Oak	Cord	
S7-19-04-05 Replicate 3-SO	IDC Final Protocol	Seasoned Oak	Cord	

PM emissions in the stove 7 IDC final protocol runs that burned red maple were measured using the 1400AB TEOM. The 1405 model was used for all other stove 7 runs.

2.6.1 Baseline Tests

Baseline tests were conducted using EPA Method 28 (M28) procedures at three of the four air control settings prescribed in that method: the highest air control setting (category 4), the lowest setting (category 1), and the manufacturer's recommended air setting for a medium-burn rate (category 2/3). Table 47 summarizes the results of the baseline modified M28 testing. Note that at both the medium-air settings, stove 7 achieved a category 3 burn rate.

Table 47. Stove 7—Summary of the Modified M28 Baseline Test Results

	Test Time (min)		Dry-Burn Rate (kg/h)		Total PM (g)		PM Emission Rate (g/h)		PM Emission Factor (g/kg)		HHV Efficiency (%)
% Burn Completed	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*100%*
High	142	192	1.91	1.57	1.07	1.37	0.45	0.43	0.24	0.27	53.1
Medium	163	222	1.65	1.36	2.14	2.11	0.79	0.57	0.47	0.42	61.5
Low	198	365	1.39	0.84	2.04	2.01	0.62	0.33	0.44	0.39	70.6

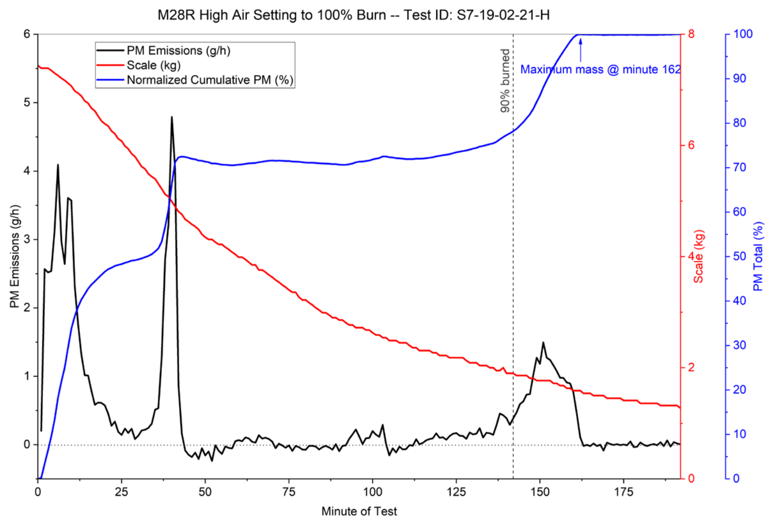
The HHV thermal efficiency of stove 7 was highest in the low-air run and lowest in the high-air run. This stove had the highest overall efficiency in the M28 tests, as compared to the other stoves tested.

PM emissions were low in all stove 7 baseline runs. Total PM, EF, and ER were slightly higher in the medium-air runs than in the other runs. The high run had the lowest total PM emissions and EF but, due to the low-air run's long test time, that run had the lowest ER. The medium run total PM and EF were 54% and 56% higher, respectively than those metrics in the high-air run and the medium-run ER was 73% higher than in the low-air run. A more detailed discussion of PM emissions follows.

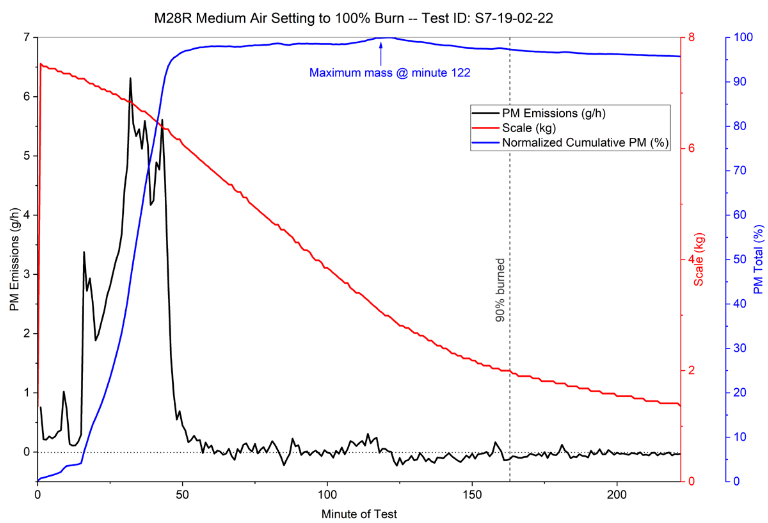
2.6.1.1 PM Emissions Profiles

Real-time plots of the three stove 7 M28 test runs are presented in Figure 47. As in the plots for the previous stoves, the TEOM PM emission rate profiles are shown in black, cumulative PM in blue, and remaining fuel load in red.

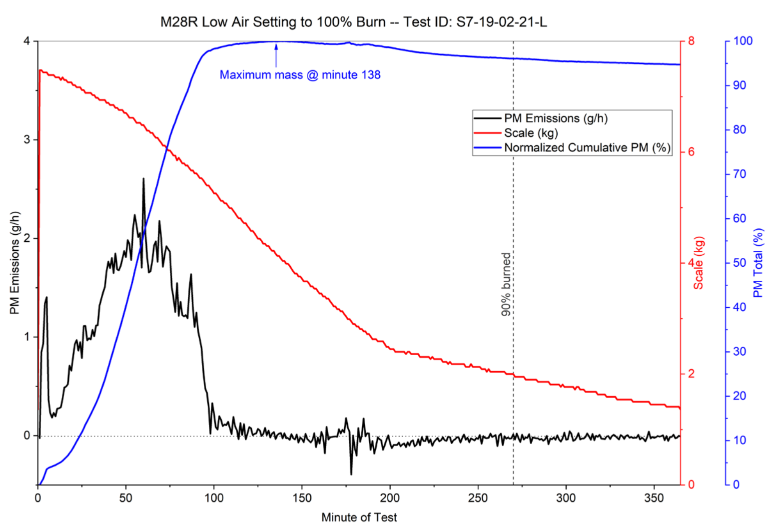
Figure 47. Stove 7—M28 Baseline Test Results



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

The maximum instantaneous emissions in stove 7 M28 runs were much lower than in the other stoves. Somewhat elevated emissions recorded in the first 10 minutes of the high-air run peaked at 4.1 g/h at minute 6, and a second short-lived elevation occurred about 25 minutes later, peaking at 4.8 g/h at minute 40. Emissions in the medium-air run were below 2 g/h for most of a 30 minute period beginning at minute 16 and peaking at 5.6 g/h at minute 37. Emissions in the low-air run were below 2 g/h in all but an 8 minute period beginning at minute 54; the instantaneous ER for that run peaked at 2.2 g/h at minute 55.

2.6.1.2 Cumulative PM Emissions

As with other stoves, maximum cumulative PM was measured midway through the stove 7 baseline runs, due to the volatilization losses that occur later in the burns. This loss was significant in the low and medium runs. In both of those runs, the maximum PM occurred substantially before 90% of the fuel was consumed. In the high-burn run, the maximum occurred after 90% fuel consumption and minimal loss occurred after that point.

The maximum cumulative PM was recorded 162 minutes into the high burn run, which occurred 19 minutes after 90% of the fuel was consumed and 30 minutes before the end of the run (100% fuel consumption). The cumulative PM measurement at the end of the high-burn test was essentially equal to that at the peak collection point. The period after maximum PM collection, during which no significant additional PM was collected and slight loss occurred, constituted 16% of the total test period.

In the medium-burn run, the maximum cumulative PM was recorded at 122 minutes, which was 42 minutes before the point of 90% fuel consumption and 100 minutes before 100% of the fuel was consumed. The cumulative PM measurement at the end of the medium burn test was 2% lower than at the peak collection point. The period after maximum PM collection, during which no significant additional PM was collected and PM loss occurred, constituted 45% of the total test period.

In the low-burn run, the maximum cumulative PM was recorded at 137 minutes, which was 134 minutes before the point of 90% fuel consumption and 228 minutes before 100% of the fuel was consumed. The cumulative PM measurement at the end of the low-burn test was 1% lower than at the peak collection point. The period after maximum PM collection, during which no significant additional PM was collected and PM loss occurred, constituted 62% of the total test period.

2.6.1.3 Ninety Percent versus 100% Fuel Combustion

As discussed above, the ER for an entire M28 test run often underestimates the rate that would occur in the field because most emissions occur early in the burns, and wood stove owners often refuel before the previous load has been completely consumed. For stove 7, 90% of total PM emissions were generated in the first 79% of the high-M28 run, the first 20% of the medium run, and the first 24% of the low-fire burn.

To more accurately reflect actual in-use conditions, we calculated PM emission parameters for the period of 90% fuel consumption, as well as at the end of the run (100% fuel combustion). For the stove 7 high-burn run, the time period between 90% and 100% fuel combustion was 50 minutes, 28% of the total run time. Total PM emissions and the EF (in g/kg) increased by 1% and 11%, respectively, between 90% and 100% combustion. However, the PM ER, the metric used to certify stoves, was 0.45 g/h at 90% fuel combustion and 0.43 g/h at 100% combustion, a reduction of 4% that is due to the lengthened averaging period.

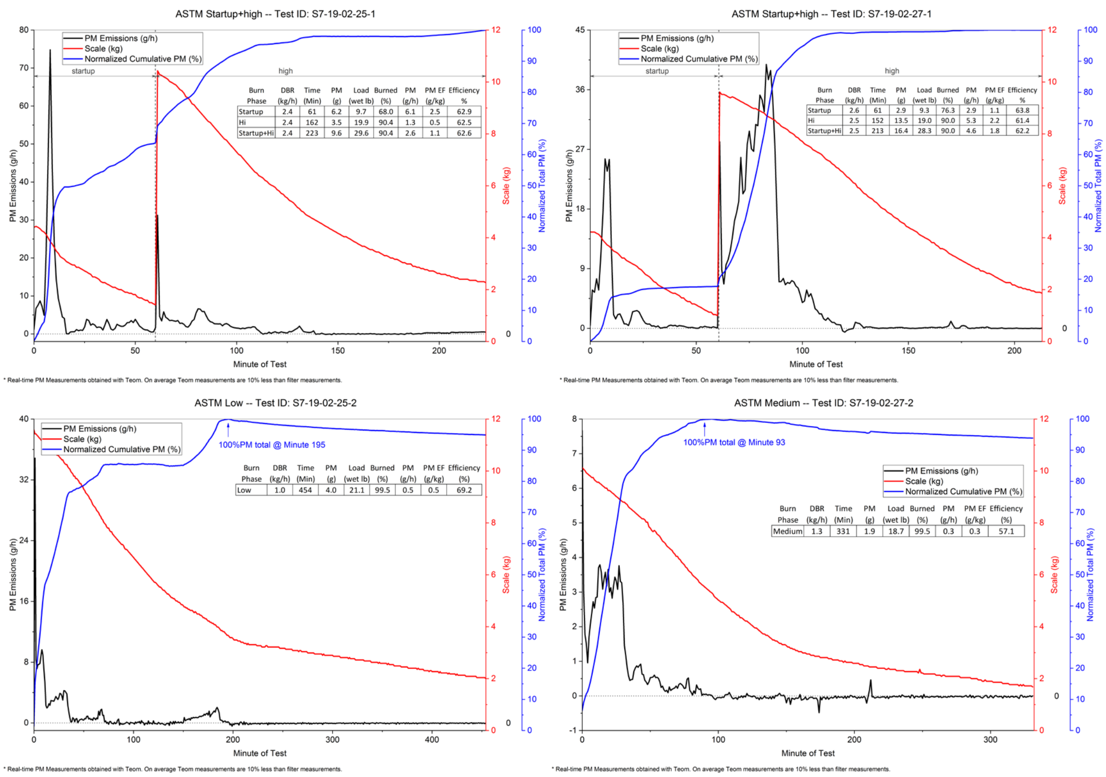
For the medium-burn run, the time period between 90% and 100% combustion was 59 minutes, 27% of the total run time. During that period, total PM emissions decreased by 1% and the PM EF decreased by 11%. The PM ER decreased by 28%, from 0.79 g/h to 0.57 g/h. For the low-burn run, the time from 90% to 100% combustion was 167 minutes, 46% of the total run time. During that period, low-burn PM emissions decreased by 1%, the EF (g/kg) decreased by 11%, and the ER rate decreased by 47%, from 0.62 g/h to 0.33 g/h.

The average ER associated with 100% combustion in the three runs was 0.44 g/h, as compared to 0.62 g/h for 90% combustion.

2.6.2 ASTM 3053-17 Tests

A single complete, ASTM 3053-17 test was conducted on stove 7 using maple cordwood. As discussed above, a complete ASTM 3053-17 test consists of two runs, one with start-up + high-air setting phase followed by a medium-air setting phase and the second with a low-air phase after the start-up + high burn. The results of these tests are shown in Figure 48. As in previous ASTM 3053-17 tests, the start-up + high-burn phase is graphed separately from the medium- or low-burn phase.

Figure 48. Stove 7—ASTM 3053-17 Runs



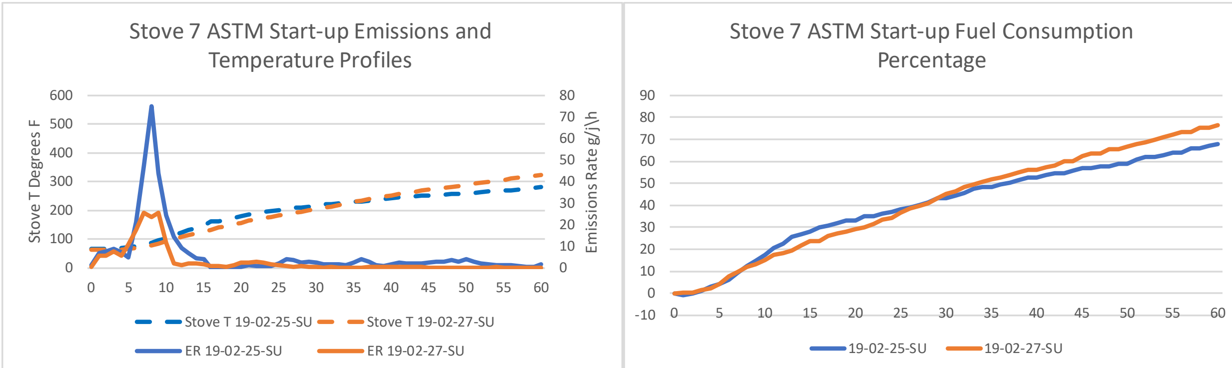
The start-up phase metrics for the two stove 7 ASTM 3053-17 runs are shown in Table 48.

Table 48. Stove 7—Comparison of ASTM 3053-17 Start-Up Phase Run Metrics

Test ID #	S7-19-02-25-1	S7-19-02-27-1
Dry-Burn Rate (kg/h)	2.38	2.63
Time (min)	61	61
Total PM (g)	6.16	2.90
PM Emission Rate (g/h)	6.06	2.85
PM Emission Factor (g/kg)	2.54	1.08
HHV Efficiency (%)	62.9	63.8

Although the start-up protocol was the same for these two runs, the PM emissions parameters in the first run were more than twice as high as in the second. The emissions and temperature profiles and fuel consumption profiles for the start-up phases of the two stove 7 ASTM 3053-17 runs are shown in Figure 49.

Figure 49. Stove 7 ASTM 3053-17 Start-Up Emissions, Stove Temperatures, and Fuel Combustion



As shown in those figures, the PM emissions in both runs peaked between minutes 7 and 9 and dropped to essentially zero by minute 16. The differences in the magnitude of the start-up emissions between the runs cannot be explained by the stove temperature or fuel consumption rate, which were essentially equal in the two runs during the emissions period. The start-up load in first run was approximately 4% heavier than in the second (4.40 versus 4.22 kg wet weight, both with dry moisture content of 15%), which may have contributed to the differential start-up emissions.

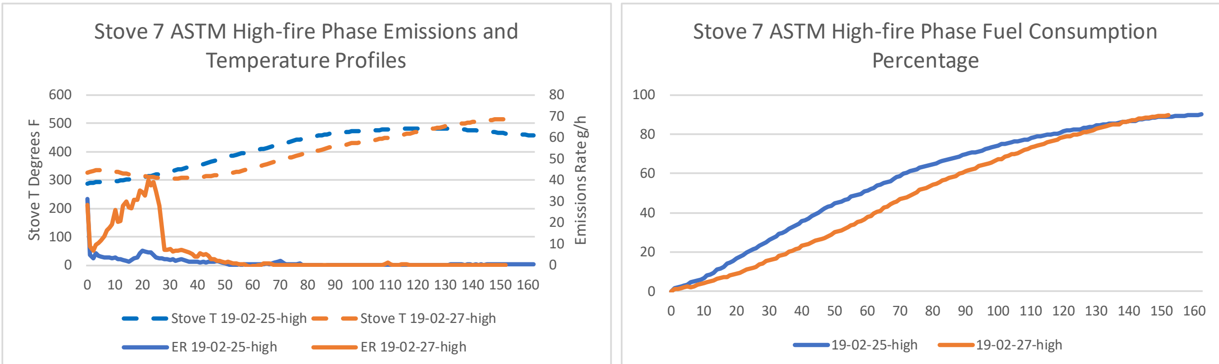
The metrics for the high-air setting of the two ASTM 3053-17 runs are shown in Table49.

Table 49. Stove 7—Comparison of ASTM 3053-17 High-Air Setting Test Metrics

Test ID #	S7-19-02-25-1	S7-19-02-27-1
Dry-Burn Rate (kg/h)	2.43	2.46
Time (min)	162	152
Total PM (g)	3.49	13.48
PM Emission Rate (g/h)	1.29	5.32
PM Emission Factor (g/kg)	0.53	2.16
HHV Efficiency (%)	62.5	61.4

In this phase, the two runs had similar dry-burn rates. However, the PM emission metrics in the second run were approximately four times those in the first. The efficiency was similar in the two runs. The emissions and temperature profiles and fuel consumption profiles for the high-air phases of the two stove 7 ASTM 3053-17 runs are shown in Figure 50.

Figure 50. Stove 7—ASTM 3053-17 High-Air Phase Emissions, Stove Temperatures, and Fuel Combustion



After an initial spurt, emissions in both runs immediately dropped to essentially zero. However, in the second run, the ER climbed again, peaking between minutes 19 and 25, before falling off to essentially zero by minute 53. Emissions in the first run also had a slight peak in the same timeframe (minutes 19 to 25), but the instantaneous ERs in the second run were five to six times higher than those in the first during that period. This difference may at least, in part, be explained by the stove temperature profiles and fuel consumption curves, which indicate a slower burn in the second run than in the first during that period. It is not clear what caused that difference; the fuel load in the first run (9.03 kg wet, 7.5 kg dry) was slightly larger than in the second (8.62 kg wet, 7.1 kg dry), but the dry moisture content in the second load (21.4%) was slightly higher than in the first (20.9%).

The metrics for the low-air phase of S7-19-02-25 and the medium-air phase of S7-19-02-27 are shown in Table 50.

Table 50. Stove 7— Comparison of ASTM 3053-17—Low- and Medium-Phase Test Metrics

Test ID #	S7-19-02-25-2-low	S7-19-02-27-2-med
Dry-Burn Rate (kg/h)	1.05	1.27
Time (min)	454	331
Total PM (g)	3.95	1.87
PM Emission Rate (g/h)	0.52	0.34
PM Emission Factor (g/kg)	0.50	0.27
HHV Efficiency (%)	69.2	57.1

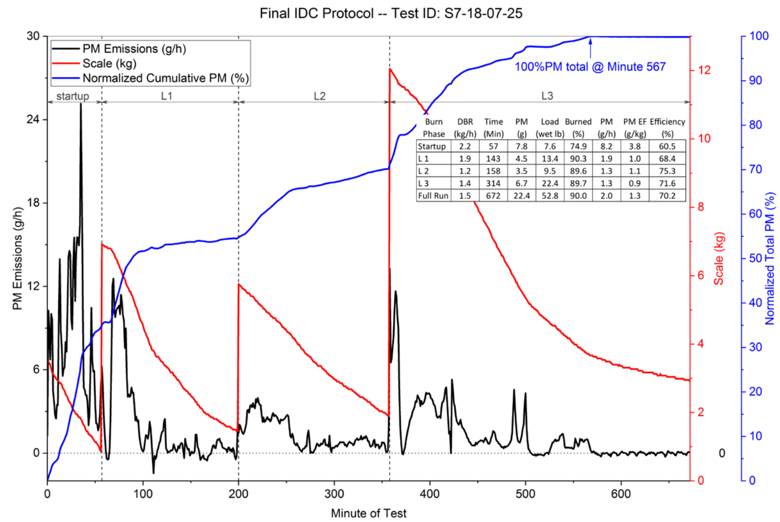
The PM emissions metrics were 1.5 to 2 times higher in the low burn than in the medium burn. However, emissions in both phases were very low (ER 0.34–0.52 g/h). HHV thermal efficiency in the low-burn phase was 69.2%, higher than that for the medium burn (57.1%).

2.6.3 IDC Tests

A total of four IDC final protocol tests, each consisting of three replicate runs, were run on stove 7. The tests used four different types of cordwood fuel: red maple, seasoned oak, wet oak, and poplar. The seasoned oak was the same wood as that used in the wet oak runs after the wood was allowed to dry. During the start-up phase of all tests, the moisture content of the fuel for all tests was approximately 17.5%. However, in subsequent loads, the average moisture content of the wet oak was 28.7% and the seasoned oak 21.2%, on a dry basis.

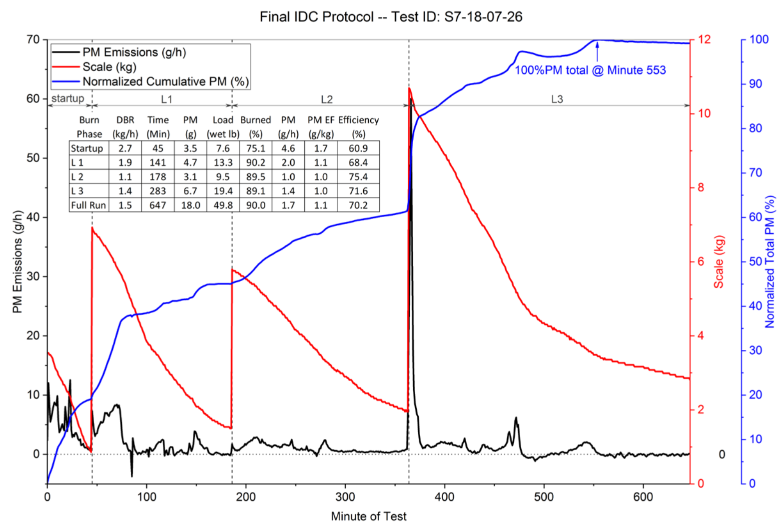
Profiles of the stove 7 red maple, seasoned oak, wet oak, and poplar IDC final protocol runs are shown in Figures 51 to 54.

Figure 51. Stove 7—IDC Final Protocol Replicate Runs with Red Maple Cordwood



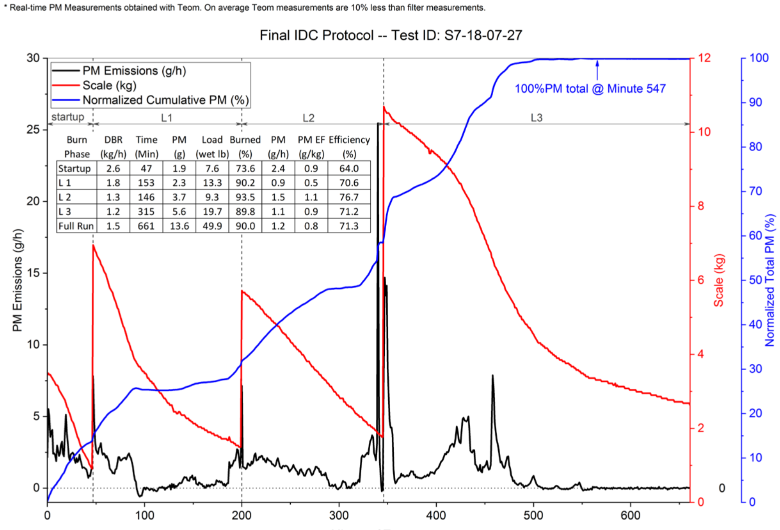
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.2	57	7.8	7.6	74.9	8.2	3.8	60.5
L 1	1.9	143	4.5	13.4	90.3	1.9	1.0	68.4
L 2	1.2	158	3.5	9.5	89.6	1.3	1.1	75.3
L 3	1.4	314	6.7	22.4	89.7	1.3	0.9	71.6
Full Run	1.5	672	22.4	52.8	90.0	2.0	1.3	70.2

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.7	45	3.5	7.6	75.1	4.6	1.7	60.9
L 1	1.9	141	4.7	13.3	90.2	2.0	1.1	68.4
L 2	1.1	178	3.1	9.5	89.5	1.0	1.0	75.4
L 3	1.4	283	6.7	19.4	89.1	1.4	1.0	71.6
Full Run	1.5	647	18.0	49.8	90.0	1.7	1.1	70.2

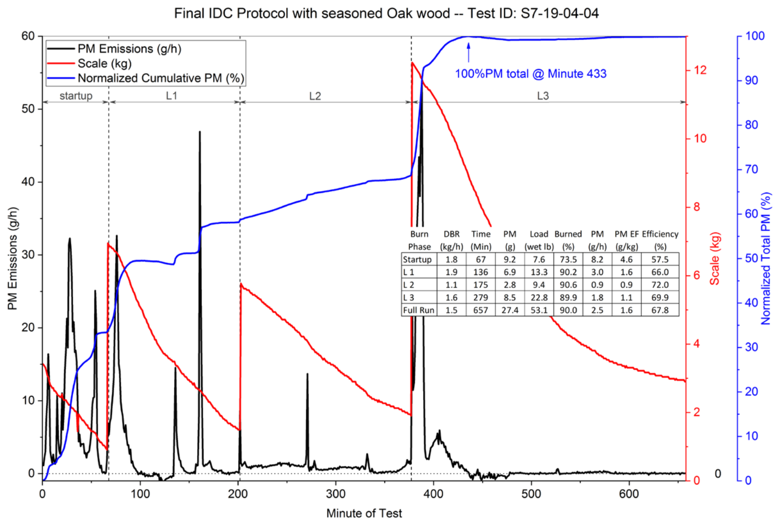
* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



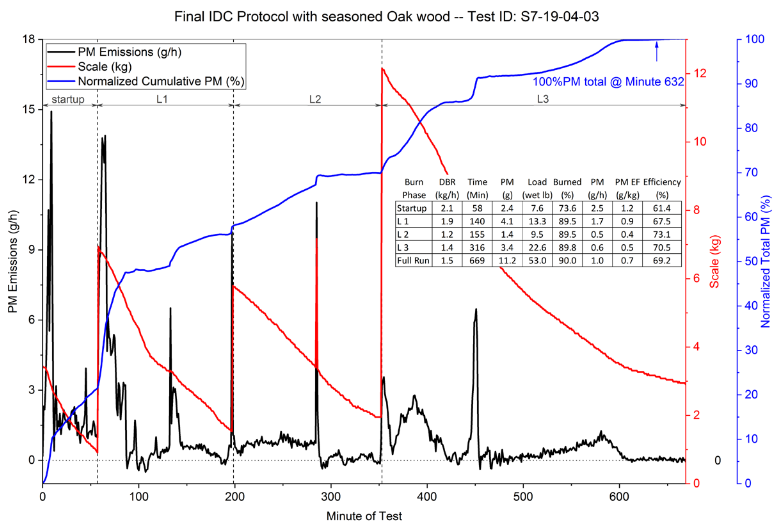
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.6	47	1.9	7.6	73.6	2.4	0.9	64.0
L 1	1.8	153	2.3	13.3	90.2	0.9	0.5	70.6
L 2	1.3	146	3.7	9.3	93.5	1.5	1.1	76.7
L 3	1.2	315	5.6	19.7	89.8	1.1	0.9	71.2
Full Run	1.5	661	13.6	49.9	90.0	1.2	0.8	71.3

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

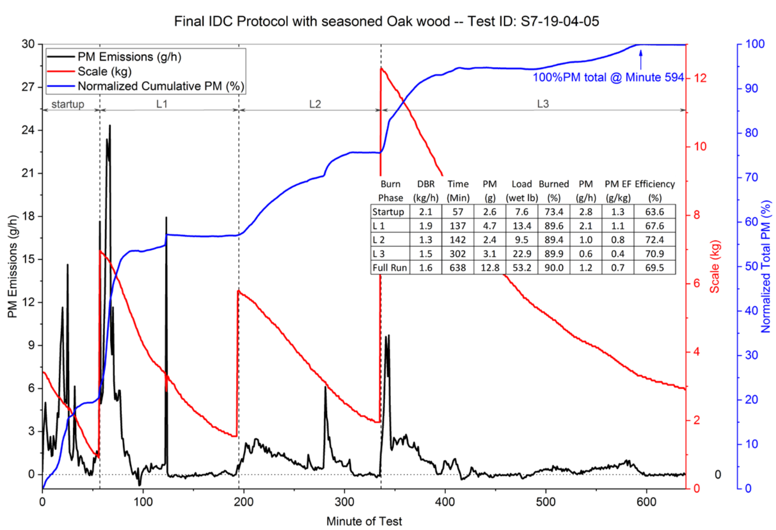
Figure 52. Stove 7—IDC Final Protocol Replicate Runs with Seasoned Oak Cordwood



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



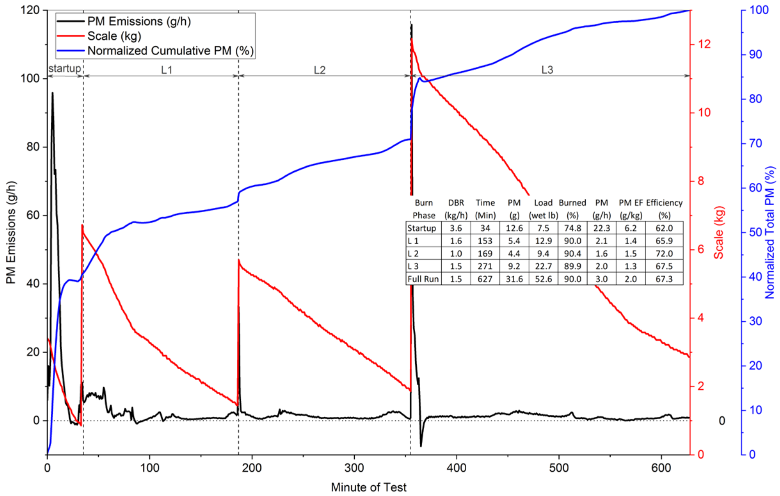
* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Figure 53. Stove 7—IDC Final Protocol Replicate Runs with Wet Oak Cordwood

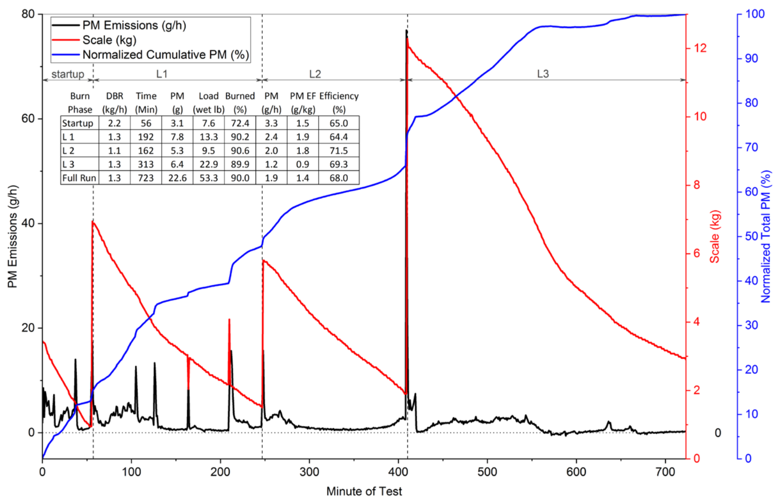
Final IDC Protocol with wet Oak wood -- Test ID: S7-19-02-20



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.6	34	12.6	7.5	74.8	22.3	6.2	62.0
L 1	1.6	153	5.4	12.9	90.0	2.1	1.4	65.9
L 2	1.0	169	4.4	9.4	90.4	1.6	1.5	72.0
L 3	1.5	271	9.2	22.7	89.9	2.0	1.3	67.5
Full Run	1.5	627	31.6	52.6	90.0	3.0	2.0	67.3

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

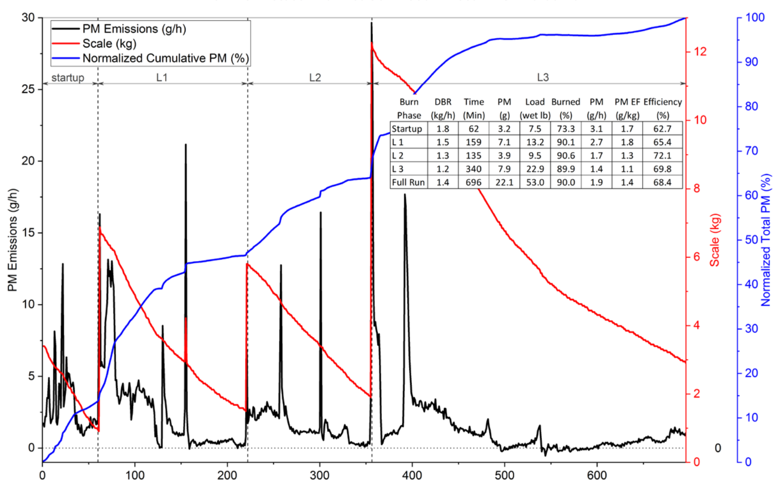
Final IDC Protocol with wet Oak wood -- Test ID: S7-19-03-25



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.2	56	3.1	7.6	72.4	3.3	1.5	65.0
L 1	1.3	192	7.8	13.3	90.2	2.4	1.9	64.4
L 2	1.1	162	5.3	9.5	90.6	2.0	1.8	71.5
L 3	1.3	313	6.4	22.9	89.9	1.2	0.9	69.3
Full Run	1.3	723	22.6	53.3	90.0	1.9	1.4	68.0

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

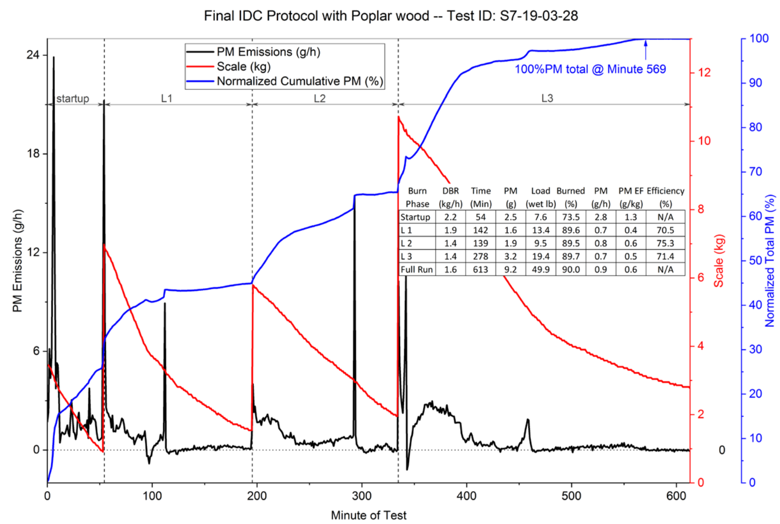
Final IDC Protocol with wet Oak wood -- Test ID: S7-19-03-26



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	1.8	62	3.2	7.5	73.3	3.1	1.7	62.7
L 1	1.5	159	7.1	13.2	90.1	2.7	1.8	65.4
L 2	1.3	135	3.9	9.5	90.6	1.7	1.3	72.1
L 3	1.2	340	7.9	22.9	89.9	1.4	1.1	69.8
Full Run	1.4	696	22.1	53.0	90.0	1.9	1.4	68.4

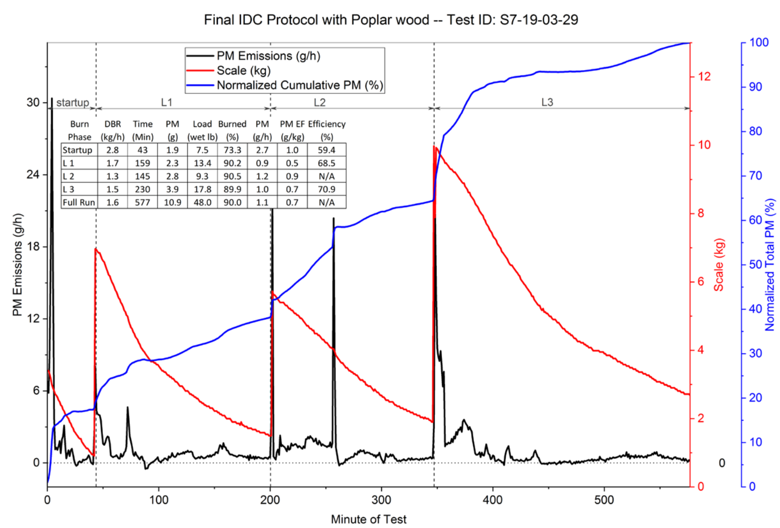
* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Figure 54. Stove 7—IDC Final Protocol Replicate Runs with Poplar Cordwood



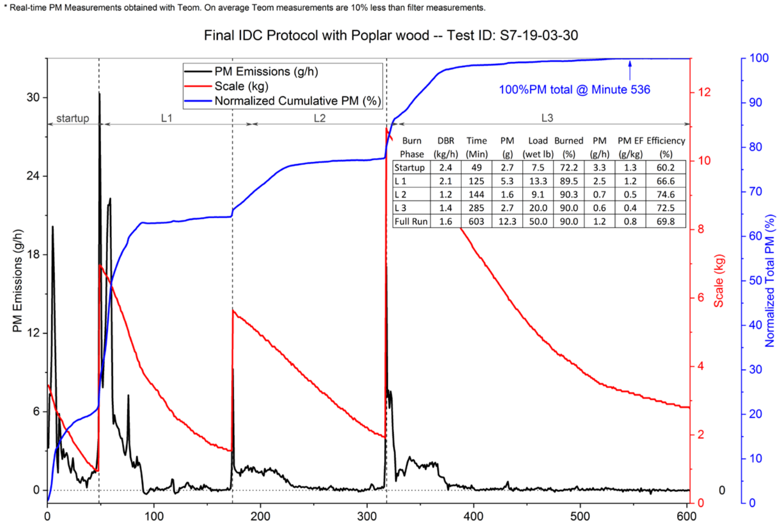
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.2	54	2.5	7.6	73.5	2.8	1.3	N/A
L 1	1.9	142	1.6	13.4	89.6	0.7	0.4	70.5
L 2	1.4	139	1.9	9.5	89.5	0.8	0.6	75.3
L 3	1.4	278	3.2	19.4	89.7	0.7	0.5	71.4
Full Run	1.6	613	9.2	49.9	90.0	0.9	0.6	N/A

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.8	43	1.9	7.5	73.3	2.7	1.0	59.4
L 1	1.7	159	2.3	13.4	90.2	0.9	0.5	68.5
L 2	1.3	145	2.8	9.3	90.5	1.2	0.9	N/A
L 3	1.5	230	3.9	17.8	89.9	1.0	0.7	70.9
Full Run	1.6	577	10.9	48.0	90.0	1.1	0.7	N/A

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.4	49	2.7	7.5	72.2	3.3	1.3	60.2
L 1	2.1	125	5.3	13.3	89.5	2.5	1.2	66.6
L 2	1.2	144	1.6	9.1	90.3	0.7	0.5	74.6
L 3	1.4	285	2.7	20.0	90.0	0.6	0.4	72.5
Full Run	1.6	603	12.3	50.0	90.0	1.2	0.8	69.8

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

The metrics for the start-up phase for the four sets of three replicate stove 7 IDC runs are shown in Table 51.

Table 51. Stove 7—Comparison of Test Metrics from Start-Up Phase of IDC Final Protocol Runs

Cordwood burned in subsequent phases	Average MC (%)	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	17.5	S7-18-07-25	2.163	57	7.75	8.16	3.77
		S7-18-07-26	2.70	45	3.47	4.62	1.71
		S7-18-07-27	2.58	47	2.01	2.57	1.00
Seasoned Oak		S7-19-04-03	2.09	58	2.41	2.49	1.19
		S7-19-04-04	1.80	67	9.18	8.22	4.56
		S7-19-04-05	2.11	57	2.63	2.76	1.31
Wet Oak		S7-19-02-20	3.60	34	12.62	22.28	6.18
		S7-19-03-25	2.17	56	3.12	3.34	1.54
		S7-19-03-26	1.79	62	3.17	3.07	1.71
Poplar		S7-19-03-28	2.23	54	2.52	2.80	1.25
		S7-19-03-29	2.79	43	1.94	2.71	0.97
		S7-19-03-30	2.45	49	2.69	3.30	1.35

Because the same start-up fuel was burned in all runs, all runs were essentially replicates in this phase. The start-up phase of the first run in the test that burned wet oak in subsequent phases produced four times more PM than in the other runs of that group. The wet oak runs, however, were not performed on sequential days and there was more than a month between the first and second runs in that group. That run had a higher start-up dry-burn rate and lower start-up phase time than any of the other 11 runs, which contributed to a start-up ER that was three to nine times higher than in the other runs.

The metrics for the high-fire phase (reload 1) for the four sets of three replicate stove 7 IDC runs are shown in Table 52.

Table 52. Stove 7—Comparison of Test Metrics from Reload 1—High-Fire Phase, IDC Final Protocol

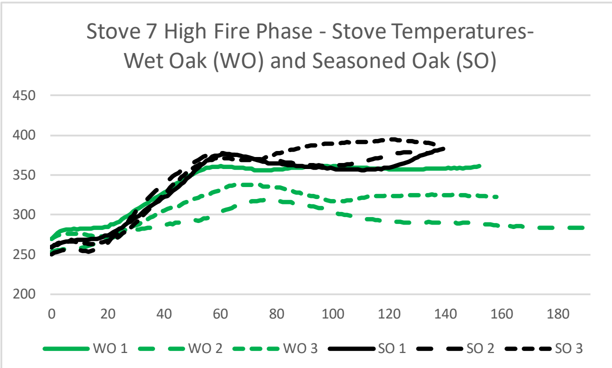
Cordwood	MC (%) Dry Basis	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	20.4	S7-18-07-25	1.87	143	4.50	1.89	1.01
	19.9	S7-18-07-26	1.89	141	4.69	1.99	1.06
	19.0	S7-18-07-27	1.76	153	2.31	0.91	0.52
Seasoned Oak	20.8	S7-19-04-03	1.89	140	4.08	1.75	0.93
	21.3	S7-19-04-04	1.94	136	6.91	3.05	1.57
	20.4	S7-19-04-05	1.95	137	4.69	2.05	1.05
Wet Oak	28.8	S7-19-02-20	1.55	153	5.38	2.11	1.36
	29.5	S7-19-03-25	1.27	192	7.80	2.44	1.92
	28.9	S7-19-03-26	1.53	159	7.13	2.69	1.76
Poplar	19.9	S7-19-03-28	1.89	142	1.62	0.68	0.36
	20.4	S7-19-03-29	1.68	159	2.30	0.87	0.52
	21.7	S7-19-03-30	2.10	125	5.26	2.52	1.20

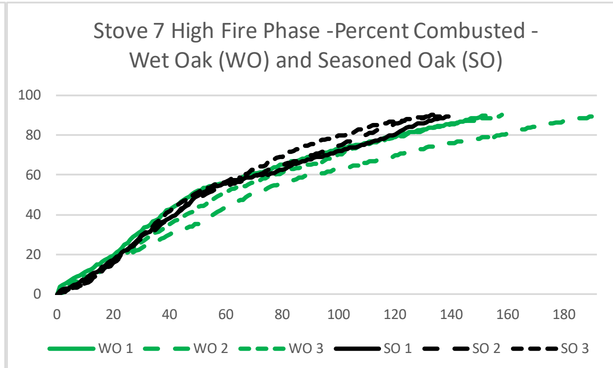
The test times in the high-fire phase were highest and the dry-burn rates lowest for the runs that burned wet oak. The high-fire phases of the wet oak runs were, on average, 30 minutes longer than in the seasoned oak runs. Run times and burn rates were similar for the other fuels. The average EF for the wet oak runs, 1.7 g/kg, was 42% higher than in the seasoned oak runs, 1.2 g/kg. However, due to the longer run times, the average high-fire phase ER for wet oak, 2.4 g/h, was similar to that measured for seasoned oak, 2.3 g/h. One of the seasoned oak runs produced an ER of 3.05 g/h, which was higher than the ERs for any of the wet oak runs or the runs that burned maple or poplar.

The EF and ER in the wet oak runs had a lower intragroup variability than the other fuel groups. The average EFs in the poplar, red maple, and seasoned oak groups were 0.7, 0.9, and 1.2 g/kg, but there was considerable intergroup overlap in the EFs of individual runs for those fuels. The same pattern was seen in the ERs. The average ERs for poplar and red maple, 1.4 g/h and 1.6 g/h, respectively, were lower than for seasoned oak, 2.3 g/h, but the ranges of the ERs in the groups overlapped.

Figure 55 compares the temperature profiles and fuel consumption in the high-fire phase of the seasoned oak and wet oak runs. Wet oak is shown in green and seasoned oak in black.

Figure 55. Stove 7—IDC High-Fire Phase—Seasoned and Wet Oak—Stove Temperatures and Fuel Consumption





The stove temperature and fuel combustion percentages in the high-fire phase first wet oak run (WO 1) were similar to those in the seasoned oak group, which may explain the fact that the high-fire PM emissions metrics for that wet oak run were similar to those in the seasoned oak group. The second and third wet oak runs (WO 2 and WO 3), which emitted more PM than the first, had lower temperatures than in the seasoned oak runs and WO 1 after the first 30 minutes of the run.

In the reload 2 burn, the maintenance phase, air controls are kept at the lowest setting and two large pieces of wood are loaded into the stove. At this point, the coal bed is well developed. The metrics measured in the phase in Stove 7 IDC runs are shown in Table 53.

Table 53. Stove 7—Comparison of Test Metrics Reload 2—Maintenance Phase, IDC Final Protocol

Cordwood	MC (%) Dry Basis	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	21.6	S7-18-07-25	1.17	158	3.51	1.33	1.13
	21.4	S7-18-07-26	1.06	178	3.08	1.04	0.98
	19.9	S7-18-07-27	1.34	146	3.75	1.54	1.15
Seasoned Oak	21.9	S7-19-04-03	1.21	155	1.37	0.53	0.44
	22.3	S7-19-04-04	1.06	175	2.75	0.94	0.89
	21.3	S7-19-04-05	1.32	142	2.38	1.01	0.76
Wet Oak	29.6	S7-19-02-20	1.02	169	4.44	1.57	1.55
	28.1	S7-19-03-25	1.09	162	5.27	1.95	1.78
	28.0	S7-19-03-26	1.32	135	3.90	1.73	1.32
Poplar	19.8	S7-19-03-28	1.37	139	1.87	0.81	0.59
	20.2	S7-19-03-29	1.29	145	2.81	1.16	0.90
	21.7	S7-19-03-30	1.25	144	1.63	0.68	0.54

Dry-burn rates were similar in all runs for all fuel types in the maintenance phase (1.1–1.4 g/h). Burn times were also similar; average burn times for this phase were 161 minutes for the red maple runs, 157 minutes for seasoned oak, 155 minutes for wet oak, and 143 minutes for poplar. All parameters were quite consistent within groups for all fuel types. The EFs and ERs for the wet oak burns were, on average, approximately twice those for the seasoned oak runs, but still low in comparison to those measured in other stoves. The average EFs for the poplar and seasoned oak runs were both 0.7 g/kg, slightly lower than the average in the red maple runs, 1.1 g/kg. The average ER for seasoned oak and poplar were also essentially equivalent, 0.83 g/h and 0.88 g/h, as compared to the average red maple value, 1.30 g/h. The EF and ER for wet oak were 1.6 g/kg and 1.75 g/h, respectively.

The metrics measured in the reload 3 overnight phase of the stove 7 IDC runs are shown in Table 54.

Table 54. Stove 7—Comparison of Test Metrics from Reload 3—Overnight Burn Phase, IDC Final Protocol

Cordwood	MC (%) Dry Basis	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	20.5	S7-18-07-25	1.42	314	6.40	1.22	0.86
	19.9	S7-18-07-26	1.37	283	6.32	1.34	0.98
	21.2	S7-18-07-27	1.23	315	5.49	1.04	0.85
Seasoned Oak	20.6	S7-19-04-03	1.42	316	3.38	0.64	0.45
	22.0	S7-19-04-04	1.60	279	8.54	1.84	1.15
	21.1	S7-19-04-05	1.49	302	3.12	0.62	0.41
Wet Oak	28.7	S7-19-02-20	1.54	271	9.16	2.03	1.31
	28.8	S7-19-03-25	1.34	313	6.43	1.23	0.92
	27.9	S7-19-03-26	1.25	340	7.90	1.39	1.12
Poplar	20.9	S7-19-03-28	1.38	278	3.17	0.68	0.49
	20.5	S7-19-03-29	1.55	230	3.89	1.02	0.66
	21.9	S7-19-03-30	1.37	285	2.72	0.57	0.42

The overnight phases of the stove 7 maple IDC runs lasted 283 to 315 minutes (4.7 to 5.3 hours). The time range for this phase was similar to the maple runs in the seasoned oak (4.7 to 5.3 hours) and wet oak runs (4.5 to 5.7 hours) and somewhat lower in the poplar runs (3.8 to 4.8 hours). The dry-burn rate was similar in all of the runs (1.2 to 1.6 kg/h).

On average, the overnight EF and ER for the wet oak runs were 67% and 50% higher than those for the seasoned oak runs, respectively, but the ranges of those metrics in the two groups overlapped. In this phase, the average EFs for the poplar and seasoned oak runs were 37% and 14% lower than for the red maple average, respectively. The average poplar and seasoned oak ERs were 42% and 25% lower than those for red maple. The average red maple, seasoned oak, wet oak, and poplar ERs for this phase were 1.2, 1.0, 1.6, and 0.8 g/h, respectively.

Table 55 shows the test metrics for the entire run of each of the IDC replicates.

Table 55. Stove 7—Comparison of Test Metrics for Entire Run of IDC Final Protocol Runs

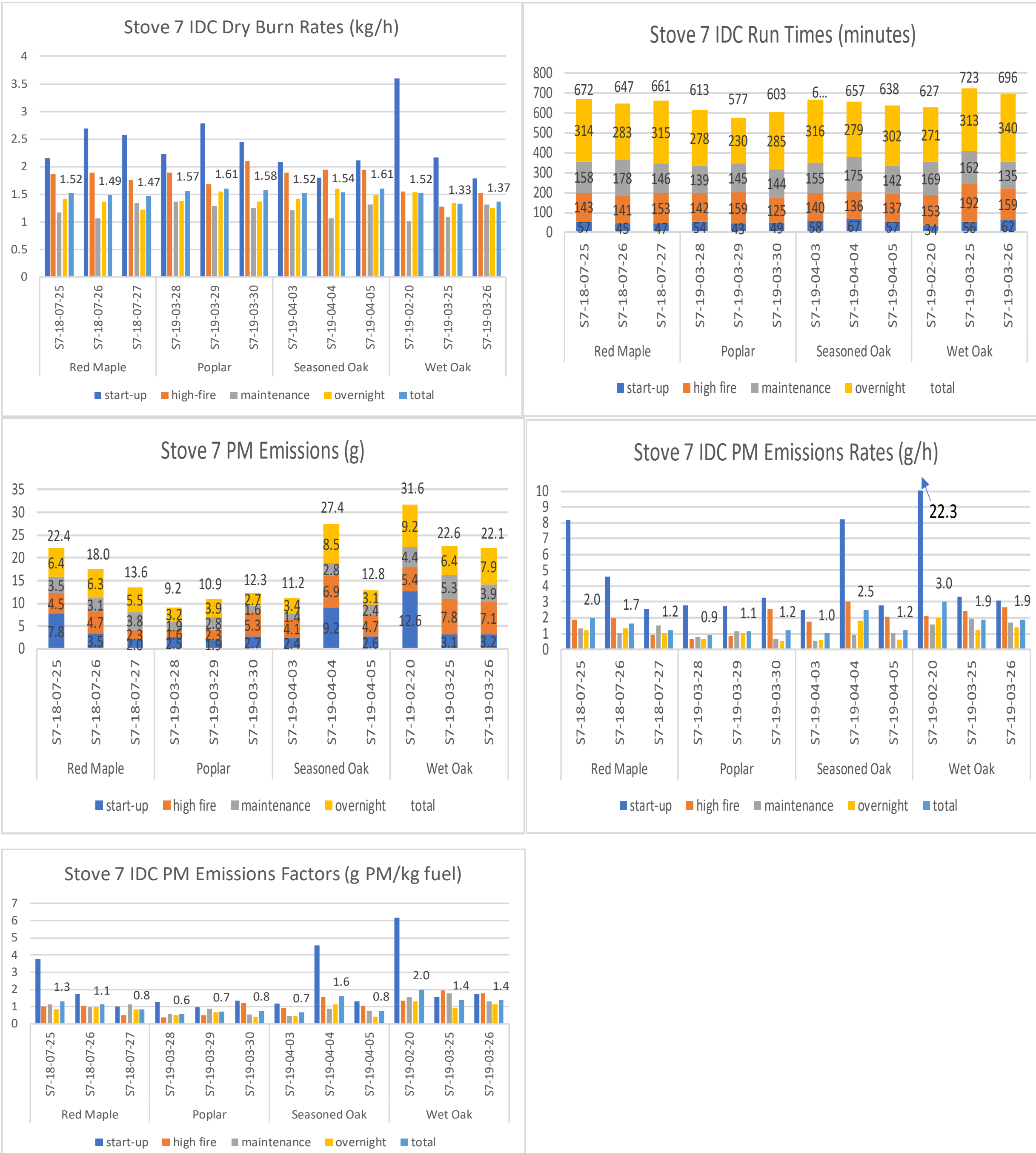
Cordwood	MC (%) Dry Basis	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	Efficiency (%)
Red Maple	20.7	S7-18-07-25	1.52	672	22.43	2.00	1.32	70.2
	20.2	S7-18-07-26	1.49	647	17.95	1.66	1.12	70.2
	20.2	S7-18-07-27	1.47	661	13.56	1.23	0.84	71.3
Seasoned Oak	20.9	S7-19-04-03	1.52	669	11.24	1.01	0.66	69.2
	21.8	S7-19-04-04	1.54	657	27.37	2.50	1.62	67.8
	20.9	S7-19-04-05	1.61	638	12.81	1.20	0.75	69.5
Wet Oak	28.9	S7-19-02-20	1.52	627	31.59	3.02	1.99	67.3
	28.9	S7-19-03-25	1.33	723	22.62	1.88	1.41	68.0
	28.2	S7-19-03-26	1.37	696	22.10	1.91	1.39	68.4
Poplar	20.3	S7-19-03-28	1.57	613	9.17	0.90	0.57	CBD
	20.4	S7-19-03-29	1.61	577	10.94	1.14	0.71	CBD
	21.8	S7-19-03-30	1.58	603	12.30	1.22	0.77	69.8

The total time to complete the stove 7 IDC red maple runs ranged from 647 to 672 minutes (10.8 to 11.2 hours), a longer period than for the other stoves and slightly longer than the 10-hour target period for completion in a single day. Test times were similar for the seasoned oak runs (10.6 to 11.2 hours) and wet oak (10.4 to 12.1 hours) and slightly lower for the poplar runs (9.6 to 10.2 hours). The HHV thermal efficiencies were between 67.3% and 71.3% for the 10 runs for which sufficient CO and CO_2 data were available for calculating that value. The wet oak efficiencies were at the lower end of that range (67.3–68.4%) and the red maple runs at the upper end (70.2–71.3%).

As with stove 6, there was more variation in the stove 7 IDC PM metrics in the seasoned oak runs than in the other fuel groups. The EF and ER in the highest emitting seasoned oak runs were both 2.5 times higher than in the lowest emitting run in that group. In the maple replicates, the highest EF and ER were 57% and 63% higher than in the lowest emitting run and a similar variability was seen in the wet oak runs; in those runs the highest EF and ER were 43% and 61% higher than the lowest. The poplar runs had the least variability; the highest EF and ER in the runs burning that species were 35% and 36% higher than the lowest. The average ERs for the entire run were 1.5 g/h for the red maple and the seasoned oak runs, 2.3 g/h for the wet oak runs, and 1.1 g/h for the poplar runs.

Figure 56 shows the test metrics by test phase for each of the IDC runs graphically.

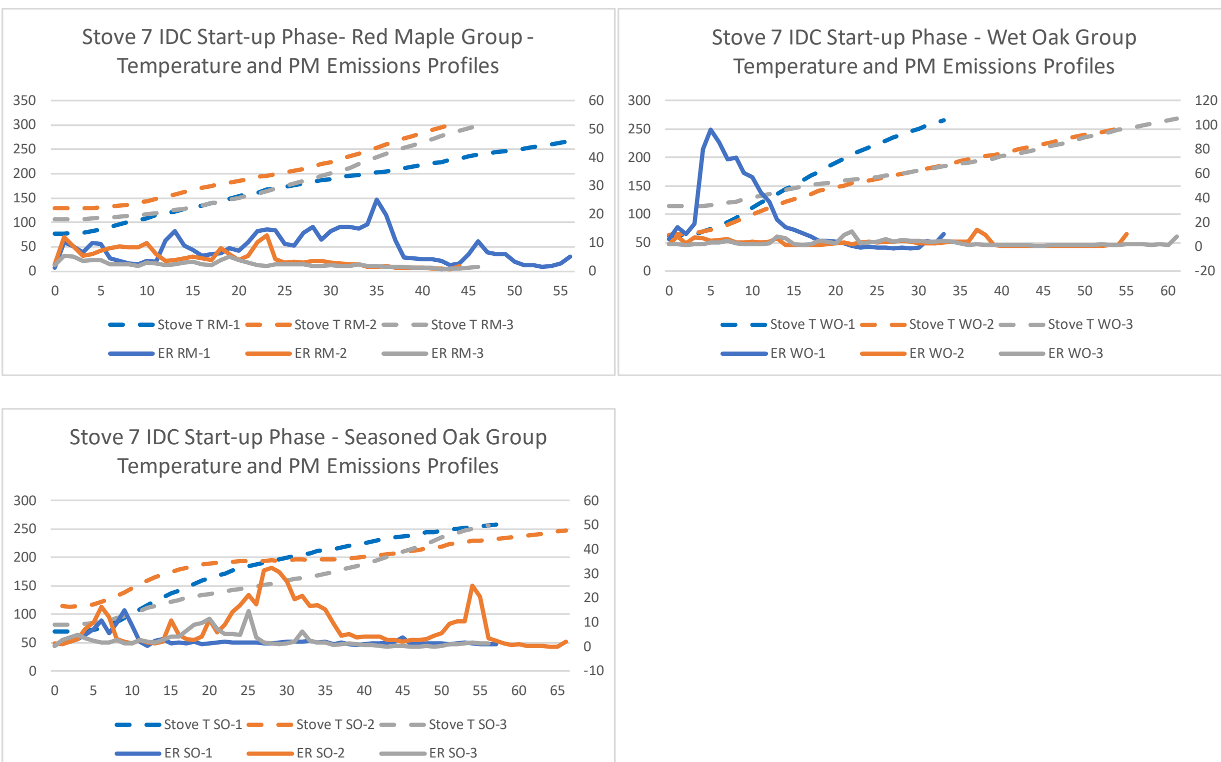
Figure 56. Stove 7—Comparison of Metrics for IDC Replicate Runs



Of particular note is the impact of PM emissions during the start-up phase on the emissions parameters for the entire run. The start-up ER and EF were at the lower end of the range seen in the other stoves. However, because stove 7 emissions in the other phases were considerably lower than those for the other stoves, start-up emissions constituted a greater percentage of total emissions for that stove than for most of the other stoves, and variability in start-up emissions for stove 7 had a greater effect on variability of total PM emissions.

As shown in Figure 56, 3 of the 12 Stove 7 IDC runs (one each in the red maple, seasoned oak, and wet oak group) had substantially greater start-up phase PM emissions than the other runs. The same start-up procedures, including start-up fuel, were used in all runs. Figure 57 shows the emissions rate and temperature profiles for the start-up phase of those three replicate groups.

Figure 57. Stove 7—Start-Up Emission and Temperature Profiles

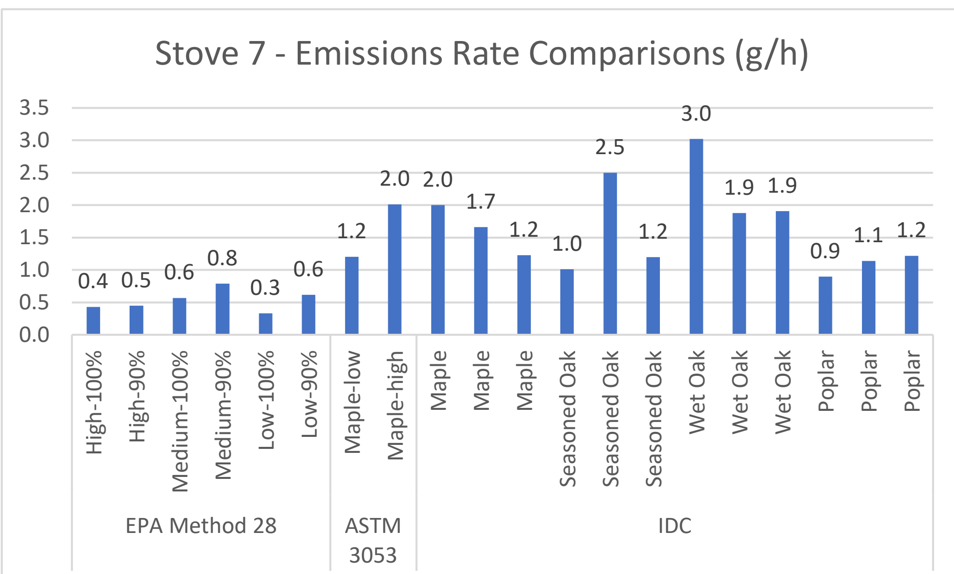


Stove temperature at the beginning of start-up did not appear to affect the ER early in that phase. However, the stove temperature for the first red maple and the second seasoned oak run leveled out midway through start-up, and emissions in those runs were substantially higher after that point for both of the runs relative to their replicates. This pattern was not seen in the wet oak group, which had substantial PM emissions early on in the run which did not correspond to stove temperature.

2.6.4 Comparison of Stove 7 Emission Rate Measurements

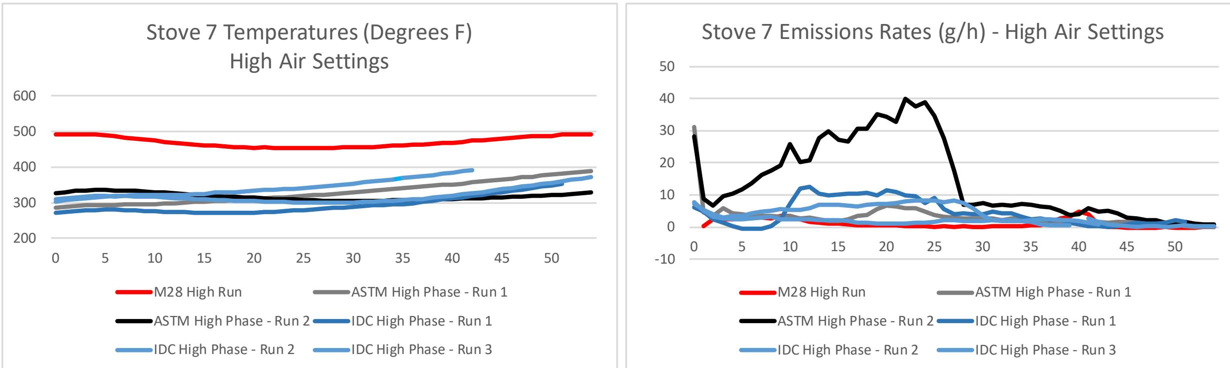
Figure 58 compares the stove 7 emission rates measured for the M28, ASTM 3053-17, and the IDC final protocol runs. ASTM 3053-17 and M28 should not be compared to the regulatory values, which are calculated using weighting factors.

Figure 58. Stove 7—Comparison of Method 28, ASTM 3053-17, and IDC Final Protocol Emissions Rate Measurements (g/h)



As shown in that figure, for stove 7, the ERs measured using the IDC final protocol were higher than those measured using M28 procedures. The maple fueled IDC runs produced ERs similar to the ASTM 3053-17 runs, which burned the same fuel. Figure 59 compares stove temperatures in the stove 7 tests when the air control was at its highest setting—he high-burn run M28 run, the high-fire phase of the ASTM 3053-17 runs, and the first half of load combustion in the high-fire phase of the IDM final protocol runs, before the air control was moved to a low setting. In both of the graphs in that figure, the M28 run is shown in red, the high-fire phase of the two ASTM 3053-17 runs in shades of gray, and the high-fire phase of the IDC runs in shades of blue.

Figure 59. Stove 7—Comparison of Temperature Profiles and Emission Rates in Burns at High-Air Setting



As shown in that figure, the temperature in the M28 high-fire run started out 180ºF higher than the highest temperature at the beginning of the high-fire phases of the IDC runs and remained at least 100ºF higher than in all IDC runs during the first 30 minutes of the run when most emissions occurred. This may at least partially explain the lower emissions rates for that portion of the M28 run, as shown in the second graph in that figure.

The temperature of the high-fire phase of the first ASTM 3053-17 run started out slightly higher than in the high-fire phase of the IDC runs. However, the temperature in that ASTM 3053-17 run decreased by about 20ºF between 4 and 29 minutes of that run. During that period, the emissions measured in that run were substantially higher than in the other ASTM 3053-17 runs and in the IDC runs.

Section 4 presents a more detailed analysis of the differences between the results for different test methods, including a comparison of the operating parameters measured in the high-fire phases of runs using different methods and a similar comparison of low-fire phase parameters.

2.7 Stove 8

Stove 8 is a single burn-rate stove with a medium-sized firebox using steel construction with non-catalytic emissions controls. This stove is different from the others in the study in that its heat setting cannot be adjusted. A total of six tests were performed on stove 8, as listed in Table 56. All burns were performed at the fixed-air setting.

Table 56. Stove 8—Test Descriptions

Test ID	Test Method	Fuel Species	Fuel Type	Description
S8-19-03-04	M28 (baseline)	Douglas Fir	Crib	Fixed fire load burned 100%
S8-19-03-09-1	ASTM 3053-17	Red Maple	Cord	Start-up (8.6 lb)[b] + fixed air (17.5 lb)
S8-19-03-09-2	ASTM 3053-17	Red Maple	Cord	Fixed air (17.0 lb)
S8-19-03-06 (Replicate 1)	IDC Final Protocol	Red Maple	Cord	Cold start bottom-up RL1 (High-fire phase) -7# fixed air RL2 (Maintenance phase) - 5# fixed air RL3 (Overnight phase) - 12# fixed air
S8-19-03-07 (Replicate 2)	IDC Final Protocol	Red Maple	Cord	Same as Replicate 1
S8-19-03-08 (Replicate 3)	IDC Final Protocol	Red Maple	Cord	Same as Replicate 1

[a] Symbol # denotes fuel loading density in pounds per cubic foot of the stove firebox (lb/ft^3).

[b] In ASTM 3053-17 testing, fuel loads are defined as the weight of the wet wood.

PM emissions were measured using the 1405 TEOM in all stove 8 test runs. The results of these stove 8 tests are presented below.

As with the other stoves, the baseline test was conducted using EPA Method 28 (M28) procedures. However, because the stove 8 air flow cannot be adjusted, only one M28 test run was performed on this stove. As stipulated in the M28 protocol, all baseline test runs burned dimensional Douglas fir as a test fuel. The results of the baseline test are presented in Table 57.

Table 57. Stove 8—Modified M28 Test Run Metrics

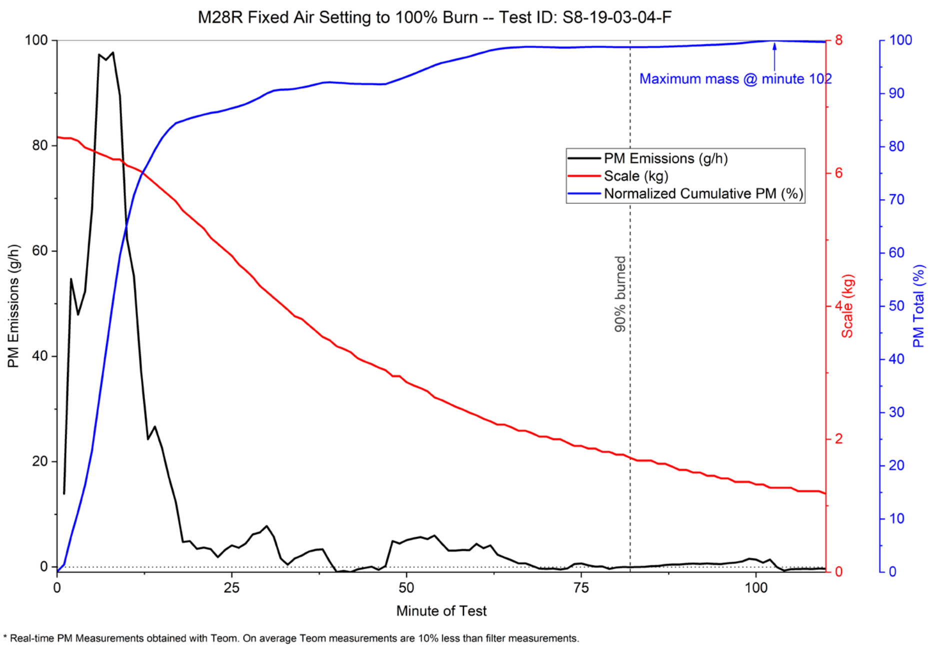
	Test Time (min)		**Dry-Burn Rate (kg/h)**		**Total PM (g)**		**PM Emission Rate (g/h)**		**PM Emission Factor (g/kg)**		**HHV Efficiency (%)**
% Burn	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*100%*
Fixed	82	110	2.94	2.44	17.08	17.25	12.50	9.41	4.25	3.86	47.9

The burn rate achieved on the fixed air setting is in EPA's category 4, the maximum burn-rate category. The HHV thermal efficiency of stove 8 measured in the baseline test, 47.9%, was higher than in stove 2, comparable to those of stoves 1 and 6, and lower than the HHVs measured in stoves 4, 5, and 7 M28 tests. A discussion of stove 8 baseline PM emissions follows.

2.7.1 PM Emission Profiles

The real-time plot of the stove 8 M28 test run is presented in Figure 60 below. As in the plots for the previous stoves, the TEOM PM emission rate profiles are shown in black, cumulative PM in blue, and remaining fuel load in red.

Figure 60. Stove 8—M28 Baseline Test Results



The maximum instantaneous emissions in the stove 8 M28 run, 97.8 g/h, occurred at minute 8 of the run. were much lower than in the other stoves. After the initial peak, the PM ER decreased to a baseline level at minute 17 that continued for the remainder of the run. At the point, 84% of total PM emissions had occurred and 18% of the fuel load had been consumed.

2.7.1.1 Cumulative PM Emissions

The maximum cumulative PM in the stove 8 baseline run was measured at minutes 102–103 of the 110-minute run, when 98% of the load had been combusted. Minimal volatilization losses occurred in the last 7 minutes of the run, reducing the total PM measurement by 0.3%.

2.7.1.2 Ninety Percent versus 100% Fuel Combustion

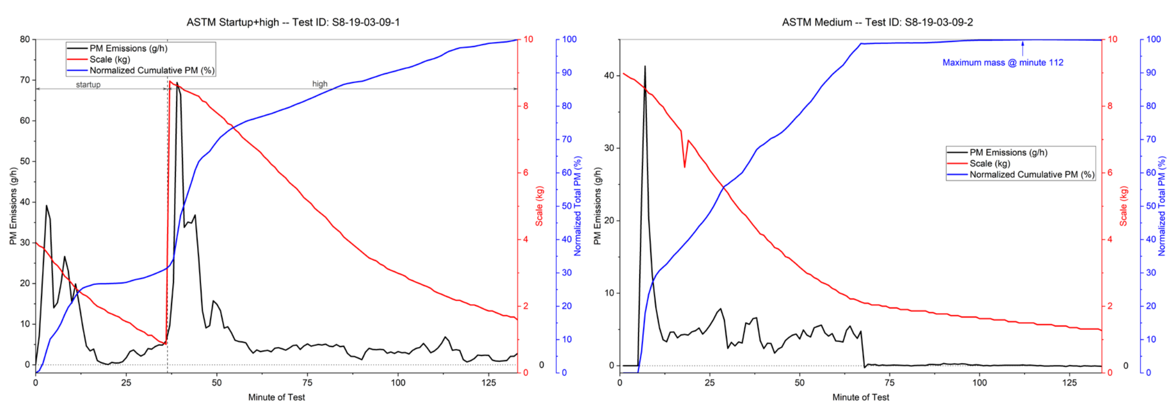
As discussed above, the ER for an entire M28 test run often underestimates the rate that would occur in the field because most emissions occur early in the burns and wood stove owners often refuel before the previous load has been completely consumed. For stove 8, 90% of total PM emissions were generated in the first 30 minutes (27%) of the M28 run.

To more accurately reflect actual in-use conditions, we calculated PM emission parameters for the period of 90% fuel consumption, as well as at the end of the run (100% fuel combustion). In the stove 8 baseline run, the time period between 90% and 100% fuel combustion was 28 minutes, 25% of the total run time. Total PM emissions increased by 1% during that period, while the EF (in g/kg) and ER (in g/h) decreased by 10% and 33%, respectively.

2.7.2 ASTM 3053-17 Tests

Due to stove 8's fixed-air setting, a single ASTM 3053-17 test run was conducted on that stove using maple cordwood. That run consisted of a start-up + fixed-air setting phase followed by a second-fixed air setting phase. The results of this tests are shown in Figure 61. As in previous ASTM 3053-17 tests, the start-up + fixed-burn phase is graphed separately from the second-fixed burn phase.

Figure 61. Stove 8—ASTM 3053-17 Runs



The metrics for each phase of the Stove 8 ASTM 3053-17 run are shown in Table 58.

Table 58. Stove 8—ASTM 3053-17 Run Metrics by Phase

Phase	Dry-fuel burned (kg)	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	HHV Efficiency (%)
Start-Up	2.59	4.20	37	5.40	8.76	2.08	62.3%
Fixed 1	5.77	3.61	96	11.87	7.42	2.06	55.2%
Fixed 2	6.37	2.85	134	5.96	2.67	0.94	55.5%
Entire Run	14.74	3.31	267	23.23	5.22	1.58	56.3%

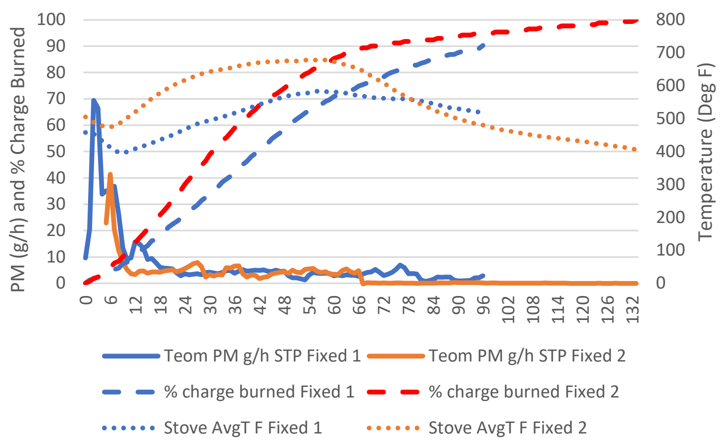
Although the air setting was the same and the fuel load size was similar (6.6 kg and 6.4 kg) in the two fixed phases, the PM ER and EF were considerably lower in the second fixed phase than the first. There are several factors that help explain this discrepancy.

First, the first fixed-air phase ended when 90% of the fuel load was combusted, while the second fixed phase was continued until 100% combustion of the whole load occurred. This is significant because the period between 90% and 100% combustion accounted for 48% of the time and only 1.2% of the total PM emissions in that phase. If that phase had ended at the point of 90% combustion (minute 70), the PM ER for that phase would be 5.06 g/h and the PM EF 1.03 g/kg.

However, that factor only explains a portion of the difference, because the total PM emissions in the first fixed phase were almost double those in the second. One factor influencing this difference is that the TEOM did not collect data in the first five minutes of the second run. As shown in Figure 62, a substantial portion (28%) of total PM emissions in the first fixed phase occurred in the first five minutes of that phase, so this data gap map be significant.

Figure 62 also compares stove temperatures and fuel combustion curves for the two phases. The stove temperature in the first fixed phase was initially 47ºF lower and remained substantially lower than in the second fixed phase throughout the burn. Fuel consumption rate was also lower in the first fixed phase than in the second during the first 30 minutes of the burns. These factors indicate a delay in the fuel light-off in the first fixed phase which may have contributed to higher emissions in that burn.

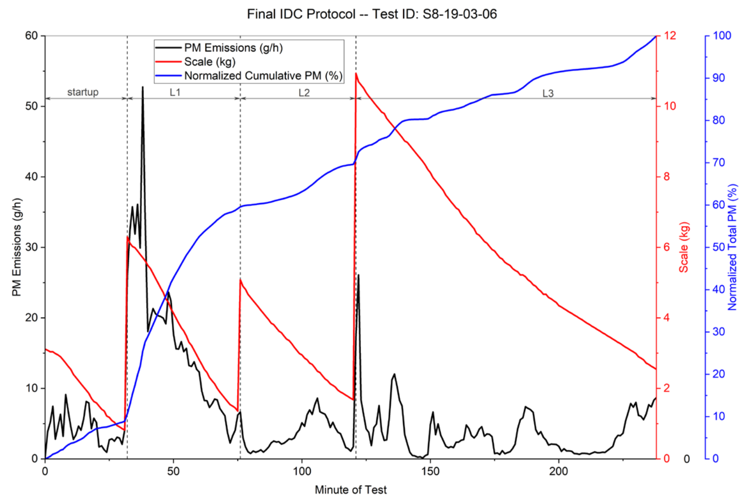
Figure 62. Stove 8—ASTM 3053-17 Emissions, Stove Temperatures, and Fuel Combustion



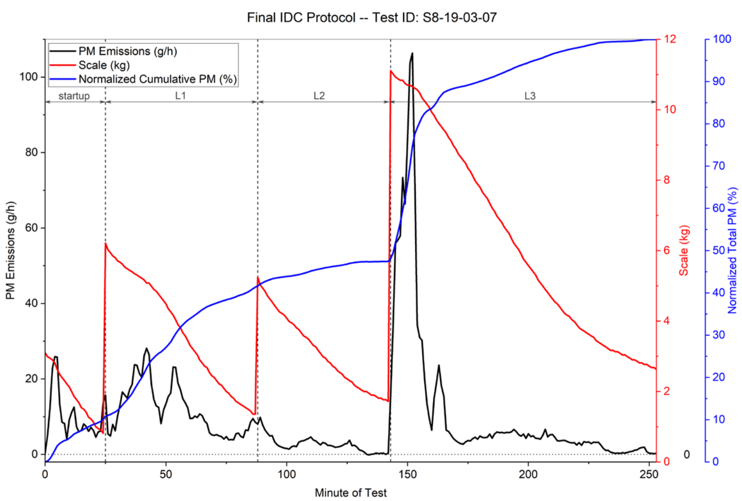
2.7.3 IDC Test

One IDC final protocol test consisting of three replicate runs was performed on stove 8 with red maple fuel. Because stove 8 is a fixed setting stove, these runs in that stove did not include the adjustments in air settings specified in the IDC method. The results of those runs are shown in Figure 63.

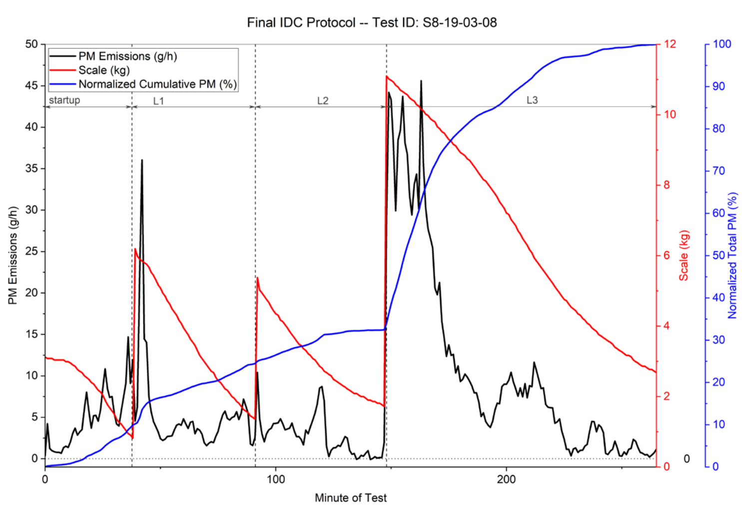
Figure 63. Stove 8—IDC Final Protocol Replicate Runs with Red Maple Cordwood



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

The metrics for all phases of three replicate stove 8 IDC runs are shown in Table 59.

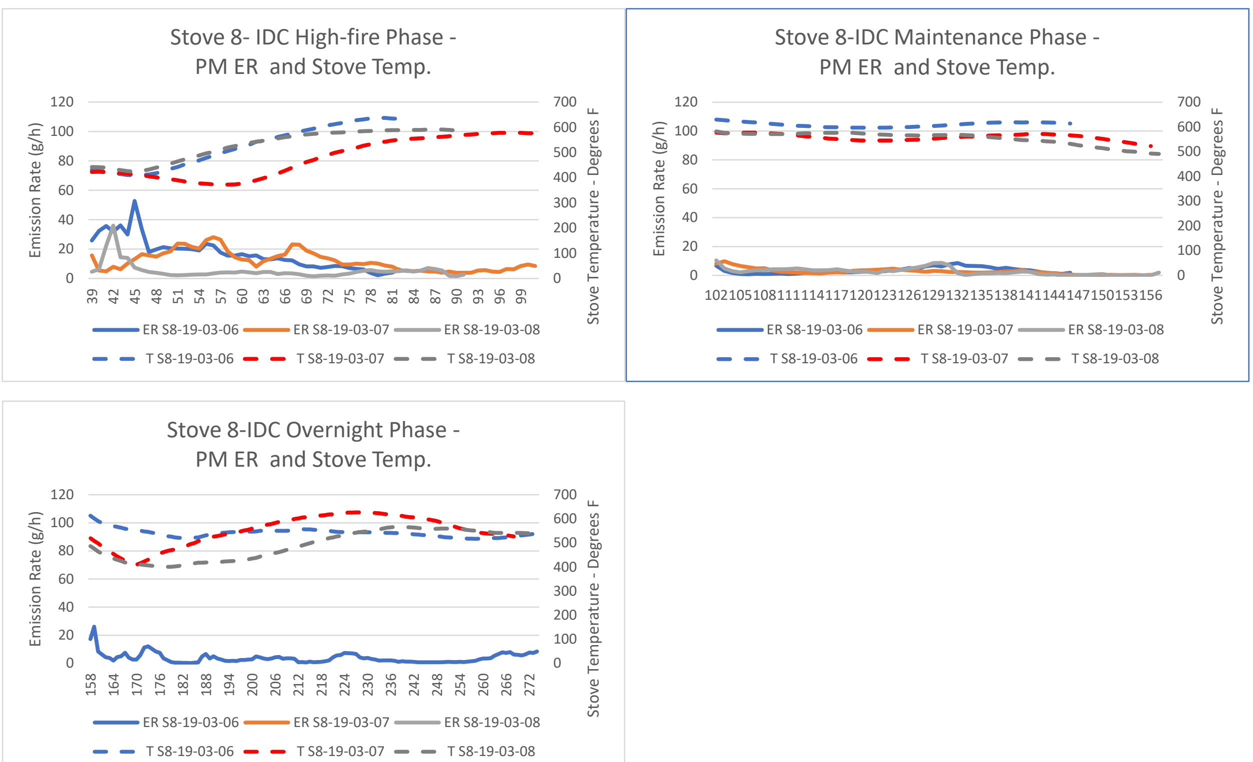
Table 59. Stove 8—Test Metrics for IDC Final Protocol Runs

Phase	Test ID #	Dry-Fuel Burned (kg)	Time (min)	Dry-Burn Rate (kg/h)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Start-Up	S8-19-03-06	1.83	32	3.43	2.20	4.13	1.20
	S8-19-03-07	1.82	25	4.37	4.07	9.77	2.24
	S8-19-03-08	1.84	39	2.83	3.18	4.90	1.73
	Mean	1.83	32.0	3.54	3.15	6.27	1.72
	Rel. Std. Dev.	0.5%	21.9%	21.9%	29.6%	48.8%	30.0%
High-fire	S8-19-03-06	4.01	44	5.47	12.39	16.89	3.09
	S8-19-03-07	3.94	63	3.75	12.52	11.93	3.18
	S8-19-03-08	3.88	53	4.39	4.65	5.27	1.20
	Mean	3.94	53.3	4.54	9.85	11.36	2.49
	Rel. Std. Dev.	1.7%	17.8%	19.1%	45.7%	51.3%	44.9%
Maintenance	S8-19-03-06	2.73	45	3.64	2.59	3.45	0.95
	S8-19-03-07	2.89	55	3.15	2.45	2.68	0.85
	S8-19-03-08	2.78	56	2.98	2.57	2.75	0.92
	Mean	2.80	52.0	3.26	2.54	2.96	0.91
	Rel. Std. Dev.	2.8%	11.7%	10.5%	2.9%	14.5%	5.7%
Overnight	S8-19-03-06	6.72	117	3.44	7.48	3.84	1.11
	S8-19-03-07	6.90	110	3.76	21.09	11.50	3.06
	S8-19-03-08	6.80	117	3.49	21.61	11.08	3.18
	Mean	6.81	114.7	3.57	16.73	8.81	2.45
	Rel. Std. Dev.	1.4%	3.5%	4.9%	47.9%	48.9%	47.3%
Entire Run	S8-19-03-06	15.29	238	3.85	24.66	6.22	1.61
	S8-19-03-07	15.55	253	3.69	40.13	9.52	2.58
	S8-19-03-08	15.30	265	3.47	32.01	7.25	2.09
	Mean	15.38	252.0	3.67	32.27	7.66	2.10
	Rel. Std. Dev.	0.9%	5.4%	5.3%	24.0%	22.0%	23.1%

The variability in the PM ER and EF in the entire run was low, with relative standard deviations of 22% and 23%, respectively. ERs and EFs were lowest and had the least inter-run variability in the maintenance phase. In the high-fire and overnight phases, the ER and EF for the highest emitting runs were approximately three times higher than those for the lowest emitting. However, while the first run, S8-19-03-06, had the highest emissions in the high-fire phase, that run had the lowest emissions in the overnight phase. Although this discussion uses the term "high fire" to describe the first reload after the start-up, the air setting was the same in all phases because this stove does not allow adjustment of that setting.

The PM ER and stove temperature profiles for the high-fire, maintenance, and overnight phases of the three stove 8 IDC runs are shown in Figure 64.

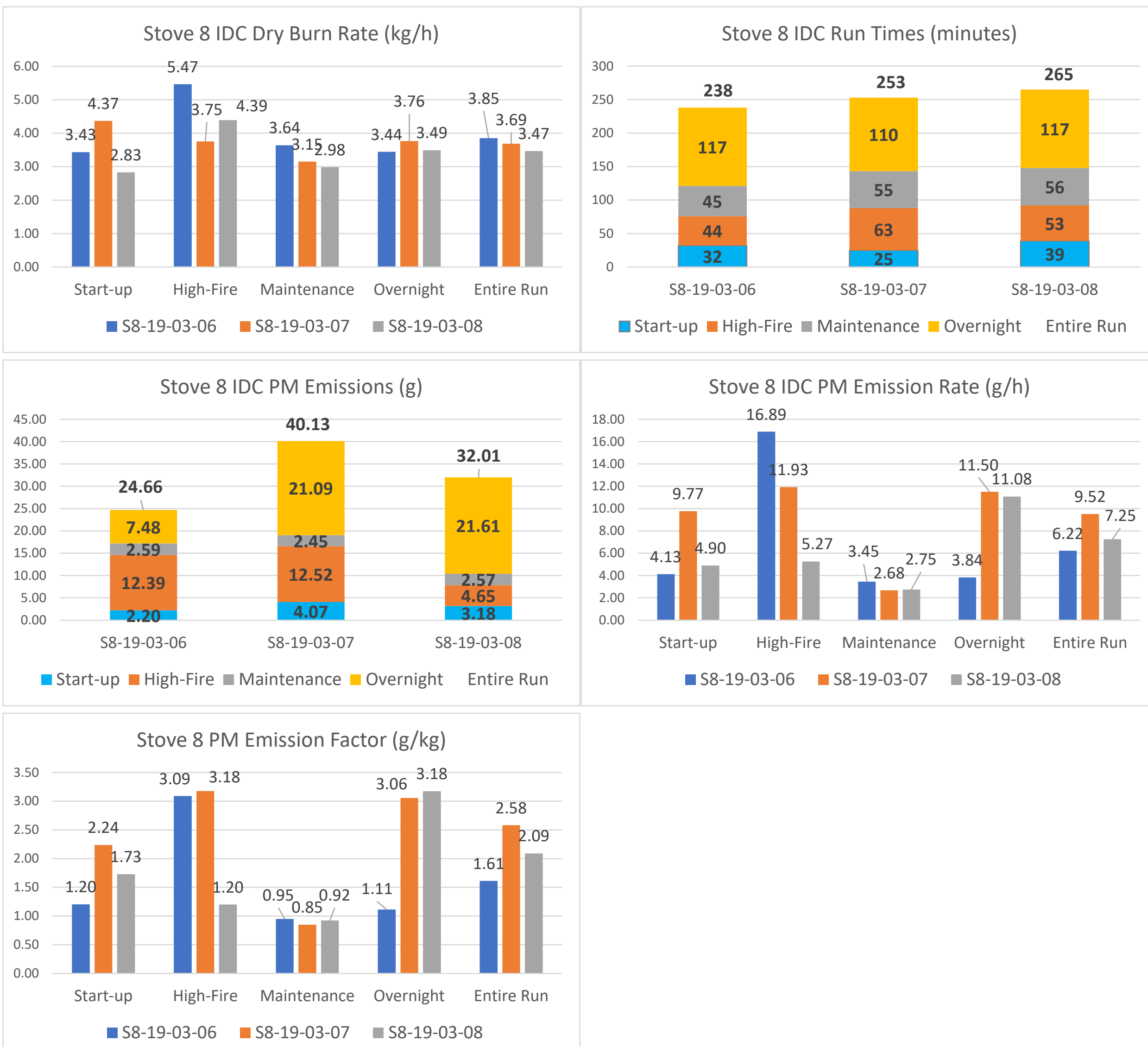
Figure 64. Stove 8—IDC Run Profiles—PM Emissions Rate (g/h) and Stove Temperature (°F)



The temperature profiles do not explain the inter-run differences in the emission patterns in the high-fire phase. Temperatures remained well above 500ºF throughout most of the maintenance phase in all runs, which may explain the low emissions in that phase. In the overnight phase, the initial temperature in run S8-19-03-06 was 94ºF to126ºF higher than in the other runs, which may explain the relatively low PM emissions in that run.

Figure 65 shows the test metrics by test phase for each of the IDC runs graphically.

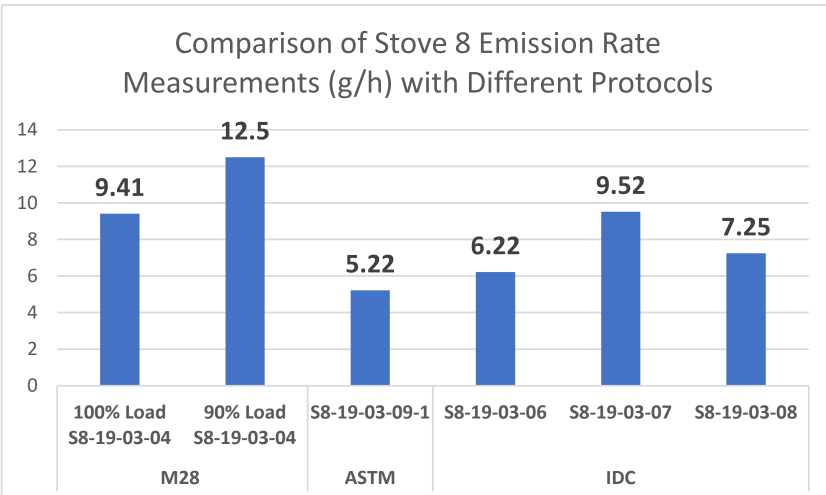
Figure 65. Stove 8—Comparison of Metrics for IDC Replicate Runs



2.7.4 Comparison of Stove 8 Emission Rate Measurements

Figure 66 compares the stove emission rates measured for the M28, ASTM 3053-17, and the IDC final protocol runs. The ASTM 3053-17 and M28 results are based on only one test run and do not constitute complete tests using those protocols.

Figure 66. Stove 8—Comparison of Method 28, ASTM 3053-17, and IDC Final Protocol Emissions Rate Measurements (g/h)



As shown in that figure, for stove 8, the ER measured with M28 was within the range of those measured using the IDC protocol and the ASTM 3053-17 result was below that range.

3 Comparative Analysis

In this section, the results of tests performed using the M28, ASTM 3053-17, and IDC protocols, as well as research runs performed to develop and refine the IDC test, are used to investigate the impact of testing, fueling, and operating parameters on PM emissions metrics and other key metrics, including thermal efficiency, expressed as HHV. Parameters evaluated include the following:

- Emissions measures when 90% versus 100% of the fuel load has been consumed.
- Start-up conditions, including start-up load configuration and stove door position.
- Load density, fuel piece size, and air settings.
- Fuel species and moisture content.

This section also includes an analysis of the replicability of the IDC test runs performed on each stove and an analysis of CO emission rates measured in the IDC tests.

3.1 One Hundred Percent versus 90% Burn of Fuel Charge

Steady-state EPA Method 28 (M28) baseline tests were run on stoves 1, 2, 4, 5, 6, and 7 at three damper settings: (1) a high-burn run at the stove's maximum burn rate (M28 Category 4), (2) a medium-burn run at the manufacturer's recommended medium-burn rate setting (category 2 or 3) and a low-burn run (category 1–3). Because the air setting on stove 8 cannot be adjusted, only one M28 run was performed on that stove. The dry-burn rate for that run was in the EPA category 4 range. All M28 tests used dimensional Douglas fir as the fuel, as prescribed in that test method.

Consistent with the M28 protocol, baseline tests were continued until 100% of the fuel was consumed. Particulate matter (PM) was measured continuously throughout the tests using a tapered element oscillating microbalance (TEOM) and personal data ram (pDR). Gravimetric samples were obtained using ASTM Method 2515-13 procedures. The continuous PM measurements show the variations in the PM emissions rate over the course of the burn and enabled a calculation of total PM emissions at the point when 90% of the load had been consumed, as well as at the end of the test (100% fuel consumption). Because, in the field, it is unlikely that stoves are reloaded with additional wood when exactly 100% of the fuel has been consumed, a burn of 100% of a load is unlikely to reflect typical in-use conditions. Assessment focused on the impact of reducing testing time to a shorter duration from the standpoint of emissions characterization.

The air settings matched those that were identified in the appliance's test report. However, the M28 tests were run to create a baseline to assess changes in test method protocols, not to attempt to replicate results from certification results. For stoves 1, 2, 5, and 6, a category 1 burn rate could not be achieved with the lowest air setting. For stoves 1 and 6, the lowest burn rate achievable was a category 3 burn rate and, as discussed above, the M28 run in the fixed-air setting for stove 8 achieved a category 4 burn rate.

The metrics measured for 90% and 100% fuel consumption for each test run are listed in Table 60. PM emissions are shown as: (1) total grams of PM emitted, (2) the emissions rate in grams PM emitted per hour (g/h), which is the metric used in stove certifications, and (3) an emissions factor based on fuel load rather than burn time, in grams of PM emitted per kilograms (kg) fuel consumed. The percentage of the load combusted at the time of the test when the maximum PM was collected is also shown in that table.

As discussed previously, ASTM 3053-17 cordwood tests were also run on three of the study stoves, stoves 1, 6, and 7. That test also allows for measurement of emission parameters for the load and medium-fire burn phases to be averaged across combustion of 100% of the fuel load. The metrics measured at 90% and 100% fuel consumption for each of the ASTM 3053-17 low and medium-fire test runs included in this study are listed in Table 61. Complete ASTM 3053-17 tests, including both a medium and low-burn phase, were run with maple fuel in all three of these stoves. In Stove 6, two additional medium setting maple burns and complete tests using beech and oak fuels were also performed and are included in Table 61.

As discussed in previous sections, due to operational problems, testing of stove 3 was discontinued and the discussion of the test results that follows does not include that stove. For stove 2, tests times and burn rates for the medium- and low-burn runs were essentially the same.

Table 60. Metrics for M28 Runs in all Stoves at 90% and 100% Combustion

	Burn-Rate Category	Run Time (min)		Dry-Burn Rate (kg/h)		Total PM (g)		PM Emission Rate (g/h)		PM Emission Factor (g/kg)		% Load Burned at Max PM Capture
% Burn Completed	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	
Stove 1												
High	4	90	123	5.21	4.2	12.14	11.71	8.09	5.67	1.55	1.35	55.5
Medium	3	168	262	2.64	1.88	13.02	12.76	4.65	2.92	1.76	1.55	68.7
Low	3	216	327	2.08	1.52	24.20	23.76	6.72	4.36	3.22	2.84	55.0
Stove 2												
High	4	112	157	1.83	1.45	5.21	5.15	2.79	1.97	1.53	1.36	78.3
Medium	2	135	199	1.52	1.15	3.64	3.60	1.61	1.09	1.06	0.94	76.2
Low	2	138	200	1.51	1.15	2.61	2.58	1.13	0.77	0.75	0.67	78.5
Stove 3												
High	4	93	141	4.73	3.48	1.54	1.42	0.99	0.60	0.21	0.17	87.6
Medium	1	403	600	0.68	0.51	1.63	1.60	0.24	0.16	0.36	0.31	
Low		-	-	-	-	-	-	-	-	-	-	-
Stove 4												
High	4	25	33	4.58	3.85	0.90	0.90	2.16	1.64	0.48	0.42	80.5
Medium	3	49	70	2.24	1.73	4.69	4.87	5.74	4.17	2.56	2.41	100
Low	1	112	157	0.99	0.79	4.83	5.04	2.59	1.93	2.62	2.43	100
Stove 5												
High	4	90	116	3.41	2.94	19.12	19.15	12.75	9.91	3.73	3.37	47.0
Medium	2	243	374	1.33	0.96	11.02	10.49	2.72	1.68	2.04	1.75	86.8
Low	2	191	298	1.69	1.20	6.31	6.46	1.98	1.30	1.17	1.08	93.2
Stove 6												
High	4	79	123	4.20	2.99	4.25	4.26	3.23	2.08	0.77	0.69	91.9
Medium	3	164	247	2.01	1.48	4.03	3.99	1.47	0.97	0.73	0.65	58.1
Low	3	189	279	1.79	1.32	15.43	15.07	4.90	3.24	2.74	2.46	52.2
Stove 7												
High	4	142	192	1.91	1.57	1.07	1.37	0.45	0.43	0.24	0.27	94.8
Medium	3	163	222	1.65	1.36	2.14	2.11	0.79	0.57	0.47	0.42	73.4
Low	1	198	365	1.39	0.84	2.04	2.01	0.62	0.33	0.44	0.39	53.4
Stove 8												
Fixed	4	82	110	2.94	2.44	17.08	17.25	12.50	9.41	4.25	3.86	98.3

Table 61. Metrics for ASTM 3053-17 Low and Medium Runs at 90% and 100% Load Combustion

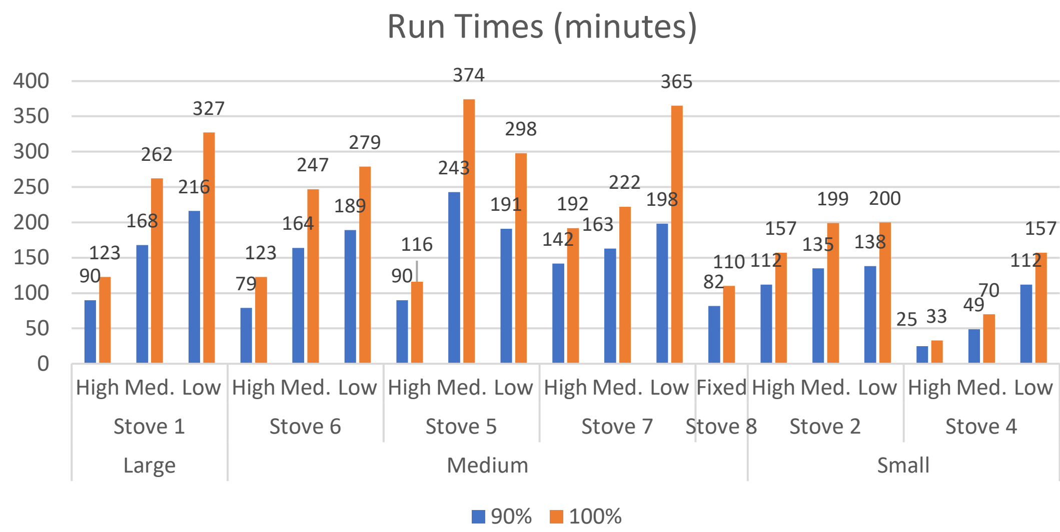
		Run Time (min)		Dry-Burn Rate (kg/h)		Total PM (g)		PM Emission Rate (g/h)		PM Emission Factor (g/kg)		% Load Burned at Max PM Capture
		90%	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	*90%*	*100%*	
Stove 1 Maple	Medium	223	430	3.24	1.87	27.2	27.1	7.3	3.8	2.3	2.0	89.7
	Low	206	340	3.06	2.06	104.3	99.8	30.4	17.6	9.9	8.5	33.1
Stove 6 Maple	Medium	210	358	2.05	1.33	29.9	28.7	8.5	4.8	4.2	3.6	29.4
	Medium	279	469	1.63	1.07	16.6	16.5	3.6	2.1	2.2	2.0	78.5
	Medium	254	454	1.75	1.08	38.1	35.4	9.0	4.7	5.1	4.3	28.4
	Low	297	500	1.58	1.05	40.2	38.6	8.1	4.6	5.1	4.4	35.5
Stove 6 Beech	Medium	385	775	1.41	0.78	77.6	70.9	12.1	5.5	8.6	7.0	82.6
	Low	444	727	1.17	0.80	88.6	88.6	12.0	7.3	10.2	9.2	34.5
Stove 6 Oak	Medium	283	445	1.65	1.16	52.5	49.7	11.1	6.7	6.8	5.8	34.7
	Low	304	502	1.67	1.12	86.9	81.5	17.2	9.7	10.3	8.7	42.2
Stove 7 Maple	Medium	207	331	1.84	1.27	1.9	1.9	0.6	0.3	0.3	0.3	56.0
	Low	282	454	1.52	1.05	4.1	4.0	0.9	0.5	0.6	0.5	82.5

The M28 and ASTM 3053-17 metrics in Tables 60 and 61 are displayed graphically and discussed below.

3.1.1 Test Time

The times associated with consumption of 90% and 100% of the fuel load for each of the M28 test runs are shown in Figure 67. Stoves are displayed in the order of firebox size from largest (stove 1) to smallest (stove 4). For stove 5, a medium-sized, non-catalytic downdraft unit, the medium-burn run time was longer than the low-burn time and that the stove 2 (a small-sized, catalytic unit) medium- and low-burn times are essentially equal. As discussed previously, the air flow rate is not adjustable in stove 8; the burn rate for the M28 run in that stove was in the range of the high-air runs in the other stoves and is included in the high-fire group in the analysis below.

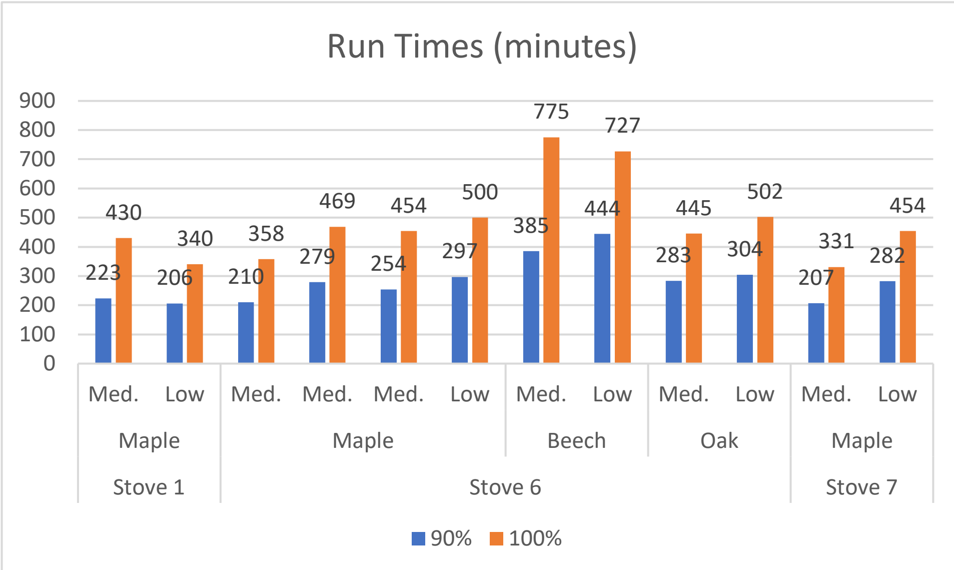
Figure 67. Method 28 Run Times at 90% and 100% Fuel Consumption



As shown in Figure 67, substantial additional time was required to consume the last 10% of the fuel loads, particularly in the lower burn runs. On average, the 100% fuel consumption periods were 35 minutes, 75 minutes, and 97 minutes longer than the 90% consumption periods for the high-, medium-, and low-burn tests, respectively. The time period between 90% and 100% fuel consumption constituted 27% of the total run times for the high burns, 32% of the medium-burn times, and 35% of the
low-burn times.

The times associated with consumption of 90% and 100% of the fuel load for each of the ASTM 3053-17 test runs are shown in Figure 68.

Figure 68. ASTM 3053-17 Low- and Medium-Burn Run Times at 90% and 100% Fuel Consumption



As with the M28 runs, substantial additional time was required to consume the last 10 of the fuel loads in the ASTM medium and low burns, as shown in Figure 68. On average, the 100% fuel consumption periods were 201 minutes longer than the 90% consumption periods. The time period between 90% and 100% fuel consumption constituted an average of 41% (range 36%–50%) of the total run times.

Table 62 shows average times to 90% and 100% fuel consumption for the three M28 runs in each stove. Stove 8 is not included in this table because only one M28 run was performed on that fixed-air setting stove. The average times to 90% and 100% fuel consumption for the medium and low burns in each complete ASTM 3053-17 test are also shown in the table.

Table 62. Average Times to 90% and 100% Fuel Consumption by Stove

		Average Time to 90% Consumption (minutes)	Average Time to 100% Consumption (minutes)	Average 100%–90% Time Difference (minutes)	Difference as % of Total Run Time
M28	Stove 1	158	237	79	32%
	Stove 2	128	185	57	31%
	Stove 4	62	87	25	28%
	Stove 5	175	263	88	31%
	Stove 6	144	216	72	34%
	Stove 7	168	260	92	33%
ASTM	Stove 1 maple	215	385	171	40%
	Stove 6 maple	245	414	169	47%
	Stove 6 beech	415	751	337	43%
	Stove 6 oak	294	474	180	40%
	Stove 7 maple	245	393	148	45%

Although there was considerable variation in run times, the percentage of total run time required to consume the last 10% of fuel was consistent from stove to stove for each test type. In the M28 runs, the average percentage of the total run time after 90% fuel consumption ranged from 28% in stove 4 to 34% in stove 6. Stove 4 is a small (0.8 ft^3 firebox) cast-iron stove and stove 6 is a medium (2.2 ft^3 firebox) steel stove, both with non-catalytic tube control systems.

The average run times in the ASTM 3053-17 was longer than in the M28 runs. The percentages of the time after 90% fuel consumption in the ASTM (40%–47%) were larger than in the M28 tests but were consistent from stove to stove. The differences between the M28 and ASTM 3053-17 run times as a percentage of time after 90% consumption can largely be explained by the larger fuel load in the ASTM protocol tests.

As shown in Table 63, the M28 data do not show a clear relationship between the percentage of run time required to burn the last 10% of fuel and firebox size or control technology. Stove 8 is included only in the high-air setting averages.

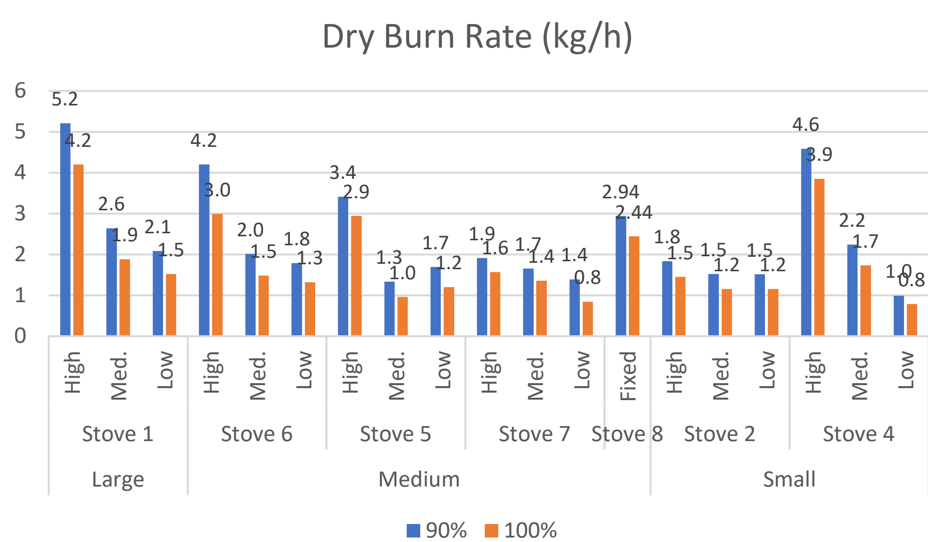
Table 63. Percent of M28 Run Time to Burn the Last 10% of the Fuel Charge

	Low Air Setting	Medium Air Setting	High Air Setting	Average
All Stoves	35%	32%	27%	31%
Small Firebox (Stoves 2 and 4)	30%	31%	26%	29%
Medium Firebox (5, 6, 7, and 8)	38%	32%	27%	33%
Large Firebox (1)	34%	36%	27%	32%
Non-cat, tube (1, 4, 6, and 8)	32%	33%	28%	31%
Non-cat, non-tube (5)	36%	35%	22%	31%
Catalytic (2)	31%	32%	29%	31%
Hybrid (7)	46%	27%	26%	33%

3.1.2 Fuel Combustion Rates

The average burn rates measured in the 90% and 100% fuel consumption periods for each of the M28 runs are shown in Figure 69. As in Figure 67, the M28 tests are ordered by stove firebox size.

Figure 69. M28 Run Fuel Combustion Rates (kg fuel consumed/hour) at 90% and 100% Fuel Consumption

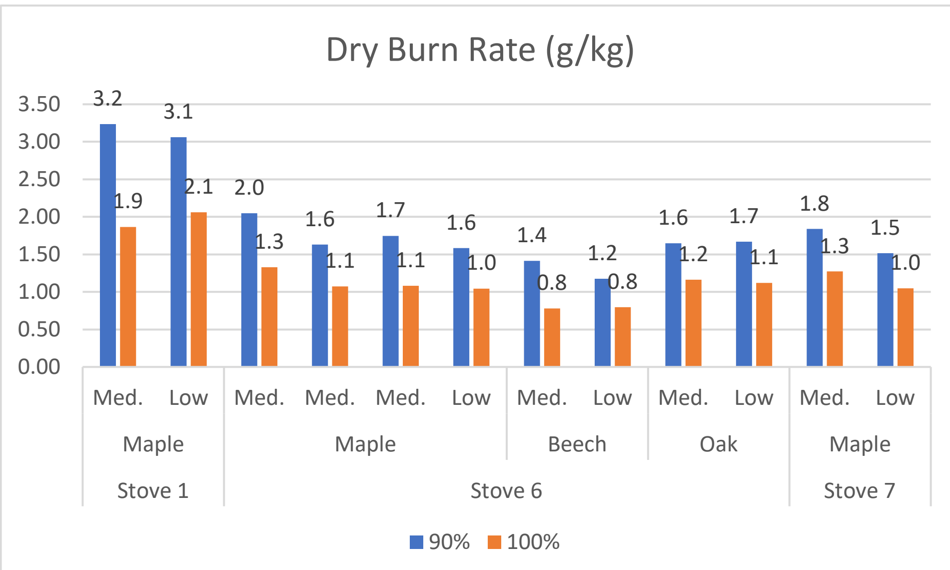


Fuel combustion rates tended to be higher in the larger stoves. However, the high-burn run, fuel combustion rate for stove 4, which has the smallest firebox, was second only to that of stove 1, the largest stove.

Burn rates associated with 90% fuel consumption for the high, medium, and low burns were, on average, 25%, 33%, and 39% higher than the 100% consumption burn rates, respectively. This pattern is consistent with the observation discussed above, that is, the percentage of total run time after 90% of fuel is consumed was higher in the lower burn runs.

Dry-burn rates at 90% and fuel consumption for the ASTM 3053-17 low and medium runs are shown in Figure 70.

Figure 70. ASTM 3035-17 High- and Medium-Run Fuel Combustion Rates (kg fuel consumed/hour) at 90% and 100% Fuel Consumption



The fuel combustion rates in the ASTM 3053-17 runs were higher in the large stove, stove 7, than in the two stoves with medium-sized fireboxes (stoves 6 and 7). Burn rates associated with 90% fuel consumption for in the ASTM 3053-17 runs were 42% to 81% higher at 100% fuel consumption. Both the smallest and largest percent differences in dry-burn rates occurred in medium-fire runs in stove 6. The smallest percent difference in dry-burn rates occurred in the run that burned oak and the largest in the run that burned beech fuel.

As can be seen in the burn profiles shown in Figure 71, burn rates in both the M28 and ASTM runs tended to drop considerably during the period between 90% and 100% load consumption. Therefore, a burn rate calculated for a 100% burn is not representative of burn conditions in the period associated with PM emissions. Because stove owners generally refuel before 100% of fuel consumption, the 100% combustion burn rates are not likely representative of actual field performance.

Figure 71. Burn Profiles (Percent of Fuel Consumed)

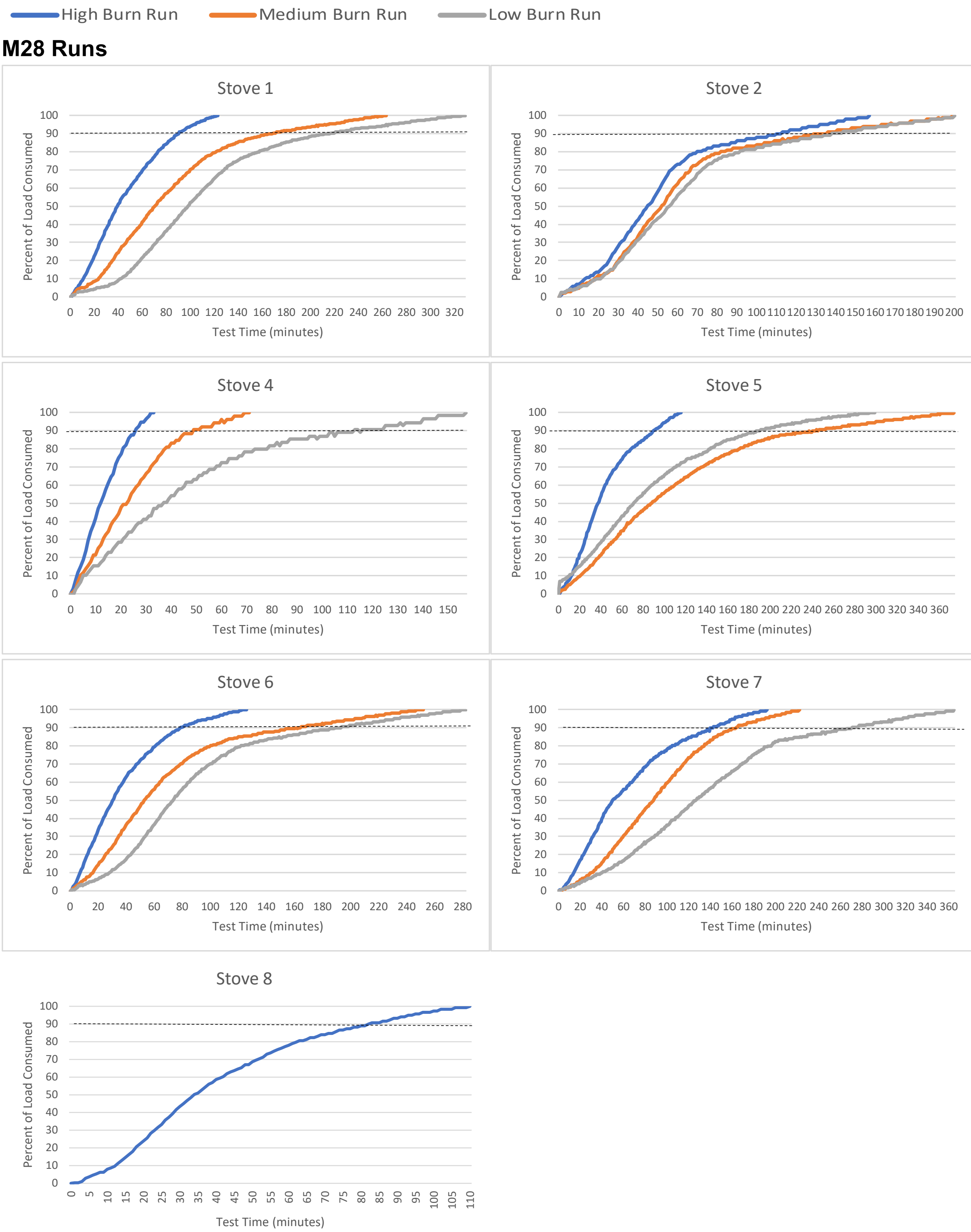
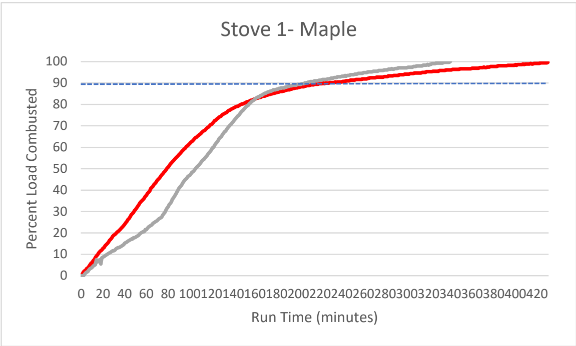
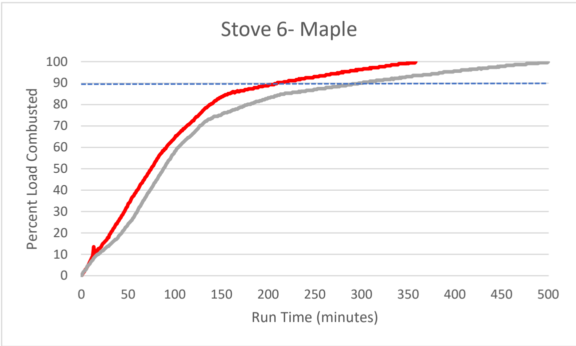
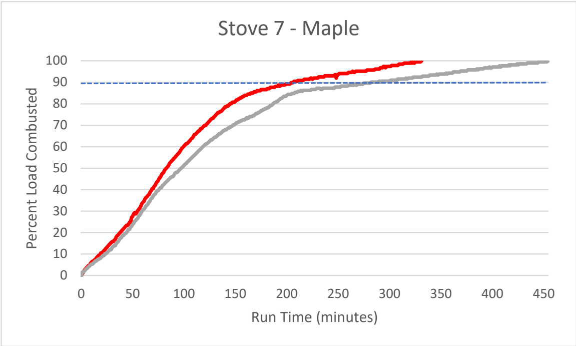


Figure 71 continued

ASTM 3053-17 Runs







As would be expected, in the M28 runs, the high-burn combustion rates for each stove were higher than the corresponding medium- and low-burn rates. However, the difference between high-burn and low-burn combustion rates varied by stove. This was particularly evident for the two small firebox stoves; for stove 4, the average combustion burn rate for the high-burn run was almost five times higher than the low-run burn rate, while for stove 2, the high-burn rate was only 26% higher than that of the low run.

Consistent with the run time results, Figures 69 and 71 show that M28 stove 5 dry-burn rates were higher in the low-burn run than the medium-burn run and that the dry-burn rates for the stove 2 medium- and low-burn runs were essentially equal. An initial lag time indicative of delayed load combustion is evident in several of the Figure 71 M28 combustion profiles, particularly in the lower fired burns. Dry-burn rates in the ASTM 3053-17 medium and low runs were similar for all stoves and fuels tested.

Despite the variation among the stoves in fuel consumption rates, the percentage difference in the dry-burn rate associated with 100% and 90% fuel consumption in the M28 tests was consistent from stove to stove. As shown in Table 64, the average 90% combustion dry-burn rates for the three runs for each stove were 25% to 37% higher than the corresponding 100% combustion rates. As with run times, the average percent difference in burn rates was lowest for stove 4 and highest for stove 6. The percent difference in the dry-burn rates at 100% and 90% combustion were more substantial in the ASTM 3053-17 runs than in the M28 runs.

Table 64. Average Dry-Burn Rate (DBR) at 90% and 100% Fuel Consumption by Stove

		Average DBR 90% Consumption (kg/h)	Average DBR 100% Consumption (kg/h)	% Difference (100% DBR-90% DBR) as % of 100% DBR
M28	**Stove 1**	3.3	2.5	-34%
	Stove 2	1.6	1.3	-30%
	Stove 4	2.6	2.1	-25%
	Stove 5	2.1	1.7	-32%
	Stove 6	2.7	1.9	-37%
	Stove 7	1.7	1.3	-36%
ASTM	**Stove 1 maple**	3.1	2.0	-60%
	Stove 6 maple	1.8	1.2	-53%
	Stove 6 beech	1.3	0.8	-64%
	Stove 6 oak	1.7	1.1	-45%
	Stove 7 maple	1.7	1.2	-45%

As shown in Table 65, the percentage difference in the M28 dry-burn rates at 90% and 100% combustion was lower for the small firebox stoves (stoves 2 and 4) than the other stoves. The difference was particularly apparent at the low-air setting. The data do not show a clear relationship between the percentage difference in dry-burn rate for 90% and 100% fuel combustion and control technology.

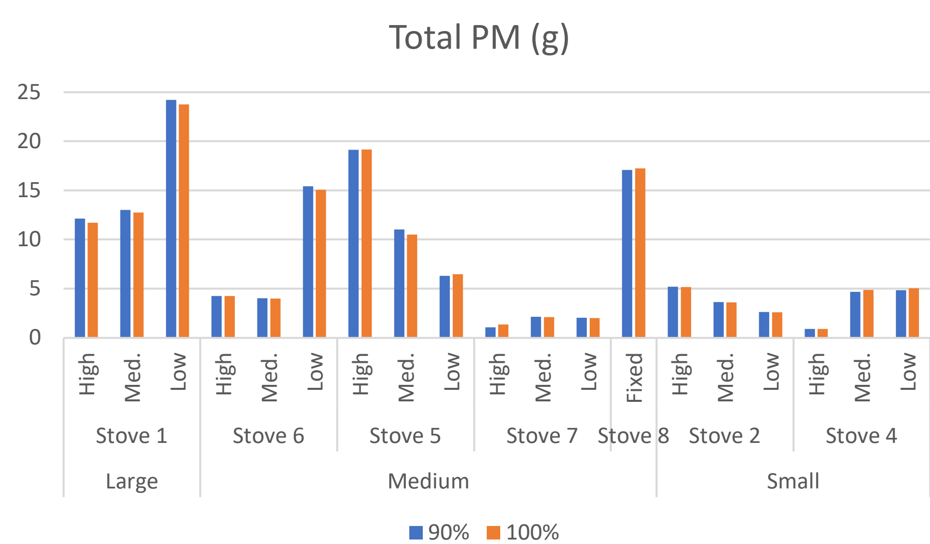
Table 65. Percent Difference in M28 Dry-Burn Rate for 100% and 90% Combustion

	Low Air Setting	Medium Air Setting	High Air Setting	Average
All Stoves	-39%	-33%	-24%	-32%
Small Firebox (Stoves 2 and 4)	-28%	-31%	-23%	-27%
Medium Firebox (5, 6, 7 and 8)	-47%	-32%	-25%	-35%
Large Firebox (1)	-37%	-40%	-24%	-34%
Non-cat, Tube (1, 4, 6 and 8)	-34%	-35%	-26%	-32%
Non-cat, Non-tube (5)	-41%	-39%	-16%	-32%
Catalytic (2)	-31%	-32%	-26%	-30%
Hybrid (7)	-65%	-21%	-22%	-36%

3.1.3 Total Particulate Matter at 90% and 100% Combustion

Figure 72 shows total particulate matter (PM) collected for each M28 test run. As discussed previously, the continuous TEOM measurements allowed for the determination of PM emissions at 90% as well as 100% of fuel consumption. Due to the difference in the stoves' firebox and load sizes, total grams of PM cannot be used for a direct comparison of stove emissions. It is, however, a useful metric for comparing emissions at 90% and 100% combustion by stove.

Figure 72. PM Emissions (g) in Method 28 Runs at 90% and 100% Combustion



Stoves varied in which air setting produced the highest PM emissions. Stoves 1 (a large, high-mass stove with non-catalytic controls) and 6 (a medium, steel, non-catalytic stove) emitted more PM with low-air settings than at high-air settings, while stoves 2 (small, high mass, catalytic) and 5 (medium, cast iron, non-catalytic) emitted substantially more PM with high-air settings. For stoves 4 (small, cast iron, non-catalytic) and 7 (medium, high mass, hybrid), PM emissions with the medium- and low-air settings were essentially equal and were higher than those for the high-air settings.

With one exception, the total PM measurement for the first 90% of fuel consumption was within 5% of that at the end of the burn. In 11 of the 18 runs (61% of the runs), the total PM measured at the end of the run was lower than the PM measured at the 90% fuel consumption point. The PM loss occurs because the hot exhaust gas with low PM emissions passes through the filter towards the end of the run and causes the more volatile PM species that were collected earlier to volatilize from the filter. There was no significant correlation between the percentage of the run time after 90% of the load was combusted and the PM loss during that period. A single exception to this was the high-air setting run for stove 7.

Total PM emissions in the low and medium ASTM 3053-17 runs at 90% and 100% combustion are shown in Figure 73. In most cases, PM emissions were higher in the low than in the medium runs, although the magnitude of that difference varied from stove to stove. No additional PM was collected between 90% and 100% combustion in any of the runs. Due to the volatilization effect discussed above, the PM measured at 100% combustion was between 0% (stove 6 beech, low run) and 9.4% (stove 6 beech, medium run) lower at 100% than at 90% combustion.

Figure 73. PM Emissions (g) in ASTM 3053-17 Low and Medium Runs at 90% and 100% Combustion

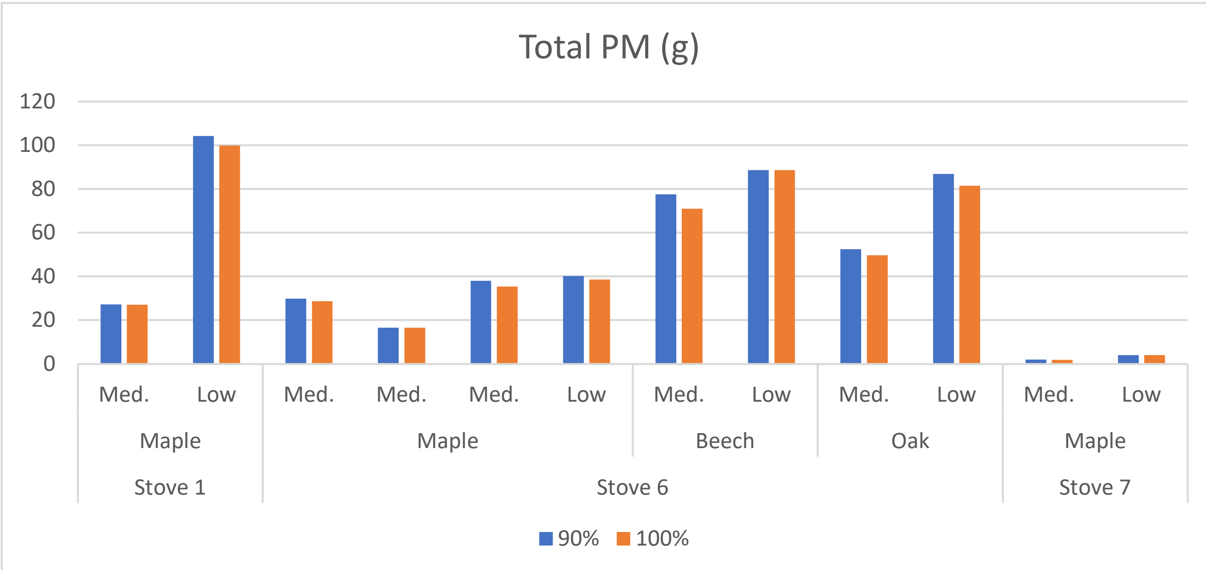


Figure 74 shows emissions profiles for the M28 runs for each stove. As can be seen in that figure, the instantaneous emission rate for the stove 7 high-burn run rose above 1 g/h for a period of 7 minutes beginning at minute 147, shortly after 90% fuel combustion occurred. Due to the low loading of this appliance, this single event contributed 22% of the PM emissions for the run.

Figure 74. M28 Run Emission Profiles

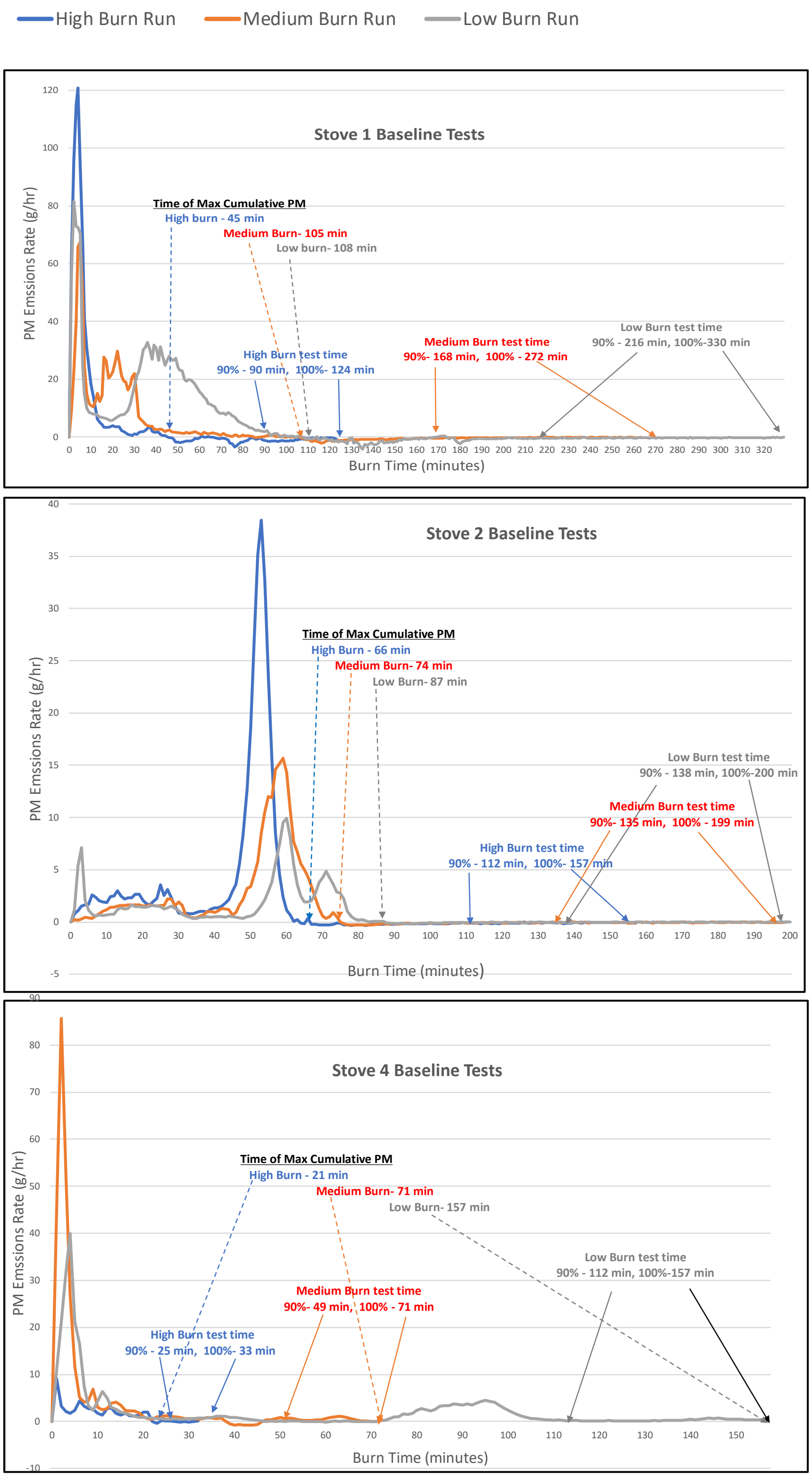


Figure 74 continued

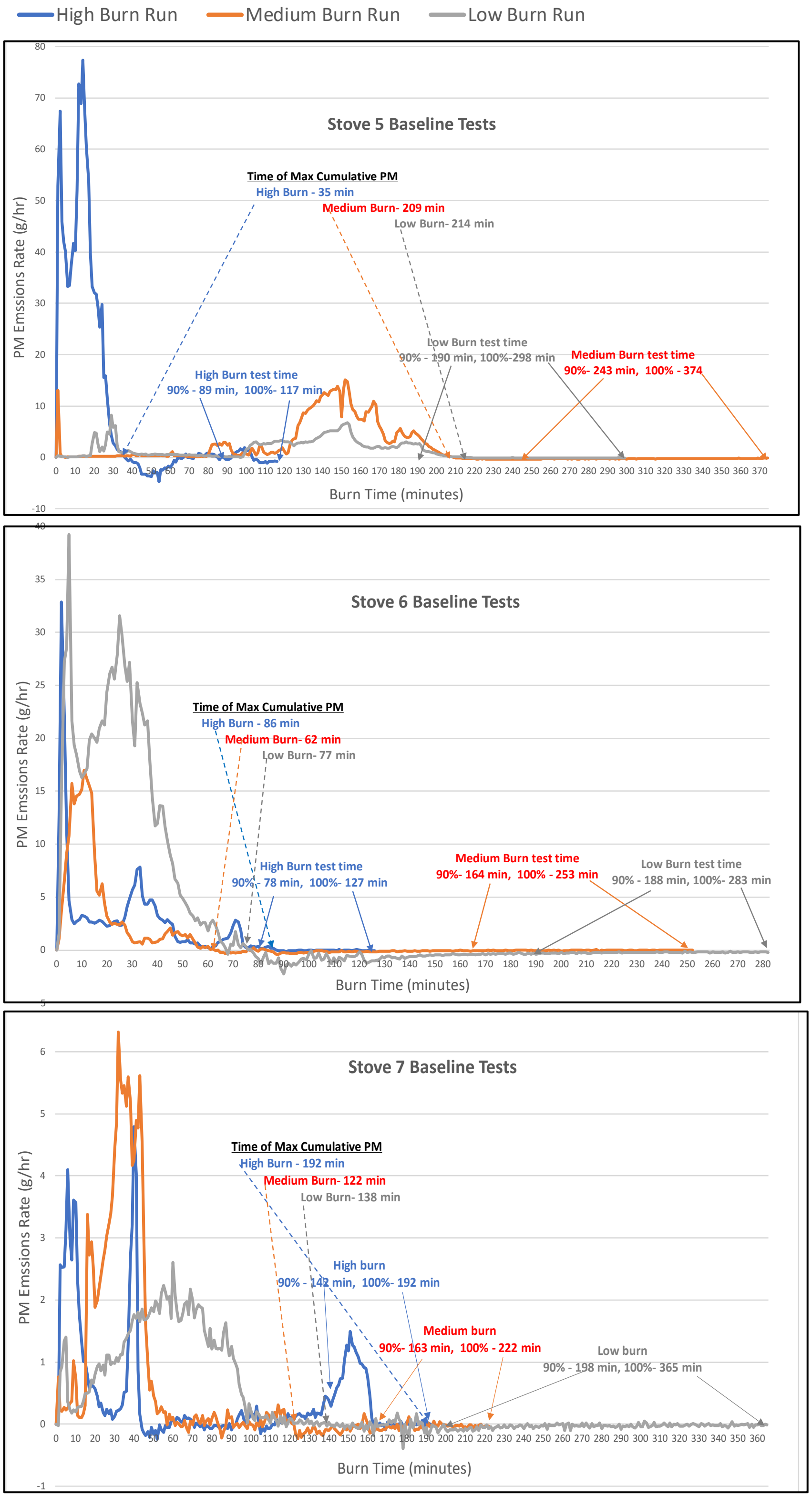
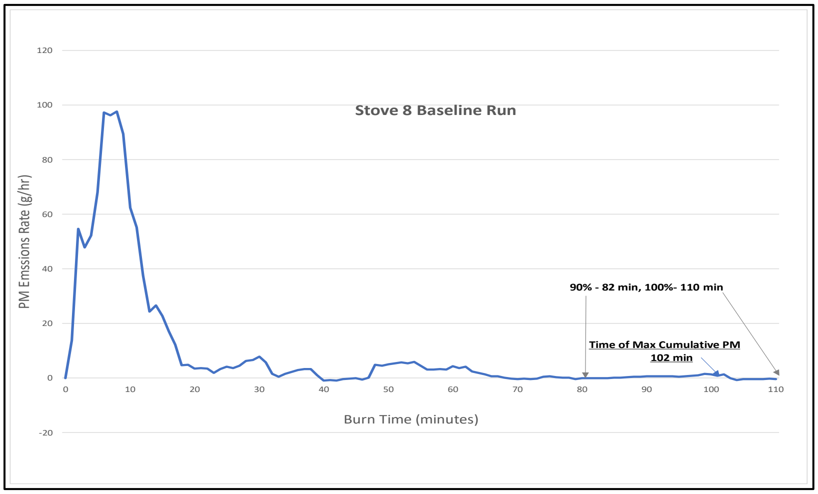


Figure 74 continued



Note that the scales in the Figure 74 graphs are very different. Stove 1, the only large stove in this group, and stove 8, the fixed-air setting stove, had a considerably higher peak PM emission rate than the other stoves, while the instantaneous emission rates for stove 7, the stove with hybrid controls, were the lowest for all burn levels.

Comparison of PM emissions at 90% and 100% combustion for each run and the average difference for each stove is shown for M28 runs in Table 66. The same information is shown for each stove and fuel species for the medium and low ASTM 3053-17 runs in Table 67.

Table 66. Comparison of M28 Total PM at 90% and 100% Combustion

		Total PM (g) at 90% Combustion	Total PM (g) at 100% Combustion	Difference (g) (PM at 100% PM at 90%)	Difference as Percent of PM at 100%
Stove 1	High	12.14	11.71	-0.43	-4%
	Medium	13.02	12.76	-0.26	-2%
	Low	24.20	23.76	-0.44	-2%
	Stove Average				-3%
Stove 2	High	5.21	5.15	-0.06	-1%
	Medium	3.64	3.60	-0.04	-1%
	Low	2.61	2.58	-0.03	-1%
	Stove Average				-1%
Stove 4	High	0.90	0.90	0	0%
	Medium	4.69	4.87	0.18	4%
	Low	4.83	5.04	0.21	4%
	Stove Average				3%
Stove 5	High	19.12	19.15	0.03	0.2%
	Medium	11.02	10.49	-0.53	-5%
	Low	6.31	6.46	0.15	2%
	Stove Average				-1%
Stove 6	High	4.25	4.26	0.01	0.2%
	Medium	4.03	3.99	-0.04	-1%
	Low	15.43	15.07	-0.36	-2%
	Stove Average				-1%
Stove 7	High	1.07	1.37	0.3	22%
	Medium	2.14	2.11	-0.03	-1%
	Low	2.04	2.01	-0.03	-1%
	Stove Average				6%
Stove 8	Fixed	17.08	17.25	0.17	1.0%

Table 67. Comparison of Total PM in ASTM 3053-17 Medium and Low Runs at 90% and 100% Combustion

		Total PM (g) at 90% Combustion	Total PM (g) at 100% Combustion	Difference (g) (PM at 100% PM at 90%)	Difference as Percent of PM at 100%
Stove 1 Maple	Medium	27.2	27.1	-0.06	-0.2%
	Low	104.3	99.8	-4.48	-4%
	Average				-2%
Stove 6 Maple	Medium	29.9	28.7	-1.22	-4%
	Low	40.2	38.6	-1.59	-4%
	Average				-4%
Stove 6 Beech	Medium	77.6	70.9	-6.67	-9%
	Low	88.6	88.6	-0.01	0%
	Average				-5%
Stove 6 Oak	Medium	52.5	49.7	-2.78	-6%
	Low	86.9	81.5	-5.36	-7%
	Average				-6%
Stove 7 Maple	Medium	1.9	1.9	-0.04	-2%
	Low	4.1	4.0	-0.10	-3%
	Average				-2%

In the M28 runs, two of the stoves (stoves 1 and 2) lost PM sample mass between the points of 90% and 100% combustion in all three runs. In three of the stoves (stoves 5, 6, and 7), additional PM was collected between 90% and 100% combustion in the high-air setting runs, but a net loss in PM occurred in that time period in the medium- and low-setting runs. In stove 4, the PM measurements at 100% combustion was equal to that at 90% in the high-air run and additional PM was collected between 90% and 100% combustion in the other two runs. As discussed above, the stove 7 high-air run was an outlier; a 7-minute burst of PM emissions that occurred shortly after the 90% combustion run contributed significant emissions to that overall low-emission run.

Total PM did not increase during the last 10% of combustion in any of the ASTM medium and low runs. PM loss of up to 9% during that period occurred in all but one of those runs.

Table 68 compares the differences in M28 PM measurements at 90% and 100% combustion by air setting, stove size, and control technology.

Table 68. Percent Difference in Total PM in M28 Runs at 100% and 90% Combustion

	Low Air Setting	Medium Air Setting	High Air Setting[4]	Average
All Stoves	0%	-1%	3% (-1%)	1%
Small Firebox (Stoves 2 and 4)	2%	1%	-1%	1%
Medium Firebox (5, 6, 7 and 8)	-1%	-2%	6% (0%)	1%
Large Firebox (1)	-2%	-2%	-4%	-3%
Non-cat, tube (1, 4, 6 and 8)	0%	0%	-1%	0%
Non-cat, non-tube (5)	2%	-5%	0%	-1%
Catalytic (2)	-1%	-1%	-1%	-1%
Hybrid (7)	-1%	-1%	22%	6%

There was no clear relationship between percentage loss in PM and air setting, stove size, or technology type.

3.1.4 Maximum Total PM Measurement

As discussed above, under the current PM measurement protocol, maximum total PM collection often occurs before the end of a test run due to volatilization late in the run.[5] As a result, the M28 test method, which measures PM only at the end of runs when 100% of the load has been consumed, frequently underestimates PM emissions. Using real-time TEOM data, the M28 runs and ASTM 3053-17 low and medium runs were analyzed to determine the time and magnitude of maximum PM capture.

Table 69 shows, for each M28 run, the time between the point of maximum PM collection and the end of the run and the TEOM measurement at 90% and 100% fuel combustion as a percentage of the maximum PM measurement. The same information is shown in Table 70 for the ASTM 3053-17 low and medium runs.

Table 69. M28 Runs—Maximum PM Measured as Percentage of PM Measured (g) at Time of 90% and 100% Fuel Combustion

	Burn	% Fuel Consumed at Max PM	Time of Max PM (minutes)	% of Run Time After Max	% of Max PM at 90% Burn Time	% of Max PM at 100% Burn Time
Stove 1	High	56%	79	64%	95%	91%
	Medium	69%	167	64%	94%	92%
	Low	55%	222	68%	94%	92%
Stove 2	High	78%	91	58%	97%	96%
	Medium	76%	125	63%	97%	95%
	Low	79%	113	57%	98%	96%
Stove 4	High	81%	21	36%	100%	99%
	Medium	100%	168	0%	96%	100%
	Low	100%	157	0%	96%	100%
Stove 5	High	47%	82	71%	96%	96%
	Medium	87%	165	44%	99%	94%
	Low	93%	84	28%	96%	98%
Stove 6	High	92%	41	33%	99%	100%
	Medium	58%	191	77%	95%	94%
	Low	52%	206	74%	93%	91%
Stove 7	High	95%	192	0%	78%	100%
	Medium	73%	100	45%	97%	96%
	Low	53%	227	62%	96%	95%
Stove 8	Fixed	98%	102	7%	98%	99%

Table 70. ASTM Runs—Maximum PM Measured as Percentage of PM Measured (g) at Time of 90% and 100% Fuel Combustion

	Burn	% Fuel Consumed at Max PM	Time of Max PM (minutes)	% of Run Time After Max	% of Max. PM at 90% Burn Time	% of Max PM at 100% Burn Time
Stove 1 Maple	Medium	90%	222	48%	100%	100%
	Low	33%	81	76%	91%	87%
Stove 6 Maple	Medium	29%	47	87%	91%	87%
	Medium	79%	118	75%	99%	99%
	Medium	28%	55	88%	85%	79%
	Low	36%	57	89%	92%	88%
Stove 6 Beech	Medium	83%	222	71%	95%	87%
	Low	35%	72	90%	91%	91%
Stove 6 Oak	Medium	35%	71	84%	87%	83%
	Low	42%	68	86%	86%	81%
Stove 7 Maple	Medium	56%	93	72%	96%	94%
	Low	83%	95	79%	96%	94%

As shown in Table 69, in the M28 runs, the maximum PM measurement occurred before 60% of the load had been consumed in 6 (32%) of the runs, before 80% of the load was consumed in 11 (58%) of the runs and before 90% fuel consumption in 13 (68%) of the test runs. In 12 of the M28 runs, the PM measurement at 90% combustion was closer to the maximum value than that at 100% and in one run those values were equal. Therefore, measuring PM emissions at 90%, rather than 100%, fuel consumption would result in a total PM measurement that is as close or closer to the maximum in 13 of the 18 M28 runs (72% of the runs).

The maximum PM measurement tended to occur considerably earlier in the ASTM 3053-17 medium and low runs, as shown in Table 70. In the ASTM runs, the maximum PM measurement occurred before 40% of the load had been consumed in 6 (50%) of the runs, before 60% of the load was consumed in 8 (67%) of the runs, and at or before 90% fuel consumption in all test runs. The ASTM PM measurements at 100% fuel loss were more than 10% lower than the maximum in 7 of the 12 runs. In 10 of the 12 ASTM 3053-17 runs, the PM measurement at 90% combustion were closer to the maximum value than that at 100%. The 90% and 100% PM values were essentially equal in the other two ASTM 3053-17 runs, and in one run those values were equal. Therefore, measuring PM emissions at 90%, rather than 100%, fuel consumption would result in a total PM measurement that is as close or closer to the maximum in all of the ASTM 3053-17 low and medium runs.

Tables 71 and 72 compare the percentage of fuel combusted at the point of maximum PM measurement and the percentage of the run time after maximum PM collection, respectively, by air setting, stove size, and control technology type for the M28 runs.

Table 71. M28 Runs—Percentage of Fuel Load Combusted at PM Maximum

	Low-Air Setting	Medium-Air Setting	High-Air Setting	Average
All Stoves	72%	77%	78%	76%
Small Firebox (Stoves 2 and 4)	90%	88%	80%	86%
Medium Firebox (5, 6, 7 and 8)	66%	73%	83%	72%
Large Firebox (1)	55%	69%	56%	60%
Non-cat, Tube (1, 4, 6 and 8)	74%	76%	82%	75%
Non-cat, Non-tube (5)	93%	87%	47%	76%
Catalytic (2)	79%	76%	78%	78%
Hybrid (7)	53%	73%	95%	74%

Table 72. M28 Runs—Percentage of Run Time After Maximum PM Collection

	Low-Air Setting	Medium-Air Setting	High-Air Setting	Average
All Stoves	48%	49%	38%	45%
Small Firebox (Stoves 2 and 4)	29%	32%	47%	36%
Medium Firebox (5, 6, 7 and 8)	55%	55%	28%	48%
Large Firebox (1)	68%	64%	64%	65%
Non-cat, Tube (1, 4, 6 and 8)	46%	47%	35%	46%
Non-cat, Non-tube (5)	28%	44%	71%	48%
Catalytic (2)	57%	63%	58%	59%
Hybrid (7)	62%	45%	0%	36%

As shown in Table 71, on average, the maximum M28 PM measurements in the small firebox stoves in this study (stoves 2 and 4) occurred when a larger percentage of the fuel load had been consumed (average 86%) than in the medium and large firebox stoves (72% and 60%, respectively). Similarly, as shown in Table 72, the percentage of the run times in the M28 runs after the maximum PM was measured was, on average, lower in the small stoves (36% of the run time) than in the medium (48%) and large (65%) stoves. However, it should be noted that there was a wide variation between the two small stoves in these parameters, as shown in Table 69. No clear relationship was seen between air setting or control technology in either of these parameters.

Tables 73 and 74 show M28 total PM measurements at 90% and 100% combustion, respectively, as a percentage of the maximum value, stratified by air setting, stove size, and control technology.

Table 73. M28 Total PM Measured (g) at 90% Fuel Combustion as a Percentage of Maximum PM (g)

	Low-Air Setting	Medium-Air Setting	High-Air Setting	Average
All Stoves	96%	96%	95%	95%
Small Firebox (Stoves 2 and 4)	97%	97%	99%	97%
Medium Firebox (5, 6, 7 and 8)	95%	97%	93%	94%
Large Firebox (1)	94%	94%	95%	94%
Non-cat, Tube (1, 4, 6 and 8)	94%	95%	98%	96%
Non-cat, Non-tube (5)	96%	99%	96%	97%
Catalytic (2)	98%	97%	97%	97%
Hybrid (7)	96%	97%	78%	90%

Table 74. M28 Total PM Measured (g) at 100% Fuel Combustion as a Percentage of Maximum PM (g)

	Low-Air Setting	Medium-Air Setting	High-Air Setting	Average
All Stoves	95%	95%	97%	96%
Small Firebox (Stoves 2 and 4)	98%	98%	98%	98%
Medium Firebox (5, 6, 7 and 8)	95%	95%	99%	96%
Large Firebox (1)	92%	92%	91%	92%
Non-cat, Tube (1, 4, 6 and 8)	94%	95%	97%	95%
Non-cat, Non-tube (5)	98%	94%	96%	96%
Catalytic (2)	96%	95%	96%	96%
Hybrid (7)	95%	96%	100%	97%

As shown in those tables, on average, the PM measurements at both 90% and 100% fuel consumption in the small firebox stoves were closer to the maximum PM measurement than in the larger stoves. This would be expected, given the greater percentage of fuel consumption at the point of maximum PM collection and the lower percentage of the run time after that point in the small stoves relative to the larger stoves, as discussed above. There was no clear association between those parameters and air setting or control technology.

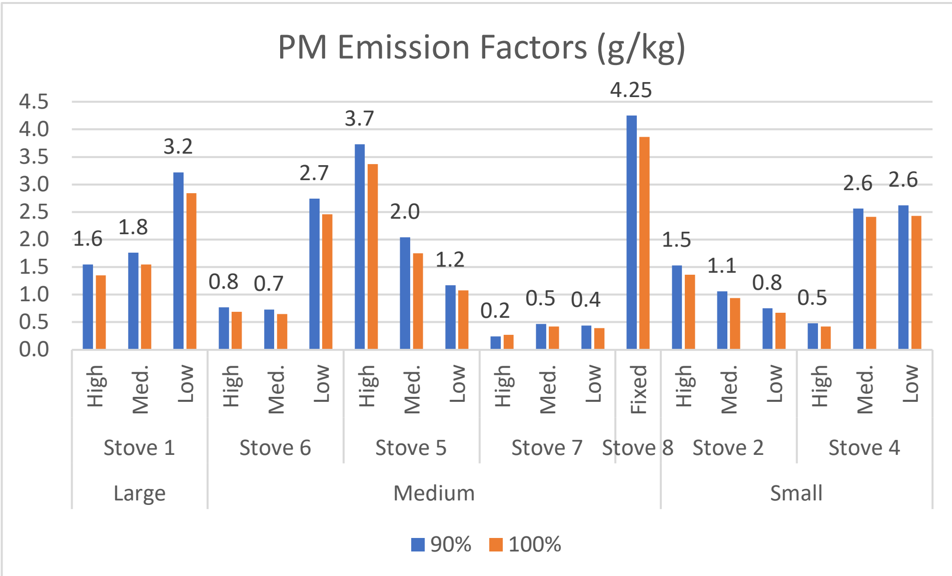
In most cases, volatilization losses in the M28 runs constituted a small percentage of the total PM collected during the burn. Therefore, emission rates, which are expressed in g/h, are often more affected by the additional run time required to achieve 100% combustion than by PM loss. Similarly, the smaller amount of fuel burned at 90% combustion increases the emission factor (in g PM/kg fuel combusted) by approximately 10%, compared to the 100% combustion factor. A more detailed discussion of emission factors and emission rates is presented below. Volatilization losses were more significant in the ASTM 3053-17 runs; however, the percentage of time between 90% and 100% fuel combustion was also higher in those runs.

3.1.5 PM Emission Factors

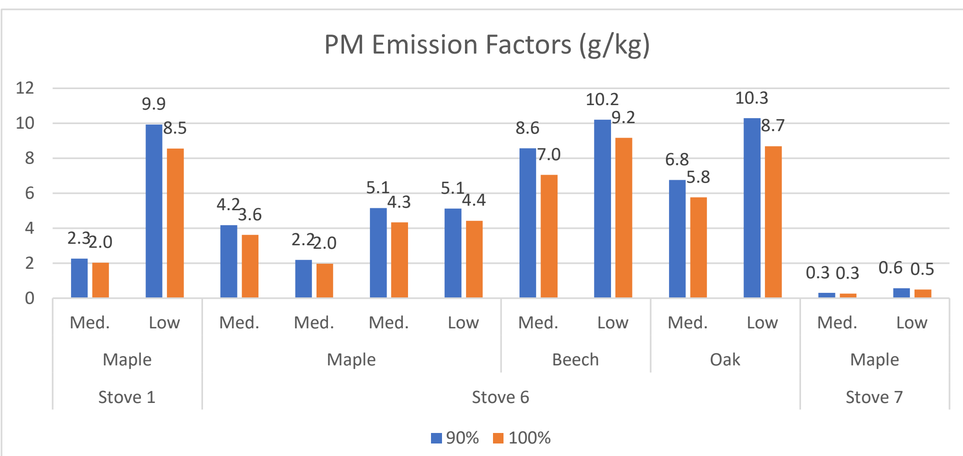
Emission factors, in grams of PM per kg fuel combusted, were calculated for 90% and 100% of fuel combustion for all M28 and ASTM runs and are shown in Figure 75.

Figure 75. PM Emission Factors at 90% and 100% Combustion

M28 Runs



ASTM 3053-17 Runs



The emission factor metric is normalized by the size of the fuel load, rather than the burn time. As discussed previously, PM emissions at the point that 90% of the fuel has been combusted in the M28 runs were very similar to the emissions associated with the 100% burn for all but one of the burns. Because, by definition, the mass of fuel burned associated with 90% of the fuel burn is 10% lower than the mass burned in the 100% test, the M28 emissions factors for the 90% burns tended to be about 10% (stove average 5%–14%) higher than those calculated for the whole burn. The M28 emissions factors for 90% and 100% combustion for each run and the average difference between those factors for each stove are shown in Table 75.

Table 75. Comparison of M28 PM Emission Factors (g/kg) at 90% and 100% Combustion

		PM Emission Factors 90% Combustion	PM Emission Factors 100% Combustion	Percentage Difference in Emission Factors (100% EF–90% EF)/ 100% EF
Stove 1	High	1.55	1.35	-15%
	Medium	1.76	1.55	-14%
	Low	3.22	2.84	-13%
	Stove Average			-14%
Stove 2	High	1.53	1.36	-13%
	Medium	1.06	0.94	-13%
	Low	0.75	0.67	-12%
	Stove Average			-12%
Stove 4	High	0.48	0.42	-14%
	Medium	2.56	2.41	-6%
	Low	2.62	2.43	-8%
	Stove Average			-9%
Stove 5	High	3.73	3.37	-11%
	Medium	2.04	1.75	-17%
	Low	1.17	1.08	-8%
	Stove Average			-12%
Stove 6	High	0.77	0.69	-12%
	Medium	0.73	0.65	-12%
	Low	2.74	2.46	-11%
	Stove Average			-12%
Stove 7	High	0.24	0.27	11%
	Medium	0.47	0.42	-12%
	Low	0.44	0.39	-13%
	Stove Average			-5%
Stove 8	Fixed	4.25	3.86	-10%

As discussed previously, the stove 7 high-burn run was different from the others because additional PM emissions occurred after 90% of the fuel had been consumed; those additional emissions were significant because of that stove’s low-emission rate. For that run, the emission factor associated with 90% combustion was approximately 11% lower than that for 100% combustion.

The ASTM 3053-17 emission factors for 90% and 100% combustion for each run and the average difference between those factors for each stove are shown in Table 76. The average ASTM 3053-17 EFs, by stove and fuel species, were 13% to 18% higher when measured at 90% than at 100% combustion. As discussed previously, the differences in the ASTM EFs at 90% and 100% combustion tended to be larger than the differences seen in the M28 runs because the ASTM runs experienced greater volatilization PM loss in the period between 90% and 100% combustion.

Table 76. Comparison of ASTM 3053-17 Medium- and Low-Run Emission Factors (g/kg) at 90% and 100% Combustion

		PM Emission Factors 90% Combustion	PM Emission Factors 100% Combustion	Difference in Emission Factors (100% EF–90% EF)/ 100% EF
Stove 1 Maple	Medium	2.3	2.0	-11%
	Low	9.9	8.5	-16%
	Average			-14%
Stove 6 Maple	Medium	4.2	3.6	-16%
	Low	5.1	4.4	-16%
	Average			-16%
Stove 6 Beech	Medium	8.6	7.0	-22%
	Low	10.2	9.2	-11%
	Average			-16%
Stove 6 Oak	Medium	6.8	5.8	-17%
	Low	10.3	8.7	-18%
	Average			-18%
Stove 7 Maple	Medium	0.3	0.3	-13%
	Low	0.6	0.5	-14%
	Average			-13%

Percentage differences in the M28 between the 100% and 90% EFs by air setting, stove size, and technology, are shown in Table 77.

Table 77. Percent Difference in PM Emission Factor

(100% EF–90% EF)/100% EF

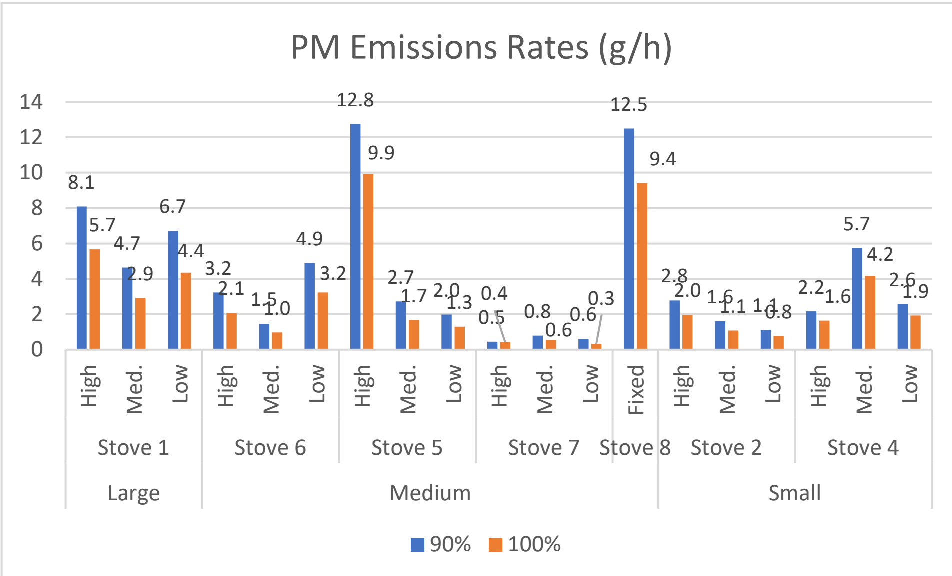
	Low-Air Setting	Medium-Air Setting	High-Air Setting	Average
All Stoves	-11%	-12%	-9% (-12%)	-11% (-12%)
Small Firebox (Stoves 2 and 4)	-10%	-9%	-13%	-11%
Medium Firebox (5, 6, 7 and 8)	-11%	-14%	-5% (-11%)	-9% (-12%)
Large Firebox (1)	-13%	-14%	-15%	-14%
Non-cat, Tube (1, 4, 6 and 8)	-11%	-11%	-13%	-12%
Non-cat, Non-tube (5)	-8%	-17%	-11%	-12%
Catalytic (2)	-12%	-13%	-13%	-12%
Hybrid (7)	-13%	-12%	11%	-5%

The values in parentheses in that table are the average for that category with the stove 7 high-air run outlier value excluded. There was no clear relationship between the change in EF between 90% and 100% combustion and air setting, firebox size, or technology.

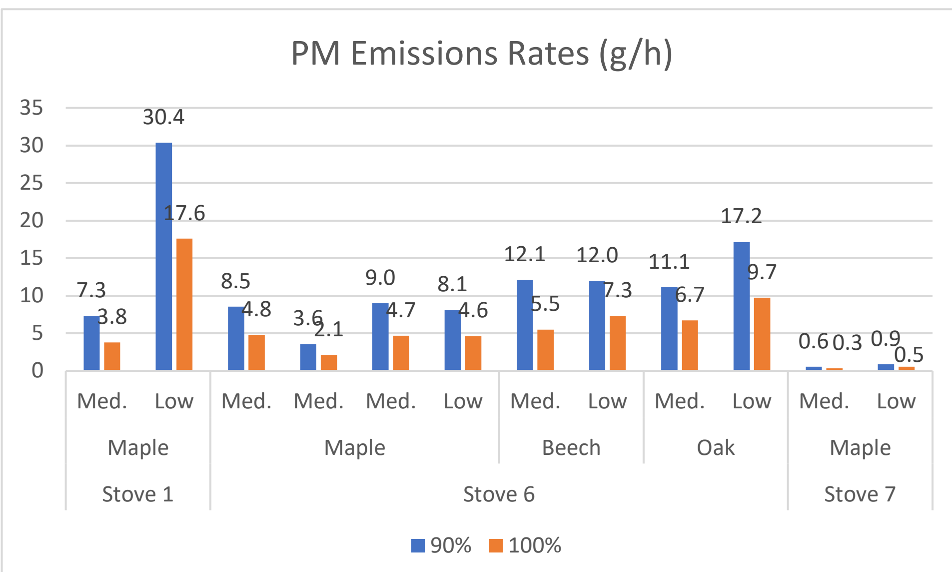
3.1.5.1 PM Emissions Rates

As discussed above, PM emission rates (ERs) are influenced by both the amount of PM collected and the length of the collection period. The PM emission rates measured in the M28 runs and the ASTM 3053-17 low and medium runs, in grams PM per hour, are shown graphically in Figure76.

Figure 76. PM Emission Rates for 90% and 100% Combustion in M28 and ASTM 3053-17 Runs
M28 Runs



ASTM 3053-17 Runs



In the M28 runs, the high-air runs produced the highest emission rates for stoves 1, 2, and 5; the medium-air run produced the highest emission rate for stove 4; and the low-burn run had the highest emission rate for stove 6.

Emission rates for all three of the stove 7 M28 burns and for both of the ASTM-3053-17 runs in that stove were considerably lower than those for the other stoves. As discussed previously, that stove is a step 2 medium-high mass unit with hybrid (catalytic and non-catalytic) controls.

The M28 PM emission rates for the high-air run in stove 5 (medium cast-iron stove with non-catalytic controls) and the fixed-air, high-burn rate run in stove 8 (medium steel stove, non-catalytic controls) were substantially higher than for all other stoves, including the large stove, stove 1, which had emissions rates higher than those of other stoves at the other air settings. The stove 5 emission rates for the medium and low burns were not elevated compared to the other stoves.

As discussed above, the PM collected after 90% of the load was burned tended to be approximately equal to or slightly higher than that measured after 100% fuel-load combustion while the time to 100% combustion was considerably longer than for combustion of 90% of the load. Therefore, PM emission rates, which are calculated by dividing PM emissions by the run time, were substantially higher for the 90% than the 100% combustion period. On average, 90% combustion emissions rates were 34%, 49%, and 54% higher than those associated with 100% combustion for high, medium, and low burns, respectively.

The percent differences in total PM, run time and ER at 100% and 90% combustion for each M28 run are shown in Table 78.

Table 78. M28 Runs—Percent Difference between 100% and 90% Load Combustion for Total PM (g), Collection Time (min), and Emission Rate (g/h)

		Test Time % Difference	Total PM % Difference	Emission Rate % Difference
Stove 1	High	27%	-4%	-43%
	Medium	36%	-2%	-59%
	Low	34%	-2%	-54%
	Stove Average	32%	-3%	-52%
Stove 2	High	29%	-1%	-42%
	Medium	32%	-1%	-48%
	Low	31%	-1%	-47%
	Stove Average	31%	-1%	-45%
Stove 4	High	24%	0%	-32%
	Medium	30%	4%	-38%
	Low	29%	4%	-34%
	Stove Average	28%	3%	-35%
Stove 5	High	22%	0%	-29%
	Medium	35%	-5%	-62%
	Low	36%	2%	-52%
	Stove Average	31%	-1%	-48%
Stove 6	High	36%	0%	-55%
	Medium	34%	-1%	-52%
	Low	32%	-2%	-51%
	Stove Average	34%	-1%	-53%
Stove 7	High	26%	22%	-5%
	Medium	27%	-1%	-39%
	Low	46%	-1%	-88%
	Stove Average	33%	6%	-44%
Stove 8	Fixed	28%	1%	-33%

Note: For each parameter, percent difference was calculated as: (parameter value at 100% combustion—value at 90%)/value at 100%.

Due to the lengthened run time needed to achieve 100% combustion, the M28 ERs for all runs, including the stove 7 high-air run, were higher at 90% than at 100% fuel consumption. In the stove 7 high-air run, additional emissions shortly after 90% of the fuel was consumed resulted in total PM emissions at 100% combustion that were 22% higher than at 90% combustion. However, because the time period needed to achieve 100% combustion was 26% higher than at 90% combustion, the ER for that run was 5% lower at 100% than at 90% combustion.

The M28 ERs for the other runs were 29% to 88% higher at 100% combustion than at 90% combustion. Although, as discussed above, the percent difference between the 100% and 90% ERs was lowest in the high-air run of stove 7, the low-air run for that stove had the highest percentage difference in the 100% and 90% ERs of all runs.

The percent differences in total PM, run time, and ER at 100% and 90% combustion for each of the ASTM 3053-17 medium and low runs are shown in Table 79.

Table 79. ASTM 3053-17 Medium and Low Runs—Percent Difference between 100% and 90% Load Combustion for Total PM (g), Collection Time (min), and Emission Rate (g/h)

		Test Time % Difference	Total PM % Difference	Emission Rate % Difference
Stove 1 Maple	Medium	48%	0%	-93%
	Low	39%	-4%	-72%
	Average	44%	-2%	-83%
Stove 6 Maple	Medium	41%	-4%	-78%
	Low	41%	-4%	-75%
	Average	41%	-4%	-76%
Stove 6 Beech	Medium	50%	-9%	-120%
	Low	39%	0%	-64%
	Average	45%	-5%	-92%
Stove 6 Oak	Medium	36%	-6%	-66%
	Low	39%	-7%	-76%
	Average	38%	-6%	-71%
Stove 7 Maple	Medium	37%	-2%	-63%
	Low	38%	-3%	-65%
	Average	38%	-2%	-64%

Due primarily to the substantially lengthened run time needed to achieve 100% combustion, the difference in the 90% and 100% ERs were even greater for the ASTM 3053-17 runs than for the M28 runs. On average, the ASTM 3053-17 ERs, by stove and fuel, were 64% to 92% higher at 90% combustion than at 100% combustion.

As discussed above, there was no clear relationship between the percent differences in the M28 runs in PM or in test time at 90% and 100% combustion and stove size or technology. The percent difference in test times was lower in the high-air runs than in the medium- and low-air runs. A comparison of the difference in M28 ERs by air setting, stove size, and technology is shown in Table 80. As in Table 77, the values in parentheses in this table are the average for that category with the stove 7 high-air run outlier value excluded.

Table 80. Percent Difference in PM Emission Rate (g/h) at 100% and 90% Combustion

	Low-Air Setting	Medium-Air Setting	High-Air Setting	Average
All Stoves	-54%	-49%	-34% (-39%)	-45% (-48%)
Small Firebox (Stoves 2 and 4)	-40%	-43%	-37%	-40%
Medium Firebox (5, 6, 7 and 8)	-64%	-51%	-30% (-39%)	-48%
Large Firebox (1)	-54%	-59%	-43%	-52%
Non-cat, Tube (1, 4, 6 and 8)	-48%	-49%	-41%	-47%
Non-cat, Non-tube (5)	-52%	-62%	-29%	-48%
Catalytic (2)	-47%	-48%	-42%	-45%
Hybrid (7)	-88%	-39%	-5%	-44%

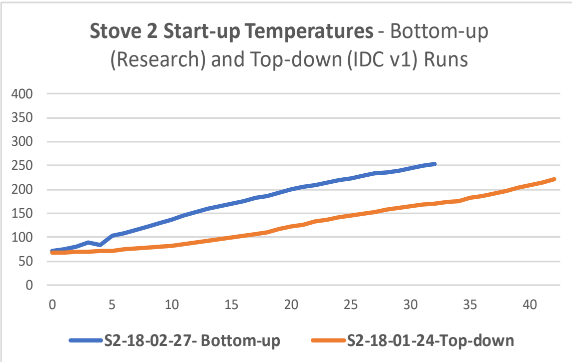
The percentage difference between the M28 ERs at 100% and 90% combustion was lower in the high-air runs than in the runs at the low- and medium-air settings. This is due to a lower percentage difference in the test times in the high-air runs, as discussed above. The difference in the 100% and 90% combustion ERs for the small firebox stoves were lower than those for the medium and large stoves at the low- and medium-air settings. However, due to the small number of stoves in each category, it is not clear that this difference is truly a function of stove size. There is no clear relationship between the difference in ER and stove technology.

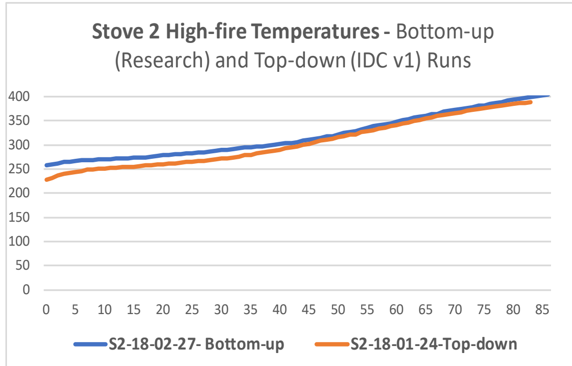
To more accurately reflect actual in-use conditions, the ER should be measured at 90% combustion rather than at 100% combustion. The 90% combustion ERs in the M28 runs were consistently higher than the ERs for the 100% combustion period in those runs. This impact of continuing the test to 100% combustion on the ER was even more substantial in the ASTM 3053-17 medium- and low-burn runs.

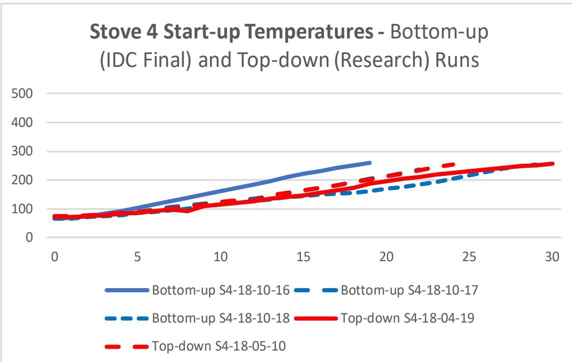
Figure 77 continued

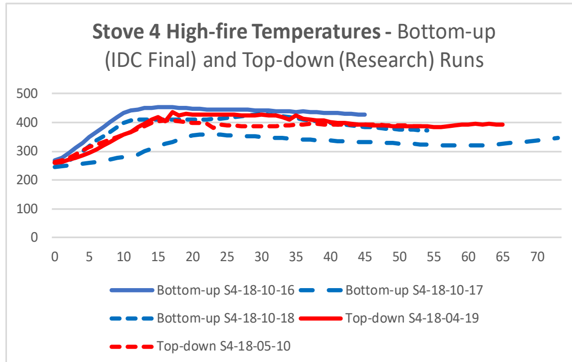
Load density 7 lb/ft^3.

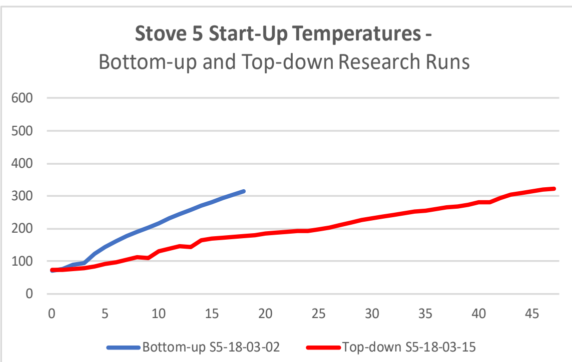
Air setting switched to low at 50% load combustion.

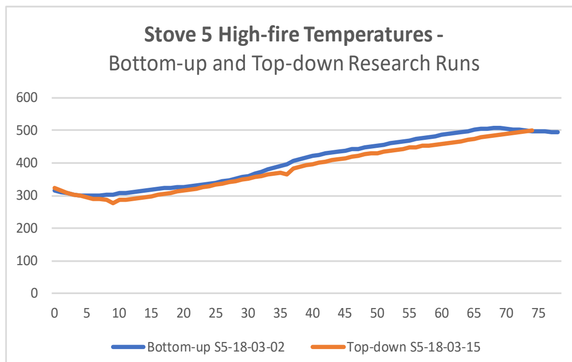


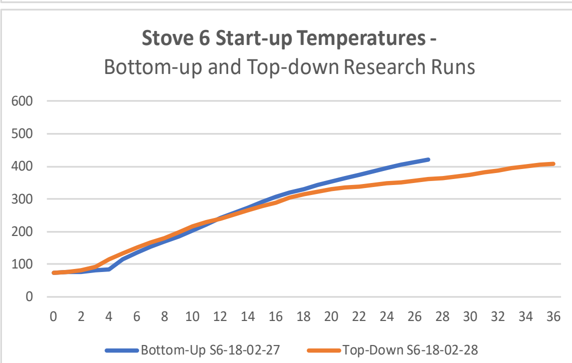












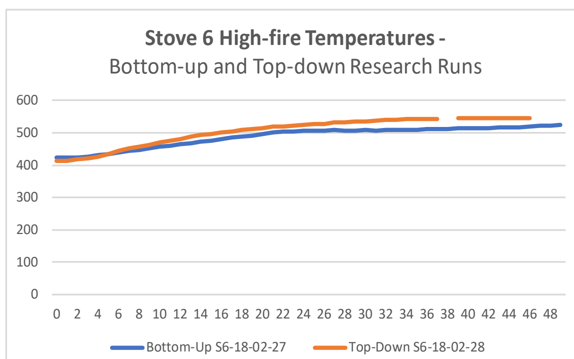
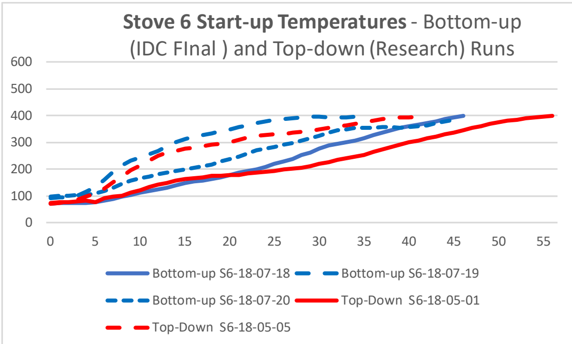
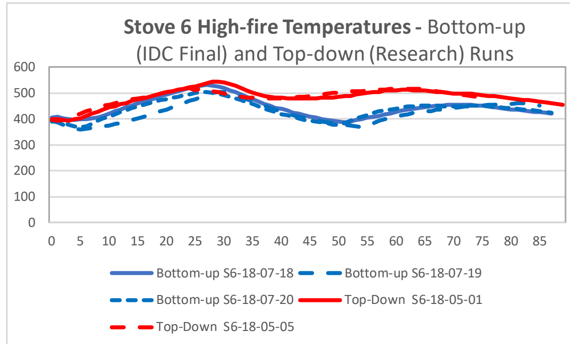


Figure 77 continued



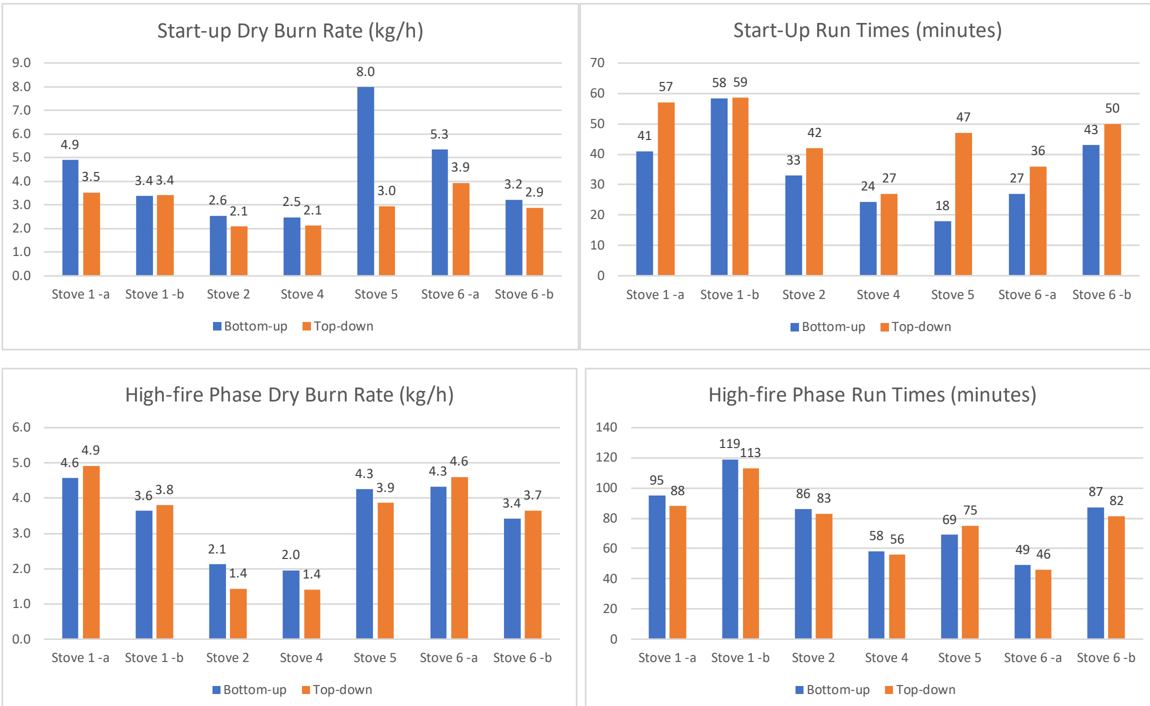


Temperatures in the start-up phase of the bottom-up runs tended to be higher than those in the top-down runs. The temperature difference was most notable in the runs for stove 2 and 5. As shown in Figure 4-11, the higher bottom-up temperatures were, in most cases, associated with higher burn rates and lower run times in the start-up phase.

However, these differences did not generally carry into the subsequent high-fire phase. As shown in Figure 77, the temperatures for most stoves at the beginning of the high-fire phase were similar for top-down and bottom runs. The stoves with the largest temperature divergences at the beginning of the high-fire phase were stove 1, which had stove temperatures up to 30°F higher in the top-down than the bottom-up runs and stove 2, in which the bottom-up temperatures were about 30°F higher than the top-down runs.

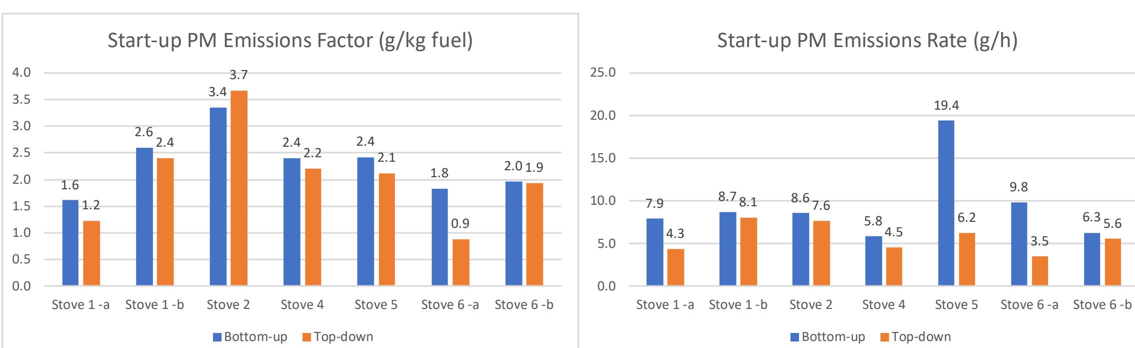
As shown in Figure 78, burn rates tended to be higher and run times shorter in the start-up phase of the bottom-up runs, which is consistent with the higher temperatures in those runs. However, there was no consistent relationship between the kindling configuration and burn rate and run times in the high-fire phase.

Figure 78. Comparison of Start-Up and High-Fire Bottom-Up and Top-Down Burn Parameters[6]



The start-up configuration also appears to influence PM emissions in the start-up phase. As shown in Figure 79, the start-up phase PM emission factor, in g PM/kg fuel combusted, tended to be slightly higher in the bottom-up runs, which had higher temperatures and higher burn rates than in the top-down runs. The differences in emission rates (in g/h) between the bottom-up and top-down runs were more pronounced due to a combination of the slightly higher PM emissions and the lower run times in that configuration group.

Figure 79. Comparison of Start-Up Bottom-Up and Top-Down PM Emission Parameters



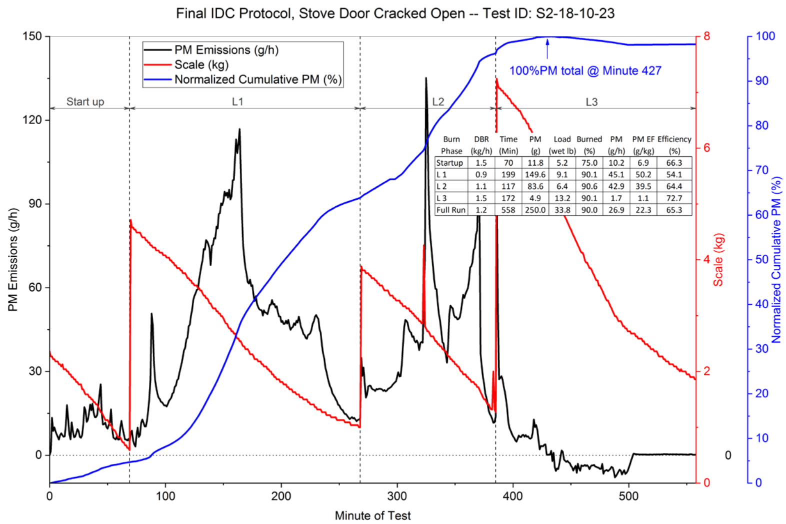
Note: Where more than one run was included the category, these metrics are the averages of the values for those runs.

3.2.2 Start-Up Door Position

Two sets of three replicate runs, a total of six test runs, were performed on stove 2. Except for the position of the stove door during the first five minutes of the runs, all fueling and operating procedures were the same for all six test runs.

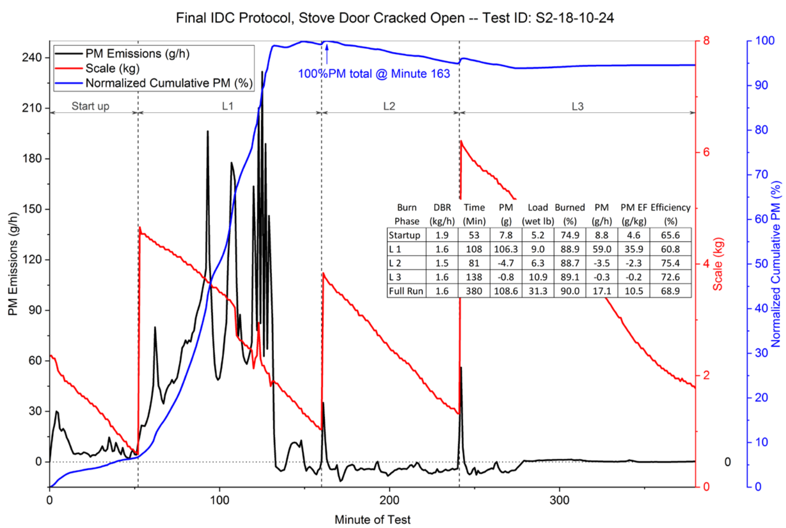
The first set of runs was performed on consecutive days in October 2018. In the first two of the October runs, the stove door was cracked open and, in the third run of that set, the door was in a wide-open position for five minutes at the beginning of the start-up period. The second set of runs was performed on consecutive days in January 2019. In that set, the door was wide open for the first five minutes of start-up for the first two runs and cracked open for that period during the third run. Effects of the door position on stove temperatures, burn rates, and PM emissions parameters in the start-up phase are discussed below. Test profiles of the stove 2 IDC runs in October 2018 and January 2019 are shown in Figures 80 and 81, respectively.

Figure 80. Stove 2—IDC Final Protocol Runs—October 2018



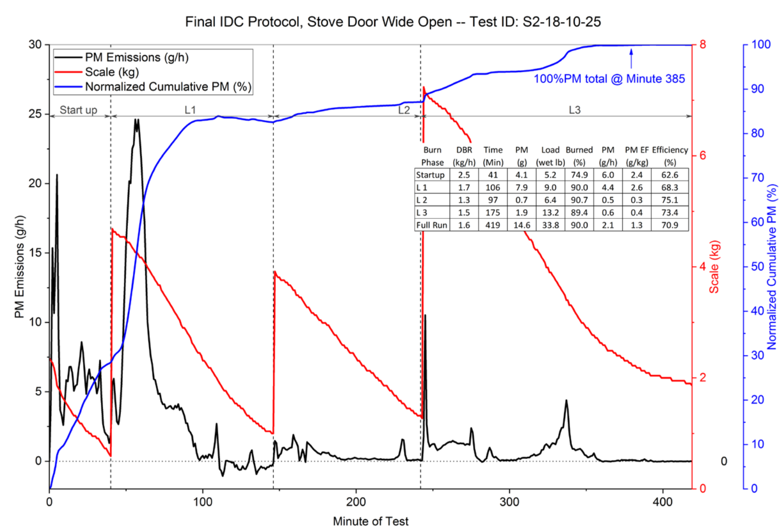
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	1.5	70	11.8	5.2	75.0	10.2	6.9	66.3
L 1	0.9	199	149.6	9.1	90.1	45.1	50.2	54.1
L 2	1.1	117	83.6	6.4	90.6	42.9	39.5	64.4
L 3	1.5	172	4.9	13.2	90.1	1.7	1.1	72.7
Full Run	1.2	558	250.0	33.8	90.0	26.9	22.3	65.3

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	1.9	53	7.8	5.2	74.9	8.8	4.6	65.6
L 1	1.6	108	106.3	9.0	88.9	59.0	35.9	60.8
L 2	1.5	81	-4.7	6.3	88.7	-3.5	-2.3	75.4
L 3	1.6	138	-0.8	10.9	89.1	-0.3	-0.2	72.6
Full Run	1.6	380	108.6	31.3	90.0	17.1	10.5	68.9

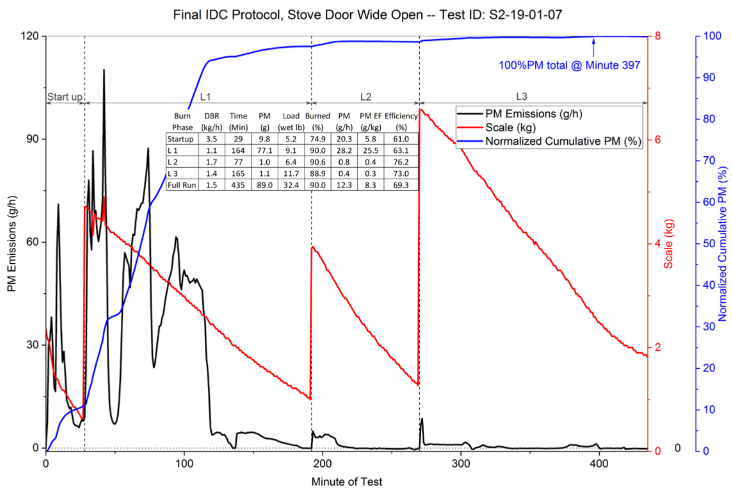
* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.5	41	4.1	5.2	74.9	6.0	2.4	62.6
L 1	1.7	106	7.9	9.0	90.0	4.4	2.6	68.3
L 2	1.3	97	0.7	6.4	90.7	0.5	0.3	75.1
L 3	1.5	175	1.9	13.2	89.4	0.6	0.4	73.4
Full Run	1.6	419	14.6	33.8	90.0	2.1	1.3	70.9

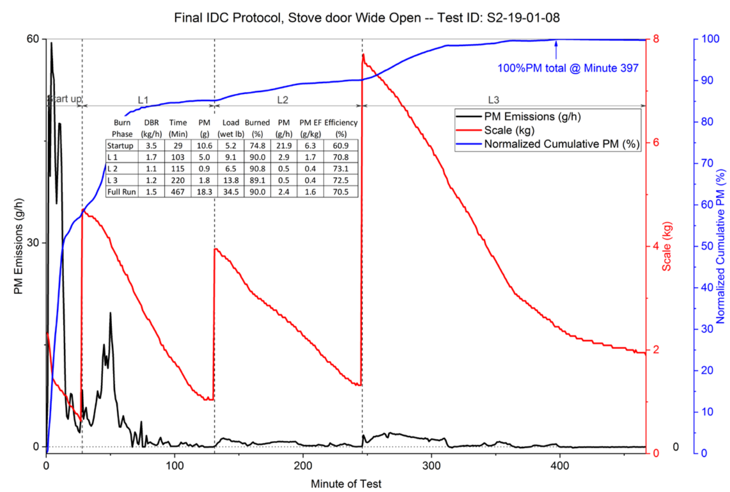
* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Figure 81. Stove 2—IDC Final Protocol Runs—January 2019



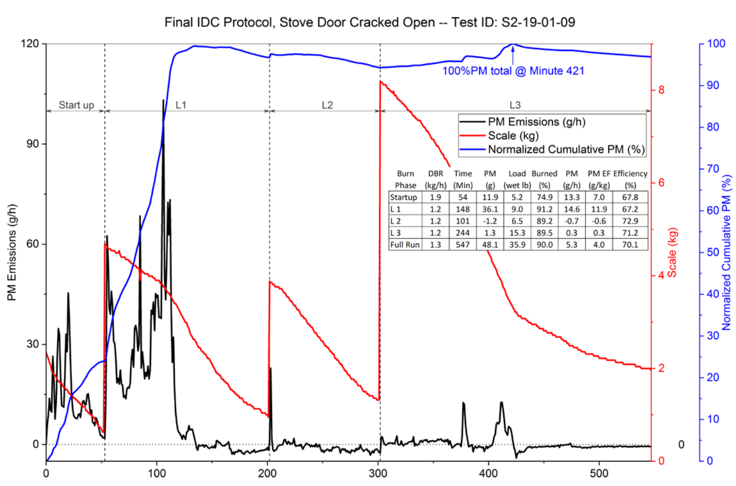
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.5	29	9.8	5.2	74.9	20.3	5.8	61.0
L 1	1.1	164	77.1	9.1	90.0	28.2	25.5	63.1
L 2	1.7	77	1.0	6.4	90.6	0.8	0.4	76.2
L 3	1.4	165	1.1	11.7	88.9	0.4	0.3	73.0
Full Run	1.5	435	89.0	32.4	90.0	12.3	8.3	69.3

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	3.5	29	10.6	5.2	74.8	21.9	6.3	60.9
L 1	1.7	103	5.0	9.1	90.0	2.9	1.7	70.8
L 2	1.1	115	0.9	6.5	90.8	0.5	0.4	73.1
L 3	1.2	220	1.8	13.8	89.1	0.5	0.4	72.5
Full Run	1.5	467	18.3	34.5	90.0	2.4	1.6	70.5

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	1.9	54	11.9	5.2	74.9	13.3	7.0	67.8
L 1	1.2	148	36.1	9.0	91.2	14.6	11.9	67.2
L 2	1.2	101	-1.2	6.5	89.2	-0.7	-0.6	72.9
L 3	1.2	244	1.3	15.3	89.5	0.3	0.3	71.2
Full Run	1.3	547	48.1	35.9	90.0	5.3	4.0	70.1

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

The test metrics for the two sets of three replicate runs are shown in Table 81.

Table 81. Stove 2—Comparison of Test Metrics in Start-Up Phase of IDC Runs

Test ID #	Door Position (5 min at start-up)	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
S4-18-10-23	cracked open	1.47	70	11.85	10.15	6.92
S4-18-10-24	cracked open	1.93	53	7.77	8.80	4.57
S4-18-10-25	wide open	2.49	41	4.13	6.05	2.43
S4-19-01-07	wide open	3.53	29	9.83	20.33	5.76
S4-19-01-08	wide open	3.50	29	10.60	21.94	6.26
S4-19-01-09	cracked open	1.89	54	11.93	13.26	7.01

In both replicate groups, the loads that started with the door wide open had higher burn rates and shorter run times than the cracked-open runs in the start-up phase. The pattern of PM emissions was less consistent in the two groups. All start-up phase PM metrics (Total PM, PM EF, and PM ER) were higher in the two runs that started with a cracked-open door than in the wide-open door run. That pattern was not seen in the start-up phase of the second set of runs. In that group, the start-up phase total PM and the EF were slightly higher in the cracked-open run than in the two wide-open runs, but the ER in the cracked-open run was considerably lower than in the other two runs, due to that run's short run time. In this discussion, the month of the run is used only to distinguish the two groups of runs, and not indicate that the month itself was a determining factor.

The metrics for the high-fire phase of the two sets of stove 2 IDC runs are shown in Table 82.

Table 82. Stove 2—Comparison of Test Metrics for IDC Reload 1—High-Fire Phase

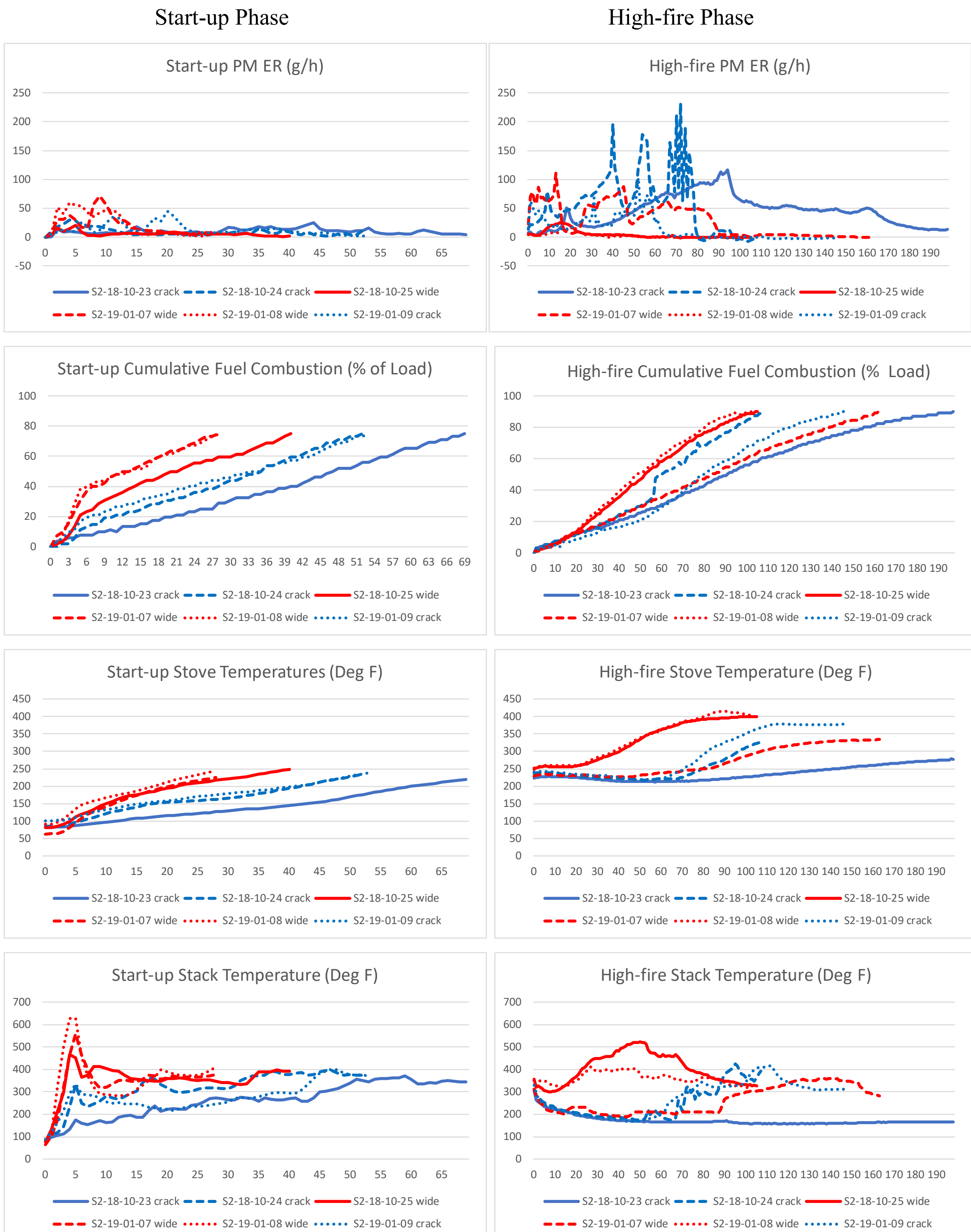
Test ID #	Door Position (5 min at start-up)	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
S4-18-10-23	cracked open	0.90	199	149.65	45.12	50.17
S4-18-10-24	cracked open	1.65	108	106.28	59.04	35.88
S4-18-10-25	wide open	1.69	106	7.85	4.44	2.62
S4-19-01-07	wide open	1.10	164	77.08	28.20	25.52
S4-19-01-08	wide open	1.73	103	5.04	2.94	1.70
S4-19-01-09	cracked open	1.23	148	36.06	14.62	11.92

In this phase, the run in the first set of tests that started with the door wide open again produced far less PM than set of runs that had the door only slightly cracked open. Two of the runs, S4-18-10-24 (cracked open) and S4-18-10-25 (wide open), had very similar high-fire phase dry-burn rates and test times. However, the PM parameters for S4-18-10-24 were more than 13 times those for S4-18-10-25. S4-18-10-23 (cracked open) had a high-fire phase burn rate that was approximately one-half and a run time approximately twice of those of the other two runs. The high-fire phase total PM and EF in that run were higher than in any other run in either sampling period. However, due to the longer test time, the ER rate for S4-18-10-23 was lower than in the other cracked open run, S4-18-10-24.

S4-19-01-08 had the highest high-fire burn rate and shortest test period, while the reverse was true for run S4-19-01-07. The run with the lowest burn rate, S4-19-01-07, produced the most PM; PM emissions in the high-fire phase (15 times those of the other runs). The ERs and EFs measured in the S4-19-01-08 and S4-19-01-07 runs were similarly divergent. Both of those runs had wide-open door positions in the beginning of the start-up period. PM emission parameters in the cracked-open run in that group were midway between those of the two wide-open runs.

The real-time emissions, combustion, and temperature profiles for the start-up and high-fire phases shown in Figure 82 provide some insight into these results. In the graphs for the figure, runs that started with the door cracked open are displayed in blue and those that started with the door wide open in red.

Figure 82. PM Emissions Profiles, Cumulative Fuel Consumption, and Temperature Profiles—Start-Up and High-Fires Phase of Stove 2 IDC Runs



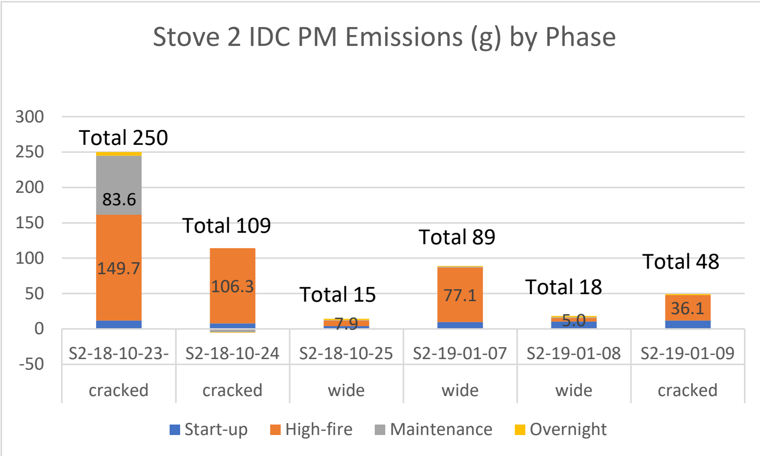
All runs with an initial wide-open door position had higher fuel combustion rates and more rapid increases in stack and stove temperatures[7] than in the cracked-open runs early in the start-up phase. The high initial combustion in the door wide-open runs resulted in higher PM emissions in the beginning of those runs, but emissions dropped more quickly in those runs than in the cracked-open runs. In particular, the stove temperature in the first run, S4-18-10-23, was lower than in all other runs throughout the start-up phase, and emissions in that run continued throughout the start-up phase.

Because start-up phase PM emissions make up a relatively small portion of the PM emissions in the entire run, any effect of the initial door position on emissions in subsequent phases are particularly important to overall emission measurements. Two of the runs that started out with the door wide open, S4-18-10-25 and S4-19-01-08, had very good combustion throughout the high-fire phase, characterized by high-stove and stack temperatures, rapid combustion rates, and low PM emissions. The third wide-open run, S4-19-01-07, had high-fire temperature, combustion, and emissions profiles that were similar to those in the cracked-open runs. Because that run had start-up profiles similar to those of the other wide-open runs, initial door position does not explain the lower temperatures and combustion rates and higher emissions seen in that run in the high-fire phase relative to the other wide-open runs.

In two of the cracked-open runs, S4-18-10-24 and S4-19-01-09, as well as in the S4-19-07 wide-open run, temperatures recovered midway through the high-fire phase, and emissions dropped as the temperatures increased. However, run S4-18-10-23, the cracked-open run with the lowest start-up temperatures and combustion rates, continued to demonstrate poor combustion and elevated emissions throughout the high-fire phase. Those conditions also continued throughout the maintenance phase of that run. It is not clear why the other runs that started with the door cracked open were able to recover midway through the high-fire phase, while the initial deficit appears to have had a more dramatic effect on burns in subsequent phases in the S4-18-10-23 run.

Figure 83 shows the PM emissions for the entire runs, by phase.

Figure 83. PM Emissions in Stove 2 IDC Runs



The continued poor combustion and low temperatures in the latter part of the high-fire phase and in the maintenance phase of run S4-18-10-23, discussed above, resulted in total PM emissions in that run that were more than twice those in all other runs. While the cracked-door position in the first five minutes of that run likely contributed to the poor combustion, it is not clear why that effect was so much more dramatic and continued for so much longer in that run than in the other door cracked-open runs. In addition, it is not clear why the wide-open run S4-19-01-07 was similar to the other wide-open runs in the start-up phase but performed more like the cracked-open runs in the high-fire phase.

It should also be noted that stove 2 is a small stove that is quite sensitive to loading and operational parameters. Although the initial door position appears to play a role in combustion and emissions in this stove, this effect may not be as significant in other stoves.

3.3 Impact of Load Density and Air Setting

3.3.1 Load Density

The IDC v1 protocol specifies a load density of 5 lb/ft^3 of small fuel pieces with air settings fully open in the high-fire phase burn and 7 lb/ft^3 of large pieces with air settings at a medium setting in the maintenance phase. The final IDC protocol requires a density of 7 lb/ft^3 of small fuel pieces with air settings fully open until 50% of the fuel load has been consumed for the high-fire phase and 5 lb/ft^3 of large pieces with air settings at the low-air setting for the maintenance phase. EPA's current stove certification method, Method 28, requires a 7 lb/ft^3 loading volume.

Paired runs in which all operating protocols were the same, except for the loading density in the high-fire and maintenance phase, are available for stoves 1, 2, 5, and 6. These runs allow for an evaluation of the effect of load density on stove temperature, burn rate and PM emissions parameters in the high-fire and maintenance phases. In all these runs, the high-air setting was maintained throughout the high-fire phase and the air setting was on medium during the maintenance phase.

The temperature profiles for the high-fire and maintenance phases of the comparative runs are shown in Figure 84. Cumulative fuel consumption (in kg) for those phases is shown in Figure 85. The cumulative fuel consumption metric, rather than percentage of load combusted, was used to track combustion rates over the course of the test because of the different load in the comparison runs. The color used for each run is consistent in the high-fire phase and maintenance phase graphs.

Figure 84. Comparison of High-Fire and Maintenance Phase Temperature Stove Profiles for Paired Runs with Different Load Densities

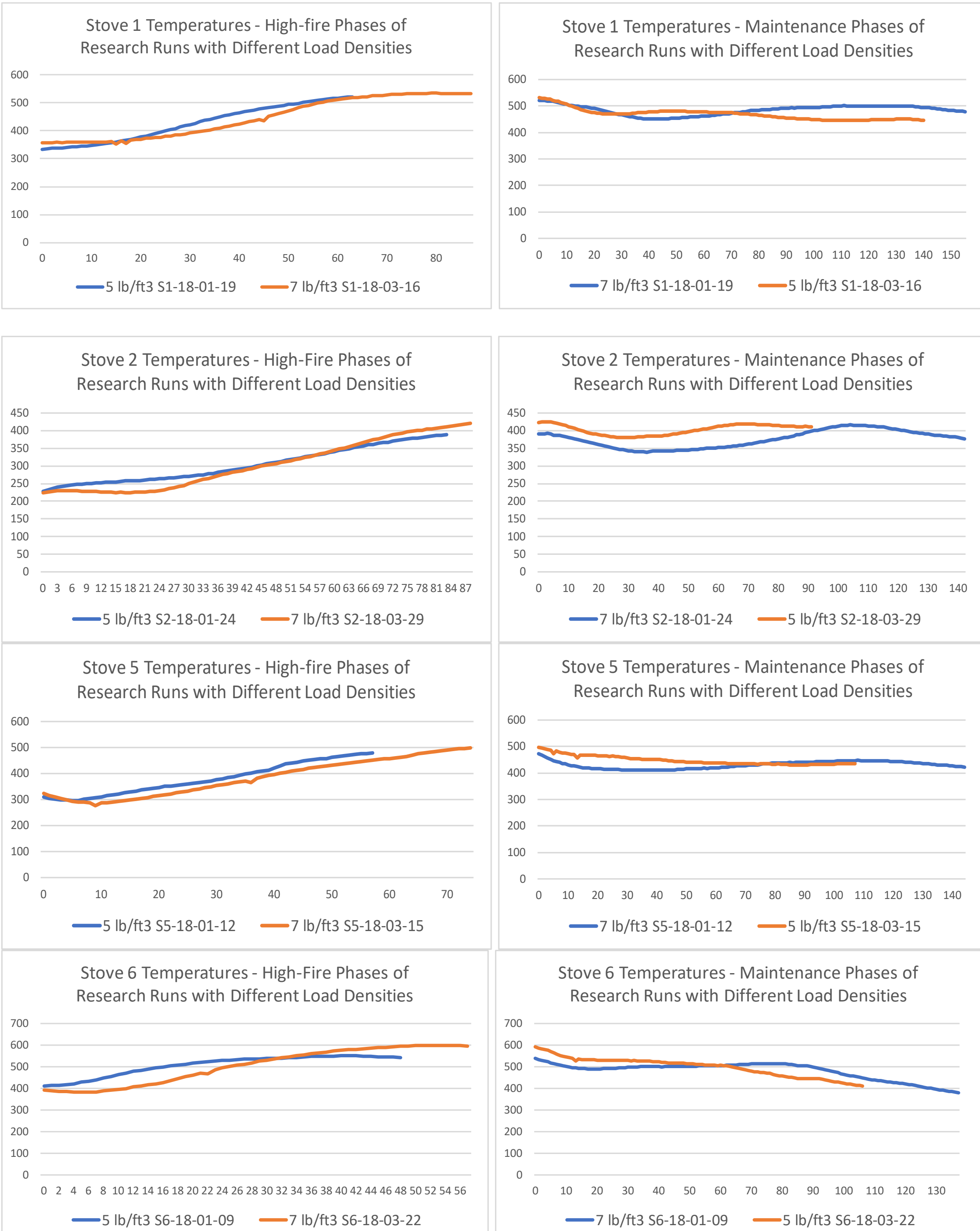
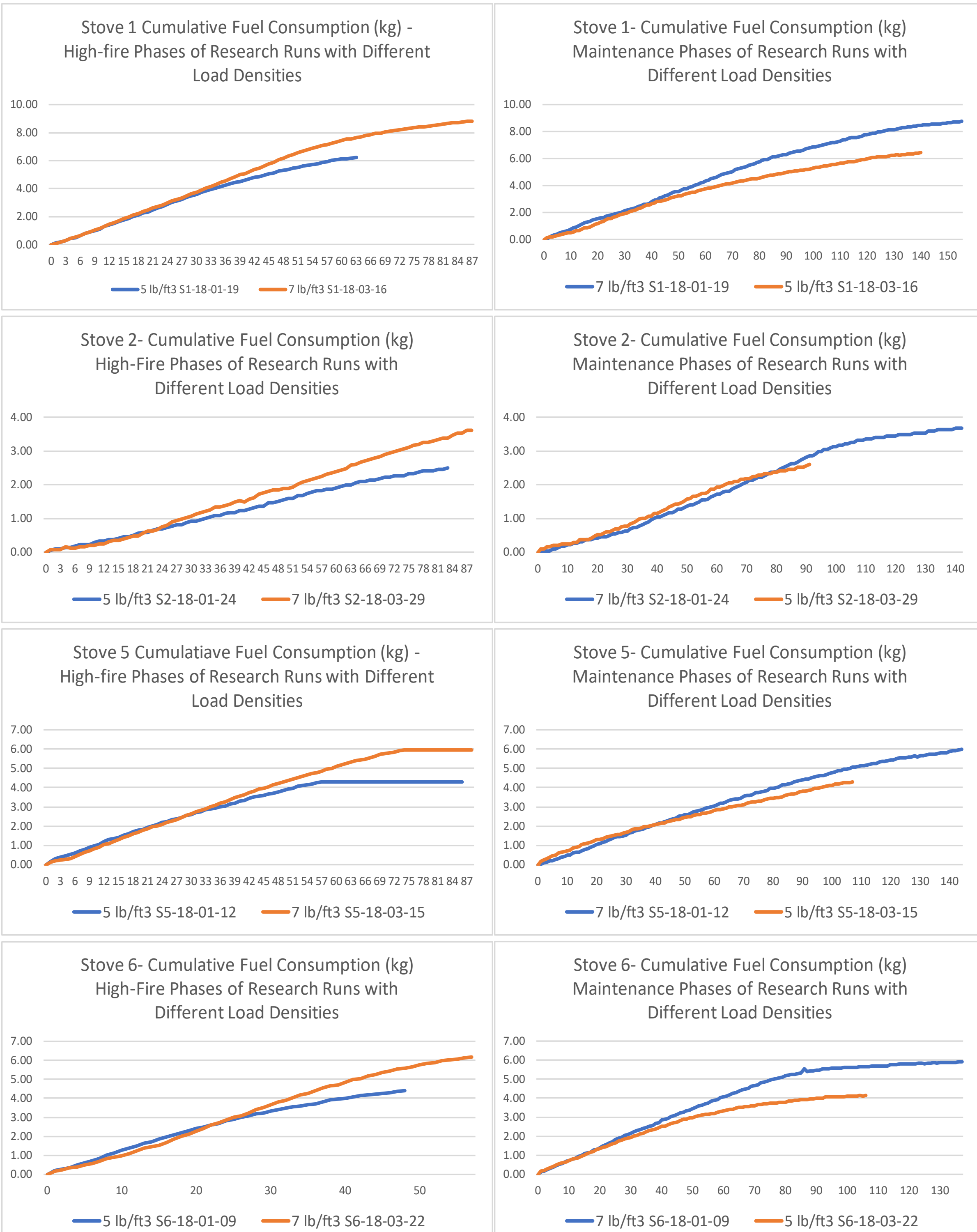


Figure 85. High-Fire and Maintenance Phase Cumulative Fuel Consumption in Runs with Different Load Densities



In high-fire phase, a period of steady or slightly decreasing stove temperature at the beginning of most of the burns was followed by increasing temperatures. For all stoves except for stove 2, the period before temperatures began to rise was longer in the runs with the larger (7 lb/ft^3) than those with the 5 lb/ft^3 loads. Fuel consumption rates tended to be similar during the first 25 to 35 minutes of the high-fire phase 5 lb/ft^3 and 7 lb/ft^3 runs for each stove.

The initial temperatures in the maintenance phases of stoves 2, 5 and 6 were higher in the run that had the higher fuel density in the high-fire phase. That difference continued through a large portion of the maintenance phases, despite the fact that the runs with higher temperatures had the lower fuel densities in that phase. Temperatures decreased in the first part of this phase and then stabilized in most of the runs.

The metrics for the high-fire and maintenance phases of the comparative runs are shown in Tables 83 and 84, respectively. In the high-fire phase of the stove 1, 2, and 6 runs, the PM emission factor and emission rates were three to six times higher for the 7 lb/ft^3 than the 5 lb/ft^3 loads. The opposite result was seen in stove 5. While high-fire phase emissions in the higher density load run in stove 5 were similar to those seen in the other stoves, emissions in the 5 lb/ft^3 run were substantially elevated relative to those in that phase of the other runs. The high-fire phase PM emission rates and emission factors in that stove were five times higher in the smaller than in the larger load run.

In the maintenance phase, stoves 2, 5, and 6 had minimal PM emissions in the runs with both load densities. However, stove 1 maintenance phase emissions were elevated, roughly twice as high as in the high-fire phase. In both phases, run S1-18-03-16 had substantially higher emissions than the comparison run S1-18-01-19, although that run had the higher fuel density in the high-fire phase and the lower fuel density in the maintenance phase.

Table 83. Comparison of High-Fire Phase Parameters in Runs with Different Fuel Densities

	Test ID	Fuel Density (lb/ft^3)	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Stove 1	S1-18-01-19	5	4.66	64	2.9	2.72	0.58
	S1-18-03-16	7	4.92	88	11.7	7.98	1.62
Stove 2	S4-18-01-24	5	1.44	83	1.6	1.14	0.79
	S4-18-03-29	7	1.99	89	10.8	7.25	3.64
Stove 5	S5-18-01-12	5	3.76	57	29.4	30.99	8.25
	S5-18-03-15	7	3.86	75	8.15	6.52	1.69
Stove 6	S6-18-01-09	5	4.46	48	1.0	1.28	0.29
	S6-18-03-22	7	5.16	58	5.2	5.35	1.04

Table 84. Comparison of Maintenance Phase Parameters in Runs with Different Fuel Densities

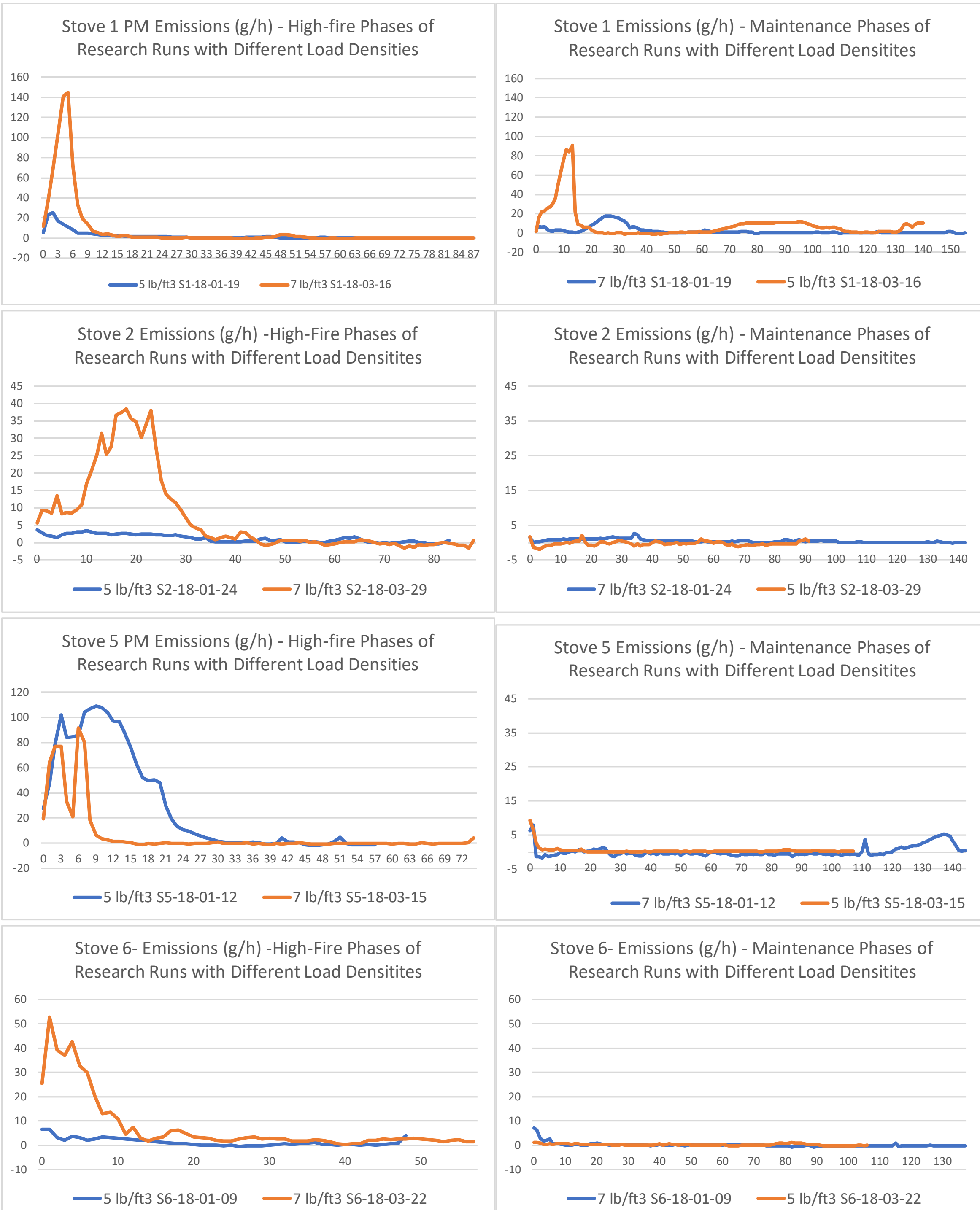
	Test ID	Fuel Density (lb/ft^3)	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Stove 1	S1-18-01-19	7	2.8	149	5.9	2.38	0.85
	S1-18-03-16	5	2.2	140	19.8	8.5	3.80
Stove 2	S4-18-01-24	7	1.25	141	1.1	0.47	0.38
	S4-18-03-29	5	1.39	91	-0.4	-0.27	-0.20
Stove 5	S5-18-01-12	7	2.19	144	0.3	0.1	0.10
	S5-18-03-15	5	2.00	107	0.7	0.4	0.20
Stove 6	S6-18-01-09	7	2.12	137	0.5	0.22	0.11
	S6-18-03-22	5	1.9	107	0.5	0.26	0.14

The emissions profiles in Figure 86 also show low high-fire phase emissions in the 5 lb/ft^3 runs for all stoves except for stove 5. High-fire PM emissions in the runs with 7 lb/ft^3 densities occurred primarily in the first part of that phase, during the period that stove temperatures were relatively stagnant. The longer emissions period for stove 2 corresponds to a longer period of level to slightly decreasing temperatures in the beginning of the burn in that stove, as shown in Figure 84.

Unlike the other stoves, there were substantial PM emissions in the 5 lb/ft^3 stove 5 run through the first 30 minutes of the high-fire phase, a period approximately 20 minutes longer than in the 7 lb/ft^3 run. The reason for the much higher high-fire PM emissions in the smaller load of this stove cannot be explained by the stove temperatures or fuel combustion parameters.

As discussed previously, PM emissions were minimal in the maintenance phase for both runs for all stoves except stove 1. The stove 1 maintenance phase emissions peaked at minute 13 in run S1-18-03-16, which had the smaller load in that phase, and at minute 26 in the other stove 1 run, S1-18-01-19. This timeframe may have been influenced by the temperatures in that phase. The initial decrease in temperature seen for all stoves leveled off sooner in run S1-18-03-16 than in S1-18-01-19. However, the temperature and fuel consumption curves for the maintenance phase of stove 1 are not substantially different from those for that phase in the other stoves and cannot explain why only stove 1 had substantial maintenance phase PM emissions. The fact that the same stove 1 run had higher emissions in both phases, despite the switching of load densities, indicates that some factor other than load size contributed to the emissions results for that stove.

Figure 86. High-Fire and Maintenance Phase PM Emissions—5 lb/ft^3 and 7 lb/ft^3



Apart from the stove 5 results, the high-fire phase results support the conclusion that higher density loads tend to produce higher PM emissions in that phase. Because the maintenance phase tended to produce minimal emissions, a test with the higher density load in the high-fire phase rather than the maintenance phase is more likely to be associated with higher emissions for those two phases combined.

Because the high-fire phase is used to heat up the stove, it is also useful to evaluate the effect of load density on temperature increases in that phase. Table 85 compares stove temperatures measured in the high-fire phase.

Table 85. Comparison of High-Fire Phase Stove Temperatures for 5 lb/ft^3 and 7 lb/ft^3 Density Runs

		Dry Fuel Burned (kg)	High-Fire Run Time	Temp. (°F) at Start of Burn	Temp. (°F) at End of Burn	Temp. Gain (°F)	Rate of Temp. Gain (°F /min)	Temp gain/kg Fuel
Stove 1	7 lb/ft3	7.21	88	356	532	176	2.0	24.4
	5 lb/ft3	4.97	64	334	521	187	2.9	37.6
	% Difference	31%	27%	6%	2%	-6%	-46%	-54%
Stove 2	7 lb/ft3	2.96	89	224	420	196	2.2	66.2
	5 lb/ft3	1.99	85	257	404	147	1.7	73.9
	% Difference	33%	4%	-15%	4%	25%	21%	-12%
Stove 5	7 lb/ft3	4.83	75	323	499	176	2.3	36.4
	5 lb/ft3	3.57	57	309	478	169	3.0	47.3
	% Difference	26%	24%	4%	4%	4%	-26%	-30%
Stove 6	7 lb/ft3	4.99	58	391	596	205	3.5	41.1
	5 lb/ft3	3.56	48	412	545	133	2.8	37.4
	% Difference	29%	17%	-5%	9%	35%	22%	9%

As shown in that table, for all stoves, the temperature at the end of the high-fire phase was higher in the runs with the higher load temperatures. However, the difference between the final and initial temperature (noted in the above table as "temperature gain") was higher in the 5 lb/ft^3 run than in the 7 lb/ft^3 run in stove 1, due to a lower initial temperature in the 5 lb/ft^3 run. The rate of temperature gain, which considers both the temperature increase during the burn and the run time of the phase, was also higher for the denser loads for all stoves except stove 1. In contrast, when the temperature gain was normalized to the dry mass of fuel burned, the temperature gain per kg fuel burned was higher in the less dense loads for all stoves except stove 6 due to the smaller load size.

The air settings in these comparison runs, a high-air setting throughout the high-fire phase and a medium-air setting in the maintenance phase, are consistent with IDC v1 but not with the IDC final protocol. In the IDC final protocol, the air setting is moved to low after 50% fuel combustion in the high-fire phase and is set to low, rather than medium, in the maintenance phase. The investigation of the impact of those operating parameters follows.

3.3.2 High-Fire Phase—Effect of Moving Air Setting to Low after 50% of Load is Combusted

As discussed above, in earlier IDC prototypes, the air setting was maintained at high throughout the high-fire phase. As shown in Figure 86, emissions under those operating conditions tended to occur early in the phase. In the IDC final protocol runs, however, the air setting is moved to low when 50% of the high-fire fuel load has been consumed. This change was introduced to reproduce field operating conditions, temper heat output, and to lower stove temperatures for maintenance and overnight phases.

Test runs performed on four of the stoves were analyzed to evaluate the impact of the air setting on high-fire phase operating and emissions parameters. For each of those stoves, the high-fire phase air setting was maintained at the high setting in one of the comparison runs and was moved to low when 50% of the high-fire load combusted in the other two runs. To minimize the possible interference of other variables, comparison runs had the same start-up kindling configuration (top-down for the stove 1 and stove 6 pairs and bottom-up for stoves 2 and 5) and a high-fire load density of 7 lb/ft^3 was used in all runs. The runs used for this analysis are listed in Table 86.

Table 86. Runs Selected to Compare Impact of High-Fire Phase Air Settings

	Start-up Configuration	High-Fire Air Setting	
		High	High to Low
Stove 1	Top-down	S1-18-03-16	S1-18-05-08
	Top-down		S1-18-05-09
Stove 2	Bottom-up	S4-18-03-29	S4-18-05-12
	Bottom-up		S4-18-05-17
Stove 5	Bottom-up	S5-18-03-02	S5-18-05-02
	Bottom-up		S5-18-05-04
Stove 6	Top-down	S6-18-03-22	S6-18-05-01
	Top-down		S6-18-05-05

Table 87 compares the high-fire phase dry-burn rates (DBR) in the comparison runs for each of the four stoves.

Table 87. Comparison of High-Fire Phase Dry-Burn Rates (DBR)

	Run ID	Air Setting	DBR (kg/h) to 50% Combustion	DBR (kg/h) after 50% Combustion	% Decrease after 50% Combustion	DBR (kg/h) Entire Phase	Avg High-Low DBR/ High Air DBR
Stove 1	S1-18-03-16	High	6.4	4.1	36%	5.1	76%
	S1-18-05-08	High-Low	5.9	3.0	50%	4.1	
	S1-18-05-09	High-Low	5.9	2.5	58%	3.6	
Stove 2	S4-18-03-29	High	2.0	2.2	-14%	2.1	66%
	S4-18-05-12	High-Low	1.2	1.9	-56%	1.4	
	S4-18-05-17	High-Low	1.3	1.2	6%	1.3	
Stove 5	S5-18-03-02	High	5.1	3.7	29%	4.3	68%
	S5-18-05-02	High-Low	5.3	1.8	66%	2.9	
	S5-18-05-04	High-Low	5.5	1.9	65%	3.0	
Stove 6	S6-18-03-22	High	6.0	4.8	20%	5.4	69%
	S6-18-05-01	High-Low	6.2	2.2	65%	3.5	
	S6-18-05-05	High-Low	7.0	2.6	63%	4.0	

In all stoves, the DBRs for the period after 50% combustion and for the entire phase were higher in the run in which the high-air setting was maintained than in either of the runs in which the air setting was switched to low. The DBRs for the entire phase in the runs in which the air setting was switched to low were 66 to 76% of those in the runs in which the high-air setting was maintained.

However, the change in the DBR after the point of 50% combustion was different for stove 2 than the other stoves. In stoves 1, 5, and 6, the DBR for the high-air run decreased between 20% and 36% after the 50% combustion point, while the DBR decrease after that point was more substantial for the high-low runs (50 to 66%). That decrease was not evident in stove 2. In two of the stove 2 runs, the DBR increased after the 50% combustion point and, in the third stove 2 run, the DBR remained roughly the same after that point. The stove 2 burns tended to be more inconsistent than in the other stoves.

Stove temperatures in the comparison runs are shown in Table 88. The percent differences in temperatures listed in that table for each stove were calculated as the difference between the temperature in the high-air run and the average temperatures for the two high-low air runs divided by the temperatures in the high-air run.

Table 88. Comparison of High-Fire Phase Stove Temperatures (°F)

		Air Setting	Initial Temp	Temp at 50% Comb.	Temp. at End of Phase	Temp. Increase at 50%	Temp. Increase after 50%	Total Temp Gain
Stove 1	18-03-16	High	356	417	532	61	115	176
	18-05-08	High-Low	334	395	480	61	85	146
	18-05-09	High-Low	345	421	458	76	37	113
	Percent Difference[8]		5%	2%	12%	-12%	47%	26%
Stove 2	18-03-29	High	224	319	420	95	101	196
	18-05-12	High-Low	226	284	396	58	112	170
	18-05-17	High-Low	223	274	367	51	93	144
	Percent Difference		0%	13%	9%	43%	-1%	20%
Stove 5	18-03-02	High	317	373	507	56	134	190
	18-05-02	High-Low	249	423	426	174	3	177
	18-05-04	High-Low	282	417	429	135	12	147
	Percent Difference		16%	-13%	16%	-176%	94%	15%
Stove 6	18-03-22	High	391	518	598	127	80	207
	18-05-01	High-Low	401	543	456	142	-87	55
	18-05-05	High-Low	395	520	479	125	-41	84
	Percent Difference		-2%	-3%	22%	-5%	180%	66%

As shown in Table 88, temperature during the high-fire phase increased more in the high-air runs than in the high-low runs in all stoves. As a result, stove temperatures at the end of the phase were 9% to 22% higher in the high-air runs than in the average of the corresponding high-low runs. As with the dry-burn rate, however, the temperature changes in stove 2 were different from those of the other stoves.

In stoves 1, 5 and 6, temperatures increased substantially (80°F to 134°F) after the point of 50% combustion in the high-air runs, while the temperature increase in that period was lower in the high-low air runs. In fact, in stove 6, the temperatures in the stove 6 high-low runs decreased by 41°F and 87°F after 50% combustion, while the temperature in that period increased by 80% in the high-air run in that stove. In stove 2, the temperature increases after 50% combustion were similar in all runs, regardless of air setting.

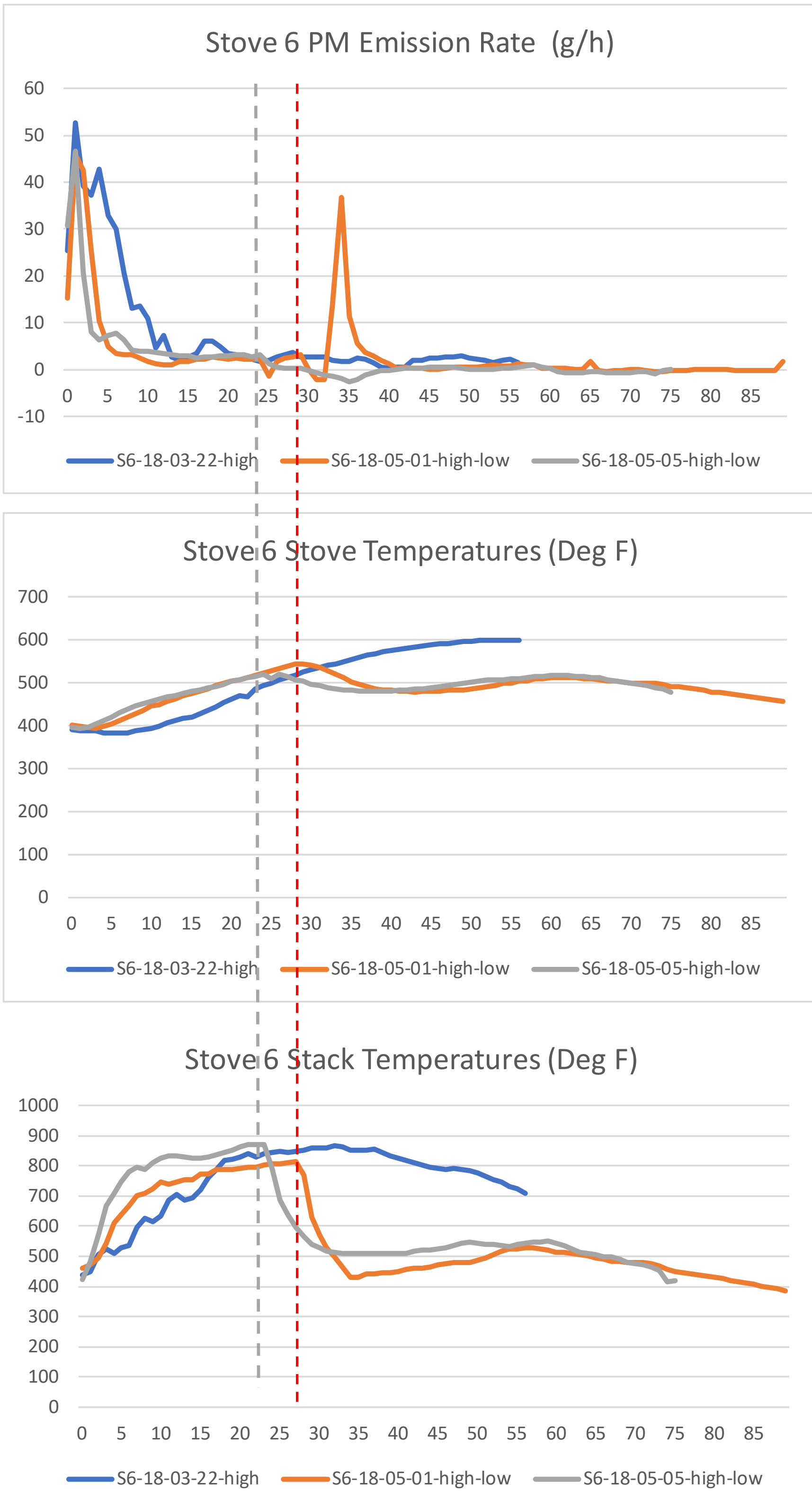
Table 89 shows PM emissions in the high and high-low air setting runs. As in the previous table, the percent differences in PM emissions were calculated, for each stove, as the difference between the PM emitted in the high-air run and the average PM emitted in the two runs in which the setting was switched to low divided by the PM emissions in the high-air run.

Table 89. Comparison of High-Fire Phase PM Emissions

		Air Setting	PM (g) Emitted at 50% Combustion	PM (g) Emitted after 50% Combustion	PM (g) Emitted in Entire Phase
Stove 1	18-03-16	High	15.6	0.3	15.8
	18-05-08	High-Low	31.5	0.3	31.8
	18-05-09	High-Low	31.5	-0.9	30.6
	Percent Difference[9]		-103%	199%	-97%
Stove 2	18-03-29	High	10.8	-0.2	10.7
	18-05-12	High-Low	21.3	-0.7	20.6
	18-05-17	High-Low	35.7	-0.3	35.4
	Percent Difference		-163%	-222%	-163%
Stove 5	18-03-02	High	26.7	0.1	26.8
	18-05-02	High-Low	1.8	-0.2	1.6
	18-05-04	High-Low	1.2	-0.9	0.3
	Percent Difference		94%	828%	96%
Stove 6	18-03-22	High	6.0	0.9	6.9
	18-05-01	High-Low	2.9	1.5	4.4
	18-05-05	High-Low	2.6	-0.1	2.5
	Percent Difference		53%	29%	50%

PM emissions in the high-fire phases of the stoves 1, 2, and 5 runs were essentially zero after the 50% combustion point, regardless of the air setting during that period. Therefore, any differences in the emissions in that phase in those stoves occurred before 50% combustion and are not related to the air setting after that fuel consumption point. As shown in Figure 87, a significant additional emissions peak occurred after the 50% combustion point in one of the stove 6 high-low runs. That figure also shows the stove and stack temperature profiles for the high-fire phase of the three stove 6 runs. The time of 50% combustion for each of the high-low runs, the point that the air setting was moved to low, is shown in those graphs with a dotted line that corresponds to the color of the profiles for those runs.

Figure 87. Stove 6 High-Fire Phase—PM Emissions and Stove and Stack Temperature Profiles for Runs with High and High-Low Air Settings



The stove and stack temperatures in both of the stove 6 high-low runs decreased immediately after the air setting was moved to low and remained substantially lower than those in the high-air run for the remainder of the phase. A burst of PM emissions occurred in one of the high-low runs, S6-18-05-01, approximately six minutes after the air setting was moved to low, at the point that the stack temperature reached its minimum level. Although the temperatures also declined substantially in the other high-low run, S6-18-05-05, after the air setting was changed, no additional significant emissions occurred during that period in that run. The reason for this difference is not clear.

In summary, the high-fire phase dry-burn rate patterns for three of the four stoves showed a consistent pattern, decreasing between 20% and 36% after 50% combustion in the high-air runs and between 50% and 66% in the high-low runs. Stove temperatures at the end of the high-fire phase for all stoves and the total temperature increase for all stoves were greater in the high-air than in the high-low runs. However, temperature changes after 50% combustion were variable, continuing to increase significantly in all high-air runs in stoves 1 and 2, remaining approximately level in the stove 5 high-low runs, and decreasing significantly in the stove 6 high-low runs. PM emissions were minimal or negative after 50% combustion in all comparison runs except for one of the high-low stove 6 runs.

The operating and emissions patterns in the high-fire phase of IDC final protocol runs were also evaluated to identify changes in those parameters when the air setting was moved to low. Table 90 summarizes the dry-burn run statistics for all IDC final protocol runs that burned red maple fuel. This data set consisted of three runs for all stoves except stove 2. As discussed previously, two sets of three IDC final protocol replicates were run on stove 2 and the results of all of those runs were included.

Table 90. Dry-Burn Rates (DBR) in High-Burn Phase of IDC Runs before and after 50% Combustion

		DBR (kg/h) Before 50% Combustion	DBR (kg/h) After 50% Combustion	DBR (kg/h)– Total Phase	DBR After 50% Combustion/ DBR Before 50%
Stove 1	Average	7.62	3.00	4.53	40%
	Std. Dev.	0.91	0.35	0.41	7%
	Rel. Std. Dev.	0.12	0.12	0.09	0.17
Stove 2	Average	1.89	1.57	1.73	83%
	Std. Dev.	0.49	0.43	0.44	13%
	Rel. Std. Dev.	0.26	0.27	0.26	0.15
Stove 4	Average	6.45	1.37	2.45	22%
	Std. Dev.	2.27	0.28	0.58	5%
	Rel. Std. Dev.	0.35	0.20	0.24	0.22
Stove 5	Average	6.27	2.35	3.57	38%
	Std. Dev.	0.45	0.41	0.32	10%
	Rel. Std. Dev.	0.07	0.17	0.09	0.25
Stove 6	Average	7.81	2.74	4.28	35%
	Std. Dev.	0.40	0.16	0.10	4%
	Rel. Std. Dev.	0.05	0.06	0.02	0.11
Stove 7	Average	3.76	1.55	2.29	42%
	Std. Dev.	0.53	0.19	0.09	10%
	Rel. Std. Dev.	0.14	0.12	0.04	0.24

As shown in that table, average dry-burn rates in the high-fire phase of all stoves decreased after 50% of the load was consumed and the air setting was moved to low. In stoves 1, 5, 6, and 7, the average dry-burn rate after 50% combustion, when the air setting was on low, was 35% to 42% of the rate before the setting change. The percentage difference in the dry-burn rate between before and after the setting change was somewhat greater in the stove 4 runs (dry-burn rate after switch was 22% of that before) and lower than the others in the stove 2 runs (dry-burn rate after the air setting was lowered was 83% of the rate before the change).

There was very little variation in dry-burn rates in the replicates in any of the stoves. The highest relative standard deviation was 0.35 for the DBR before 50% combustion in stove 4.

Temperature statistics for the high-burn phase of these runs are shown in Table 91.

Table 91. Stove Temperatures (ºF) in High-Burn Phase of IDC Runs

		Initial Temp	Temp at 50% Combustion	Temp at End of Phase	Temp Change before 50% Combustion	Temp Change after 50% Combustion	Total Temp Change
Stove 1	Average	307	399	440	92	40	132
	Std. Dev.	14	21	40	18	43	51
	Rel. Std. Dev.	0.04	0.05	0.09	0.19	1.07	0.39
Stove 2	Average	238	277	353	39	76	115
	Std. Dev.	11	54	49	44	19	39
	Rel. Std. Dev.	0.05	0.20	0.14	1.14	0.25	0.34
Stove 4	Average	257	392	381	135	-12	123
	Std. Dev.	11	37	41	26	23	31
	Rel. Std. Dev.	0.04	0.09	0.11	0.19	-1.95	0.25
Stove 5	Average	258	381	396	123	15	139
	Std. Dev.	29	50	6	22	44	23
	Rel. Std. Dev.	0.11	0.13	0.02	0.17	2.87	0.16
Stove 6	Average	396	510	434	114	-76	38
	Std. Dev.	9	13	18	6	29	24
	Rel. Std. Dev.	0.02	0.03	0.04	0.05	-0.39	0.62
Stove 7	Average	295	373	395	79	22	100
	Std. Dev.	21	17	16	14	31	29
	Rel. Std. Dev.	0.07	0.05	0.04	0.18	1.45	0.29

As shown in that table, there was good inter-run agreement for all stoves in the temperatures at the beginning of the phase, at 50% combustion, and at the end of the run, and in the total temperature change. In all stoves except stove 2, temperatures changed less after 50% combustion and those changes were more variable from run to run than those observed in the earlier part of the run. The average temperatures in stoves 4 and 6 decreased after the air setting was lowered at the 50% combustion point. The maximum average increase during that period was 76ºF in stove 2.

PM emissions statistics for these runs are shown in Table 92.

Table 92. PM Emissions in High-Burn Phase of IDC Runs before and after 50% Combustion

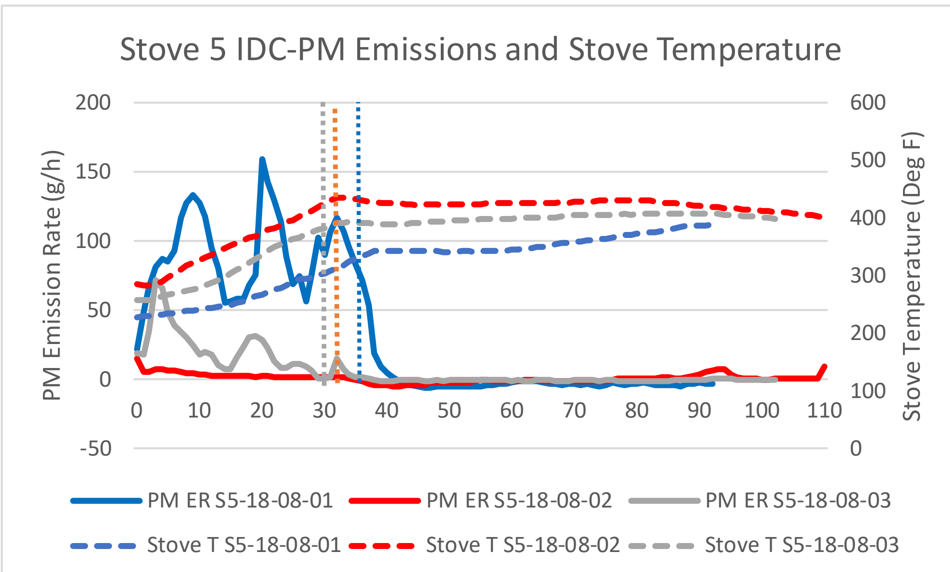
		Total PM (g)			PM Emission Rate (g/h)			PM Emission Factor (g/kg)		
		Before 50% Comb.	After 50% Comb.	Entire Phase	Before 50% Comb.	After 50% Comb.	Entire Phase	Before 50% Comb.	After 50% Comb.	Entire Phase
Stove 1	Avg	13.07	9.20	22.27	20.27	6.47	13.07	2.65	2.36	2.51
	SD	2.26	10.88	8.66	5.21	7.17	2.26	0.48	2.79	0.96
	Rel SD	0.17	1.18	0.39	0.26	1.11	0.17	0.18	1.18	0.38
Stove 2	Avg	44.45	19.18	63.63	35.85	14.90	44.45	21.52	11.85	17.26
	SD	32.50	31.38	57.73	26.25	21.83	32.50	15.73	19.30	15.63
	Rel SD	0.73	1.64	0.91	0.73	1.47	0.73	0.73	1.63	0.91
Stove 4	Avg	7.31	2.05	9.35	30.29	2.33	7.31	5.80	2.06	4.15
	SD	5.92	2.92	8.84	12.81	3.23	5.92	4.73	2.92	3.92
	Rel SD	0.81	1.43	0.94	0.42	1.39	0.81	0.82	1.42	0.94
Stove 5	Avg	22.70	-0.03	22.67	40.17	-0.04	22.70	6.80	-0.01	3.78
	SD	27.91	0.18	27.75	47.04	0.17	27.91	8.29	0.07	4.60
	Rel SD	1.23	-6.83	1.22	1.17	-4.56	1.23	1.22	-7.03	1.22
Stove 6	Avg	7.30	23.78	31.08	16.52	23.98	7.30	2.12	8.75	5.06
	SD	2.73	0.70	2.94	5.84	2.03	2.73	0.76	0.26	0.46
	Rel SD	0.37	0.03	0.09	0.35	0.08	0.37	0.36	0.03	0.09
Stove 7	Avg	3.03	0.77	3.80	3.59	0.51	3.03	0.99	0.32	0.70
	SD	1.27	0.38	1.34	1.20	0.30	1.27	0.41	0.16	0.24
	Rel SD	0.42	0.50	0.35	0.33	0.58	0.42	0.42	0.50	0.35

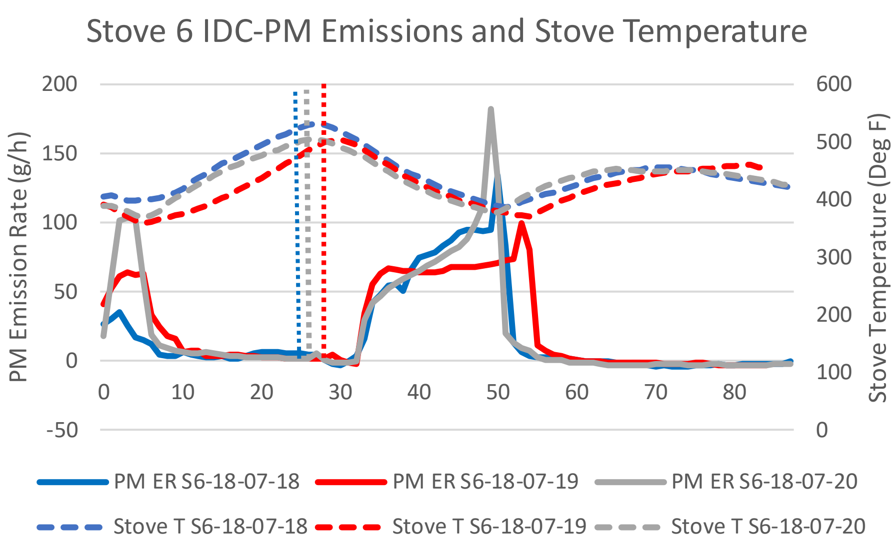
In approximately half of the IDC final protocol runs, minimal PM emissions occurred after the air setting was lowered. However, unlike in the previous analysis, significant additional PM was collected after 50% combustion in one or more runs in all stoves except stove 5.

Average total PM and PM emission factors (in g/kg) were substantially higher before 50% combustion than after that point in stoves 2, 4, 5, and 7. Those parameters were similar in the two periods in stove 1 and substantially higher after 50% combustion in stove 6. The average PM emission rate, which considers run time as well as emissions, was higher before than after the 50% combustion point for all stoves except stove 6. The stove 6 emission rate after the air setting switch was 45% higher than the rate before that point.

The differences in emissions after the air setting was moved to low can at least partially be explained by the stove temperature changes in that period, as illustrated in Figure 88. In that figure, the time of 50% combustion for each run is marked with a vertical dotted line that corresponds to the color of the run emissions and temperature profile lines for that run.

Figure 88. Stoves 5 and 6 High-Fire Phase PM Emissions and Stove Temperature Profiles





In stove 5, temperatures leveled off but did not decrease after the air setting was switched to low, while the temperatures in all three stove 6 runs dropped for an approximately 23-minute period after that point. During the period of temperature decline, significant additional PM emissions occurred in stove 6. PM emissions were not significant in stove 5 after the change in the air setting, probably due to the ability of that stove to maintain its temperature during that period. These temperature and emission impacts are consistent with the results of the high-low research runs discussed above for those stoves, an indication that the response to the lowered air setting is consistent in each of the stoves but different between the two stoves.

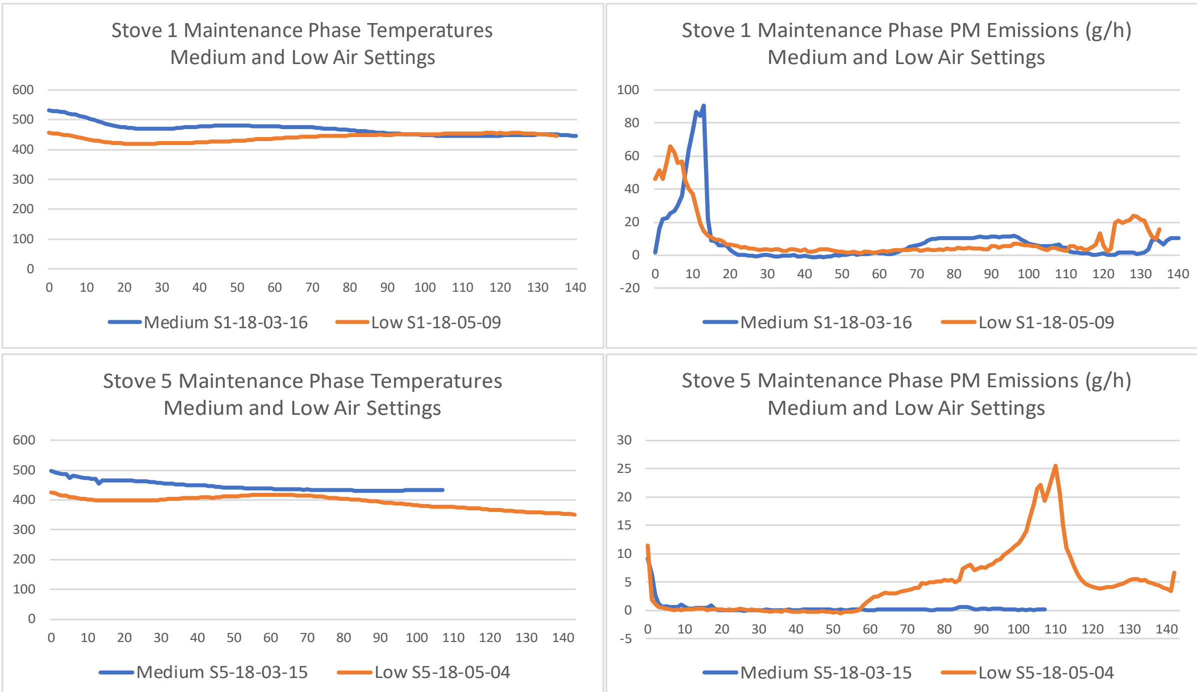
Stove 5 and 6 have similar sized medium fireboxes and are both controlled by non-catalytic systems. However, stove 5 is constructed of cast iron and has a non-tube design, while stove 6 employs tubes and is made of steel. The material and design of the stoves may contribute to the ability of the stoves to retain heat when the air setting is reduced.

Current test protocols do not require changing air settings in the middle of a fuel load. However, in field situations, stove owners are likely to turn down the air setting during a burn. The above data indicate that changing the air setting can significantly influence appliance performance and that this influence is not the same in all stoves. Therefore, it is critical that this element be included in the protocol in order to assess an appliance's capacity to respond to an air change setting while still actively burning a load.

3.3.3 Medium- versus Low-Air Setting in Maintenance Phase

As discussed above, IDC v1 specified a medium-air setting in the maintenance phase, while the IDC final protocol directs that the temperature be left at the lowest setting for that phase. The impact of the maintenance phase air setting was evaluated by comparing runs with medium- and low-air settings in stoves 1 and 5. Figure 89 shows the temperature and emissions profiles for the medium- and low-air setting maintenance phase run in each of those stoves. The fuel densities for all these runs were 7 lb/ft^3 in the high-fire phase and 5 lb/ft^3 in the maintenance phase, and the air settings were switched from the high to low in the high-fire phase when 50% of fuel was combusted, consistent with the IDC Final Protocol conditions.

Figure 89. Temperature and Emissions Profiles for Medium- and Low-Maintenance Phases



The maintenance phase metrics for these runs are shown in Table 93.

Table 93. Metrics for Medium- and Low-Air Maintenance Phases

Stove #	Test ID	Air Setting	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
1	S1-18-03-16	Medium	2.2	140	19.8	8.5	3.8
1	S1-18-05-09	Low	2.4	135	23.6	10.5	4.4
5	S5-18-03-15	Medium	2	107	0.7	0.4	0.2
5	S5-18-05-04	Low	1.8	142	11.3	4.8	2.7

Dry-burn rates were similar at the two air settings for both stoves. In stove 1, run times at medium- and low-air settings were similar. In stove 5, the low-air maintenance phase run time was 33% longer than the run time for the medium-air phase.

PM emissions were similar in the low- and medium-air maintenance phases of the stove 1 runs and were highest in the first 20 minutes of that phase. During that period, stove temperatures decreased by 56ºF in the medium-air run and 36ºF in the low-air run. The emission profiles were also similar in the first hour of the stove 5 low- and medium-maintenance phases, but emissions in the low-air run began to increase again at the time that the stove temperature began to drop in that run and peaked between minutes 104 and 112. The emission factors and emission rates in the stove 5 maintenance phase at the low-air settings were 14 and 12 times higher than in the maintenance phase at medium-air settings, respectively.

Table 94 shows the initial and ending stove temperatures in the stove 1 and stove 5 comparison runs.

Table 94. Stove Temperatures in Medium- and Low-Air Maintenance Phases

Stove #	Test ID	Air Setting	Initial Stove Temp. (ºF)	Ending Stove Temp. (ºF)	Temp. Loss (ºF)
1	S1-18-03-16	Medium	531	446	85
1	S1-18-05-09	Low	456	446	10
5	S5-18-03-15	Medium	497	435	62
5	S5-18-05-04	Low	436	350	86

The stove temperatures at the start of the maintenance phase of the stove 1 and stove 5 comparison runs were substantially higher (75ºF and 61ºF, respectively) in the medium-air run than the low-air run. In stove 1, the temperature difference decreased over the course of the run and the stove temperatures in the medium- and low-setting runs were essentially the same by minute 90 and were equivalent at the end of the run. The temperature of stove 1 decreased by 85ºF in the medium-air maintenance phase and 10ºF in the low-air maintenance phase. In stove 5, the initial temperature difference decreased to less than 20ºF between minutes 59 and 67 of the phase, but the temperature in the low-air run dropped further subsequently and ended the phase 85ºF lower than in the run with the medium-air setting.

Because the stove temperature at the end of the maintenance phase may influence the burn in the subsequent, overnight phase, temperature changes in the medium- and low-M28 runs were compared in all stoves and the medium and low phase of the red maple ASTM 3053-17 tests in stoves 1, 6, and 7 to further investigate the effect of the air setting on stove temperatures, as shown in Table 95.

Table 95. Stove Temperatures in Medium- and Low-M28 and ASTM 3053-17 Runs

Test	Stove	Air Setting	Initial Temp	Temp at 90% Comb.	Temp at 100% Comb.	Temp, Loss at 90%	Temp Loss at 100%
M28	Stove 1	Medium	494	492	375	2	119
		Low	427	440	374	-13	53
		Difference	67	52	1	15	66
	Stove 2	Medium	467	421	370	46	97
		Low	442	433	402	9	40
		Difference	25	-12	-32	37	57
	Stove 4	Medium	399	494	421	-95	-22
		Low	361	330	298	31	63
		Difference	38	164	123	-126	-85
	Stove 5	Medium	408	305	246	103	162
		Low	386	357	288	29	98
		Difference	22	-52	-42	74	64
	Stove 6	Medium	412	383	350	29	62
		Low	410	383	348	27	62
		Difference	2	0	2	2	0
	Stove 7	Medium	450	480	440	-30	10
		Low	440	399	368	41	72
		Difference	10	81	72	-71	-62
ASTM 3053-17	Stove 1	Medium	493	398	296	95	197
		Low	507	491	368	16	139
		Difference	-14	-93	-72	79	58
	Stove 6	Medium	508	364	315	144	193
		Low	511	332	272	179	239
		Difference	-3	32	43	-35	-46
	Stove 7	Medium	506	459	375	47	131
		Low	449	345	324	104	125
		Difference	57	114	51	-57	6

As with the research runs discussed above, no clear pattern of temperature change or temperature at the end of the phase was apparent in these runs. Temperatures at 90% were higher in the medium-M28 runs in stoves 1, 4, and 7 and in the medium ASTM 3053-17 phase in stoves 6 and 7. The 90% combustion temperatures were higher in the low-air M28 stove 2 and 5 runs and in the stove 1 ASTM 3053-17 low-air phase. Those relationships were similar at 100% combustion, except that the stove 1 temperatures were essentially equivalent at the end of the M28 medium- and low-air runs. The temperature at 90% combustion was higher than the initial temperature in three of the runs; the low-air stove 1 run and the medium-air runs in stoves 4 and 7. At 100% combustion, only the stove 4 medium run continued to record a temperature higher than the initial temperature.

3.3.4 Effect of Maintenance Phase Burn on Overnight Phase

The study also investigated the impact of eliminating the maintenance phase on the subsequent overnight phase. Table 96 shows the metrics for the overnight phases of pairs of research runs in stoves 1, 2, 4, 5, and 6. In each of those runs, the high-burn phase was conducted according to the IDC final protocol (fuel density of 7 lb/ft^3, high setting switched to low air at 50% fuel combustion). In runs that included a maintenance phase, that phase also adhered to the IDC final protocol specifications (fuel density 5 lb/ft^3, low-air setting). In the runs with no maintenance phase, the run moved directly from the high-fire to the overnight phase.

Table 96. Metrics for Overnight Phases in Runs with and without Maintenance Phases

Test ID	Maintenance Phase?	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
S1-18-05-08	No	2.5	297	90.2	18.2	7.3
S1-18-05-09	Yes	2.4	271	93.7	20.7	8.6
S4-18-05-12	No	1.2	260	-1.6	-0.4	-0.3
S4-18-05-17	Yes	1.2	262	2.4	0.5	0.5
S4-18-04-19	No	1.2	152	8.5	3.3	2.7
S4-18-05-10	Yes	1.1	169	10.3	3.7	3.3
S5-18-05-02	No	1.7	284	4.9	1	0.6
S5-18-05-04	Yes	1.7	297	16.7	3.4	2
S6-18-05-05	No	1.7	264	25.2	5.7	3.5
S6-18-05-01	Yes	1.5	260	29.5	6.8	4.5

The elimination of the maintenance phase did not appear to affect run times or burn rates in the subsequent overnight phase. However, in all stoves, the overnight emission rate and emission factor for the run that included a maintenance run was higher than in the runs in which the maintenance phase was eliminated. In most cases, the difference in emissions in the paired runs were modest, although there was a wide variation between stoves in overnight phase PM emissions. For stoves 1, 4, and 6, the overnight phase emission factors for the runs with a maintenance phase were 18% to 29% higher than in the no-maintenance phase runs, and the ERs differed by 14 to 19%. Stove 2 measured small negative PM emissions measures in the overnight phase of the no maintenance run and small positive emissions in the run that included a maintenance phase. Stove 5 showed a more substantial difference in emissions between the two runs.

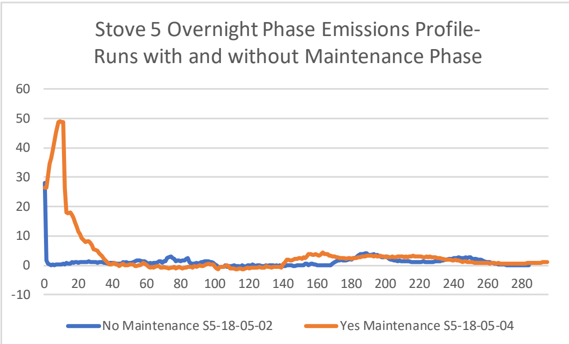
Most of the overnight phase PM emissions occurred early in the burns. As shown in Table 97, in all stoves except for stove 2, stove temperatures at the start of the overnight phase were higher when that phase followed directly after the high-fire phase than in the runs with an intervening low-air setting maintenance phase. The lower temperatures at the beginning of the overnight phases that followed the maintenance phases may explain the higher PM emissions in those runs.

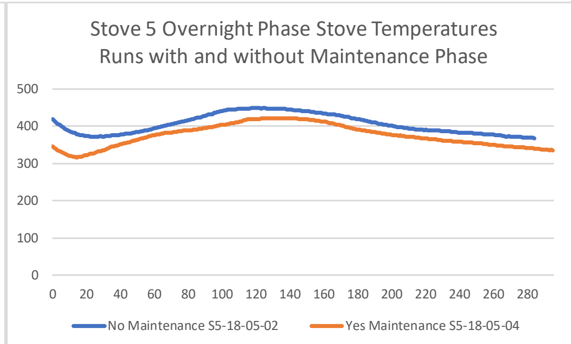
Table 97. Stove Temperatures at the Beginning of the Overnight Phase

Stove	Average Stove Temperature–Runs with No Maintenance Phase	Average Stove Temperature–Runs with Maintenance Phase	Temperature Difference
1	479	433	46
2	399	404	-5
4	389	340	49
5	420	345	75
6	474	354	120

Figure 90 illustrates this effect in stove 5, the stove with the largest difference in overnight phase PM emissions between the run with and without a maintenance phase. Most of the emissions in the overnight phase of the stove 5 run that included a maintenance phase occurred in the first 30 minutes of the phase, when the discrepancy between the temperatures in the two runs was at it its greatest.

Figure 90. Emissions and Temperature in the Overnight Phase of Stove 5 Runs with and without Maintenance Phases





The maintenance phase is intended to represent a period of semi-attended stove operation after the coal bed is well established. In the field, stoves are frequently operated in that mode during the day between the initial start-up and temperature ramp-up phases, and the period of prolonged non-attended operation in the nighttime hours. Further, as shown above, the exclusion of the maintenance period in test runs can result in higher initial temperatures and lower emissions in the subsequent overnight phase. Therefore, exclusion of a maintenance phase in test runs would not reproduce real world operating conditions and would likely lead to an undercounting of PM emissions that would be encountered in field operation.

3.4 Impact of Fuel Species and Moisture Content

While most of the cordwood runs in this study burned red maple, the impact of burning other wood species was investigated in two stoves, stove 6 and 7. This is an important consideration because stove owners burn a variety of fuels, including, at times, wood that is not well seasoned.

3.4.1 Effect of Fuel Species and Moisture Content—Stove 6 Results

In stove 6, fuel species impacts were evaluated with a series of ASTM 3053-17 and IDC final protocol runs. Complete ASTM 3053-17 tests, which each consist of two runs, were performed with red maple, seasoned oak, and beech. IDC final protocol tests, which each consist of three replicate runs, were performed in that stove using red maple, seasoned oak, and wet (non-seasoned) oak cordwood.

3.4.1.1 Stove 6 ASTM 3053-17 Runs

Each of the two runs in the ASTM 3053-17 tests has a start-up phase and a high-fire phase. In one of the two runs, the high-fire phase is followed by a medium-fire phase, and, in the other, by a low-fire phase. In addition to the two red maple runs that constituted a complete ASTM 3053-17 test, two additional runs were performed using that fuel. In both of those runs, the high-fire phase was followed by a medium-air setting burn. PM emissions were measured using the 1400AB TEOM in the runs in the complete maple tests and using the 1405 TEOM in all other ASTM 3053-17 runs in stove 6.

The ASTM 3053-17 run test metrics for the start-up phase are shown in Table 98.

Table 98. Stove 6—Comparison of ASTM 3053-17 Start-Up Phase Metrics by Fuel Type

Test ID #	Fuel Type	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	Efficiency (%)
S6-18-06-07-1	Maple	4.84	38	2.20	3.48	0.72	49.1
S6-18-06-08-1	Maple	5.07	34	3.15	5.55	1.10	53.0
S6-19-01-31-1	Maple	5.50	36	2.86	4.76	0.87	57.2
S6-19-04-01-1	Maple	4.94	43	3.67	5.12	1.04	58.8
S6-19-04-04-1	Beech	5.15	38	2.78	4.39	0.85	57.9
S6-19-04-05-1	Beech	4.08	48	5.03	6.28	1.54	54.5
S6-19-04-07-1	Oak	5.02	39	3.05	4.69	0.94	55.9
S6-19-04-08-1	Oak	3.96	50	2.87	3.45	0.87	53.3

The start-up phase test times were, on average, slightly higher and the dry-burn rate slightly lower in the oak and beech runs than in the maple runs. However, there was a considerable overlap in the ranges of those parameters among the species. The start-up PM EFs for all runs ranged from 0.85–1.10 g/kg, with the exception of a low value of 0.72 g/kg for the first maple run and a high value of 1.54 g/kg for the second beech run. ERs ranged from 3.45–6.28 g/h. Average start-up phase ERs were 4.7 g/h for the maple burns, 5.3 g/h for beech, and 4.2 g/h for oak cordwood, but there was considerable overlap in the ERs of individual runs in each group.

The metrics for the high-fire phase are shown in Table 99.

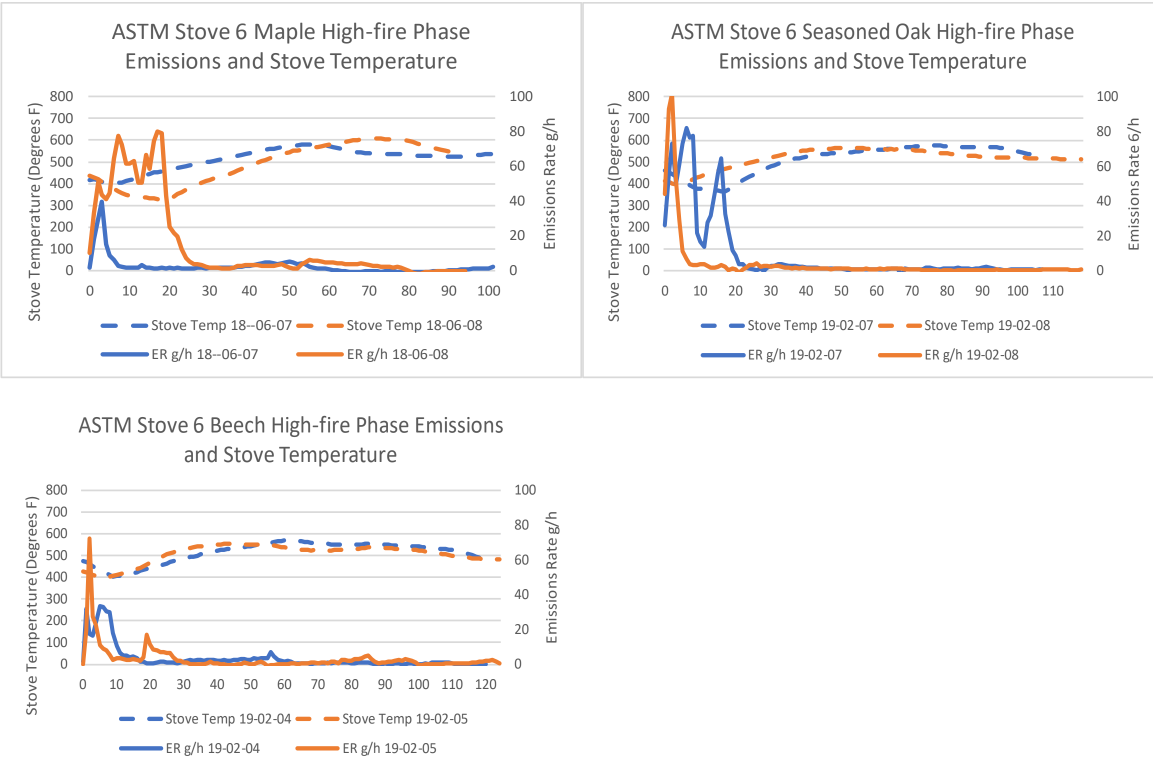
Table 99. Stove 6—Comparison of ASTM 3053-17 High-Air Setting Test Metrics by Fuel Type

Test ID #	Fuel Type	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	Efficiency (%)
S6-18-06-07-1	Maple	4.47	101	4.06	2.41	0.54	50.6
S6-18-06-08-1	Maple	4.52	94	22.93	14.64	3.24	48.4
S6-19-01-31-1	Maple	4.55	95	8.52	5.38	1.18	50.1
S6-19-04-01-1	Maple	6.18	71	7.71	6.52	1.05	54.8
S6-19-04-04-1	Beech	3.63	120	6.66	3.33	0.92	50.2
S6-19-04-05-1	Beech	3.55	124	6.22	3.01	0.85	51.5
S6-19-04-07-1	Oak	4.05	107	17.33	9.72	2.40	50.3
S6-19-04-08-1	Oak	3.70	118	7.82	3.98	1.07	50.4

High-fire phase run times were highest and dry-burn rates lowest for the runs that burned beech fuel; the reverse was true for the maple burns. There was no overlap in those metrics between groups. The beech fueled runs also produced less PM and had lower EFs and ERs than all other runs except for the first maple burn. There was considerable intragroup variation in the emissions in both the maple and oak runs. The high-fire phase EF and ER were six times higher in the highest emitting than in the lowest emitting red maple run. Similarly, the EF and ER for the higher emitting oak burn for this phase were more than twice as high as for the other oak run.

It appears that the variability in PM emissions in the maple and seasoned oak burn groups in the high-fire phase may be linked to stove temperatures. As shown in Figure 91, temperatures in that phase of the highest emitting maple run and the higher emitting seasoned oak burn dipped to below 400ºF early in the run while those temperatures remained above that temperature in the lowest emitting maple run and the lower emitting seasoned oak run. The temperature dip also did not occur in the beech runs, which did not have a wide divergence in emissions.

Figure 91. Stove 6—ASTM 3053-17 High-Fire Phase Emissions and Temperature Profiles



The ASTM 3053-17 high-fire phase ends when 90% of the fuel load is consumed. At that point, the stove is moved to the air setting for the next phase for an hour. At the end of the hour, a full charge of 12 lb/ft^3 is reloaded and a low- or medium-fire burn is conducted. The metrics for the three low fire phase burns (one with each wood species) are shown in Table 100.

Table 100. Stove 6—Comparison of Low-Air Setting Metrics in ASTM 3053-17 Runs with Different Fuels

Test ID #	Fuel Type	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	Efficiency (%)
S6-18-06-07-2	Maple	1.05	500	38.57	4.63	4.43	60.7
S6-19-04-05-2	Beech	0.80	727	88.59	7.31	9.17	50.1
S6-19-04-08-2	Oak	1.12	502	81.54	9.75	8.69	57.3

At the low-air setting, the test time was longer and the dry burn-rate lower in the beech fuel run than in the maple and oak fueled runs. The EFs in the low-burn phases of the beech and oak runs were twice that of the maple burn. The ER for the beech burn was 1.6 times higher and the oak burn 2.1 times higher than the maple burn.

The metrics for the five medium-fire phase runs (three maple, one beech, and one seasoned oak) are shown in Table 101.

Table 101. Stove 6—Comparison of Medium-Air Setting Metrics in ASTM 3053-17 Runs with Different Fuels

Test ID #	Fuel Type	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	Efficiency (%)
S6-18-06-08-2	Maple	1.33	358	28.69	4.81	3.61	61.4
S6-19-01-31-2	Maple	1.07	469	16.54	2.12	1.97	58.7
S6-19-04-01-2	Maple	1.11	454	35.44	4.68	4.23	59.5
S6-19-04-04-2	Beech	0.78	775	70.94	5.49	7.04	58.1
S6-19-04-07-2	Oak	1.16	445	49.70	6.70	5.76	59.0

The run time and dry-burn rate for the medium-fire phase of the oak burn were within the range of those maple runs. That phase of the beech-fueled run had a longer run time and a lower burn rate than for the other fuels. The PM emission metrics were lower for all of the maple runs than those for either of the other fuels. The EFs for the beech and oak runs were approximately twice those of the average maple EF and the ERs for the beech and oak runs were 42% and 73% higher than the average maple ER, respectively. Note, however, that there was also substantial variability in the PM emission metrics within the maple group.

In all low- and medium-fire runs, most of the PM was emitted early in the run and some amount of PM loss occurred later in the run, as was the case in the M28 runs. In the three low-fire phase runs, the PM measurements at the end of the phase was 9% to 19% lower than at the maximum. For the four of the five medium-phase runs, 13% to 21% of the maximum PM was lost. In the other medium-phase run, S6-19-01-31, a red maple-fueled run, only 1% of total PM was lost, although the maximum PM measurement occurred after 25% of the run.

3.4.1.2 Stove 6 IDC runs

A total of nine final IDC protocol runs were performed on stove 6. Three replicate runs burned red maple, three seasoned oak, and three wet oak. During the start-up phase of all tests, the moisture content of the cordwood fuel was approximately 17.5%. However, in subsequent loads, the average moisture content, on a dry basis, was 21.4% for the seasoned oak, 28.1% for the wet oak, and 21.1% for the maple runs.

The metrics for the start-up phase for the three sets of three replicate stove 6 IDC runs are shown in Table 102. PM emissions were measured using the 1400AB TEOM in the stove 6 IDC red maple runs and using the 1405 TEOM model in the remaining IDC runs in that stove.

Table 102. Stove 6—Comparison of Test Metrics from Start-Up Phase of IDC Final Protocol Runs

Fuel	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	S6-18-07-18	2.96	47	7.44	9.50	3.20
	S6-18-07-19	3.79	36	3.76	6.27	1.65
	S6-18-07-20	2.90	46	2.32	3.03	1.04
	Mean	3.21 [2.65 - 3.78]	43.0 [36.1 - 49.9]	4.51 [1.54 - 7.49]	6.27 [2.61 - 9.93]	1.96 [0.70 - 3.22]
	Rel. Std Dev	0.15	0.14	0.59	0.52	0.57
Seasoned Oak	S6-19-03-13	3.34	41	4.73	6.92	2.07
	S6-19-03-18	3.38	41	3.05	4.46	1.32
	S6-19-03-19	3.07	44	2.3	3.14	1.02
	Mean	3.26 [3.07 - 3.45]	42.0 [40.0 - 44.0]	3.36 [1.95 - 4.77]	4.84 [2.67 - 7.01]	1.47 [0.86 - 2.08]
	Rel. Std Dev	0.05	0.04	0.37	0.40	0.37
Wet Oak	S6-19-04-18	4.21	33	2.51	4.57	1.09
	S6-19-03-21	3.37	39	2.24	3.45	1.02
	S6-19-03-22	3.57	39	6.83	10.51	2.95
	Mean	3.72 [3.24 - 4.21]	37.0 [33.1 - 40.9]	3.86 [0.95 - 6.77]	6.18 [1.88 - 10.47]	1.69 [0.45 - 2.93]
	Rel. Std Dev	0.12	0.09	0.67	0.61	0.65
All Fuels	Mean	3.40	40.7	3.91	5.76	1.71
	Std Deviation	0.42	4.6	2.01	2.76	0.85
	Rel. Std Dev	0.12	0.11	0.51	0.48	0.50

Because the same start-up fuel and fueling procedures were used in all tests, the nine IDC runs are replicates of each other in this phase. The mean start-up ER and EF were 5.8 g/h and 1.7 g/kg, respectively for the nine runs. The highest ER and EF were about three times higher than the lowest.

The metrics for the high-fire phase of the IDC runs are shown in Table 103.

Table 103. Stove 6—Comparison of Test Metrics from High-Fire Phase of IDC Final Protocol Runs by Fuel Type

Fuel	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	S6-18-07-18	3.4	88	27.7	18.89	5.56
	S6-18-07-19	3.46	86	33.03	23.05	6.67
	S6-18-07-20	3.39	88	32.49	22.15	6.54
	Mean [95% CI]	3.42 [3.37-3.46]	87.3 [86.0-88.6]	31.07 [27.75-34.39]	21.36 [18.89 -23.84]	6.26 [5.57-6.94]
	Rel. Std Dev	0.01	0.01	0.09	0.10	0.10
Seasoned Oak	S6-19-03-13	2.5	120	9.69	4.84	1.94
	S6-19-03-18	2.57	114	9.65	5.08	1.97
	S6-19-03-19	2.77	107	27.21	15.26	5.51
	Mean [95% CI]	2.61 [2.45-2.77]	113.7 [106.3-121.0]	15.52 [4.06-26.98]	8.39 [1.66-15.12]	3.14 [0.84-5.46]
	Rel. Std Dev	0.05	0.06	0.65	0.71	0.65
Wet Oak	S6-19-04-18	1.70	162	55.27	20.47	12.01
	S6-19-03-21	2.57	108	47.29	26.27	10.21
	S6-19-03-22	2.51	109	64.64	35.58	14.15
	Mean [95% CI]	2.26 [1.71-2.81]	126.3 [91.38-161.29]	55.73 [45.91-65.56]	27.44 [18.81-36.07]	12.12 [9.89-14.36]
	Rel. Std Dev	0.22	0.24	0.16	0.28	0.16

In the high-fire phase, the run times were lower and the dry-burn rates higher in all of the red maple runs than in any of the seasoned or wet oak runs. This intergroup difference was significant at $p = 0.05$. Burn rates and run times were somewhat more variable in the wet oak group than in the other groups; the first wet oak run had a burn rate 30% lower and a run time 50% higher than the other runs in that group.

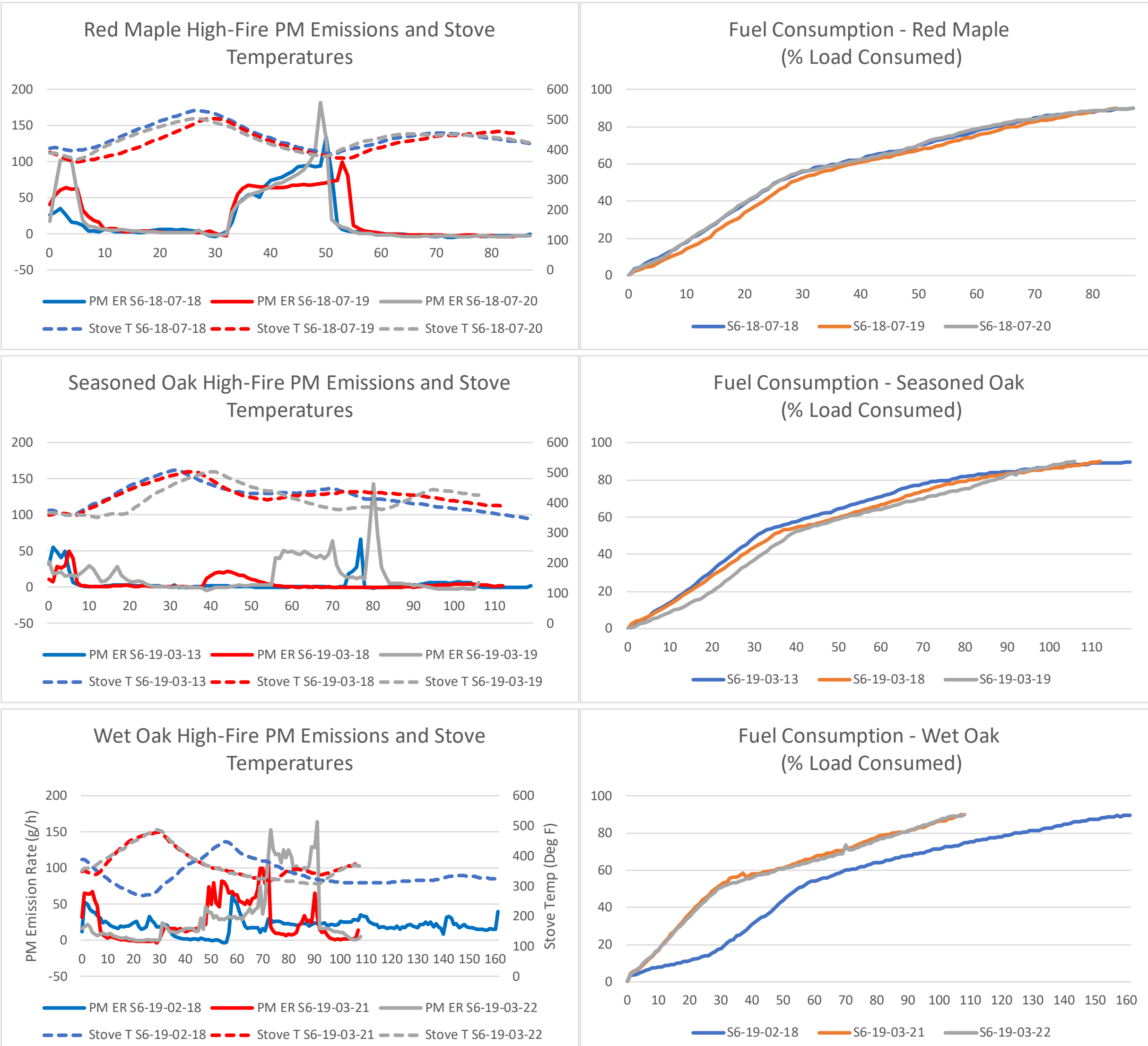
The red maple replicates and wet oak replicates had low-intragroup variability in PM emissions. The PM emissions, EF, and ER for the highest emitting red maple run were only about 20% higher than for the lowest. In the high-fire phase of the wet oak runs, the PM emissions, PM EF, and PM ER for the highest emitting replicate were 37%, 39%, and 74% greater than the lowest emitting run, respectively. There was considerably more variability in PM emissions in the seasoned oak group; the emissions in the third run in that group were about three times higher than in the other seasoned oak runs.

PM emissions and the PM EF in the high-fire phase of the red maple fueled runs were significantly higher than those that burned seasoned oak and significantly lower than in the wet oak runs. The average wet oak EF was almost twice that of the red maple runs. Due to the shorter test times in the red maple runs, the average ER for that group was not significantly different than the average wet oak ER; however, both the wet oak and red maple ERs were significantly higher than the ER for the seasoned oak runs.

Two of the seasoned oak runs had essentially equal PM emissions that were approximately three times lower than in the maple runs and five to six times lower than the wet oak emissions. PM emissions in the third seasoned oak run were higher, in the range of those in the maple group.

The temperature, emission, and fuel consumption profiles for these runs, shown in Figure 92, provide some insight into the reason for those differences.

Figure 92. Stove 6 IDC High-Fire Phase Emissions, Stove Temperatures, and Fuel Consumption



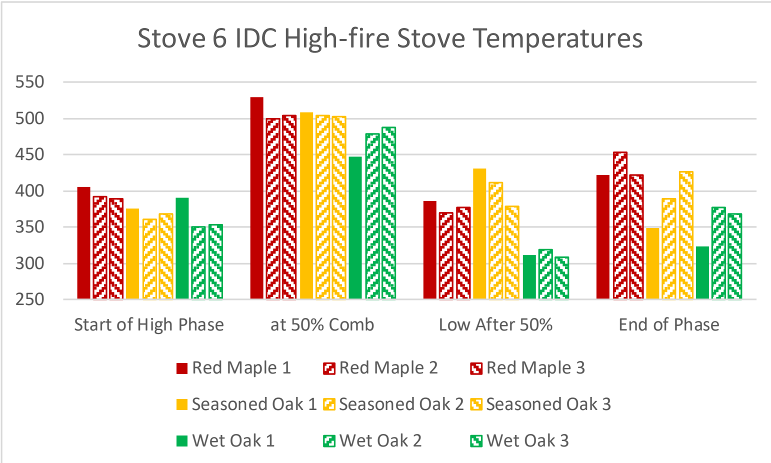
As discussed previously, in the high-fire phase of the stove 6 red maple runs, temperatures and fuel consumption rates were fairly consistent from run to run. In all red maple runs in that stove, stove temperatures decreased and significant emissions occurred in the first 25 minutes after 50% combustion, when the air setting was moved to low. The second run in that group, S6-18-07-19, had a slightly lower fuel consumption rate and slightly lower temperatures than in the other runs, which lengthened the emission period and increased the total PM measured in the second half of that run.

Temperature profiles in the seasoned and wet-fueled runs also tended to show increasing temperatures in the first part of the high-fire phase, followed by temperature decreases after the air setting was moved to low at 50% combustion. Table 104 and Figure 93 compare the temperatures in the nine runs at four points in the high-fire phase of the nine runs; at the beginning of the phase, at the time of 50% combustion, the minimum temperature after the air setting was switched to low, and at the end of phase. The first wet oak run and, to a lesser extent, the third seasoned oak run had temperature patterns different from the other runs in those groups; those runs are discussed in more detail below.

Table 104. Stove 6—Comparison of Temperatures in High-Fire Phase of IDC Final Protocol Runs by Fuel Type

Fuel	Test ID #	Temp. at Start of High-Fire Phase	Temp. at 50% Combustion	Low Temp. After 50% Combustion	End Temp.
Red Maple	S6-18-07-18	406	530	386	422
	S6-18-07-19	392	500	370	453
	S6-18-07-20	389	504	378	422
	Mean [95% CI]	396 [385-406]	511 [493-530]	378 [369-387]	432 [414-453]
	Rel. Std Dev[10]	2.3%	3.2%	2.1%	4.1%
Seasoned Oak	S6-19-03-13	376	508	431	349
	S6-19-03-18	361	504	411	389
	S6-19-03-19	369	502	379	426
	Mean [95% CI]	369 [360-377]	505 [501-508]	407 [377-436]	388 [344-432]
	Rel. Std Dev	2.0%	0.6%	6.4%	9.9%
Wet Oak	S6-19-04-18	390	448	311	324
	S6-19-03-21	350	479	319	378
	S6-19-03-22	353	488	308	368
	Mean [95% CI]	364 [339-390]	472 [448-495]	313 [306-319]	357 [324-389]
	Rel. Std Dev	6.1%	4.4%	1.8%	8.1%

Figure 93. High-Fire Phase Stove Temperatures



Stove temperatures at the beginning and end of the high-fire phase tended to be higher in the red maple runs than in either of the oak fueled groups. On average, the red maple stove temperatures were 27°F higher than in the seasoned oak runs and 31°F higher than the wet oak runs at the beginning on the phase and 44°F and 76°F higher than the seasoned and wet oak groups, respectively, at the end of the phase. The difference in starting temperature in the red maple and seasoned oak groups and in the ending temperature between both the red maple and the seasoned oak groups and the wet oak group were significant at $p = 0.05$.

The temperature increased substantially in all runs during combustion of the first 50% of the high-fire load, when the air setting was on high. Temperatures at 50% combustion were similar in the red maple and seasoned oak groups and were significantly higher in both of those groups than the wet oak temperatures. Temperatures in all fuel groups decreased when the air setting was moved to low at the 50% combustion point. The lowest temperatures reached in that period were significantly lower in the wet oak runs that in the red maple and seasoned oak runs. Minimum temperatures for two of the three seasoned oak runs were higher than in the maple runs, but the average difference in the minimum temperature between those two fuel groups was not significant.

The smaller temperature decrease in the low-air setting period of the phase in the first two seasoned oak runs may partially explain the lower emissions in those runs relative to the red maple runs. The fuel consumption graphs in Figure 92 indicate a delay in full light-off of the load at the beginning of the phase; that run required 25 minutes longer to reach 50% combustion than the other seasoned oak runs. This lag is also seen in the stove temperatures in that run; the initial increase in stove temperatures in that run began six to seven minutes later and was more gradual than in the other seasoned oak runs. After the air setting was switched to low, the temperatures in that run dropped further than in the other seasoned oak run, dipping to levels similar to those in the red maple group. PM emissions in that run were also similar to those in the red maple runs.

Fuel consumption in the second and third runs of the wet oak group was similar to the other fuel groups. As with the other fuel groups, temperatures increased in the first half of those runs, while the air setting was on high; however, at 50% combustion, the average temperatures in the wet oak runs were 40ºF to 50ºF lower than in the other groups. The average minimum temperatures after the air setting was moved to low were 65ºF lower in the wet oak runs than the red maple runs and 95ºF lower than in the seasoned oak runs.

The fuel consumption and temperature profiles for the first wet oak run, as shown in Figure 92, are substantially different from those of the eight other runs. Light-off was delayed for approximately 30 minutes in the beginning of the phase in that run, resulting in an initial decrease in stove temperature of approximately 130ºF during that period. After that point, temperatures increased, but continued to be lower than in the other runs at 50% combustion and at the end of the phase. Although emissions in that run continued over a longer time period, probably due to the lower temperatures, total PM emissions for that run were similar to the other wet oak runs. Because the high-fire phase time was considerably lengthened by the late light-off, the emission rate, in g/h, was lower in that run than in the other wet oak runs.

In the maintenance phase, the air setting is kept at the lowest setting and two large pieces of wood are loaded into the stove. At this point, the coal bed is well developed. The metrics measured in the phase in stove 6 IDC runs are shown in Table 105.

Table 105. Stove 6—Comparison of Test Metrics for Maintenance Phase of IDC Final Protocol Runs by Fuel Type

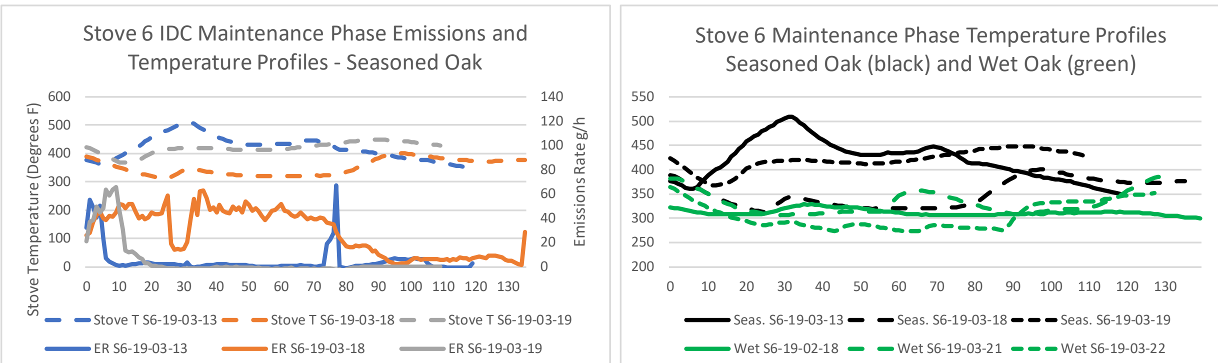
Fuel	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	S6-18-07-18	1.50	140	35.11	15.05	10.00
	S6-18-07-19	1.55	138	10.24	4.45	2.87
	S6-18-07-20	1.30	161	32.94	12.28	9.44
	Mean [95% CI]	1.45 [1.30-1.60]	146.3 [131.9-160.8]	26.10 [10.51-41.68]	10.59 [4.37-16.81]	7.44 [2.95-11.92]
	Rel. Std Dev	0.09	0.09	0.53	0.52	0.53
Seasoned Oak	S6-19-03-13	1.74	`120	27.67	13.83	7.96
	S6-19-03-18	1.56	136	63.42	27.98	17.98
	S6-19-03-19	1.9	110	9.34	5.09	2.68
	Mean [95% CI]	1.73 [1.54-1.93]	123 [102.4-143.8]	33.48 [2.35-64.60]	15.63 [2.56-28.70]	9.54 [0.75-18.33]
	Rel. Std Dev	0.10	0.15	0.82	0.74	0.81
Wet Oak	S6-19-04-18	1.38	140	91.38	39.16	28.39
	S6-19-03-21	1.51	130	51.29	23.67	15.63
	S6-19-03-22	1.54	128	91.33	42.81	27.79
	Mean [95% CI]	1.48 [1.38-1.57]	132.7 [125.4-139.9]	78.00 [51.84-104.18]	35.21 [23.71-46.71]	23.94 [15.79-32.08]
	Rel. Std Dev	0.06	0.05	0.30	0.29	0.30

In the maintenance phase, the dry-burn rates were lower for all fuels than in the previous phases. The dry-burn rates were slightly higher in the seasoned oak runs than in the red maple and wet oak burns, but that difference was not significant at the $p = 0.05$ level.

There was more variability in PM emissions in this phase within the fuel groups than in the other phases, particularly in the seasoned oak group. Average Total PM, PM ER, and PM EF in the wet oak group were significantly higher than in the red maple group. Those PM metrics were also higher in the seasoned oak than in the red maple group, but that difference was not significant. On average, the maintenance phase EFs for the seasoned oak and wet oak runs were 28% and 2.5 times greater than those for the red maple runs. The average maintenance phase ERs for seasoned oak, 15.6 g/h, and wet oak, 35.2 g/h, were 48% and 2.3 times higher than the maple ER, 10.6 g/h, respectively.

PM emissions in one of the seasoned oak replicates, S6-19-03-18, were substantially higher than in the other runs with that fuel and similar to the emissions in the wet oak runs. The weight and fuel content of the fuel load in that run were essentially the same as in the other runs in that group. As shown in Figure 94, the higher PM emissions in the maintenance phase of run S6-19-03 can be at least partly explained by stove temperatures, because the stove temperatures in that phase of the high-emitting seasoned oak run were much lower than in the other seasoned oak runs and similar to those in the wet oak runs. The reason for the lower temperatures in the maintenance phase of that run is not clear.

Figure 94. Variability in Stove 6 Seasoned Oak Maintenance Phase Emissions and Temperatures



The final phase of the IDC protocol represents a long burn, such as an overnight burn or a burn during the day when the fire will be unattended for a significant amount of time. During this phase, the coal bed is raked, and the user loads as much wood as possible, using large and small pieces. The metrics measured in the overnight phase of the stove 6 IDC runs are shown in Table 106.

Table 106. Stove 6—Comparison of Test Metrics for Overnight Phase of IDC Final Protocol Runs by Fuel Type

Fuel	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	S6-18-07-18	1.43	260	72.48	16.7	11.7
	S6-18-07-19	1.64	250	122.77	29.47	17.93
	S6-18-07-20	1.61	263	44.85	10.23	6.35
	Mean [95% CI]	1.56 [1.43-1.69]	257.7 [250.0-265.4]	80.03 [35.33-124.74]	18.80 [7.74-29.88]	11.99 [5.44-18.55]
	Rel. Std Dev	0.07	0.03	0.49	0.52	0.48
Seasoned Oak	S6-19-03-13	1.51	328	86.91	15.9	10.51
	S6-19-03-18	1.65	299	106.96	21.46	12.98
	S6-19-03-19	1.6	308	48.01	9.35	5.86
	Mean [95% CI]	1.59 [1.51-1.67]	311.7 [294.9-328.5]	80.63 [46.61-114.54]	15.57 [8.71-22.43]	9.78 [5.69-13.87]
	Rel. Std Dev	0.04	0.05	0.37	0.39	0.37
Wet Oak	S6-19-04-18	2.65	251	217.43	51.98	19.62
	S6-19-03-21	1.72	277	121.57	26.33	15.33
	S6-19-03-22	1.65	284	155.03	32.75	19.8
	Mean [95% CI]	2.01 [1.37-2.64]	270.7 [251.0-290.3]	164.7 [109.6-219.7]	37.02 [21.94-52.12]	18.25 [15.39-21.11]
	Rel. Std Dev	0.28	0.06	0.30	0.36	0.14

The overnight phases of the stove 6 maple IDC runs lasted 250 to 263 minutes (4.2 to 4.4 hours). The range of times for this phase was similar for the wet oak runs (4.4 to 4.7 hours) and significantly higher for the seasoned oak runs (5.0 to 5.5 hours). The dry-burn rate was similar in all of the runs except for the first wet oak burn, which had a dry-burn rate more than 50% higher than all other runs. Note that the fuel load in that run was approximately 40% larger than in the other two wet oak runs.

On average, the overnight EF and ER for the wet oak runs were approximately twice those for the seasoned oak runs. The average overnight red maple EF and ER were slightly (about 20%) higher than those for the seasoned oak. The average red maple, seasoned oak, and wet oak ERs for this phase were 18.8, 15.6, and 37.0 g/h, respectively.

Table 107 shows the test metrics for the entire run of each of the IDC replicates.

Table 107. Stove 6—Comparison of Test Metrics for Entire IDC Final Protocol Runs by Fuel Type

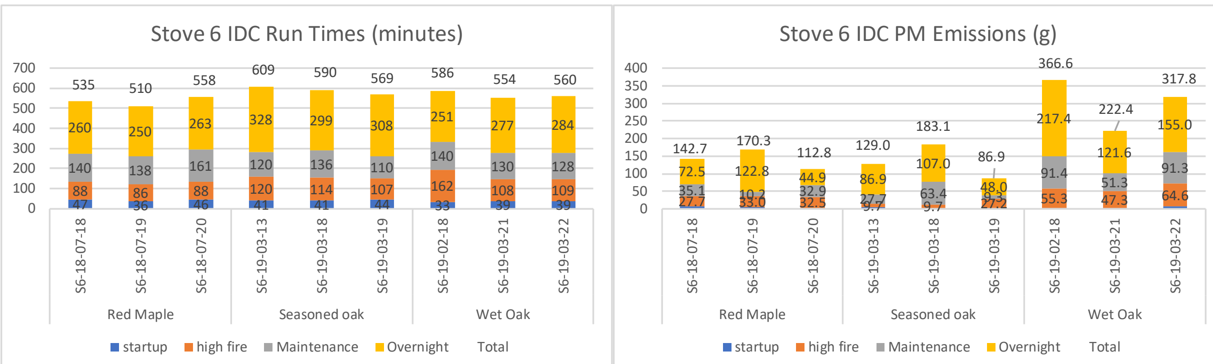
Fuel	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	HHV Efficiency %)
Red Maple	S6-18-07-18	1.91	535	142.73	16.01	8.39	61.4
	S6-18-07-19	2.08	510	170.30	20.03	9.65	62.2
	S6-18-07-20	1.91	558	112.75	12.12	6.35	60.4
	Mean [95% CI]	1.97 [1.86-2.08]	534.3 [507.4-561.5]	141.93 [109.4-174.5]	16.05 [11.6-20.5]	8.13 [6.25-10.01]	61.3 [60.3-62.4]
	Rel. Std Dev	0.05	0.04	0.20	0.25	0.20	0.01
Seasoned Oak	S6-19-03-13	1.87	609	128.99	12.71	6.78	61.1
	S6-19-03-18	1.93	590	183.08	18.62	9.65	61
	S6-19-03-19	1.99	569	86.87	9.16	4.6	62.6
	Mean [95% CI]	1.93 [1.86-2.00]	589.3 [566.7-612.0]	132.98 [78.40-187.56]	13.50 [8.09-18.90]	7.01 [4.14-9.88]	61.6 [60.6-62.6]
	Rel. Std Dev	0.03	0.03	0.36	0.35	0.36	0.01
Wet Oak	S6-19-04-18	2.17	586	366.6	37.54	17.28	56.9
	S6-19-03-21	1.95	554	222.4	24.09	12.33	57.5
	S6-19-03-22	1.93	560	317.82	34.05	17.66	56.8
	Mean [95% CI]	2.02 [1.87-2.17]	566.7 [547.4-585.9]	302.27 [219.3-385.3]	31.89 [24.0-39.8]	15.76 [12.4-19.1]	57.07 [56.6-57.5]
	Rel. Std Dev	0.07	0.03	0.24	0.22	0.19	0.01

Dry-burn rates and test times for the entire run were quite consistent among the replicates in all fuel groups. The total time to complete the stove 6 IDC red maple runs ranged from 510 to 558 minutes (8.5 to 9.3 hours), a longer period than for some of the other stoves, but still less than the 10-hour period that would be feasible for completion in a single day. The time range for the seasoned oak runs (9.5 to 10.2 hours) and wet oak (9.2 to 9.8 hours) were higher than those of the red maple runs. The average test time for the seasoned oak runs was significantly higher than for red maple ($p = 0.05$). The HHV efficiencies were similar in all red maple and seasoned oak runs and were significantly lower in the wet oak runs.

The PM metrics in the seasoned oak group were somewhat more variable than in the other fuel groups. The EF and ER in the highest emitting seasoned oak runs were approximately two times higher than in the lowest emitting run in that group. The highest red maple EF and ER were 52% and 65% higher than the lowest and, for the wet oak runs, the highest EF and ER were 41% and 43% higher than the lowest, respectively.

PM emissions and run times for the nine runs, by phase, are shown in Figure 95.

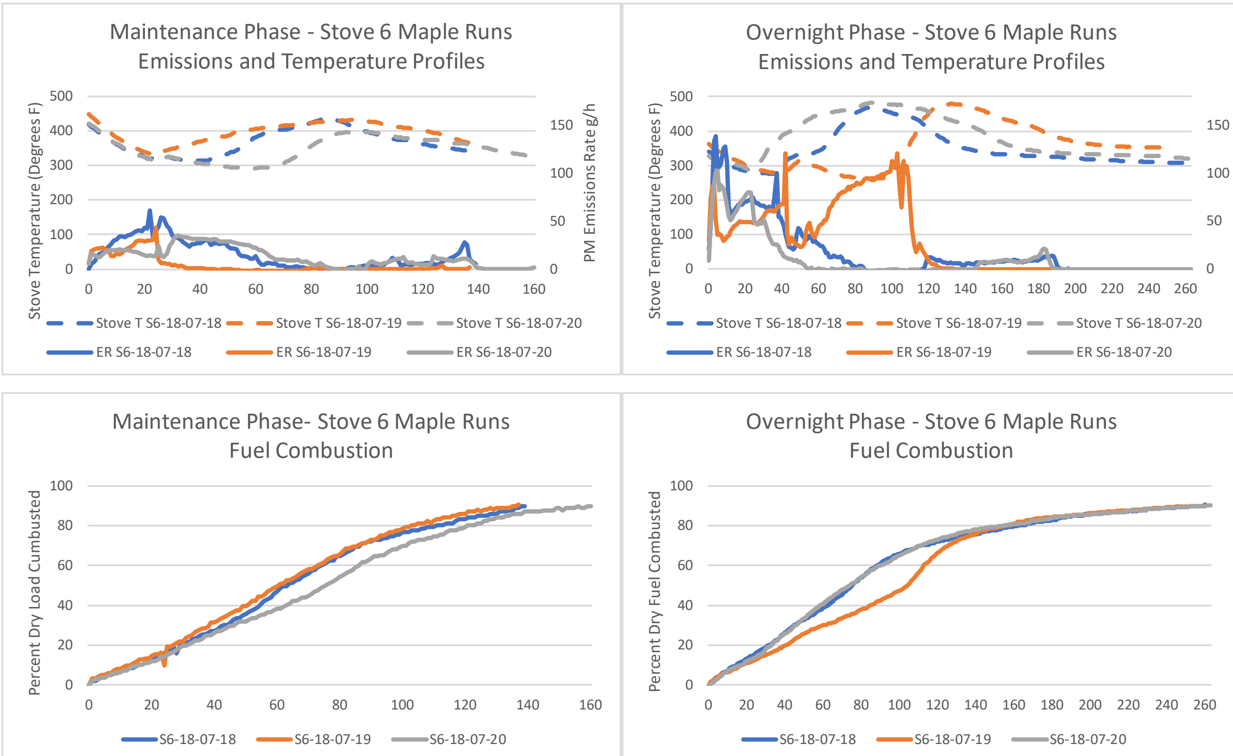
Figure 95. Stove 6 IDC Runs—Run Times and PM Emissions by Phase



As discussed previously, PM emissions for the wet oak group were higher than those for other fuels in all phases except for start-up. For the entire run, the average total PM, and the ER and EF were significantly higher for the wet oak group than the other fuels. The ER and EF for the entire second red maple run, S6-18-08-19, were higher than in the other two runs, largely because of the higher emissions in the overnight phase of that run. Note that the PM emissions in the previous phase, the maintenance phase, were lower in that run than in the other two red maple runs.

This differences in relative emissions in the stove 6 red maple runs in the maintenance and overnight phase can be explained, at least in part, by comparing the stove temperature patterns in those two phases, as shown in Figure 96. As in previous graphs, the PM emission profiles for the three replicate runs are denoted with solid lines and the stove temperatures for those runs with corresponding dotted lines.

Figure 96. Comparison of Emissions and Temperature Profiles and Fuel Combustion Curves for the Maintenance and Overnight Phases of the Stove 6 Red Maple IDC Runs



The stove temperature decreased at the beginning of the maintenance phase in all runs, coinciding with a period of significant PM emissions. However, the temperature recovered quickly in the maintenance phase of run 2 (red in Figure 96), coinciding with a decrease in emissions. Stove temperatures decreased further and recovered more slowly in the maintenance phase of run 1 (blue), and even more so in run 3 (gray), resulting in emissions over a longer period and higher ERs and EFs for those runs than in run 2. A different pattern occurred in the overnight phase. In that phase, the stove temperature in run 2 began to recover from the initial decrease, as it did in the other runs. However, unlike the other runs, the run 2 temperatures experienced a second period of decreasing temperatures, during which the temperature dropped below 300°F. During that second temperature drop, significant additional emissions occurred in run 2.

As can be seen in Figure 96, the fuel consumption rate was also lower for run 2 than for the other turns during that period of the overnight phase, and then picked up after about 100 minutes into the phase when the temperature was increasing. This is indicative of a second fuel light-off. The run 2 overnight emissions dropped to insignificant levels soon after this second light-off occurred.

3.4.2 Effect of Fuel Species and Moisture Content—Stove 7 IDC Results

A total of four IDC final protocol tests, each consisting of three replicate runs, were run on stove 7. The four tests used four different types of cordwood fuel: red maple, seasoned oak, wet oak, and poplar. During the start-up phase of all tests, the moisture content of the fuel for all tests was approximately 17.5%. However, in subsequent loads, the average moisture content of the seasoned oak, on a dry basis, was 21.2%, while the wet oak cordwood was 28.7%.

The metrics for the start-up phase for the four sets of stove 7 IDC runs are shown in Table 108. The 1400AB TEOM was used to measured PM emissions in the maple runs and the 1405 model was used in the stove 7 IDC runs that burned the other fuels.

Table 108. Stove 7—Comparison of Test Metrics from Start-Up Phase of IDC Final Protocol Runs by Fuel Type

Fuel	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	S7-18-07-25	2.163	57	7.75	8.16	3.77
	S7-18-07-26	2.7	45	3.47	4.62	1.71
	S7-18-07-27	2.58	47	2.01	2.57	1
	Mean [95% CI]	2.48 [2.16-2.80]	49.7 [42.4-56.9]	4.41 [1.03-7.79]	5.12 [1.94-8.32]	2.16 [0.53-3.79]
	Rel. Std. Dev.	0.11	0.13	0.68	0.55	0.67
Seasoned Oak	S7-19-04-03	2.09	58	2.41	2.49	1.19
	S7-19-04-04	1.8	67	9.18	8.22	4.56
	S7-19-04-05	2.11	57	2.63	2.76	1.31
	Mean [95% CI]	2.00 [1.80-2.20]	60.7 [54.4-66.9]	4.74 [0.39-9.09]	4.49 [0.83-8.15]	2.35 [0.19-4.52]
	Rel. Std. Dev.	0.09	0.09	0.81	0.72	0.81
Wet Oak	S7-19-04-20	3.6	34	12.62	22.28	6.18
	S7-19-03-25	2.17	56	3.12	3.34	1.54
	S7-19-03-26	1.79	62	3.17	3.07	1.71
	Mean [95% CI]	2.52 [1.44-3.60]	50.7 [34.0-67.3]	6.30 [0.11-12.49]	9.56 [-2.90-22.03]	3.14 [0.17-6.12]
	Rel. Std. Dev.	0.38	0.29	0.87	1.15	0.84
Poplar	S7-19-03-28	2.23	54	2.52	2.8	1.25
	S7-19-03-29	2.79	43	1.94	2.71	0.97
	S7-19-03-30	2.45	49	2.69	3.3	1.35
	Mean [95% CI]	2.49 [2.17-2.81]	48.7 [47.4-54.9]	2.38 [1.94-2.83]	2.94 [2.58-3.30]	1.19 [0.97-1.41]
	Rel. Std. Dev.	0.11	0.11	0.16	0.11	0.17
All Fuels	Mean	2.37	52.42	4.46	5.53	2.21
	Std. Dev.	0.50	9.13	3.45	5.66	1.68
	Rel. Std. Dev.	0.21	0.17	0.77	1.02	0.76

The same operational and fueling protocols were used for these runs, so they are essentially all replicates. The start-up phase of the first run in the test that burned wet oak in subsequent phases produced four times more PM than in the other runs of that group. The wet oak runs, however, were not performed on sequential days and there was more than a month between the first and second runs in that group. That run had a higher start-up dry-burn rate and lower start-up phase time than any of the other 11 runs, which contributed to a start-up ER that was three to nine times higher than in the other runs. The metrics for the high-fire phase for the four sets of three replicate stove 6 IDC runs are shown in Table 109.

Table 109. Stove 7—Comparison of Test Metrics for High-Fire Phase of IDC Final Protocol Runs by Fuel Type

Fuel	MC (%) Dry Basis	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	20.4	S7-18-07-25	1.87	143	4.5	1.89	1.01
	19.9	S7-18-07-26	1.89	141	4.69	1.99	1.06
	19.0	S7-18-07-27	1.76	153	2.31	0.91	0.52
		Mean [95% CI]	1.84 [1.76-1.94]	145.7 [138.4-152.9]	3.83 [2.34-5.33]	1.60 [0.94-2.27]	0.86 [0.53-1.20]
		Rel. Std. Dev.	0.04	0.04	0.35	0.37	0.35
Seasoned Oak	20.8	S7-19-04-03	1.89	140	4.08	1.75	0.93
	21.3	S7-19-04-04	1.94	136	6.91	3.05	1.57
	20.4	S7-19-04-05	1.95	137	4.69	2.05	1.05
		Mean [95% CI]	1.93 [1.89-1.96]	137.7 [135.3-140.0]	5.23 [3.54-6.91]	2.28 [1.51-3.05]	1.18 [0.80-1.57]
		Rel. Std. Dev.	0.02	0.02	0.28	0.30	0.29
Wet Oak	28.8	S7-19-04-20	1.55	153	5.38	2.11	1.36
	29.5	S7-19-03-25	1.27	192	7.8	2.44	1.92
	28.9	S7-19-03-26	1.53	159	7.13	2.69	1.76
		Mean [95% CI]	1.45 [1.27-1.63]	168.0 [144.0-191.8]	6.77 [5.36-8.18]	2.41 [2.08-2.74]	1.68 [1.35-2.01]
		Rel. Std. Dev.	0.11	0.13	0.18	0.12	0.17
Poplar	19.9	S7-19-03-28	1.89	142	1.62	0.68	0.36
	20.4	S7-19-03-29	1.68	159	2.3	0.87	0.52
	21.7	S7-19-03-30	2.1	125	5.26	2.52	1.2
		Mean [95% CI]	1.89 [1.65-2.13]	142.0 [122.8-161.2]	3.06 [0.87-5.25]	1.36 [0.21-2.50]	0.69 [0.19-1.20]
		Rel. Std. Dev.	0.11	0.12	0.63	0.75	0.64

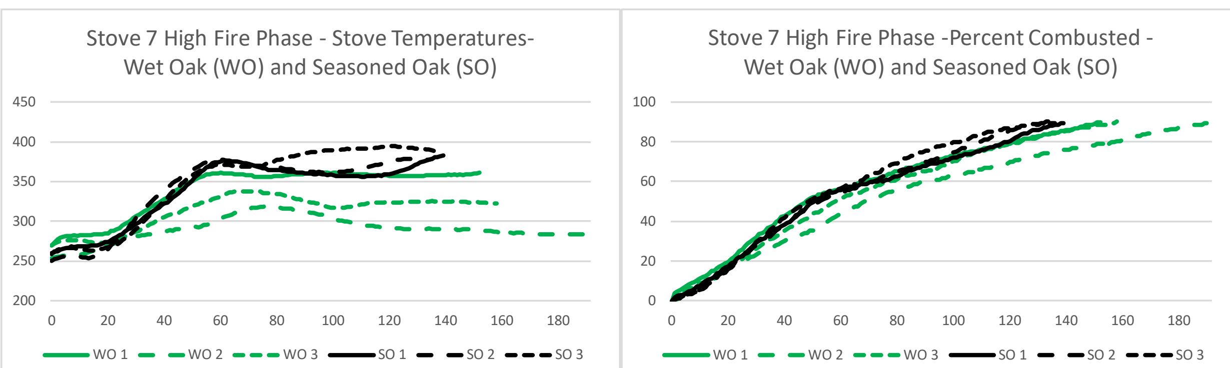
The run times in the high-fire phase were highest and the dry-burn rates lowest for the runs that burned wet oak. The average wet oak high-fire phase dry-burn rates was significantly lower than those for all other fuels and the average wet oak high-fire phase run times were significantly higher than in the seasoned oak group. The high-fire phase of the wet oak runs was, on average, 30 minutes longer than the seasoned oak runs. Run times and burn rates were similar for the other fuels.

The average total PM emissions and EF in the wet oak runs were significantly higher than in the red maple and poplar groups. The average EF for the wet oak runs, 1.7 g/kg, was 42% higher than that of the seasoned oak runs, 1.2 g/kg. However, due to the longer run times, the average high-fire phase ER for wet oak, 2.4 g/h, was similar to that of the seasoned oak, 2.3 g/h. One of the seasoned oak runs produced an ER of 3.05 g/h, which was higher than in any of the wet oak runs, as well as the runs that burned maple or poplar.

The EF and ER in the wet oak runs had a lower intragroup variability than the other fuel groups. The average EFs in the poplar, red maple, and seasoned oak groups were 0.7, 0.9, and 1.2 g/kg, but there was considerable intergroup overlap in the EFs of individual runs for those fuels. The same pattern was seen in the ERs; the average ERs for poplar and red maple, 1.4 and 1.6 g/h, respectively, were lower than for seasoned oak, 2.3 g/h, but the ranges of the ERs in the groups overlapped and those differences were not significant.

Figure 97 compares the temperature profiles and fuel consumption in the high-fire phase of the seasoned oak and wet oak runs. Wet oak is shown in green and seasoned oak in black.

Figure 97. Stove 7 IDC High-Fire Phase—Seasoned and Wet Oak—Stove Temperatures and Fuel Consumption



The stove temperature and fuel combustion percentages in the high-fire phase first wet oak run (denoted as WO 1 in Figure 97) were similar to those in the seasoned oak group, which may explain the finding that the high fire PM emission metrics for that wet oak run were similar to those in the seasoned oak group. After the first 30 minutes, the second and third wet oak runs (WO 2 and WO 3) had lower temperatures than in the seasoned oak runs and WO 1, which may explain the higher PM emissions in those runs.

The maintenance phase metrics measured for the stove 7 IDC runs are shown in Table 110.

Table 110. Stove 7—Comparison of Test Metrics for Maintenance Phase, IDC Final Protocol by Fuel Type

Fuel	MC (%) Dry Basis	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	21.6	S7-18-07-25	1.17	158	3.51	1.33	1.13
	21.4	S7-18-07-26	1.06	178	3.08	1.04	0.98
	19.9	S7-18-07-27	1.34	146	3.75	1.54	1.15
		Mean [95% CI]	1.19 [1.03-1.35]	160.7 [142.4-179.0]	3.45 [3.06-3.83]	1.30 [1.04-1.59]	1.09 [0.98-1.19]
		Rel. Std. Dev.	0.12	0.10	0.10	0.19	0.09
Seasoned Oak	21.9	S7-19-04-03	1.21	155	1.37	0.53	0.44
	22.3	S7-19-04-04	1.06	175	2.75	0.94	0.89
	21.3	S7-19-04-05	1.32	142	2.38	1.01	0.76
		Mean [95% CI]	1.20 [1.05-1.34]	157.3 [138.5-176.1]	2.17 [1.36-2.97]	0.83 [0.53-1.12]	0.70 [0.43-0.96]
		Rel. Std. Dev.	0.11	0.11	0.33	0.31	0.33
Wet Oak	29.6	S7-19-04-20	1.02	169	4.44	1.57	1.55
	28.1	S7-19-03-25	1.09	162	5.27	1.95	1.78
	28	S7-19-03-26	1.32	135	3.9	1.73	1.32
		Mean [95% CI]	1.14 [0.97-1.43]	155.3 [135.0-175.6]	4.54 [3.76-5.32]	1.75 [1.53-1.97]	1.55 [1.29-1.81]
		Rel. Std. Dev.	0.14	0.12	0.15	0.11	0.15
Poplar	19.8	S7-19-03-28	1.37	139	1.87	0.81	0.59
	20.2	S7-19-03-29	1.29	145	2.81	1.16	0.9
	21.7	S7-19-03-30	1.25	144	1.63	0.68	0.54
		Mean [95% CI]	1.30 [1.23-1.37]	142.7 [139.0-146.3]	2.10 [1.40-2.81]	0.88 [0.60-1.16]	0.68 [0.46-0.90]
		Rel. Std. Dev.	0.05	0.02	0.30	0.28	0.29

Dry-burn rates in the maintenance phase were similar in all runs for all fuel types in the maintenance phase (1.1–1.4 g/h). Burn times were also similar; average burn times for this phase were 161 minutes of red maple, 157 for seasoned oak, 155 for wet oak, and 143 minutes for poplar. There was good intragroup consistency for all parameters and all fuel types. The EFs and ERs for the wet oak burns were, on average, approximately twice those for the seasoned oak runs, but low in comparison to those measured in other stoves. The average EFs for the poplar and seasoned oak runs were both 0.7 g/kg, which was significantly lower than the average in the red maple runs, 1.1 g/kg. The mean EF in the wet oaks runs, 1.5 g/kg, was significantly higher than in all other fuel groups. The average ER for seasoned oak and poplar were also essentially equivalent, 0.83 g/h and 0.88 g/h, as compared to the average red maple value, 1.30 g/h and for wet oak, 1.75 g/h.

The metrics for the overnight phase of the stove 7 IDC runs are shown in Table 111.

Table 111. Stove 7—Comparison of Test Metrics from Overnight Burn Phase, IDC Final Protocol

Fuel	MC (%) Dry Basis	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Red Maple	20.5	S7-18-07-25	1.42	314	6.4	1.22	0.86
	19.9	S7-18-07-26	1.37	283	6.32	1.34	0.98
	21.2	S7-18-07-27	1.23	315	5.49	1.04	0.85
		Mean [95% CI]	1.34 [1.23-1.45]	304.0 [283.4-324.6]	6.07 [5.50-6.64]	1.20 [1.03-1.37]	0.90 [0.81-0.98]
		Rel. Std. Dev.	0.07	0.06	0.08	0.13	0.08
Seasoned Oak	20.6	S7-19-04-03	1.42	316	3.38	0.64	0.45
	22.0	S7-19-04-04	1.6	279	8.54	1.84	1.15
	21.1	S7-19-04-05	1.49	302	3.12	0.62	0.41
		Mean [95% CI]	1.50 [1.40-1.61]	299.0 [277.9-320.1]	5.01 [1.55-8.47]	1.03 [0.24-1.82]	0.67 [0.20-1.14]
		Rel. Std. Dev.	0.06	0.06	0.61	0.68	0.62
Wet Oak	28.7	S7-19-04-20	1.54	271	9.16	2.03	1.31
	28.8	S7-19-03-25	1.34	313	6.43	1.23	0.92
	27.9	S7-19-03-26	1.25	340	7.9	1.39	1.12
		Mean [95% CI]	1.38 [1.21-1.54]	308.0 [268.6-347.3]	7.83 [6.28-9.38]	1.55 [1.07-2.03]	1.12 [0.90-1.34]
		Rel. Std. Dev.	0.11	0.11	0.17	0.27	0.17
Poplar	20.9	S7-19-03-28	1.38	278	3.17	0.68	0.49
	20.5	S7-19-03-29	1.55	230	3.89	1.02	0.66
	21.9	S7-19-03-30	1.37	285	2.72	0.57	0.42
		Mean [95% CI]	1.43 [1.34-1.55]	264.3 [230.4-298.2]	3.26 [2.59-3.93]	0.76 [0.49-1.02]	0.52 [0.38-0.66]
		Rel. Std. Dev.	0.07	0.11	0.18	0.31	0.24

The overnight phases of the stove 7 maple IDC runs lasted 283 to 315 minutes (4.7 to 5.3 hours). The range of times for this phase was similar for the seasoned oak (4.7 to 5.3 hours) and wet oak runs (4.5 to 5.7 hours) and somewhat lower in the poplar runs (3.8 to 4.8 hours). That difference was not significant. The dry-burn rate was similar in all of the runs (1.2 to 1.6 kg/h).

On average, the overnight EF and ER for the wet oak runs were 67% and 50% higher than those for the seasoned oak runs, respectively, but there was an overlap between the ranges of both of those metrics in the two groups and this difference was not significant. In this phase, the average EFs for the poplar and seasoned oak runs were 37% and 14%, respectively, lower than the red maple average. The average poplar and seasoned oak ERs were 42% and 25% lower than those for red maple. The average red maple, seasoned oak, wet oak, and poplar ERs for this phase were 1.2, 1.0, 1.6, and 0.8 g/h, respectively. The average ER and EF for the poplar runs were significantly lower than in the red maple and wet oak runs.

Table 112 shows the test metrics for the entire run of each of the IDC replicates.

Table 112. Stove 7—Test Metrics for Entire Run of IDC Final Protocol Runs

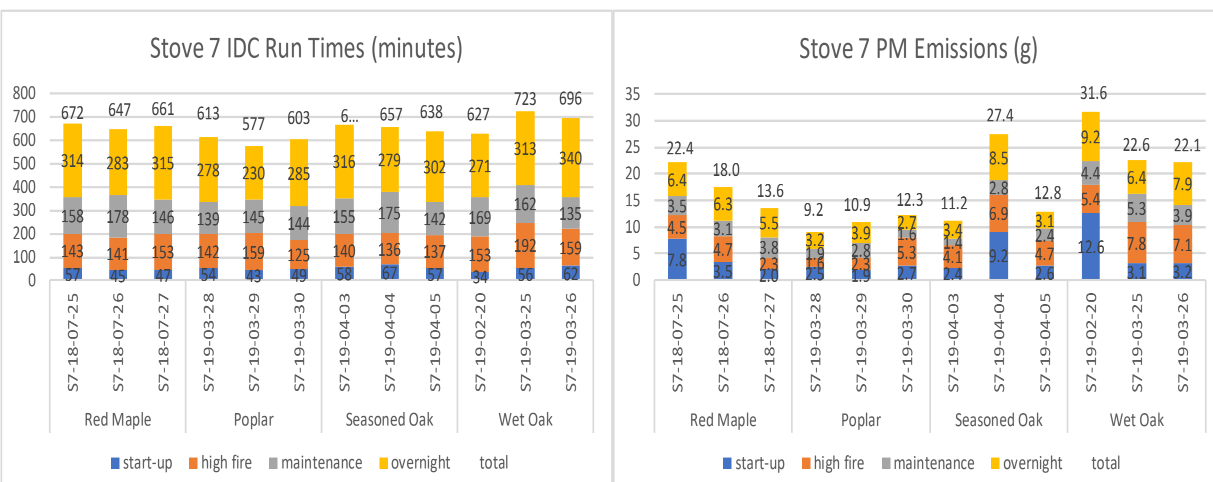
Fuel	MC (%) Dry Basis	Test ID #	Dry-Burn Rate (kg/h)	Time (min)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	HHV Efficiency (%)
Red Maple	20.7	S7-18-07-25	1.52	672	22.43	2	1.32	70.2
	20.2	S7-18-07-26	1.49	647	17.95	1.66	1.12	70.2
	20.2	S7-18-07-27	1.47	661	13.56	1.23	0.84	71.3
		Mean [95% CI]	1.49 [1.46-1.52]	660.0 [646-674]	17.98 [13.0-23.0]	1.63 [1.19-2.07]	1.09 [0.84-1.37]	70.6 [69.9-71.3]
		Rel. Std. Dev.	0.02	0.02	0.25	0.24	0.22	0.01
Seasoned Oak	20.9	S7-19-04-03	1.52	669	11.24	1.01	0.66	69.2
	21.8	S7-19-04-04	1.54	657	27.37	2.5	1.62	67.8
	20.9	S7-19-04-05	1.61	638	12.81	1.2	0.75	69.5
		Mean [95% CI]	1.56 [1.50-1.61]	654.7 [637-672]	17.14 [7.1-27.2]	1.57 [0.65-2.49]	1.01 [0.41-1.61]	68.8 [67.8-69.9]
		Rel. Std. Dev.	0.03	0.02	0.52	0.52	0.52	0.01
Wet Oak	28.9	S7-19-04-20	1.52	627	31.59	3.02	1.99	67.3
	28.9	S7-19-03-25	1.33	723	22.62	1.88	1.41	68
	28.2	S7-19-03-26	1.37	696	22.1	1.91	1.39	68.4
		Mean [95% CI]	1.41 [1.29-1.52]	682.0 [626-738]	25.44 [19.4-31.5]	2.27 [1.53-3.01]	1.60 [1.21-1.98]	67.9 [67.3-68.5]
		Rel. Std. Dev.	0.07	0.07	0.21	0.29	0.21	0.01
Poplar	20.3	S7-19-03-28	1.57	613	9.17	0.9	0.57	CBD
	20.4	S7-19-03-29	1.61	577	10.94	1.14	0.71	CBD
	21.8	S7-19-03-30	1.58	603	12.3	1.22	0.77	69.8
		Mean [95% CI]	1.59 [1.56-1.61]	597.7 [577-619]	10.80 [9.0-12.6]	1.09 [0.90-1.28]	0.68 [0.57-0.80]	
		Rel. Std. Dev.	0.01	0.03	0.15	0.15	0.15	

The total time to complete the stove 7 IDC red maple runs ranged from 647 to 672 minutes (10.8 to 11.2 hours), a longer period than for the other stoves and slightly longer than the 10-hour target period. The time range was similar for the seasoned oak runs (10.6 to 11.2 hours) and wet oak (10.4 to 12.1 hours) and significantly lower for the poplar runs (9.6 to 10.2 hours). The HHV efficiencies were between 67.3% and 71.3% for the 10 runs for which sufficient CO and CO_2 data were available for calculating that value. For all three red maple runs, the HHV thermal efficiency was between 70.2% and 71.3%. The average HHV thermal efficiency for the red maples was higher than that for either of the oak groups.

As with stove 6, there was more variation in the Stove IDC PM metrics in the seasoned oak runs than in the other fuel groups. The EF and ER in the highest emitting seasoned oak runs were both 2.5 times higher than in the lowest emitting run in that group. The highest EF and ER were 57% and 63% higher for the highest than the lowest red maple run. A similar variability was seen in the wet oak runs; in those runs the highest EF and ER were 43% and 61% higher than the lowest. The poplar runs had the least variability, with the highest EF and ER in the runs burning that species 35% and 36% higher than the lowest. The average ERs for the entire run were 1.5 g/h for the red maple and the seasoned oak runs, 2.3 g/h for the wet oak runs, and 1.1 g/h for the poplar runs. The poplar EF was significantly lower than those for wet oak and red maple, and the poplar ER was significantly lower than that for wet oak.

Figure 98 shows run times and PM emissions by test phase for each of the IDC runs graphically.

Figure 98. Stove 7 IDC Runs—Run Times and PM Emissions by Phase and Fuel Type



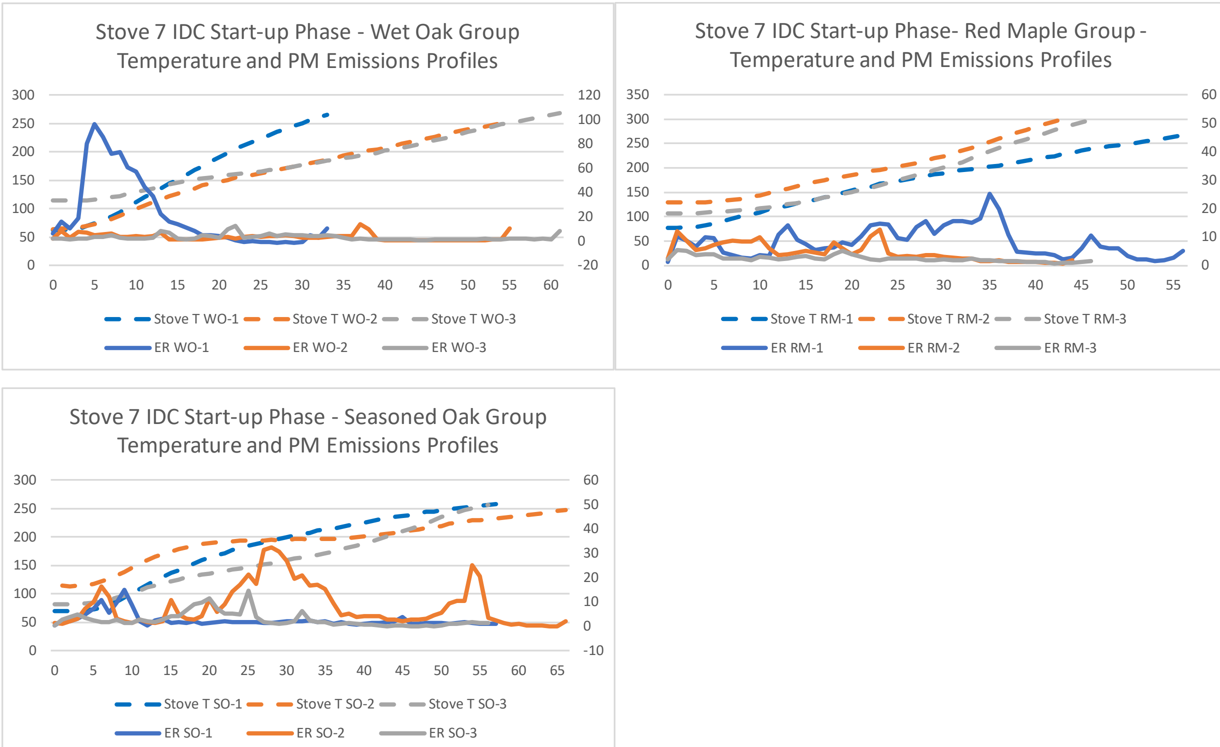
Of particular note is the impact of PM emissions during the start-up phase on the emissions parameters for the entire run. Although the start-up ER and EF were at the lower end of the range seen in the other stoves, stove 7 emissions in the other phases were considerably lower than those for the other stoves. Therefore, as shown in Table 113, start-up emissions constituted a greater percentage of total emissions for that stove than for most of the other stoves, and variability in start-up emissions for stove 7 had a greater effect on variability of total PM emissions.

Table 113. IDC Start-Up PM Metrics—All Stoves

	Stove 1	Stove 2	Stove 4	Stove 5	Stove 6	Stove 7
Start-Up EF (g/kg)	2.6	5.5	2.4	7.6	1.7	2.2
Start-Up ER (g/h)	8.7	13.4	5.8	24.1	6.3	5.1
Start-Up PM (g)	8.5	9.4	2.3	16.3	3.9	4.5
PM Entire Run (g)	105.3	88.1	31.6	43.4	192.4	17.8
Start-Up PM as a % of Total	8%	11%	7%	38%	2%	25%

As shown in Figure 98, three of the 12 stove 7 IDC runs (one each in the red maple, seasoned oak, and wet oak groups) had substantially greater start-up PM emissions than the other runs. The same start-up procedures were used in all runs. Figure 99 shows the emission rate and temperature profiles for the start-up phase of those three replicate groups.

Figure 99. Start-Up Emissions and Temperature Profiles



Stove temperatures at the beginning of the start-up phase were similar for the replicates in the red maple and seasoned oak groups and did not appear to affect emissions in those groups early in the phase. However, the stove temperature for the first red maple and the second seasoned oak run leveled out midway through start-up, and emissions were substantially higher after that point for both of the runs relative to their replicates. This pattern was not seen in the wet oak group, which had substantial PM emissions early in the run that did not correspond to stove temperature.

3.4.3 Comparison Effect of Moisture Content—Stoves 6 and 7

The IDC final protocol runs burning wet and seasoned oak in stoves 6 and 7 allowed an investigation of the effect of moisture content on stoves with two different types of emission control technologies. The results of those tests, by phase, are presented above. Table 114 shows key metrics from the those runs as the average of the three replicate runs in that test.

Table 114. Summary of the Entire IDC Final Protocol Test Results with Seasoned and Wet Oak in Stoves 6 and 7

	Stove 6			Stove 7		
	Seasoned	Wet	Percent Difference	Seasoned	Wet	Percent Difference
Moisture Content (%)	21.2	28.7	35%	21.4	28.1	31%
Dry-Burn Rate (kg/h)	1.93	2.02	5%	1.56	1.41	-10%
Total PM (g)	132.98	302.27	127%	17.14	25.44	48%
PM Emission Rate (g/h)	13.5	31.89	136%	1.57	2.27	44%
PM Emission Factor (g/kg)	7.01	15.76	125%	1.01	1.6	58%
HHV Efficiency	61.6	57.1	-7.3%	68.8	67.9	-1.3%

The higher moisture content (MC) of the wet oak fuel had less of an effect on the performance of stove 7 than on stove 6. The 31% difference in MC in the wet and seasoned fuel resulted in a 55% increase in the PM EF and a 44% increase in the PM ER in stove 7. However, the 35% difference in MC in the wet and seasoned oak in stove 6 fuels resulted in a 125% increase in the PM EF and a 136% increase in the ER for that stove.

Stoves 6 and 7 both have medium sized fireboxes. However, stove 6 is constructed of steel, while stove 7 is a high-mass unit. In addition, while stove 6 uses non-catalytic controls and is step 1 certified to emit <4.0 g/h, stove 7 has a hybrid (catalytic and non-catalytic) control system and is step 2 certified to emit <2.0 g/h. The use of wet wood reduced the HHV thermal efficiency of stove 6 by 7.3%, while the efficiency of stove 7 was reduced by only 1.3%. In addition, the stove 7 control system was much more effective than that of stove 6. The combination of the higher efficiency of the combustion unit and the control system in stove 7 allowed that stove to achieve an ER of 2.3 g/h, even when wet fuel was burned. This is important because manufacturers recommend the use of seasoned fuel, but stove owners often do not let the wood dry sufficiently before use.

3.5 Comparison of M28, ASTM 3053-17, and IDC results

As discussed above, the M28 crib wood test is the current FRM and the ASTM 3053-17 cordwood test has been approved as a Broadly Applicable ATM to certify compliance with the emissions limits for wood stoves. Although there is general agreement that testing procedures should move towards cordwood tests, several concerns have been identified with the ASTM 3053-17 test, as discussed in section 1. The IDC protocol was developed in an effort to address those concerns and to provide an emission test that is reproducible and more accurately represents operating and fueling conditions in the field.

Tests using all three of the testing protocols were performed on three of the study stoves, stoves 1, 6, and 7. The M28 runs burned Douglas fir dimensional lumber, as specified in that protocol, while the ASTM 3053-17 and IDC tests included in this section burned maple cordwood. This section compares key parameters measured using the three test methods in each of the three stoves.

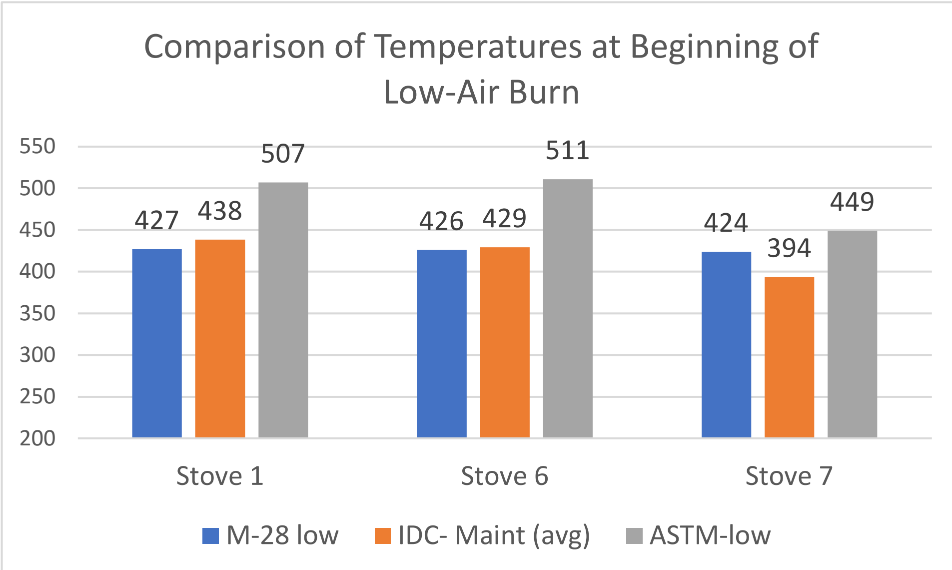
3.5.1 Stove Temperature

The stove temperature at the beginning of a test burn can affect the stove performance and emissions during that phase. Review of data from IDC stove protocol v1 found that starting temperatures for reloads 2 and 3 (the maintenance overnight phases) were higher than M28 runs. In response to industry concern about this issue, researchers made changes to the IDC stove protocol to modify starting stove temperatures.

The medium and low burns in the ASTM 3053-17 test are preceded by the burn of a large load at the highest setting. In residential use, the air setting is often turned down once the stove heats the room, which can occur long before the full-fuel charge is burned. Therefore, there was concern that the temperature at the end of a high-air burn of a large fuel load would result in temperatures at the beginning of the following phase that are atypical of those seen in the field.

Stove temperatures at the beginning of the low-air burns for the three stoves that were tested by all three of the protocols (M28, ASTM 3053-17, and IDC) are shown in Figure 100. The temperatures shown for the IDC tests are the average temperature at the beginning of the maintenance phase for the three replicate runs. The air setting in the IDC maintenance phase is low and the setting in the burn that precedes that phase is switched from high to low when 50% of the load is combusted.

Figure 100. Temperatures (°F) at Beginning of M28, ASTM 3053-17, and IDC Low-Air Phases



When comparing results of the different test methods, initial temperatures for ASTM 3053-17 in the low-air burns in all three stoves were substantially higher than in the M28 and final IDC stove runs. The differences between the ASTM 3053-17 and M28 temperatures in stoves 1 and 6 were particularly large, 80°F and 85°F respectively. Both of those stoves have non-catalytic tube emissions controls, while stove 7, which exhibited a smaller increased temperature in the ASTM 3053-17 runs (25°F), has a hybrid control system.

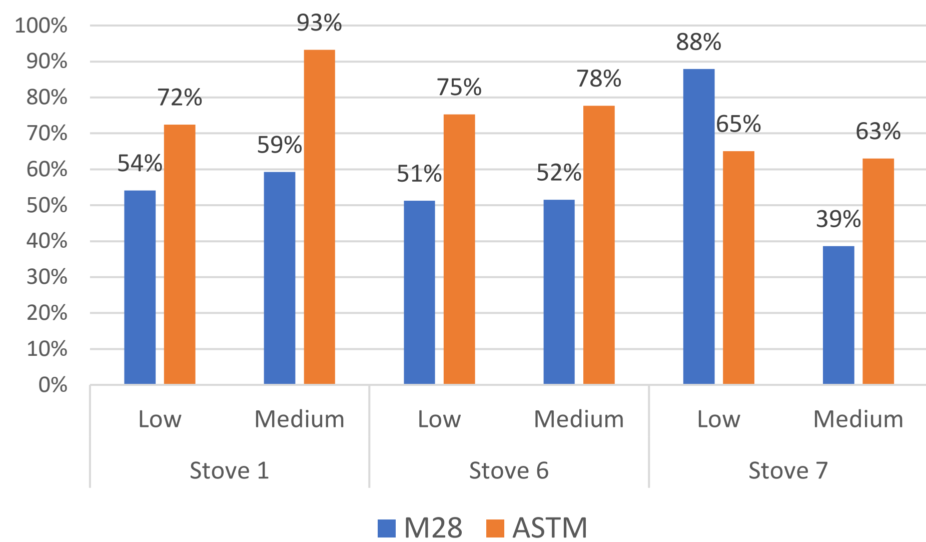
Initial test-burn temperatures that are higher than those typical in the field are of particular concern for stoves with non-catalytic controls because higher temperatures prime the secondary combustion controls for optimum performance. The increased efficiency of the early period of the burn, when most emissions occur, coupled with the optimization of the control system, can result in uncharacteristically low-emission rates in burns with increased initial temperatures, as was seen in the ASTM 3053-17 runs. Note that the initial temperatures in the IDC maintenance phases were similar to those in the M28 runs.

3.5.2 Load Size

The ASTM 3053-17 method requires very large fuel loads in the low and medium phases that are burned to 100% combustion. Large loads sometimes produce higher emissions early in the burn. However, larger loads can dramatically increase the length of the run time, particularly in the charcoal combustion period later in the run, when minimal additional PM emissions are produced. The extended run time during that period of minimal emissions reduces the ER, which is calculated as grams of PM emitted per hour (g/h). As discussed previously, more volatile PM species collected earlier in the burn also can be driven off the PM filter during the charcoal combustion period, resulting in reduced PM measurements.

As discussed in section 4.1, the ERs in the M28 runs were significantly higher at 90% than at 100% fuel consumption. However, the larger load size in the ASTM 3053-17 method further exacerbated this impact. Figure 101 shows the percentage difference between the ERs at 90% and 100% combustion for the low and medium burn ASTM 3053-17 and M28 runs for the three stoves tested with both methods. In five of those six runs, the percent difference between the 90% and 100% combustion ERs were higher in the ASTM 3053-17 tests than when the M28 methodology was used.

Figure 101. Percent Difference Between PM Emissions Rates (ER) at 100% and 90% Load Combustion in ASTM 3053-17 and M28 Medium- and Low-Air Runs



3.5.3 Run Duration

NESCAUM assessed the impact of the test methods on run duration (minutes of testing). The current emission standard is expressed in terms of PM emitted divide by test time and, as discussed above, the test is continued until the entire fuel charge is burned. Because most emissions occur early in a burn, an extended run time reduces the average emission rate and masks peak emission periods that occur in the first few hours of testing. Table 115 compares the run times stoves 1, 6, 7, and 8 during the high-, medium-, and low-burn phases for the ASTM 3053-17, M28, and IDC runs. In this table, IDC maintenance phase times are compared to the medium burns in the other tests and the IDC overnight phases are compared to the low-burn phases of the other tests. All M28 runs burned Douglas fir.

Table 115. Comparison of Run Times for ASTM 3053-17, M28, and IDC Runs by Phase

			Phase Run Time (minutes)		
Stove	Cordwood Species	Burn Phase	ASTM 3053-17	M28	IDC
Stove 1	Maple	High	119	123	119
	Maple	Medium	430	262	143
	Maple	Low	340	327	221
Stove 6	Maple	High	98	123	87
	Maple	Medium	358	247	146
	Maple	Low	500	279	258
	Oak	High	113	123	114
	Oak	Medium	445	247	122
	Oak	Low	502	279	312
Stove 7	Maple	High	157	192	146
	Maple	Medium	331	222	161
	Maple	Low	454	365	304
Stove 8	Maple	Fixed	96	110	53

As shown in that table, the run times for the high-fire phases of the ASTM 3053-17 tests tended to be similar to the corresponding phases for the other methods. However, the average run time for the ASTM-3053-17 medium phases were 60% and 173% higher than the corresponding average M28 and IDC run times, respectively, and the average ASTM-2053-17 low-phase run time was 44% greater than the M28 and 64% greater than the IDC run times for that phase.

Table 116 compares total run times for the three types of tests in those stoves. This parameter is important in considering the impact of testing time on testing costs. The M28 test times reported in that table are the sum of the test times for all runs reported in the stove's certification test report. Because the M28 test times do not include start-up periods and pre-burn run times were not available for all certification tests, start-up times are also not included in the below table for the IDC and ASTM-3053-17 tests. The ASTM-3053-17 times reported in that table are the total of the run times for the two high-fire, the medium-fire, and the low-fire phases in those tests. The IDC run times in the table are the total of the high-fire, maintenance, and overnight phase run times for all three replicate tests combined.

Table 116. Comparison of Total Run Times (Minutes) for Complete ASTM 3053-17, M28, and IDC Tests without Start-Up

Stove	Cordwood Fuel	ASTM 3053-17	M28 certification test	IDC–Sum of 3 Replicates Runs
Stove 1	Maple	1008	1641	1448
Stove 6	Maple	1053	1309	1474
Stove 6	Oak	1172	1309	1642
Stove 7	Maple	1099	1675	1831

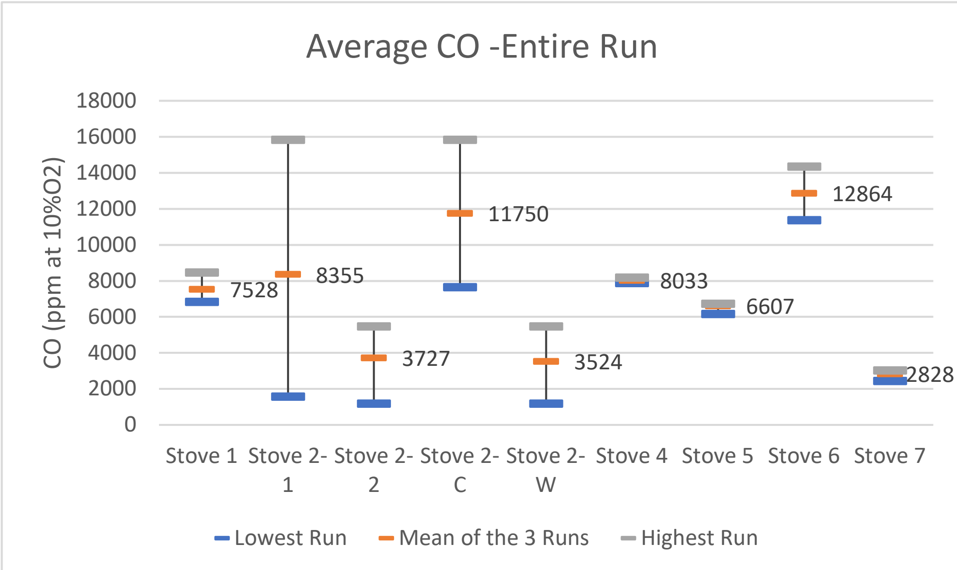
The total time for the three replicate IDC runs is higher than the corresponding ASTM 3053-17 run times and, for stoves 6 and 7, higher than the M28 certification test time. However, unlike the other tests, the IDC test generates three replicates that can be used to assess variability in emissions. The IDC test is designed so that each of the three runs can be performed in a one-day period.

3.6 Carbon Monoxide (CO) Emissions

Although the emissions tests are primarily designed to determine compliance with the NSPS PM limits, concentrations of other emitted gases, including carbon monoxide (CO), carbon dioxde (CO_2), and oxygen (O_2), are also measured continuously during the test period. These concentrations are used to calculate thermal thermal efficiencies and, in some of the analyses of stove data in section 2, the ratio of CO/CO_2 concentrations was used as a continuous indicator of the efficiency of the burn because CO is a product of incomplete combustion and CO_2 of complete combustion.

In addition to being an indicator of inefficient burns, CO is a criteria air pollutant that is particularly hazardous in poorly ventilated indoor environments. NESCAUM performed a preliminary analysis of CO emissions produced in the maple-fueled IDC tests in stoves–7. Average CO concentrations for the entire runs are shown in Figure 102.

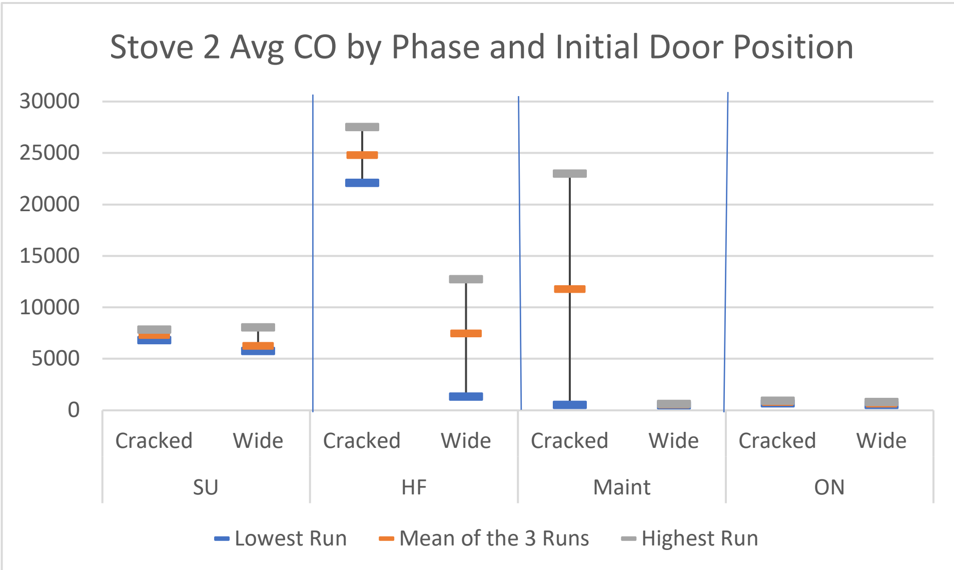
Figure 102. Average CO Concentration (in ppm at 10% O_2)—Entire IDC Runs



Stove 2 results are grouped in two ways, the initial set of three replicates and according to the initial door position, cracked (denoted above as C) or wide open (W).

Average CO concentrations across the entire runs were lowest in stove 7 and highest in stove 6. CO emissions for the entire run were also low in the stove 2 runs that started with the door wide open (labeled stove 2-W) and in the cracked-door run in the second group of runs (labeled stove 2-2). CO emissions in the stove 2 runs were more variable than in the other stoves. The major inter-run variability in stove 2 CO levels occurred in the high-fire and maintenance phases, as shown in Figure 103.

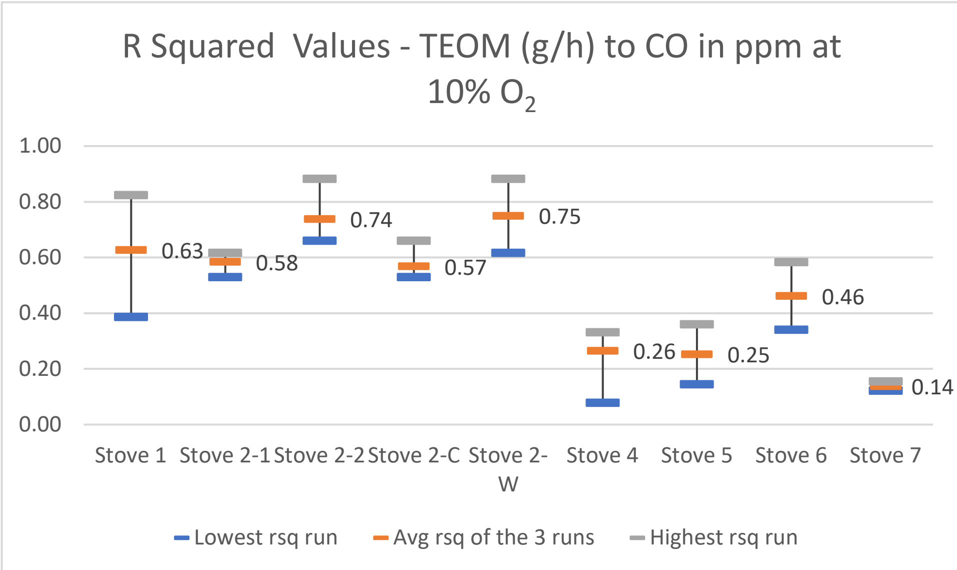
Figure 103. Average Stove 2 CO Concentration (in ppm at 10% O_2)—by Phase and Initial Door Position



Start-up (SU) CO emissions were similar in all stove 2 runs. High-fire (HF) phase CO was considerably higher in all of the runs with the door initially cracked open than in the wide-open door runs. The higher CO levels carried over to the maintenance phase in one of the cracked-open runs. CO emissions in the maintenance phases of the other stove 2 runs and in the overnight phases of all of the stove 2 runs were low.

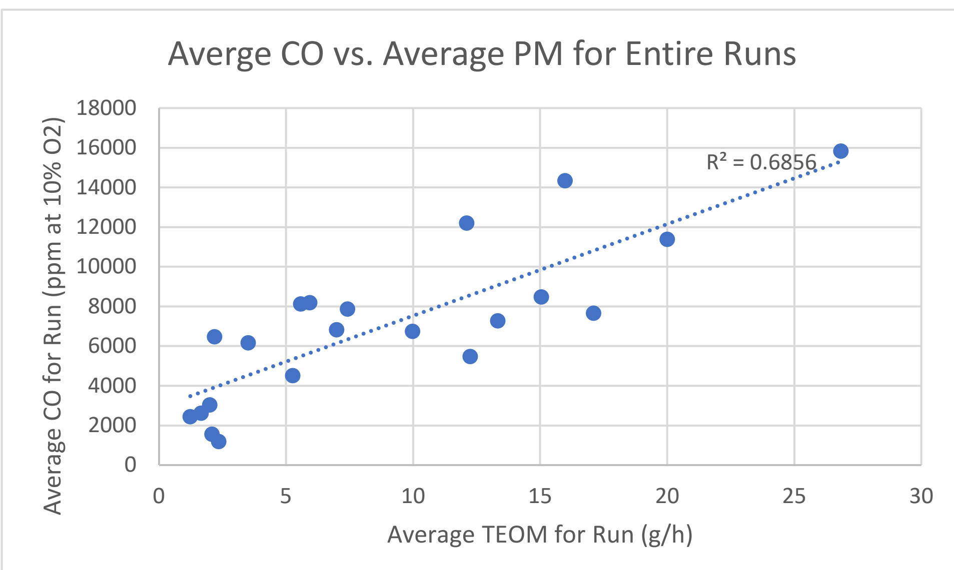
One minute CO measurements correlated well with TEOM PM measurements in the stove 1 and stove 2 runs and correlated least well in the stove 7 runs, as shown in Figure 104.

Figure 104. Correlation between One-Minute CO and PM Measurements by Stove



The average CO correlated well ($r^2 = 0.69$) with average PM2.5 (TEOM measurement for entire runs, as shown in Figure 105. Stoves with low $PM_{2.5}$ emissions (e.g., stove 7) also had lower CO emisisons.

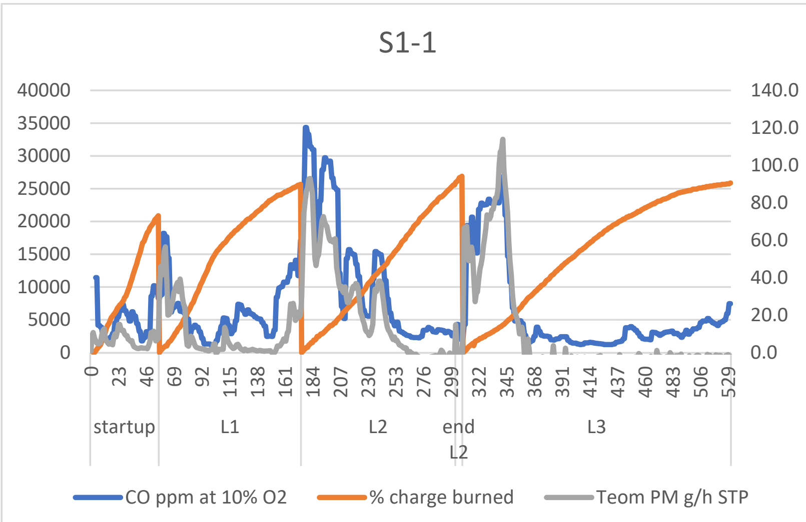
Figure 105. Correlation Average CO and PM Measurements for Entire Runs



The graphs in Figure 106 show the CO and PM profiles, along with the percent fuel combustion, for each of the runs. Correlations between CO and PM emissions are evident in some of the runs, particularly in stoves 1 and 2. However, while PM emissions tend to be low late in a burn, CO levels increased or remained high late in some phases of runs with stoves 1, 4, 5, and 6.

Figure 106. PM and CO Emissions Profiles and Percent of Load Combusted

Stove 1: IDC Runs



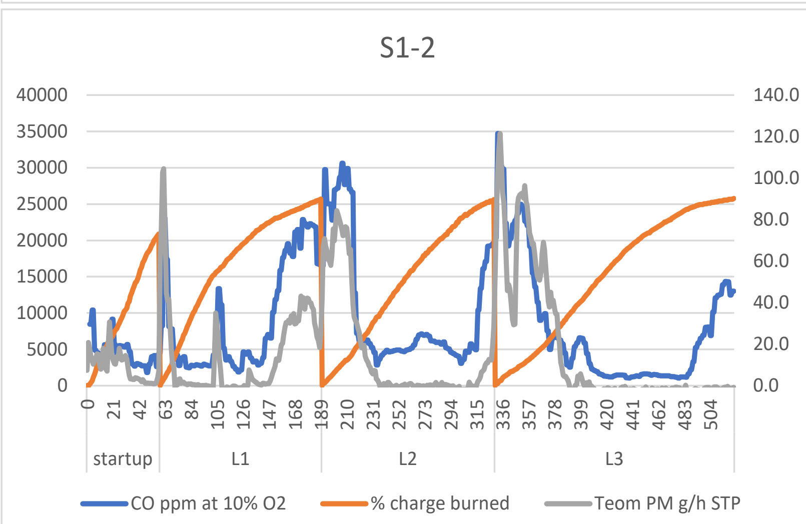
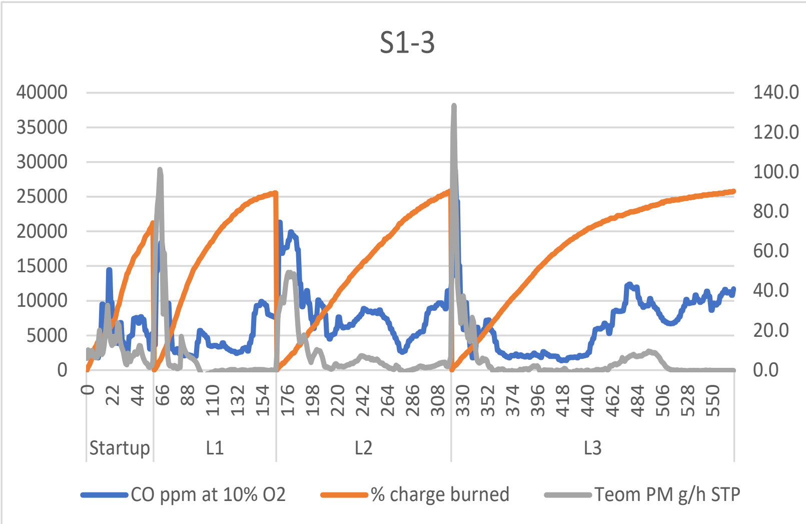
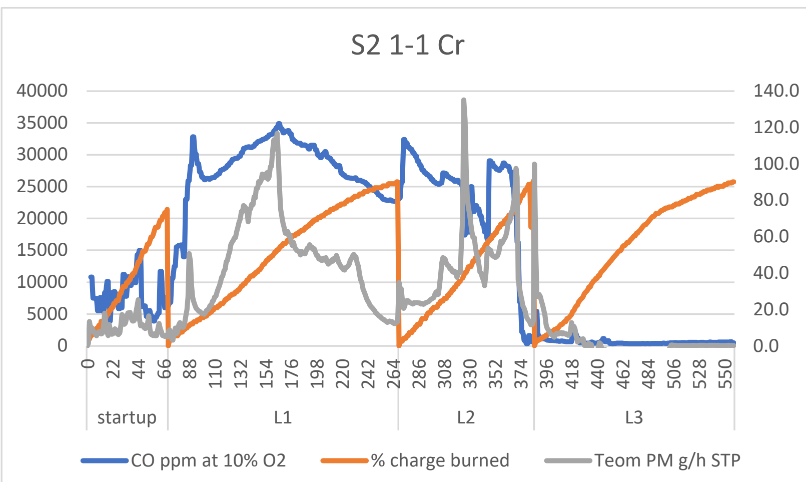


Figure 106 continued



Stove 2: IDC Runs with Door Initially Cracked Open



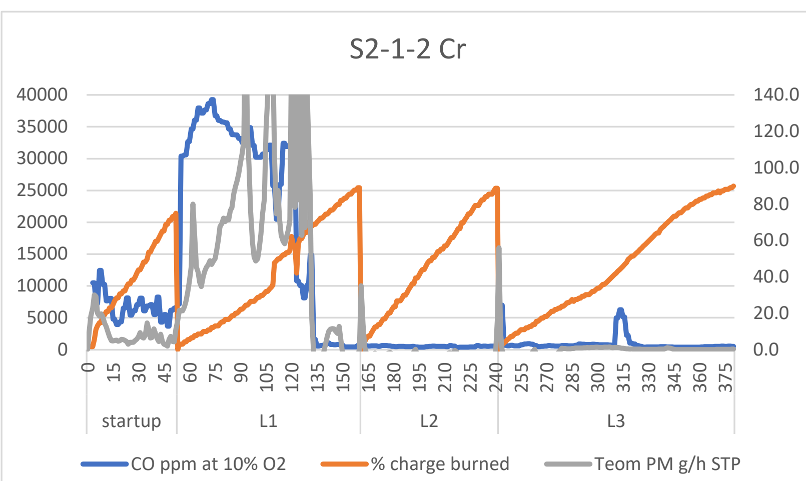
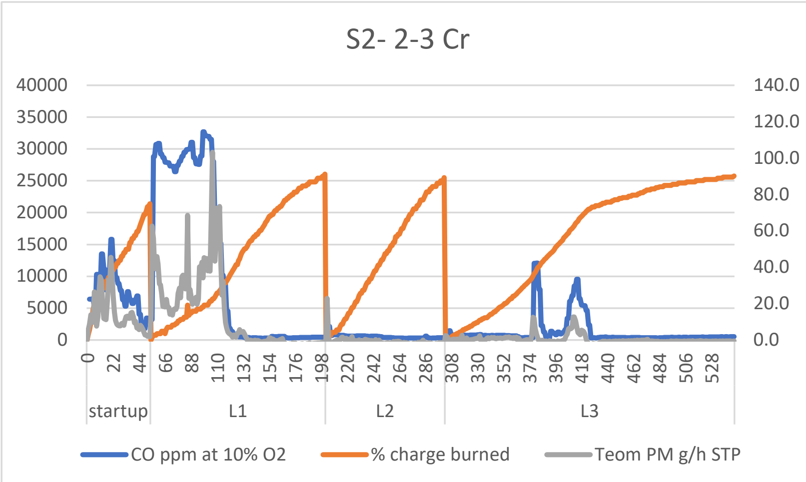
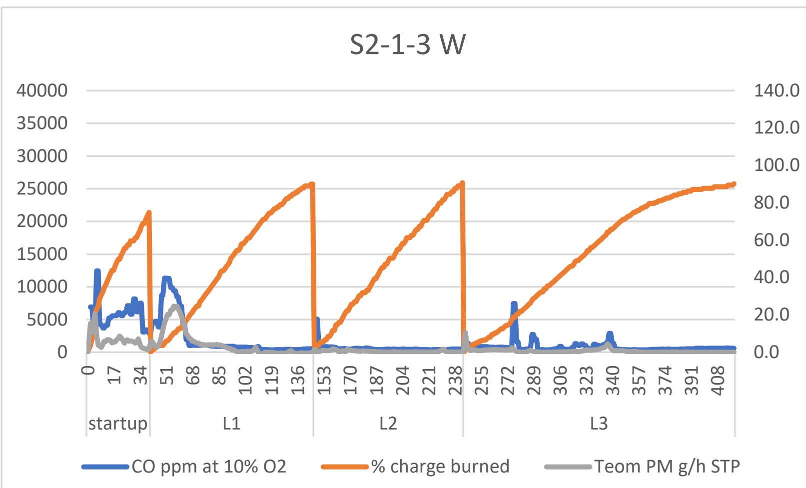


Figure 106 continuted



Stove 2: Runs with Door Initially Wide Open



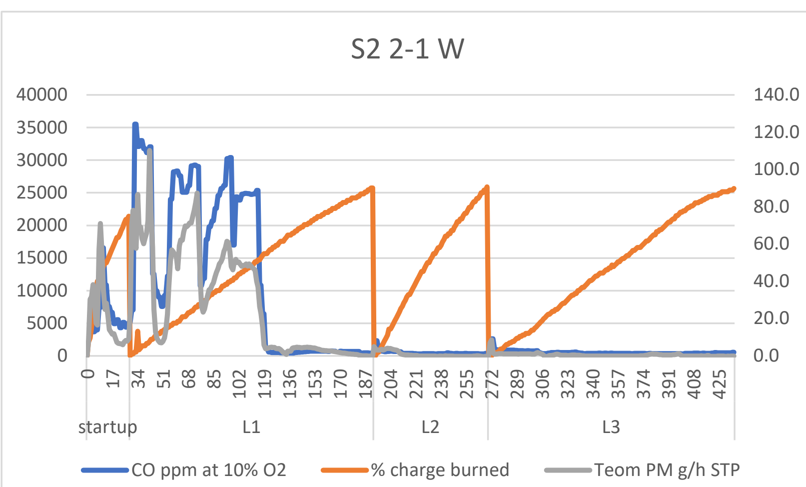
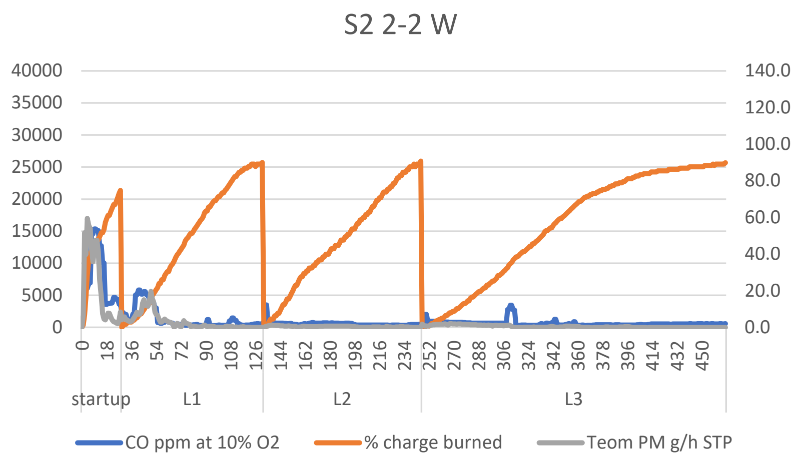
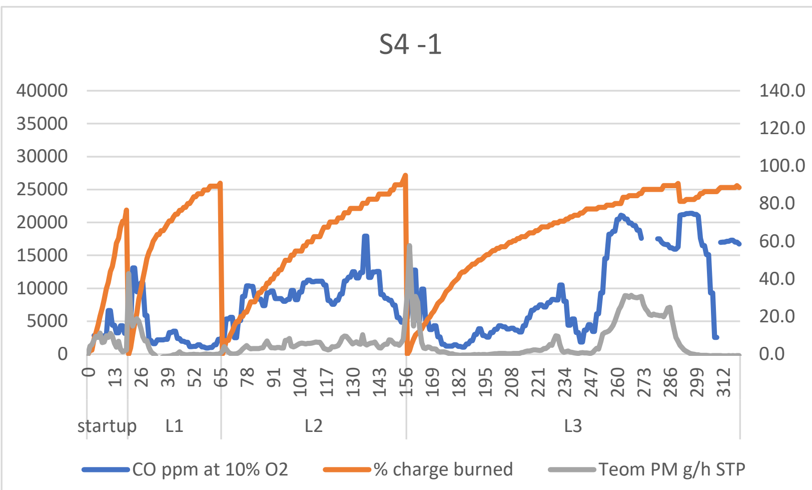


Figure 106 continued



Stove 4: Runs



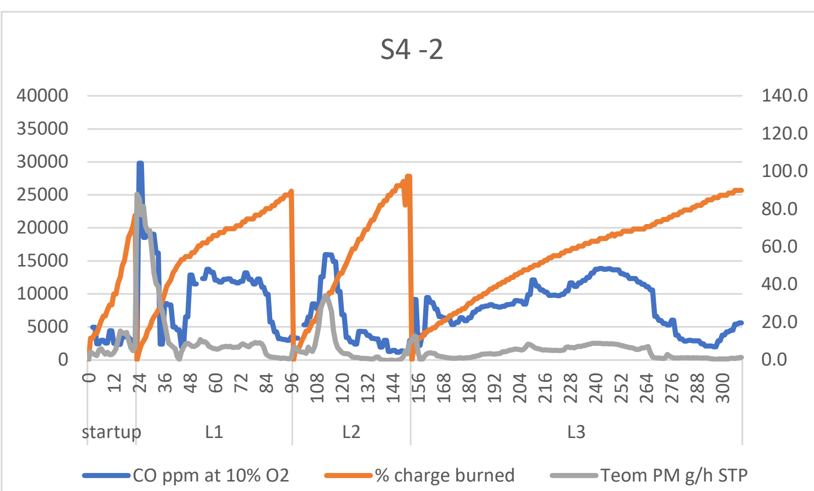
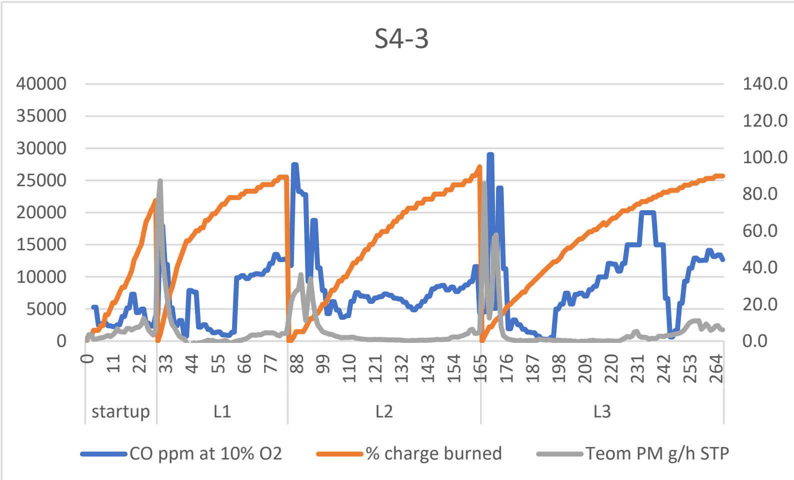
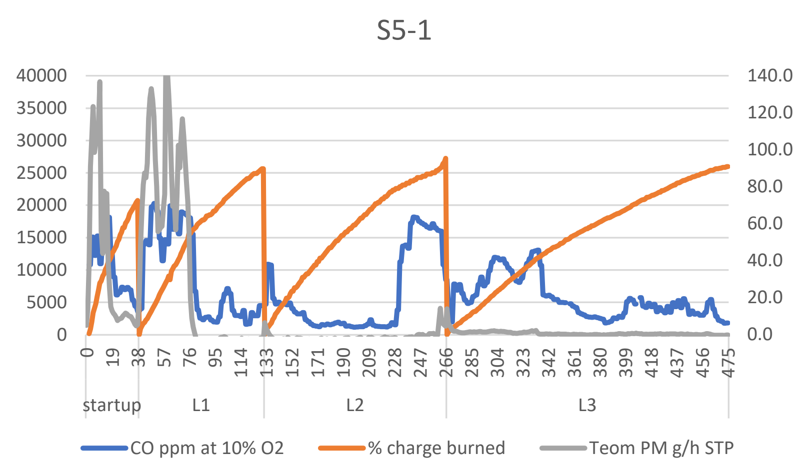


Figure 106 continued



Stove 5: Runs



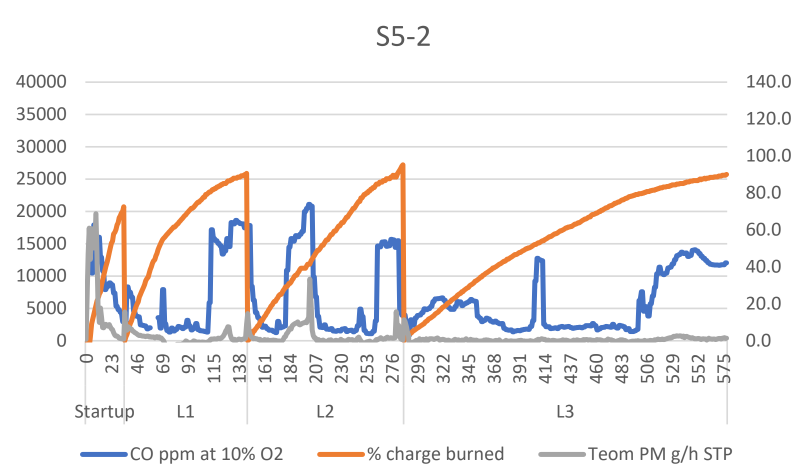
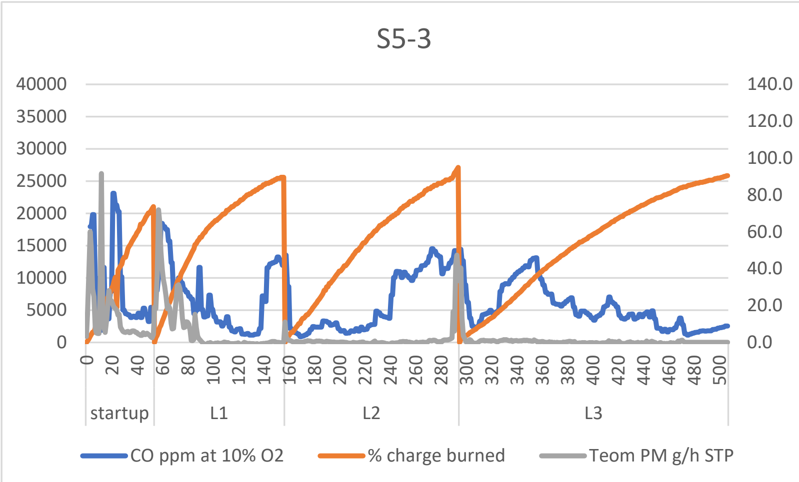
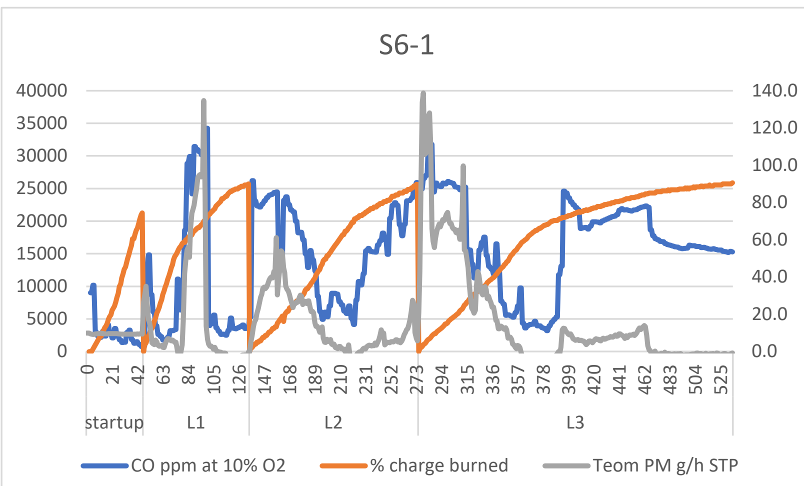


Figure 106 continued



Stove 6: Maple



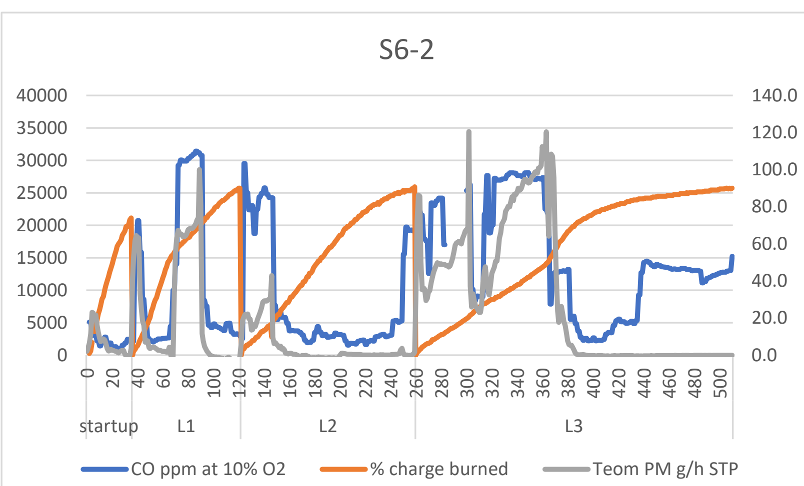
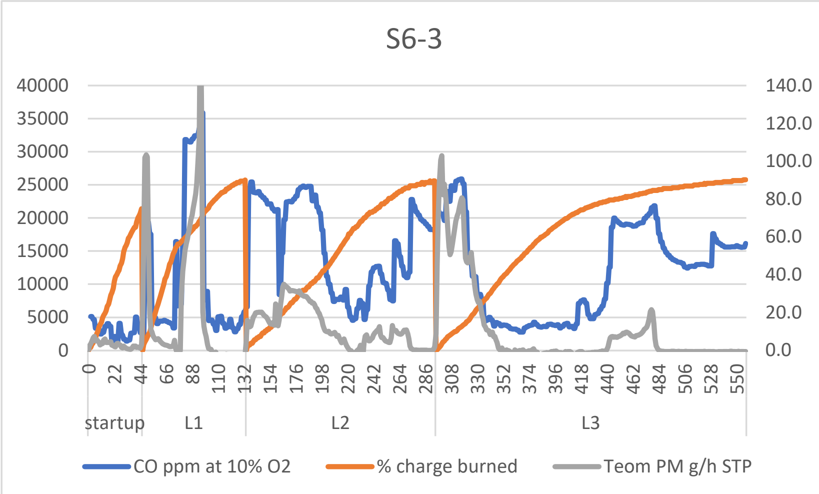
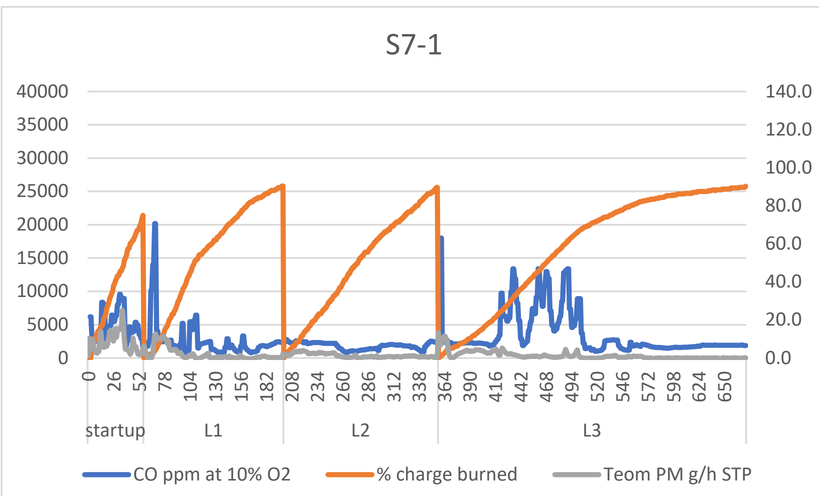


Figure 106 continued



Stove 7: Maple



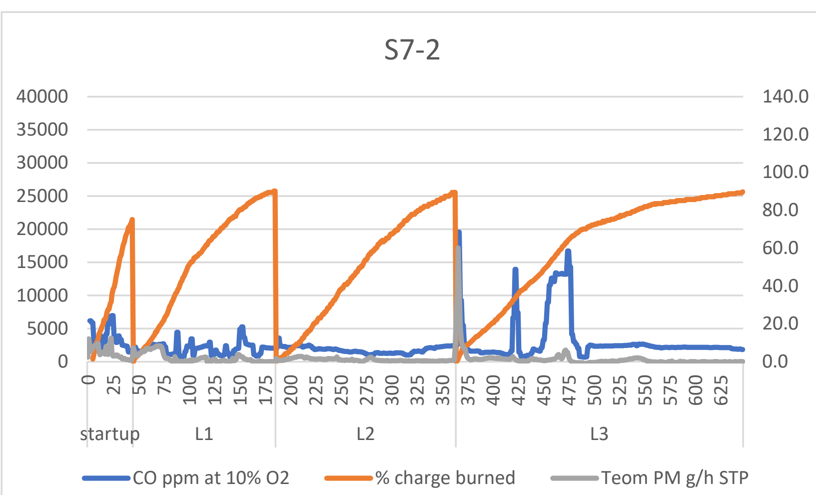
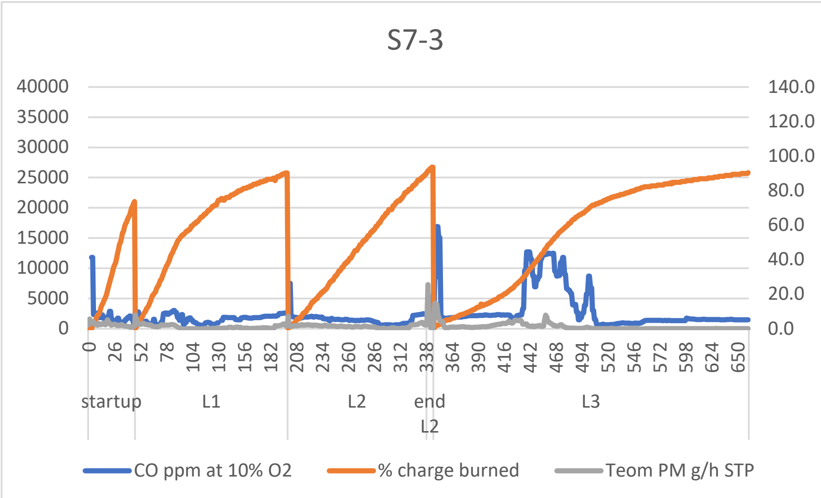


Figure 106 continued



3.7 Comparison of IDC Replicates

A complete IDC final protocol test consists of three replicate test runs. At least one set of three replicate runs was performed on each of the seven stoves in this study. In all cases, the runs were conducted on consecutive days by the same operator using the same fuel in order to minimize method variability. This section analyzes the variability in operating parameters and test results measured in the replicate runs.

The run parameters associated with the entire protocol for each run are listed in Table 117 and shown graphically in Figure 107. The two sets of three stove 2 runs, which were separated by 74 days, are reported here separately. All tests discussed in this section burned red maple cordwood. Additional IDC tests were performed on stoves 6 and 7 with other fuel species. The effect of fuel species on emissions and stove performance is discussed in section 4.3.

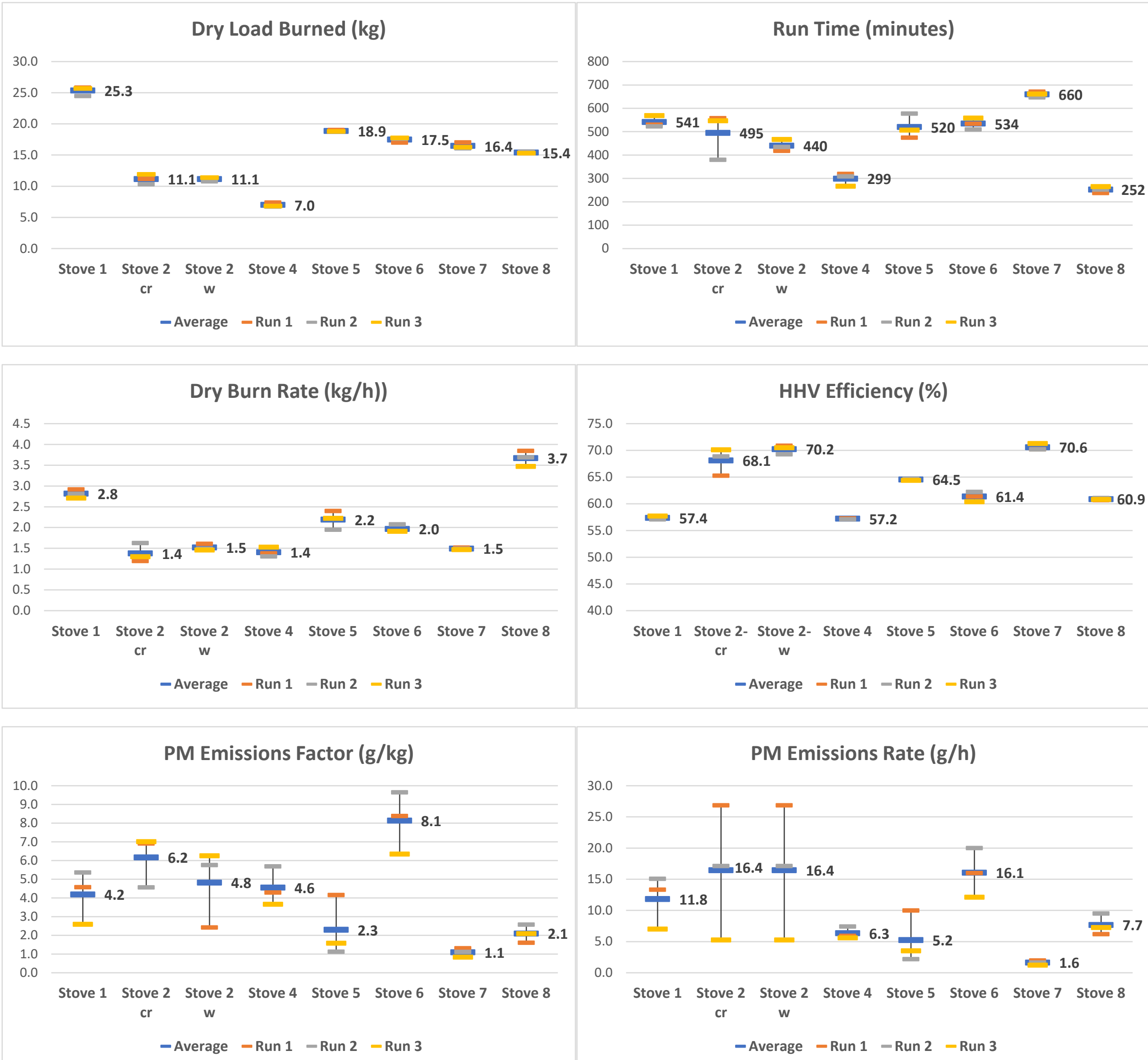
Table 117. Parameters for Entire Runs—IDC Protocol

Stove	Run ID#	Dry Load Burned (kg)	Time (min)	Dry-Burn Rate (kg/h)	Total PM (g)	PM ER (g/h)	PM EF (g/kg)	HHV Efficiency (%)
Stove 1	S1-18-08-08	25.83	531	2.92	118.2	13.36	4.58	57.3
	S1-18-08-09	24.47	523	2.81	131.4	15.08	5.37	57.1
	S1-18-08-10	25.68	569	2.71	66.4	7.00	2.59	57.7
	Mean	25.33	541	2.81	105.33	11.81	4.18	57.4
	Std. Dev.	0.75	24.6	0.11	34.36	4.26	1.43	0.3
	Rel. St. Dev.	3%	5%	4%	33%	36%	34%	0.5%
Stove 2 **Door initially cracked**	S2-18-10-23	11.19	558	1.2	250	26.88	6.92	65.3
	S2-18-10-24	10.34	380	1.63	108.57	17.14	4.57	68.9
	S2-19-01-09	11.88	547	1.3	48.07	5.27	7.01	70.1
	Mean	11.14	495.0	1.38	135.55	16.43	6.17	68.10
	Std. Dev.	0.77	99.7	0.23	103.63	10.82	1.38	2.5
	Rel. St. Dev.	7%	20%	16%	76%	66%	22%	4%
Stove 2 **Door initially wide open**	S2-18-10-25	11.25	419	1.61	14.58	2.09	2.43	70.9
	S2-19-01-07	10.78	435	1.49	89.02	12.28	5.76	69.3
	S2-19-01-08	11.38	467	1.46	18.3	2.35	6.26	70.5
	Mean	11.14	440.3	1.52	40.63	5.57	4.82	70.2
	Std. Dev.	0.32	24.4	0.08	41.95	5.81	2.08	0.8
	Rel. St. Dev.	3%	6%	5%	103%	104%	43%	1%
Stove 4	S4-18-10-16	7.38	320	1.38	31.7	5.94	4.3	57.3
	S4-18-10-17	6.74	309	1.31	38.3	7.44	5.69	57.1
	S4-18-10-18	6.82	267	1.53	24.9	5.6	3.66	CBD
	Mean	6.98	298.7	1.41	31.63	6.33	4.55	57.2
	Std. Dev.	0.35	28	0.11	6.7	0.98	1.04	0.1
	Rel. St. Dev.	5%	9%	8%	21%	15%	23%	0%
Stove 5	S5-18-08-01	19.03	475	2.4	79.2	10	4.16	64.5
	S5-18-08-02	18.76	578	1.95	21.2	2.2	1.13	64.7
	S5-18-08-03	18.77	507	2.22	29.7	3.52	1.58	64.4
	Mean	18.85	520	2.19	43.37	5.24	2.29	64.5
	Std. Dev.	0.15	52.7	0.23	31.32	4.17	1.64	0.2
	Rel. St. Dev.	1%	10%	10%	72%	80%	71%	0.2%
Stove 6	S6-18-07-18	17.01	535	1.91	142.73	16.01	8.39	61.4
	S6-18-07-19	17.64	510	2.08	170.3	20.03	9.65	62.3
	S6-18-07-20	17.75	558	1.91	112.75	12.12	6.35	60.4
	Mean	17.47	534.3	1.97	141.93	16.05	8.13	61.37
	Std. Dev.	0.4	24	0.1	28.78	3.96	1.67	1
	Rel. St. Dev.	2%	4%	5%	20%	25%	20%	2%

Table 117 continued

Stove	Run ID#	Dry Load Burned (kg)	Time (min)	Dry-Burn Rate (kg/h)	Total PM (g)	PM ER (g/h)	PM EF (g/kg)	HHV Efficiency (%)
Stove 7	S7-18-07-25	17.02	672	1.52	22.43	2	1.32	70.2
	S7-18-07-26	16.08	647	1.49	17.95	1.66	1.12	70.2
	S7-18-07-27	16.23	661	1.47	13.56	1.23	0.84	71.3
	Mean	16.44	660	1.49	17.98	1.63	1.09	70.6
	Std. Dev.	0.51	12.5	0.03	4.44	0.39	0.24	0.6
	Rel. St. Dev.	3%	2%	2%	25%	24%	22%	0.9%
Stove 8	S8-19-03-06	15.29	238	3.85	24.66	6.22	1.61	60.7
	S8-19-03-07	15.55	253	3.69	40.13	9.52	2.58	61.1
	S8-19-03-08	15.3	265	3.47	32.01	7.25	2.09	60.8
	Mean	15.38	252	3.67	32.27	7.66	2.10	60.9
	Std. Dev.	0.15	14	0.19	7.74	1.69	0.48	0.2
	Rel. St. Dev.	0.9%	5%	5%	24%	22%	23%	0.3%

Figure 107. Run Parameters—Entire IDC Protocol



The total dry-fuel loads burned were very consistent in the replicate runs in all stoves. The fuel load in each run was no more than 6% higher or lower than the average load for the three runs for that stove. Run times in stoves 1, 6, 7, and 8 and the stove 2 runs with the door initially open were the least variable, and the stove 5 runs and stove 2 runs with the door initially cracked open had the widest variation. The longest stove 2 cracked open run was 13% longer than the average run time for the replicates in that group, while, for stove 7, the longest run time was only 2% longer than the average. Dry-burn rates showed a similar pattern—the lowest variabilities in that parameter were seen in stoves 1, 6, 7, and

8 and the wide-open stove 2 runs, and the highest in the stove 2 cracked-open runs and in the stove 5 test. The minimum and maximum dry-burn rates in the Stove 2 cracked-open runs were 13% below and 18% above the average for that test, respectively, while the dry-burn rates for the stove 7 runs were all within 2% of the average rate for that stove.

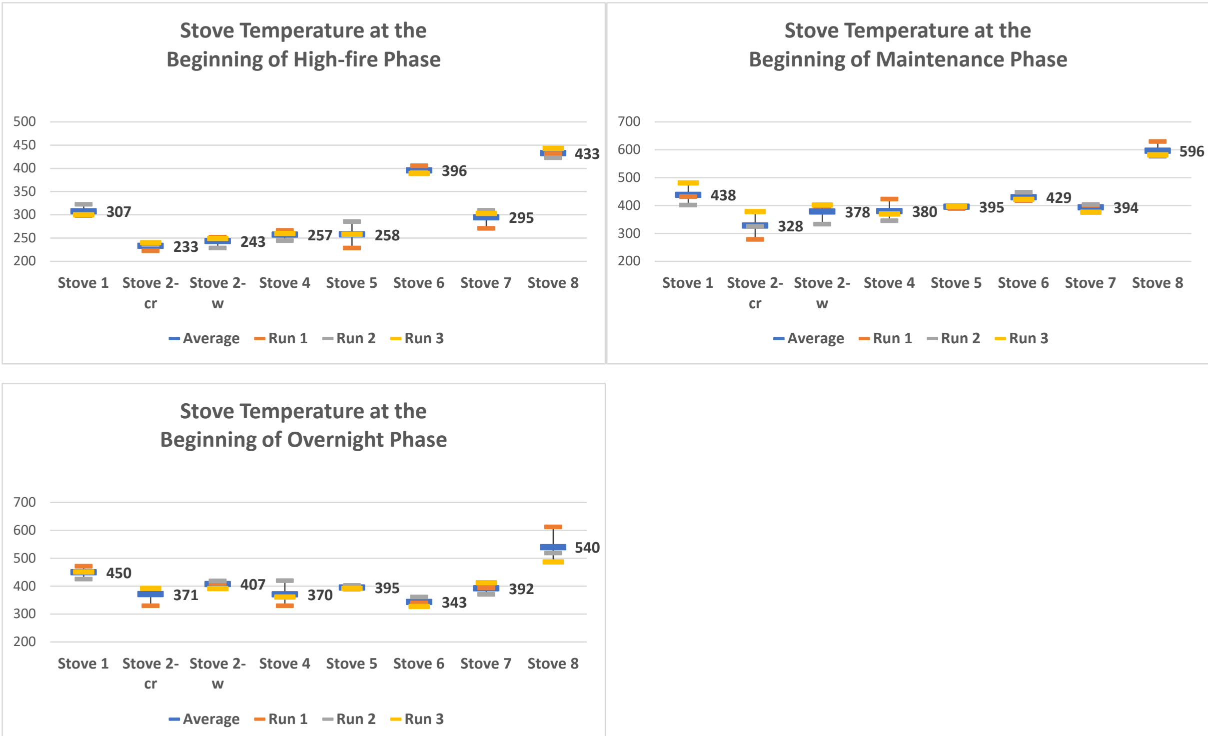
HHV thermal efficiencies were very consistent between runs for each stove. The stove 2 cracked-open door runs showed the most variability in efficiency; however, the efficiencies in those runs were within 3% above and 4% below the average. The HHV thermal efficiencies in all other tests, including the stove 2 door open runs, varied by no more than 1.5% above or below the average value for the stove.

There was considerably more variability between runs in the PM emissions factor (EF), in g/kg, and emissions rate (ER), as shown in Table 117. Because the fuel loads in replicate runs were essentially equal for each stove, the EF is primarily determined by the total PM emitted during the run. The ER is influenced by both PM emissions and the length of the run.

The PM EFs were least variable (relative standard deviation 20–23%) in the stove 2 cracked-open door runs and the runs in stoves 4, 6, 7, and 8 and were most variable in the stove 5 test (relative standard deviation of 71%). For the PM ER, stove 4, 6, 7, and 8 had the lowest and stoves 2 and 5 the highest percent variability.

Stove temperatures during a phase are often linked to PM emissions during that phase, so variability in that parameter between runs is often associated with divergent emissions in those runs. Figure 108 shows the variability in stove temperatures between runs at the start of the high-fire, maintenance, and overnight burn phases for each stove.

Figure 108. Stove Temperatures (ºF)—Hgh-Fire, Maintenance, and Overnight Phases



Stove 5 showed the greatest temperature variability at the beginning of the high-fire phase, a difference of 57ºF between the hottest and coolest run, while stove 6, the stove with the least temperature variability at that point, had a difference of only 17ºF. However, at the beginning of the other two phases, the variability in temperatures between runs was lower in the stove 5 test than for the other stoves, a temperature difference of 9ºF and 13ºF between the warmest and coolest stove 5 runs at the start of the maintenance and overnight phases, respectively. The stove 2 runs were the most variable (99ºF difference between runs) at the beginning of the maintenance phase and stove 8 was the most variable at the start of the overnight phase, a difference of 126ºF between the hottest and coolest stove at that point of the run. The stove 8 temperatures were higher than in the other stoves, particularly in the overnight phase, because the air setting cannot be turned down in that fixed setting stove. As discussed below, temperature profiles can vary significantly during the course of a burn, even when initial temperatures are similar.

The following stove-by-stove replicability discussion investigates the variability between runs by phase (start-up, high-fire, maintenance, and overnight burns). The analyses compare real-time PM emissions rate profiles with real-time stove and stack temperatures, fuel consumption percentages, and the ratio of CO/CO_2 emissions for each phase with significant inter-run variability in PM emissions. Because CO is a product of incomplete combustion and CO_2 is a product of complete combustion, this ratio is an indication of the instantaneous efficiency of the burn.

In many cases, a strong association was seen between elevated PM emission rates and lower stove and stack temperatures, slower fuel consumption, and a higher CO/CO_2 ratio.

3.7.1 Stove 1

One complete IDC final protocol test, consisting of three replicate runs, was performed on stove 1, a large high-mass stove with non-catalytic controls that is step 1 certified at an ER of <3.0 g/h. Table 118 shows the test metrics for each phase and the entire run of each of the stove 1 IDC replicates.

Table 118. Stove 1—Comparison of Test Metrics for Each Phase and the Entire IDC Protocol

Phase	Run ID#	Dry Load Burned (kg)	Time (min)	Dry-Burn Rate (kg/h)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Start-Up	S1-18-08-08	3.23	57	3.4	6.5	6.87	2.02
	S1-18-08-09	3.21	59	3.27	8.9	9.03	2.76
	S1-18-08-10	3.30	59	3.36	10.1	10.23	3.04
	Mean	3.25	58.3	3.34	8.50	8.71	2.61
	Std. Dev.	0.05	1.2	0.07	1.83	1.70	0.53
	Rel. St. Dev.	0.01	0.02	0.02	0.22	0.20	0.20
High-Fire	S1-18-08-08	7.25	118	3.68	20.7	10.52	2.86
	S1-18-08-09	7.2	131	3.3	31.6	14.48	4.39
	S1-18-08-10	7.1	108	3.94	14.5	8.07	2.05
	Mean	7.18	119.0	3.64	22.27	11.02	3.10
	Std. Dev.	0.08	11.5	0.32	8.66	3.23	1.19
	Rel. St. Dev.	0.01	0.10	0.09	0.39	0.29	0.38
Maintenance	S1-18-08-08	5.29	134	2.37	52.2	23.37	9.86
	S1-18-08-09	4.98	140	2.13	36.9	15.79	7.40
	S1-18-08-10	5.1	154	1.99	21	8.2	4.12
	Mean	5.12	142.7	2.16	36.70	15.79	7.13
	Std. Dev.	0.16	10.3	0.19	15.60	7.59	2.88
	Rel. St. Dev.	0.03	0.07	0.09	0.43	0.48	0.40
Overnight	S1-18-08-08	10.06	222	2.72	38.8	10.49	3.86
	S1-18-08-09	9.07	193	2.82	54.1	16.81	5.96
	S1-18-08-10	10.18	248	2.46	20.8	5.03	2.04
	Mean	9.77	221.0	2.67	37.90	10.78	3.95
	Std. Dev.	0.61	27.5	0.19	16.67	5.90	1.96
	Rel. St. Dev.	0.06	0.12	0.07	0.44	0.55	0.50
Entire Run	S1-18-08-08	25.83	531	2.92	118.2	13.36	4.58
	S1-18-08-09	24.47	523	2.81	131.4	15.08	5.37
	S1-18-08-10	25.68	569	2.71	66.4	7.00	2.59
	Mean	25.33	541.0	2.81	105.33	11.81	4.18
	Std. Dev.	0.75	24.6	0.11	34.36	4.26	1.43
	Rel. St. Dev.	0.03	0.05	0.04	0.33	0.36	0.34

The total time to complete the runs ranged from 523 to 569 minutes (8.7 to 9.5 hours). The longest run was only 9% longer than the shortest. Run times and burn rates in each phase and for the entire protocol were similar in the three runs. The HHV efficiency for the entire protocol, 57.3%, 57.1%, and 57.7%, did not vary significantly among the replicate tests.

There was more variability in the PM metrics. All of the PM metrics (total PM, PM Emission Rate, and PM Emission Factor) were approximately twice as high in the second run, S1-18-08-09, the highest-emitting run, than in the third run, S1-18-08-10, the lowest-emitting run.

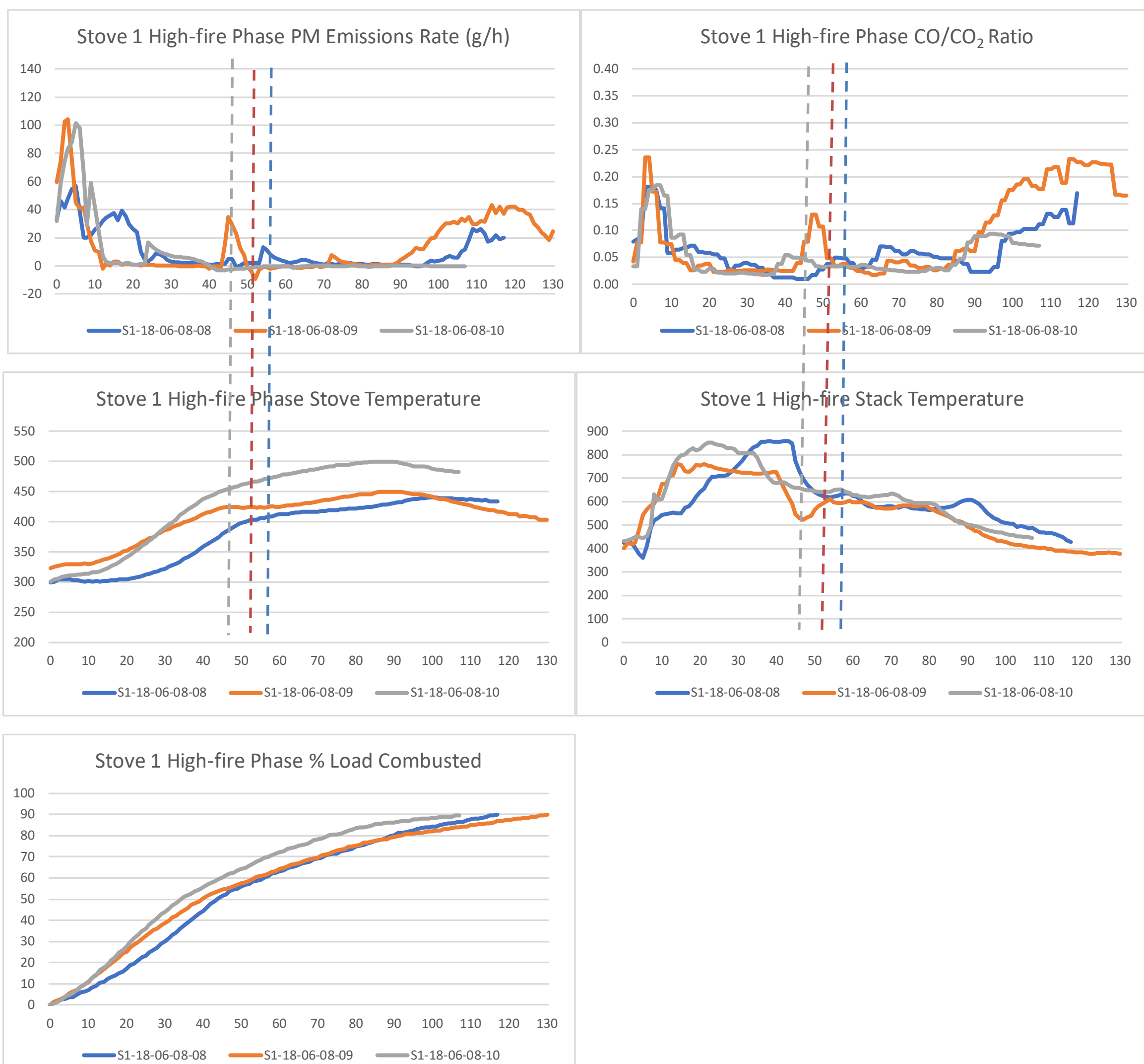
Figure 109 shows the test metrics by test phase for each of the stove 1 IDC runs graphically.

Figure 109. Stove 1—Comparison of Metrics for IDC Replicate Runs by Phase

Total PM emissions and the PM EF and ER for all phases except start-up were lowest in S1-18-08-10 (run 3). PM metrics were highest in S1-18-08 (Run 1) in the maintenance phase and highest in S1-18-09 (run 2) in the high-fire and overnight phases. The start-up phase contributed a small percentage of total PM emissions. The analysis below investigates factors that may help explain the PM emission differences in the runs in the high-fire, maintenance, and overnight phases.

Figure 110 shows the real-time profiles for the high-fire phases of the stove 1 IDC runs. The dotted lines in the figure indicate that 50% of the load was combusted and, according to the IDC final protocol, the air setting was moved from high to low.

Figure 110. Stove 1 IDC Run Profiles for the High-Fire Phase



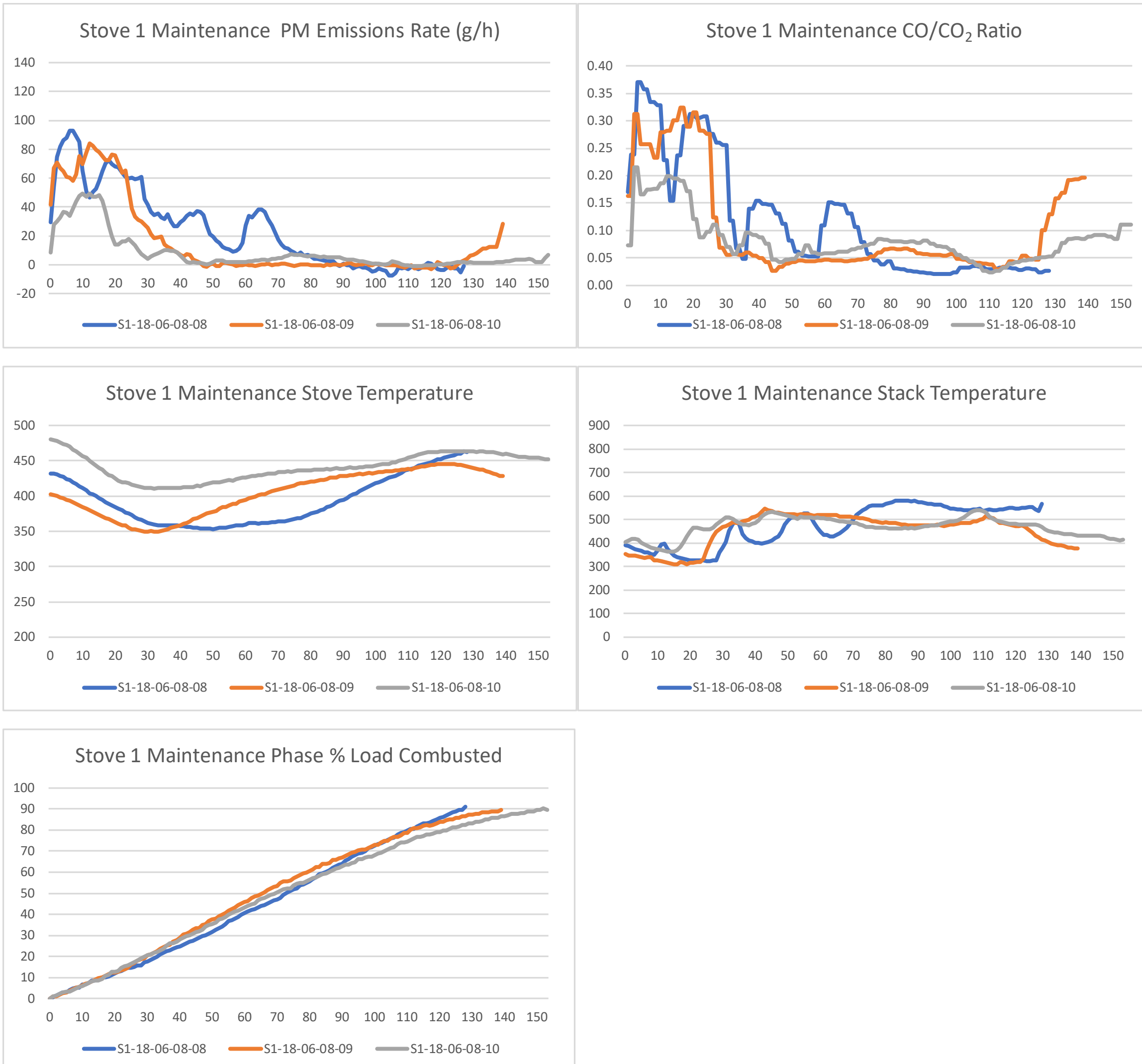
As shown in Figure 110, the high-fire phase PM emission profiles for the stove 1 replicates correlated well with the ratio of carbon monoxide to carbon dioxide (CO/CO_2) concentrations measured in the exhaust (R squared values are 0.42, 0.53, and 0.50 for runs 1, 2, and 3, respectively). Because CO is a product of incomplete combustion and CO_2 is a product of complete combustion, this ratio is an indication of the instantaneous efficiency of the burn.

In this phase, total PM emissions in the third run (S1-18-06-10), which is shown in gray in the above graphs, was 30% lower than in the first run (S1-18-06-08), shown in orange, and less than half those in the second run, (S1-18-06-09), which is shown in blue. As shown in Figure 110, all runs had a period of elevated PM emissions in the beginning of the phase. That initial emission period was about 10 minutes longer in run 1 than in the others runs; in that extended emissions period, stove and stack temperatures were lower and the CO/CO_2 ratio slightly higher in run 1 than in the other runs.

In the high-fire phase of the IDC protocol, the air setting is moved from high to low when 50% of the load has been combusted. Run 3 high-fire phase PM emissions were minimal after the air setting was moved to low. In the other runs, additional PM emissions occurred shortly after the air setting was moved and again at the end of the phase. The higher PM emissions in the high-fire phase of runs 1 and 2, as compared to run 3, are largely due to the additional emissions that occurred in those runs in the low-air portion of the phase. The stove temperatures were highest in run 3 during that period.

Stove 1 IDC maintenance phase real-time profiles are shown in Figure 111.

Figure 111. Stove 1 IDC Maintenance Phase Profiles



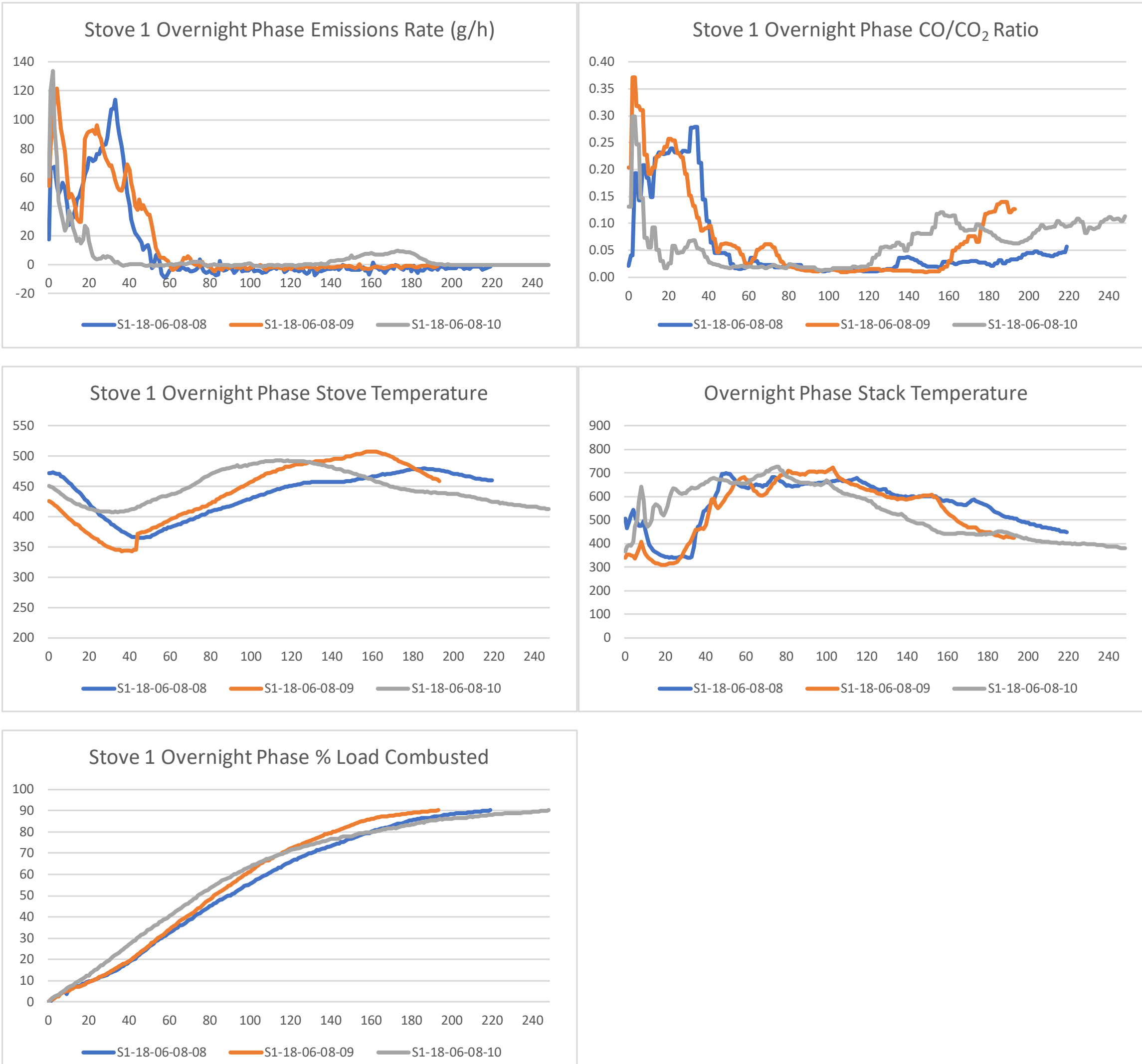
As in the previous phase, maintenance phase PM emissions correlated well with the CO/CO_2 ratio, an indicator of inefficient combustion. All runs had an initial period of emissions in the maintenance phase. In runs 2 and 3, that initial period was approximately 40 minutes long, and run 2 emissions during that period were higher than in run 3. Minimal PM emissions occurred after that period in both run 2 and 3. In run 1, however, emissions continued for an additional 35 minutes and emissions during that additional period were responsible for the higher total maintenance phase emissions for run 1 relative to the other runs.

Stove temperatures were consistent with this pattern. Stove temperatures in run 3, the lowest-emitting run, started higher than in the other runs and continued to be higher than the other runs throughout the phase. Stove temperatures decreased in all runs at the beginning of the phase. In runs 2 and 3, temperature began to increase again at about minute 30; however, the run 1 temperature increase did not begin until about minute 60, consistent with the longer period of emissions in that run.

In run 1, both PM emissions and the CO/CO_2 ratio decreased between minutes 50 and 60; that decrease was followed by a period of elevated emissions and an elevated CO/CO_2 ratio through approximately minute 70. Although run 1 stove temperatures did not change substantially during that period, stack temperatures in that run were significantly higher in the 50 to 60 minute period, when PM emissions were low, and then decreased in the subsequent 10 minutes, at the time that emissions were elevated.

Stove 1 overnight phase profiles are shown in Figure 112.

Figure 112. Stove 1 Overnight Phase Profiles



As in the previous phases, Stove 1 PM emissions correlated well with the CO/CO_2 ratio in the overnight phase. In this phase, run 3 PM emissions, as well as the CO/CO_2 ratio, dropped quickly after an initial peak. That drop corresponded with the initiation of a temperature increase in that phase. The other two runs had longer periods of emissions at the beginning of the phase, corresponding to stove and stack temperatures that were considerably lower than in run 3, which was the run with the lowest emissions.

3.7.2 Stove 2

Two sets of three replicate IDC final protocol runs were performed on stove 2, a small high-mass stove with catalytic controls that is step 2 certified at an ER <2.0 g/h. Except for the position of the stove door during the first five minutes of the start-up phase, the fueling and operating procedure were the same for all six test runs.

In the first set of runs, performed on consecutive days in October 2018, the stove door was in a cracked-open position during the first five minutes of the first two runs and wide open in the third. In the second set of runs, performed on consecutive days in January 2019, the door was wide open for the first five minutes of the first two runs and cracked open for that period in the third run. The effect of the door position on stove temperatures, burn rates, and PM emissions parameters in the start-up phase are discussed in detail earlier in this report.

The metrics associated with all phases of the six stove 2 IDC runs are shown in Table 119. The initial door position is designated in the run ID# as "c" for cracked open or "w" for wide open.

The total time to complete the stove 2 IDC runs ranged from 380 to 558 minutes. The longest run was 57% higher than the shortest. The longest and the shortest runs both had the door cracked open in the first five minutes and were performed on sequential days.

Average burn rates for the entire protocol were 36% higher in the shortest run (S2-18-10-24) than in the longest run (S2-18-10-23). A wide range of total PM emissions were measured. Run S2-18-10-23 emitted 2.5 times more PM than the next highest emitting run and 17 times the PM emitted by the lowest emitting run. Although the highest emitting run had the lowest burn rate, the burn rates did not correlate with emissions. The run with the second highest emissions, S2-18-10-24, had the highest burn rate. The S2-18-10-23 ER and EF for the entire run were also substantially higher than for all other runs.

HHV thermal efficiencies for the entire runs are shown in Table 120. Although the efficiencies measured in the runs did not diverge substantially, the run with the lowest efficiency (S2-18-10-23) produced the highest PM emissions, ER, and EF, while those PM metrics were lowest in the run that had the highest efficiency (S2-18-10-25).

Table 119. Stove 2—Comparison of Test Metrics for All Phases of the IDC Runs

Test Phase	Run ID#	Dry Load Burned (kg)	Time (min)	Dry-Burn Rate (kg/h)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Start-Up	S2-18-10-23-c	1.71	70	1.47	11.85	10.15	6.92
	S2-18-10-24-c	1.70	53	1.93	7.77	8.80	4.57
	S2-18-10-25-w	1.70	41	2.49	4.13	6.05	2.43
	S2-19-01-07-w	1.71	29	3.53	9.83	20.33	5.76
	S2-19-01-08-w	1.69	29	3.50	10.6	21.94	6.26
	S2-19-01-09-c	1.70	54	1.89	11.93	13.26	7.01
	Mean	1.70	46.00	2.47	9.35	13.42	5.49
	Std. Dev.	0.008	16.07	0.87	2.98	6.43	1.75
	Rel. St. Dev.	0.004	0.35	0.35	0.32	0.48	0.32
High-Fire	S2-18-10-23--c	2.98	199	0.9	149.65	45.12	50.17
	S2-18-10-24-c	2.96	108	1.65	106.28	59.04	35.88
	S2-18-10-25-w	2.99	106	1.69	7.85	4.44	2.62
	S2-19-01-07-w	3.02	164	1.1	77.08	28.2	25.52
	S2-19-01-08-w	2.97	103	1.73	5.04	2.94	1.7
	S2-19-01-09-c	3.03	148	1.23	36.06	14.62	11.92
	Mean	2.99	138.00	1.38	63.66	25.73	21.30
	Std. Dev.	0.03	39.10	0.35	57.80	22.75	19.42
	Rel. St. Dev.	0.009	0.28	0.26	0.91	0.88	0.91
Maintenance	S2-18-10-23-c	2.12	117	1.09	83.58	42.86	39.48
	S2-18-10-24-c	2.09	81	1.55	-4.72	-3.5	-2.26
	S2-18-10-25-w	2.17	97	1.34	0.73	0.45	0.34
	S2-19-01-07-w	2.17	77	1.69	0.97	0.76	0.45
	S2-19-01-08-w	2.15	115	1.12	0.90	0.47	0.42
	S2-19-01-09-c	2.09	101	1.24	-1.25	-0.74	-0.6
	Mean	2.13	98.00	1.34	13.37	6.72	6.31
	Std. Dev.	0.04	16.67	0.24	34.47	17.78	16.29
	Rel. St. Dev.	0.02	0.17	0.18	2.58	2.65	2.58
Overnight	S2-18-10-23--c	4.37	172	1.53	4.92	1.72	1.13
	S2-18-10-24-c	3.59	138	1.56	-0.76	-0.33	-0.21
	S2-18-10-25-w	4.38	175	1.50	1.86	0.64	0.43
	S2-19-01-07-w	3.89	165	1.41	1.14	0.42	0.29
	S2-19-01-08-w	4.57	220	1.25	1.76	0.48	0.39
	S2-19-01-09-c	5.05	244	1.24	1.32	0.33	0.26
	Mean	4.31	185.67	1.42	1.71	0.54	0.38
	Std. Dev.	0.51	38.94	0.14	1.84	0.67	0.43
	Rel. St. Dev.	0.12	0.21	0.10	1.08	1.23	1.13

Table 119 continued

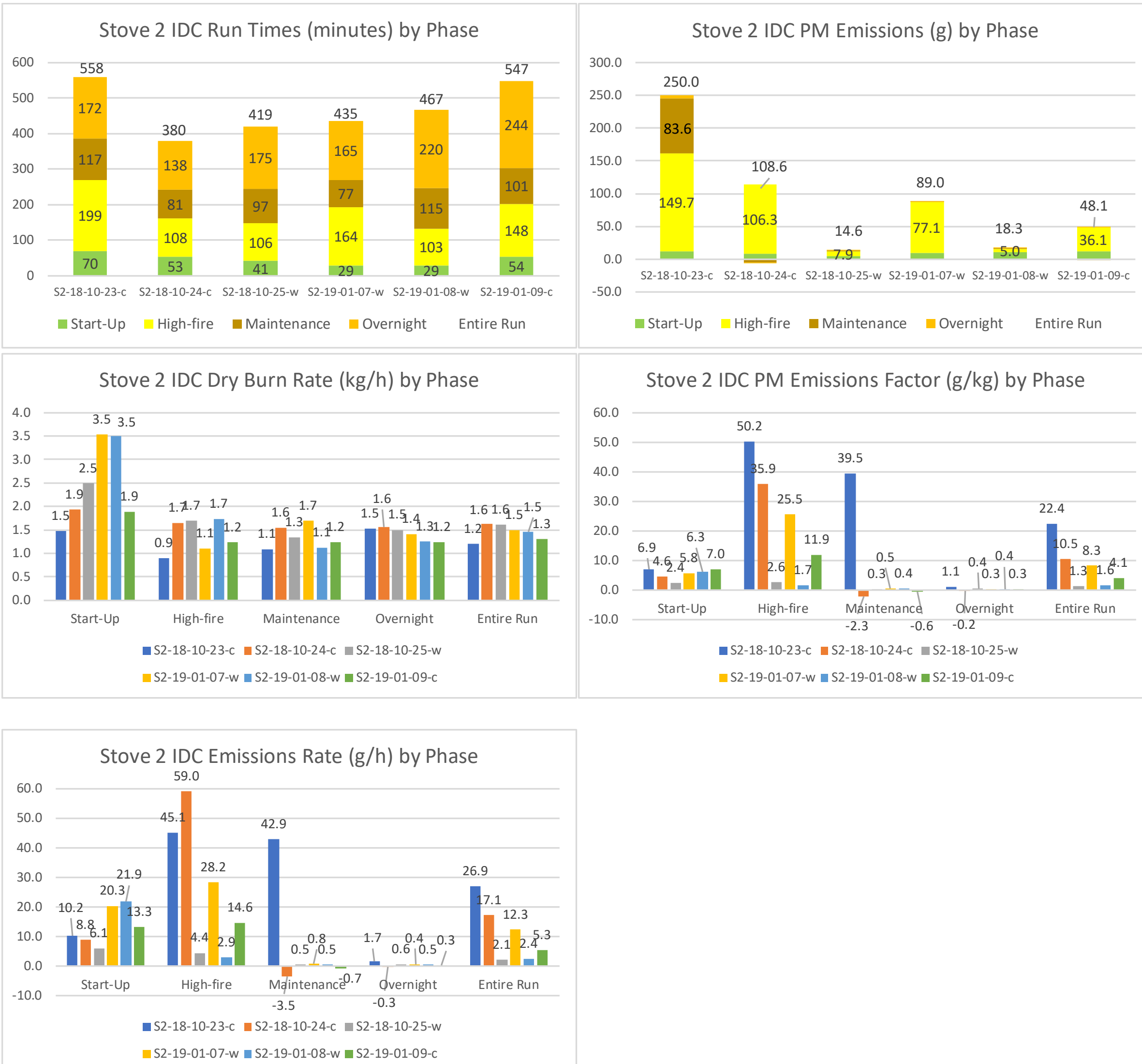
Test Phase	Run ID#	Dry Load Burned (kg)	Time (min)	Dry-Burn Rate (kg/h)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Entire Run	S2-18-10-23-c	11.19	558	1.2	250	26.88	6.92
	S2-18-10-24-c	10.34	380	1.63	108.57	17.14	4.57
	S2-18-10-25-w	11.25	419	1.61	14.58	2.09	2.43
	S2-19-01-07-w	10.78	435	1.49	89.02	12.28	5.76
	S2-19-01-08-w	11.38	467	1.46	18.3	2.35	6.26
	S2-19-01-09-c	11.88	547	1.3	48.07	5.27	7.01
	Mean	11.14	467.67	1.45	88.09	11.00	5.49
	Std. Dev.	0.53	71.52	0.17	87.76	9.78	1.75
	Rel. St. Dev.	0.05	0.15	0.12	1.00	0.89	0.32

Table 120. PM Metrics and Thermal Efficiencies of Entire Protocols—Stove 2

Test ID #	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)	HHV Efficiency (%)
S2-18-10-23-c	250.00	26.88	22.35	65.3
S2-18-10-24-c	108.57	17.14	10.50	68.9
S2-18-10-25-w	14.58	2.09	1.30	70.9
S2-19-01-07-w	89.02	12.28	8.25	69.3
S2-19-01-08-w	18.30	2.35	1.61	70.5
S2-19-01-09-v	48.07	5.27	4.05	70.1

Figure 113 shows the test metrics by test phase for each of the IDC runs graphically.

Figure 113. Stove 2—Comparison of Metrics for IDC Runs by Phase

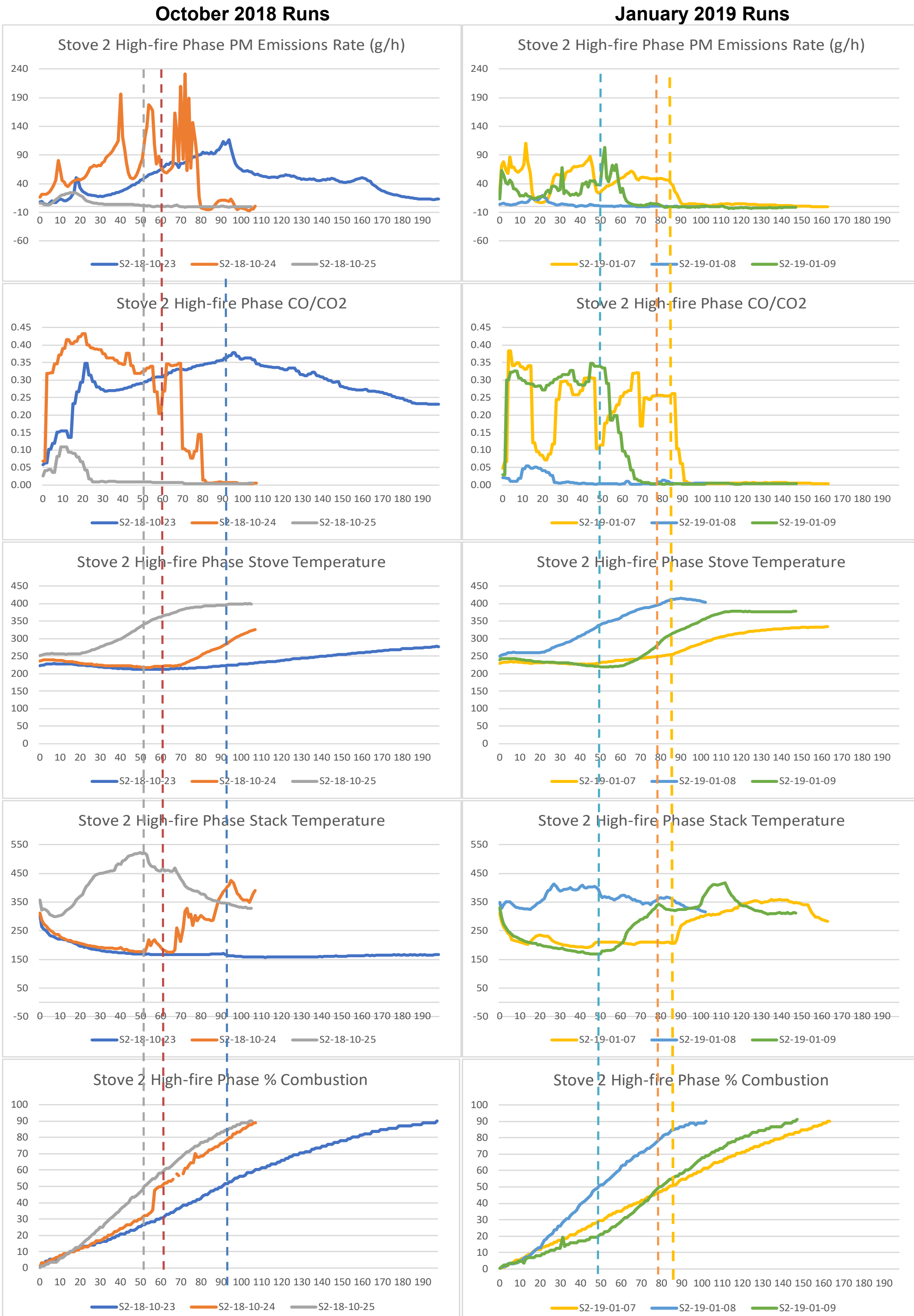


The wide-open door position in the first five minutes of the start-up runs was associated with a higher burn rate in the start-up phase and may have increased the ER in that phase. However, the increased open door start-up phase ER was primarily due to the shorter test times, rather than increased PM emissions, and did not affect the overall ER for entire run. Therefore, it does not appear that the initial door position is an important factor in emission test results.

The PM emission results illustrated in Figure 113 are very different from those for stove 1 discussed above. In the three stove 1 IDC runs, significant emissions were produced in the high-fire, maintenance, and the overnight burns. However, in five of the six stove 2 runs, PM emissions were largely confined to the high-fire phase. Only the first run, S2-18-10-23, had significant PM emissions in the maintenance phase; that run also recorded a small amount of additional emissions in the overnight phase. Emissions in two of the runs, one in each of the testing periods, were low throughout the entire run.

Real-time run profiles for the high-fire phase of the two sets of stove 2 IDC runs are shown in Figure 114. As in the stove 1 high-fire phase profiles, the dashed lines indicate the point of 50% combustion for each run, when the air setting was moved from high to low.

Figure 114. Stove 2 IDC Replicates—High-Fire Phase Profiles



The emissions pattern in the first run, S2-18-10-23, was very different from those in all the other runs in the high-fire phase. While the magnitude of the peak PM emissions rate and the CO/CO_2 ratio in the high-fire phase of that run were in the range of those seen in the runs, the burn lasted 35 to 96 minutes longer in that run than in the others and significant PM emissions and an elevated CO/CO_2 ratio continued throughout the burn, peaking at the time that the air setting was moved to low. Fifty-two percent of the high-fire phase PM emissions in that run occurred after the switch to the low setting. The stove and stack temperatures in the high-fire phase of S2-18-10-23 stayed relatively flat and low throughout the phase and the fuel consumption rate was slower than in the other runs.

The second run, S2-18-10-24, was the only other run in which a significant portion of PM emissions occurred after the air setting was moved to low. Thirty percent of total high-fire phase emissions in that run occurred in the 18 minutes after the air setting was lowered. The CO/CO_2 ratio also continued to be elevated and both the stove and the stack temperatures increased during that period. The combustion rate was considerably higher and the run time was approximately 91 minutes shorter for the high-fire phase in the second run than in the first run.

In the other four stove 2 IDC runs, the third run in the first replicate group and all three runs in the second replicate group, minimal emissions occurred after the air setting was moved to low. The real-time patterns seen in those four runs fell into two categories. Runs S2-18-10-25 and S2-19-01-08 had very low PM emissions and a low CO/CO_2 ratio throughout that phase, with a small peak in both of those parameters in in the first 20 minutes of the phase. The temperature profiles were also similar for those two runs; the stove temperature remained flat and slightly higher than in the other runs during the first 20 minutes of the phase and then rapidly increased to levels substantially higher than in the other runs. The stack temperature in the low emitting runs started the phase at a level similar to the other runs but stayed high while the others dipped substantially. Combustion rates were also higher in the low-emitting runs after the first few minutes of the phase.

The other two runs, S2-19-01-07 and S2-19-01-09, recorded significant PM emissions and relatively high CO/CO_2 ratios while the air setting was on high, but both of those parameters dropped to near zero after the setting was switched to low. Stack and stove temperatures were low in the first part of the phase in both of these runs but began to increase in S2-19-01-07 when the air setting was switched to low and, in S2-19-09, approximately 10 minutes before that switch occurred.

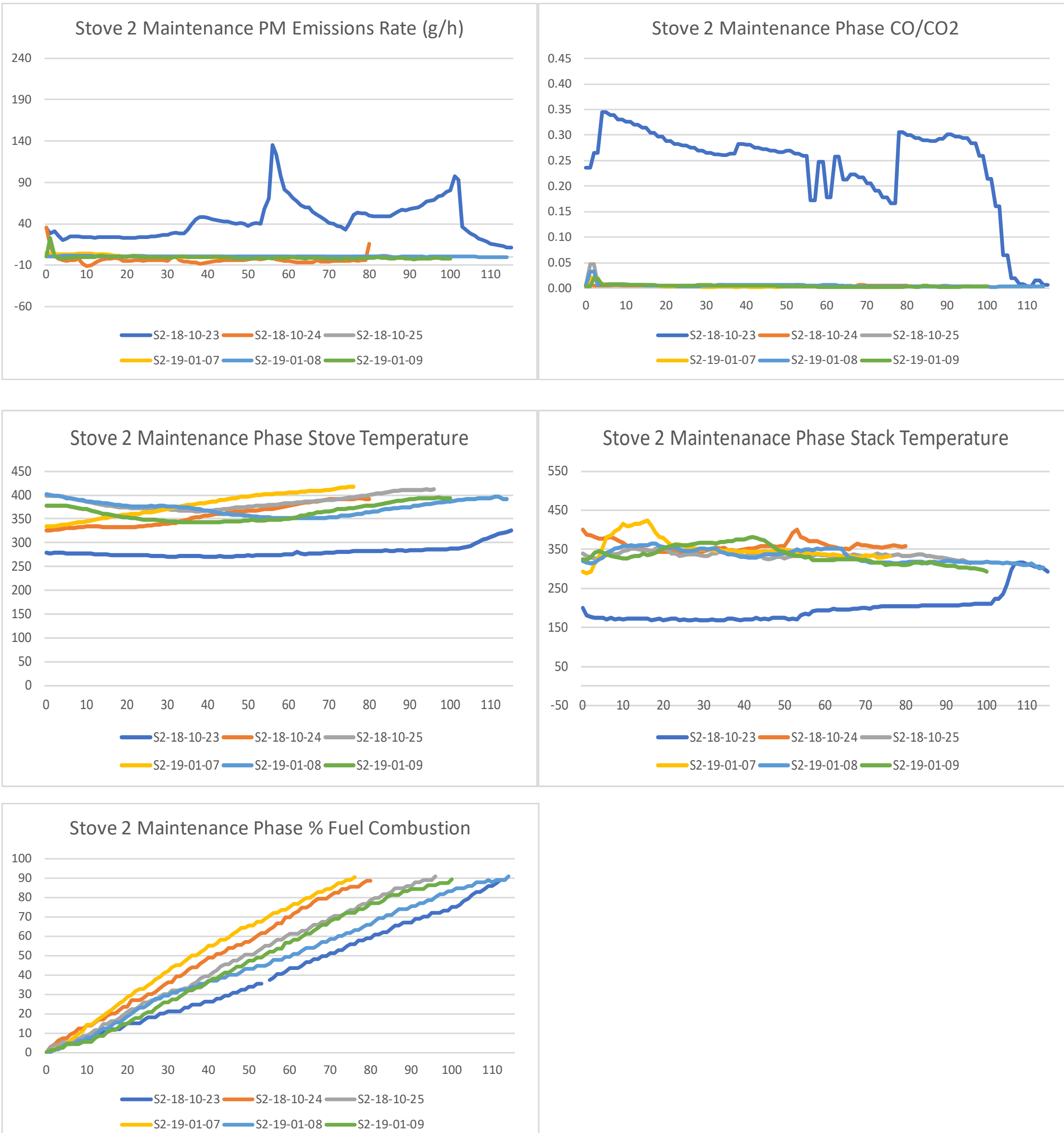
In summary, four distinct high-fire phase burn patterns were observed in the six IDC stove 2 runs:

- S2-18-10-23: Significant PM emissions, elevated CO/CO_2 ratio, low burn rate, and low stove and stack temperature throughout the phase. High-fire phase run time substantially longer than the other runs.
- S2-18-10-24: Significant PM emissions, elevated CO/CO_2 ratio, and low-stove and stack temperatures continued for several minutes after the air setting was switched to low. Shortest high-fire phase run time.
- S2-18-10-25 and S2-18-19-01-8: Small peak of PM emissions and CO/CO_2 ratio early in the phase followed by increasing stove and stack temperatures and near-zero emissions and CO/CO_2 ratio.
- S2-19-01-07 and S2-19-01-09: Relatively high PM emissions and elevated CO/CO_2 ratio before air setting was switched to low, then near-zero levels. Stove and stack temperatures begin to increase before or at the time that the air setting was moved.

Stove 2 clearly did not operate consistently from run to run in this phase.

Figure 115 shows the run profiles for the maintenance phase.

Figure 115. Stove 2 Maintenance Phase Profiles



As shown in Figure 115, only the first run, S2-18-10-23, had significant maintenance phase PM emissions. That run had a significantly higher maintenance phase CO/CO_2 ratio than in the other runs through almost the entire phase. The burn rate in the maintenance phase of that run was also lower than in the other runs. The much higher maintenance phase emissions and less efficient burn in S2-18-10-23 may be explained by stove and stack temperatures. As discussed above, that run did not achieve elevated stove temperatures in the high-fire phase and as a result, the maintenance phase of S2-18-10-23 began with a stove temperature 47ºF to 123ºF lower and a stack temperature 93ºF to 200ºF lower than in the other runs. The maintenance phase burn was also not able to increase that temperature substantially; the temperature in that run remained substantially lower than in the other runs until near the end of the run when emissions dropped off. The failure to achieve a higher temperature in this phase is associated with a less efficient burn that produced higher emissions. In addition, the stove temperature may not have been sufficiently high to trigger the operation of the stove's catalytic controls, as discussed below.

The stove temperature at the beginning of the overnight phase of the first run was 61ºF to 89ºF lower than in the other runs increased to a level similar to the other runs by 40 minutes into the phase. A relatively small amount of additional PM emissions occurred in the early part of the overnight phase of the first run, but no subsequent emissions occurred in that run. No significant PM emissions occurred in the overnight phases of the other five stove 2 IDC runs.

The fact that the stove temperature in run S2-18-20-23 did not reach 300ºF until the end of the maintenance run, while that temperature was achieved during the high-fire burn in the other runs, explains the emissions that continued throughout that phase and, unlike the other runs, continued into the maintenance load. Stove 2 is controlled by a catalytic device that becomes activated when stove temperatures are elevated. Until that device is activated, the stove essentially runs uncontrolled. The rapid drop in PM emissions seen in the stove 2 runs when the stove temperature reached approximately 300ºF is an indication that the catalytic converter activated at about that temperature. That activation occurred much later in run S2-18-10-23 than in the other runs.

The reason for the differences in the temperature profiles is less clear. In the first five minutes of start-up, the stove door was cracked open in three of the runs and wide open in the other three runs. Although the burn rates were higher and the start-up phase run time lower in the runs that started with the door wide open, the stove temperatures at the end of the start-up phase was similar in the two groups. The starting temperature of the stove ranged from 62ºF in run S2-19-01-07 to 101ºF in run S2-19-01-09, but starting temperature did not correlate with the length of the start-up phase, the temperature at the end of the start-up phase, the time that the stove temperature reached 300ºF, or the PM emissions.

While each set of IDC stove 2 tests was run on sequential days, there were approximately 12 weeks between the two sets of runs. However, other than the first run on the first day, which was different from all other runs, there was no clear difference between the range of temperatures or the emission profiles in the first and second group of runs. It is very clear, however, that stove 2 does not burn consistently, even with a standardized fueling protocol, and that differences in the stove temperature profile have a strong impact on the effectiveness of the catalytic control system.

3.7.3 Stove 4

Three replicate IDC runs were performed on consecutive days on stove 4, a small cast-iron stove with non-catalytic controls that is step 1 certified at an ER <4.0 g/h. Table 121 shows the test metrics for each phase and the entire run of each of the IDC replicates.

Table 121. Stove 4—Comparison of Test Metrics for Each Phase and the Entire IDC Protocol

Phase	Run ID#	Dry Load Burned (kg)	Time (min)	Dry-Burn Rate (kg/h)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Start-Up	S4-18-10-16	0.97	20	2.9	2	6.14	2.12
	S4-18-10-17	0.97	23	2.52	2.5	6.49	2.57
	S4-18-10-18	0.97	30	1.94	2.4	4.88	2.52
	Mean	0.97	24.33	2.45	2.30	5.84	2.40
	Std. Dev.	0.00	5.13	0.48	0.26	0.85	0.25
	Rel. St. Dev.	0.00	0.21	0.20	0.12	0.15	0.10
High-Fire	S4-18-10-16	1.85	46	2.41	2.7	3.55	1.47
	S4-18-10-17	1.8	74	1.46	19.4	15.72	10.74
	S4-18-10-18	1.84	55	2.01	6	6.49	3.23
	Mean	1.83	58.33	1.96	9.37	8.59	5.15
	Std. Dev.	0.03	14.29	0.48	8.84	6.35	4.92
	Rel. St. Dev.	0.01	0.25	0.24	0.94	0.74	0.96
Maintenance	S4-18-10-16	1.36	91	0.9	7.5	4.92	5.49
	S4-18-10-17	1.41	56	1.51	5.9	6.31	4.19
	S4-18-10-18	1.4	81	1.04	6.9	5.15	4.96
	Mean	1.39	76.00	1.15	6.77	5.46	4.88
	Std. Dev.	0.03	18.03	0.32	0.81	0.75	0.65
	Rel. St. Dev.	0.02	0.24	0.28	0.12	0.14	0.13
Overnight	S4-18-10-16	3.2	163	1.18	19.5	7.17	6.08
	S4-18-10-17	2.56	156	0.98	10.6	4.06	4.12
	S4-18-10-18	2.6	101	1.55	9.6	5.69	3.68
	Mean	2.79	140.00	1.24	13.23	5.64	4.63
	Std. Dev.	0.36	33.96	0.29	5.45	1.56	1.28
	Rel. St. Dev.	0.13	0.24	0.23	0.41	0.28	0.28
Entire Run	S4-18-10-16	7.38	320	1.38	31.7	5.94	4.3
	S4-18-10-17	6.74	309	1.31	38.3	7.44	5.69
	S4-18-10-18	6.82	267	1.53	24.9	5.6	3.66
	Mean	6.98	298.67	1.41	31.63	6.33	4.55
	Std. Dev.	0.35	27.97	0.11	6.70	0.98	1.04
	Rel. St. Dev.	0.05	0.09	0.08	0.21	0.15	0.23

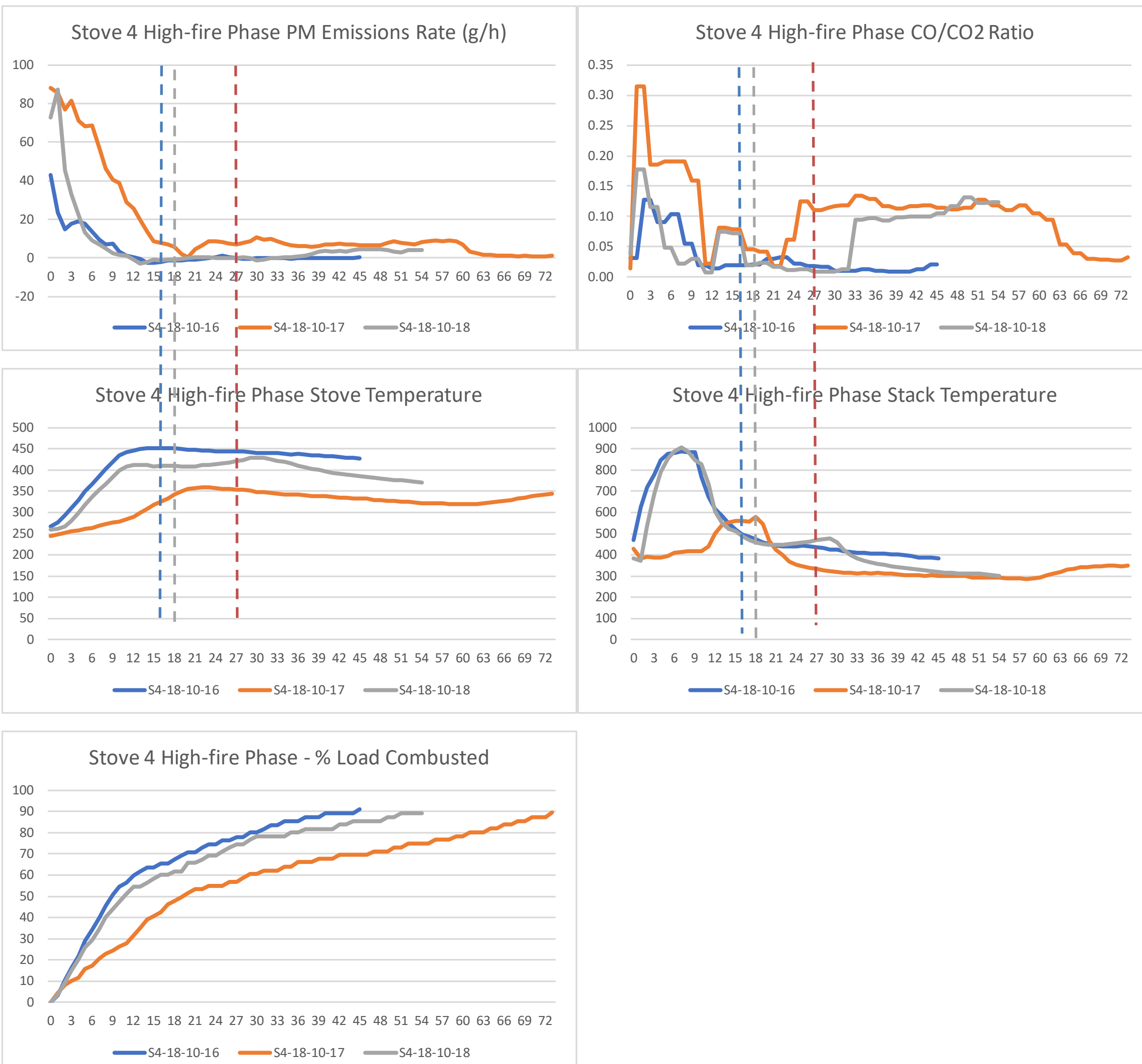
The total time to complete the stove 4 IDC runs ranged from 267 to 320 minutes (4.5 to 5.3 hours), clearly feasible for completion in a single day. The longest run was 20% longer than the shortest. The HHV efficiencies in the first two runs were similar, 56.2% and 57.0%, respectively. The efficiency could not be determined in the third run due to limitations in the carbon monoxide and carbon dioxide data. PM emissions were highest in the second run, S4-18-10-17, and lowest in the third run, S4-18-10-8; however, the highest EF and ER were only 55% and 33% higher than the lowest.

Figure 116 shows the test metrics by test phase for each of the IDC runs graphically.

Figure 116. Stove 4—Comparison of Metrics for IDC Replicate Runs by Phase

The PM metrics were similar in the three runs with two exceptions: PM emissions were elevated relative to the other runs in run 2 in the high-fire phase and in run 1 in the overnight phase. Figures 117 and 118 show the profiles for the run parameters for those two phases. Again, the time of 50% combustion for each run, when the air setting was moved to low, is shown with dotted lines on the high-fire phase graphs.

Figure 117. Stove 4 High-Fire Phase Profiles

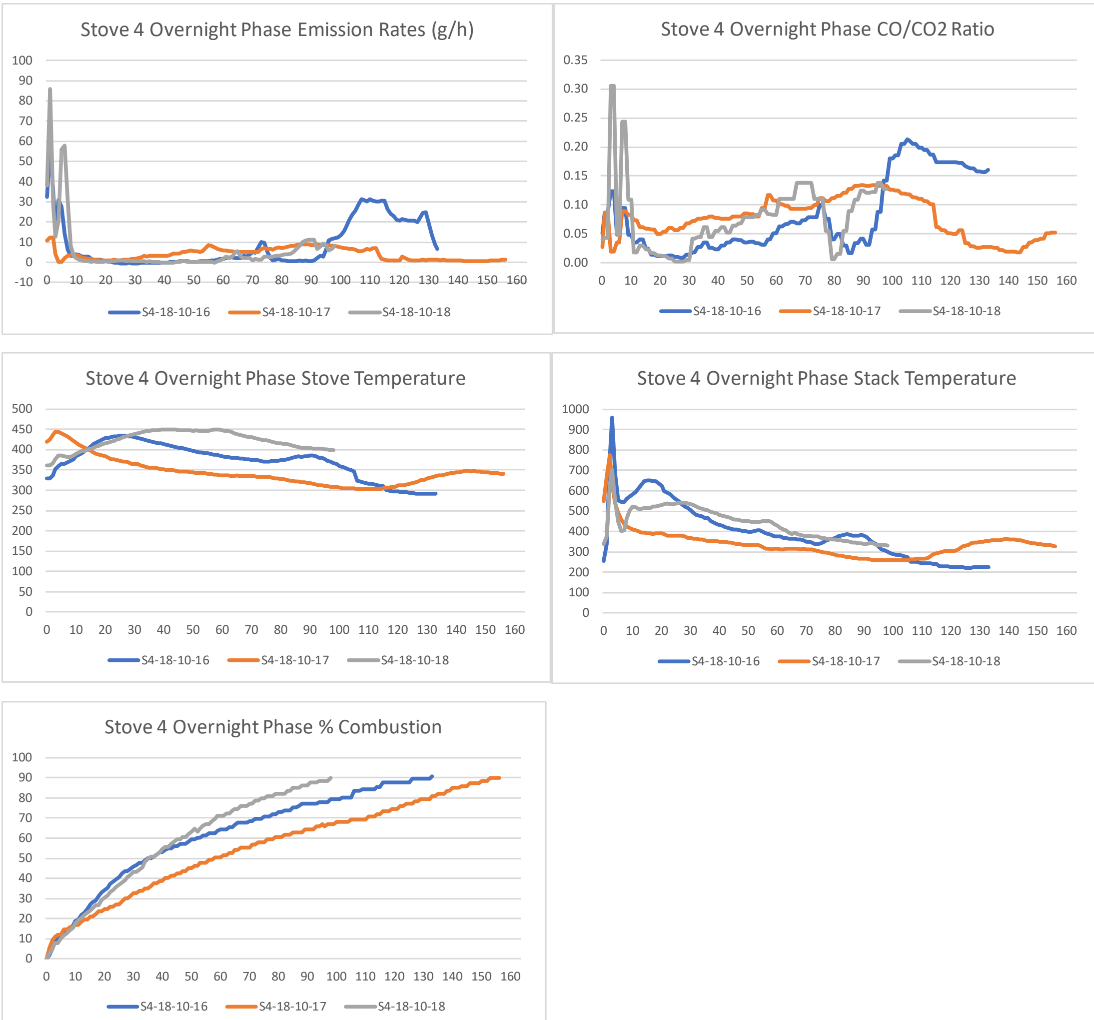


The higher PM emissions in the high-fire phase of the second run (S4-18-10-17) can be explained by the temperatures and combustion rates in that run. The stove temperatures in the three runs were similar at the start of the phase, but temperatures in runs 1 and 3 increased rapidly during the period when the stove was operated at the high-air setting. In run 2, however, the temperature increased more slowly during the high-air setting period and was more than 50ºF cooler than in the other runs at the point of 50% combustion, when the air setting was moved to low and stove temperatures started to decline. The combustion rate in that run was lower and the CO/CO_2 ratio higher during most of the high-fire phase.

The temperature, combustion, and efficiency patterns are consistent with the PM emission profile for run 2. An initial period of elevated PM emissions occurred in the beginning of the high-fire phase in all three runs, but that phase lasted longer in run 2 than in the other runs and additional emissions in that run continued after the air setting was set to low. The reason for the difference in the burns is not known because this phase started at virtually the same temperatures in all runs, similar sized loads were burned, and the same protocol was followed on consecutive days.

The real-time profiles for the overnight phase are shown in Figure 118.

Figure 118. Stove 4 Overnight Phase Profiles



The higher PM emissions measured in run 1 in this phase relative to the other runs primarily occurred at the end of the run, beginning at minute 92 and peaking at minute 110. During that period, run1 stove and stack temperatures and the fuel combustion rate decreased and the CO/CO_2 ratio increased, while the reverse was true for run 2. Run 3 ended shortly into that period.

3.7.4 Stove 5

Three replicate IDC runs were performed on consecutive days on stove 5, a medium-sized cast-iron stove with non-catalytic controls that is step 1 certified at an ER <2.0 g/h. Table 122 shows the test metrics for each phase and the entire run of each of the IDC replicates.

Table 122. Stove 5—Comparison of Test Metrics for Each Phase and the Entire IDC Protocol

Phase	Run ID#	Dry Load Burned (kg)	Time (min)	Dry-Burn Rate (kg/h)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Start-Up	S5-18-08-01	2.13	39	3.28	25.6	39.38	12.01
	S5-18-08-02	2.12	35	3.64	11.1	19.1	5.25
	S5-18-08-03	2.25	54	2.5	12.3	13.69	5.48
	Mean	2.17	42.67	3.14	16.33	24.06	7.58
	Std. Dev.	0.07	10.02	0.58	8.05	13.54	3.84
	Rel. St. Dev.	0.03	0.23	0.19	0.49	0.56	0.51
High-Fire	S5-18-08-01	4.85	93	3.13	54.2	34.99	11.18
	S5-18-08-02	4.86	111	2.63	2.1	1.12	0.42
	S5-18-08-03	4.69	103	2.73	11.7	6.83	2.5
	Mean	4.80	102.33	2.83	22.67	14.31	4.70
	Std. Dev.	0.10	9.02	0.26	27.73	18.13	5.71
	Rel. St. Dev.	0.02	0.09	0.09	1.22	1.27	1.21
Maintenance	S5-18-08-01	3.73	135	1.66	-3.2	-1.44	-0.87
	S5-18-08-02	3.66	141	1.56	5.6	2.4	1.54
	S5-18-08-03	3.66	138	1.59	3.4	1.48	0.93
	Mean	3.68	138.00	1.60	1.93	0.81	0.53
	Std. Dev.	0.04	3.00	0.05	4.58	2.00	1.25
	Rel. St. Dev.	0.01	0.02	0.03	2.37	2.47	2.35
Overnight	S5-18-08-01	8.32	208	2.4	2.6	0.75	0.31
	S5-18-08-02	8.11	291	1.67	2.3	0.48	0.29
	S5-18-08-03	8.17	212	2.31	2.3	0.65	0.28
	Mean	8.20	237.00	2.13	2.40	0.63	0.29
	Std. Dev.	0.11	46.81	0.40	0.17	0.14	0.02
	Rel. St. Dev.	0.01	0.20	0.19	0.07	0.22	0.05
Entire Run	S5-18-08-01	19.03	475	2.4	79.2	10	4.16
	S5-18-08-02	18.76	578	1.95	21.2	2.2	1.13
	S5-18-08-03	18.77	507	2.22	29.7	3.52	1.58
	Mean	18.85	520.00	2.19	43.37	5.24	2.29
	Std. Dev.	0.15	52.72	0.23	31.32	4.17	1.64
	Rel. St. Dev.	0.01	0.10	0.10	0.72	0.80	0.71

The total time to complete the stove 5 IDC runs ranged from 475 to 578 minutes (7.9 to 9.6 hours), a longer period than for some of the other stoves, but still less than the 10-hour period that would be feasible for completion in a single day. The run time for the longest run (run 2) was 23% longer than the shortest (run 1). The HHV efficiencies were similar in all three runs, 64.5%, 64.7%, and 64.4% for runs 1, 2, and 3, respectively.

The PM parameters were significantly higher in run 1 than in the other runs. The total PM emissions and EF for the entire run 1 were both 3.7 times higher than in run 2, the lowest emitting run. The run 1 ER (10.0 g/h) was 4.4 times higher than the run 2 ER (2.2 g/h).

Figure119 shows the test metrics by test phase for each of the IDC runs graphically.

Figure 119. Stove 5—Comparison of Metrics for IDC Replicate Runs by Phase

As can be seen in that figure, dry-burn rates were highest in the start-up and high-fire phases. Burn times were similar in the three runs for all phases except for the overnight burn, which was about 50% longer in run 2 than in the other runs. Unlike in the results of the previous stoves, emissions in the start-up phase made up a significant portion of total PM emissions in all stove 5 runs, constituting 32%, 53%, and 41% of the total PM emissions in runs 1, 2 and 3, respectively. The start-up load is considerably smaller than the other loads and, in the stove 5 runs, represented 11–12% of fuel burned over the entire run. High-fire phase emissions also contributed significant emissions in runs 1 and 3, representing 68% and 39% of total PM emissions in those runs, respectively. Twenty-five to twenty-six percent of total fuel is burned during the high-fire burn.

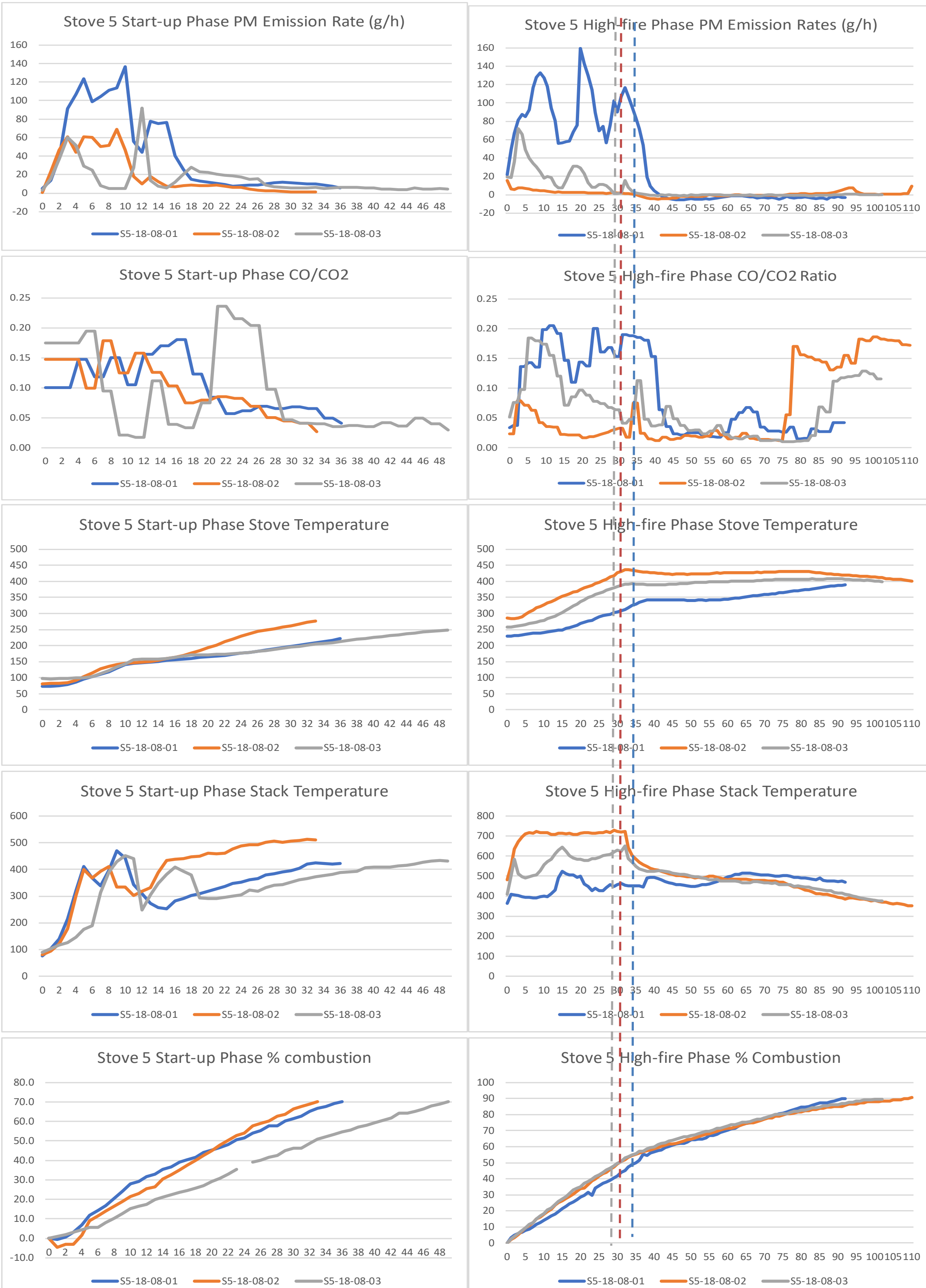
The start-up and high-fire phase PM emissions parameters were considerably higher in run 1 than in the other runs. Start-up emissions in run 1 were about twice those in runs 2 and 3. In the high-fire phase, run 1 emissions were 26 times higher than run 2 emissions and five times higher than in run 3. In the maintenance phase, run 2 emissions were higher than those of the other runs. PM emissions during that phase in run 1 were negative, an indication that the stove did not emit significant PM during that phase and volatilization loss occurred from the filter.

This discussion will focus on the start-up, high-fire, and maintenance phases. Figure 120 shows the profiles for the start-up and high-fire phases of the stove 5 IDC runs.

Figure 120. Stove 5 IDC Start-Up and High-Fire Phase Profiles

Start-up Phase

High-fire Phase



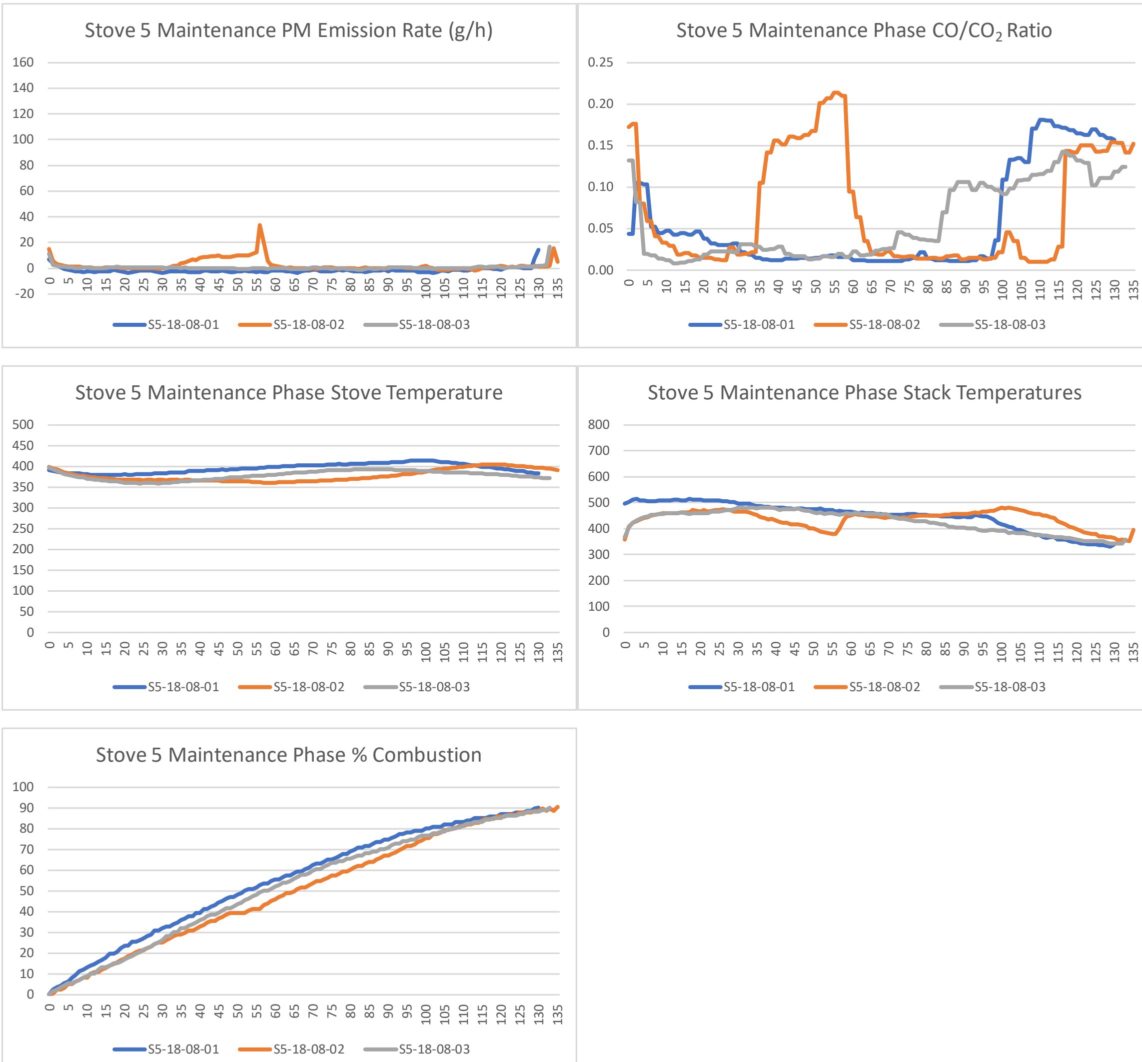
Neither the stack and stove temperatures nor the CO/CO_2 ratio explain why PM emissions in minutes 3–11 of the start-up phase were considerably higher in run 1 (S5-18-08-01) than in the other runs. In that period, stove temperatures in all runs were similar and stack temperatures and the CO/CO_2 ratio in run 1 were within the range of those in the other runs. The run 1 combustion rate was slightly higher than those of the other runs in that period.

Elevated PM emissions continued in run 1 in minutes 13–15 of the start-up phase, after emissions in the other runs had dropped to minimal levels. In that period, the elevated emissions in run 1 did show a relationship with the other parameters that was more like those seen in previous analyses. During that period, the CO/CO_2 ratio was higher and the stack temperature was lower in run 1 than in the other runs. Stove temperatures were similar in all runs during that period.

In the high-fire phase, PM emissions were elevated in run 1 relative to the other runs throughout the first 40 minutes of the phase. During that period, the CO/CO_2 ratio was higher and the stove and stack temperatures substantially lower for that run than for the other runs. Although the magnitude of the run 1 and run 3 PM emissions were different, the real-time emissions pattern was similar in the two runs; in both cases, PM emissions dropped to minimal levels a few minutes after the air setting was shifted to low. run 2 recorded stove and stack temperatures considerably higher than those of the other runs during the period that emissions occurred in those runs.

Emissions in the maintenance phase were much lower, but, unlike in the previous two phases, PM emissions in this phase were higher in run 2 than in the other runs. Maintenance phase real-time run profiles are shown in Figure 121. For consistency, the scales of these graphs are the same as those for the previous phases for this stove.

Figure 121. Stove 5 IDC Maintenance Phase Profiles

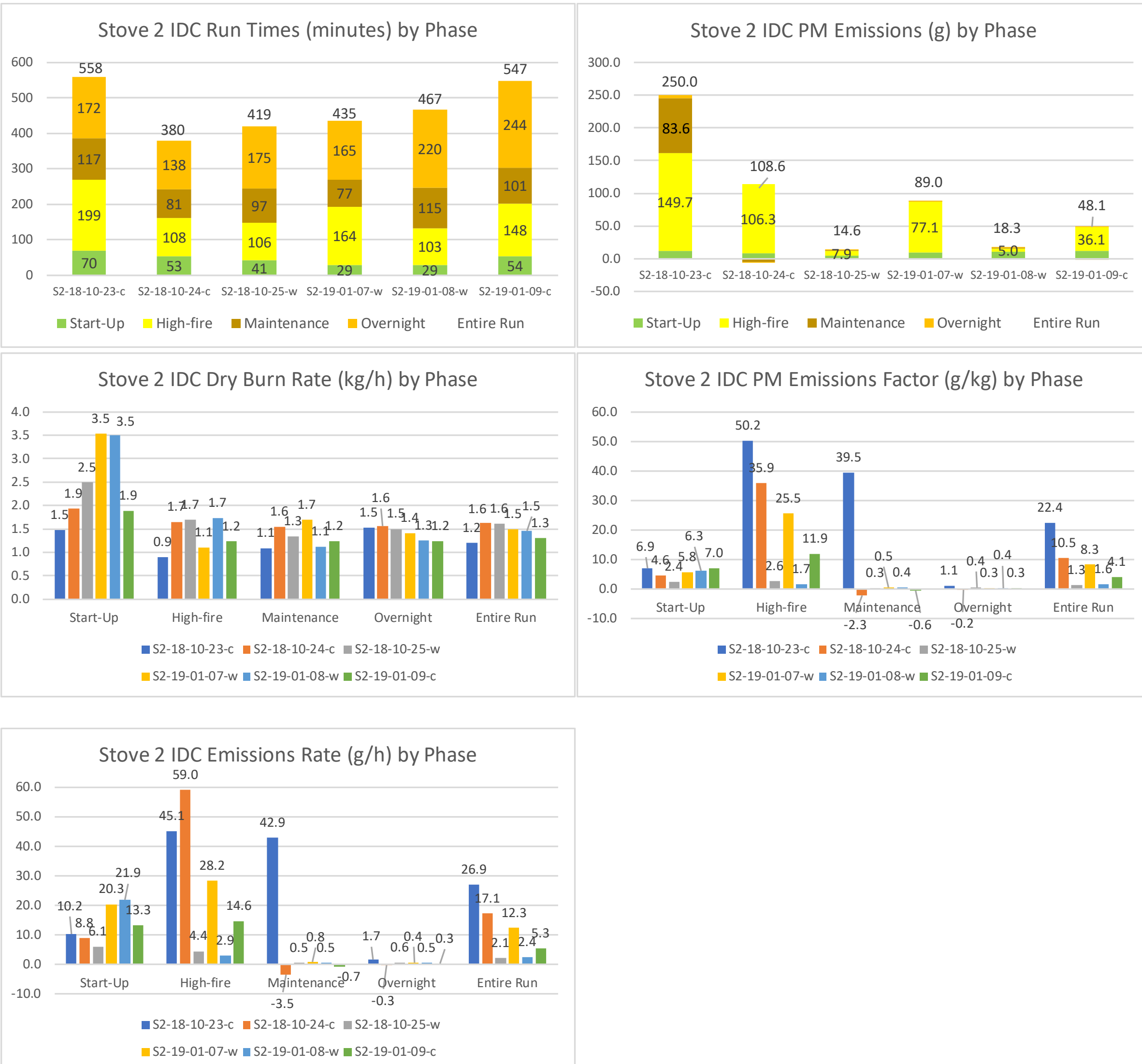


As shown in that figure, the significant PM emissions in the second run, S5-18-08-02, occurred in a 25-minute period beginning at minute 35. In that period, the CO/CO_2 ratio was highly elevated relative to fuel combustion, and stove and stack temperatures were lower than in the other runs. It is not clear what caused the poor combustion conditions, reduced temperatures, and increased higher PM emissions in run 2 relative to the other runs during that 25-minute period.

3.7.5 Stove 6

A total of nine final IDC protocol runs were performed on stove 6, a medium-sized steel stove with non-catalytic controls that is step 1 certified at an emissions rate of <4.0 g/h. Three replicate runs burned red maple, three seasoned oak, and three wet oak fuel species. This analysis will be confined to the three runs that burned red maple in order to be consistent with the discussions of the other stoves in this section. The impact of burning different fuel species is discussed in section 4.3. Table 123 shows the metrics for each phase and the entire protocol of the red maple stove 6 runs.

Figure 113. Stove 2—Comparison of Metrics for IDC Runs by Phase



The wide-open door position in the first five minutes of the start-up runs was associated with a higher burn rate in the start-up phase and may have increased the ER in that phase. However, the increased open door start-up phase ER was primarily due to the shorter test times, rather than increased PM emissions, and did not affect the overall ER for entire run. Therefore, it does not appear that the initial door position is an important factor in emission test results.

The total time to complete the stove 6 IDC red maple runs ranged from 510 to 558 minutes (8.5 to 9.3 hours), a longer period than for some of the other stoves, but still less than the 10-hour period that would be feasible for completion in a single day. The run times and burn rates were very similar in the three runs; the second run, S6-18-07-19, had a slightly higher (8%) burn rate and slightly shorter (5–9%) run time than the other two runs. The HHV efficiencies were also similar in all red maple runs, 61.4%, 62.3%, and 60.4%, in runs 1, 2, and 3, respectively.

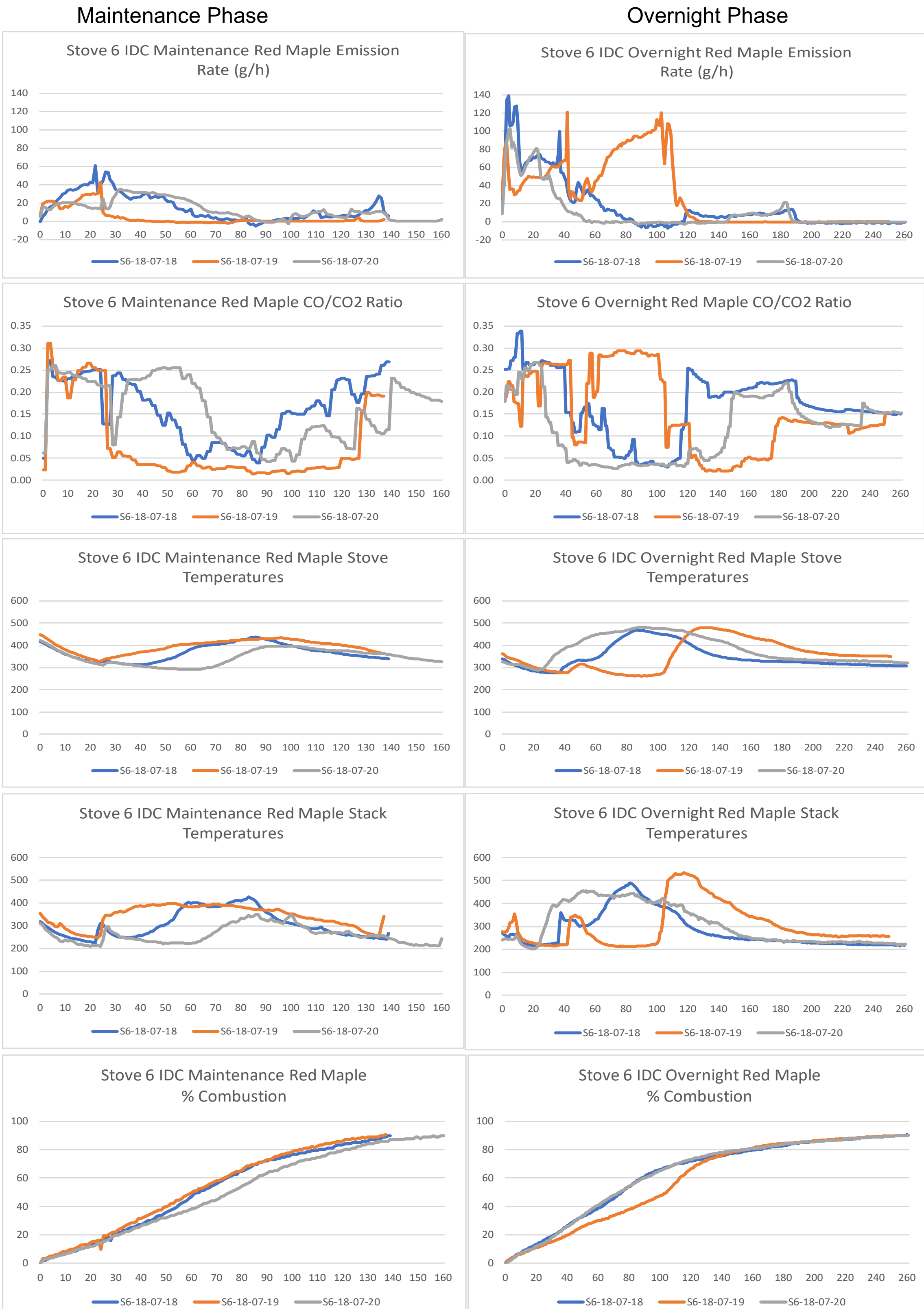
The PM emissions were somewhat more variable between runs. The total PM, PM EF, and PM ER in the highest emitting run, S6-18-07-19, were 51%, 52%, and 65% higher than in the lowest (S6-18-07-20), respectively. These parameters are shown graphically by phase in Figure 122.

Figure 122. Stove 6 IDC Red Maple Run Parameters

Start-up PM emissions were highest in the first run and lowest in the third, but the total PM and run time of the start-up phase were too low for those differences to significantly affect the PM metrics for the entire runs. Because the metrics for the high-fire phase were similar for all runs, the below analysis focuses on the maintenance and overnight phases. In the maintenance phase, PM emissions in runs 1 and 3 were more than three times higher than in run 2. The opposite was the case in the overnight phase; in that phase, run 2 emissions were 69% higher than those in run 1 and 2.7 times higher than in run 3.

Figure 123 shows the real-time profiles of the maintenance phase of the stove 6 IDC runs.

Figure 123. Stove 6—IDC Maintenance and Overnight Phase Red Maple Profiles



As discussed above, maintenance phase PM emissions for the second stove 6 run, S6-18-07-19, were approximately one-third of those for the other two runs. As can be seen in Figure 123, PM emissions in that run were similar to those in the other runs in the beginning of the phase but dropped quickly after a peak at 24 minutes and were near-zero after minute 34, while emissions in the other runs continued for much of the phase. At the time that the run 2 emissions dropped, the CO/CO_2 ratio decreased sharply and the stove and stack temperatures increased. The temperature increase and CO/CO_2 ratio decrease occurred later in the other two runs.

PM emissions in the overnight phase were highest in run 2 and lowest in run 3. As shown in Figure 123, emissions in the overnight phase, as in the maintenance phase, were similar early in the phase. However, run 3 emissions peaked at minute 5 and had dropped to below 10 g/h by minute 46. Run 1 overnight phase PM emissions peaked at minute 9 and were below 10 g/h at 74 minutes. Emissions in run 2 continued much longer, peaking at minute 42 and again at minute 103 and remaining above 10 g/h until minute 120.

The much longer emissions period in the overnight phase of run 2 is consistent with a much lower temperature during that period in that run relative to the other runs. The run 2 stove and stack temperatures were at least 100°F lower than in both other runs from minutes 68 to 96 and 62 to 96, respectively. The run 2 CO/CO_2 ratio was elevated during that period. The fuel consumption rate was also lower in run 2 than in the other runs during that period, increasing at about minute 105. The reason for the slower, less efficient, cooler burn in run 2 relative to the other runs is not known.

As discussed above, run 1 overnight emissions, although not as high as those of run 2, were significantly higher than in run 3. This difference is primarily because the PM emissions period at the beginning of the phase was approximately 30 minutes longer in run 1 than in run 3. Run 3 stove and stack temperatures were higher and the CO/CO_2 ratio lower than those of run 1 in that period.

3.7.6 Stove 7

A total of four IDC final protocol tests, each consisting of three replicate runs, were run on stove 7, a medium-sized high-mass stove with non-catalytic controls that is step certified at an emission rate <2 g/h. The four tests used four different types of cordwood fuel: red maple, seasoned oak, wet oak, and poplar. As with stove 6, the discussion below is limited to the red maple results in order to be consistent with the replicability assessments of the other stoves. The effect of burning different fuel species is discussed in section 4.3. Table 124 shows the metrics for each phase and the entire protocol of the red maple stove 7 runs.

Table 124. Stove 7—Comparison of Red Maple Run Metrics for Each Phase and the Entire IDC Protocol

Phase	Run ID#	Dry Load Burned (kg)	Time (min)	Dry-Burn Rate (kg/h)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Start-Up	S7-18-07-25	2.06	57	2.16	7.75	8.16	3.77
	S7-18-07-26	2.03	45	2.7	3.47	4.62	1.71
	S7-18-07-27	2.02	47	2.58	2.01	2.57	1
	Mean	2.04	49.67	2.48	4.41	5.12	2.16
	Std. Dev.	0.02	6.43	0.28	2.98	2.83	1.44
	Rel. St. Dev.	0.01	0.13	0.11	0.68	0.55	0.67
High-Fire	S7-18-07-25	4.45	143	1.87	4.5	1.89	1.01
	S7-18-07-26	4.44	141	1.89	4.69	1.99	1.06
	S7-18-07-27	4.49	153	1.76	2.31	0.91	0.52
	Mean	4.46	145.67	1.84	3.83	1.60	0.86
	Std. Dev.	0.03	6.43	0.07	1.32	0.60	0.30
	Rel. St. Dev.	0.01	0.04	0.04	0.35	0.37	0.35
Maintenance	S7-18-07-25	3.09	158	1.17	3.51	1.33	1.13
	S7-18-07-26	3.14	178	1.06	3.08	1.04	0.98
	S7-18-07-27	3.25	146	1.34	3.75	1.54	1.15
	Mean	3.16	160.67	1.19	3.45	1.30	1.09
	Std. Dev.	0.08	16.17	0.14	0.34	0.25	0.09
	Rel. St. Dev.	0.03	0.10	0.12	0.10	0.19	0.09
Overnight	S7-18-07-25	7.42	314	1.42	6.4	1.22	0.86
	S7-18-07-26	6.48	283	1.37	6.32	1.34	0.98
	S7-18-07-27	6.46	315	1.23	5.49	1.04	0.85
	Mean	6.79	304.00	1.34	6.07	1.20	0.90
	Std. Dev.	0.55	18.19	0.10	0.50	0.15	0.07
	Rel. St. Dev.	0.08	0.06	0.07	0.08	0.13	0.08
Entire Run	S7-18-07-25	17.02	672	1.52	22.43	2	1.32
	S7-18-07-26	16.08	647	1.49	17.95	1.66	1.12
	S7-18-07-27	16.23	661	1.47	13.56	1.23	0.84
	Mean	16.44	660.00	1.49	17.98	1.63	1.09
	Std. Dev.	0.51	12.53	0.03	4.44	0.39	0.24
	Rel. St. Dev.	0.03	0.02	0.02	0.25	0.24	0.22

The total time to complete the stove 7 IDC red maple runs ranged from 647 to 672 minutes (10.8 to 11.2 hours), a longer period than for the other stoves and slightly longer than the 10-hour target period for completion in a single day. The differences between the highest and lowest run times and burn rates were less than 4%. The HHV thermal efficiencies were also similar in all red maple runs, 70.2%, 70.2%, and 71.3% in runs 1, 2, and 3, respectively.

There was somewhat more variability in the PM emission metrics. The highest EF and ER were 57% and 63% higher for the highest (S7-18-07-25) than in the lowest emitting (S7-18-02-27) red maple run.

These parameters are shown graphically by phase in Figure 124.

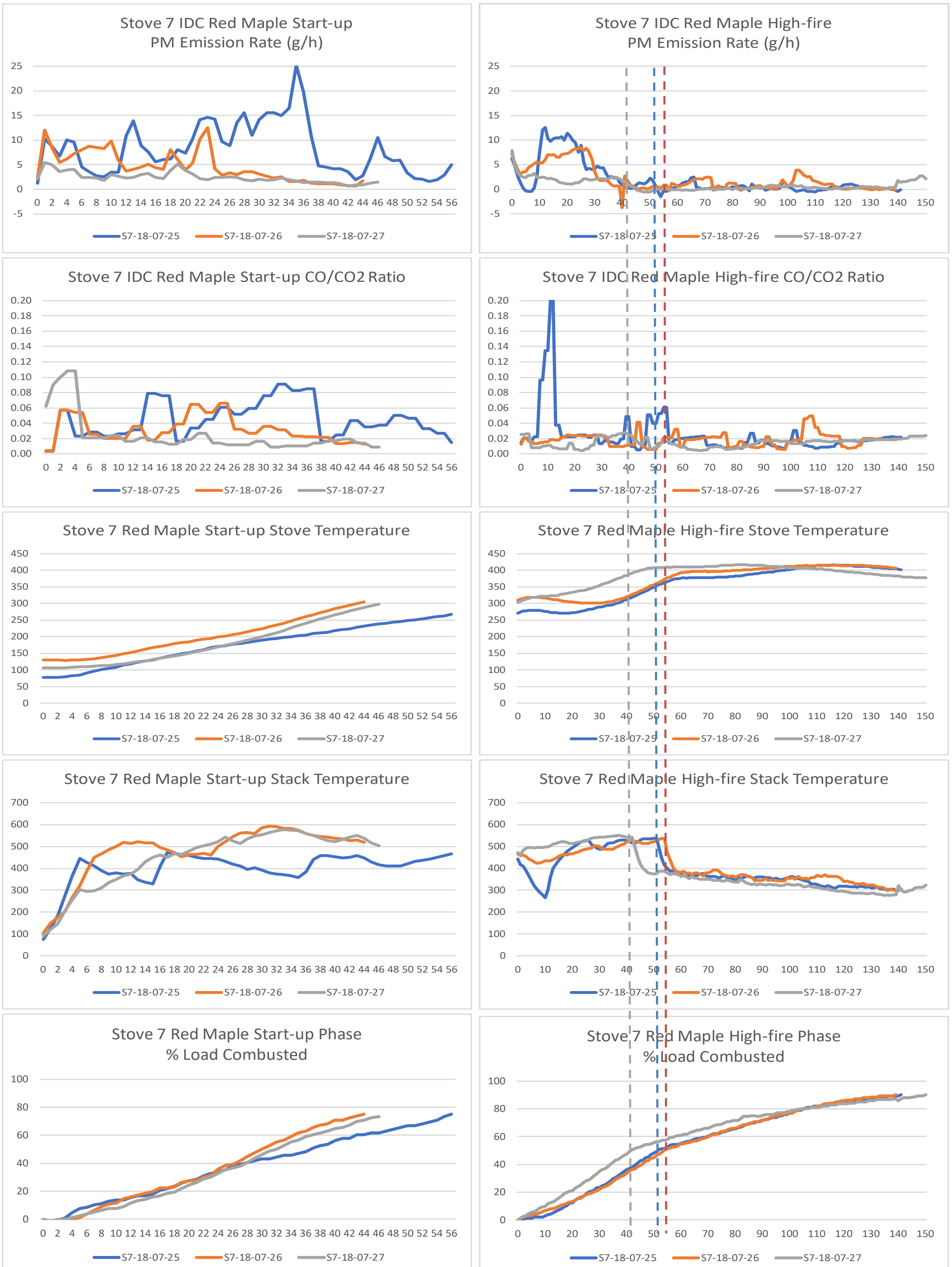
Figure 124. Stove 7—IDC Red Maple Run Parameters

Because stove 7 has higher efficiency and lower emissions, small differences in emissions in the tests of this stove have a more substantial impact on variability in metrics than with the other stoves. The ERs for the entire protocol for all runs were at or below the 2 g/h certification ER for this stove. The most substantial differences in the PM metrics among the runs were in the start-up phase and the high-fire phase. In the start-up phase, S7-18-07-25 (run 1) emissions were higher than those in S7-18-07-26 (run 2), which in turn were higher than in S7-18-07-02 (run 3). In the high-fire phase, run 1 and 2 emissions were similar and approximately twice those of run 3.

Because maintenance and overnight phase emissions were similar in the three runs, the analysis below will focus on the start-up and high-fire phases. The real-time profiles of those phases are shown in Figure 125. As in the previous presentations of high-fire results, the time that 50% combustion of the loads occurred, when the air setting was moved from high to low, is indicated with a dotted line in the graphs for those phases.

Figure 125. Stove 7—IDC Start-Up and High-Fire Phase Red Maple Profiles

Start-up Phase | High-fire Phase



As with previous stoves, the above factors do not give much insight into PM emissions early in the start-up phase. However, the higher PM emissions in run 1 in the second half of that phase correlated with a higher CO/CO_2 ratio and lower stove and stack temperatures and fuel consumption rate relative to the other runs in that period.

The excess high-fire phase PM emissions in run 1 and 2 relative to run 3 occurred almost entirely in a 20-minute period beginning at about minute 10. During that period, the CO/CO_2 ratio was elevated in run 1 but not in run 2. At the beginning of the phase, the stove temperature in run 2 and run 3 were essentially equal and more than 30°F higher than in run 1. However, during the period that PM emissions occurred in runs 1 and 2, the run 3 stove temperature increased steadily while the stove temperatures in run 1 and 2 decreased or remained level, resulting in run 3 stove temperatures that were up to 62°F higher than those in the other runs during that period. The combustion rate was also higher in run 3 than in the other runs during that time.

Note, however, that the emissions from stove 7 were very low overall, and that the magnitude of the differences in emissions between the runs would not have been significant in a stove with higher total emissions.

3.7.7 Stove 8

One complete IDC final protocol test, consisting of three replicate runs, was run on stove 8, a medium-sized steel stove with non-catalytic controls that is step 1 certified at an emission rate <4 g/h. These runs differed from the IDC runs performed on the other stoves because the air setting is fixed on this stove, therefore the burn rate could not be adjusted. The metrics for all phases of the stove 8 IDC runs are shown in Table 125.

Table 125. Stove 8—Comparison of Metrics for Each Phase and the Entire IDC Protocol

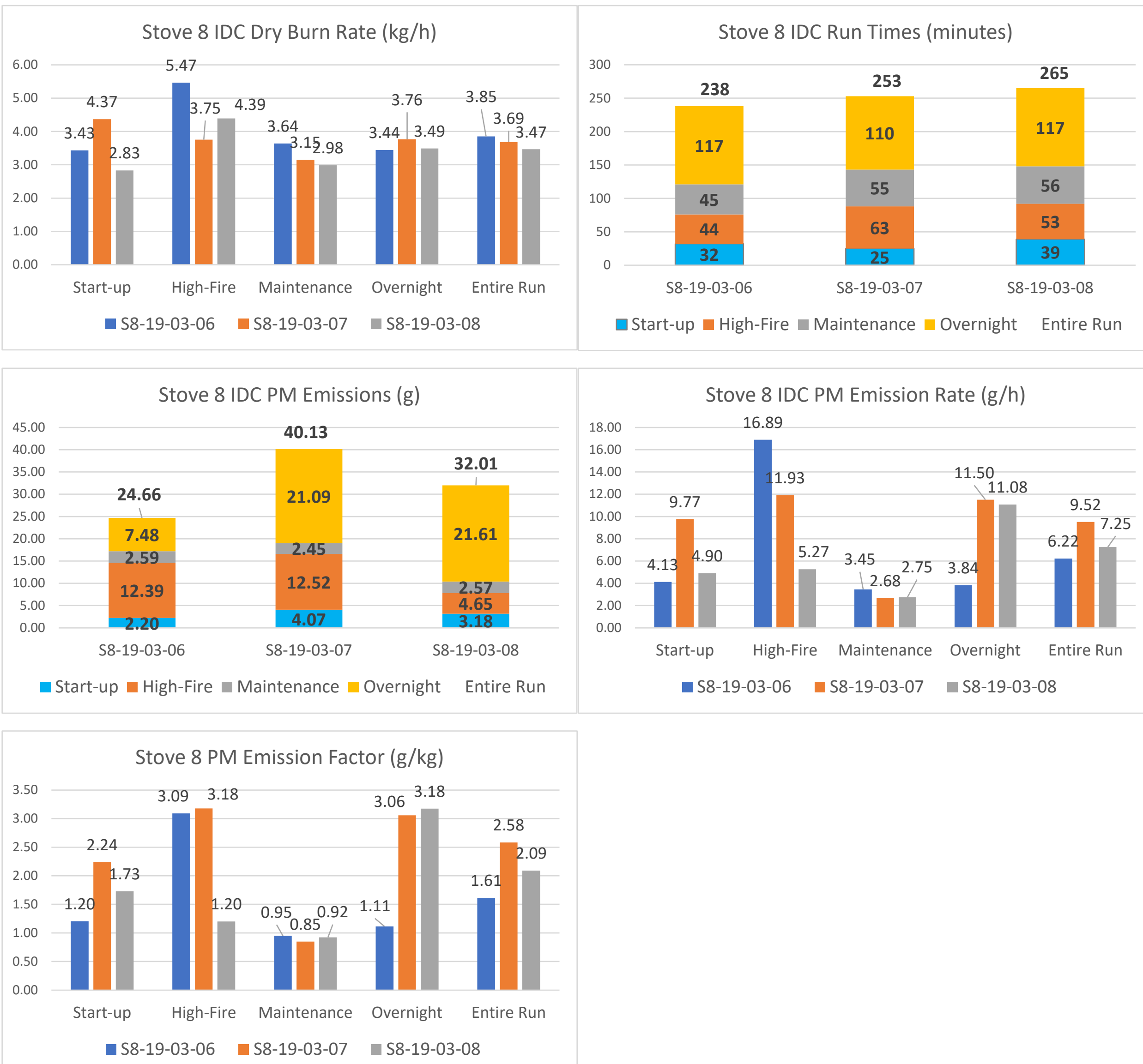
Phase	Run ID#	Dry Load Burned (kg)	Time (min)	Dry-Burn Rate (kg/h)	Total PM (g)	PM Emission Rate (g/h)	PM Emission Factor (g/kg)
Start-Up	S8-19-03-06	1.83	32	3.43	2.20	4.13	1.20
	S8-19-03-07	1.82	25	4.37	4.07	9.77	2.24
	S8-19-03-08	1.84	39	2.83	3.18	4.90	1.73
	Mean	1.83	32	3.54	3.15	6.27	1.72
	Std. Dev.	0.01	7	0.78	0.93	3.06	0.52
	Rel. St. Dev.	1%	22%	22%	30%	49%	30%
High-Fire	S8-19-03-06	4.01	44	5.47	12.39	16.89	3.09
	S8-19-03-07	3.94	63	3.75	12.52	11.93	3.18
	S8-19-03-08	3.88	53	4.39	4.65	5.27	1.20
	Mean	3.94	53	4.54	9.85	11.36	2.49
	Std. Dev.	0.07	10	0.87	4.51	5.83	1.12
	Rel. St. Dev.	2%	18%	19%	46%	51%	45%
Maintenance	S8-19-03-06	2.73	45	3.64	2.59	3.45	0.95
	S8-19-03-07	2.89	55	3.15	2.45	2.68	0.85
	S8-19-03-08	2.78	56	2.98	2.57	2.75	0.92
	Mean	2.80	52	3.26	2.54	2.96	0.91
	Std. Dev.	0.08	6	0.34	0.07	0.43	0.05
	Rel. St. Dev.	3%	12%	11%	3%	14%	6%
Overnight	S8-19-03-06	6.72	117	3.44	7.48	3.84	1.11
	S8-19-03-07	6.90	110	3.76	21.09	11.50	3.06
	S8-19-03-08	6.80	117	3.49	21.61	11.08	3.18
	Mean	6.81	115	3.57	16.73	8.81	2.45
	Std. Dev.	0.09	4	0.17	8.01	4.31	1.16
	Rel. St. Dev.	1%	4%	5%	48%	49%	47%
Entire Run	S8-19-03-06	15.29	238	3.85	24.66	6.22	1.61
	S8-19-03-07	15.55	253	3.69	40.13	9.52	2.58
	S8-19-03-08	15.30	265	3.47	32.01	7.25	2.09
	Mean	15.38	252	3.67	32.27	7.66	2.10
	Std. Dev.	0.15	14	0.19	7.74	1.69	0.48
	Rel. St. Dev.	1%	5%	5%	24%	22%	23%

The total time to complete the stove 8 IDC runs ranged from 238 to 265 minutes (4.0 to 4.4 hours), so the runs can easily be completed in a single day. The highest run time was 11% longer than the shortest. The HHV thermal efficiencies were essentially the same in the three runs, 60.7%, 61.1%, and 60.8% in runs 1, 2, and 3, respectively.

There was somewhat more variability in the PM emission metrics. The highest EF and ER were 60% and 53% higher for the highest (S8-19-03-07) than in the lowest emitting (S8-19-03-06) run.

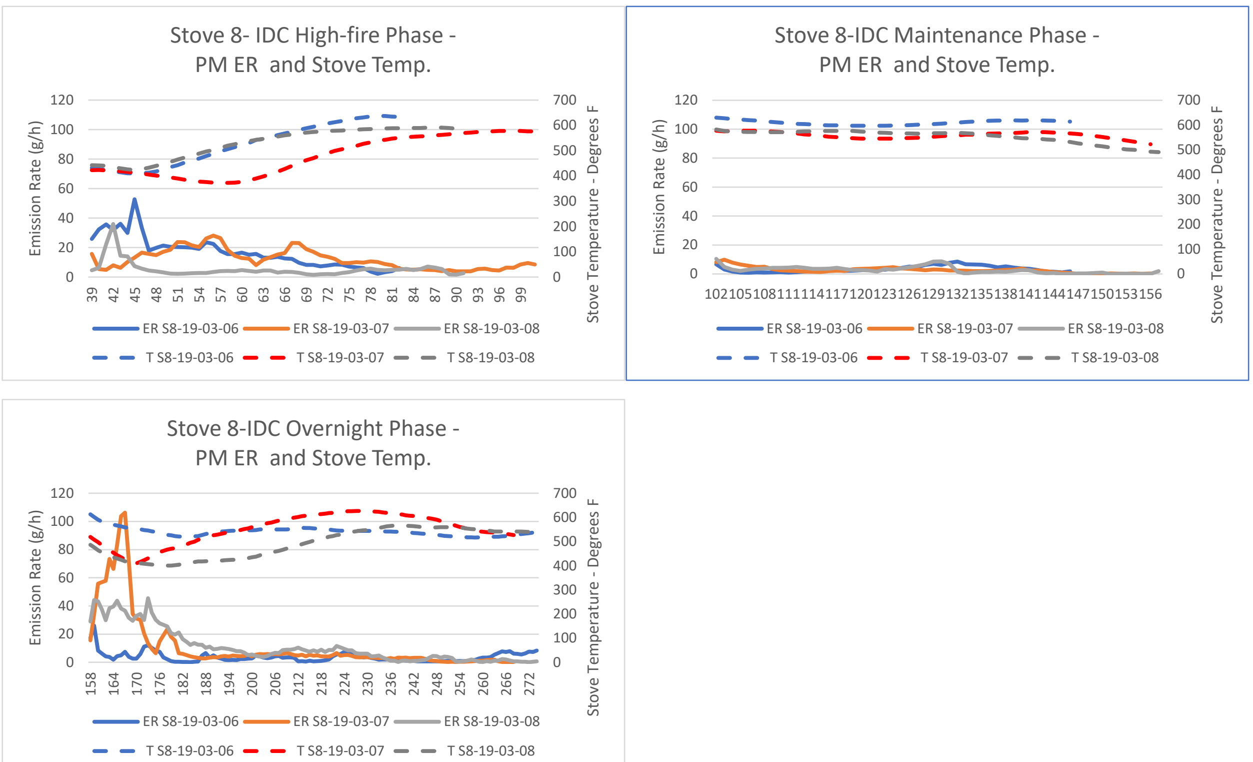
These parameters are shown graphically by phase in Figure 126.

Figure 126. Stove 8 IDC Run Parameters



PM emissions in the start-up and maintenance phases were similar in the three runs. However, emissions in the high-fire phase were lower in S8-19-03-08 (run 3) than in the other runs, while, in the overnight phase, emissions were lower in S8-19-0306 (run 1) than in the other runs. The air setting cannot be adjusted on stove 8, so all burns were conducted at the same air flow, which produced a relatively high-burn rate. As a result, the stove temperatures were higher at the start of the maintenance and overnight phases in stove 8 than in the other stoves. The temperature and PM emissions rate profiles for the high-fire, maintenance, and overnight phases of the stove 8 IDC runs are shown in Figure 127.

Figure 127. Stove 8—IDC Run Profiles—PM Emissions Rate (g/h) and Stove Temperature (ºF)



Temperatures remained well above 500ºF throughout most of the maintenance phase in all runs, which may explain the consistently low emissions in that phase. In the overnight phase, the initial temperature in run S8-19-03-06 was 94ºF to126ºF higher than in the other runs, which may explain the relatively low-PM emissions in that run. The temperature profiles do not explain the inter-run differences in the emission patterns in the high-fire phase.

3.7.8 Summary—Appliance Performance Variability

As discussed above, the relative standard deviation (standard deviation divided by the mean) of the ER measurements in the three replicate IDC runs for each stove was used as an indicator of the reproducibility of the IDC measurements in that stove. Relative standard deviations for the replicate runs in the seven study stoves that burned red maple fuel are shown in Table 126 below.

Table 126. Emission Rate Statistics—IDC Maple Replicates

	Mean g/h	Standard Deviation g/h	Relative Standard Deviation %	Range (Max-Min) g/h
Stove 1	11.81	4.26	36%	8.08
Stove 2–cracked	16.43	10.82	66%	21.61
Stove 2–wide	5.57	5.81	104%	10.19
Stove 4	6.33	0.98	15%	1.84
Stove 5	5.24	4.17	80%	7.80
Stove 6	16.05	3.96	25%	7.91
Stove 7	1.63	0.39	24%	0.77
Stove 8	7.66	1.69	22%	3.30

As shown in Table 126, the PM ERs for the replicate IDC runs in stoves 1,4, 6,7, and 8 showed good reproducibility according to the relative standard deviation metric. The relative standard deviation for the stove 1 runs was 36% and was less than or equal to 25% in stoves 4, 6, 7, and 8. The relative standard deviations were considerably higher in stove 5 (80%) and in stove 2 (66% for the stove 2 runs in which the stove door was initially cracked open and 104% in the runs with an initial wide-open door position).

The mean ER for the replicates and the ER range (maximum ER minus minimum ER) measured in the replicate runs are also shown in Table 126. This is a measure of the absolute difference in the ER seen in the runs, without an adjustment for the mean concentration. Although the relative standard deviation was considerably higher for stove 5 than for stoves 1 and 6, the ER range was similar in those three stoves. This discrepancy in the metrics is because the mean ER in stove 5 is approximately one-half that of stove 1 and one-third that of stove 6. Stove 2 showed high variability and stoves 4, 7, and 8 the lowest variability with both the relative and absolute metrics.

Inter-run variability could, in many cases, be explained by examining burn parameters. PM emissions rates tended to be higher with lower stove and stack temperatures, slower fuel consumption, and a higher CO/CO_2 ratio. The higher variability in the PM ER in stoves 2 and can largely be explained by the inconsistency of the burn parameters in those stoves.

This analysis demonstrates the importance of replicate runs in a test method. The replicate runs enable the IDC tests to distinguish stoves that tend to produce consistent emission results from those that do not. This is essential, because stoves that do not produce consistent results in the laboratory are unlikely to perform consistently in the field.

3.8 Stove Design and Technology

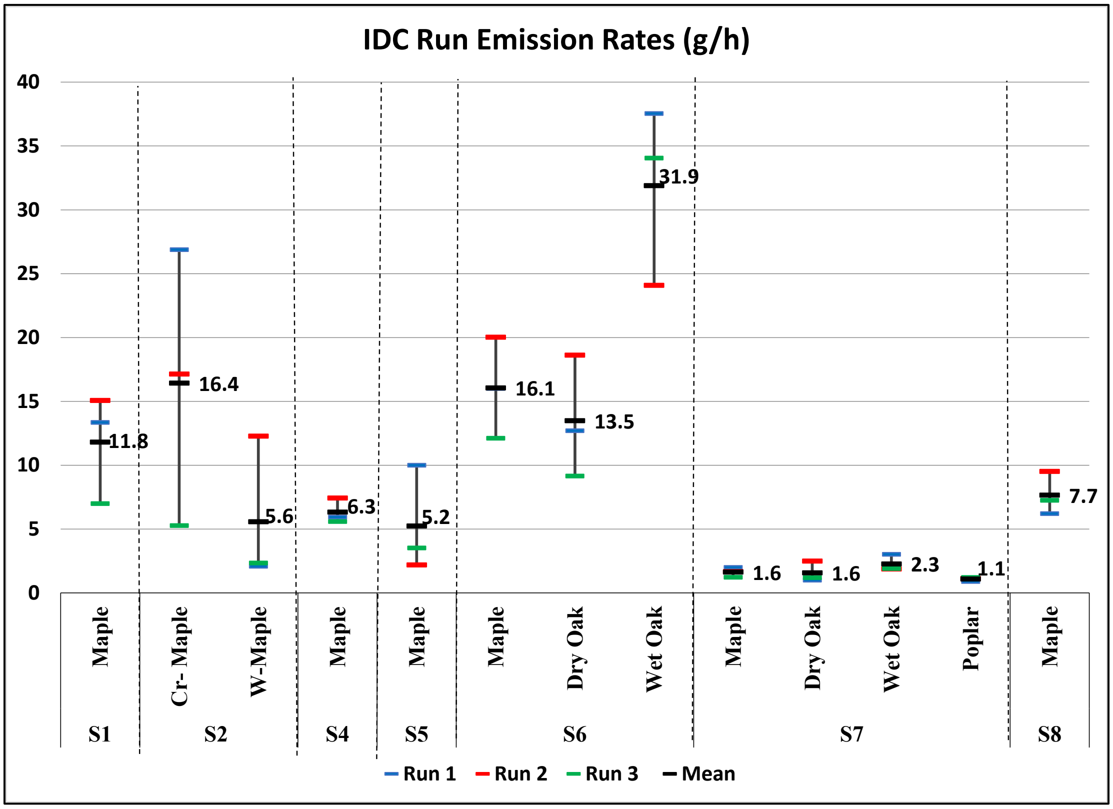
The ultimate goal of replacing the current certification test procedures is to promote the design and manufacture of wood stoves that burn cleaner under the varying operational and fueling conditions when used in homes. The stoves evaluated in this study were chosen to represent a range of sizes, construction materials, and control technologies, as shown in Table 127.

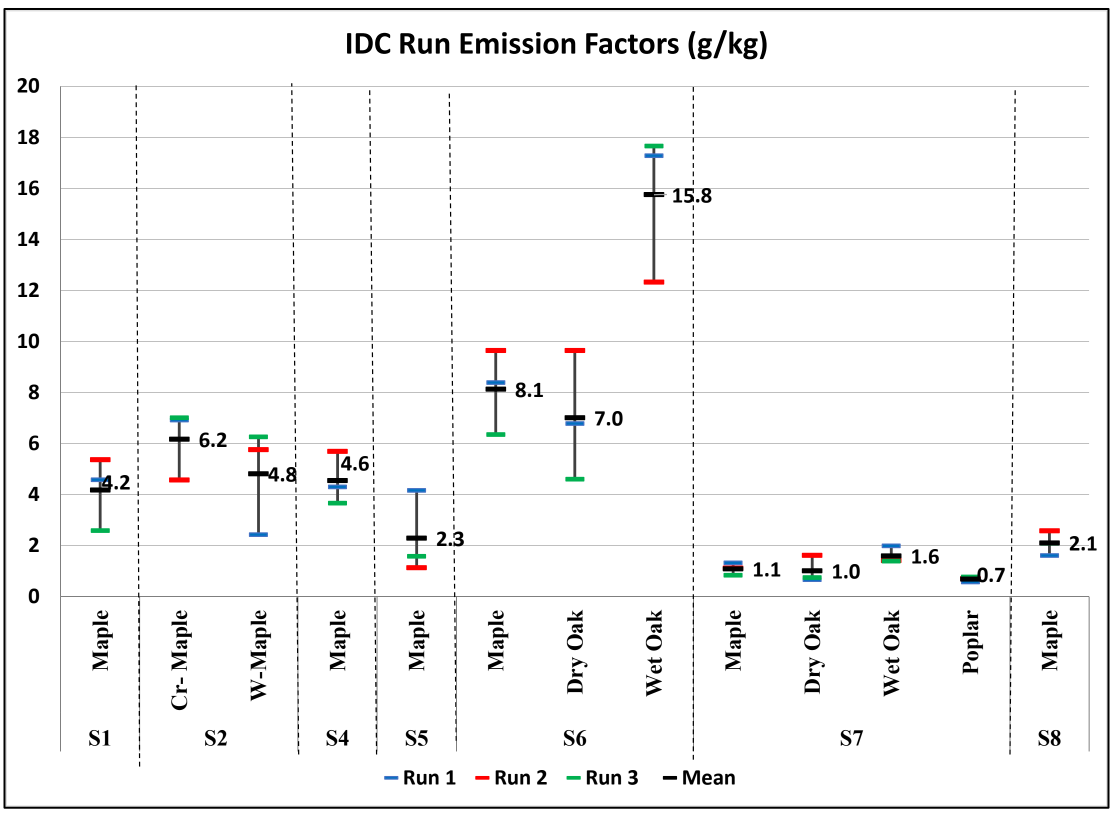
Table 127. Stove Characteristics

Stove #	Construction Type	Firebox Size	Emission Controls	EPA Certification
Stove 1	High mass	3.1 ft^3 - Large	Non-catalytic tube	Step 1
Stove 2	Steel	1.3 ft^3 - Small	Catalytic	Step 2
Stove 3	Steel	3.2 ft^3 - Large	Catalytic	Step 1
Stove 4	Cast iron	0.8 ft^3 - Small	Non-catalytic tube	Step 1
Stove 5	Cast iron	2.1 ft^3 - Medium	Non-catalytic non-tube	Step 1
Stove 6	Steel	2.2 ft^3 - Medium	Non-catalytic tube	Step 1
Stove 7	High mass	1.9 ft^3 - Medium	Hybrid - catalytic and non-catalytic	Step 2
Stove 8	Steel	1.8 ft^3 - Medium	Non-catalytic non-tube	Step 1

The ERs, in g/h, and EFs, in g/kg, measured in those seven stoves are shown in Figure 128. PM emissions were measured using the 1400AB TEOM in the IDC maple fueled runs in stoves 1, 4, 5, 6 and 7 and the 1405 TEOM was used to measured PM emissions in the stoves 2 and 8 maple IDC runs, the wet and seasoned oak runs in stove 6, and the poplar and wet and seasoned oak runs in stove 7. As discussed previously, a previous evaluation of data from collocated 1400AB and 1405 TEOMs showed excellent correlation between the measurements with the two instruments; however, the 1400AB PM measurements were 8 to 13% lower than the levels measured with the 1405.

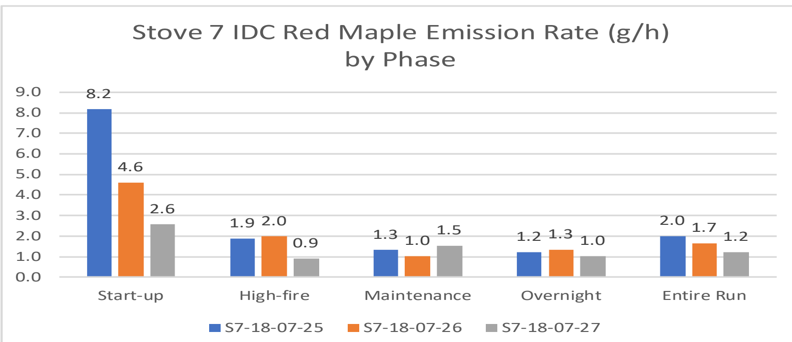
Figure 128. IDC Run Emission Rates (g/h) and Emission Factors (g/kg) by Stove and Fuel





As shown in Figure 128, the ER, in g/h, and EF, in g/kg, were considerably lower in stove 7, the only stove with hybrid catalytic/noncatalytic controls than in the other stoves. Stove 7 was the only stove in this group that was able to demonstrate compliance with the NSPS step 2 cordwood ER limit, 2.5 g/h, using the IDC test procedures, which are designed to measure performance over a range of typical operating conditions, it is likely that stove 7 would also perform well in the field. The stove 7 ER also complied with the step 2 limit with a range of fuel species and moisture contents and showed low variability in replicate tests. Therefore, it is likely that stove 7 would also perform consistently well under the range of fueling and operational conditions commonly encountered in the field.

Figure 129. PM Results (g/h) for IDC Runs—Entire Protocol



As shown in Figure 129, above, stove 7 performed well across the burn phases. As is typical with wood stoves, emissions were highest during the start-up phase. The most substantial differences in the PM metrics among the runs were in the start-up phase and the high-fire phase. In the start-up phase, S7-18-07-25 (run 1) emissions were higher than those in S7-18-07-26 (run 2), which in turn were higher than in S7-18-07-02 (run 3). In the high-fire phase, run 1 and 2 emissions were similar and approximately twice those of run 3. However, these values were still low compared to the other stoves tested in this study. Because stove 7 is a highly efficient and low-emitting device, small differences in emissions in the tests have a more substantial impact, on a percentage basis, on variability metrics than with the other stoves.

It is not the intention of this study to promote any particular stove technology options or designs. Rather, the testing protocol's efficacy should drive technology innovation, allowing manufacturers to determine the best engineering solutions. Moreover, only one hybrid stove was tested in this group. However, the test results suggest, and results from additional stoves that will be reported subsequently, support the conclusion that employment of hybrid control technology can produce clean-burning residential wood stoves.

4 Findings and Recommendations

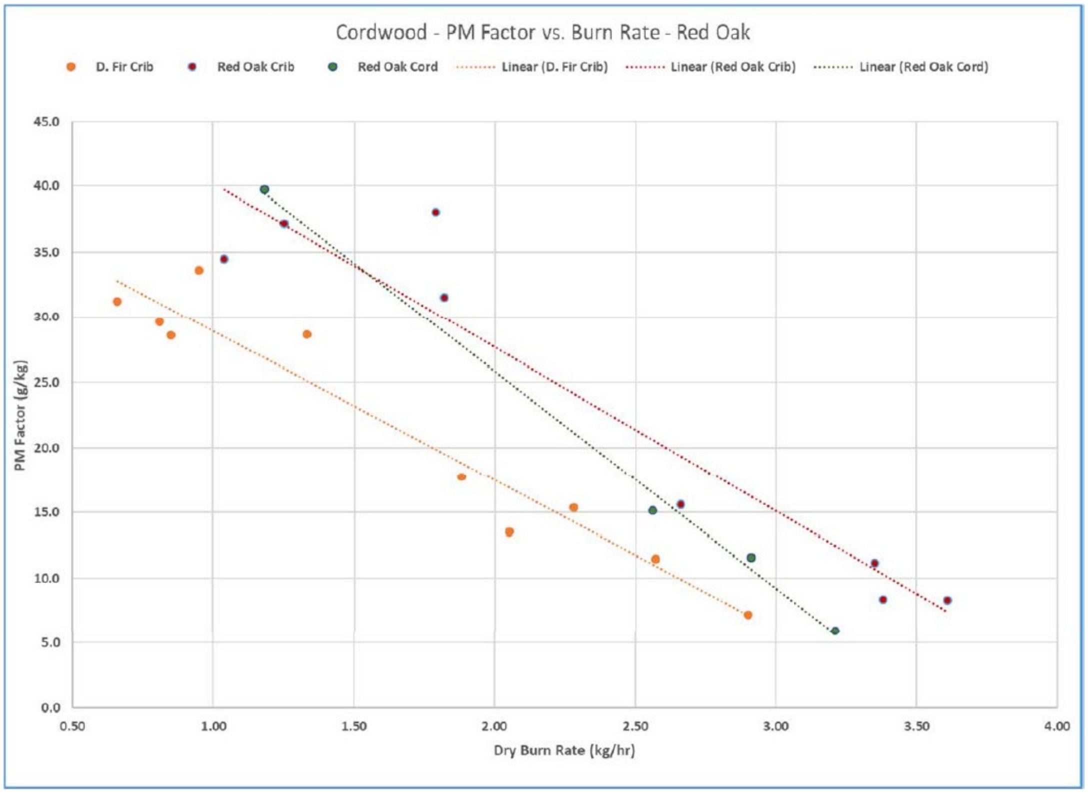
EPA has long been aware that federal certification methods for residential wood heaters are not representative of the operation of those appliances in the field. EPA's 1998 Residential Wood Combustion Technology Review stated that "(i)t is generally recognized that these [certification] tests do not simulate the way that a stove is used in the 'real world."' The report goes on to observe that because "(w)ood stoves are designed, out of necessity, to pass the certification test and consequently, their design is not necessarily optimal for low emission performance under actual in-home use." (Houck, 1998) Industry, states in the U.S., and EPA are all on record supporting changes to the protocols used to test wood heating devices to make the emission certification process more representative of real-world emissions.

Test method development is complex and requires significant investment in data gathering and analysis. The work conducted under this contract was guided by the EPA's direction in their 2016 Discussion Paper on Cordwood test methods, which stated that "the goal of robust new test methods should be to assess an appliance's ability to operate cleanly under highly variable conditions, both in terms of fueling and operations" (EPA, 2016). A primary goal of this project was to develop a test method applicable to all types of stove cordwood that would challenge those devices to achieve a clean burn under a range of operating and fueling conditions that closely replicate in-field operations. An effective new test method that better characterizes real-world emissions must address all aspects of the three primary components of the test procedure: (1) fueling, (2) operations, and (3) PM measurement, as EPA indicates in its 2016 paper.

Emission test development efforts have largely focused on changing the form of the certification fuel from the dimensional lumber crib wood currently prescribed in M28 to cordwood. However, such a change is not sufficient to yield major improvements in the test method. A 2017 EPA study found that "differences in PM emissions and burn rates are greater between species than between crib wood and cordwood in the same species" (Cole, 2017). Those results are illustrated in Figure 130.

Figure 130. EPA Study Comparing Emission Factors from Crib Wood and Cordwood

(Cole, 2017)



The study presented in this report provide data that enhance the understanding of wood stove emissions and support the development of an effective emission certification protocol for these appliances. Key findings from the study are summarized in this section, along with recommendations regarding how the findings might be incorporated into a certification test procedure that better reflects the performance of wood stoves when installed in a home.

4.1 Current Certification Test Methods

The current EPA wood stove regulatory program relies on a single test of a prototype model to certify a model line. Other EPA programs, like the mobile source program, also use a model line certification process. However, unlike those programs, determination of compliance with EPA's residential wood heater program is limited to that certification test, while other programs include rigorous compliance monitoring procedures, including in-use testing. The use of a single certification test as the sole determinant of compliance with emissions standards places a significant burden on that test. Manufacturers, of necessity, design and adjust their wood heaters to pass the certification test.

The current methods assess appliance operation at a single-fuel configuration, with a set number of wood pieces and specified spacing, and under specified operating conditions. An appliance that performs well under certification test conditions may perform very differently under variable fueling and operating conditions typical in the field. Because the current test is not representative of in-use stove operation, tuning the appliance to those tests may not result in optimal performance in the field. In the preamble of the 2015 NSPS [13678], EPA expressed support for a change in test methods, stating that there is "a critical need for test methods that reflect the 'real world' with cordwood, cold starts, cycling, moisture, heat demand and shorter averaging periods" and encouraged the development of improved methods that have "sufficiently demonstrated that they can be relied upon for regulatory purposes."

Researchers have documented that due to the limited correlation between certification test values and in-field performance, existing certification tests may significantly underestimate emissions and exposures in the field. A European meta-study found that PM and VOC emissions from residential wood heating appliances in Austria, measured according to European National (EN) standard steady-state test protocols, were significantly lower than the results obtained when those appliances were tested under real-life operating conditions (Reichert et al, 2018). EPA measured emissions and performance of four central heating appliance in a laboratory using appliance load profiles generated by a simulation program for heat demand of a home in Syracuse, NY in the place of the loads specified in the certification test. PM emissions measured under those conditions were generally higher than those measured using the certification test method (Gullett, 2012).

The current certification test procedures, which burn a single-fuel configuration at one heat setting for the entire fuel load and do not include start-up or reloading events, do not reflect typical in-use practices. Observed in-home usage patterns are highly variable, and this variability persists regardless of the device's location or type (Ahmadi, 2019). In recognition of this variability, current steady-state testing should be replaced with a test method that incorporates a range of burn conditions and fuel load configurations that mimic the variable operating patterns seen in the field. This departure from current certification practice would better reflect device performance in actual home use.

4.2 Suitability of ASTM 3053-17

Although the ASTM 3053-17 test, which has been approved as a Broadly Applicable Approved ATM, has the advantage of using cordwood, rather than crib wood, this method shares many of the weaknesses of current compliance test methods and introduces new issues of concern. The fueling and operating conditions employed by the ASTM 3053-17 cordwood test method do not represent the highly variable nature of in-field wood stove use.

A NESCAUM review of the ASTM 3053-17 test method and compliance test reports that used that method identified the following concerns:

- The ASTM 3053-17 method allows the manufacturer to determine the firebox volume on the basis of the manufacturer's determination of the usable firebox volume. The method lacks criteria for or limitations on those determinations. Other methods, such as M28, require the use of actual dimensions of the firebox with allowances for subtracting areas not deemed as useable firebox volume. Firebox volume is a key component in determining the amount of fuel used in certification testing.
- The ASTM 3053-17 method allows the manufacturer to provide instructions to the testing laboratory that include specifications for fuel dimensions, as well as loading and spacing configurations, that contradict typical homeowner operations and more closely resemble crib wood test beds than the less-structured loading patterns typical in consumer use.
- The ASTM 3053-17 method is silent on fuel length specifications, allowing the manufacturer to determine the length of fuel used with no restrictions. This allows the manufacturer to test with fuel lengths that optimize appliance performance but may not reflect homeowner operation.
- The ASTM 3053-17 method allows the manufacturer instructions to determine fuel placement and spacing with no restrictions, which introduces significant variability in how testing is conducted and allows fuel placement procedures that may not reflect common homeowner practices.
- The ASTM 3053-17 method allows the low- and medium-load test burns to continue until 100% of the load has been consumed while, in the field, consumers typically reload fuel before all of the previous load has been consumed.
- The ASTM 3053-17 method allows for multiple definitions for the end of the test in the high-fire phase.
- The ASTM 3053-17 method allows manufacturers to modify coal-bed conditions, including removal of coals.
- The ASTM 3053-17 method does not specify parameters that adequately define the medium-burn rate.
- The ASTM 3053-17 test does not include replicate runs that would enable an assessment of the reproducibility of results.

- The ASTM 3053-17 cordwood test method identifies a range of acceptable fuel specific gravities but does not limit the test species that can be utilized. This allows the tester to choose from a variety of fuel species within a single test, introducing potentially significant variability issues.
- The medium- and low-burn phases of the ASTM 3053-17 test often begin at substantially elevated temperatures because those phases are immediately preceded by the burn of a large load at the highest air setting.
- The high temperatures associated with the large ASTM 3053-17 loads create high-humidity conditions in the dilution tunnel, raising concerns about PM loss and the accuracy of PM measurements. Real-time PM data shows higher PM losses with ASTM 053-17 than M28 test runs.

In this study, ASTM 3053-17 cordwood tests were conducted on four stoves: Stoves 1, 6, 7 and 8. Those tests were used to evaluate the impact of operating and fueling conditions on test results and the comparability of the results to those measured using other procedures. In stove 6, complete ASTM tests were performed with three different fuel types; maple, red oak, and beech; allowing for a comparative analysis of the effect of fuel type on the stove's performance and emissions.

The study determined that due to the large load sizes required by the ASTM 3053-17, tests conducted with that method had long run times. In the medium- and low-burn phases of the stove 1, 6, and 7 ASTM 3053-17 maple tests, run times were, on average 118 minutes (44%) longer than in the corresponding M28 runs in those stoves. The increased run time included an extended period after 100% of PM emissions had been collected; on average, that period constituted 65% of the M28 run time and 75% of the ASTM 3053-17 maple fuel run times for the stove 1, 6, and 7 medium and low burns. An extended run time reduces the ER, which is expressed in grams per hour.

Much like M28, ASTM 3053-17 measures average performance across long steady-state burns and provides limited information about emissions that occur during cold-starts, fuel reloads, and the end phases of stove operation. In addition, those procedures do not generate replicate data that would allow for an assessment of the reproducibility of results. Based on the study data and the review of the ASTM 3053-17 protocol, the team concluded that ASTM 3053-17 does not address the issues EPA seeks to resolve in adopting new test methods.

4.3 Representativeness of IDC Stove Test Methods

While no test procedure can capture the full range of factors that affect emissions from wood burning devices in the real-world, the study evaluated a variety of factors to develop IDC stove test procedures that are more representative of in-use conditions than the current certification tests. The research focused on developing a protocol that would (1) characterize variability with greater precision than current methods; (2) capture a range of representative operations, including start-up, reload periods, and a variety of heat loads; (3) include a PM measurement approach that provides information to manufacturers that can be used to improve design to minimize emissions; (4) create better measures of efficiency; and (5) reduce the time required to conduct certification tests. The aim was to develop a single-day test that would allow for replicate testing without appreciably increasing certification test costs as compared to M28.

The IDC test measures PM and carbon monoxide (CO) emissions, heating efficiency, and operating parameters such as temperatures and air flow. Real-time PM emission data are collected using a tapered element oscillating microbalance (TEOM) placed in a dilution tunnel. Use of a dilution tunnel allows the flue gas to cool and PM to condense prior to measurement so more volatile PM species are included. The operational protocol is designed to mimic a range of observed in-home usage patterns and to assess an appliance's performance under different heat loads, coal-bed conditions, and fuel placement configurations. In this study, IDC protocol tests were successfully completed on a wide range of stoves types, including stoves that:

- Ranged in size from 0.80 ft^3 to 3.2 ft^3.
- Used different firebox fuel loading configurations—east/west, north/south, and top-loading.
- Used different manufacturing materials, including steel, cast iron, and high-mass materials.
- Employed different control technologies, including catalytic, non-catalytic, and hybrid approaches.
- Included both variable- and single-burn rate stoves.

The IDC stove testing found that non-catalytic stoves exhibit a higher variability in stove performance than catalytic hybrid stoves. The research also found that typically, emission rates measured using the IDC stove testing procedures are higher than those measured with other protocols, at least partially, because of the shorter run-time duration. However, the testing also showed that a well-performing stove, like the hybrid stove 7, can meet current EPA emission standards for cordwood testing using the IDC stove protocol. Based on this phase of the evaluation of those procedures, the researchers concluded that the IDC stove protocol represents a viable approach to improve wood stove testing, as detailed in the sections below.

4.4 IDC Stove Operational Protocol Elements

As discussed above, NESCAUM identified several shortcomings of current certification test procedures. The current test methods do not include replicate testing. The lack of replicate testing introduces uncertainty into the test results and does not allow for an evaluation of variability of stove performance. Current procedures burn a single fuel configuration at one heat setting for the entire fuel load and do not include start-up or reloading events, which is not representative of typical in-use operating practices. Additionally, current testing procedures reduce the impact of peak emission periods on calculated emissions rates by allowing the appliance to burn the full-fuel charge, a practice that does not reflect typical homeowner operation. Typically, stoves are not operated in consistent batch loads under steady-state conditions as currently tested. Batch sizes (fuel loads) vary, and heat settings are changed both before loading a batch and while burning it. This section details key elements incorporated into the IDC protocol to improve appliance assessment.

4.4.1 Reloading Events

Current EPA and ASTM test methods do not assess the impact of multiple reloading events using different sized fuel loads. Research targeted on developing test methods for wood cookstoves found that fuel reloading could be an important factor causing discrepancy between laboratory and field emissions (Deng, 2018). Researchers assessed this parameter and found that different stove technologies performed differently with reloads of varying sizes. This element has been embedded in the operational protocol to ensure this element is assessed in the IDC protocol.

4.4.2 Replicate Testing

Current EPA and ASTM test methods conduct hot-to-hot, steady-state tests in three to four predefined test categories and do not include replicate tests runs. The lack of replicates makes it impossible to determine or assess method precision or reproducibility. Studies have shown that biomass testing may, in fact, benefit from more than three replicates (Wang, 2014). Assessment of wood-fired cookstoves requires a minimum of three and up to ten replicates to provide statistical confidence that the results are valid. (A follow-up study completed by Lawrence Berkeley National Laboratory found that “(i)n the stove design and laboratory testing phase, researchers need to conduct a relatively large number of replicate tests to ensure with some confidence that the improvements of stove performance and emission levels are truly achieved” (Wang, 2013, p.16). While the number of replicates that can be reasonably required is limited by cost considerations, a certification test method with no replicates makes it impossible to assess appliance performance variability.

Typical stack testing protocols for other source types require that three tests be performed (an “n” of 3), while current testing for wood devices requires only one data point in four different load categories with no repeat runs.

Unlike ASTM 3053 or M28, the IDC protocol requires completion of three replicate test runs. The results from this study demonstrated that five of the seven stoves tested produced relatively consistent emissions in the replicate runs, while the other two did not and would likely not perform consistently in the field. Requiring replicate testing as part of the certification process is important to ensure that a stove model can dependably meet emission standards. This element of the IDC test can help promote the design and manufacture of wood stoves that are more likely to achieve consistent emission performance both in the laboratory and once installed in a home.

4.4.3 Testing to 90% versus 100% Fuel Burn

This study highlights a weakness in current emissions testing procedures for wood stoves that results in an underrepresentation of typical emissions rates during in-field use of those appliances. The current FRM crib wood testing procedure, M28, measures the average PM ER over the burn of 100% of a fuel load. Combustion of 100% of the fuel load is also required in the high- and medium-burn phases of the ASTM 3053-17 alternative cordwood method. This does not represent operating conditions in the field, because stove operators generally add additional wood before 100% of the previous load has been consumed. Because most emissions occur early in the burn, the lengthened run time associated with continuing the test until 100% of the load is consumed reduces the measured emission rate in g/h.

In the seven stoves that were tested in this study using M28 procedures, the average ER at 100% combustion was 35% to 53% lower than at 90%, largely as a result of the extended run time. The difference was even more substantial for the ASTM 3053-17 runs, due to the larger loads required by that method. The ERs for the medium and low ASTM 3053-17 burns that used maple fuel were 63% to 93% lower at 100% than at 90% combustion. To more accurately reflect actual in-use conditions, the operational protocol for the end of the phase and run should occur when 90% of the fuel load has been consumed rather than the 100% load combustion approach used in ASTM 3053-17 and M28.

4.4.4 Burn-Phase Modes

The portion of the burn that occurs in various modes can have a significant impact on stove emissions. Current certification test protocols do not accurately represent real-world use patterns. The testing done in this study evaluated the emission impacts of various elements of the IDC method designed to provide emission metrics that better represent in-use operations. The impact of using four loading events as opposed to one in the M28 and ASTM 3053-17 protocols was evaluated and suggests that emissions are higher when including all phases, including a separate start-up phase and a “maintenance—semi-active attended burn” phase that represents a typical component of wood stove operation in the residential setting.

4.4.5 Stove Temperature

The temperature of a stove at the beginning of a burn plays a crucial part in determining how the appliance will perform during a run. This issue is important for several reasons: (1) higher starting stove temperatures lead to better light off and lower emissions; (2) higher temperatures provide significant benefit to non-catalytic devices, with higher refractory temperatures and other combustion conditions; and (3) higher temperatures prime secondary combustion for optimum performance. Therefore, a testing protocol that produces higher starting temperatures than would typically be seen in real-world settings may underpredict in-use emissions.

M28 requires a stove to maintain the run-burn rate for an hour before starting a test run. In ASTM 3053-17, a large high-burn run is completed immediately prior to the medium and low burns. The researchers compared stove data from the low-fire burns in the M28, ASTM 3053-17, and draft IDC protocols and found the data suggest that ASTM 3053-17 procedures result in an artificially high temperature at the beginning of that test phase.

Data from the research runs in this study supported a modification to the original IDC protocol to lower the average stove temperature before beginning the final phase (RL3), the phase which simulates long, low-burn periods. This change is reflected in the final IDC stove protocol.

4.4.6 Coal-Bed Conditions

EPA research has already identified the lack of representativeness of coal-bed conditions, as stated in their 1998 report: "The EPA certification procedure has been described as an art. Achieving a successful low burn rate condition and coal-bed preparation are particularly challenging and they are quite unlike how a stove is usually used in a home" (McCrillis, 1998, iii).

Both M28 and ASTM 3053-17 allow the manufacturer instructions or lab testing crew to optimize coal-bed conditions. Existing methods do not require assessing how the appliance performs with different coal-bed conditions. The IDC assesses three different coal-bed conditions. The loads are burned to 90%, which means that reloads assess light-off performance with coal-bed conditions at approximately 10%, 15%, and 20% of total firebox volume.

4.5 IDC Stove Fueling Protocol Elements

The study evaluated the impact of wood species, fuel-load volumes, and moisture content on emissions. These factors are important because stove owners burn a variety of fuels, including, at times, wood that is not well seasoned. However, it is also important that test methods provide fuel requirements that are specific enough that the results can be reproduced. The current IDC protocol requires the use of maple fuel, which is available in all regions of the U.S. and, in the study tests, produced results that were within the range of those seen with different fuels. Moisture content also significantly affected emission results, although that impact was not as substantial in a well-controlled stove. It is important that test procedures include specifications that also account for that variable.

M28 and ASTM 3053-17 allow significant modifications to the fueling protocol via the use of manufacturer's instructions to the lab. The IDC stove protocol attempts to standardize fueling protocols across certification test runs and eliminate the use of manufacturers' instructions to modify fueling protocols. While no single fueling protocol can be representative of all field operations, the IDC stove protocol seeks to obtain data on a range of fueling practices and ensure that the appliance will operate well with different piece spacing and sizes.

4.5.1 Fuel Species/Density

Wood species, density, moisture, resin content, and bark all impact emissions from combustion (Butcher, 2016). M28 only allows the use of one fuel, Douglas fir. ASTM 3053-17 cordwood tests allow the use of any species within a specific gravity range of 0.48 to 0.73 on a dry basis. This allows a large number of species to be used in the ATM 3053-17 testing, which introduces new and significant variability issues. When developing this element of the protocol, ASTM commented that it was their professional judgment that there will not be much difference in emissions across species under the specific gravity range stipulated in the ASTM method.

Many studies have found that species affect emissions, but the nature of the impact was affected by study designs. In the 2004 study, "Chemical Characterization of Fine Particle Emissions from the Wood Stove Combustion of Prevalent United States Tree Species," researchers found a high variability in emissions from combustion of species allowed by the draft ASTM method (Fine, 2004). A 2013 study found that three parameters strongly affected emission outcomes—"the kind of wood, its physical properties, and the availability of oxygen" (Orasche, 2013). EPA assessed uncontrolled emission impacts of varying species in a pre-NSPS stove. One of EPA's primary conclusions in that study was that "(s)tudy results seem to indicate that species does matter in terms of PM emissions, at least on the pre-1988 stove used in the species study (which had minimal emission control technology) (Cole, 2017)." Those results confirmed findings of other studies that demonstrate that the use of different species introduces variability into testing results and is often more substantial than the differences between the combustion of crib and cordwood, and contradicts the underlying position of the ASTM in allowing a range of species.

In this study, complete ASTM 3053-17 tests were performed using three fuel species in stove 6: maple, oak, and beech. In addition, complete IDC tests were performed using maple and oak fuel in stove 6 and maple, oak, and poplar fuel in stove 7. The number of samples was not sufficient to demonstrate significant inter-species differences in emissions rates. However, the data support the conclusion that allowing a range of species introduces additional variability into test results.

To address the concerns of limiting variability, the IDC stove protocol recommends use of one widely available species, maple, with specified allowable densities for testing all residential wood heater devices. The protocol could expand to include another hardwood such as oak. The protocol also has the flexibility to incorporate additional runs with another fuel type, such as poplar, pine, or birch, in order to test stove performance with a range of commonly used fuels.

4.5.2 Fuel-Load Volume

Fuel-load configuration is a critical variable in assessing appliance performance. Variation in the number of pieces loaded, the loading arrangement, and the size of the coal bed is required to evaluate how the unit will work under the range of loading conditions the appliance will experience in the field. An EPA study suggests that the wood-load amount has a more significant effect on PM emission rates (not necessarily emission factors) than burn rate. (Leese, 1989) This is because the higher stack flow values at higher burn rates (which have lower g/kg PM emission factors) and the lower stack-flow values at lower burn rates (which have higher g/kg PM emission factors) tend to counterbalance each other with respect to grams per kilogram PM emission rates.

The recommended fueling procedures in both M28 and ASTM 3053-17 perpetuate an inaccurate assumption that users load a consistent number of pieces and load size in their wood stoves. Studies as far back as the 1980's have shown that the fuel load specifications in the current test methods are not representative of homeowner practices. In 1985, the Oregon Department of Environmental Quality (DEQ) conducted a study to better understand how much wood users typically load into their stove. The DEQ had been assuming the typical load was 7 pounds of wood per cubic foot of volume in the firebox. At that time, industry asserted that it should be 17 lb/ft^3. A detailed study of nine homes found an average load density of 5.4 lb/ft^3 (Stockton, 1985).

The M28 protocol uses a single loading density of about 7 lb/ft^3 for all test runs, while the ASTM 3053-17 protocol density requires 10 lb/ft^3 for the high-fire load, and 12 lb/ft^3 for the medium- and low-load test runs. In this study, paired sets of research runs with different load densities were performed in four stoves; one run in each stove with a load density of 5 lb/ft^3 in the high-fire phase (RL1) and 7 lb/ft^3 in the maintenance phase (RL2) and the other run with those densities reversed. The higher density high-fire loads tended to produce more PM emissions in that phase, while PM emissions in the maintenance phase were minimal with both densities.

The IDC stove protocol uses four different loading volumes (4 lb/ft^3, 5 lb/ft^3, 7 lb/ft^3, and 12 lb/ft^3) to assess appliance performance under different fuel-load volumes. By requiring the appliance to burn in a variety of fuel-load conditions, along with different coal-bed conditions, fuel-piece sizes and operating conditions, the IDC stove protocol allows an assessment of appliance performance over a broad range of conditions.

4.6 PM Measurement Elements

PM sampling and measurement can introduce significant variability into certification testing. PM is not an absolute quantity, but rather an operationally defined metric. Different sampling methods produce different PM emission results, even when other conditions are held constant. EPA's current FRM for PM measurement is ASTM 2515. Review of this test method by the research team found that ASTM 2515 does not properly control for excessive dilution tunnel temperature, dewpoint, or relative humidity at the sample filter. Lower tunnel flow rates introduce water issues that have significant impact on method precision. Lower tunnel flows can also cause extremely high-tunnel temperatures, up to 80°C on high-fire burns. At these temperatures, little to no condensation of semi-volatile organic compounds (SVOCs) will occur, resulting in under-measurement of PM.

The IDC stove protocol addresses issues with PM measurement issues by incorporating new humidity, dilution tunnel temperature, and tunnel flow requirements. Meeting these limits will require higher tunnel flows than are normally used. The combination of higher tunnel flows and lower PM emissions from clean devices such as pellet stoves requires additional precision in the filter weighing process. A semi-micro balance with resolution of at least 0.01 mg is necessary, and for some test protocols and devices, a micro balance (1 µg resolution) may be needed. In addition to a better balance, improved filter handling and weighing procedures would be needed, as recommended in the group findings. Moving to TEOM measurements, such as those used in this study resolves measurement resolution issues.

The IDC stove protocol also incorporates the use of a TEOM to obtain real-time PM measurements. Use of this measurement approach increases measurement precision and provides additional options for regulatory metrics in future rules, such as one-hour rolling average emission standards. The real-time measurements also provide data useful for improving stove design.

4.7 Stove Design and Technology

The ultimate goal of improved test procedures is to promote the design and manufacture of wood stoves that burn cleaner under common operational conditions. The results from this study suggest that certain stove designs and emission control strategies are able to perform well under a broad range of in-field situations, while others are not. While it is not the intention of this study to promote any particular stove technology options or designs, the test results will be useful for driving technology innovation and engineering better performing residential wood stoves.

5 References

Ahmadi, M., et al., “Investigation of real-life operating patterns of wood-burning appliances using stack temperature data,” Journal of the Air & Waste Management Association, 2019, 70:4, 393-409, DOI: 10.1080/10962247.2020.1726838.

Butcher, T. and Trojanowski, R., “Summary of Literature Review for Wood Species Impact on Emissions.” September 2016, Brookhaven National Laboratory.

Cole, D., “Final Report: Wood Species Testing Using Crib and Cordwood in a Pre-NSPS Residential Wood Heater.” US EPA, March 4, 2017. Prepared under EPA Contract No. EP-D-12-001Work Assignment #4-08. Available at: https://doi.org/10.1016/j.envpol.2018.09.064.EPA 2016 US EPA Office Air Quality Planning and Standards, “Process for Developing Improved Cordwood Test Methods for Wood Heaters.” USEPA, March 2016. Available at: https://www.epa.gov/burnwise/process-developing-improved-cordwood-test-methods-wood-heaters. Accessed on January 10, 2021.

Deng, M., et al., “The impact of cookstove operation on PM2.5 and CO emissions: A comparison of laboratory and field measurements.” Environmental Pollution, Volume 243, Part B, 2018, Pages 1087-1095, ISSN 0269-7491.

Fine, P., et al., “Chemical Characterization of Fine Particle Emissions from the Wood stove Combustion of Prevalent United States Tree Species.” Environmental Engineering Science – Environmental Engineering Science. 21. 705-721. 10.1089/ees.2004.21.705.

Franziska K., et al., “Emission characterization of modern wood stoves under real-life oriented operating conditions.” Atmospheric Environment, Volume 192, 2018, Pages 257-266, ISSN 1352-2310, https://doi.org/10.1016/j.atmosenv.2018.08.024.

Gullett, B., et al., “Environmental, Energy Market, and Health Characterization of Wood-Fired Hydronic Heater Technologies.” NYSERDA, 2012. Prepared under contract #10665.

Houck, J. and Pitzman, L., “Emission Factors for New Certified Residential Wood Heaters.” Omni, 2008. Available at: https://www3.epa.gov/ttnchie1/conference/ei17/session4/houck.pdf. Accessed January 10, 2021.

Houck, J. and Tiegs, P., “Residential Wood Combustion Technology Review Volume 1. Technical Report.” U.S. Environmental Protection Agency, Washington, D.C., EPA/600/R-98/174a (NTIS PB99-122111), 1998. Available at: https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NRMRL&dirEntryID=90399

Intertek, “Inspection Tests and Evaluation of SBI - Series 1.7 (Blackcomb) Emissions and Efficiency - EPA (43615).” April 27, 2018, p. 160-163. Available at: https://sbiweb.blob.core.windows.net/media/4563/blackcombii-17-series.pdf.

Leese, K., et al., "Effects of Burn Rate, Wood Species, Moisture Content and Weight of Wood Loaded on Woodstove Emissions." U.S. Environmental Protection Agency by Research Triangle Institute, Research Triangle Park, NC. EPA-600/2-89-025. 1989. Available at: https://www3.epa.gov/ttnchie1/ap42/ch01/related/woodstove.pdf.

McCrillis, R.C., "Residential Wood Combustion Technology Review, Volume 1. Technical Report." U.S. Environmental Protection Agency by OMNI Environmental Services, Inc., Beaverton, OR. EPA-600/R-98-174a. 1998.

Naeher L.P., et al., "Woodsmoke Health Effects: A Review." Inhal. Toxicol. 2007 Jan;19(1):67-106. DOIi: 10.1080/08958370600985875.

NATA, "2011 National Air Toxics Assessment." US EPA, 2015. Available at: https://www.epa.gov/national-air-toxics-assessment/2011-nata-assessment-results. Accessed on January 10, 2021.

Orasche, J., et al., "Comparison of Emissions from Wood Combustion. Part 2: Impact of Combustion Conditions on Emission Factors and Characteristics of Particle-Bound Organic Species and Polycyclic Aromatic Hydrocarbon (PAH)-Related Toxicological Potential." Energy & Fuels, 27 (3), 1482-1491, 2013. DOI: 10.1021/ef301506h.

Reichart, G., et al., "beReal - Development of a New Test Method for Firewood Roomheaters Reflecting Real Life Operation." 24th Biomass Conference and Exhibition, 6-9 June 2016, Amsterdam, The Netherlands.

Reichert, G., et al., "Effect of draught conditions and ignition technique on combustion performance of firewood roomheaters." Renewable Energy, Volume 105, 2017, Pages 547-560, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2016.12.017.

Smith, W., et al., "Evaluation of Wood Fuel Moisture Measurement Accuracy for Cordwood-Fired Advanced Hydronic Heaters." March 2014, NYSERDA.

Stockton, B., "Addressing the Issue of Wood Loading Factors of Woodstoves: How much wood to homeowners load in their stoves?" January 14, 1985. EPA document A-84-49-II-I-64, p. 3.

University of Tennessee Agricultural Extension Service, "W179 Wood Products Information - Moisture Content of 'Seasoned' Firewood." University of Tennessee, Knoxville; April 2010. Available at: https://trace.tennessee.edu/utk_agexfores/101/.

Wang, et al., "How many replicate tests do I need? – Variability of cookstove performance and emissions has implications for obtaining useful results." Ernest Orlando Lawrence Berkley National Laboratory, February 2013. Available at: https://www.osti.gov/servlets/purl/1172123.

Wöhler, M., et al., "Investigation of real life operation of biomass room heating appliances – Results of a European survey." Applied Energy, Volume 169, 2016, Pages 240-249,ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2016.01.119.

Appendix A—Procedure for Processing and Visualizing Lab Data for the Stove Test Method Project

This document describes the steps, formulas, templates, and tools that are used in the processing and visualizing of lab measurement data in the stove test method project.

A.1 Basic Elements of the Procedure

At the highest level, for each test run the procedure involves merging Hearth Lab Solutions (HLS) lab data and TEOM data into a single Excel spreadsheet that calculates test metrics including run duration, total PM, PM emission rate, PM emission factor, and dry-burn rate in each load. There are multiple points in the procedure at which the quality and integrity of data are checked. Figure A-1 shows a schematic of the entire procedure. The sources of data are as follows:

HLS Realtime Data: Stove test data are recorded by HLS in the lab during the test. HLS creates one Excel file for each stove and data records from each test are added in a separate worksheet in the file. The name of each worksheet is a combination of the test date and stove number, as shown in Figure 2. A separate metadata file describes each HLS parameter.

Fueling Table: HLS creates a table for each test that includes details of fueling during the test, such as date of the test, fuel species, fuel moisture content (MC), fuel weight, the time that new fuel pieces are added, and coal-bed weights. For IDC tests, additional details about fueling calculations, kindling, and individual fuel piece weights and MC are recorded. Figure 3 shows an example of the fueling data table. HLS creates a single Excel file in which each IDC test has a separate worksheet to record fueling data. Fueling data for all ASTM 3053-17 test runs are recorded in one worksheet in the same spreadsheet.

Result Summary Table: HLS maintains an Excel spreadsheet that summarizes all test results. In the first worksheet of this file, ("Results Summary") each new test is added in a row with information about stove number, test date, burn setting, duration, overall emissions rates, filter catch data, and measurement precision. In other worksheets of this file, technical descriptions of each stove are recorded. Figure A-4 shows a snapshot of the Results Summary worksheet.

Run List Summary: NESCAUM has created an Excel spreadsheet to record and track date, stove number, and short description of all test runs. The latest version of this file is available upon request from NESCAUM. Figure A-5 shows a snapshot of this file.

TEOM Raw Data: TEOM measurement data for each test are saved in an Excel file. Each file includes separate worksheets for TEOM data, pDR1500 data, log data as recorded at HLS during the test on the TEOM laptop, and tunnel temperature and relative humidity (RH) data. In the "log" worksheet, test protocol, date, and important times and notes are recorded. NESCAUM generates these files after each test.

Processing Template: To facilitate the merging, cleaning, and processing of the test data, several Excel spreadsheets called Data Processing Templates (DPTs) are created. The main purpose of using DPTs is to have a fast, correct, and consistent data processing procedure for all tests. Because the timing, fueling steps, and terminology for each test protocol are different, separate DPTs have been developed for the IDC, ASTM, M28R, and beReal tests. All test data cleaning, quality checks, and calculations occur in the template file. The structure of the DPT for IDC test and formulas are explained in the Data Processing Template and Formulas section below.

Figure A-1. Schematic of the Data Processing and Visualization Procedure

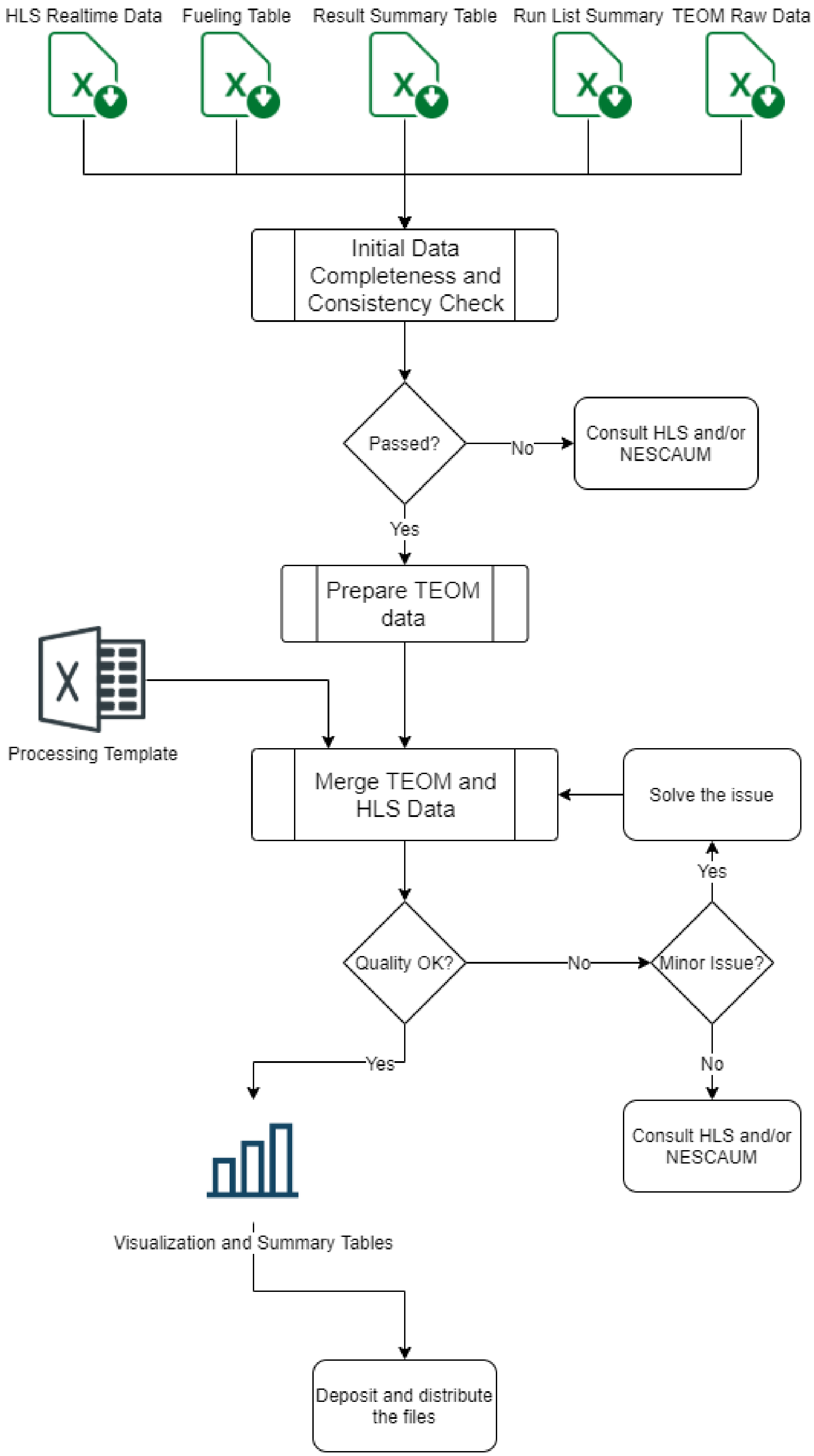


Figure A-2. Snapshot of HLS Real-Time Data for Stove 16

	A	B	C	D	E	F	G	H	I	J	K
1	RecNum	TestTime	TunFlow	Mtr1Flow	Mtr2Flow	LabTemp	Met1T	Filt1T	Met2T	Filt2T	TopT
2	0	0	231	0.01	0	56	56	56	0	0	0
3	1	1	229	0.01	0.01	62	62	62	63	62	62
4	2	2	230	0.01	0.01	62	62	62	63	62	62
5	3	3	229	0.01	0.01	62	62	63	63	62	62
6	4	4	231	0.01	0.01	62	62	62	63	62	62
7	5	0	229	2	1.99	63	62	63	63	62	62
8	6	1	229	1.99	2	62	62	62	63	62	64
9	7	2	226	1.99	2	63	62	64	63	62	64
10	8	3	219	2	2	63	62	65	63	63	70
11	9	4	211	2	2	63	63	67	64	66	83
12	10	5	209	2	1.99	63	63	70	64	67	105
13	11	6	221	2	2	63	62	69	63	67	137
14	12	7	225	1.99	1.99	63	63	69	64	67	174
15	13	8	229	2	2	63	63	68	63	67	210
16	14	9	232	2.01	2	64	63	68	64	67	241
17	15	10	233	2.01	2	63	63	68	64	67	264
18	16	11	233	2	2	64	63	67	64	66	280
19	17	12	234	2	2	64	64	68	64	67	293
20	18	13	234	2.01	2	64	63	67	64	67	308
21	19	14	235	2.01	1.99	65	64	68	65	67	319
22	20	15	234	1.99	1.99	65	64	68	65	67	332
23	21	16	235	1.99	2	64	64	68	65	67	348
24	22	17	233	1.98	2	65	64	69	65	68	369
25	23	18	231	1.99	2	64	64	68	64	68	396
26	24	19	231	2.01	2	65	64	69	65	68	416
27	25	20	231	2	2	65	64	68	65	68	429
28	26	21	232	1.99	2	65	64	68	65	68	439
29	27	22	231	2	2	65	64	68	64	67	448
30	28	23	230	1.99	1.99	65	64	68	65	68	455
31	29	24	231	2	2	65	64	67	65	67	461
32	30	25	231	2.01	2	65	64	68	65	68	466
33	31	26	231	2	1.99	65	64	68	64	67	468

... **Stove162009181** | Stove162009202 | Stove162009232 | Stove162009253 | Stove162010302

Figure A-3. Snapshot of Fueling Table

4/15/2020 IDC Maple

Phase	Start Time	Start ET	End ET	Ld, wet lb	MC, dry %	Start Coals, lb	End Coals, lb	DBR, kg/hr
Start Up	9:11	0	40	11.1	17.6	0.0	2.8	
High		40	251	19.41	20.2	2.8	4.7	
Medium		251	520	14.1	21.0	4.7	6.1	
Low		520	1049	33.8	19.4	6.1	9.4	
Average		0	1049	67.31	20.0	0.0	9.4	

Figure A-4. Snapshot of the Results Summary

	A	B	C	D	E	M	N	O	P	Q
1	FileName	StoveName	Task		Setting	Test Time, min	Dry Burn Rate, kg/hr	Avg PM Rate, g/hr	PM Factor, g/kg	Stove Diff temp, deg F
61	Stove172004211	Stove17	2421	ASTM Maple	High	188		7.3		544
62	Stove172004212	Stove17	2421	ASTM Maple	Low	947		0.4		-305
63	Stove172004231	Stove17	2421	ASTM Maple	High	162		8.5		603
64	Stove172004232	Stove17	2421	ASTM Maple	Medium	665		0.4		-279
65	Stove72004291	Stove7	2421	IDC Maple	IDC	619		1.5		305
66	Stove7B2005011	Stove7B	2421	IDC Maple	IDC	676		4.2		308
67	Stove72005061	Stove7	2421	IDC Spruce	IDC	676		1.9		309
68	Stove72005072	Stove7	2421	IDC Spruce	IDC	610		5.7		308
69	Stove72005083	Stove7	2421	IDC Spruce	IDC	681		2.4		301
70	Stove162009141	Stove16	2421	IDC Maple, 20" EW	IDC	525		16.4		339
71	Stove162009161	Stove16	2421	IDC Maple, 16" NS	IDC	521		21.8		295
72	Stove162009181	Stove16	2421	IDC Maple, 16" CC	IDC	375		14.8		366
73	Stove162009202	Stove16	2421	IDC Maple, 16" CC	IDC	367		9.5		337
74	Stove162009232	Stove16	2421	IDC Maple, 20" EW	IDC	462		11.7		305
75	Stove162009253	Stove16	2421	IDC Maple, 20" EW	IDC	401		10.1		390
76	Stove162010302	Stove16	2421	IDC Maple, 16" NS	IDC	572		11.9		275
77	Stove162011023	Stove16	2421	IDC Maple, 16" NS	IDC	532		7.8		333
78	Stove162011043	Stove16	2421	IDC Maple, 16" CC	IDC	515		9.6		291
79	Stove162011164	Stove16	2421	IDC Maple, 16" EW	IDC	536		17.8		284
80	Stove232012121	Stove23	2421	ASTM Beech	High	192		7.1		446
81	Stove232012122	Stove23	2421	ASTM Beech	Low	844		1.2		-278
82	Stove232012131	Stove23	2421	ASTM Beech	High	183		2.0		416
83	Stove232012132	Stove23	2421	ASTM Beech	Medium	476		1.1		-168
84										
85										
86										
87										

Results Summary | Run Results | Stove 1 | Stove 2 | Stove 3 | Stove 4 | Stove5 | Stove 6 | Stove 7 | St

Figure A-5. Snapshot the Run List Summary File

	A	B	C	D	E
	date	stove #		desc	3 IDC variants: V1, V2, and Final
9					
0	20-09-14	S16		IDC maple R&D	20", E-W loading, bottom up start
1	20-09-16	S16		IDC maple R&D	16" N-S
2	20-09-18	S16		IDC maple R&D	16" criss-cross pattern.
3	20-09-20	S16		IDC maple R&D	16" Criss-cross pattern, run 2
4	20-09-23	S16		IDC maple R&D	20" E-W, bottom up kindling
5	20-09-25	S16		IDC maple R&D	20" maple e-w loading
6	20-10-31	S16		IDC maple R&D	16" N-S loading, Tunnel flow nominal 23
7					

A.2 Data Preparation Procedure

The basic elements and actions of the data preparation procedure are shown in Figure A-1. At the highest level, the procedure consists of the five steps listed below. The structure of the DPT files and how the files are named are explained in the File Naming Conventions and Data Processing Template and Formula sections of this document.

Step 1: The current versions of five data files containing test information (HLS Realtime Data, Fueling Table, Result Summary Table, Run List Summary, and TEOM Raw Data) are collected and reviewed. If the test information in any of these files is missing or corrupted, HLS and/or NESCAUM is contacted to fix the problem. First, the reviewer checks the consistency of stove number, date, time, and protocol of the test across all five files. Then, completeness of data is checked. If information is not consistent or not complete, HLS and/or NESCAUM is contacted to find the source of inconsistency and resolve it.

Step 2: After passing the initial completeness and consistency check, the TEOM data file is prepared before being merged with HLS real-time data. In addition to the 1-minute PM concentration with room PM subtracted, the tunnel gas temperature, relative humidity (RH), and dew point (DP) is reported every 10 seconds. These data are used to calculate RH at the TEOM filter and water content in the tunnel flow. Because HLS data acquisition is performed at a 1-minute intervals, tunnel temperature, RH, and DP are averaged over a 1-minute period before being merged and used in formulas with the HLS data. Averaging is performed in a separate worksheet named “1-min T-RH-DP” in the TEOM data Excel file. The PM measurement data (in the “1-min Teom” worksheet) are collected at a 1-minute interval and do not need to be averaged.

Figure A-6. Snapshot of the TEOM Data Spreadsheet After Processing

A	B	C	D	E	F	G	H
# of Records	9760		Time	RH (%)	T (C)	DP (C)	
Start Hour:	7		7:43:00	27.66818	8.67	-9.21273	
Start Min:	43		7:44:00	44.36909	9.091818	-2.73909	
End Hour:	21		7:45:00	80.07833	10.725	7.325833	
End Min:	53		7:46:00	99.02182	15.99909	15.85273	
			7:47:00	100	23.73909	23.73727	
			7:48:00	74.31417	30.1725	23.30167	
			7:49:00	22.28455	32.70636	8.551818	
			7:50:00	21.41667	30.86833	6.439167	
			7:51:00	26.57667	27.915	7.0925	
			7:52:00	36.29818	25.55364	9.638182	
			7:53:00	45.55417	23.96667	11.62583	
			7:54:00	47.65	22.93727	11.38545	
			7:55:00	49.89583	22.17333	11.38583	
			7:56:00	49.91636	21.60455	10.88182	
			7:57:00	48.6	21.14636	10.09182	
			7:58:00	48.50417	20.78583	9.733333	
			7:59:00	42.83917	20.37333	7.550833	
			8:00:00	39.07909	19.86364	5.7	
			8:01:00	38.765	19.41917	5.170833	
			8:02:00	39.29727	19.10545	5.083636	
			8:03:00	40.06083	18.89583	5.175833	
			8:04:00	45.45417	18.80333	6.953333	
			8:05:00	54.08818	18.90182	9.601818	
			8:06:00	57.36667	19.10583	10.6525	
			8:07:00	53.35833	19.29333	9.768333	
			8:08:00	50.49091	19.43	9.106364	
			8:09:00	50.00583	19.61833	9.130833	
			8:10:00	50.97833	19.82333	9.591667	

Teom 20-04-23 S17 | T-RH-DP | log | 1-min Teom | **1-min T-RH-DP**

The last action in this step is re-naming the TEOM file. The name convention for the prepared TEOM data file is explained in the File Naming Conventions section. Figure A-7 shows several TEOM data files prepared and renamed on a local disk storage.

Figure A-7. Prepared TEOM Data Files

19-12-17 Stove 10 Teom PM.xlsx	1/9/2020 2:57 PM	Microsoft Excel W...	823 KB
19-12-18 Stove 10 Teom PM.xlsx	1/9/2020 11:56 AM	Microsoft Excel W...	879 KB
19-12-19 Stove 10 Teom PM.xlsx	1/9/2020 11:57 AM	Microsoft Excel W...	800 KB
19-12-20 Stove 10 Teom PM.xlsx	1/9/2020 11:58 AM	Microsoft Excel W...	842 KB
19-12-21 Stove 10 Teom PM.xlsx	1/9/2020 11:58 AM	Microsoft Excel W...	1,141 KB
20-01-10 Stove 13 Teom PM.xlsx	1/12/2020 3:32 PM	Microsoft Excel W...	776 KB
20-01-11 Stove 13 Teom PM.xlsx	1/12/2020 3:32 PM	Microsoft Excel W...	1,109 KB
20-01-12 Stove 13 Teom PM.xlsx	1/12/2020 3:32 PM	Microsoft Excel W...	1,100 KB
20-04-21 Stove 17 Teom PM.xlsx	6/16/2020 12:28 AM	Microsoft Excel W...	2,378 KB
20-04-23 Stove 17 Teom PM.xlsx	6/16/2020 12:36 AM	Microsoft Excel W...	2,114 KB

Step 3 and 4: These two steps are performed simultaneously and involve several sub-steps that need to be taken carefully and in the right order. First, a copy of the latest version of the corresponding DPT is created and renamed to be worked on. The naming convention for the processed data files are described in the File Naming Conventions section, below. Here, we call this copy the “processed data file.”

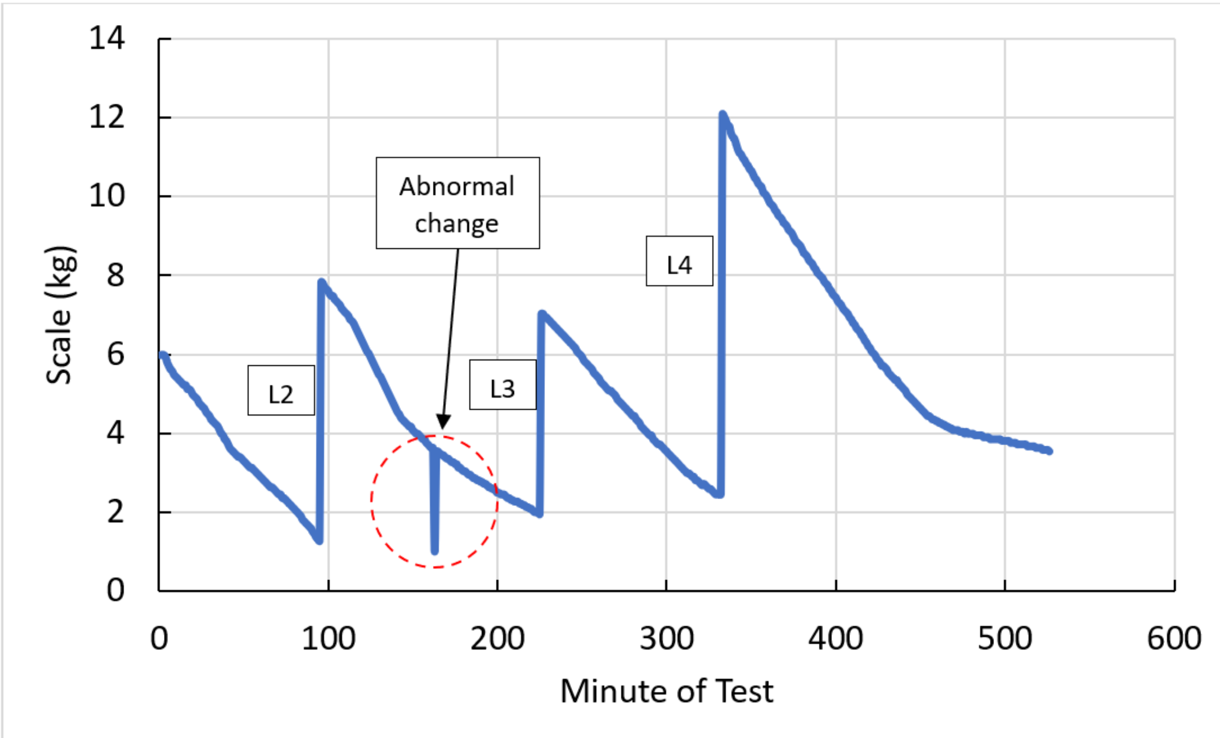
HLS real-time data and fueling data are copied from the original sources into the processed data file. Because the IDC protocol requires four loads of fuel during the test run, (now referred to as L1, L2, L3, and L4 but referred to as high, medium, and low burns in earlier versions) identifying start and end times of each burn load is critical in the calculation of test metrics. All start/end times of the loads are recorded in the fueling data table by the HLS test operator. To check the accuracy of those data, the data processor checks to see that the time recorded in the fueling data table is consistent with those typical in real-time data. To do that check, the record in the HLS real-time data where the fueling table says the new load was added is located. At this point in the data, a sudden jump in the scale reading should be observed because a load of wood is added to the stove. If the recorded time in the fueling table does not match with a sudden change of scale readings within a ±1 minute range, HLS and/or NESCAUM are contacted to investigate the source of the issue and resolve it. Figure A-8 shows an example of a sudden increase in scale reading at the time a new load was added to the stove.

Another data quality check is performed at this point. First, the scale reading data are plotted. The scale reading plot should look like a smooth downward curve between two loads. If there is an abnormal jump or drop in data, it is investigated. If the scale reading was incorrect for one point, that point is removed and replaced with interpolation of the readings before and after it. Figure A-9 shows an abnormal change in the scale reading which would be investigated and resolved.

Figure A-8. Example Sudden Change in the Scale Readings Following Loading

T	U	V	W	X	Y	Z	AA
start / end of burns marker	TT/ ET	clock time	Tun Flow CFM	Stove AvgT F	Stack Temp F	Scale (kg)	scale loss delta
startup	0	8:58	247	68	69	5.98	
	92	10:30	225	366	568	1.36	0.09
	93	10:31	224	372	573	1.32	0.04
	94	10:32	226	377	571	1.27	0.05
L1	95	10:33	220	384	435	7.84	-6.57
	96	10:34	226	383	463	7.80	0.04
	97	10:35	228	383	448	7.71	0.09

Figure A-9. Normal and Abnormal Changes in Scale Recorded Data



The next action is to link the processed data file to the prepared TEOM file. Unlike the HLS real-time data, TEOM data are not copied and pasted directly into the processed data spreadsheet. Three columns in the processed data file are linked to the corresponding TEOM prepared file: (1) column AD (header: "Teom PM ug/m3 STP") is linked to column C in the "1-min Teom" worksheet; (2) column AM (header: "RH @ TEOM") is linked to column E in the "1-min T-RH-DP" worksheet, and (3) column AN (header: "DP @ TEOM") is linked to column G in the "1-min T-RH-DP" worksheet. Once these columns are linked and auto-populated, TEOM data are loaded into the processed data file. Typically, a spike in the TEOM PM readings occurs a few minutes after anew load is added to the stove. This is used to double-check the consistency of data. The lack of a discernable peak in TEOM reading near the start times of new loads can be sign of an issue that needs further investigation. Figure A-11 shows PM jumps at the start of new loads.

At this point, all test metric calculations should be updated automatically. A summary of test results is presented in the "Table" worksheet. Because the Stack Loss Method (SLM) for efficiency calculation is very sensitive to CO and CO_2 concentrations, even one negative or zero reading from those sensors can corrupt the whole efficiency calculation. If in the summary table any of the efficiency values are negative or extremely large, it is because there was an issue in CO and CO_2 readings in columns AI and AJ (headers: “StkCO” and “StkCO2”) of the first worksheet. To solve this issue, the data points should be investigated manually. If there are only one or a few negative or zero readings, those values can be replaced by the interpolated values. However, if the CO and/or CO_2 sensors have recorded many zero or negative values, interpolation is not appropriate and the efficiency calculation for that load is not reliable and should be replaced with “N/A” in the summary table. An example of a summary table is shown in Figure 10. Efficiency value in each load is calculated independently of other loads. Therefore, putting “N/A” for one load does not have any impact on other loads. However, efficiency of the full run cannot be calculated if there is a N/A for one or more loads because that calculation needs efficiency values for all loads.

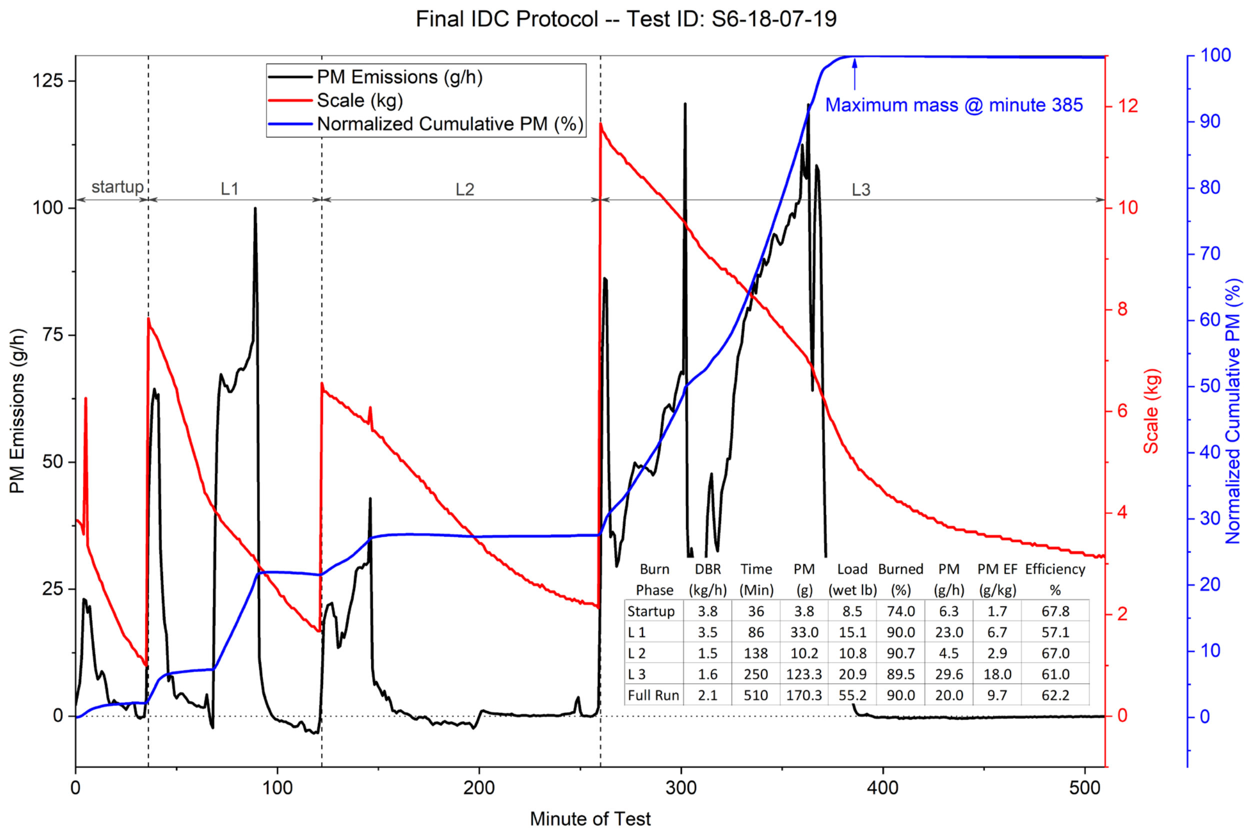
Figure A-10. Summary Table with “N/A” for Efficiency

Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency (%)
Startup	2.4	95	60.6	13.2	78.8	38.2	16.0	49.8
L 1	2.2	130	19.9	14.5	89.6	9.2	4.2	54.3
L 2	2.1	107	27.2	11.2	90.2	15.2	7.3	N/A
L 3	2.2	193	9.9	21.3	88.3	3.1	1.4	59.8
Full Run	2.2	525	117.5	60.1	90.0	13.4	6.1	N/A
Emission rate without Startup (g/h):						8.0		

Step 5: The next step in the procedure is reporting the results. The major method of reporting the results is with charts and plots that are prepared with OriginPro software. Processed data from the Excel spreadsheet are copied into OriginPro software which prepares the needed charts. An example of a data visualization is shown in Figure A-11. Another way of reporting the results is with summary tables. For this purpose, an Excel spreadsheet is created, as shown in Figure A-12. All cells in these tables are linked to the processed data files, so that, if a file is modified, the summary results update automatically.
The latest version of this summary table is uploaded to a filesharing location**.**

Step 6: The last step of the procedure is to upload all new and modified.

Figure A-11. Example of Test Result Visualization



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)	Efficiency %
Startup	3.8	36	3.8	8.5	74.0	6.3	1.7	67.8
L 1	3.5	86	33.0	15.1	90.0	23.0	6.7	57.1
L 2	1.5	138	10.2	10.8	90.7	4.5	2.9	67.0
L 3	1.6	250	123.3	20.9	89.5	29.6	18.0	61.0
Full Run	2.1	510	170.3	55.2	90.0	20.0	9.7	62.2

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Figure A-12. Snapshot of the Summary Tables Spreadsheet

STOVE 1

Test Method	Test ID	Load	Fuel	Burn Rate (kg/h)	Total PM (g)	PM Emission Rat (g/h)
M28 R	S1-17-10-03	High	Douglas fir (crib)	4.20	11.71	5.71
	S1-17-10-06	Medium	Douglas fir (crib)	1.81	12.76	2.91
	S1-17-10-04	Low	Douglas fir (crib)	1.52	23.72	4.33
	S1-17-11-07	Demo Test				
R&D (IDC v1)	S1-18-01-19	Startup	Red Maple (cord)	3.42	6.50	6.61
		High	Red Maple (cord)	4.66	2.90	2.72
		Medium	Red Maple (cord)	2.80	5.90	2.38
		Low	Red Maple (cord)	2.03	118.80	19.91
		Full Run	Red Maple (cord)	2.58	134.30	12.65
ASTM	S1-18-05-31-1	Startup+Hi	Red Maple (cord)	4.92	64.99	21.54
	S1-18-06-04-1	Startup+Hi	Red Maple (cord)	5.03	43.25	14.50
	S1-18-06-04-2	Medium	Red Maple (cord)	1.87	27.10	3.78
	S1-18-05-31-2	Low	Red Maple (cord)	2.06	99.81	17.61
R&D	S1-18-03-01	Startup	Red Maple (cord)	4.90	5.40	7.90
		7# at high	Red Maple (cord)	4.57	11.94	7.54
R&D	S1-18-03-16	Startup	Red Maple (cord)	3.53	4.13	4.34
		7# at high	Red Maple (cord)	4.92	11.71	7.98
		5# at medium	Red Maple (cord)	2.22	19.82	8.50
		Full Run	Red Maple (cord)	3.31	35.66	7.51
R&D	S1-18-05-08	Startup	Red Maple (cord)	3.39	6.41	6.64
		7# 50% at high 50% at low	Red Maple (cord)	4.08	25.62	14.78

Stove List | Temperature | Stove1 | Stove2 | Stove3 | Stove4 | Stove5 | Stove6 | Stove7a | Stove7b | Stove8

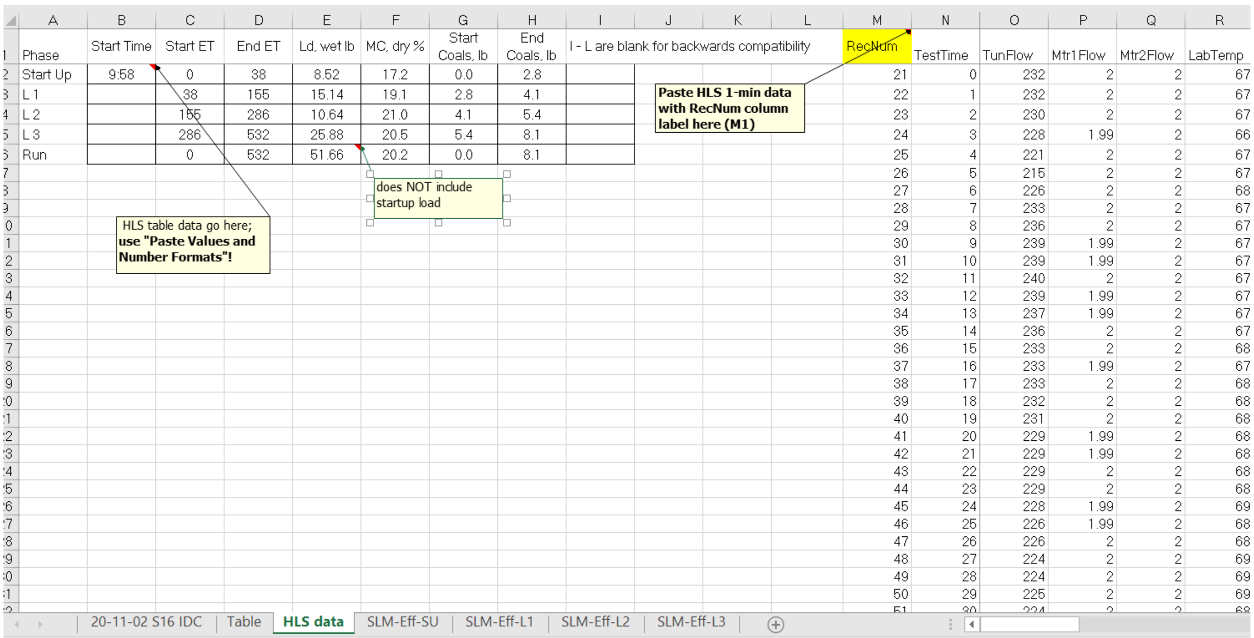
A.3 Data Processing Template and Formulas

Several Excel spreadsheets called Data Processing Templates (DPTs) are prepared in specific formats to facilitate data preparation and calculations. For IDC protocol tests there is one DPT, but for ASTM there are three DPTs, one for each load burn. Although some small details of DPT files are slightly different, they all have the same structure and functions. The IDC DPT is explained in this section.

The IDC DPT spreadsheet has seven worksheets, as shown in Figure A-13. All cells and columns that require some sort of modification or an action during the procedure have comments explaining what and how that should be done. As explained in the File Naming Conventions section, only the name of the first worksheet needs to be changed for a new test. Changing the name of the first worksheet to show the date and stove number is another check point for data consistency control.

The “HLS data” worksheet is designed to contain both the HLS real-time data and fueling table. Data from those two sources are copied and pasted into the designated cells in this worksheet. Figure A-13 shows a snapshot of “HLS data” worksheet after data rows are copied and pasted.

Figure A-13. Example of HLS Real-Time and Fueling Data in the DPT Spreadsheet



Phase	Start Time	Start ET	End ET	Ld, wet lb	MC, dry %	Start Coals, lb	End Coals, lb	I - L are blank for backwards compatibility
Start Up	9:58	0	38	8.52	17.2	0.0	2.8	
L 1		38	155	15.14	19.1	2.8	4.1	
L 2		155	286	10.64	21.0	4.1	5.4	
L 3		286	532	25.88	20.5	5.4	8.1	
Run		0	532	51.66	20.2	0.0	8.1	

RecNum	TestTime	TunFlow	Mtr1 Flow	Mtr2Flow	LabTemp
21	0	232	2	2	67
22	1	232	2	2	67
23	2	230	2	2	67
24	3	228	1.99	2	66
25	4	221	2	2	67
26	5	215	2	2	67
27	6	226	2	2	68
28	7	233	2	2	67
29	8	236	2	2	67
30	9	239	1.99	2	67
31	10	239	1.99	2	67
32	11	240	2	2	67
33	12	239	1.99	2	67
34	13	237	1.99	2	67
35	14	236	2	2	67
36	15	233	2	2	68
37	16	233	1.99	2	67
38	17	233	2	2	68
39	18	232	2	2	68
40	19	231	2	2	68
41	20	229	1.99	2	68
42	21	229	1.99	2	68
43	22	229	2	2	68
44	23	229	2	2	68
45	24	228	1.99	2	69
46	25	226	1.99	2	68
47	26	226	2	2	68
48	27	224	2	2	69
49	28	224	2	2	69
50	29	225	2	2	69
51	30	224	2	2	68

The first worksheet is where most of the calculations and data quality checks occur. Data cells and fueling information cells in this worksheet are linked to the cells in the HLS data. Therefore, they automatically update when new data is copied into the “HLS data” worksheet. Steps 3 and 4 in the Data Preparation Procedure section of this document explain how the consistency between real-time data and fueling data is checked. When the correct start time of a new load is identified, the corresponding row in column T of the first worksheet is marked with the load description. An example is shown in Figure A-14. In this case, the first load (high load) starts at minute 39 of the test. A jump in the scale reading (column Z) confirms that. Therefore, “L1” is entered in column T at the row that is identified to be the start of the new load. A similar procedure is repeated for all loads and to mark the last row of the test data with the word “end.” It is important to put the right abbreviation (“L1”, “L2”, “L3”, and “end”) because the formulas in cells O10-O13 look up these abbreviations to find the cumulative PM emitted during each load burn. This part of the worksheet is shown in Figure 15. As the notes in the snapshot of the spreadsheet show, the looked-up values for cumulative PM emissions are used in columns Q, R, and S calculations which are total PM emitted (grams), emissions rate (g/h), and emission factor (g/kg). Therefore, it is critical to put the right abbreviation in the correct row of column T so those test metrics are calculated correctly.

Figure A-14. Identifying and Marking Rows to Identify Start Time for Phases

	S	T	U	V	W	X	Y	Z	AA	AB	AC
1	PM EF, g/kg dry	start / end of burns marker	TT/ ET	clock time	Tun Flow CFM	Stove AvgT F	Stack Temp F	Scale (kg)	scale loss delta	% charge burned	% charge remaining
2	5.0										
3	1.7										
4	3.2										
5	3.2										
6	3.0	startup	0	9:58	232					0.0	100.0
42			36	10:34	229	312	557	1.41	0.04	63.5	36.5
43			37	10:35	229	320	560	1.36	0.05	64.8	35.2
44			38	10:36	229	328	567	1.27	0.09	67.1	32.9
45		L1	39	10:37	223	336	493	8.14	-6.87	0.0	100.0
46			40	10:38	226	341	482	8.03	0.11	1.6	98.4
47			41	10:39	229	344	452	7.94	0.09	2.9	97.1
48			42	10:40	229	345	457	7.85	0.09	4.2	95.8
49			43	10:41	229	346	506	7.80	0.05	4.9	95.1
50			44	10:42	228	348	560	7.71	0.09	6.2	93.8
51			45	10:43	228	352	594	7.57	0.14	8.3	91.7
52			46	10:44	226	357	645	7.48	0.09	9.6	90.4
53			47	10:45	225	365	665	7.35	0.13	11.5	88.5
54			48	10:46	223	373	674	7.21	0.14	13.5	86.5
55			49	10:47	225	379	682	7.12	0.09	14.8	85.2
56			50	10:48	224	386	706	6.98	0.14	16.9	83.1
57			51	10:49	224	393	723	6.85	0.13	18.7	81.3
58			52	10:50	224	399	737	6.71	0.14	20.8	79.2
59			53	10:51	225	407	739	6.58	0.13	22.7	77.3

Put L1, L2, L3, and End in appropriate cells to update calculation table

EDIT !!! G2-3-4-5

Figure A-15. Lookup Formulas for Obtaining Cumulative PM Emissions During Each Phase

	J	K	L	M	N	O	P	Q	R	S
, %	Start Coals, lb	Start Coals kg	End Coals lb	End Coals, kg	dry fuel burnd kg	DBR, kg/hr	dry load kg	PM emitted, g	g/h	PM EF, g/kg dry
2	0.0	0.00	2.8	1.27	2.03	3.1	3.3	10.1	15.5	5.0
1	2.8	1.27	4.1	1.86	5.18	2.7	5.8	9.0	4.6	1.7
)	4.1	1.86	5.4	2.45	3.40	1.7	4.0	11.0	5.6	3.2
5	5.4	2.45	8.1	3.67	8.52	2.0	9.7	26.9	6.3	8.2
2	0.0	0.00	8.1	3.67	19.13	2.2	22.8	57.0	6.4	3.0
			w/out startup		17.1	2.1	19.5	46.9	**5.7**	2.4
						teom cum pm, g				
					start L1	10.1	0.0	0.0		
					start L2	19.1	0.0	0.0		
					start L3	30.1	3.0	3.0		
om Mark's data					end 90	57.0	0.0	0.0		
timate										
a										

used in col. QRS; enter Put L1, L2, L3, and End in appropriate cells of col. T to read pm (g) values from col. AG

Once the load start times are marked, all calculations are updated automatically. The following formulas are used for the test metrics and parameters.

Burn Duration (m)

Equation A-1

$$t_{burn} = t_{start} - t_{end}$$

Where t_{start} and t_{end} are the start and end minutes of the load burn. Cells E2-E5 in the first worksheet of the DPT spreadsheet are filled with this formula.

Wood Load Mass, Wet (kg)

Equation A-2

$$M_{fWet} = \frac{M_{fWet(lb)}}{2.20462}$$

Where $M_{fWet(lb)}$ is the weight of the wet fuel in pounds that is measured by the test operator and recorded in the fueling data table. Cells G3-G6 are filled with this formula.

Start Coals Mass (kg)

Equation A-3 $$M_{CS} = \frac{M_{CS(lb)}}{2.20462}$$

Where $M_{CS(lb)}$ is the weight of the coal bed at the start of the burn phase in pounds that is measured by the test operator and recorded in the fueling data table. Cells K2-K6 are filled with this formula.

End Coals Mass (kg)

Equation A-4 $$M_{CE} = \frac{M_{CE(lb)}}{2.20462}$$

Where $M_{CE(lb)}$ is the weight of the coal bed at the end of the burn phase in pounds that is measured by the test operator and recorded in the fueling data table. Cells M2-M6 are filled with this formula.

Actual Scale Reading (kg)

Equation A-5 $$M_{fScale} = M_{fWet} + M_{CS}$$

At the start of each load, this parameter is used as a reference value to check the accuracy of scale readings recorded in the real-time data. The scale readings in the fueling data table are read and recorded by the operator, while the real-time data are collected and recorded by sensors and a computer. Therefore, comparing M_{fScale} at the start of each load with the scale reading in the real-time data is another method of data quality control. Cells H2-H6 are filled with this formula.

Dry-Fuel Load (kg)

Equation A-6 $$M_{fDry} = \frac{M_{fWet}}{1+MC_{dry}}$$

Where M_{fWet} is the wet fuel mass and MC_{dry} is the average dry-basis wood moisture content. This parameter is used in the calculation of dry-burn rate. Cells P2-P5 are filled with this formula.

Dry-Fuel Burned (kg)

At the end of a burn phase, coals remain that accumulated over the course of the run. To calculate net mass of the wood burned during each burning phase, the net coal mass should be subtracted from the dry fuel load:

Equation A-7 $$M_{fbDry} = M_{fDry} - (M_{CE} - M_{CS})$$

Cells N2-N5 are filled with this formula.

Dry-Burn Rate (kg/h)

Equation A-8 $$\boldsymbol{DBR = \frac{M_{fbDry}}{t_{burn}/60}}$$

Where t_{burn} is the burn duration in minutes. Cells O2-O6 are filled with this formula.

PM Emitted (g)

$PM_{Cumulative}$: Cumulative mass of PM emissions at the end of each load is read directly from the corresponding row in column AG, as explained before (see Figure 15). Cells O10-O13 contain the $PM_{Cumulative}$ at the end of each burn phase, and cells O2-O6 contain $PM_{Cumulative}$ during each burn phase by subtracting two consecutive $PM_{Cumulative}$ values in cells O2-O6.

PM Rate (g/h)

Equation A-9 $$\boldsymbol{PM_{Rate} = \frac{PM_{Cumulative}}{t_{burn}/60}}$$

PM emission rate for each burn phase is calculated by dividing $PM_{Cumulative}$ in that phase by its duration. Cells R2-R6 are filled with this formula.

PM Emission Factor (g/kg)

Equation A-10 $$\boldsymbol{PM_{Factor} = \frac{PM_{Cumulative}}{M_{fbDry}}}$$

PM emission factor for each burn phase is calculated by dividing $PM_{Cumulative}$ in that phase by the mass of dry fuel burned duration that phase. Cells S2-S6 are filled with this formula.

The SLM efficiency calculations are based on the formulas and relationships presented in the Canadian standard CSA B415.1-10.

A.4 File Naming Conventions

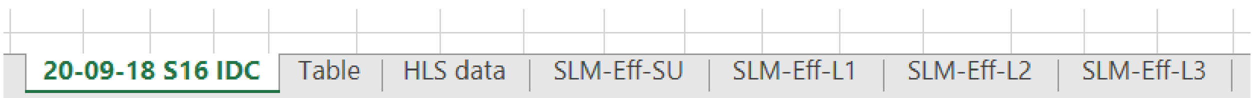
A.4.1TEOM Data File

The convention for naming the prepared TEOM data file is “*[yy-mm-dd] Stove [N] Teom PM.xlsx*” where *yy-mm-dd* is the test data and *N* is the stove number. Therefore, each TEOM data file has a unique file name that shows test date and stove number. For instance, *20-09-20 Stove 16 Teom PM.xlsx* is the name of TEOM data for the test on Stove 16 performed on September 20, 2020.

A.4.2 IDC Processed Data File

The convention for naming the IDC process data files is "*yy-mm-dd S[N] Teom PM and HLS data_IDC.xlsx*", where *yy-mm-dd* is the test data and *N* is the stove number. For instance, *20-09-18 S16 Teom PM and HLS data_IDC.xlsx* is the name of the IDC processed data file for the test on Stove 16 performed on September 18, 2020.

Inside the spreadsheet, only the name of the first worksheet needs to be changed for every new test. The naming convention is "*yy-mm-dd S[N] IDC*" where *yy-mm-dd* is the test data and *N* is the stove number. For the example data file, the first worksheet is "20-09-18 S16 IDC." The names of all the other worksheets remain unchanged.



A.4.3 ASTM Processed Data File

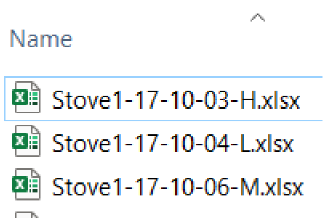
Unlike IDC tests, data for each burn load of an ASTM 3053-17 test are processed in separate files. Therefore, there are three variants of the naming convention for ASTM processed data files. The general file name structure is "*[yy-mm-dd] S[N] Teom PM and HLS data_ASTM [Load_Type].xlsx*" where *yy-mm-dd* is the test data, *N* is the stove number, and *Load_Type* is either "Startup-Hi," "Med," or "Low" depending on the test load.

For instance, "18-05-31 S1 Teom PM and HLS data_ASTM Startup-Hi.xlsx" is the file name for an ASTM startup+high burn test performed on stove 1 on May 31, 2018. And "19-02-05 S6 Teom PM and HLS data_ASTM Low.xlsx" is the name for the ASTM medium-burn test performed on stove 6 on February 5, 2019. Similarly, "19-02-25 S7 Teom PM and HLS data_ASTM Low.xlsx" is the file name for the ASTM low-burn test performed on stove 7 on February 25, 2019.

The naming convention for the first worksheet inside each spreadsheet is similar to the IDC naming convention. The only difference is that, instead of the word "IDC" at the end of the name, "*ASTM [Load_Type]*" is used. For instance, the first worksheet of the processed spreadsheet of the ASTM low-burn test in the previous example is "19-02-25 S7 ASTM Low."

A.4.4 M28R Processed Data File

The naming convention for M28R processed data file is "*Stove[N]-[yy-mm-dd]-[Load_Type].xlsx,*" where *N* is the stove number, *yy-mm-dd* is the test date, and *Load_Type* is either H, L, or M, which stands for a high, low, or medium burn. In the following snapshot, three M28R processed data files are shown: a high-load test on October 3, 2017, a low-load test on October 4, 2017, and a medium-load test on October 6, 2017, all on stove 1.



Endnotes

1 beReal—Advanced Testing Methods for Better Real Life Performance of Biomass Heating Appliances: http://www.bereal-project.eu/

2 ASTM, International, formerly known as the American Society for Testing and Materials.

3 ASTM International, formerly known as American Society for Testing and Materials, is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services.

4 Note that the values in parentheses in the “all stoves” and “medium firebox” high air cells are the average for that category if the outlier stove 7 high air result is excluded.

5 Note that further volatilization loss can occur during post-run filter equilibration.

6 Where more than one run was included the category, these metrics are the averages of the values for those runs.

7 Note that “stack temperature” is the temperature measured by a probe located on the surface of the exhaust stack and “stove temperature” is the average of the measurements of five probes on the stove surface (top, bottom, back, and two sides).

8 Calculated as (Temperature for High Run—Average of Temperatures for High-Low Runs)/Temperature for High Run.

9 Calculated as (PM Emitted in High Run—Average of PM Emitted in High-Low Runs)/PM Emitted in High Run.

10 Relative Standard Deviation is calculated as the mean divided by the sample standard deviation.

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