Final Report

Wood Species Testing Using Crib and Cordwood in a Pre-NSPS Residential Wood Heater

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Disclaimer

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Acknowledgement

This project was carried out by SC&A under the direction of EPA, with all testing and data handling performed by Hearthlab Solutions, under subcontract to SC&A. An experimental design team consisting of personnel from the EPA Office of Air Quality and Standards, the Northeast States for Coordinated Air Use Management (NESCAUM), Brookhaven National Laboratory, SC&A and Hearthlab Solutions convened weekly to discuss testing, review data and suggest future test runs. The participation of all these organizations ensured a smooth and logical progression to the testing.

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1. Introduction

Numerous stakeholders including industry, EPA, state and local agencies generally agree that a revised testing approach is needed to better represent "real-world" emissions from residential wood heaters. It is thought that using a fuel burned in homes ("cordwood") rather than current certification test methods using dimensional lumber ("crib wood") will improve the correlation of laboratory performance when compared to field performance. The EPA has identified a process for informing the development of an EPA reference test method that measures particulate matter emissions from the combustion of cordwood fuel.[1] This cordwood-based test method may be required in the future for certification of new residential wood heaters.

Historically, there has been a scarcity of data characterizing emissions performance of wood stoves while burning cordwood. Basic research into many variables related to cordwood (species, size, loading density, etc.) is needed prior to the adoption of a measurement approach as federal reference method. This study is a first step in informing EPA on these variables and is focused primarily on one; wood species. The Vermont Castings Vigilant™ parlor stove, which pre-dates 1988 EPA emissions regulations on residential wood heaters, was chosen so that burn characteristics and emissions from various wood species could be evaluated absent any sophisticated emissions reduction technology. The objective was that the 'raw' emissions characteristics, and differences between species, if any, be identified.

Five wood species were chosen for this study: Red Oak, Ash, Red Maple, White Birch, and White Pine. The study included burning these species in both "crib" form (similar to the dimensional lumber used in current EPA Method 28R) and as split cordwood. Crib tests provided a comparative link to Method 28's methodology, including enforced fuel spacing and precise dimensions, versus the more random loading which occurs when burning cordwood. For this project, Douglas fir was included during the crib testing only, importantly relating its status as the currently required standard fuel to the other species that were the subject of this study. Douglas fir cordwood was not tested at this time due to various restrictions on transporting wood.

In total, 39 crib tests and 14 tests using cordwood fuel were performed. Particulate matter (PM) and carbon monoxide (CO) emissions were measured as well as burn rates, stove temperatures and stack gas concentrations. In addition, real-time data was collected from other instrumentation at 1 minute intervals.

All end-of-test results, real-time data and graphical representations (a preliminary data analysis) were consolidated into a single workbook of spreadsheets; the primary product of this work effort. The data is presented in a format that allows relatively easy analysis by an interested party. This report provides the background procedures, methods and structure of the study and is meant to supplement the spreadsheet workbook of results.[2]

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[1] EPA's March 2016 discussion paper entitled "Process for Developing Improved Cordwood Test Methods for Wood Heaters is available at https://www.epa.gov/sites/production/files/2016-03/documents/discussion_paper_-_process_for_dev_imp_cwtm_030916.pdf.

[2] The spreadsheet workbook of results is available in EPA's docket for the Process for Developing Improved Cordwood Test Methods for Wood Heaters: https://www.regulations.gov/docket?D=EPA-HQ-OAR-2016-0130.

2. Project Management

Technical direction was provided to prime contractor SC&A by the EPA Work Assignment Contracting Officer's Representative (WACOR). Consultation on quality assurance (QA) was provided to the WACOR by the EPA/OAQPS QA Officer, and project team members of the EPA's Measurement Technology Group. SC&A provided project management and direction to subcontractor Hearthlab Solutions. Hearthlab Solutions performed all the testing in this study at its solid fuel laboratory in Randolph, Vermont.

An advisory group was convened on a weekly conference call to discuss the accumulated data set, identify future data needs and coordinate planning for subsequent test runs. This group consisted of personnel from SC&A, EPA, NESCAUM, Brookhaven National laboratory and Hearthlab Solutions. The project management experience, technical expertise, and organizational skills of this group provided the foundation for a smooth, logical progression to this data driven effort.

3. Experimental Design

During each weekly meeting, prior to commencement of testing, the goals of the project were decided based on the total number of tests available and EPA's data objectives. The project goals were as follows:

- Characterize "baseline" emissions burning Douglas fir cribs at high and low air settings;
- Characterize emissions burning different fuel species using the same crib configuration and air settings as those used for Douglas fir; and
- Characterize emissions burning cordwood fuel of the same mix of species.

Five wood species were chosen based on wide availability. These were Red Oak, Red Maple, White Birch, Ash and White Pine. Logs were obtained of each species and in the case of all but the Red Oak, dimensional lumber was milled into crib dimensions (nominal 2x4 and 4x4) and the same tree was used to cut and split enough of each species for cordwood testing. In the case of Red Oak, the source of the crib wood and cordwood were different trees from different parts of Vermont.

Wood was conditioned under indoor ambient conditions until it reached approximately 21% moisture content (dry basis). Once conditioned, the wood was placed in a humidity controlled room for the duration of the project. Moisture content, assumed to be an important variable in emissions from burning wood, was controlled and kept close to 20% for all test runs. The data provide actual measured moisture content as well as the variation present during testing.

The specific gravity of each of the wood species (including Douglas fir) was measured and recorded. The volumes of short blocks of the 4x4 dimensional lumber were measured and recorded (four for each species) with the blocks then dried to constant weight at 212 degrees Fahrenheit (F). Once a constant weight was achieved, the mass of each block was measured and the specific gravity calculated. Reported in the final spreadsheets are the specific gravities for each block and averages for each species on a dry weight basis.

3.1 Crib Wood Testing

Thirty-nine crib tests were conducted and generally followed EPA Method 28[3] although some deviation from the method was needed to accommodate the Vigilant stove as it was not designed for operation according to such a protocol. As a result, the fuel loading density was roughly half that which Method 28 requires, and fuel length was significantly shorter at 15" rather than the required 20". (However, one test was conducted burning 20" fir on 9/10/16.) Two 2x4s and two 4x4's made up the crib loads and the dimensions were identical for all species. The approach was designed to match fuel load configuration (volume) between species rather than targeting a repeated load mass. Appendix A describes and illustrates the procedure.

Nine Douglas fir tests were performed, five at the low air setting and four at the high air setting. Relative to the other tested species, extra tests were performed with Douglas fir in order to form a more robust baseline. For the other tested species, the test plan included running at least three tests at the high setting and two tests at the low setting. Medium settings were included for Red Oak (three tests) and an "Extra Low" setting was used for a single White Birch test. One additional Red Maple test run was conducted at the high setting. These additional tests were included to help "fill in" what were perceived by the experimental design group as potential data gaps.

3.2 Cordwood Testing

Fourteen tests runs were conducted using cordwood fuel of four species: Red Oak, Red Maple, White Birch and Ash. Douglas fir cordwood was not available for this study and it was decided by the experimental design group to abandon White Pine due to its physical and combustion properties. Very low density puts White Pine very low on the specific gravity range, consistent coalbed formation is problematic (or impossible) and, while emissions performance did not fall outside the range of other species, these difficulties with White Pine led to the conclusion it should not be considered as a test fuel for this study, going forward.

The experimental design group decided that a constant "batch volume" should be used to compare crib to cordwood results to minimize air flow and combustion differences. A fixed rectangular form/cage was therefore used to assemble a volume of cordwood equivalent to the volume of the crib batch (two 2x4, two 4x4, spaced and 15" length). The form had a rectangular volume of 10" x 15" x 8" tall. A general rule was used that required two smaller cordwood pieces (approximating 2x4s) and two larger cordwood pieces (approximating 4x4s), with any remaining volume filled in by one or two additional pieces of cordwood. The resulting load was considered the cordwood equivalent of the crib load. Each load was tied together with twine to allow loading of the cordwood batch all at once and to ensure placement very close to its "as assembled" configuration. A picture of each cordwood batch as assembled is included in the workbook of consolidated data spreadsheets.[4]

The Vigilant stove includes a row of primary air holes near coalbed level in the rear firebox wall. During crib testing, this row of holes was not blocked because the crib spacers enforce a 0.75-inch gap (i.e. the wood cannot touch the wall). These air holes could potentially be blocked when

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[3] EPA Method 28 is available at https://www.epa.gov/emc/method-28-certification-and-auditing-wood-heaters.

[4] Available at https://www.regulations.gov/docket?D=EPA-HQ-OAR-2016-0130.

loading cordwood. The decision was made to enforce spacing for the cordwood by adding two 0.75" vertical rails to the rear wall so that the same spacing would be enforced as with crib wood.

The cordwood testing procedure followed that described in Appendix A of this report, except that cordwood was used. Pre-burn fuel was comprised of smaller pieces and/or chunks of wood (roughly 2x4 equivalent) of the same species as the test load. Stove operation, coalbed size and air settings were identical to those during crib testing.

The test plan included running at least two high fire tests and one low fire test with each of the four species (Red Oak, Red Maple, White Birch and Ash). These data were generated along with the addition of one test on the high setting for both Red Oak and Red Maple.

4. Sampling Procedure and Equipment

This section discusses the measured pollutant, the sampling procedure used for pollutant measurement, the fueling and operational protocol used for the subject wood heater and the type of wood heater used for this study.

4.1 Sampling Procedure

The primary sampled pollutant for this work was particulate matter 10 micrometers or less in diameter (PM_{10}), denoted simply PM herein. EPA Method 5g[5] (consistent with ASTM E2515[6]), the current EPA reference method for PM measurement in solid fuel burning residential heaters, was used. The method employs a dilution tunnel of specific dimensions and dual-train sampling (through 47mm diameter filter media) with post-test gravimetric analysis. The method specifies operation of the sampling system, sampling procedures, calibration requirements and post-test analysis. Deviations from the prescribed sampling method during this study were as follows:

- The dilution tunnel dimensions were consistent with ASTM 2515, except that the horizontal tunnel section was of 12" diameter. The sampling section (vertical) was six inches in diameter.

- Sampling employed 47mm polytetrafluoroethylene (PTFE) coated filters, rather than the Method 5G-specific glass fiber filters.

- Constant dilution tunnel and sample flows were carefully maintained in an effort to reduce operational variation allowed by ASTM 2515, with the goal being to ensure higher precision for the nature of the data outputs required.

Parallel measurements of PM concentration were made in the dilution tunnel by NESCAUM personnel using both a tapered element oscillating microbalance (TEOM) and a Thermo Fisher personal DataRAM (pDR). NESCAUM's TEOM and pDR results are not included in this report. In an effort to correlate TEOM and EPA dual train filter measurements, the face velocities of each of the filtration media were matched. This required the EPA dual trains to run at faster flow rates than would have normally been chosen, given the relatively high emissions of the Vigilant

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[5] Method 5G is available at https://www.epa.gov/emc/method-5g-particulate-matter-wood-heaters-dilution-tunnel
[6] ASTM E2515 is available at https://www.astm.org/Standards/E2515.htm

stove. As a result, filter sets were changed more often because of filter overloading (pressure drop, loss of sample flow), as recorded in the data provided in the workbook spreadsheets. Discussion of the potential bias this builds into the results is provided in the *Limitations* section.

Of secondary interest were stack gas analysis for Carbon Dioxide (CO_2) and carbon monoxide (CO). Measurements were made in the flue of the subject appliance in accordance with CSA B415.1-10.[7] Measurements of CO and CO_2 provided measures of CO emissions, combustion efficiency, overall efficiency and air-to-fuel ratio. While these data were secondary to the primary PM data, they are useful in diagnosing run-to-run variability and examining how different wood species and/or loading configurations react when burned. Such measurements may also be useful in diagnosing stove variability between labs and future efforts to understand combustion efficiency as related to moisture variability in cordwood fuel.

4.2 Fueling and Operational Protocol

EPA Method 28R[8] (an update to Method 28) is the required fueling and operational protocol for use with residential wood heaters. By necessity and as explained earlier Method 28R was used for this project's protocol, though specific exceptions were made to this protocol to facilitate the use of the Vigilant stove. Much of the variation was directly related to certain objectives of the work (i.e. to focus on study variables including species, air settings and cordwood vs. crib fuel) and some modifications were necessary to accommodate the use of a pre-NSPS stove. Variations from Method 28 included:

- Wood species and load configuration were different from Method 28 requirements (as these were major planned variables for the study);
- Fuel length was shorter than what Method 28 requires;
- Wood loading density varied from that required by Method 28;
- Stove delta T requirements were waived (this is a metric that validates tests for certification purposes); and
- Chimney was of proper height (15 feet) but was a single wall black pipe rather than an insulated chimney.

Sections 3.1 and 3.2 discuss the crib and cordwood testing performed and how the loads of each were prepared. Appendix A of this report contains a description of the fueling and operational protocol used in this study, applicable to both the crib and cordwood loads.

[7] Canadian Standard Association (CSA) B415.1-10 is available at http://shop.csa.ca/en/canada/fuels-and-appliances/b4151-10-r2015/invt/27013322010.

[8] EPA Method 28R, an update on EPA Method 28, is available in the current NSPS for wood heaters: https://www.federalregister.gov/documents/2015/03/16/2015-03733/standards-of-performance-for-new-residential-wood-heaters-new-residential-hydronic-heaters-and#page-13728.

4.3 Subject Wood Heater

A Vermont Castings Vigilant™ parlor stove was the subject wood heater used in this study. The Vigilant pre-dates emissions regulations and therefore lacks sophisticated emissions control technology. The rationale for choosing this wood heater was to isolate the species variable (regarding emissions) independently of control technology. The measurement of uncontrolled emissions was desired, from burning different species using both dimensional cribs and cordwood.

The Vigilant is an entirely cast-iron stove constructed of cemented and bolted together stove plates. The unit was obtained second hand and, because of its age and unknown history, the stove was rebuilt professionally prior to testing to ensure operational reliability and combustion performance consistent with the original intended stove design.

Of note is that the Vigilant stove is not an entirely technology-free stove. The stove is operated in an updraft mode primarily for startup but also includes a bypass damper which, when activated, directs combustion gasses downward through a passage in the bottom rear wall of the firebox. The technology built into this stove is primarily related to heating efficiency and not emissions control. The stove was operated in the downdraft mode for all tests in this study and therefore the difference (positive or negative) of updraft versus downdraft mode are unknown; this operational variable was not the subject of this study. By design, the Vigilant stove has a thermostatically-adjusted primary air control. This control was bypassed for all tests to remove the potential for variation in primary air setting within and between test runs.

As noted in previous sections, because the Vigilant was not designed with respect to Method 28 fueling requirements, it could not be expected to perform within the precise parameters of the method, especially with differing fuel species. In fact, the lowest setting of the stove was soon determined "too low" as continuous combustion at that burn rate was unsustainable and physical adjustments to the test settings were made. Four different test settings were used in the crib and cordwood tests. The associated fixed air setting for each of these were as follows:

- High – air shutter propped fully open;
- Medium – three one-inch holes in the closed air shutter;
- Low – two one-inch holes drilled in the closed air shutter; and
- Extra Low – a single one-inch hole in the closed air shutter.

5. Quality Assurance

A Quality Assurance Project Plan (QAPP) was developed specifically for this project and met EPA's Category II requirements. The QAPP was based on the guidance and requirements for quality assurance project plans, as specified by the EPA, and by the quality management plan (QMP) of EPA's Office of Air Quality Planning and Standards (OAQPS). The QAPP described project organization, responsibilities, laboratory procedures, documentation and reporting. Approval signatures on the final QAPP were received from EPA in December 2016. All procedures, sampling, analysis and data handling in this study adhered to the QAPP's requirements.

6. Results

The entirety of the data generated by this study was consolidated into an Excel™ spreadsheet workbook of results, which is the primary work product of the project. The spreadsheet workbook is available online.[9] Real-time measurements of test parameters (e.g., dilution tunnel flow, sample volumes) and performance measurements (e.g., temperatures, gas concentrations, scale weight) are included as separate sheets for each test run. Test results were also consolidated in a single summary spreadsheet within the overall workbook. For each test run, the summary spreadsheet includes the following data:

- Date of test run;
- Fuel (wood species and whether crib or cordwood);
- Test setting (high, medium, low and extra low air settings on the Vigilant);
- Test time (elapsed minutes);
- PM (grams/hour);
- PM (grams/kilogram wood burned);
- CO (grams/kilogram wood burned);
- Burn rate (dry kilogram wood/hour);
- Train 1 time 0 front filter catch (mg PM);
- Train 2 time 0 front filter catch (mg PM);
- Final PM precision (%);
- Notes (from each test run);
- Wet Wood Loaded (kg);
- Average moisture content (%);
- Dry wood loaded (kg);
- Dry wood burned (kg);
- Fuel consumed (% of wood burned, based on loaded wet wood).

Appendix B of this report shows a table summarizing the results of all test runs, listed chronologically.

Data is also presented graphically within the spreadsheet workbook to facilitate review and illustrate possible, although not confirmed, trend lines. It should be noted that the primary goal of this project was generation of the data set; further analysis of the data was not within the scope of this project.

Sample graphs from the spreadsheet workbook of results are provided on the following pages to illustrate various presentations of the data that were made. Figure 1 shows PM Factor (grams of PM per kilogram of wood burned) versus Burn Rate (kilograms wood burned per hour) for the 6 different crib species tested: Douglas fir, Red Maple, Red Oak, White Birch and White Pine. Figure 2 also presents results based on the crib wood tests, but for PM emissions rate (grams of PM per hour) instead of PM Factor. Finally, Figure 3 presents cordwood results for Red Oak, showing PM Factor (g/kg) versus burn rate (g/hr) based not only on the Red Oak cordwood results, but also based on Red Oak crib results and Douglas fir crib results, for comparison. A

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[9] The spreadsheet workbook of results is available in EPA's docket for the Process for Developing Improved Cordwood Test Methods for Wood Heaters: https://www.regulations.gov/docket?D=EPA-HQ-OAR-2016-0130.

trend line was fitted to the data in each graph for illustrative purposes, although the limitations of the data set should be considered, and additional analyses should be conducted, prior to drawing definite conclusions. The complete data set is available in the spreadsheet workbook for further analysis.

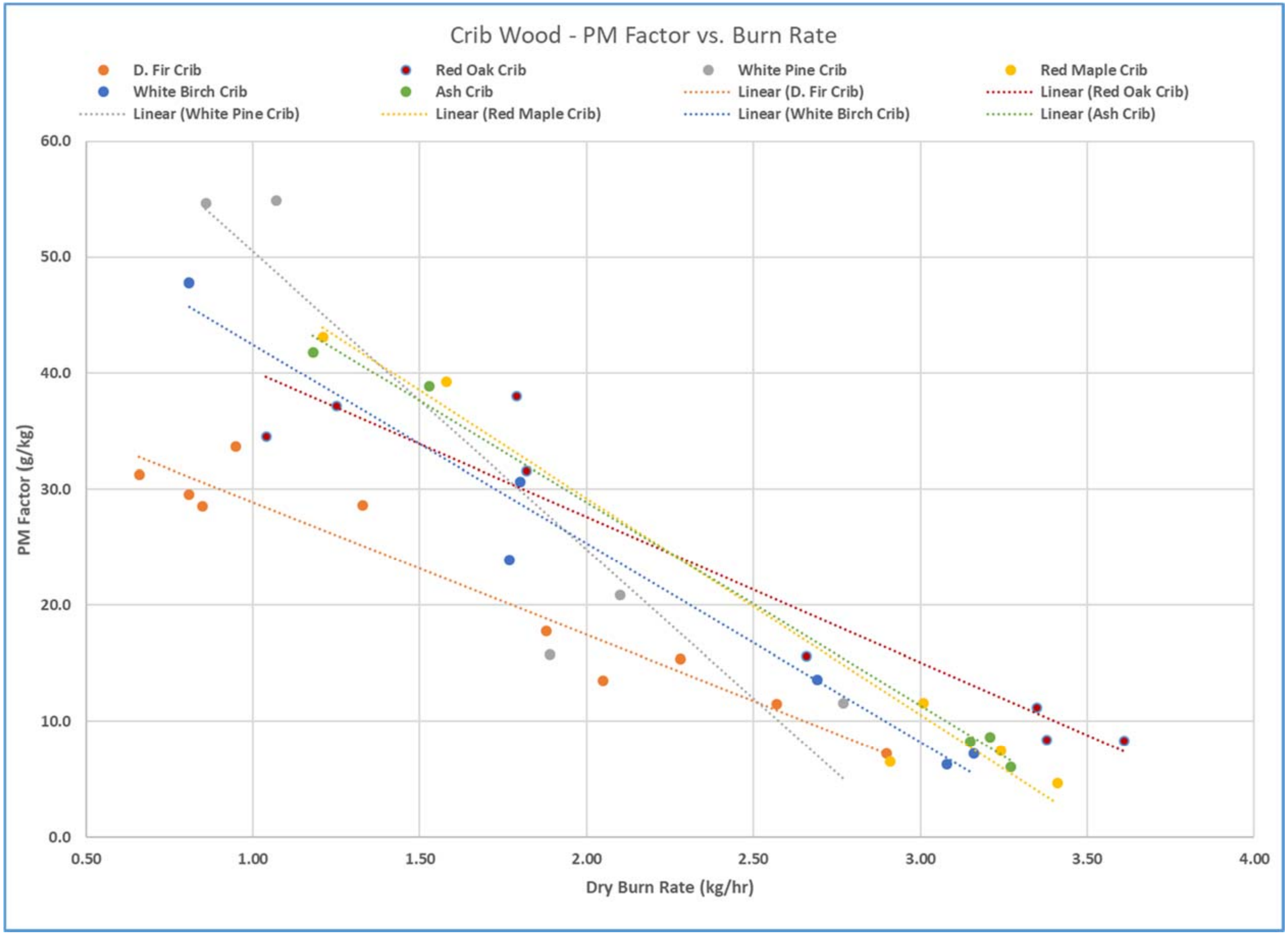

Figure 1. PM Factor (g/kg) versus Burn Rate (kg/hr) for the Crib Wood Species tested

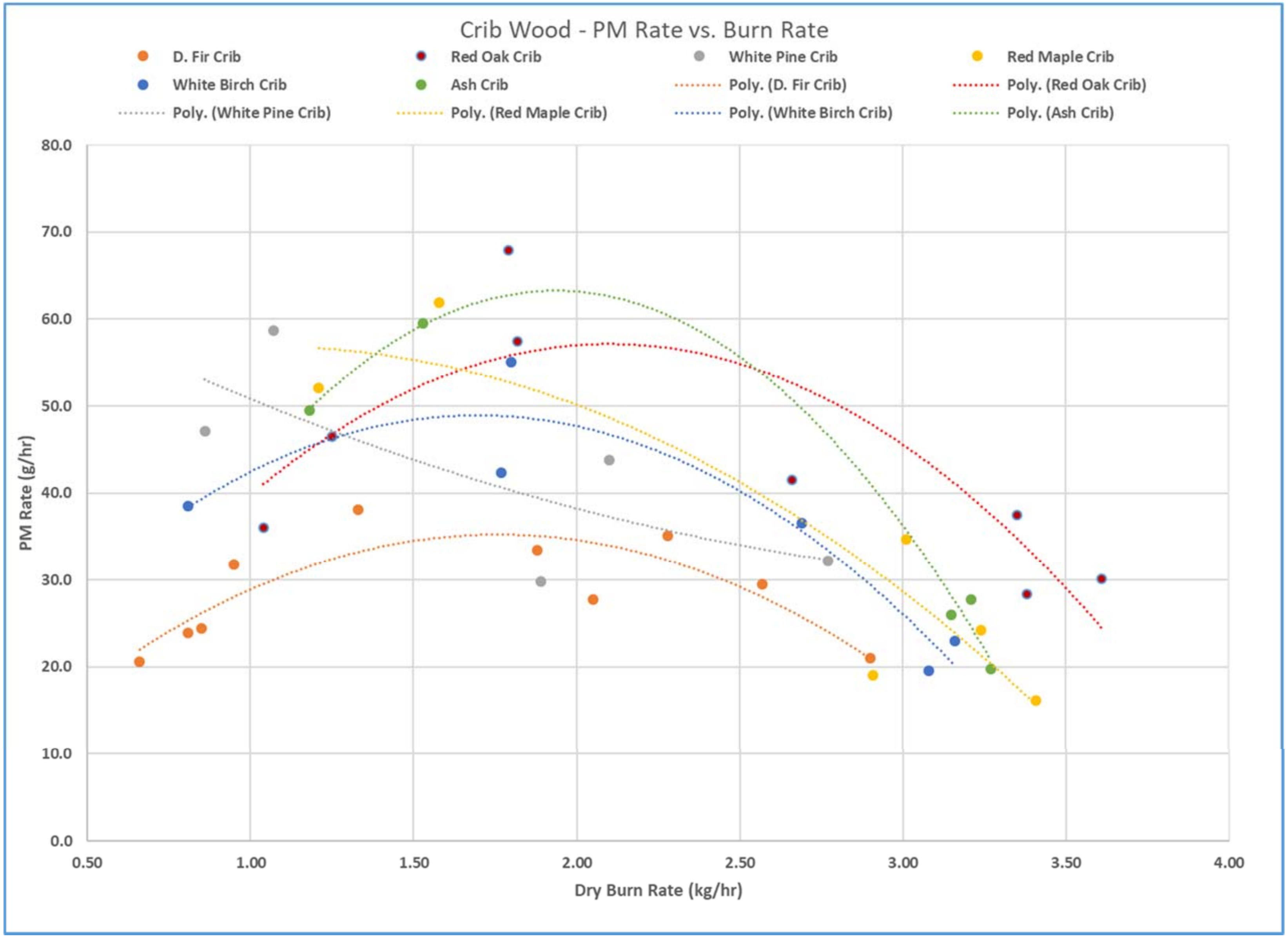

Figure 2. PM Rate (g/hr) versus Burn Rate (kg/hr) for the Crib Wood Species tested

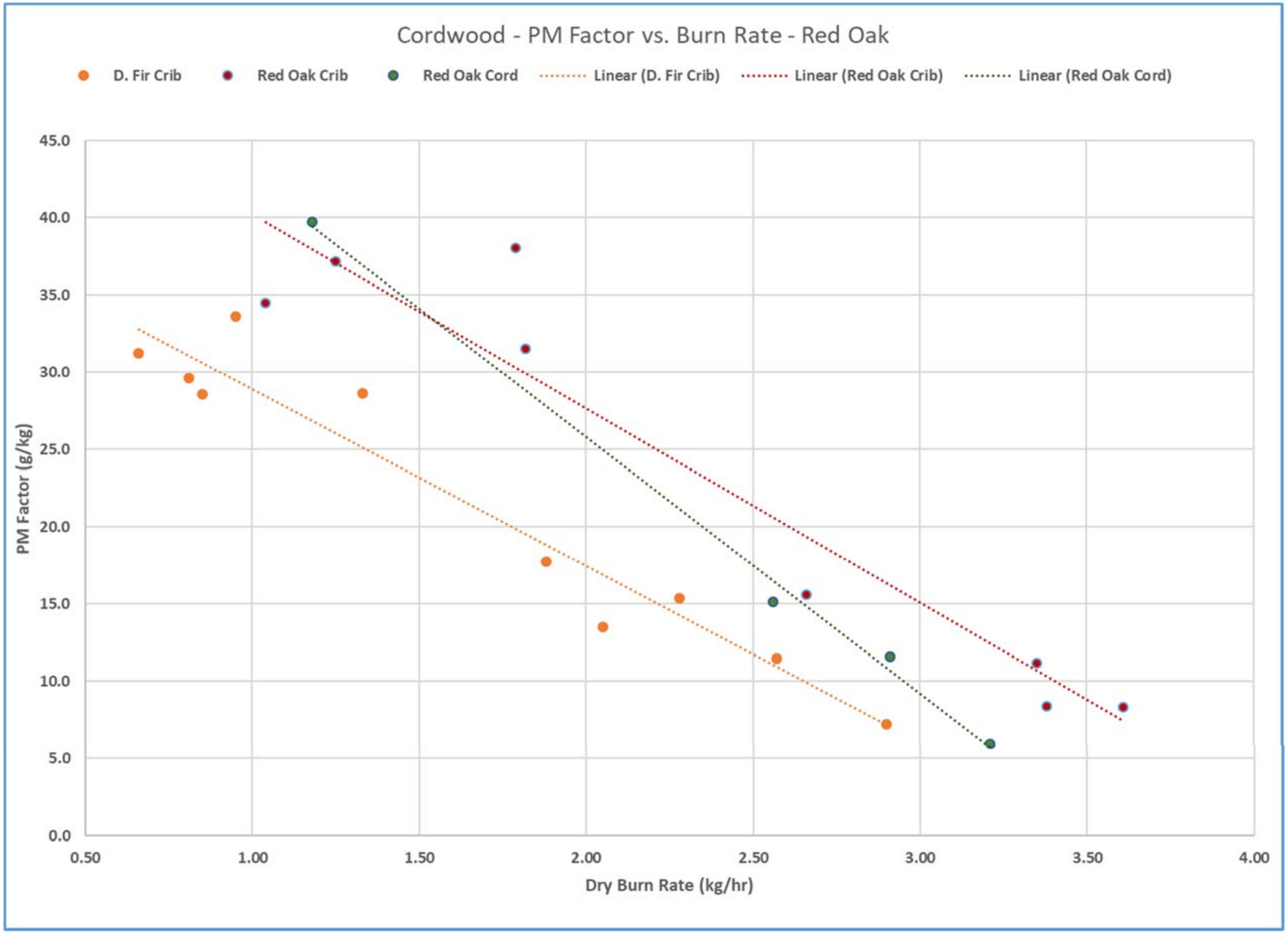

Figure 3. PM Factor (g/kg) versus Burn Rate (kg/hr) for Red Oak Cordwood with Comparison to Crib

7. Conclusions

A data set characterizing the emissions of the Vigilant stove burning six species of crib wood fuel and four species of cordwood fuel has been produced, based upon data from 39 crib test runs and 14 cordwood test runs. To the extent possible, the species variable was isolated in an attempt to (a) provide a focused look at how fuel species affects PM emissions and burn rate, and (b) provide a comparison between crib wood and cordwood fuel within each species.

The final data set is provided in the form of a consolidated workbook of spreadsheets, which includes all real-time data, notes, final emissions results and some preliminary analysis in the form of characteristic graphs of PM and CO emissions versus burn rate. Presentations of data in graphical form during the study helped inform the study directionally. These presentations also illustrate possible trends/phenomena that, while not the basis for firm conclusions, merit further examination and analysis.

For example, the graphed data (a portion of which is shown in Section 6 of this report) suggests to some in the experimental design group that differences in PM emissions and burn rates are greater between species than between crib wood and cordwood in the same species. This preliminary conclusion requires statistical analysis of the provided data for confirmation and is outside the scope of this project. Additional data to supplement this initial data set would also be useful if that conclusion were necessary to draw with greater certainty. In general, much additional analysis is possible, including statistical validation and correlation to determine the impact of different species on PM emissions and burn rates, as well as the impact of crib wood versus cordwood on PM emissions and burn rates. The consolidated workbook of spreadsheet results provides a platform for these analyses to be performed.

8. Variability, Precision and Potential Limitations

The very nature of emissions measurements involves variability in sampling, analytical and combustion processes. Burning wood in a woodstove adds expected variability to the above list of variables, adding greater uncertainty to the results. To the extent possible, the experimental design limited reasonable variables through controlling parameters such as pre-test conditions, consistent wood moisture and consistent stove operation. Batch combustion of wood includes many variables that may not be controlled such as settling of pieces during the combustion cycle, the way air flows around one set of logs versus another, spacing between the fuel pieces, and sap pockets within the fuel, to name a few. Such variables cannot be controlled and add variability to the overall measurement. One possibility is that a larger data set would help qualify data, given that the natural variability of cordwood combustion adds variability to the measured data.

One objective criterion to qualify results is dual train precision. An internal limit of 3% (deviation from the mean) was imposed which, if exceeded, triggered a review of procedures, calibrations, and raw data. In general, test data was considered valid (at least in early stages) if calibrations and test parameters were within the operational limits determined by the experimental design group and/or dictated by the applicable test methods.

Dual train precision was very good throughout testing with about 1% being typical and few exceptions above 3%. Noted earlier, sample trains where often swapped out during testing (as many as four dual trains were used on individual tests) due to heavy filter loading and associated loss of adequate sample flow. Each filter set change implies that filters were exposed to a high vacuum (15 to 20 in Hg) during use. It is unknown how this factor might bias results and should be considered, for example, when comparing a test without filter changes to a test with several filter set changes.

The last three tests of this study sought to demonstrate the potential biases that may be present within this data set. Sample flows for the vast majority of tests were nominally 2.7 liters per minute (lpm). The last three tests in this study included running the two sample trains at different rates, one at nominally 2.7 lpm and one at nominally 1.2 lpm. This implies that one train operated at a higher vacuum for at least a portion of the test. Actual measured maximum sample vacuums (the differential pressure across the filter media) were between zero and five inches Hg for the slower sample train and between 12 and 20 inches Hg for the faster running sample train. As hypothesized, the faster flowing train showed lower calculated PM emissions for all three tests; potentially a function of higher vacuum (including a post-test leak check and subsequent burst of flow) or the higher sample flow itself. Further evidence of a difference is seen in the calculated dual train precision. PM precision was very good throughout testing; however, the last three tests had precisions of 6.5 to 7.8% and is considered very poor for testing of this type. Identical calibrations, leak checks and post test procedures were used so the differences in PM precision for these last three tests are believed to be indicative of a bias within this data. Other biases may be present related to the relative contribution of background PM (very small) or sample processing errors associated with handing several sample trains for a single test run, for instance.

Appreciable moisture on filters was not a problem during this study however this was determined only by post-test desiccation. Typically, when moisture accumulates appreciably on filter media, a resulting sudden pressure drop (and flow loss) is witnessed. This did not happen to a degree that indicated a problem. As a final qualitative note, particulate catch was usually very aromatic and sticky in nature, particularly on low air setting test runs. This is indication of a high VOC portion and perhaps should be considered when considering sample loss due to high vacuum, high filter flow rates or other unidentified effects.

The potential bias demonstrated above is not conclusive nor quantified. It should be noted that cleaner burning devices will have much less filter loading. Any bias that may be present in this particular data set may be unique to this data set (and wood heater) and likely does not directly apply, at least to the same degree, to cleaner wood heaters which emit less PM.

Appendix A: Vigilant Testing Protocol

Vigilant Test Plan

This test will have one test period. Prior to this test period a bed of coals will be established through a pre-burn. A crib of wood will be consumed during the test period. (Note: this protocol may also be used for cordwood, with adjustment to wood load description.)

Fuel

Kindling: 5 lbs of approximately 1" cross section and 12" length, any dry scrap wood.

Pre-burn fuel: 8" lengths of 2x4, enough pieces to constitute approximately 110% of the main fuel load mass. Consider using the least expensive and most abundant 2x4's in the fuel supply. This amount of wood may appear like a lot but it is needed to achieve a consistent coal bed.

Test Fuel: 2x4s and 4x4s spaced according to EPA Method28. Spacers should be the same species as the test fuel. The loading density should be less than 7lb/ft^3, consisting of two 2X4's and two 4X4's[10]. Note: the test load pictured below is 15" in length (20" would be required by Method 28).

Procedure

-Clean all ash from the sand at the bottom of the stove, then add more sand as necessary to maintain a 1-inch thickness layer. (Note: the stove's manual does specify keeping the sand layer at 1.5". However, there are groves at the bottom of the stove that would be covered if the sand layer were greater than 1", making ash removal difficult and requiring new sand to be added each run, which would cause some inconsistency run-to-run. An inch or less of sand allows for easy ash removal and less chance of having to add more sand for each test run.)

-Ensure secondary air control ("teardrop valve") is set to 50% open.

-Select two 2x4s and two 4x4s and record moisture content. Take four measurements at the center, and an inch from a side at depths of both 1/4"and 3/4"

-Record the weight and moisture of each piece individually.

-Nail 4 spacers to each piece and build the crib fuel charge as pictured below. Record the weight.

-Multiply the total loading test charge mass by 1.1, and prepare as many 8" 2x4 sections as are necessary to most closely approximate this number.

-Crumple sufficient pieces of newspaper to evenly cover the bottom surface of the stove. Record weight of paper.

-Cover the bottom surface with crumpled newspaper and begin to stack kindling in a crisscross

[10] Deviation from EPA Method 28

fashion with spacing of approximately 1" between pieces as shown in Figure 1, making a tower of kindling.

Figure A-1: Kindling layout

-Ensure the stove's bypass is open and the air setting is "high"; ignite the kindling in multiple places to establish an even burn and close the stove door once it is clear the fire will sustain itself.

-Burn down to 1.5 lbs. and break up the kindling (Note: there should be very little yellow flaming).

-Load preburn 2x4s in layers atop the kindling. The first layer is four or six pieces of 2x4 laid flat. The next layer is 2x4s on edge spaced ¾ - 1" apart. Continue the layers (on edge if possible) until all the pieces are stacked. (The exact structure should just be consistent for every test and will depend on firebox dimensions.) It is important to space the pieces and expose as much wood surface as possible. The preburn fuel charge layout may be seen in Figure A-2. The actual layout will vary based on how many pieces are needed to equal 110% of the fuel charge weight.

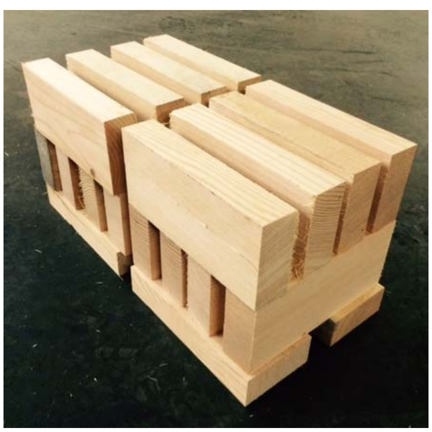

Figure A-2: Preburn fuel charge layout

-Keep door cracked open until the fire will sustain itself; then close the door.

-Close bypass after approximately 25% of the preburn fuel charge weight is consumed (e.g., at a fuel load weight of 11 to 14 lbs, depending on the fuel's density). Immediately afterward, adjust the primary flap to the test setting.

-Allow to burn untouched until approximately 80 to 85% of the preburn fuel charge weight is consumed (i.e., until the weight of the preburn has burned down to 15-20% of the preburn fuel charge weight, which requires approximately 1 hour).

-Immediately prior to loading the test fuel charge, open the bypass and doors, break up and spread out the coals. The goal is little or no yellow flaming and small chunks. Make sure the coal bed is evenly formed.

-Start PM sampling immediately prior to loading the test fuel.

-Load the test fuel charge. The 2x4's must go on the bottom followed by a layer of 4x4's. The fuel should be loaded so that spacers touch the back wall of the firebox.

Figure A-3: Test fuel charge layout

-Close door immediately with bypass open.

-Close bypass immediately.

-Move the air control to the test setting immediately

Measurements

-All standard temperatures and stove mass. Record stove mass with stove empty, with kindling added, before and after addition of preburn, before and after addition of test fuel charge. Record stove surface temperatures at introduction of the test fuel charge. (Temperatures and scale readings are recorded at one minute intervals throughout the test cycle.)

-Dual PM trains should be used, all filters EMFAB, PTFE coated glass fiber.

-PM sampling (both TEOM and filter) in the dilution tunnel shall be started 1 minute before test fuel charge is added. Prior to the start of PM sampling the TEOM shall be sampling room air.

-All PM sampling will be stopped when 95% of the test fuel weight has been consumed.

-Flue gas CO and CO_2 will be measured throughout the test period.

Appendix B: Test Results Summary

Chronological summary of test results.

Date	Fuel	Test Setting*	Test Elapsed Time (min)	PM (g/hr)	PM (g/kg)	CO (g/kg)	Burn Rate, dry (kg/hr)	Final PM Dual Train Precision (%)*
8/16/16	D. fir crib	high	125	27.7	13.5	196	2.05	
8/21/16	D. fir crib	high	136	33.4	17.8	234	1.88	1.4
8/23/16	D. fir crib	high	102	29.5	11.5	168	2.57	0.3
8/25/16	D. fir crib	high	119	35.1	15.4	220	2.28	1.9
8/27/16	D. fir crib	Low	260	24.4	28.6	459	0.85	0.0
8/31/16	Red oak crib	high	99	37.4	11.2	186	3.35	2.6
9/1/16	Red oak crib	high	94	30.1	8.4	158	3.61	0.1
9/3/16	D. fir crib	low	212	38.1	28.6	315	1.33	3.8
9/10/16	D. fir crib	high	103	21.0	7.3	115	2.90	0.4
9/20/16	D. fir crib	low	247	20.6	31.3	477	0.66	3.4
9/21/16	Red oak crib	high	98	28.3	8.4	159	3.38	1.9
9/22/16	Red oak crib	low	300	36.0	34.5	294	1.04	3.7
9/27/16	Red oak crib	low	268	46.5	37.2	268	1.25	0.7
10/15/16	White Pine crib	high	74	32.2	11.6	148	2.77	3.0
10/15/16	White Pine crib	high	100	43.8	20.9	222	2.10	0.9
10/16/16	White Pine crib	low	234	47.1	54.6	382	0.86	0.8
10/18/16	White Pine crib	low	177	58.7	54.8	399	1.07	0.8
10/21/16	White Pine crib	high	101	29.8	15.8	179	1.89	2.8
10/30/16	Red Maple Crib	high	99	34.7	11.6	149	3.01	0.1
10/30/16	Red Maple Crib	high	92	24.2	7.5	116	3.24	1.2
10/31/16	Red Maple Crib	low	233	52.1	43.1	235	1.21	0.3
11/3/16	White Birch Crib	high	117	36.5	13.6	131	2.69	0.4
11/5/16	White Birch Crib	low	171	55.1	30.7	201	1.80	3.7
11/6/16	Red Maple Crib	low	189	61.9	39.3	243	1.58	0.4
11/7/16	White Birch Crib	high	95	23.0	7.3	127	3.16	1.4
11/15/16	Red Maple Crib	high	100	19.0	6.5	134	2.91	1.1
11/16/16	Ash Crib	high	107	27.7	8.6	162	3.21	2.8
11/17/16	Ash Crib	high	107	26.0	8.3	183	3.15	0.5
11/19/16	Ash Crib	low	225	59.5	38.9	251	1.53	1.4
11/20/16	White Birch Crib	low	169	42.4	23.9	184	1.77	0.7
11/22/16	White Birch Crib	high	100	19.6	6.3	113	3.08	0.4
11/26/16	Ash Crib	low	268	49.5	41.8	252	1.18	0.4

Date	Fuel	Test Setting*	Test Elapsed Time (min)	PM (g/hr)	PM (g/kg)	CO (g/kg)	Burn Rate, dry (kg/hr)	Final PM Dual Train Precision (%)*
11/30/16	Ash Crib	high	105	19.8	6.1	164	3.27	0.4
12/19/16	D. fir crib	low	152	23.9	29.6	426	0.81	0.9
12/20/16	D. fir crib	low	221	31.8	33.7	408	0.95	1.9
12/26/16	Red oak crib	Med	137	41.5	15.6	218	2.66	0.2
12/27/16	Red oak crib	Med	204	67.9	38.0	281	1.79	1.7
12/30/16	Red oak crib	Med	179	57.4	31.6	269	1.82	0.2
1/4/17	White Birch Crib	Ex Low	313	38.5	47.8	242	0.81	1.3
1/13/17	White Birch Cord	High	122	44.7	15.9	164	2.81	1.0
1/14/17	White Birch Cord	High	123	28.2	8.5	150	3.31	0.2
2/7/17	Red Maple Cord	High	105	27.1	7.9	124	3.41	0.2
2/11/17	Red Maple Cord	Low	324	44.4	39.0	237	1.14	0.1
2/12/17	White Birch Cord	Low	335	64.3	55.8	248	1.15	1.0
2/14/17	Red Maple Cord	High	121	21.9	8.3	131	2.64	0.6
2/17/17	Ash Cord	High	109	45.2	13.7	201	3.30	2.3
2/18/17	Ash Cord	Low	297	51.1	40.8	232	1.25	1.5
2/23/17	Ash Cord	High	121	51.0	14.9	254	3.44	3.6
2/28/17	Red Oak Cord	High	109	19.1	5.9	124	3.21	1.3
2/28/17	Red Oak Cord	High	136	33.7	11.6	174	2.91	1.8
3/4/17	Red Oak Cord	Low	275	46.8	39.7	212	1.18	0.8
3/16/17	Red Maple Crib	High	86	16.1	4.7	115	3.41	6.5
3/17/17	Red Maple Cord	High	112	33.8	11.3	156	2.98	7.4
3/18/17	Red Oak Cord	High	148	38.7	15.2	183	2.56	7.8

*Dual train precision is the percentage deviation of each train from the mean.