Energy Efficiency and Emissions of a Biomass Pellet Fired Hydronic Heater Using Multiple Fuels

Final Report

Prepared for the

New York State Energy Research and Development Authority

Albany, NY
nyserda.ny.gov

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ABSTRACT

This report characterizes the thermal performance and air pollutant emissions from a pellet-fired hydronic heater (PBHH) burning both premium hardwood and switchgrass fuels. The PBHH was operated under three load conditions: 25% (minimum); 100%; and during a simulated load profile indicative of a typical 232 m^2 house during the first two weeks in January in Syracuse, NY (i.e., Syracuse cycle). Duplicate test runs were conducted at each load condition with measurements made throughout each 6-hour run period. Measurements were made to determine thermal efficiency and quantify a variety of air pollutants including criteria and related gases, volatile organic compounds and carbonyls, gas-phase polycyclic aromatic hydrocarbons, polycyclic dibenzodioxins and furans, gaseous hydrochloric acid, total particulate matter, particle number and size, elemental/organic carbon, optical black carbon, particle morphology, particle elemental composition, and particle-phase semivolatile organics. Samples of both the fuel and bottom ash were also collected and analyzed for a variety of important parameters. The data from the study showed that hardwood provided the highest thermal efficiency of the two fuels tested. In addition, the emissions of most air pollutants were highest for hardwood combustion at 25% load whereas switchgrass combustion produced higher emissions for the Syracuse cycle and at 100% load. Comparison of these data to historical information for other appliances burning similar fuels indicated at least generally comparable results.

ACKNOWLEDGEMENTS

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ACRONYMS AND ABBREVIATIONS

AA	atomic absorption
APCS	air pollution control system
ASTM	American Society for Testing and Materials (now ASTM International)
BC	black carbon
BTU	British thermal units
CEM	continuous emission monitor
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CRADA	cooperative research and development agreement
DAS	data acquisition system
DNPH	dinitrophenylhydrazine
DQI	data quality indicator
DQO	data quality objective
dscm	dry standard cubic meter(s)
EC	elemental carbon
EF	emission factor
ELPI	electrical low-pressure impactor
EPA	U.S. Environmental Protection Agency
FID	flame ionization detector
GC	gas chromatography
HCl	hydrochloric acid
HEPA	high-efficiency particulate air
HHV	high heating value
HPLC	high performance liquid chromatography
HRGC	high resolution gas chromatography
HRMS	high resolution mass spectrometry
LOI	loss on ignition
LRMS	low resolution mass spectrometry
MJ	megajoule
MOP	miscellaneous operating procedure
MS	mass spectrometry
NDIR	non-dispersive infrared
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NO	nitrogen monoxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NRMRL	National Risk Management Research Laboratory

NYSERDA	New York State Energy Research and Development Authority
OC	organic carbon
PAH	polycyclic aromatic hydrocarbon
PAX	photoacoustic extinctiometer
PBHH	pellet-burning hydronic heater
PCDD/F	polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans
PFI	Pellet Fuels Institute
PM	particulate matter
$PM_{2.5}$	particulate matter ≤ 2.5 microns
PTFE	polytetrafluoroethylene
QA	quality assurance
QAPP	quality assurance project plan
QC	quality control
RPD	relative percent difference
RTP	Research Triangle Park
SIM	selected ion monitoring
SO_2	sulfur dioxide
SOP	standard operating procedure
SVOC	semivolatile organic compound
TEM	transmission electron microscope
THC	total hydrocarbon
TOT	thermal-optical transmittance
TPS	thermophoretic sampler
VOC	volatile organic compound
XRF	X-ray fluorescence

EXECUTIVE SUMMARY

Various types of biomass are readily available for New York State residential heating. Wood-pellet hydronic heaters were found to be cleaner burning (less air pollutant emissions) and more efficient than conventional outdoor wood-fired hydronic heaters designed to cycle from full load to idle or gasification units (primarily of European design) (Kinsey et al., 2012). However, the unknown performance of this type of technology using non-woody biomass pellets and the uncertainty over emissions of particles and other products of incomplete combustion leave numerous questions regarding the environmental, health, and energy implications for this type of alternative home heating.

The goal of this research was to fully characterize the thermal efficiency and emissions of particulate matter (PM) and other pollutants from a hydronic heater using non-woody pellets to provide NYSERDA with a preliminary environmental and energy assessment of the environmental impact of hydronic heaters using non-woody fuel pellets. Testing was conducted on a REKA HKRST/V-FSK 20 pellet-burning hydronic heater (PBHH) while burning premium hardwood and switchgrass pellets. The switchgrass pellets were supplied by Dr. Jerry Cherney of Cornell University who also provided technical support.

The PBHH characterization determined the thermal performance and emissions for a broad array of pollutants under 3 load conditions burning hardwood pellets and switchgrass pellets. Load conditions were: 25% of nameplate rating; 100% of nameplate rating; and Syracuse load conditions. Technical specifications for the PBHH identify a minimum load of 21 MJ/h (5.8 kW), nominally 30% of nameplate rating. While 15% of nameplate rating was desired, 25% was the lowest load we could reliably control without overheating of the PBHH. Controlled hot water temperatures were lowered significantly to 66 °C to achieve this heat load. Hardwood pellets were Pellet Fuel Institute (PFI) certified Premium Grade Hardwood Pellets (Fiber Energy Products, LLC; Mountain View, AR) packed in 40-pound plastic bags. Switchgrass pellets were Biomass Pellet Fuel (SwitchGreen, Kingston, Ontario CANADA) packed in 40-pound plastic bags. Fuel samples collected during operations were analyzed for proximate, ultimate, and ash minerals by Standard Laboratories (Cresson, PA).

The basic test protocol was based on ASTM Method E2515-11 (Figure E-1). However, several modifications were necessary to accommodate the test program objectives and to accommodate facility and funding limitations. One of the most significant modifications was the change in all test periods to 6 hours to accommodate a reasonable simulation of the Syracuse load cycle. Further, the heat capacity of the PBHH and recirculating water required over an hour to reach control temperature from a cold start and longer to achieve conditions resembling a steady state combustion bed. The PBHH was lit at the beginning of each operational week and allowed to run overnight prior to testing in an attempt to achieve a representative fuel bed. Overnight operations were performed using an auxiliary water/air heat exchanger to provide load since facility requirements precluded over-night operation with cooling water. Cooling water was set to achieve initial heat load for each test at least an hour before starting the test.

Figure E-1. Hydronic heater testing facility

The PBHH was operated at constant conditions during each test with cooling water flow the only operating parameter adjusted to maintain desired load. The fuel feed, forced combustion air, reciprocating grate, etc. operated during the testing according to commands from the operating computer program. Induced draft fan at the stack and induced draft fan on the dilution duct were operated at constant rates over the entire test. To achieve low heat loads without overheating, the PBHH was set to 66 °C water temperature during 25% load and Syracuse load tests while set to 75 °C during 100% load tests. During testing, the heat transferred to the cooling water was adjusted by adjusting the flowrate of the cooling water. Flowrate was adjusted every 10 minutes throughout the 6-hour test and maintained constant through the 10-minute period despite changes in cooling water differential temperature or changes in inlet hot water temperature. The temperature differential of the cooling water across the heat exchanger was used to estimate the flow required to meet desired heat load.

A fill level was marked with tape around the interior of the fuel hopper. The PBHH was operational overnight with test fuel in the hopper. Pellet fuel was added to the fill level immediately prior to beginning each test. Fuel was added during each test to maintain fuel over the screw conveyer and prevent air flow to or from the firebox. The lid was maintained in a closed and latched position when not adding fuel. At the end of the test, fuel feed for the PBHH was paused while fuel was added to the fill line. After re-initiating fuel feed, the firebox was opened and ash was sampled from the end of the moving grate. Weight of fuel added was monitored through the run for use in

efficiency and emissions calculations. The hopper, screws, and firebox were emptied completely of fuel and ash prior to changing fuel.

Emission sampling was conducted on a suite of air pollutants consisting of both continuous measurements and time-integrated sampling to determine key appliance operating parameters as well as gas- and particle-phase emissions. The continuous measurements included temperature and flow throughout the system, as well as additional temperature measurements conducted in locations such as the combustion zone, stack, and dilution tunnel. The measurement methods and sampling locations used in the program are provided in Table E-1.

Table E-1. Measurement Methods and Sampling Locations

Pollutant	Measurement Technique	Test Method or Instrument[a]	Time Scale	Sampling Location
Total PM emissions	Filter gravimetric	Modified ASTM Method E2515-11	Time-integrated	Dilution duct
Particle size distribution (including PM$_{2.5}$)	On-line cascade impactor	Dekati Electrical Low Pressure Impactor (ELPI)	Continuous	Dilution duct
Particle morphology[b]	Transmission electron microscopy (TEM)	Thermophoretic sampler (TPS) + analysis of TEM grids	Time-integrated	Secondary dilution manifold
Organic C/Elemental C (OC/EC)	Thermal-optical transmission (TOT)	NIOSH Method 5040; pre-fired quartz filters in multi-sampler	Time-integrated	Dilution duct
		Sunset Model 4 OC/EC analyzer (optional)	Semi-continuous	Secondary dilution manifold
Optical black carbon	Optical absorption	Magee AE-22 Aethalometer and PAX Extinctiometer (optional)	Continuous	Secondary dilution manifold
Total gas- and particle-phase polycyclic aromatic hydrocarbons	Impingers by gas chromatography/low resolution mass spectroscopy (GC/LRMS) and XAD resin + filter by GC/LRMS	Modified EPA Method 5, 0010, 23, and 26A (filter + XAD resin + impingers)	Time-integrated (1 sample/test)	Stack
Gaseous polychlorinated dibenzodioxins and furans	XAD resin/filter by high-resolution gas chromatography/mass spectrometry (GC/HRMS)			
Hydrochloric acid	Impingers by ion chromatography			
Volatile organic compounds (VOCs) and carbonyls	SUMMA canisters by GC/MS (VOCs) and DNPH sorbent cartridges by high pressure liquid chromatography (carbonyls)	EPA Methods TO-15 and TO-11A	Time-integrated (2 samples/ test)	Dilution duct
Filter-based semivolatile organic compounds	GC/MS	Thermal extraction of quartz OC/EC filters	Time-integrated	Dilution duct
Particle elemental composition	X-ray fluorescence (XRF)	Analysis of Teflon filters in multi-sampler by EPA Method IO-3.3	Time-integrated	Dilution duct

Pollutant	Measurement Technique	Test Method or Instrument[a]	Time Scale	Sampling Location
Bottom ash	Loss on ignition (LOI)	Muffle furnace or thermal gravimetric analysis	1 sample/test	Grab samples
	Elemental composition	Atomic absorption (AA)		
SO_2	Fourier transform infrared spectroscopy (FTIR)	Closed-cell IMACC spectrometer	Continuous	Dilution duct
CO	Non-dispersive infrared (NDIR) analysis	EPA Method 10B	Continuous	Stack
CO_2	NDIR	EPA Method 3A	Continuous	Stack and dilution duct
O_2	Paramagnetic analysis	EPA Method 3A	Continuous	Dilution duct
NOx	Chemiluminescence analysis	EPA Method 7E	Continuous	Dilution duct
Total hydrocarbons (THC)	Heated flame ionization detector (FID)	EPA Method 3C	Continuous	Dilution duct
CH_4	FTIR	Closed-cell IMACC spectrometer	Continuous	Dilution duct

[a] See main text for acronyms of analytical methods; additional compounds measured with FTIR are not given in this Table, but discussed later in the report

Due to a leak discovered in the continuous emission monitoring system, either the closed-cell Fourier Transform Infrared (FTIR) instrument (CO, CH_4, NH_3, NO_x, and SO_2) or analysis of the SUMMA canisters (N_2O) were used for data analysis. The NDIR, paramagnetic, FID, and chemiluminescence instruments did not produce useful measurements, and no valid data were collected for CO_2 or THC.

For each test run, emission factors for the target pollutants were calculated in terms of mass of fuel burned, energy input, and energy output according to the calculation scheme shown in Section 5. For both gases and particles, the test average results for the two runs conducted at each fuel and load condition are provided in Section 7 which, except for stack PAHs, PCDD/PCDFs, and HCl, are background-corrected unless otherwise indicated. Since only two tests were conducted at each condition, the standard error (deviation) could not be calculated as is usually done. Instead, the summary data tables show the relative percent difference (RPD) for the two tests. RPD is defined as the difference between emission factor values from duplicate tests divided by the average of the duplicates multiplied by 100 and is an indicator of the variability observed between the two test runs. The data are also provided in graphical form generally in both engineering and SI units. Note that in the graphs, the bars indicate the range of values for each parameter and not the RPD or standard error. The bars are provided to generally indicate the amount of variability observed between the two test average values which was oftentimes considerable. A summary of the test results is shown in Table E-2.

Table E-2. Test Average Thermal Efficiency and Emission Factors

Pollutant	Units	25% Load		Syracuse Cycle		100% Load	
		Wood	**Grass**	**Wood**	**Grass**	**Wood**	**Grass**
Thermal efficiency	percent	79	63	94	72	89	81
CO	g/kg fuel	36.9	32.8	18.5	19.1	11.4	2.25
CH$_4$	g/kg fuel	1.96	0.9	0.305	0.839	0.0751	0.138
NH$_3$	mg/kg fuel	4.9	226	10.5	59.4	25.6	8.94
N$_2$O	mg/kg fuel	76.9	209	27.9	168	20.4	42.8
NO$_x$	mg/kg fuel	9.90	186	205	102	ND	10.2
SO$_2$	mg/kg fuel	117	ND	25.3	ND	390	438
Total VOCs and carbonyls	mg/kg fuel	2490	1780	205	1320	21.4	88.7
Gaseous PAHs	mg/kg fuel	114	11.7	3.43	71.7	2.66	22.9
Total PCDD/Fs	ng TEQ/kg fuel	0.158	0.223	0.0929	0.455	0.320	0.105
Total halides (HCl)	mg/kg fuel	1.53	2.70	ND	2.53	4.43	13.5
Total PM	g/kg fuel	2.91	1.30	0.269	0.761	0.401	0.662
Particle number	particles/kg fuel	2.07E+14	2.30E+14	7.65E+13	1.48E+14	6.78E+13	7.18E+13
Elemental carbon	mg/kg fuel	20.0	11.1	10.2	83.8	90.0	292
Organic carbon	mg/kg fuel	1075	572	33.1	392	1.78	62.8
Optical black carbon	mg/kg fuel	145	62.3	29.1	162	180	420
Elemental Cr[b]	g/kg fuel	1.85E-03	6.05E-04	3.94E-05	4.08E-04	1.53E-05	2.00E-05
Elemental Mn[b]	g/kg fuel	2.87E-03	1.45E-04	2.19E-04	5.34E-05	9.51E-05	2.89E-05
Elemental Pb[b]	g/kg fuel	6.25E-03	1.38E-04	2.55E-04	6.26E-04	2.03E-04	3.68E-04
Total SVOCs[c]	mg/kg fuel	439	124	3.70	79.4	0.640	9.16

Three significant figures. Numbers shown in red face type are a single test value. All others are an average of two test runs.
[b] Note that the emissions of Cr, Mn, and Pb are components of the total PM emission factor shown above and not additional emissions.
[c] Note that the SVOCs are components of the total organic carbon emission factor shown above and not additional emissions.

Based on the study results, the following conclusions were reached:

1. The combustion of hardwood exhibited the highest thermal efficiency at all load conditions. Of the three loads tested with hardwood, the highest efficiency was for operation during the Syracuse cycle which was the most indicative of "real world" conditions.

2. With respect to reduced and oxidized carbonaceous gases, the same general trend was observed as was the case for the particle-phase constituents namely, hardwood produced higher emissions at 25% load and switchgrass had the highest emissions during the Syracuse cycle and at 100% load.

3. For reduced and oxidized nitrogen compounds, grass combustion generally had the highest gaseous emissions as compared to hardwood.

4. For the speciated gas-phase VOCs/carbonyls and PAHs, the combustion of hardwood generally produced the highest emissions at 25% load whereas during the Syracuse cycle and 100% load, switchgrass exhibited the higher emissions.

5. For particle-phase air pollutants, the combustion of hardwood generally produced the highest emissions at 25% load whereas during the Syracuse cycle and 100% load switchgrass exhibited the higher emissions.

6. Comparing the current results to historical data for similar hydronic heaters, the data reported here were comparable to the unit tested for NYSERDA in 2010 using hardwood pellets during the Syracuse cycle and generally similar to Appliance D tested by Chandrasekaran et al. (2013a) burning both fuel types depending on load.

7. The lack of U. S. technical support severely hampered operation and testing of the REKA appliance evaluated in this study.

1 Project Background and Objectives

Various types of biomass are readily available for New York State residential heating. Wood-pellet hydronic heaters were found to be cleaner burning (less air pollutant emissions) and more efficient than conventional outdoor wood-fired hydronic heaters designed to cycle from full load to idle or gasification units (primarily of European design) (Kinsey et al., 2012). However, the unknown performance of this type of technology using non-woody biomass pellets and the uncertainty over emissions of particles and other products of incomplete combustion leave numerous questions regarding the environmental, health, and energy implications for this type of alternative home heating.

The goal of this project is to fully characterize the thermal efficiency and emissions of particulate matter (PM) and other pollutants from a hydronic heater using non-woody pellets. This research effort will provide NYSERDA with a preliminary environmental and energy assessment of the environmental impact of hydronic heaters using non-woody fuel pellets.

This report provides the results of testing conducted on a REKA HKRST/V-FSK 20 pellet-burning hydronic heater (PBHH) while burning premium hardwood and switchgrass pellets. The switchgrass pellets were supplied by Dr. Jerry Cherney of Cornell University who also provided technical support. The project was designed to supplement previous research characterizing the emissions and energy efficiency of four outdoor wood-burning hydronic heaters as described by Kinsey et al. (2012). The project was predominantly funded by the New York State Energy Research and Development Authority (NYSERDA; Agreement 32984) through a Cooperative Research and Development Agreement (CRADA) 79514 with the U. S. Environmental Protection Agency, National Risk Management Research Laboratory, Air and Energy Management Division (EPA) located at Research Triangle Park, NC.

This document covers in detail the background, objectives, technical approach, quality assurance/quality control (QA/QC), experimental results, and references associated with the research. EPA was assisted in this effort by its in-house contractor, Jacobs Technology, through EPA Contract EP-C-15-008. Mr. Carl Singer acted as the contractor lead for the study.

2 Experimental Approach

2.1 Facility Description

Figure 2-1 depicts the components of the hydronic heater test facility located at EPA's research campus in Research Triangle Park (RTP), NC. The unit was located outside the EPA High Bay facility, allowing testing under ambient conditions. The diluted flue gas was ducted into the facility for ease of sampling and connection to the air pollution control system (APCS). The facility duct work configuration and flows were generally based on ASTM International (ASTM) Method E2515-11, Standard Test Method for Determination of Particulate Matter Emissions Collected by a Dilution Tunnel (see the References section for a listing of the ASTM and other methods associated with this work). The stack from the PBHH is 0.2 m in diameter and is 1.35 m in length insulated with 3.8 cm high temperature fiberglass insulation. Because the stack was shorter than the 6-m installation requirements, an induced draft fan (Tjernlund Model AD-1; White Bear Lake, MN) was installed per manufacturer's recommendation in the stack downstream of the sampling point. A conical hood cone was placed above the outlet of the stack to entrain the unit exhaust and ambient dilution air. The cone was connected to a 0.25 m (outside diameter) stainless steel duct surrounded by an outdoor sampling platform outfitted with vertically oriented 7.6 cm ports to support particulate sampling, continuous emission monitors, and velocity measurements.
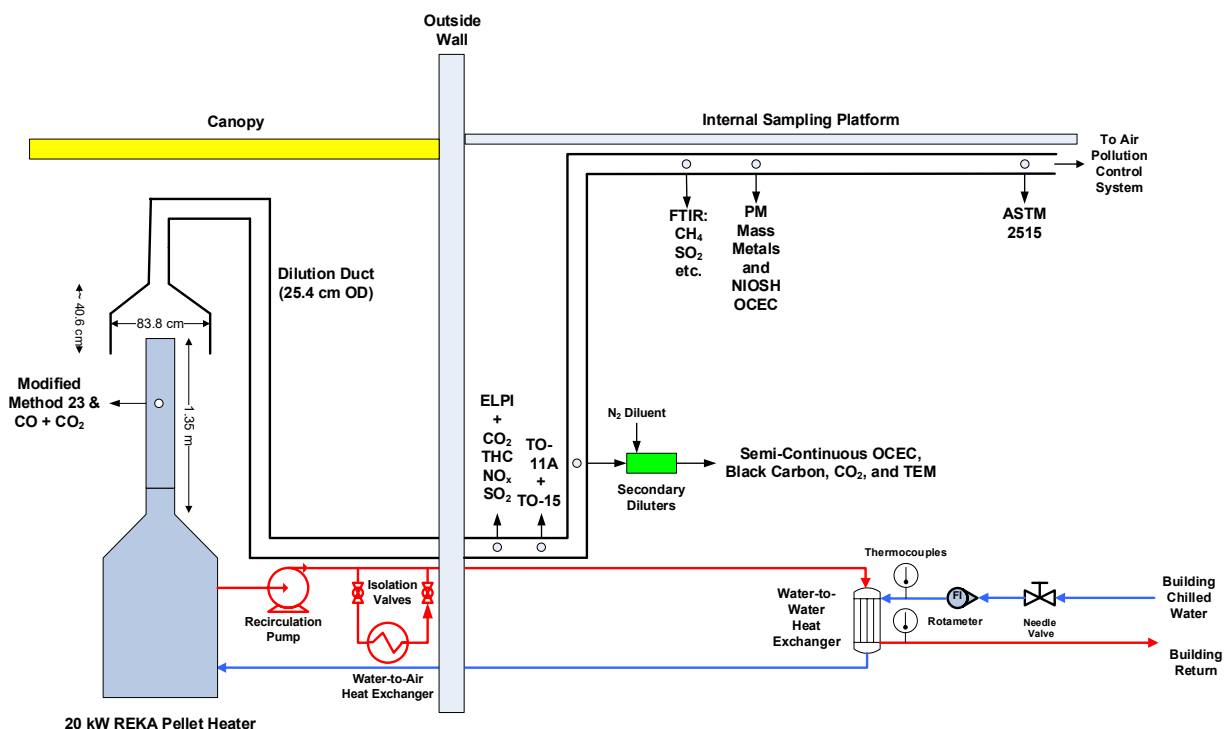
Figure 2-1. Hydronic heater testing facility

The outside duct was connected to a horizontal indoor sampling platform set up to accommodate sensitive measurement equipment and other stack measurement methods. The diluted and cooled

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exhaust gases were transferred into the building through a 0.25-m (outside) diameter and approximately 12 m long stainless steel duct with multiple sampling ports. The temperatures within the indoor dilution sampling duct were slightly below ambient. This sampling section was connected to the APCS manifold for treatment prior to release to the atmosphere. The air duct system moves 19.8–20.4 dry standard cubic meters (dscm) per minute of air, which correlates to an approximate dilution ratio of 15 to 1 from the PBHH stack at full firing rate. Flows and pressures were controlled by adjusting the facility APCS induction draft fan. All instruments/samplers were connected to their respective sampling port using 0.95- or 0.63-cm (outside diameter) stainless steel probes and sample lines.

A secondary dilution manifold was installed for continuous measurements of black carbon and particle morphology at the location indicated in Figure 2-1. A model DI-1000 stainless steel eductor operated with nitrogen (Dekati, Kangasala, Finland) was used with a stainless steel porous tube diluter (Lyyranen et al. 2004) to sample and dilute exhaust from the dilution duct. The dilution ratio was controlled by changing the flow of nitrogen to the eductor and the probe to optimize particle concentrations for the black carbon instrumentation. The dilution ratio was determined by measuring the CO_2 concentrations in the secondary dilution system with a CO_2 analyzer (Model 820, Li-Cor Biosciences, Lincoln, NE) and comparing it to the CO_2 concentrations in the dilution duct. This is discussed in detail in Section 5.

2.1.1 Pellet Burning Hydronic Heater (PBHH)

The PBHH tested during this test program was a Reka HKRST/V-FSK 20, shown in Figure 2-2. The complete unit consists of a flat-bottom fuel bin, a hydronic heater, and an ash bin. Fuel was conveyed from the fuel bin with a feed screw and dropped onto a reciprocating push-grate in a stair-step fashion where the fuel was burned by adding under-fire and overfire air. Ash and cinders are conveyed to the ash bin by a feed screw at the discharge of the moving push-grate. The heat is transferred within the hydronic heater by a two-pass steel-plate heat exchanger with 50 mm fire tubes. The fire tubes were kept clear by an automated compressed air soot blower which back-flushed the tubes creating high transient PM emissions during each event. Recirculating water from the hydronic heater is passed to a water loop passing through a water-to-water heat exchanger simulating the space (residential house) to be heated. Fuel feed was controlled by a computer operating system using temperature and oxygen sensors in the stack which turns the screw feeder on and off to meet the heat load demand. The unit was not equipped with a secondary combustion zone for emissions control.

No U. S. technical support for the REKA PBHH was available for installation and tuning of the hydronic heater which resulted in severe delays in execution of the project. System operators made their best attempt to operate the system in as appropriate manner as possible for both fuels tested. During commissioning, the PBHH was found to overheat when running in "idle" mode, i.e. with no heat load, causing a water blowdown and shutdown of the PBHH. This PBHH controlled water temperature by adjusting forced air for combustion. Under idle conditions at this test facility, even without operating the induced draft fan, combustion continued under natural draft conditions. Fuel feed was controlled by an independent system based on stack oxygen concentration and continued

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to provide fuel during idle conditions until overheating resulted in shutdown. An auxiliary water-to-air heat exchanger (Modine Model HSB; West Kingston, RI) was added to the hot water distribution system before testing to remove heat during periods when the unit was functioning in an "idle" condition. The PBHH control scheme would seem to require some mitigation for in-home operation under low load conditions however no guidance was provided in manufacturer's installation instructions.
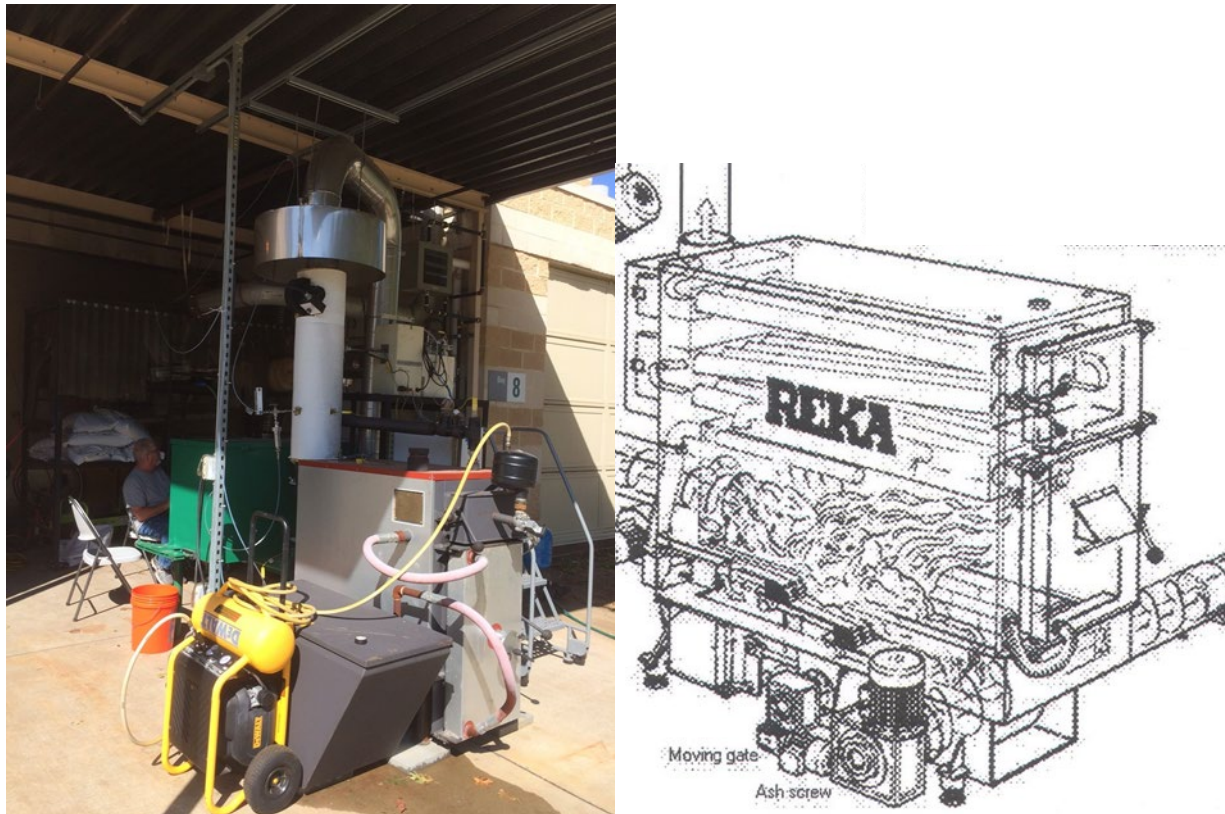
Figure 2-2. Reka HKRST/V-FSK 20 PBHH tested

2.1.2 Heat Load Profiles

Three heat load profiles were evaluated in the study. Two of these were steady state operation at 100% load, 72 MJ/h (68,300 Btu/h) and minimum attainable load which was 25% load or 18 MJ/h heat output and the third was the Syracuse heat load cycle. The heat load profile (Figure 2-3) referred to as the Syracuse heat load cycle, is derived from a simulation program for heat demand for a 232 m^2 home in Syracuse, NY, developed by Brookhaven National Laboratory. The program uses an averaged hour-per-hour heat load for the first two weeks of January averaged over 25 years (Kinsey et al., 2012). The average daily heat load for the first two weeks in January is approximately 827 megajoules (MJ) (784,000 British Thermal Units [Btu]) with a maximum heat load of approximately 36 MJ/h (34,000 Btu/h) (1 Btu = 0.00105587 MJ). The Syracuse cycle has been approximated by a polynomial over a 24-hour period:

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$Q\ (BTU/h) = \text{-}0.0143\ x^6 + 0.9261\ x^5 - 21.129\ x^4 + 204.05\ x^3 - 852.18\ x^2 + 1674.7\ x + 30947$
    (3-1)

Due to facility and financial limitations, all tests were limited to 6 hours of active testing. For this testing, the Syracuse cycle was compressed from a 24-hour cycle to a 6-hour cycle. A target heat load for any elapsed time in the cycle can be calculated. For this testing, heat load was adjusted every 10 minutes to simulate the Syracuse cycle. Heat load targets were calculated for each 10-minute interval through the test period.
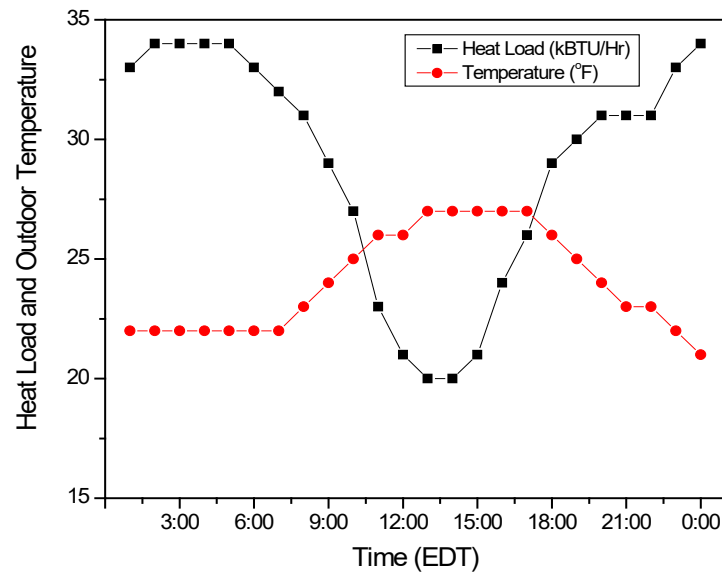
Figure 2-3. Simulated Syracuse, NY, area heat load profile for January

2.1.3 Heat Load Demand Control

The heat load demand was simulated by extracting the PBHH outlet heat with a water/water heat exchanger coupled to EPA's High-Bay Building chilled water supply. The unit was manually operated in a mode where hot water is continuously circulated through the water/water heat exchanger and the PBHH's water jacket. The piping system to and from the PBHH consists of 2.5-cm steel pipe insulated with high-density urethane. The inlet and outlet temperatures of both the chilled water and recirculated hot water were monitored. Hot water exiting the PBHH was nominally controlled to 75 °C for100% load testing and 66 °C for 25% load and Syracuse load testing but the temperature varied somewhat with the firing cycle per the PBHH control scheme. Hot water flow was constant utilizing a single circulating pump. The hot water temperature exiting the heat exchanger and returning to the heater changed temperature in response to applied load controlled with chill water flow. The inlet and outlet temperatures of both the chilled water and recirculated hot water were monitored. The chilled water flow rate was monitored and controlled with a manual rotameter installed upstream of the heat exchanger to determine heat load. The heat

load removed from the hot water is calculated from the temperature difference in the chill water across the heat exchanger multiplied by the mass flow of chill water using the following formula:

$$Q = F \, C_p \, \Delta T \qquad\qquad\qquad (3\text{-}2)$$

where F is the mass flow rate of cooling water through the heat exchanger, C_p is the heat capacity of the cooling water, and ΔT is the difference between the inlet and outlet temperature of the cooling water.

2.2   Test Protocol

The PBHH characterization determined the thermal performance and emissions for a broad array of pollutants under 3 load conditions burning hardwood pellets or switchgrass pellets. Load conditions were 25% of nameplate rating, 100% of nameplate rating, and Syracuse Load conditions. Technical Specifications for the PBHH identify minimum load of 21 MJ/h (5.8 kW), nominally 30% of nameplate rating. While 15% of nameplate rating was desired, 25% was the lowest load we could reliably control without overheating of the PBHH; controlled hot water temperatures were lowered significantly to 66 °C to achieve this heat load. Hardwood pellets were Pellet Fuel Institute (PFI) certified Premium Grade Hardwood Pellets (Fiber Energy Products, LLC; Mountain View, AR) packed in 40-pound plastic bags. Switchgrass pellets were Biomass Pellet Fuel (SwitchGreen, Kingston Ontario) packed in 40-pound plastic bags. Fuel samples collected during operations were analyzed for Proximate, Ultimate, and Ash Mineral by Standard Laboratories, Cresson, PA. The fuel analyses are summarized in Table 2.1

The test protocol was based on ASTM Method E2515-11 however several modifications were necessary to accommodate the test program objectives and to accommodate facility and funding limitations. One of the most significant changes was modification of all test periods to 6 hours to accommodate a reasonable simulation of the Syracuse load cycle. Further, the heat capacity of the PBHH and recirculating water required over an hour to reach control temperature from a cold start and longer to achieve conditions resembling a steady state combustion bed. The PBHH was lit at the beginning of each operational week and allowed to run overnight prior to testing in an attempt to achieve a representative fuel bed. Overnight operations were performed using an auxiliary water/air heat exchanger to provide load since facility requirements precluded over-night operation with cooling water. Cooling water was set to achieve initial heat load for each test at least an hour before starting the test.

Table 2.1. Fuel Analysis Results

Parameter Measured	Hardwood Pellets	Switchgrass Pellets
Proximate Analysis (as received)		
Moisture	4.66%	10.41%
Volatile Matter	80.34%	72.62%
Fixed Carbon	14.00%	12.71%
Ash	1.00%	4.26%
Ultimate Analysis (as received)		
Sulfur	0.09%	0.12%
Carbon	47.91%	42.79%
Hydrogen	5.79%	5.44%
Nitrogen	0.31%	0.82%
Oxygen (by difference)	40.24%	36.16%
GCV (Btu/lb)	7736	7526
Ash Mineral Analysis		
Silicon Dioxide	26.57%	62.99%
Aluminum Oxide	2.40%	7.55%
Ferric Oxide	4.89%	3.63%
Titanium Dioxide	0.27%	0.06%
Phosphorus Pentoxide	0.80%	1.00%
Calcium Oxide	36.63%	10.69%
Magnesium Oxide	2.58%	3.65%
Sodium Oxide	0.44%	1.41%
Potassium Oxide	11.76%	6.42%
Sulfur Trioxide	13.91%	2.32%

The PBHH was operated at constant conditions during each test, with chilled water flow the only operating parameter adjusted to maintain desired load. Program conditions for each test are summarized in Appendix A. The fuel feed, forced combustion air, reciprocating grate, etc. operated during the testing according to program conditions. Induced draft fan at the stack and induced draft fan on the dilution duct were operated at constant rates over the entire test. To achieve low heat loads without overheating, the PBHH was set to 66 °C water temperature during 25% load and Syracuse load tests while set to 75 °C during 100% load tests. During testing, the heat transferred to the chilled water was adjusted by adjusting the flowrate of the chilled water. Flowrate was adjusted every 10 minutes throughout the 6-hour test and maintained constant through the 10-minute period despite changes in chilled water differential temperature or changes in inlet hot water temperature. The temperature differential of the chilled water across the heat exchanger was used to estimate the flow required to meet desired heat load. The heat load achieved during each test is shown in Appendix B.

A fill level was marked with tape around the interior of the fuel hopper. The PBHH was operational overnight with test fuel in the hopper. Pellet fuel was added to the fill level immediately prior to beginning each test. Fuel was added during each test in order to maintain fuel over the screw conveyer and prevent air flow to or from the firebox. The lid was maintained in a closed and latched position when not adding fuel. At the end of the test, fuel feed for the PBHH was paused while fuel was added to the fill line. After re-initiating fuel feed, the firebox was opened and ash was sampled from the end of the moving grate. Weight of fuel added was monitored throughout the run for efficiency and emissions calculations. The hopper, screws, and firebox were emptied completely of fuel and ash prior to changing fuel.

3 Sampling Procedures

3.1 Overall Approach

Emission sampling was conducted on a suite of pollutants consisting of both continuous measurements and time-integrated sampling to determine key appliance operating parameters as well as gas- and particle-phase emissions. The continuous measurements included temperature and flow throughout the system, as well as additional temperature measurements conducted in locations such as the combustion zone, stack, and dilution tunnel.

3.2 Sampling Techniques

The conventional extractive sampling techniques are based on established EPA or ASTM methods, or their modified versions, adapted to this PBHH source. In general, the data obtained from conventional extractive methods were considered "reference" data and used to evaluate the data obtained from the continuous measurement techniques.

3.2.1 Flue Gas Volumetric Flow Rate (EPA Methods 1A and 2C)

Dilution duct velocities were determined using a Shortridge airfoil due to the low velocity head at this site and the small profile of the airfoil. The round 10-inch duct was traversed before and after each test at sample points identified in EPA Method 1A, Sample and Velocity Traverses for Stationary Sources with Small Stacks or Ducts: 6.7%, 25%, 75% and 93.3% of duct diameter excluding nipple on orthogonal axis. The Shortridge output velocity at each point with an arithmetic averaging of the data points. Velocity was measured at the centroid of the duct during each test to assure steady state flow for particulate measurements. Average velocity was converted to volumetric flow rate using the cross-sectional area of the duct.

3.2.2 Gaseous Continuous Emissions Monitoring

Continuous emissions monitoring (CEM) of gaseous pollutant concentrations were also performed during each test. CO_2 was monitored in the stack with CO_2, SO_2, nitrogen oxide (NO_x), CO and total hydrocarbons (THC) determined in the dilution duct using established EPA methods 3A, 6C, 7E, 10, and 25A. Due to resource constraints, calibration was performed prior to the test program with all subsequent QA checks being performed through the bias line. However, during data analysis a discrepancy was observed between CO_2 concentrations measured in the dilution duct and the mass of fuel burned. It was concluded that a bias, presumably a leak, had been introduced into the dilution duct during repair and replacement operations that occurred immediately before and during the first test. All dilution duct CEM data were considered unreliable for emissions estimates. Therefore, either the closed-cell Fourier Transform Infrared (FTIR) instrument (CO, CH_4, NH_3, NO_x, and SO_2) or analysis of the SUMMA canisters (N_2O) were used. The NDIR, paramagnetic, FID, and chemiluminescence instruments did not produce useful measurements, and no valid data were available for stack CO_2 or THC. The dilution duct CO_2 remained the most

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reliable indicator of trends arising from PBHH cycles required to estimate dilution factors for measurements made with secondary nitrogen dilution.

A closed-cell FTIR spectrometer was also used as outlined in Section 4.3.2. The use of the closed-cell FTIR was a last-minute substitution due to the loss of other continuous analyzers for CH_4 and SO_2 originally planned for use in the program. Due to the leak in the CEM bench, however, the FTIR data were also used to determine CO, NH_3, and NO_x.

3.2.3 Hydrochloric Acid (HCl)/Semivolatile and Nonvolatile Sampling Train

The standard EPA Method 26A train, the EPA Method 23 train, and the EPA Method 0010 sampling train are versions of EPA Method 5 that were used for sampling. The Method 23 train was modified to include impingers styled like the Method 26A train so that total halides (mainly HCl) can also be collected. The modification consisted of using impingers that contain a 0.1 N sodium hydroxide solution to absorb total halides. The gas was then measured with a calibrated dry gas meter.

The train consists mainly of a heated probe, heated box containing a cyclone and filter, water-cooled condenser, water-cooled XAD-2 cartridge, impinger train for water determination (which has been modified for the HCl collection), leak-free vacuum line, vacuum pump, and a dry gas and orifice meter with flow control valves and vacuum gauge. Temperatures were measured and recorded in the hot box (set at 125 °C), at the impinger train outlet, at the XAD-2 cartridge outlet (maintained to be below ambient temperature), and at the inlet and outlet of the dry gas meter. Leak checks were conducted at the beginning and end of each sampling run. Prior to sampling all glassware, probes, glass wool, and aluminum foil were cleaned or purchased clean.

Hydrochloric acid from sodium hydroxide impingers were analyzed by high-performance liquid chromatography (HPLC) ion-chromatograph (IC) using a conductivity detector (CD). The IC was calibrated using commercial prepared standards.

3.2.4 VOC and Carbonyl Sampling Train

Volatile organics were sampled via Method TO-15, Determination of Volatile Organic Compounds (VOCs) in Air Collected in Specially-Prepared Canisters and Analyzed by Gas Chromatography/Mass Spectrometry (GC/MS). Sampling for VOCs were conducted using laboratory-supplied 6-L SUMMA canisters connected to an Entech 1800 (Simi Valley, CA) canister sampler and an in-line metal filter (frit). The canister sampler was equipped with a mass flow controller assembly to allow for fill sampling times of 180 minutes. The canisters were cleaned and evacuated before sampling using the Entech 3100 canister cleaner following the standard operating procedure (SOP) associated with this work. Two 180-minute samples were sequentially drawn for each 360-minute test.

Carbonyls were sampled via EPA Method TO-11A, Determination of Formaldehyde and Other Aldehydes in Indoor Air Using a Solid Adsorbent Cartridge. This method utilizes commercially

available cartridges (Supelco LpDNPH H30, PN 505323, Sigma-Aldrich, St. Louis, MO) followed by high performance liquid chromatography (HPLC) analysis (Agilent 1100 LC, Agilent Technologies, Santa Clara, CA). Samples were collected on 2,4-dinitrophenylhydrazine (DNPH) cartridges by drawing air from the sampling line at a sampling rates in the range of 250-500 mL/min using a calibrated mass flow controller and pump. Carbonyl sampling was timed to coincide with SUMMA canister sampling with a 180-minute duration per sample. Breakthrough of carbonyls during sampling was determined during at least one test per condition by sampling with two DNPH cartridges in series. After collection, samples were placed in the original pouch and stored in a refrigerator before analysis. DNPH cartridges were analyzed within two weeks of collection. The sampling was conducted according to the applicable miscellaneous operating procedure (MOP).

3.2.5 Total PM Mass Measurements

For the determination of total PM mass emissions on a time-integrated basis, the PM emission measurements followed the general procedures outlined in ASTM Method E2515-11. The sampling system for this test method consists of duplicate dual-filter dry sampling trains sampling from the dilution duct. Both particulate sampling trains were operated simultaneously at a sample flow rate not exceeding 0.007 m^3/min. The total particulate results obtained from the two sampling trains were averaged to determine the particulate emissions and compared as a QC check on the data. Each sampling train had two filters in series.

To achieve project objectives, several modifications to the sampling procedures in ASTM E2515-11 were found necessary. The first modification consisted of replacing the glass filters with 47-mm Emfab Pallflex TX40HI20WW filters (Pall Life Sciences, Ann Arbor, MI) which consist of pure borosilicate glass microfibers reinforced with woven glass cloth and bonded with polytetrafluoroethylene (PTFE); filters were changed during testing as required to maintain sample flow. A second modification involved replacing the Teflon filter holders with two 47-mm stainless steel filter holders (Pall Life Sciences, Ann Arbor, MI) which are grounded to prevent particles losses. Finally, instead of using a straight probe oriented perpendicular to the flow stream, a custom-made stainless-steel PM sampling probe oriented directly into the flow was used. Considering these modifications, the mass of PM was determined using filter weights recovered per EPA Method 5 instead of weighing the entire assembly. A front-half acetone rinse was recovered and incorporated in total PM mass.

Samples for particle morphology were taken using a thermophoretic particle sampler (TPS; R.J. Lee Group, Monroeville, PA). The TPS is designed to sample from ambient conditions, rather than the duct. To obtain a representative sample from the dilution tunnel the TPS was contained within a stainless-steel chamber (61 cm x 25 cm x 31 cm) connected to the secondary dilution system (described in Section 2.1). A pump was used to draw a sample from the secondary dilution system into the chamber. To prevent overloading of the sample the TPS was operated for only 10 minutes of the test. Two samples were obtained, one for each fuel while the heater was operating on the Syracuse cycle.

3.2.6 PM Number and Size Measurements

A Dekati ELPI (ELPI software, Version 4.0) was used to provide real-time (10-sec) particle size distributions (PSDs). The ELPI generates a PSD by first charging the particles with a unipolar diode charger, which charges the particles based on geometrical diameter before they enter a cascade impactor. The charged particles impact the stages on the impactor based on their inertia (i.e., their aerodynamic diameter [equivalent unit density spheres]). A multi-channel electrometer measures the charge of the particles as they land on each of the stages, giving current values for each stage in f-amps. These current values are then converted to number of particles on each stage and, if the density of the particle is known (or assumed), the mass of the particles on each of the stages can also be found.

The differential number distribution, dN/dlog(Dp), is determined from the current distribution by dividing these currents for each channel by conversion values for each channel. This conversion vector was calculated by the manufacturer from the charger efficiency values for the stage's midpoint diameter. The stage's midpoint diameter is the average of the cut point of the stage of interest and the stage above. These midpoint diameters are determined for both the Stokes and aerodynamic diameters. These particle numbers are then normalized by dividing by the logarithmic width of the stage (either in terms of aerodynamic or Stokes diameter). Mass distributions, dM/Dlog(Dp), are then easily found by taking the number distribution and multiplying it by the mass of each spherical particle assuming unit density.

3.2.7 OCEC and PM Elemental Composition

The National Institute for Occupational Safety and Health (NIOSH) Method 5040, Diesel Particulate Matter (as Elemental Carbon), was used for OC/EC analyses. The first step in OC/EC sampling involves filter preparation. The 47-mm quartz filters were pre-fired by placing them in an oven at 900 °C overnight to remove any residual carbon present. Samples were collected directly from the dilution duct onto the pre-fired quartz filters using an unheated polished stainless-steel PM probe oriented into the flow, stainless-steel filter holder, calibrated mass flow controller, and sampling pump. Three samples were drawn during a 6-hour test cycle. The exposed filters were then sampled with a 1.5 cm^2 punch in a radial fashion and analyzed by thermal-optical transmittance (TOT).

Sampling was conducted using two multi-filter samplers (Figure 3-1). One multi-filter sampler was equipped with four Pall 47-mm stainless-steel filter holders (Pall Life Sciences, Ann Arbor, MI), each containing one pre-fired Pall Tissuquartz™ quartz filter acting as the primary filter for OC/EC. The other multi-filter sampler was equipped with four dual-filter trains consisting of two Pall 25-mm stainless-steel filter holders connected in series. The first filter holder contained a pre-weighed Teflon filter (Pall Teflo™) with the backup filter holder containing a pre-fired Pall Tissuquartz™ filter. The backup quartz filters were analyzed for OC/EC using NIOSH 5040. The OC concentration on the backup quartz filters was subtracted from that found on the primary 47-mm filters to compensate for gas-phase organic artifacts. The 25-mm Teflon filters were analyzed gravimetrically to determine total PM mass and subsequently analyzed by an outside laboratory (Chester LabNet, Tigard, OR) for elemental composition using EPA Method IO-3.3 (X-ray

fluorescence [XRF]). Filter samples were collected at approximately the beginning, middle, and end of each test period to represent the entire operating cycle using the same type particle probes as ASTM 2515-11 described above. For the 47-mm quartz filters, three samples of one hour each were collected. In the case of the three 25-mm filter sets, the sampling time was 20 minutes each.
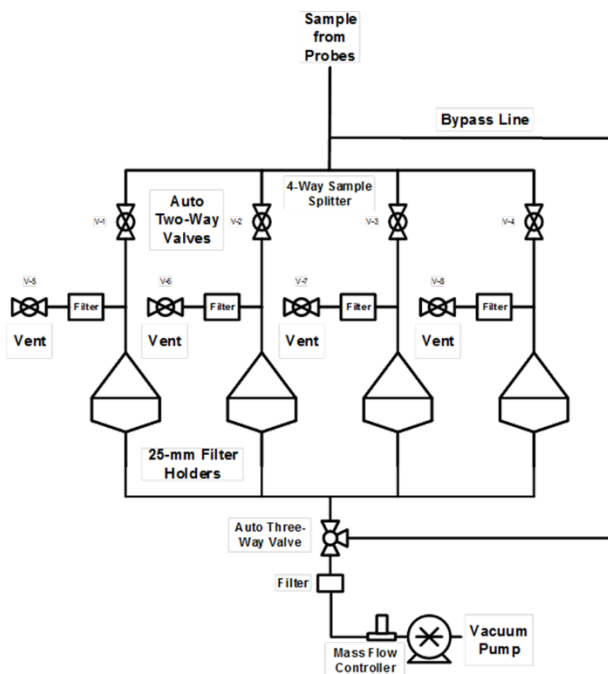
Figure 3-1. Diagram of multi-filter sampler

3.2.8 Black Carbon Measurements (Aethalometer and PAX)

The AE-22 Aethalometer™ (Magee Scientific, Berkeley, CA) is an instrument that provided a near real-time readout of the concentration of BC aerosol particles. The Aethalometer™ uses a continuous filtration and optical absorption measurement method to give a continuous readout of optical black carbon (OBC) real-time data. The Aethalometer used the SW:AF985d4 software package.

A PAX photoacoustic extinctiometer (DMT, Longmont, CO) using the PAX.exe software package was also used for the on-line measurement of optical black carbon. The primary quantity reported by the instrument is the absorption coefficient B_{abs}. The instrument also measures aerosol scattering with an inverse nephelometer and a photomultiplier tube, which reports the scattering coefficient B_{scat}. Both light absorption and scattering coefficients were measured with a 1-s sampling rate.

The AE-22 and the PAX sampled emissions from the secondary dilution manifold. The diluted emissions were split between the instruments using a custom-made stainless steel aerosol splitter.

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3.2.9 PM Semivolatile Organic Compounds (SVOCs)

After analysis for OC/EC, the 47-mm quartz filters were subsequently solvent extracted and analyzed for SVOCs using the methodology described in Section 4 below. Like OC/EC, the samples analyzed represented the three one-hour sampling periods conducted during each test run.

3.2.10 Bottom Ash Evaluation

Grab samples of the bottom ash were taken at the end of each test from the ash drop-out inside the unit, cooled, and stored in sealed glass containers. Sample aliquots were sent to Standard Laboratories, Inc. to be analyzed for elemental composition by atomic absorption (AA) spectroscopy and mass loss upon heating in air (loss-on-ignition; LOI).

3.2.11 Fuel Sampling

A composite fuel sample was collected for each fuel type, hardwood pellets and switchgrass pellets, for subsequent fuel analysis. Each fuel type was received as a single lot and considered homogeneous. Each composite was comprised of 3 grab samples recovered from separate bags of fuel. Samples were taken from newly opened bags prior to adding the remainder to achieve bin fill level prior to testing. Grab samples were acquired on separate test days and stored in sealed freezer bags prior to shipping for analysis.

3.3 Sample Recovery and Preservation

Following completion of a test run, each time-integrated sampling train was recovered in a clean area, and the cleanup procedure started as soon as the probe was removed from the source location. During transport between the test facility and the designated recovery (an adjacent laboratory), both ends of the heated probe and openings of the impinger assembly were covered with aluminum foil or sealed with ground glass caps. The organic rinses of the train were performed as specified in EPA Method 23.

Samples were recovered on-site in the inorganics preparation laboratory located adjacent to the test facility. Sample recovery procedures were followed as detailed in the appropriate methods. Accordingly, samples shipped to outside laboratories were preserved as prescribed in the method(s).

3.4 Sample Collection and Frequency

The sampling methods and sampling frequency for all the target pollutants are listed in Table 3-2. Details of each method is described in detail in Section 4 below.

Table 3-2. Measurement Methods and Sampling Locations

Pollutant	Measurement Technique	Test Method or Instrument	Time Scale	Sampling Location
Total PM emissions	Filter gravimetric	Modified ASTM Method E2515-11	Time-integrated	Dilution duct
Particle size distribution (including $PM_{2.5}$)	On-line cascade impactor	Dekati ELPI	Continuous	Dilution duct
Particle morphology[b]	SEM/TEM	Thermophoretic sampler (TPS) + analysis of TEM grids	Time-integrated	Secondary dilution manifold
OC/EC	TOT	NIOSH Method 5040; pre-fired quartz filters in multi-sampler	Time-integrated	Dilution duct
		Sunset model 4 OC/EC analyzer (optional)	Semi-continuous	Secondary dilution manifold
BC	Optical absorption	Magee AE-22 Aethalometer and PAX extinctiometer (optional)	Continuous	Secondary dilution manifold
Total gas- and particle-phase PAHs	Impingers by GC/LRMS and XAD resin + filter by GC/LRMS	Modified EPA Method 5, 0010, 23, and 26A (filter + XAD + impingers)	Time-integrated (1 sample/test)	Stack
PCDD/Fs	XAD/filter by high-resolution GC/MS			
HCl	Impingers by ion chromatography			
VOCs and carbonyls	SUMMA canisters by GC/MS and DNPH cartridges by HPLC	EPA Methods TO-15 and TO-11A	Time-integrated (2 samples/ test)	Dilution duct
Filter-based SVOCs	GC/MS	Thermal extraction of quartz OC/EC filters	Time-integrated	Dilution duct
Particle elemental composition	XRF	Analysis of Teflon filters in multi-sampler by EPA Method IO-3.3	Time-integrated	Dilution duct
Bottom ash	Loss on ignition (LOI)	Muffle furnace or thermal gravimetric analysis	1 sample/test	Grab samples
	Elemental composition	AA		
SO_2	FTIR	IMACC	Continuous	Dilution duct
CO	Non-dispersive infrared (NDIR) analysis	EPA Method 10B	Continuous	Stack
CO_2	NDIR	EPA Method 3A	Continuous	Stack and dilution duct
O_2	Paramagnetic analysis	EPA Method 3A	Continuous	Dilution duct
NOx	Chemiluminescence analysis	EPA Method 7E	Continuous	Dilution duct
THC	Heated flame ionization detector (FID)	EPA Method 3C	Continuous	Dilution duct

Pollutant	Measurement Technique	Test Method or Instrument	Time Scale	Sampling Location
CH$_4$	FTIR	IMACC	Continuous	Dilution duct

4   Measurement Methods and Procedures

Established methods were used to measure the thermal parameters and various pollutants of interest described below. For standardized EPA and ASTM methods, no other written procedure is generally required. However, for non-standard methods, a specialized protocol is available and was used in the program.

4.1   Heat Load Demand Measurements and Efficiency Determination

Heat load represents the heat delivered through the heat exchanger to cooling water on this test facility and is regulated by the flow of cooling water provided to the heat exchanger. Heat load was determined as the product of the mass flow of cooling water, the heat capacity of the cooling water, and the difference in temperature of the cooling water exiting and entering the heat exchanger as presented above. The temperature of the water circulating to the PBHH does not factor into the heat load calculation but is important in determining the amount of cooling water required to produce a specified heat load.

Mass flow of cooling water was controlled by a manually controlled rotameter at the inlet to the heat exchanger. Volumetric flow was manually recorded at 10-minute intervals during testing and converted to mass flow using a density of 8.34 pounds per gallon. Mass flow was corrected/calibrated using timed catches of water flowing through the heat exchanger at 11 L/min (3.0 gallons per minute). Volumetric flow was adjusted based on real time estimates of heat load with some consideration for the expected changes in PBHH water inlet temperature. The temperature of the inlet water changes during the firing cycle resulting in changes in heat transfer through the heat exchanger.

Temperatures across the heat exchanger were measured by Type K thermocouples and logged to a Personal Daq/55 and PDQ2 expansion module data acquisition system (Measurement Computing Corporation, Norton, MA). The analog outputs of the thermocouples were connected to a DAS for monitoring and recording with a sampling frequency of 1 second.

Efficiency is calculated based on the total energy transferred to the cooling water during the tests and the total energy input during the test: the gross calorific value of fuel fed to the PBHH. The amount of fuel fed to the PBHH is determined by the mass of fuel added to the fuel hopper during each test to maintain a constant volume in the hopper.

The gross calorific value (aka higher heating value) of fuel fed was determined by fuel analysis on an as received (wet) basis. Fuel samples were analyzed for Proximate (ASTM D2961, D3302, D3173, D3175M, D3172, D3174), Ultimate (ASTM D4239 METHOD B, D3178, D5373, D3176), and gross calorific value (ASTM D5865) by Standard Laboratories, Cresson PA. Carbon content, a component of Ultimate analysis, was used for subsequent dilution calculations. In addition, the ash mineral content of the fuel was analyzed by ASTM D2795 and ASTM D3682.

4.2   Equipment Calibration

System preventive maintenance was performed prior to the start of the test program. All major components were checked to ensure operability and repaired or replaced if required. The EPA Metrology Laboratory calibrated instruments such as meter boxes for sample volume prior to the start of the sampling program. Laboratory equipment maintenance is conducted as recommended by the manufacturer on an as-needed basis. Any leaks developed were repaired, parts lubricated as recommended by the manufacturer, and manometers filled and checked for leaks. Replacement parts, including fuses, pumps, spare tubing, compression fittings, etc., were maintained in the laboratory to minimize downtime. Specific procedures are outlined below.

4.2.1   CEM Calibration Procedures

CEM calibration is performed using various standard gases (Airgas Specialty Gases, Durham, NC) similar to the calibration procedures outlined in EPA Method 7E. A three-point calibration (zero, mid, and span) was made prior to beginning the test program except for the dilution duct CO_2 CEM; no mid-range calibration gas was available upon determining expected duct concentration. Range considerations necessitated a relocation of dilution duct CO immediately prior to beginning the test program resulting in loss of the three-point calibration for this instrument. A two-point bias check was made daily before each test and a two-point drift check after each test, using the same zero and span gases. All gas cylinders used for calibration are certified by the suppliers that they are traceable to NIST standards within manufacturer-specified limits.

4.2.2   Sampling Equipment Calibration

EPA certified methods require that a laboratory record be maintained of all calibrations. The requirements are based on the standard reference test method from which each respective method was derived. The method specifies minimal calibration activities – standard pitot need not be calibrated but should be inspected and cleaned, if necessary, prior to each certification test.

The volume metering systems were calibrated prior to the testing by the EPA Metrology Laboratory using a wet-test meter, as permitted in the method. All thermocouples were calibrated before and after the project. Thermometric fixed points (i.e., ice bath and boiling water) are adequate standards for this task. These calibrations were also performed and documented by the EPA Metrology Laboratory. The portion of the volume metering system from the pump to the orifice meter must be leak checked following each test, using the procedure described in EPA Method 5, section 5.6. Barometers must be calibrated semiannually by reference to a mercury

barometer or a local National Weather Service station. Corrections should be made at a rate of -0.1 in mercury (Hg) per 100 ft of elevation above sea level.

All instrument mass flow controllers and meter boxes were calibrated annually by the EPA Metrology Laboratory and documented accordingly.

4.2.3 On-Line PM Instrumentation

Instruments were calibrated prior to the start of experiments according to the manufacturer's instructions, unless noted. Specific information on the use and calibration of each instrument is covered in instrument-specific manuals or Miscellaneous Operating Procedures.

4.3 Continuous Monitoring of Gaseous Pollutants

4.3.1 CEM Bench

Several primary gaseous flue-gas constituents were analyzed continuously using a CEM system that includes monitors for CO, CO_2, O_2, NO_x, and THC. The analog outputs of the analyzers were connected to a Personal Daq/55 and PDQ2 expansion module data acquisition system (Measurement Computing Corporation, Norton, MA). The analog outputs of the analyzers are connected to a DAS for monitoring and recording with a sampling frequency of 1 second.

Sample gases are extracted for CEM analysis through a fixed stainless-steel probe at each location. Sample from the stack was passed through a sample cooler to remove water and transported to the CEM in Teflon tubing. Sample from the dilution duct was extracted with a heated head pump and transported to a manifold through heated Teflon tubing. The dilution duct sample was then split with moist sample transported to the total hydrocarbon analyzer through heated Teflon tubing while the remaining sample was passed through a sample cooler to remove water and transported to the CEMs in Teflon tubing.

Note: Analysis subsequent to data collection, indicated that these CEM measurements were problematic, inconsistent with species mass balances, and in poor agreement with parallel FTIR measurements. Further investigation revealed the presence of a systemic leak in the CEM plumbing. As a result, the CEM data are not included. However, except for measurements of CO_2 and CH_4, parallel FTIR measurements of CO, O_2, and NO_x are substituted. Description of the CEM measurements is included here for completeness.

The CO_2 in the stack were determined using a California Analytical Instruments (Orange, CA) Model ZRH NDIR analyzer. The CO_2 in the dilution duct were measured using a LI-COR (Lincoln, NE) Model 820. These analyzers operate by directing identical infrared beams through an optical sample cell and a sealed optical reference cell. A detector located at the opposite end of the cells continuously measures the difference in the amount of infrared energy absorbed within each cell. This difference is a measure of the concentration of the component of interest in the

sample. The infrared gas analyzer measures gas concentration based on the principle that each type of gas component shows a unique absorption line spectrum in the infrared region.

CO was measured in the dilution duct using a California Analytical Instruments (Orange, CA) Model 300 NDIR analyzer operating on the same principal as CO_2 analyzers. This unit was relocated from the stack immediately prior to beginning the test program to provide adequate range for the location.

The NO_x analyzer (Model 400-HCLD, California Analytical Instruments, Orange, CA) to be used in the study operates via chemiluminescence. Sample is directed to a converter where the NO_2 component is dissociated to form NO. A small portion of the sample flow is metered into a vacuum (reaction chamber) where it is allowed contact with an excess of ozone from an integral ozonator. NO and ozone react to form NO_2, a portion (~10% at room temperature) of which is elevated to an excited state. The excited molecules return to ground state and give off light of a characteristic frequency. This light is detected by a photomultiplier tube, and the output is amplified and scaled to read directly in parts per million by volume.

Total hydrocarbon concentrations were measured using a California Analytical Instruments Model 300 heated FID.

4.3.2 Closed-Cell FTIR

An extractive cell based FTIR spectrometer was configured for sampling from the dilution duct. The FTIR system used for this study was an Industrial Monitor and Control Corporation (IMACC; Round Rock, TX), spectrometer equipped with a Micheleson inferometer, a zinc selenide beam splitter, a mercury cadmium telluride detector, and a 12-L, 1-m multi-pass gas cell with gold-coated mirrors and a stainless steel coated body. The interferometer performs an optical inverse Fourier transform on the entering IR radiation. This modulated IR beam passes through the gas sample where it is absorbed to various extents at different wavelengths by the various molecules present. Buried in the IR spectrum is the absorption "fingerprint" of all gases in the air sample through which the IR beam passes. This is caused by IR radiation interacting with the molecules and the interaction resulting in molecules absorbing specific wavelengths or "colors" of the radiation. The absorption adds energy to the molecule and causes it to vibrate and rotate faster. The vibrations and rotations of molecules are dictated by their structure. This means the patterns of "colors" that are absorbed are also unique to each molecule. The presence of a specific pattern is unequivocal evidence of the presence of a specific compound and the intensity of the absorption is proportional to the concentration of the compound in the path.

The IR source used in the FTIR is a SiC ceramic at a temperature of 1550 K. The IR radiation goes through an interferometer that modulates the infrared radiation. Spectra were produced from 300 co-added interferograms (5-minute scan time) that were apodized with Happ-Genzel function, and then transformed to yield a single-beam spectrum with a nominal 0.5 cm^{-1} resolution. Reference spectra were generated using E-trans from the Hitran database, and the use of the Pacific Northwest

Laboratories (PNL) spectral library. A graphical software package was used to create and test custom analysis routines for the FTIR. All routines created can have full linearity correction, lines-shift correction, and cross interference correction as well as dynamic reference selection to provide real-time matching of the method.

The IMACC spectrometer was interfaced to a laptop computer via computer cables. Spectral data were collected at 5-minute intervals at a nominal 0.5 cm^{-1} resolution using IMACC FTIR Software Suite. For this experimental design, a pump system was installed to pull the sample through the cell at a rate of approximately 45-55 liters per minute. The sample was drawn from the constant volume sampler. The sampling lines were heated to 100 °C.

For each analyte of interest there is a specific wavelength which is measured and the concentration values are determined. Interfering species are identified as well. Single beam spectra collected during the testing phase were converted to absorbance spectra. This was done by either selecting a background spectrum prior to running a burn or by generating a synthetic background spectrum. The IMACC software suite and IMACC Quantify was used to generate the concentration values. It allows the user to shift references as needed, save residuals and do linearity and bias plots. The software is based on linear regression.

4.4   Volatile Organic Compound and Carbonyl Analyses

VOCs were analyzed by EPA Method TO-15 in SIM mode using an Agilent Model 6890/5973N GC/MS (Agilent Technologies, Santa Clara, CA) using Agilent ChemStation E.02.01 software. Sample aliquots were taken from canister samplers by an Entech 7500A Autosampler (Entech Instruments Inc., Simi Valley CA) and preconcentrated using an Entech 7150 Preconcentrator followed by GC/MS analysis. NIST traceable VOC gas standards (Linde Electronics and Specialty Gases, Stewartsville, NJ) were used to prepare calibration standard samples in canisters with an Entech 4600A Dynamic Diluter, which were used to calibrate the GC/MS instrument response. Samples were analyzed within a week of sampling. A lab blank sample was analyzed with each GC/MS analytical sequence and was used to blank correct sample concentrations. The QC procedures and data validation criteria specified in the method SOP were followed.

N$_2$O concentrations were measured in the SUMMA canisters by analyzing canister samples on a SRI Model 8610C GC with an electron capture detector (SRI Instruments, Torrance, CA). The GC uses a backflush system controlled by a 10-port valve and a 183-cm (6-ft) Hayesep D precolumn with a 366-cm (12-ft) Poropak Q analytical column. The GC detector is a 5 mCi 63 Ni 140 BN electron capture detector. The makeup gas was 10% methane in argon (Airgas National Welders; Raleigh, NC). The instrument was calibrated using specially prepared calibration standard samples in canisters. Calibration standards were prepared from a certified N$_2$O cylinder (Airgas-National Welders; Raleigh, NC) following the same methods as preparing the VOC calibration standards in canisters using the Entech 4600A Dynamic Diluter.

Carbonyls were analyzed via EPA Method TO-11A by HPLC. DNPH cartridge samples were extracted with 6 mL of carbonyl-free acetonitrile (Burdick and Jackson). The exact volume of each extract was determined gravimetrically and the density of acetonitrile. The extracts were analyzed

by HPLC using an Agilent Model 1100 HPLC with a diode array detector and Agilent ChemStation A.10.02 software. Samples were extracted and analyzed within 2 weeks of sampling. A lab blank DNPH sample was analyzed with each HPLC analytical sequence and was used to blank correct sample concentrations. Carbonyl-DNPH standards (Sigma-Aldrich, St. Louis, MO) were used to calibrate the HPLC instrument response for each target analyte. The extraction and HPLC analytical procedures for the carbonyl analysis followed MOP 2700, Standard Operating Procedure for Determination of Carbonyls in Ambient Air Collected on DNPH-Coated Silica Cartridges Using the Agilent 1100 HPLC.

4.5 Gaseous PAH Analyses

The target PAH compounds from the Method 23 train filter and sorbent were analyzed using modified EPA Method 8270D on a Thermo GC Trace 1310/ISQ (Thermo Scientific, Inc., Milan, IT/Austin, TX USA) using Xcaliber 2.2 software. Labeled standards for PAHs were added to the XAD-2 trap before the sample is collected. The surrogate recoveries were measured relative to the internal standards and are a measure of the sampling train collection efficiency. Internal standards were added before extraction. Before analysis, a third set of labeled standards were added to quantitate the recovery through the extraction and concentration process. The semivolatile XAD and filter samples were prepared for analysis by solvent extraction using toluene and then a concentration by three-ball Snyder column; then the sample was split for PCDD/F and PAH analysis. The portion for the PAH analysis was 10% of the total. The PAH portions were filtered through silica gel and concentrated to final volume in a TurboVap II using nitrogen blowdown. The extract was prescreened to determine the level of dilution needed for PAH analysis. Samples were analyzed using selected ion monitoring (SIM) mode. All surrogate standard recoveries fell within the standard method criteria (25% to 130%) except Naphthalene which was below on several samples. This is an early adoption of the three-spike style of standards for PAH analysis, modeled after the three-spike style of Method 23 for PCDD/F.

After being split for HCl analysis, select impinger solutions were extracted by liquid-liquid extraction and screened for PAHs. The amount of PAH was <5% of the amount found on the filter and XAD resin, therefore the impingers were not extracted and analyzed for PAHs.

4.6 Gaseous PCDD/PCDF Analyses

The Method 23 XAD and TX40 filter samples were extracted and cleaned up according to EPA Method 23 and analyzed for PCDD/F using HRGC/HRMS consisting of a Hewlett-Packard gas chromatograph 6890 Series (Agilent Technologies Inc., Wilmington, DE) equipped with a CTC Analytics Combi PAL autosampler (CTC Analytics, Switzerland) and coupled to a Micromass Premiere (Waters Inc., UK) double-focusing high resolution mass spectrometer using Masslynx 4.1 software. The chromatographic column used was an RTX-Dioxin 2 (Restek, Bellefonte, PA, USA).

The standards used for chlorinated dioxin/furan identification and quantification were a mixture of standards containing tetra- to octa-PCDD/F native and C-labeled congeners designed for modified EPA Method 23 (ED-2521, EDF-4137A, EDF-4136A, EF-4134, ED-4135, Cambridge Isotope Laboratories Inc., Andover, MA). The PCDD/F calibration solutions were prepared in-house and contained native PCDD/F congeners at concentrations from 0.5 (ICAL1) to 20 (ICAL6) ng/mL.

Initial concentration steps were performed using a three-ball Snyder column, and then 10% of the extracts were separated for PAH analysis. The remainder of the extract were combined, concentrated, and solvent-exchanged into hexane. The extract was cleaned by a PowerPrep (Fluid Management Systems Inc., Watertown, MA) for PCDD/F analysis. The PowerPrep is an automated device that performs the cleanup specified in Method 23. A keeper (decane) is used after extract cleanup with the PowerPrep to prevent samples from going to dryness.

4.7   Gaseous Halide (HCl) Analyses

The sodium hydroxide solutions from the Method 23 samples were analyzed for HCl according to Method 26A analytical procedure. Samples were analyzed for chloride using a Dionex (Sunnyvale, CA) DX500 chromatography system. This HPLC system used a GP40 gradient HPLC pump, a CD 20 conductivity detector, and an AS40 automated sampler. The IC system used a Dionex AS12a 4 mm x 200 mm analytical column, and an AS12A 4 mm x 50 mm guard column. The analysis used a 2.7 mM Na_2CO_3 and 0.3 mM $NaHCO_3$ eluent pumping at 1.5 mL per minute. The chloride calibration standard was prepared by Dionex (Lot# 23-116VY) and is traceable to NIST Standard 3182. Standards and sample 1 to 10 dilutions were prepared volumetrically using an Eppendorf (Hamburg Germany) Repeater M4 pipette.

4.8   Total PM Mass Analyses

For the determination of total PM mass emissions on a time-integrated basis, the PM emission measurements adhered to the procedures outlined in ASTM Method E2515-11, Standard Test Method for Determination of Particulate Matter Emissions Collected by a Dilution Tunnel with the exceptions noted in Section 3.2.1. The filter pre- and post-weighing was performed in the EPA temperature and humidity-controlled weigh room using an ATI Cahn Model C-44 (Thermo Fischer Scientific, Waltham, MA) analytical balance. The weighing room is kept at 22 ± 2 ° C and 35 ± 5 % relative humidity where the filters are equilibrated for at least 24 hours before tare and final weighing.

4.9   Particle Number and Size Determination

As discussed above, particle number concentration and size distribution were determined using the Dekati ELPI instrument. The instrument was set up to perform one complete scan every 10 sec during the entire 6-hr run. The total number concentration was calculated by averaging the total particle count for all the impactor stages during each scan conducted over the 6-hr test period. A composite particle size distribution (PSD) was also produced by calculating the average

differential number ($dN/dlogD_p$) in each size bin for each test and combining these into a complete PSD. The composite PSD was then converted to a mono-modal lognormal distribution and summary statistics calculated from the data.

Daily checks on the ELPI were performed by zeroing the electrometers using a flush of high-efficiency particulate air (HEPA) and by performing a leak check, flow rate check, and instrument zero check using a HEPA filter. Multiple pre-test zeroing of the electrometers was performed to assure reliable measurements.

4.10 OCEC and Black Carbon Analyses

4.10.1 Laboratory OCEC Analyses

Particulate OC/EC analysis of 47-mm and 25-mm quartz filter samples was performed in-house according to a modified version of the NIOSH Method 5040 using a Sunset Model A TOT carbon analyzer (Sunset Laboratories, Portland, OR) running the Sunset NIOSH870.par software program. The laboratory analysis consists of heating up a filter section in steps from ambient temperature to 870 °C. Carbon species are volatilized off the filter, oxidized to CO_2, reduced to CH_4, and quantified with a flame ionization detector (FID). Laser transmittance is used to correct for pyrolyzed OC. The split between organic (low temperature) and elemental (high temperature) carbon is operationally defined. The detection limit is 0.2 µg carbon/cm².

4.10.2 Semi-Continuous OCEC Analyzer

Operation of the Sunset Laboratories Model 4 semi-continuous OC/EC analyzer followed the procedures outlined in the manufacturer's operating manual. Like the laboratory system, the instrument also ran the Sunset NIOSH870.par operating and analysis software. The principle behind this instrument is very similar to that of the OC/EC model instrument described in Section 4.10.1 except CO_2 is measured directly with a non-dispersive infrared spectrometer. As with the integrated sample described above, quartz filters used with the semi-continuous instrument were pre-conditioned in an internal oven following the instrument procedures prior to sampling. Each sample has an area of 1.2 square centimeters and was collected semi-continuously, from the secondary dilution system (discussed in detail in Section 2.1) for ten minutes followed by onboard analysis of the sample for eighteen minutes. These measurements were considered non-critical as they were sampled in addition to the collected time-integrated filters discussed in Section 4.10.1.

4.10.3 Optical Black Carbon

The AE-22 Aethalometer provided a continuous measurement (10 s time resolution) of the attenuation at 880 nm of PM deposited on a filter spot. The attenuation is converted to OBC concentration using the manufacturer's calibration. Filter based measurement of black carbon attenuation is subject to a loading artifact leading to an underestimate of the OBC concentrations. As strongly absorbing PM loads on the filter, the optical path length through the filter is reduced

as the light scatter is reduced by the aerosol. The black carbon concentration is corrected by method derived by Virkkula et al (2007):

$$BC_{corrected} = (1 + k \times ATN) \times BC_{measured}$$

Where BC$_{corrected}$ is the black carbon concentration corrected for filter loading, k is the correction factor which is dependent upon the particle properties, ATN is the filter attenuation at 880 nm and BC$_{measured}$ is the concentration reported by the AE-22. The k factor cannot be estimated when black carbon concentrations are changing through filter advances. To overcome this limitation a comparison between BC$_{corrected}$ and B_{abs} measured by the PAX was made to determine the k factor that provided the highest correlation between the two measurements.

4.11   PM Elemental Analyses

Elemental analyses of Teflon filter samples were performed by Chester LabNet using XRF as described in EPA Method IO-3.3. This method is applicable to the quantitative analysis of aerosols deposited on a variety of filter types for the elements sodium (Na) through uranium (U). The QC checks set by the laboratory include a QA standard, which is a multi-element thin-film vapor-deposited National Institute of Standards and Technology (NIST) certified standard on Mylar manufactured by Micromatter, Inc. (Vancouver, BC, Canada). Elements analyzed were aluminum (Al), silicon (Si), potassium (K), sulfur (S), calcium (Ca), titanium (Ti), vanadium (V), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), and lead (Pb).

4.12   Particle Morphology

Samples for particle visualization were deposited on TEM grids and analyzed by R. J. Lee Group using a Transmission Electron Microscope. Samples were analyzed for particle count to determine aerosol concentration, particle morphology and elemental composition.

4.13   PM Semivolatile Organics Analyses

Sixty-one pre-heated (550 ºC, 12 h) quartz filters were collected as part of the study. These filters were collected with the intent of performing organic matter speciation. Prior to speciation, all quartz filter samples were stored at -65°C for less than one year.

The organic and elemental carbon (OC and EC) composition on each PM filter (1.5 cm^2) was measured using thermal-optical analysis and a modified NIOSH 5040 method (Cassinelli and O'Connor, 1998). Total extractable OC was estimated using these OC-EC values. To ensure adequate OC mass for a successful gas chromatography mass spectrometry (GC-MS) analysis, a sample compositing strategy was required. The OC sample loads and resulting filter composite strategy is available upon request. Past studies have demonstrated that at least 100 ug of filter OC is required to achieve reasonable GC-MS results (or about 0.3 ug OC for a 300 µl final extract volume). However, lower OC concentrations were used for this data set due to the high sensitivity of the GC-MS. All filter-based, organic compound emission factors are normalized to OC in this report.

The extraction and GC-MS conditions used for this investigation were described earlier (Hays et al., 2013; Hays et al., 2011; Hays et al., 2002). Briefly, prior to undergoing a solvent extraction, each quartz filter composite was placed in a 50-ml glass jar and spiked with an internal standard mixture containing d-8 naphthalene and C-13 levoglucosan compounds. Internal standard spike volumes changed on the basis of anticipated final volume of extract. Use of the internal standard method allowed us to compensate for extraction losses and changes in MS response over 24 hr. Filters (typically *n*=3) were extracted twice (50 min and 5 min) ultrasonically with roughly 10 ml of a 2/2/1 vol/vol hexane, benzene and isopropanol solution (HIB). Each extract was filtered with a 0.2 µm PTFE filter (Supelco, Iso-Disc[TM]) and then concentrated to between 0.3 ml and 1 ml depending upon the OC concentration extracted. Sample extracts underwent derivation to convert the organic acids and levoglucosan to their methyl ester and silyl-ester analogs. Methylation was performed by reacting 50 µl of sample extract with 50 µl of in-house prepared diazomethane reagent and 15 µl of methanol and allowing the reaction to proceed for at least 1 hour. The hydroxyl groups on levoglucosan were silylated by reacting 10 µl of sample extract with 50 µl of BSTFA reagent (Sigma Aldrich, St. Louis, MS). The reaction was allowed to proceed for 30 minutes at 70°C and then allowed to sit at room temperature overnight to ensure completion. The neutral and derivatized extracts were analyzed as described below.

Sample extracts were analyzed by GC-MS for a total of 115 organic compounds representing eleven compound classes. The compound classes included normal-alkanes, branched-alkanes, polycyclic aromatic hydrocarbons (PAH), anhydrosugars, aromatic, resin, alkanoic, and fatty acids, aliphatic diacids, phytosterols, and methoxyphenols. The methoxyphenols were analyzed using thermal extraction (TE)-GC-MS (TDS3, Gerstel Inc, Baltimore MD, and Agilent Technologies 6890/5973 MS [q]). For TE-GC-MS, a 1 µl volume of each sample extract was injected manually onto a baked Carbotrap F/Carbotrap C adsorbent tube. The solvent from each sample spike was evaporated by flowing nitrogen across each adsorbent tube for 60 seconds at a rate of 50 ml/min. All other organic compounds were analyzed using a GC-MS (Agilent 7673A/7000 series triple quadrupole [qqq] system interfaced to a liquid sample auto-injector).

4.14 Fuel Analyses

Ultimate, proximate, and ash mineral content by Standard Laboratories, Inc. ASTM Methods D2961, D3302, D3173, D3175M, D3172, D3174, D4239 METHOD B, D3178, D5373, D3179, D3176, D5865, D4208, D2795, and D3682 were used during the analyses conducted.

4.15 Bottom Ash Analyses

Collected bottom ash samples were analyzed for mass loss upon heating in air or oxygen atmosphere by Standard Laboratories, Inc. Bottom ash samples were also analyzed by Standard Laboratories, Inc. for elemental composition by AA spectroscopy using ASTM D3682.

5 Data Analysis

The overall objective of this project is to assess the energy efficiency of the PBHH and the emissions of target compounds as a function of fuel input, energy input, and energy output. Energy efficiency calculations have been limited to thermal efficiency considering the heat delivered to a simulated load and the gross calorific value of the fuel fed to the PBHH. Emissions are calculated from measured concentrations and dilution duct flow. Measurements from the stack and from secondary dilution are corrected to dilution duct concentrations in the process of calculating emissions.

5.1 Thermal Efficiency

Thermal efficiency is used to determine the overall ability of the system to generate useful heat by transferring it to meet the load demand (thermal efficiency). Thermal efficiency in this project was defined as the heat delivered to the water/water heat exchanger (heat output) divided by the calculated energy input of the fuel (gross calorific value [HHV]) of the heater defined as:

$$\eta_t = \frac{Q_o}{Q_i}$$

(5-1)

where:

η_t = the thermal efficiency,
Q_o = the useful heat delivered to cooling water,
Q_i = the energy input to the heater during the test.

The useful heat delivered was calculated using the inlet and outlet temperatures of the cooling water for the heat exchanger used to simulate the heat load demand, the water flow rate at each temperature reading, and the heat capacity of water. In practice, the heat transfer rate was averaged over the entire test and multiplied by the run time:

$$Q_O = \frac{\sum_1^n F C_p \, \Delta T}{n} t$$

(5-2)

where:

F = mass flow rate of water,
C_p = heat capacity of water (4.18 kJ/kg -°C),
ΔT = temperature difference between cooling water outlet and cooling water inlet,
= $T_0 - T_i$
T_0 = outlet temperature,
T_i = inlet temperature, and
t = run time

The energy input was calculated from the mass of fuel fed during the test and the gross calorific:

$$Q_i = M_f \cdot HHV_f$$

<div align="right">(5-3)</div>

where:

M_f	=	mass of fuel burned and
HHV_f	=	higher heating value of the fuel

5.2 Emission Calculations

For each test run, emission factors for the target pollutants were calculated in terms of mass of fuel burned, energy input, and energy output. The mass emission (M_x) for a set burn time t for each target compound is calculated in the dilution tunnel as follows:

$$M_x = \Sigma_t(C_{x,t} - C_{x,a}) \cdot V \cdot t$$

<div align="right">(5-4)</div>

where:

$C_{x,t}$	=	the concentration (mass/volume) of the target compound x in the dilution duct,
$C_{x,a}$	=	the ambient concentration (mass/volume) of the target compound x, and
V	=	the volumetric flow rate (volume/time) in the dilution tunnel at time t.

Concentrations from the Method 23 train (HCl, PAH, PCDD/DF) at the stack are an exception to this procedure as no ambient concentration was available. Most concentrations were determined on a test average basis; volatiles and semi-volatiles (i.e. TO11 and TO15 samples) were split into two independent 3-hour samples. The ambient concentration for total PM utilized an ambient air sample extracted beside the PBHH during 100% load operation firing switchgrass pellets. Remaining concentrations were corrected with concentrations determined from dilution duct sampling with no firing (i.e. cold) of the PBHH.

Volumetric flow rate was determined by multiplying the average of the dilution duct velocity measured before and after each test by the cross-sectional area of the dilution duct at the point measured. The 10-inch duct had a cross-sectional area of 0.0506 m^2 (0.545 ft^2). Emission factors were calculated and reported in three bases: per mass of fuel burned, per unit of energy input, and per unit of energy output.

The emission factor per mass of fuel burned ($EF_{m,x}$) is calculated as:

$$EF_{m,x} = \frac{M_x}{M_f}$$
(5-5)

The emission factor per energy input $EF_{Input,x}$ is defined as the mass of pollutant (x) per fuel energy generated by the PBHH unit:

$$EF_{Input,x} = \frac{M_x}{Q_i}$$
(5-6)

The emission factor per energy output is defined as the mass of pollutant (x) discharged per useful room heat produced by the heating unit:

$$EF_{Output,x} = \frac{M_x}{Q_o}$$
(5-7)

5.3   Dilution Factor

Measurements made at the stack or after secondary dilution were corrected to dilution duct concentrations using a dilution factor. Due to failure in the CEM measurements, estimates were made for CO_2 concentrations in the dilution duct for use in dilution factor calculations. The average CO_2 in the dilution duct was estimated based on the mass of fuel burned in each test (M_f), the carbon concentration in the fuel from the ultimate analysis, and the volumetric flow rate determined for the test. The calculation estimates the volume of CO_2 emitted divided by the volume of flow in the dilution duct corrected for ambient CO_2 concentration:

$$C_{CO2,t} = \frac{M_f \cdot \%C}{100 \cdot t} \cdot \frac{1}{MW_{Carbon}} \cdot \frac{SV}{V} + C_{CO2,a}$$
(5-8)

where:

$C_{CO2,t}$	=	the CO_2 concentration in the duct,
$C_{CO2,a}$	=	the ambient concentration of CO_2,
$\%C$	=	the carbon concentration in the fuel (weight percent),
MW_{Carbon}	=	the molecular weight of carbon, and
SV	=	the specific volume of an ideal gas at 20 °C and 1 atmosphere.

Concentrations measured at the stack or on secondary dilution were corrected to dilution duct concentrations for emission calculations.

The dilution factor at the stack was based on the estimated dilution duct CO_2 concentration and the average stack CO_2 concentration:

$$DF = \frac{C_{CO2,t} - C_{CO2,a}}{Stack\ CO2} \qquad (5\text{-}9)$$

The dilution used for secondary dilution was performed with nitrogen containing minimal CO_2:

$$DF = \frac{C_{CO2,t}}{SD_{CO2,t}} \qquad (5\text{-}10)$$

where:

$SD_{CO2,t}$	=	secondary dilution CO_2 concentration during sample interval

Because the nature of operations and the short-term nature of the measurements taken on secondary dilution, each measurement was corrected using time specific dilution factors. Due to the quality of duct CO_2 measurements, time specific dilution duct CO_2 concentrations were estimated using the average dilution duct CO_2 measurements for the specific sampling time, average dilution duct CO_2 concentrations for total test time, and the average fuel based estimate of dilution duct CO_2 concentrations calculated as above:

$$C_{CO2,t} = \frac{Fuel\ Based\ Average\ CO2}{CEM\ Test\ average\ CO2} \cdot CEM\ sample\ average\ CO2 \qquad (5\text{-}11)$$

6 Quality Assurance and Quality Control

6.1 Overall Objectives
The overall objectives of the program were to:

1. Develop PM and gaseous emission factors and chemical source profiles for a PBHH operating at different load demand rates while burning multiple non-woody fuel types.

2. Determine the energy efficiency of the pellet-burning appliance using different fuel types and load demands.

3. Determine, if possible, the effect of non-woody fuel properties on the PM and gas-phase emissions as compared to premium wood pellets.

4. Assess, to the degree possible, any adverse effects of burning non-woody biomass fuels on the appliance tested.

All of the above objectives were met as discussed in Section 7 below except for the testing of multiple non-woody fuel types. In this study, due to resource constraints, only switchgrass pellets were evaluated.

6.2 Data Quality Objectives (DQOs)
The DQOs for the project are as follows:

1. Determine the total PM mass emission factor (g/kg fuel) and thermal efficiency within ± 25% (relative percent difference [RPD]) for duplicate measurements conducted on each fuel type at the same load demand.

2. Where possible, achieve an agreement within ± 25% (RPD) between the time-integrated and continuous measurement of the same pollutant or chemical characteristic.

3. Attain a data recovery and analysis of at least 90% of the samples and/or 90% of the continuous monitoring time scheduled for all sampling runs conducted.

4. If possible, ensure that the samples collected are representative of the normal operation of the appliance as determined by the comparison to any similar data published in the literature.

Regarding DQO 1 for total PM, the data shown in Table 7-5 below indicates that this goal was met for all fuel and load conditions apart from switchgrass combustion at 25% and 100% load. At 25% load, the RPD for the duplicate tests was ~ 35% and at 100% load ~ 40%. Even this level of agreement is remarkable due to the high variability in the emissions observed during each test and between test runs. For thermal efficiency, DQO 1 was met for switchgrass combustion at all load conditions but not for hardwood combustion. In the case of hardwood, the variation between tests

ranged from 30% for the Syracuse cycle to a factor of 2.5 for 25% load. This is not surprising due to the high variability seen from test to test.

For DQO 2, this goal was not met since there were no concurrent time-integrated and continuous measurements conducted for any of the parameters measured. In the case of DQO 3, the 90% goal was met for all samples collected and continuous monitoring conducted in the program. Finally, DQO 4 was met by comparing the data collected in this study to both prior work for NYSERDA conducted by NRMRL and data published in the literature as described in Section 8 below.

6.3   Data Quality Indicator Goals (DQIs)

DQIs were established for the measurement program as outlined in the approved Quality Assurance Project Plan (QAPP). The following sections provide the quality assurance and quality control activities for each set of parameters measured along with compliance with the DQI goals outlined in the QAPP and the implications on data quality for those not complying with a particular DQI.

6.3.1   Stack Testing and Thermal Measurement Parameters

Stack concentrations were calculated as emissions using the duct flow measured with the Shortridge airfoil. While this is consistent with the overall ASTM E2515 approach, it represents a deviation from the planned emission factor-based approach. The Shortridge airfoil calibration was checked before initiating the test program and was found to be within instrument specification of ± 7 feet per minute plus 3% of reading. Readings during the test program ranged from ~900 to 1300 feet per minute. As a result, stack flow measurements are expected to be accurate within ± 3.5%.

Thermal performance of the PBHH was determined by the heat transferred from hot water circulating through the boiler to cold water supplied by the facility. Cold water temperature entering and exiting the heat exchanger was measured with Type K thermocouples calibrated over the range of 10 °C to 100 °C. The expanded uncertainty for any single measurement was ± 0.93 °C at the heat exchanger inlet and ± 0.60 °C at the heat exchanger outlet. With one second polling over a 6-hour test, the random error around a run average temperature would be minimal. The combined standard uncertainty for each thermocouple (after calibration) was ± 0.06 °C

The chilled water flow through the heat exchanger was controlled and monitored through a rotameter. Flow through the rotameter was checked gravimetrically during hardwood testing (10/24/2016) and after completion of switchgrass testing (11/17/2016) yielding correction factors of 1.04 and 1.02 respectively. Accuracy is well within the DQI goal of ± 10 %. A 1.03 correction factor was applied to all flow readings, the average correction from both checks.

6.3.2 Continuous Emission Monitoring

CEM's sampled from both the PBHH stack and from the dilution duct. On conclusion of the sampling program, a substantial discrepancy was observed between the dilution duct CO_2 measurements and the CO_2 expected from fuel combustion. This anomaly had not been noticed during the test campaign due to the decision to forego routine direct calibration checks relying instead on bias and drift checks. Despite acceptable pre-campaign direct calibration, it was concluded that a leak must have developed in the sampling train. Low dilution duct CO_2 measurements were confirmed with analysis of TO15 samples for CO_2. The measurements for most pollutants at the dilution duct were abandoned in favor of what was considered more reliable FTIR measurements. The dilution duct CO_2 measurements were adjusted based on fuel use to allow time resolved estimates of dilution factors for measurements using secondary dilution off the duct. Discussion of other dilution duct CEM measurements has been omitted for brevity as they were not used in this report.

Prior to initiating the sampling program, the stack CO_2 CEM was calibrated directly to the analyzer with certified ($\pm$ 5%) calibration gas. Calibration checks, directly to the analyzer, were performed on 10/14/2016 with nitrogen, 9.0% CO_2 in nitrogen, and 18.1% CO_2 in nitrogen. Calibration error was found to be 2.49% of span for zero gas, 0.31% of span for mid-range gas, and -2.62% of span for high range gas. Daily bias checks were performed prior to testing except for the 10/25/2016 test; data acquisition difficulties resulted in testing delays on the 25th necessitating omission of this QA check. In addition, daily drift checks were performed after each test. Furthermore, on 11/10/2016 the upscale drift check failed to achieve lineout due to unexpected expansion of response time. Results for these checks are presented in Table 6.1. All data was corrected based on daily bias and drift checks.

Prior to initiating the sampling program, the dilution duct CO_2 CEM was calibrated directly to the analyzer with certified ($\pm$5%) calibration gas. Calibration checks, directly to the analyzer, were performed on 10/12/2016 with nitrogen and 4509 ppmv CO_2 in nitrogen. Calibration error was found to be 1.5% of span for zero gas and 0.2% of span for high range gas; no midrange gas was tested for this instrument. Daily bias checks were performed prior to testing except for the 10/25/2016 test; data acquisition difficulties resulted in testing delays on the 25th necessitating omission of this QA check. Furthermore, the bias check on 11/10/2016 failed to achieve lineout due to unexpected expansion of response time. In addition, daily drift checks were performed after testing.

The drift check failed to achieve lineout for 10/09/2016 test due to unexpected expansion of response time. Results for these checks are presented in Table 6.2. All data was corrected based on daily bias and drift checks.

Table 6.1. Daily Stack CO$_2$ Quality Assurance Checks

Date	10202016	10212016	10252016	10262016	10272016	11032016	11042016	11082016	11092016	11102016	11152016
Zero Bias	1.17%	-0.76%	NA	-1.19%	-1.46%	4.42%	-2.23%	-0.55%	0.06%	-0.29%	-0.55%
Upscale Bias	7.13%	3.81%	NA	4.81%	4.10%	2.55%	7.07%	2.93%	1.16%	3.68%	0.74%
Zero Drift	-1.93%	8.38%	NA	-0.27%	-0.84%	-6.65%	2.04%	0.61%	-0.34%	Failed	0.22%
Upscale Drift	-3.33%	-5.30%	NA	-0.71%	0.06%	4.52%	-1.12%	-1.77%	2.52%	Failed	2.60%

Table 6.2. Daily Dilution Duct CO$_2$ Quality Assurance Checks

Date	10202016	10212016	10252016	10262016	10272016	11032016	11042016	11082016	11092016	11102016	11152016
Zero Bias	-4.95%	-6.47%	NA	0.95%	1.15%	0.82%	0.85%	0.87%	0.97%	Failed	0.78%
Upscale Bias	1.20%	2.47%	NA	-8.31%	-11.76%	-10.05%	-9.59%	-10.84%	-8.26%	Failed	-7.99%
Zero Drift	-1.53%	1.29%	NA	0.20%	-0.42%	0.03%	-0.26%	0.10%	Failed	NA	0.14%
Upscale Drift	1.27%	-2.88%	NA	-3.45%	-2.98%	0.46%	-1.09%	2.58%	Failed	NA	-1.84%

6.3.3 Total PM and Filter Mass

Dry gas meters were calibrated approximately 4 months prior to beginning hydronic heater tests. Two dry gas meters were used to meter sample volumes for the paired PM trains and a third dry gas meter used for ambient air PM blank train. All calibration readings were within 2% of the average gamma. No further pre-test volume check was performed; however, the accuracy of the volume measurements was confirmed by successful calibration drift checks after the test program. Drift was well within ± 5% drift tolerance: -2.2% and 0.7% for the paired PM train meters and 0.7% for the ambient air PM train meter.

All glass fiber filters for PM were weighed to constant weight with a stability requirement of ± 0.5mg as associated with Method 5. Except for two filters for one hardwood 25% Load run (10/21/2017), all filters were stable at < ± 0.07 mg. Total catch per train ranged from 2.059 mg to 25.927 mg. Filters were weights were checked against a standard 200 mg weight with a tolerance of 0.003 mg.

All PM concentrations were corrected for ambient air PM contributions. Ambient air was sampled near the PBHH while running at full load with switchgrass on 11/16/2016. For the majority of measurements, the ambient background was less than 5% of the average test concentration. For the hardwood 100% load test on 10/19/2016, ambient background was 5.6% of the measured PM concentration. For the hardwood Syracuse load tests on 10/26 2016 and 10/27/2016, ambient background was 15% of measured PM concentration for both tests.

6.3.4 Total Halide Emissions

Samples collected for halide determination were collected from the Method 23 train used for PAHs and PCDD/Fs sampling from the PBHH stack prior to dilution. Two meter boxes were used during the testing for the Method 23 and HCl tests; both were calibrated ~ 4 months prior to beginning hydronic heater tests. All calibration readings were within 2% of the average gamma. No further pre-test volume check was performed; however, the accuracy of the volume measurements was confirmed by successful calibration drift checks after the test program. Drift was well within ±5% drift tolerance: 0.5% and 0.7%.

The chloride concentrations and emissions are flagged because the chloride measured in the train liquid are not large compared to the liquid in the field blank. The DQO goal blank sample concentration having less than 5% of a test sample concentration. The field blank liquid chloride concentration ranged from 16 to 106% of test liquid concentration. Following Method 26A procedures, the test concentrations were background corrected for the chloride in the field blank.

6.3.5 In-Stack PAHs and PCDD/Fs

Samples collected for PAHs and PCDD/Fs s utilized a Method 23 train sampling from the PBHH stack prior to dilution. Two meter boxes were used during the testing for the Method 23 trains; both were calibrated ~ 4 months prior to beginning hydronic heater tests. All calibration readings

were within 2% of the average gamma. No further pre-test volume check was performed; however, the accuracy of the volume measurements was confirmed by successful calibration drift checks after the test program. Drift was well within ± 5% drift tolerance: 0.5% and 0.7%.

A field blank for the Method 23 sample train was created during operations on 11/15/2016. The field blank contained ≤ 9% of any PAHs recovered compared to a DQI goal of <50%; sufficient analyte was recovered during tests to attribute PAH's to the sample. The majority of analytes in the field blank sample were below level of detection. Using the TEQ level of detection for compounds not detected, the field blank remained <50% of each of the components quantified for all samples. The majority of analytes achieved much better performance with these criteria with notable exceptions for the low toxicity and low concentration compounds 1,2,3,4,6,7,8,9 – OCDD and 1,2,3,4,6,7,8,9 – OCDF. Over the total TEQ, the blanks at the level of detection for compounds not detected are less than 3.4% of test samples.

The Sampling to Extraction hold time DQI of 60 days was met for the first batch of samples but was exceeded by around 40 days for the second batch of samples. The samples were stored in the cold and dark, and the hold times are believed to have been established for methods which include much more labile compounds not just PAHs and PCDD/Fs It is not expected for the extra 40 days before extraction to have any significant effect on the samples.

The recovery criteria DQI for PAHs was set for this project similar to the criteria for Method 23. Because this is a process that is designed to provide a more rigorous QA than Method 8270 the criteria have not been fully developed. For the Pre-extraction spikes and the pre-sampling spikes, the criteria were set at 25-130%. The pre-sampling spike was between 47 and 105% with the exception of two very high level samples and interference is suspected. Because the actual quantitation of the targets is by isotope dilution this is not expected to cause significant error in the reported values. The Pre-extraction spike had 4 compounds that were consistently above the criteria between 130-200% and the Naphthalene recovery was below 25% for half of the samples. Again, because the actual target quantitation was by Isotope dilution this is not expected to cause significant error to the values.

The Recovery Criteria for the PCDD/Fs were met except for the first two samples which had high TeCDD Presampling recovery that because the actual quantitation is isotope dilution it is not expected to cause significant error in the reported values.

6.3.6 VOCs and Carbonyls

The data quality indicators and associated corrective action for the analysis of VOCs and carbonyl samples are outlined in Table 6-1 of the QAPP. These DQIs follow guidelines set out by EPA Methods TO-15 and TO-11A. The balance used to measure carbonyl extract weights was checked every day and was within 0.2 mg of calibration weight meeting DQI goals. Pressure checks of canisters used for TO-15 analysis were within 4.2 kPa of expected value within DQI acceptance criteria. For carbonyl sampling, flow rate checks were within 10% of DQI criteria, except one day

where it was within 16%. Carbonyls measured in field blanks were all below 80 ng/cartridge levels except one outlier that was 900 ng/cartridge. This value was still <30% of average measured values for that day, meeting the DQI criteria.

For VOCs, a daily calibration runs were analyzed to determine system performance each day, and acceptable recoveries within 30% of expected values were achieved with exception of 6% of values. In the case of carbonyls, a daily calibration run was analyzed for every 5 sample runs that were mostly 15% of expected values except three data points, where these were within 22%. One sample was analyzed in replicate during each analytical sequence with acceptable precision that was mostly within 10% relative percent difference. When this criterion is not met, the data were flagged for further evaluation. Detailed information on the results from the QA samples is available upon request.

6.3.7 Particle Number and Size

The Dekati Electrical Low Pressure Impactor was used to determine particle number and aerodynamic size during the study. Three DQI goals were established in the approved QAPP for the following parameters:

- Leak check: < 10 mbar/min
- Flow check: 10 ± 1 Lpm
- Zero check (HEPA filter): < 50 particles/cm^3

These checks were performed daily before each test conducted. Leak check and zero check results were read directly off the instrument. The flow check was determined using a TSI Model 4140 portable flow meter checked against a Gilibrator® bubble flow meter.

All daily checks were easily within the DQI limits shown above. The following are the ranges of values obtained for each parameter:

- Leak check: 0 - 4 mbar/min
- Flow check: 9.65 - 10.2 Lpm
- Zero check: 2 - 7 particles/cm^3

Thus, the ELPI data are of high quality and acceptable for use during data analyses.

6.3.8 Optical Black Carbon

The Aethalometer (Model AE22) was used to measure optical black carbon and UV absorbing particulate matter during the study. The DQI goal for the Aethalometer was a daily zero check using a HEPA filter. Throughout the duration of the study the black carbon concentrations during the daily zero check was less than the background value of 660 ng/m^3. BC concentrations tended

to vary during the zero check due to instrument noise; however, zero-check values were always less than the 30 Mm-1 absolute DQI objective and at least three orders of magnitude lower than the lowest average concentration measured during testing.

6.3.9 Laboratory and Semi-Continuous OCEC
Quality control procedures for the laboratory OCEC analysis were applied according to the approved Quality Assurance Project Plan. A brief description of these practices is provided in Section 6.3.10 below.

6.3.10 PM SVOCs
Either an average response factor or linear regression was used for calibration and to quantify organic compound concentrations in the samples. The calibration range varied by target compound class. It was 0.1 ng/µl – 1 ng/µl for most polycyclic aromatic hydrocarbons (PAH) and 0.625 ng/µl – 6.25 ng/µl for most alkanes. A 5-level levoglucosan standard range of 12.75 ng/µl to 130 ng/µl was used, while a the three-level organic acid calibration range was 2 ng/µl – 16 ng/µl. A mid-level continuing calibration of 10 ng/µl was used for methoxyphenol analytes. A mid-level check standard was run daily and used to assess target recovery. If the daily mid-level check standard failed to pass the laboratory's minimum acceptance criterion (80% of compounds must agree to within 25% of actual fixed concentration value of standard), it was used as a daily continuing calibration that updated all target responses. All the methoxyphenol targets were quantified using a continuing calibration. Detection limits were determined for all target organic compounds as described in EPA document SW-846 (EPA, 2014) with n=7; t statistic= 3.14. Typical detection limits for the instrument used in this study were provided elsewhere (Hays et al., 2011). Values that fall below the detection limit threshold were reported as not detected (ND). Matrix spikes that considered all standard compounds were performed to determine extraction recovery. Matrix spike recoveries were used as an additional data quality check, and typical values are also reported in Hays et al. (2011). Several of the methoxy phenols matrix spike targets were acceptable while others were lower than expected.

Automated integration results for individual peaks were reviewed and corrected if applicable. Retention times are critical for the predictability of target analyte components. Because the GC was equipped with electronically programmable control (EPC), retention times shifted less than 0.1 min throughout the analysis period. Target analyte validity was also determined using fragment isotopic ratios that exceeded the minimum signal/noise ratio of 3 to 1 and had good proximity to mid-level check standard retention times. Additional quality control was performed by monitoring the internal standard response of all samples. Precision was demonstrated by triplicate injection checks of composite samples. Background correction was performed using dilution tunnel blank tests for all samples except for those burning hardwood pellets at full load and one test at low load. Those emission factor values are given 'as is'. In certain cases, background subtractions produced negative values. Negative values and non-detects were treated as 'missing' during generation of descriptive statistics. Elution of individual phytosterol compounds was putatively observed for

experiments conducted for both hardwood and switchgrass pellets. However, the vast majority of tests didn't show these compounds, which are not reported here due to the lack of phytosterol standards. Compliance with the DQIs in the QAPP for PM analysis were achieved for this study unless explicitly noted above.

6.3.11 Closed Cell FTIR

As mentioned above, a closed cell FTIR was a last-minute addition to the program and used to measure CH_4, SO_2, CO, NH_3, and NO_x. In order to verify that the FTIR spectrometer is operating correctly a series of Quality Control checks were performed daily. MOP-6807 was followed with the certain alterations to the following procedures. 2.1.2 Stray *Light*, 2.1.3.2 *Random Baseline Noise,* 2.1.3.3 *Signal Strength*, 2.1.3.4 *Signal –beam Spectrum*, and 2.1.3.5 *Wavenumber Shifts and Changes in Resolution* were conducted and recorded daily. Since the cell based system is closed and the path length fixed the zero path length descriptions cannot be followed in some procedures.

7   Experimental Results

The experimental results for the REKA hydronic heater tested are provided in this section. Thermal efficiency is discussed first followed by gas- and particle-phase pollutants. For both gases and particles, the test average results for the two runs conducted at each fuel and load condition are provided which, except for stack PAHs, PCDD/PCDFs, and HCl, are background-corrected unless otherwise indicated. Since only two tests were conducted at each condition, the standard error (deviation) could not be calculated as is usually done. Instead, the summary data tables show the relative percent difference (RPD) for the two tests. RPD is defined as the difference between emission factor values from duplicate tests divided by the average of the duplicates multiplied by 100 and is an indicator of the variability observed between the two test runs. The data are also provided in graphical form generally in both engineering and SI units. Note that in the graphs, the bars indicate the range of values for each parameter and not the RPD or standard error. The bars are provided to generally indicate the amount of variability observed between the two test average values which was oftentimes considerable.

For the gaseous pollutants determined by on-line monitoring, the test averages are a simple mean of the continuous measurements made over the 6-hour test period. In the case of the VOCs, two sample sets (one set equals 1 SUMMA canister for VOCs and one DNPH cartridge for carbonyls) were collected during each test each having a duration of 3 hours. The test average was determined from the two sample sets. For the PAH data from the modified Method 23 sample train, data are available for the 16 compounds determined over the entire period of each test. Test average emissions are determined from the two sample sets collected for each fuel/load condition. Finally, in the case of the PCDDs and PCDFs, the samples were composited prior to analysis since it is normally difficult to obtain enough sample mass for this type of analysis. In this study, however, the levels for most of the target compounds were in range but some were above the calibration range. The blank train had very low levels as expected therefore the compounds are believed to be from the combustor and not a method artifact.

For determination of average total PM mass emissions, the data from the modified ASTM Method 2515 sample train was used as operated over the entire 6-hour period. Note that each individual test average can represent multiple filter sets (two filters sampling at the same time) collected during the run depending on loading. Total PM mass was also determined from the 25-mm Teflon filters with three samples of 20 minutes each collected during each run. Although these samples only represent 1/6 of the total test time, these data correlated well with the 2515 results and thus appear representative of the entire test run. For PM number, the average emission factor was determined from the continuous EPLI data output for the 6-hour test period. The ELPI data were also used to develop a composite particle size distribution (PSD) for each test by combining data from all the scans conducted at 10-sec intervals throughout the 6-hour test. In the case of EC/OC, the test averages were derived from the three 1-hour 47-mm quartz filters samples. These same filters were also used for the determination of particle-phase SVOCs after EC/OC analysis. Optical black carbon averages were determined from the continuous Aethalometer data output after correction for secondary dilution of the sample extracted from the dilution duct. Elemental analyses by XRF were conducted on the 25-mm Teflon filters after gravimetric analysis.

Finally, in the discussion of the test results, the data expressed in terms of mass of pollutant per mass of fuel burned were generally used for the observations made. It should be noted that the

same general trends were also present in the results expressed in terms of mass of pollutant per heat input or heat output and thus the generalizations should be similar regardless of which reporting convention is used. The experimental results are provided in the following subsections.

7.1   Thermal Efficiency

The thermal efficiency of the unit was determined as described above with the average results provided in Table 7-1 and shown graphically in Figure 7-1. Note that the bars in the figure represent the range of values obtained not the measurement uncertainty.

Table 7-1. Thermal Efficiency Summary

Fuel Type	Load Condition	Value[a]	Average Thermal Efficiency (%)[b]
Hardwood	25%	Average	79
		RPD	85
	Syracuse Cycle	Average	94
		RPD	27
	100%	Average	89
		RPD	
Switchgrass	25%	Average	63
		RPD	17
	Syracuse Cycle	Average	72
		RPD	9.7
	100%	Average	81
		RPD	12

[a] **RPD = relative percent difference in efficiency for the two test runs conducted at each fuel/load condition.**
[b] **Two significant figures. "Average" for hardwood at 100% load is from a single test**
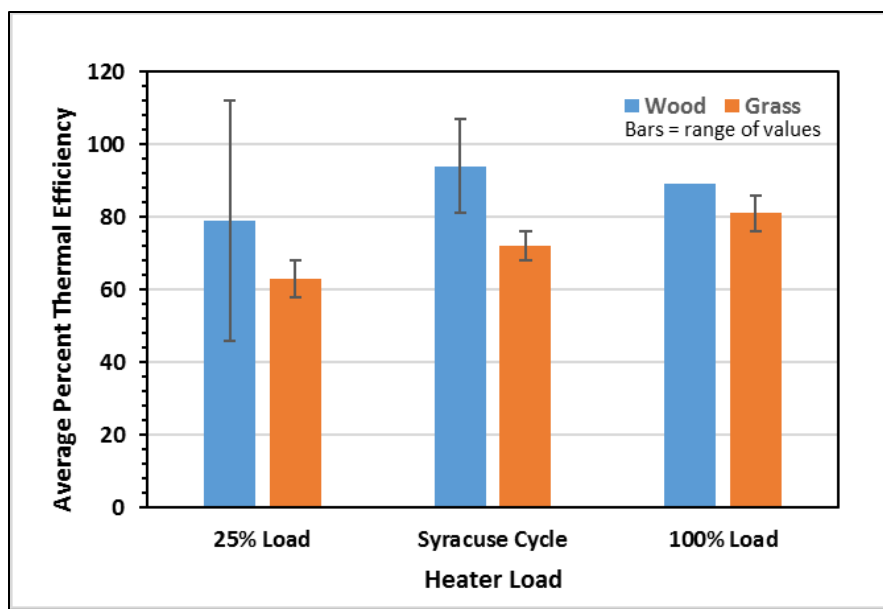
Figure 7-1. Average thermal efficiency by fuel and load condition

As shown in Figure 7-1, the thermal efficiency for both fuels generally increased with load and a higher efficiency was always observed for hardwood combustion as compared to switchgrass. In the case of wood, the Syracuse cycle had the highest efficiency at 94% followed by 89% for 100% load and 79% load at 25% load, respectively. For grass pellet combustion, the efficiency varied from 63 to 81% with the highest efficiency at 100% load. In addition, for hardwood operating at 25% load and during the Syracuse cycle the efficiency values obtained from the two tests were highly variable as evidenced by the range of values shown in Figure 7-1.

7.2   Gas Phase Pollutants

7.2.1 Criteria and Related Gaseous Emissions

The test average emission factors (EFs) for the gaseous pollutants monitored during the study are provided in Tables 7-2 and 7-3 expressed in terms of engineering and SI units, respectively. These data are also shown graphically in Figures 7-2 and 7-3 with test-specific results provided in Appendix C. Due to the leak in the CEM bench discovered during the data analysis, these results were derived from either the closed-cell FTIR instrument (CO, CH_4, NH_3, NO_x, and SO_2) or analysis of the SUMMA canisters (N_2O) after appropriate background subtraction. As described previously no valid data were available for CO_2 or THC.

For the EFs of gaseous nitrogen compounds in Figure 7-3a several trends were observed. In the case of NH_3, grass produced 6-46x higher emissions except at 100% load where the EF for wood was a factor of 3 higher. For hardwood pellets, the NH_3 EF increased by a factor of ~ 5 from 4.9 mg/kg fuel at 25% load to ~ 25.6 mg/kg fuel at 100% load which is not what would be expected. One would expect that reduced nitrogen should be most prevalent at low load and then decrease with increasing load. In the case of switchgrass, the trend is the reverse with the emission factor at

25% load (226 mg NH_3/kg fuel) being a factor of 25 higher than at 100% load (8.94 mg NH_3/kg fuel). The trend for switchgrass is more understandable from combustion theory.

In the case of N_2O (partially oxidized nitrogen), the EFs in Figure 7-3a show a factor of 2-6 higher emissions for grass as compared to wood. The EFs for both fuels also generally decrease from 76.9 and 209 mg/kg fuel for wood and grass at 25% load, respectively, to 20.4 and 42.8 mg/kg fuel at 100% load. This is counterintuitive since the emission factors of oxidized nitrogen species such as N_2O should increase with increasing combustion temperature indicative of higher load. Finally, the NO_x emissions from both fuels appear to be most prevalent for the Syracuse cycle rather than at 100% load. It would be expected that NO_x should be highest at the highest load (highest temperatures) tested. The EFs for grass were ~ 18x higher than wood for 25% load as compared to the Syracuse cycle which showed the opposite trend of the NO_x emissions being about half that observed for wood. Emissions of nitrogen containing species is complicated by relative contributions of thermal NO and fuel nitrogen, complex interactions between temperature and excess oxygen, and large relative differences in the fuel nitrogen contents of the hardwood (0.31%) and switchgrass (0.82%) fuels.

Table 7-2. Test Average Gaseous Emissions (Engineering Units)

Reporting Units	Pollutant[b]	Test Average Pollutant Emissions[a]					
		25% Load		Syracuse Cycle		100% Load	
		Wood	Grass	Wood	Grass	Wood	Grass
lb/MMBTU Input	CO	4.77	4.36	2.39	2.54	1.47	0.299
	RPD	64.2	1.25	36.9	13.2	28.3	65.0
	CH$_4$	0.253	0.120	0.0394	0.111	0.00971	0.0183
	RPD	31.4	10.5	25.2	30.9	57.8	86.6
	NH$_3$	0.000633	0.0301	0.00135	0.00789	0.00331	0.00119
	RPD	179	47.6	NA	80.4	38.3	25.4
	N$_2$O	0.00994	0.0278	0.00361	0.0223	0.00263	0.00569
	RPD	NA	28.3	40.8	1.78	61.5	3.80
	NO$_x$	0.00128	0.0247	0.0265	0.0135	ND	0.00136
	RPD	NA	56.6	NA	105	NA	NA
	SO$_2$	0.0151	ND	0.00327	ND	0.0504	0.0582
	RPD	NA	NA	NA	NA	32.4	4.13
lb/MMBTU Output	CO	6.37	7.01	2.51	3.51	1.43	0.362
	RPD	23.6	16.4	11.5	4.10	2.90	53.9
	CH$_4$	2.83	1.44	0.333	1.15	0.0718	0.165
	RPD	57.0	7.13	50.1	21.9	33.6	76.5
	NH$_3$	0.00471	0.357	0.00981	0.0807	0.0247	0.0111
	RPD	152	225	NA	72.6	13.2	37.3
	N$_2$O	0.0686	0.333	0.0293	0.232	0.0194	0.0528
	RPD	NA	10.8	15.6	10.9	37.5	8.40
	NO$_x$	0.00883	0.307	0.193	0.138	ND	0.0134
	RPD	NA	72.4	NA	98.1	NA	NA
	SO$_2$	0.104	ND	0.0237	ND	0.378	0.541
	RPD	NA	NA	NA	NA	7.09	16.3

[a] Red face type = single test value only; blue ND = non-detect; NA = not applicable. Three significant figures
[b] RPD = relative percent difference in emission factors for the two test runs conducted at each fuel/load condition

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Table 7-3. Test Average Gaseous Emissions (SI Units)

Reporting Units	Pollutant[b]	Test Average Pollutant Emissions[a]					
		25% Load		Syracuse Load		100% Load	
		Wood	Grass	Wood	Grass	Wood	Grass
g/kg fuel	CO	36.9	32.8	18.5	19.1	11.4	2.25
	RPD	64.2	1.25	36.9	13.2	28.3	65.0
	CH_4	1.96	0.900	0.305	0.839	0.0751	0.138
	RPD	31.4	10.5	25.2	30.9	57.8	86.6
mg/kg fuel	NH_3	4.90	226	10.5	59.4	25.6	8.94
	RPD	179	47.6	NA	80.4	38.3	25.4
	N_2O	76.9	209	27.9	168	20.4	42.8
	RPD	NA	28.3	40.8	1.78	61.5	3.80
	NO_x	9.90	186	205	102	ND	10.2
	RPD	NA	56.6	NA	105	NA	NA
	SO_2	117	ND	25.3	ND	390	438
	RPD	NA	NA	NA	NA	32.4	4.13
g/MJ Input	CO	2.05	1.88	1.03	1.10	0.632	0.129
	RPD	64.2	1.25	36.9	13.2	28.3	65.0
	CH_4	0.109	0.0515	0.0170	0.0480	0.00418	0.00787
	RPD	31.4	10.5	25.2	30.9	57.8	86.6
mg/MJ Input	NH_3	0.273	12.9	0.582	3.40	1.42	0.512
	RPD	179	47.6	NA	80.4	38.3	25.4
	N_2O	4.28	12.0	1.55	9.59	1.13	2.45
	RPD	NA	28.3	40.8	1.78	61.5	3.80
	NO_x	0.551	10.6	11.4	5.83	ND	0.585
	RPD	NA	56.6	NA	105	NA	NA
	SO_2	6.51	ND	1.41	ND	21.7	25.0
	RPD	NA	NA	NA	NA	32.4	4.13
g/MJ Output	CO	2.74	3.02	1.08	1.51	0.615	0.156
	RPD	23.6	16.4	11.5	4.10	2.90	53.9
	CH_4	1.22	0.621	0.144	0.496	0.0309	0.0712
	RPD	56.96	7.13	50.07	21.91	33.6	76.5
mg/MJ Output	NH_3	2.03	154	4.22	34.7	10.6	4.79
	RPD	152	225	NA	72.6	13.2	37.3
	N_2O	29.5	143	12.6	99.9	8.35	22.7
	RPD	NA	10.8	15.6	10.9	37.5	8.40
	NO_x	3.80	132	82.9	59.2	ND	5.77
	RPD	NA	72.4	NA	98.1	NA	NA

Reporting Units	Pollutant[b]	Test Average Pollutant Emissions[a]					
		25% Load		Syracuse Load		100% Load	
		Wood	Grass	Wood	Grass	Wood	Grass
mg/MJ Output	SO$_2$	44.9	ND	10.2	ND	163	233
	RPD	NA	NA	NA	NA	7.09	16.3

[a] Red face type = single test value only; blue ND = non-detect; NA = not applicable; Three significant figures
[b] RPD = relative percent difference in emission factors for the two test runs conducted at each fuel/load condition
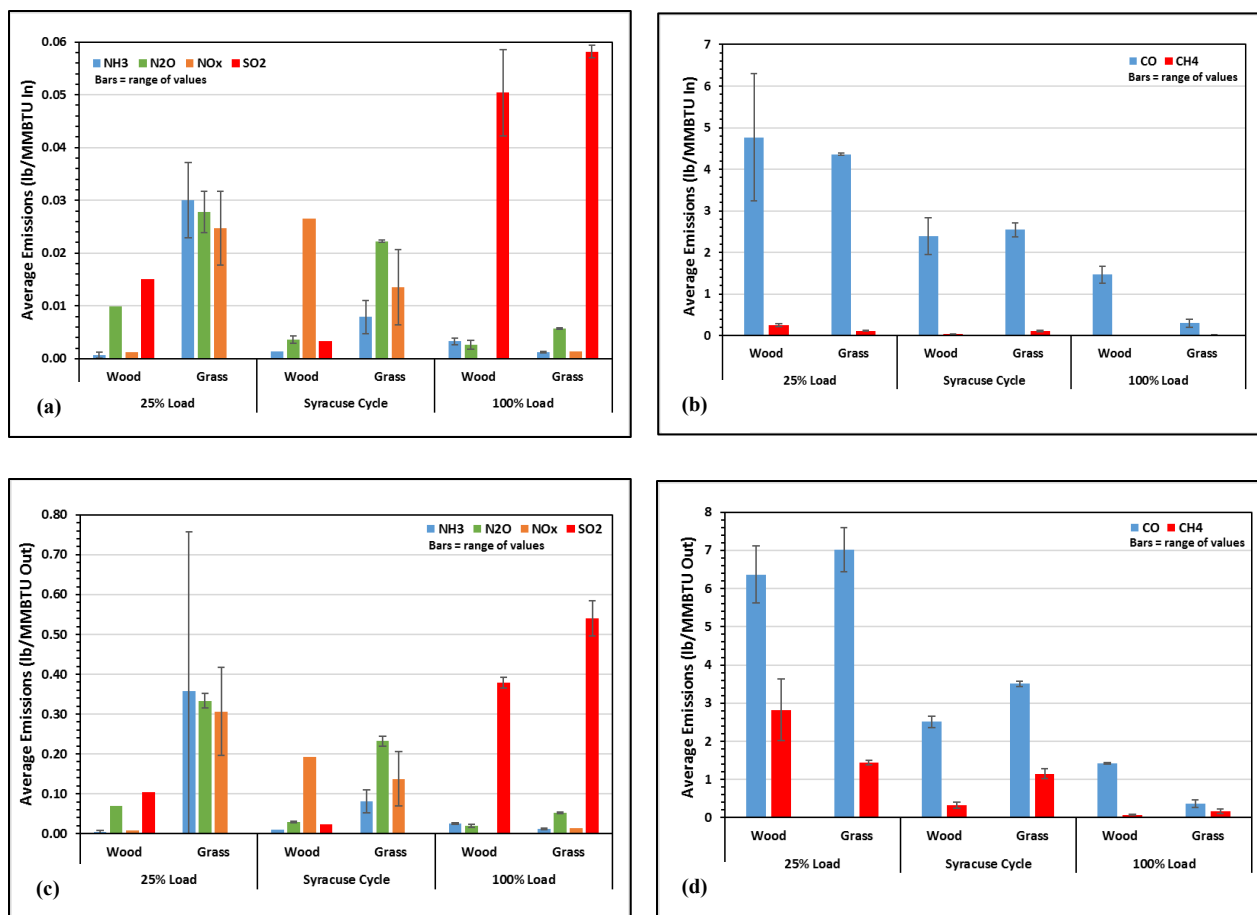
Figure 7-2. Test average gaseous emission factors (engineering units) for nitrogen and sulfur compounds (a) and (c) as well as organic gases (b) and (d)

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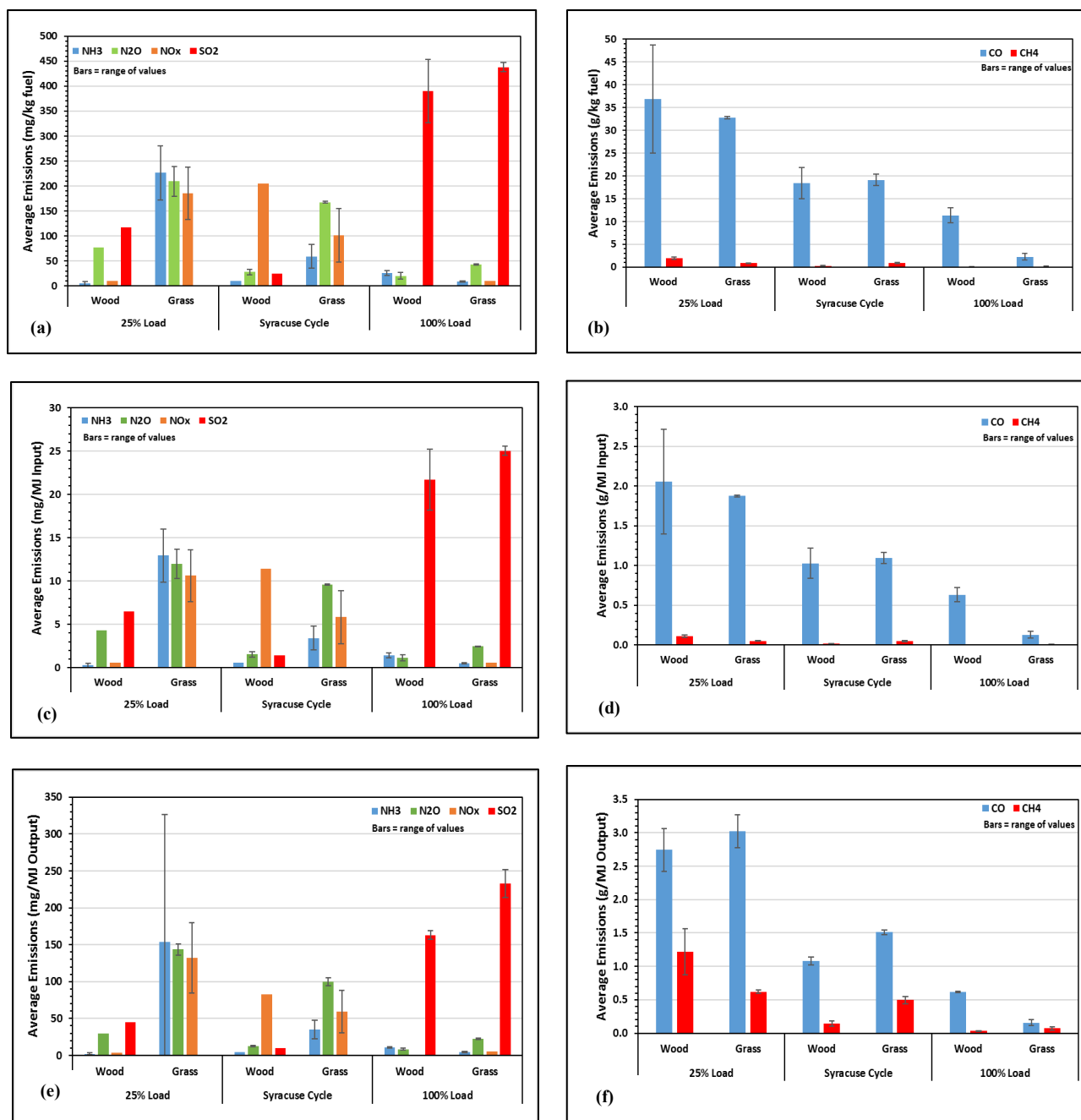
Figure 7-3. Test average gaseous emission factors (SI units) for nitrogen and sulfur compounds (a), (c), and (e) as well as organic gases (b), (d), and (f)

For sulfur and organic pollutants in Figure 7-3a and 3b the emission trends are generally more of what would be expected. Here, the SO_2 generally increases with load (e.g., a factor of more than 3x for hardwood at 100% load as compared to 25% load) with CO and CH_4 generally decreasing with increasing combustion temperature for both fuels typical at higher load. There does not,

however, seem to be any significant SO_2 measured for switchgrass pellets burned at 25% load and during the Syracuse cycle.

7.2.2 Volatile Organic and Carbonyl Compounds

Speciated volatile organic compounds (VOCs) were characterized in the hydronic heater emissions during operation using hardwood and switchgrass fuels and under the three heat load conditions. VOC samples were taken during the first and second half of each emissions test and were analyzed following EPA Methods TO-15 and TO-11A for a total of 132 target VOCs. All tests were performed in duplicate for each fuel/load condition. Emission factors were calculated for speciated VOCs on a mass to mass fuel burned and mass to heat input and output bases and EFs were averaged over each test condition. Average speciated total VOC emission factor values are given in Table 7-4 for each test condition in mass per fuel burned units and per heat input and output. RPDs listed in the table was calculated for the duplicate runs. Detailed results are provided in Appendix C.

Table 7-4. Average Total VOC and Carbonyl Emissions.

Fuel Type	Load Condition	Value	Average Total VOC and Carbonyl Emissions[a]				
			mg/kg fuel	mg/MJ Input	lb/MMBTU Input	mg/MJ Output	lb/MMBTU Output
Hardwood	25%	Average	2940	163	0.379	241	0.560
		RPD[b]	22.0	22.0		66.0	
	Syracuse Cycle	Average	205	11.4	0.0265	12.6	0.0293
		RPD	45.0	45.0		69.0	
	100%	Average	21.4	1.19	0.00276	1.13	0.00262
		RPD	61.0	61.0		37.0	
Switchgrass	25%	Average	1780	102	0.237	162	0.376
		RPD	24.0	24.0		6.00	
	Syracuse Cycle	Average	1320	75.2	0.175	104	0.242
		RPD	24.0	24.0		15.0	
	100%	Average	88.7	5.07	0.0118	6.16	0.0143
		RPD	24.0	54.0		42.0	

[a] **Three significant figures**
[b] **RPD = relative percent difference in emission factors for the two test runs conducted at each fuel/load condition**

Figure 7-4 summarizes the total VOC emission factor values for each test condition on a mass per mass fuel burned basis (Figure 7-4a), mass per heat input basis (Figure 7-4b) and mass per heat output basis (Figure 7-4c) all in SI units. Note that the bars shown in these figures represent the range in values for the two tests conducted. Similar trends were observed for the total speciated VOC emission factors by mass per fuel burned and per heat input/output as shown in Figure 7-4. Generally, and similar to the CO and CH$_4$ data, total speciated VOC emissions were highest for the 25% heat load conditions using both hardwood and switchgrass fuels and for Syracuse cycle using switchgrass. As expected, the 100% heat load had the lowest total VOC emissions for both fuels. Large differences in emission factors for the two fuels were observed under the same heat load conditions. The trends in VOC emissions between the two fuels were consistent regardless of whether results were normalized as mass/fuel or mass/heat input or output. The hydronic heater operating on switchgrass produced between 4-8 times higher total VOC emissions compared to hardwood pellets for both 100% load and Syracuse cycle. However, for 25% load conditions, total VOC emissions for hardwood tests were approximately 50-60% higher than the switchgrass tests.

Figure 7-5 shows the individual VOC emission factors for the 16 most abundant VOCs measured in the hydronic heater emissions for each test condition in mass per heat input. The VOCs with the highest emission factors measured from the hydronic heater included carbonyls (e.g. formaldehyde, acetaldehyde, acetone, acrolein), aromatics, and unsaturated hydrocarbons compared to 4-12% for other test conditions). Many of the major VOCs measured in the hydronic heater emissions are considered as partial combustion products typically found in biomass burning and other combustion related emissions. Some of these VOCs are also classified as air toxics and hazardous air pollutants of concern.

7.2.3 Gaseous PAH Emissions
The background-corrected test average EFs for total speciated gas phase PAHs are shown in Table 7-5 along with the relative percent difference (RPD) between the two tests conducted at each fuel/load condition. These data are also shown graphically in Figures 7-6 and 7-7 in engineering and SI units, respectively. Detailed data for each test is shown in Appendix C.

Figure 7-4. Total speciated VOC emission factors in terms of: (a) mass per mass of fuel burned; (b) mass per heat input; and (c) mass per heat output. Bars represent range of values

50
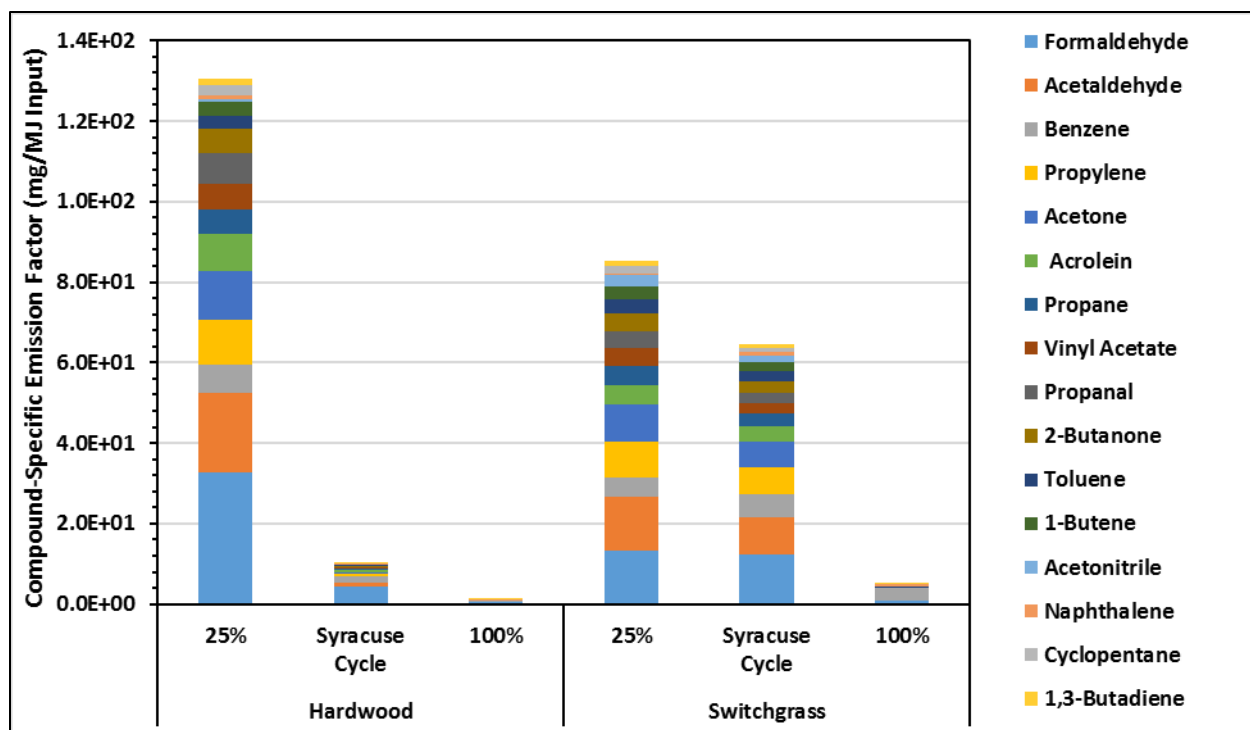
Figure 7-5. Speciated VOC emission factors in mass per heat input (mg/MJ) for the 16 most abundant VOCs averaged over each test condition

Table 7-5. Test Average Total Gaseous PAHs

Fuel Type	Load Condition	Value[b]	Average Total Gaseous PAH Emissions[a]				
			mg/kg fuel	mg/MJ Input	lb/MMBTU Input	mg/MJ Output	lb/MMBTU Output
Hardwood	25%	Average	114	6.32	0.0147	6.19	0.0144
		RPD	173	173		140	
	Syracuse Cycle	Average	3.43	0.191	0.000443	0.204	0.000473
		RPD	13.2	13.2		12.5	
	100%	Average	2.66	0.148	0.000343	0.132	0.000307
		RPD	153	153		141	
Switchgrass	25%	Average	11.7	0.670	0.00156	1.09	0.00253
		RPD	17.4	17.4		34.8	
	Syracuse Cycle	Average	71.7	4.10	0.00951	5.69	0.0132
		RPD	18.8	18.8		27.9	
	100%	Average	22.9	1.31	0.00304	1.56	0.00363
		RPD	101	101		91.7	

[a] **Three significant figures**
[b] **RPD = relative percent difference in emission factors for the two test runs conducted at each fuel/load condition**

As indicated in Figure 7-7a, the PAH EF for hardwood drops by a factor of ~ 42 with increasing load from 25% to 100% whereas the opposite is the case for switchgrass. For switchgrass, the PAH emissions rise with increasing load most notably for the Syracuse cycle which exhibited a factor of ~ 6x higher emissions than at 25% load. This trend is counterintuitive. Heavy organics should be more easily consumed at the higher combustion temperature occurring during the Syracuse cycle and at 100% load. Obviously, there are processes occurring in the REKA heater at these two load conditions for grass pellets which are not consistent with the wood fuel combustion. Also, except at 25% load, the PAH emissions for switchgrass are a factor of ~ 9-21x higher than hardwood indicating a significant fuel effect. It is interesting to note that the independent VOC and PAH measurements both indicate decreased emissions with increasing load for the hardwood fuel, but increasing emissions with increasing load for the switchgrass fuel, even though both fuels exhibit similar volatile and fixed carbon values. While both fuels contain large fractions of volatile carbon (80 and 73%), it is possible that this volatile matter may be more easily liberated at lower temperatures for the switchgrass fuel leading to increased VOC and PAH emissions if this carbon volatilization is enhanced by high (high load) combustion temperatures while the fuel is still in the process of being fed by auger into the firebox. This combination could result in volatile species bypassing or being partially oxidized within the flame. Determination of loss-on-ignition via thermogravimetric analysis may shed light upon any differences in volatile matter evolution.
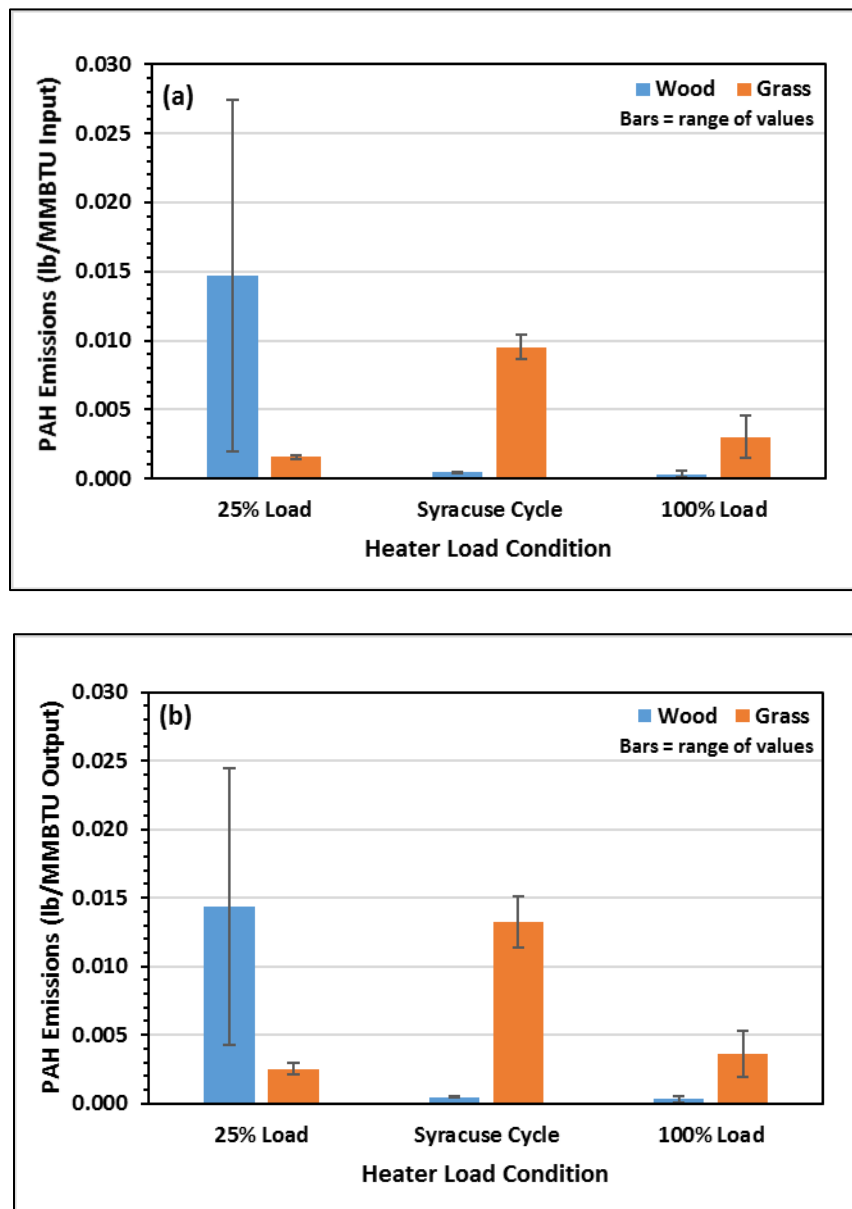
Figure 7-6. Test average total emission factors (engineering units) for gaseous PAH compounds in terms of: (a) mass per heat input; and (b) mass per heat output
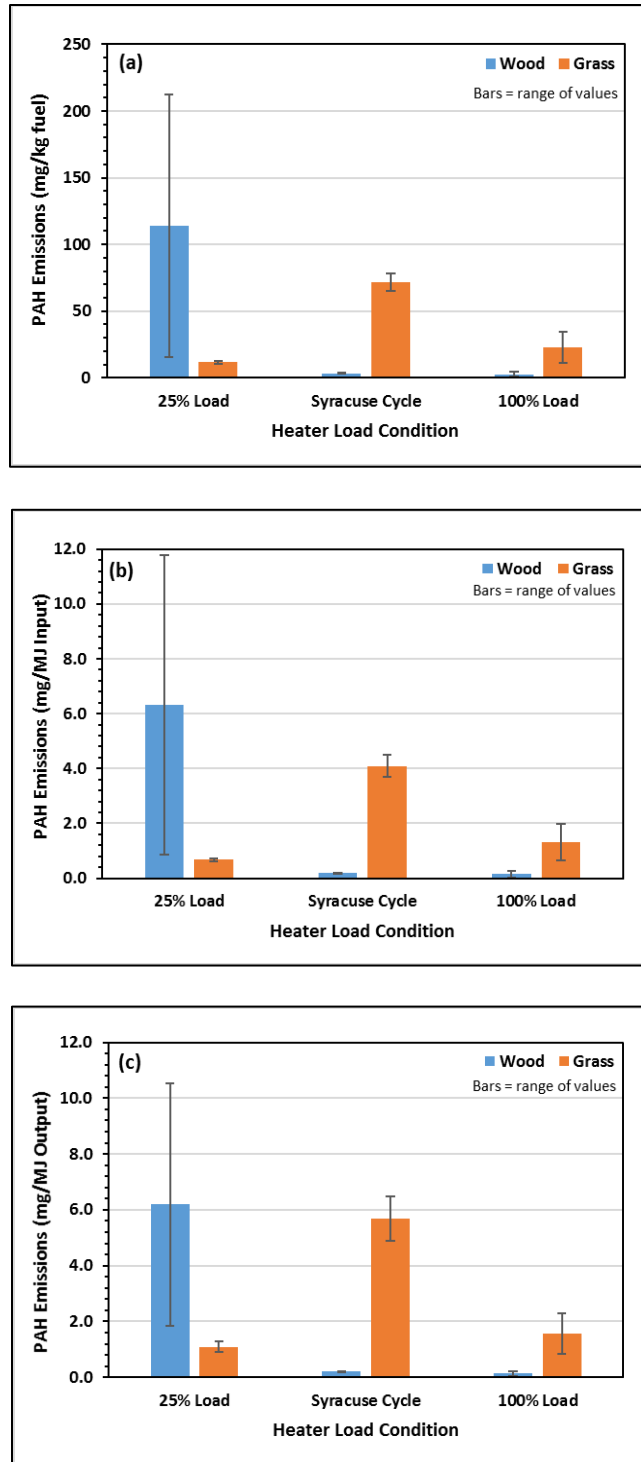
Figure 7-7. Test average total emission factors (SI units) for gaseous PAH compounds in terms of: (a) mass per mass of fuel burned; (b) mass per heat input; and (c) mass per heat output.

Looking at the relative abundances of the 16 target PAH compounds measured, Figure 7-8 shows test average emission factors as determined for each fuel/load condition in terms of heat input. As

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shown in this figure for hardwood at 25% load, significant quantities of acenapthylene, flourene, phenanthrene, anthracene, fluoranthene, and pyrene are present. At higher loads, PAHs are evident only in trace quantities. In the case of switchgrass, napthalene is the most predominate species present in the emissions for all load conditions, especially during the Syracuse cycle. For grass during the Syracuse cycle, substantial quantities of acenapthylene, phenanthrene, and chrysene are also present. The same species are also present in similar proportions at 100% load except at much lower levels. These compounds are considered as hazardous air pollutants under the Clean Air Act. Tables detailing the specific emission factor for each compound determined in each test is provided in Appendix C.
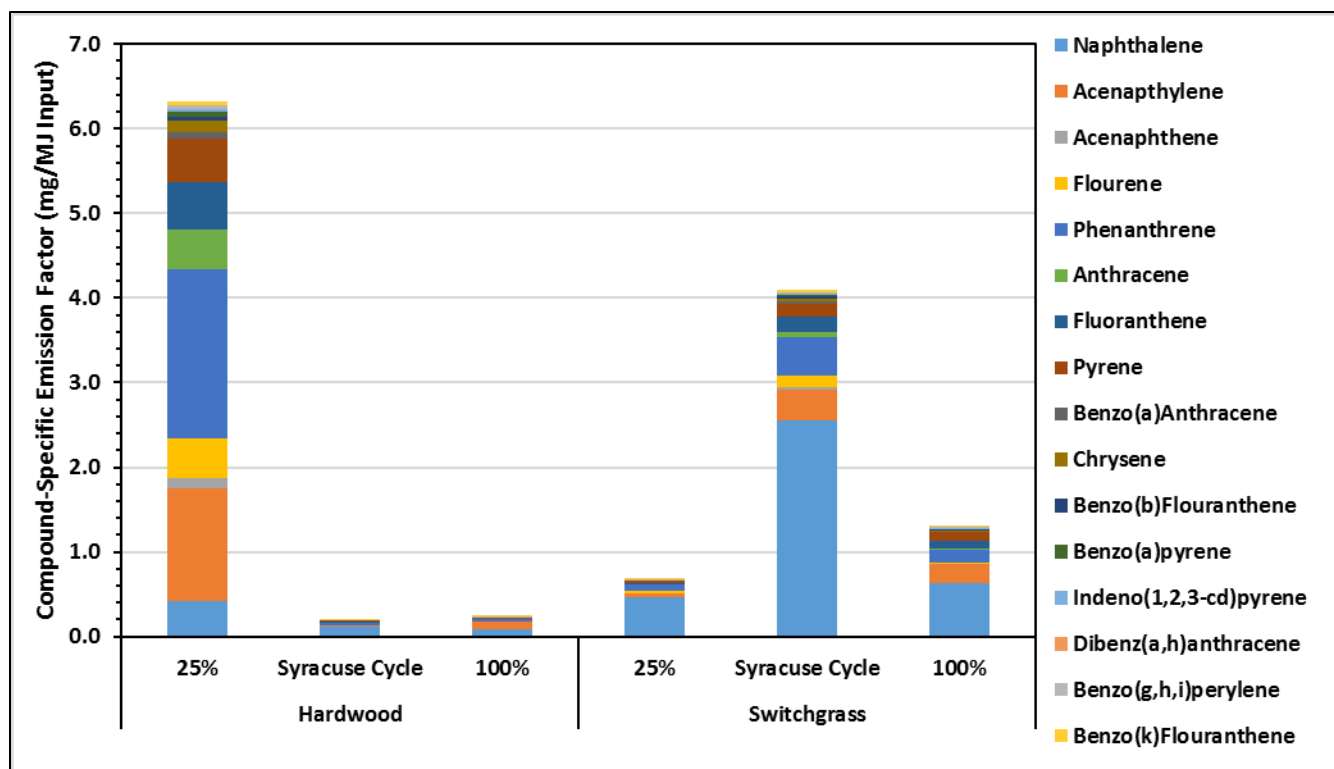
Figure 7-8. Test average emission factors for the 16 target PAH compounds determined using EPA Method 23 for each fuel and load condition.

7.2.4 Dioxin and Furan Emissions

The EFs for total speciated PCDDs and PCDFs in terms of toxic equivalent mass for each fuel and load condition are shown in Table 7-6 and graphically in Figures 7-9 and 7-10 in terms of engineering and SI units, respectively. Recall that these results reflect composite emission factors derived from the samples collected for each of the two tests at each fuel/load condition which were combined prior to GC/MS analysis. Thus, RPD could not be calculated. Compound-specific results are shown in Appendix C.

Table 7-6. Test Average Total PCDD/PCDF Emission Factors

| Fuel Type | Load Condition | Composite Total PCDD/PCDF Emissions[a] | | | | |
		ng TEQ/kg fuel	ng TEQ/MJ Input	lb TEQ/MMBTU Input	ng TEQ/MJ Output	lb TEQ/MMBTU Output
Hardwood	25%	0.158	0.00880	2.04E-11	0.0136	3.16E-11
	Syracuse Cycle	0.0929	0.00517	1.20E-11	0.00556	1.29E-11
	100%	0.320	0.0178	4.14E-11	0.0199	4.63E-11
Switchgrass	25%	0.223	0.0128	2.97E-11	0.0206	4.78E-11
	Syracuse Cycle	0.455	0.0260	6.03E-11	0.0359	8.35E-11
	100%	0.105	0.00601	1.40E-11	0.00742	1.72E-11

[a] Three significant figures

As shown in the Figure 7-10a, except for operation at 100% load, the combustion of switchgrass pellets produced ~ 1.4 – 5x more PCDD/PCDFs that was the case for hardwood. For wood at 100% load, the PCCD/PCDFs produced were a factor of ~ 3x higher than was the case for grass. This result is counterintuitive since the chlorine content of the switchgrass pellets was about twice that of hardwood. It might be expected, therefore, that the fuel with the highest chlorine content should always create the highest PCDD/PCDF emissions which was found not to be the case at 100% load.

The relative abundances of the PCDD/PCDF compounds observed is also informative. Figure 7-11 shows the composite emission factor for each compound analyzed in terms of heat input. As indicated by the figure, the highest emission factors observed for all fuels and loads were 2,3,7,8-TCDD, 1,2,3,7,8-PeCDD, 2,3,7,8- TCDF, and 2,3,4,7,8-PeCDF the exact amount of which depended on fuel and load condition. Only relatively minor amounts of the other compounds were present in the samples collected. Unlike certain VOCs and PAHs, all of the compounds identified in Figure 7-8 are considered by EPA to be air toxics.
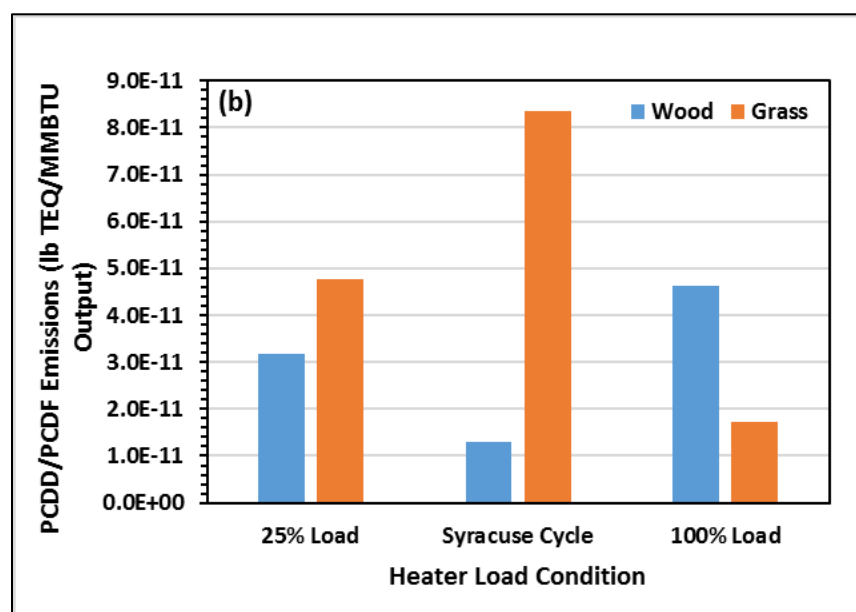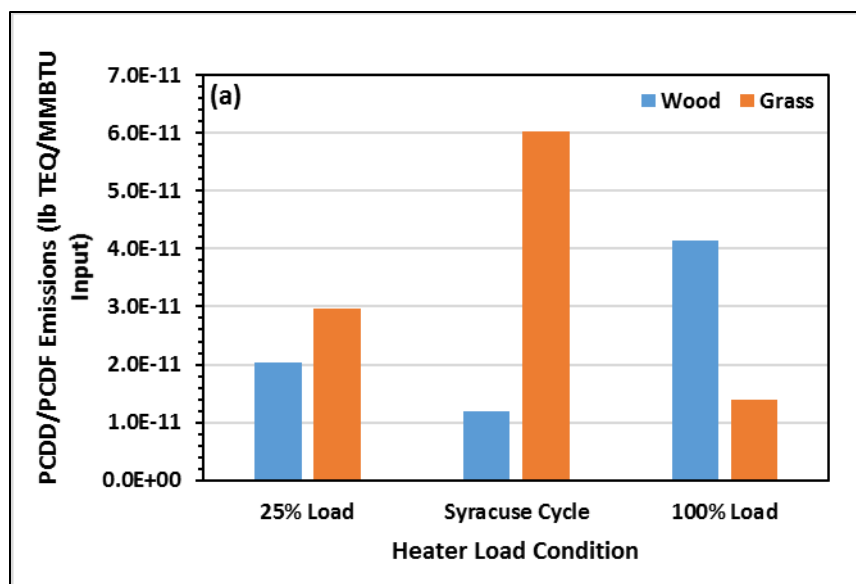
Figure 7-9. Composite total emission factors (engineering units) for PCDD/PCDF compounds in terms of: (a) mass per heat input; and (b) mass per heat output
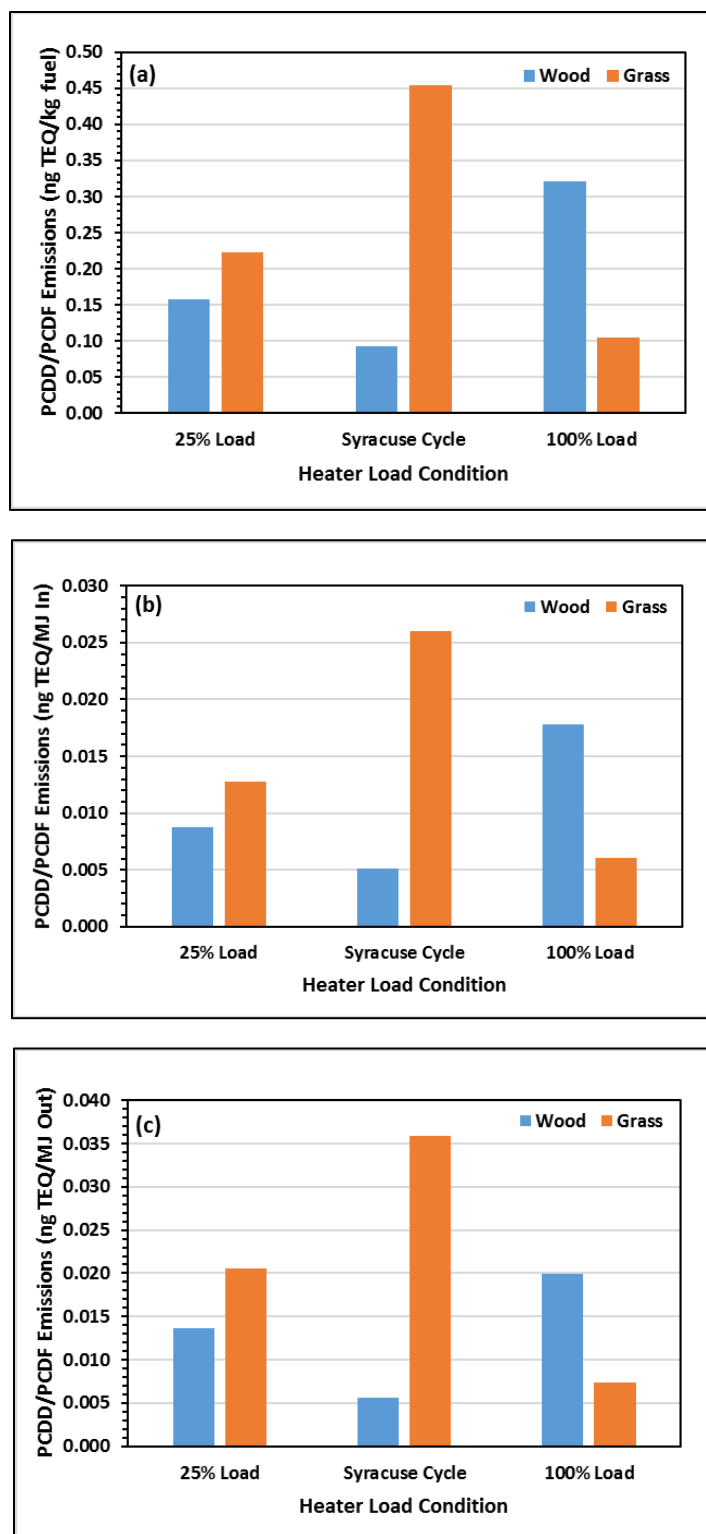
Figure 7-10. Composite total emission factors (SI units) for PCDD/PCDF compounds in terms of: (a) mass per mass of fuel burned; (b) mass per heat input; and (c) mass per heat output.
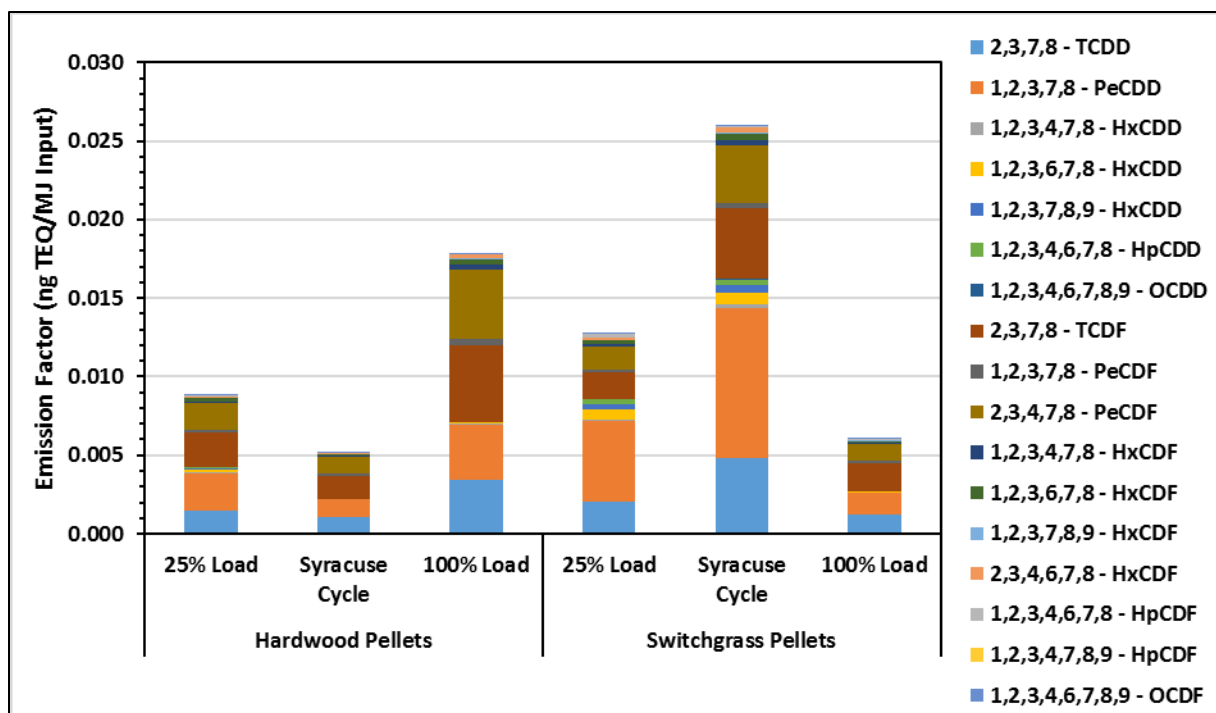
Figure 7-11. Composite emission factors for the 17 PCDD/PCDF compounds measured using EPA Method 23 for each fuel and load condition.

7.2.5 Total Halide Emissions

HCl impinger sample emission factor data is presented in Table 7-7. The plots for emission factors in terms of g of HCl per kg of fuel, g of HCl per MJ input, and in terms of g of HCl per MJ output are presented in Figure 7-12. As shown in Figure 7-12, the HCl emissions for wood were about the same regardless of load condition. Also, one set of samples for the hardwood/Syracuse cycle tests had concentrations below the field blank value that resulted in chlorides below detection limits after the blank correction. It can also be observed in all load cases that switchgrass contributed higher emission rates than the wood pellets with the emissions increasing with load.

Table 7-7. Test Average HCl Emission Factors

| Fuel Type | Load Condition | Value | Average HCl Emissions | | | | |
			mg/kg fuel	mg/MJ Input	lb/MMBTU Input	mg/MJ Output	lb/MMBTU Output
Hardwood	25%	Average	1.53	85.1	0.000198	138	0.000320
		RPD	200	23.2		103	
	Syracuse Cycle	Average	ND^c	ND	ND	ND	ND
		RPD	ND	ND		ND	
	100%	Average	4.43	246	0.000572	226	0.000526
		RPD	115	115		96.7	
Switchgrass	25%	Average	2.70	154	0.000358	245	0.000570
		RPD	25.4	25.4		7.9	
	Syracuse Cycle	Average	2.53	145	0.000335	201	0.000468
		RPD	33.6	33.6		42.4	
	100%	Average	13.5	769	0.00179	913	0.00212
		RPD	126	126		119	

^{a} **Three significant figures**
^{b} **RPD = relative percent difference in emission factors for the two test runs conducted at each fuel/load condition**
^{c}**ND = not detected after blank correction**

60
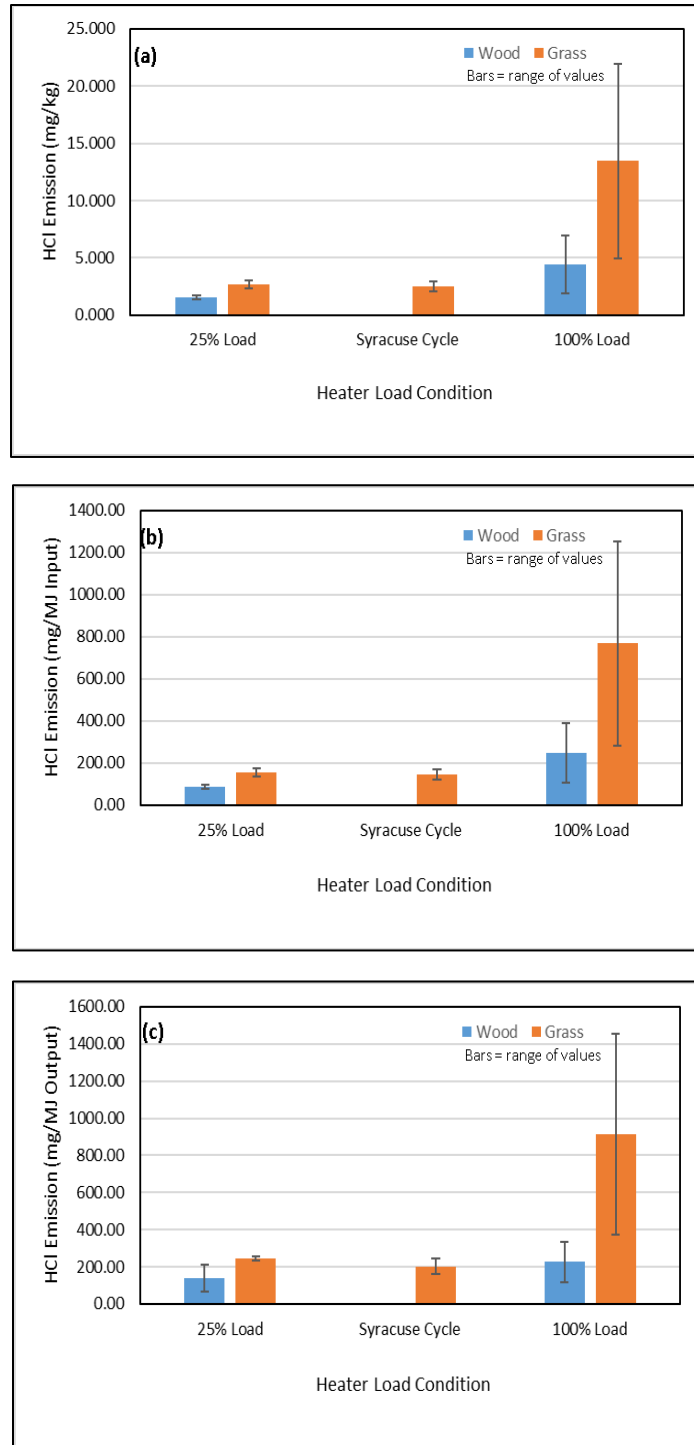
Figure 7-12. Test average total emission factors (SI units) for HCl in terms of: (a) mass per mass of fuel burned; (b) mass per heat input; and (c) mass per heat output.

7.3   Particle Phase Pollutants

7.3.1 Total Particulate Matter Emissions

The average total PM emission factors derived from the modified ASTM 2515 sample trains are shown in Table 7-8 along with the associated RPD for the two tests conducted at each fuel/load condition. These data are also shown graphically in Figure 7-13 and 7-14 in terms of both engineering and SI units, respectively. Also shown in these figures are data from the pellet-fired hydronic heater tested in the previous study (labeled "Former PBHH") conducted by EPA for NYSERDA (Kinsey et al., 2012). More detailed results for the individual tests are provided in Appendix D.

Table 7-8. Test Average Total Particulate Matter Emission Factors

| Fuel Type | Load Condition | Value[b] | Average Total Particulate Emissions[a] | | | | |
			g/kg fuel	g/MJ Input	lb/MMBTU Input	g/MJ Output	lb/MMBTU Output
Hardwood	25%	Average	2.91	0.162	0.376	0.249	0.578
		RPD	2.02	2.02		82.9	
	Syracuse Cycle	Average	0.269	0.0150	0.0348	0.0159	0.0368
		RPD	25.1	25.1		0.540	
	100%	Average	0.401	0.0223	0.0518	0.0219	0.0509
		RPD	11.0	11.0		14.6	
Switchgrass	25%	Average	1.30	0.0744	0.173	0.118	0.274
		RPD	34.9	34.9		17.6	
	Syracuse Cycle	Average	0.761	0.0435	0.101	0.0599	0.139
		RPD	23.5	23.5		14.4	
	100%	Average	0.662	0.0378	0.0879	0.0462	0.107
		RPD	39.7	39.7		27.8	

[a] **Three significant figures**
[b] **RPD = relative percent difference in emission factors for the two test runs conducted at each fuel/load condition**

As indicated by the emission factors provided in Figure 7-14a, the total PM emission factor generally drops by a factor of ~ 8 for hardwood and a factor of ~ 1.8 for switchgrass with increasing load. The only exception is for wood during the Syracuse cycle which produces slightly lower PM than at 100%. In addition, except at 25% load, the PM emission factors for switchgrass combustion are a factor of ~ 2-3x higher than for hardwood. It is interesting that wood combustion at 25% load produces total PM mass/mass fuel which is more than twice that for grass. Finally, it appears that the total PM emission factors for the burning of hardwood pellets over the Syracuse cycle were generally similar to total PM emissions from the European 2-stage unit tested previously for NYSERDA.
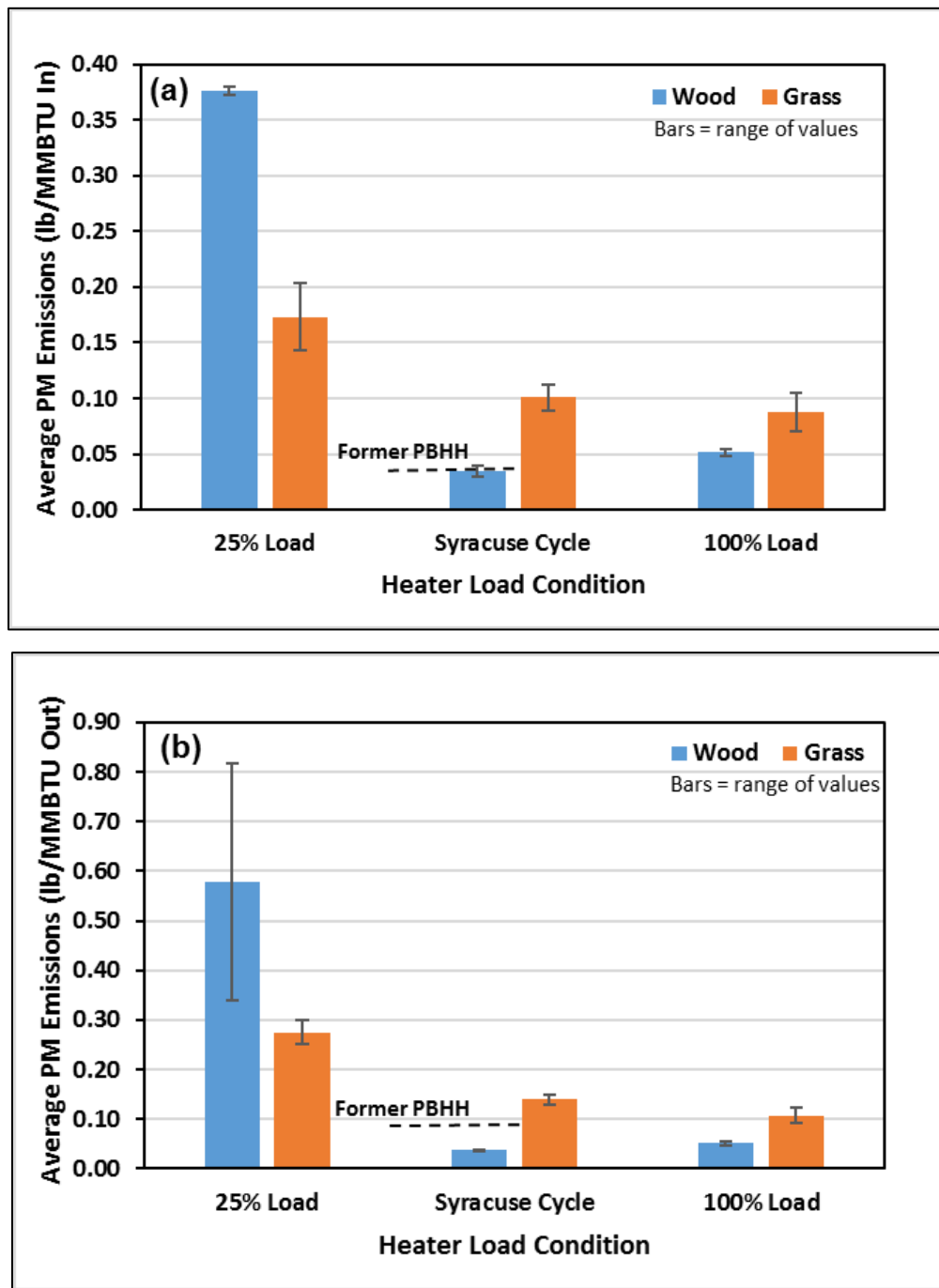
Figure 7-13. Total PM mass emission factors (engineering units) in terms of: (a) mass per heat input; and (b) mass per heat output; Dashed line represents "Former PBHH" which refers to pellet-fired hydronic heater tested previously (Kinsey et al., 2012)
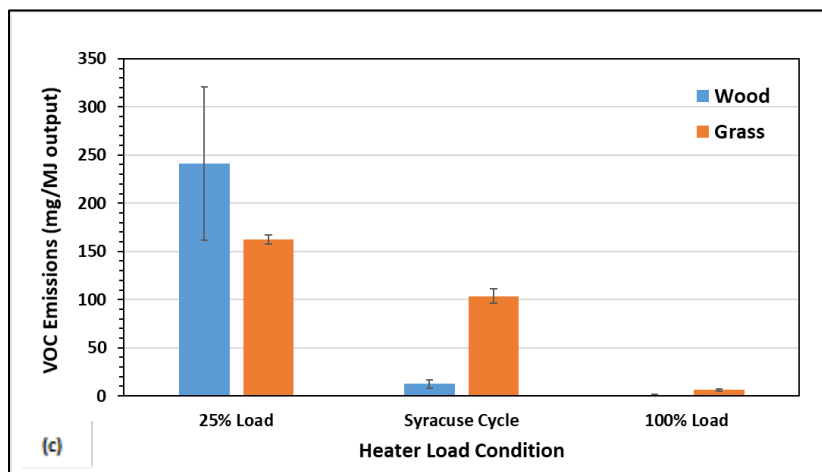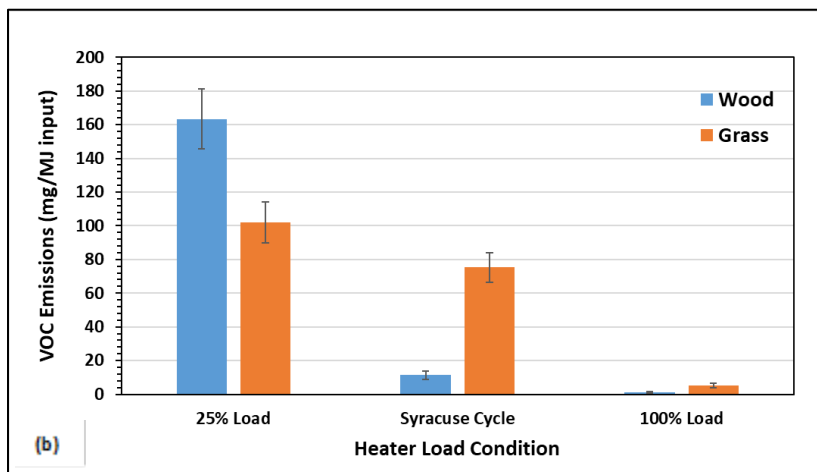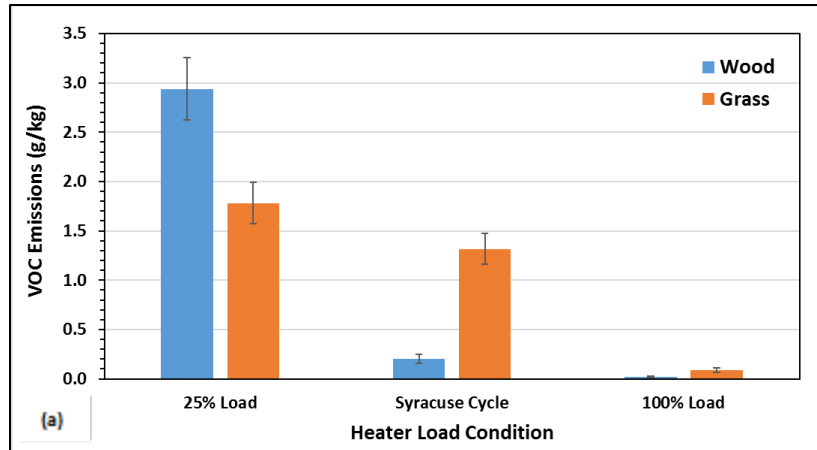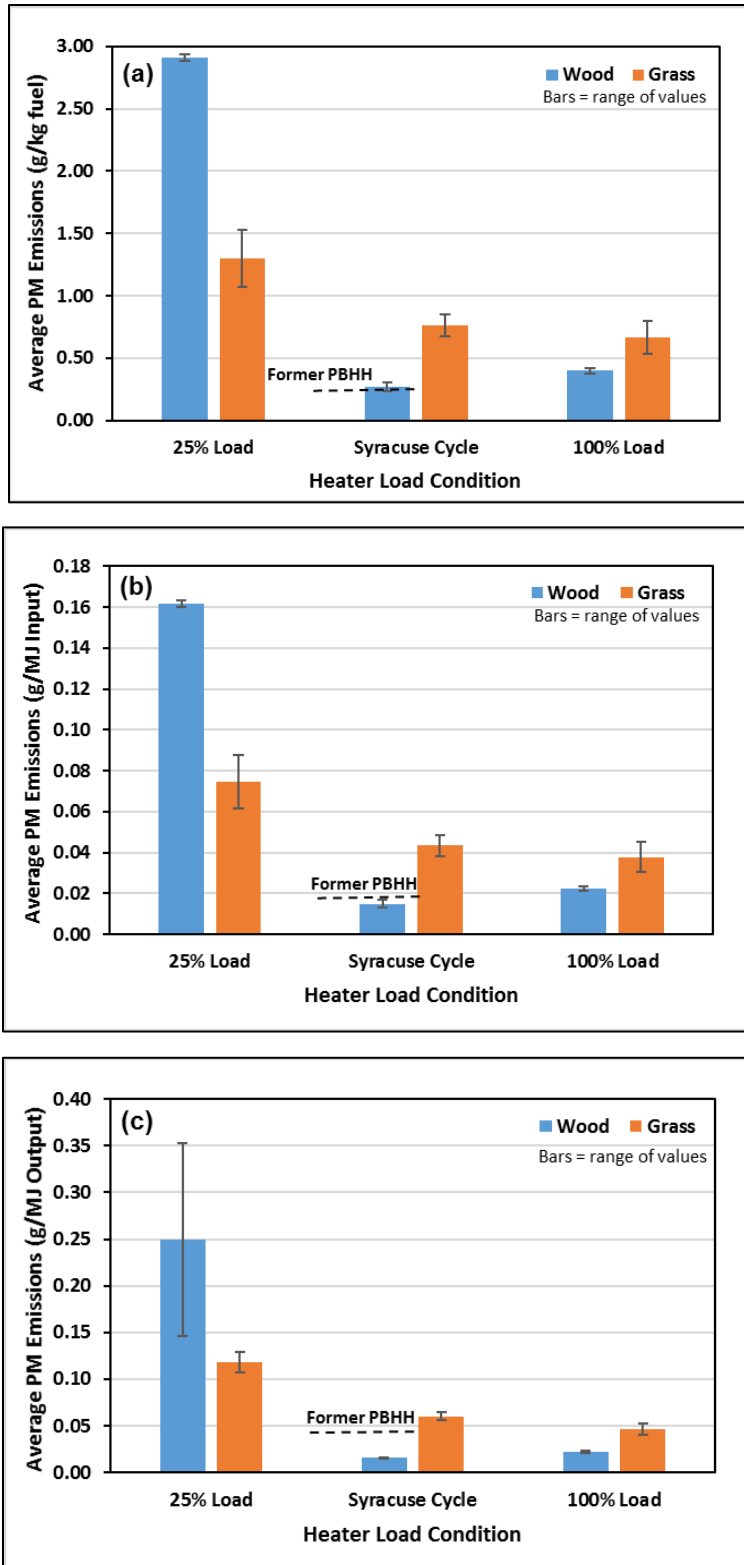
**Figure 7-14.** Total PM emission factors (SI units) in terms of: (a) mass per mass of fuel burned; (b) mass per heat input; and (c) mass per heat output; Dashed line represents "Former PBHH" which refers to pellet-fired hydronic heater tested previously (Kinsey et al., 2012)

Emission factor data from the Method 2515 filters were compared to similar results for the 25-mm Teflon filters by simple linear regression analysis. The regression constant of 1 from this analysis showed that the Teflon filters produced total PM emission factors similar to those determined by Method 2515 with a correlation constant (r^2) of 0.8. Recall that 3 Teflon filter samples of 20 minutes each were collected during each test and as such are more "snapshots" of the emissions from the hydronic heater rather than overall test averages. It was surprising that the Teflon results agree so well with those from the Method 2515 trains considering the high variability in the PM emissions observed by the ELPI instrument as discussed below. Therefore, total PM emission factors for the Teflon filter sampling will not be reported here but are included in Appendix D.

7.3.2 Particle Number Emissions

Time histories of the total particle number concentrations for each test from the ELPI are shown in Figure 7-15 for hardwood and 7-16 for switchgrass. These plots represent particles ranging in size from 30 nm to < 10 µm in aerodynamic diameter (equivalent unit density spheres). It should also be noted that a soot blow event generally preceded the transition from low fire to high fire producing large quantities of black carbon soot contributing substantially to the high variability in emissions observed over the 6-hour test runs.

As illustrated by Figures 7-15 and 7-16, the operational pattern for the duplicate tests were generally similar except for switchgrass combustion during the Syracuse cycle (Figure 7-16c and 7-16d). Here, the particle concentration time histories are substantially different. Also of note is the concentration histories of grass combustion at 100% load (Figures 7-16e and 7-16f) which were quite different from those of wood combustion (Figures 7-15e and 7-15f). In Figures 7-16e and 7-16f a sawtooth pattern was seen for switchgrass as compared to Figures 7-15e and 7-15f for hardwood where a more typical high/low fire cycle was evident. It should be noted, however, that the time scales plotted on the abscissas are not identical for the six plots presented in Figures 7-15 and 7-16.

The average total particle number concentration and standard deviation determined during each test run from the on-line ELPI analyzer is shown in Figure 7-17 for both fuels. As shown in Figure 7-17, switchgrass generally produced higher particle number concentrations for all load conditions as reflected in the emission factors provided below.

The average total particle number emission factors calculated from the ELPI data are provided in Table 7-9 along with the associated RPD for the two tests conducted at each fuel and load condition. The emissions factor data are also shown graphically in Figure 7-18 and 7-19 in terms of both engineering and SI units, respectively. Also provided in Figure 7-19a is the emission factor for the European hydronic heater tested previously for NYSERDA (Kinsey et al., 2012). Test specific PM number emission factor results are provided in Appendix D.
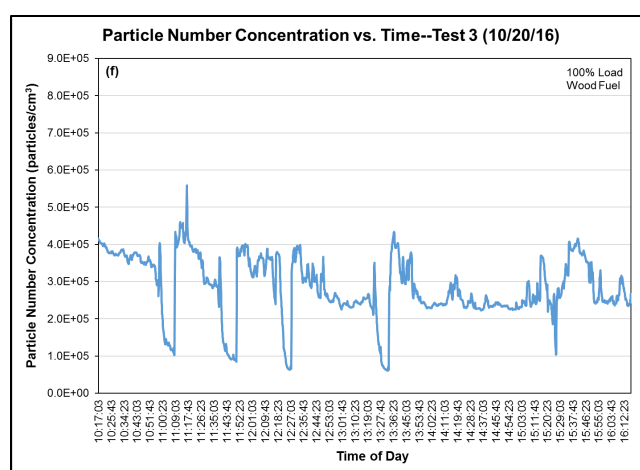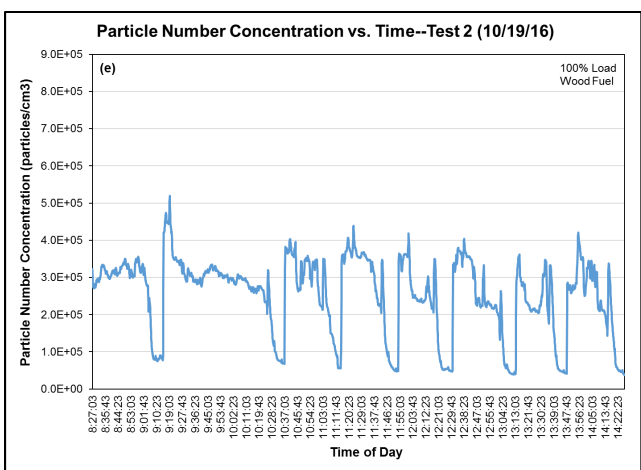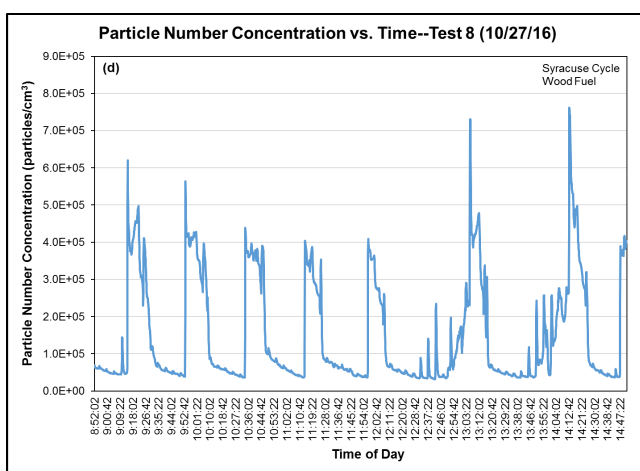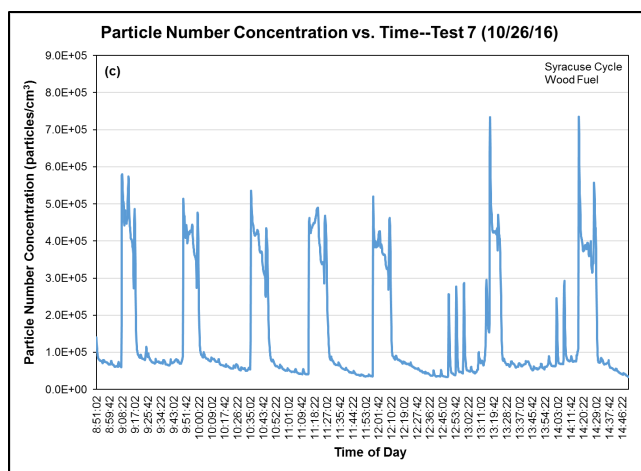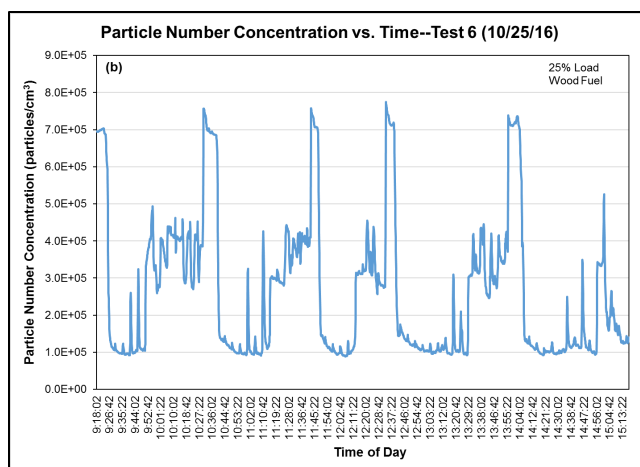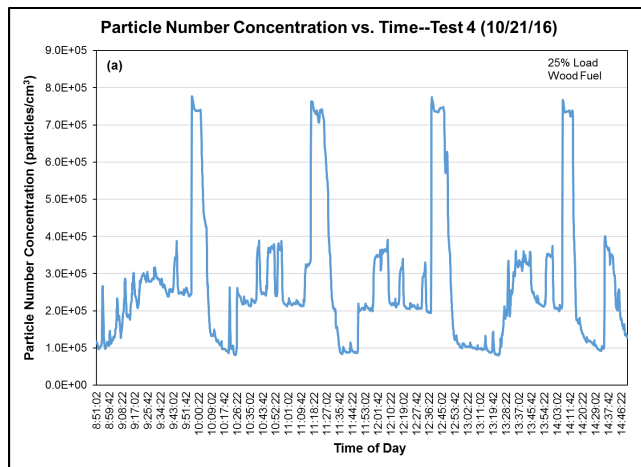
Figure 7-15. Total particle number concentration time histories for hardwood combustion at 25% load (a and b), during the Syracuse cycle (c and d), and 100% load (e and f)
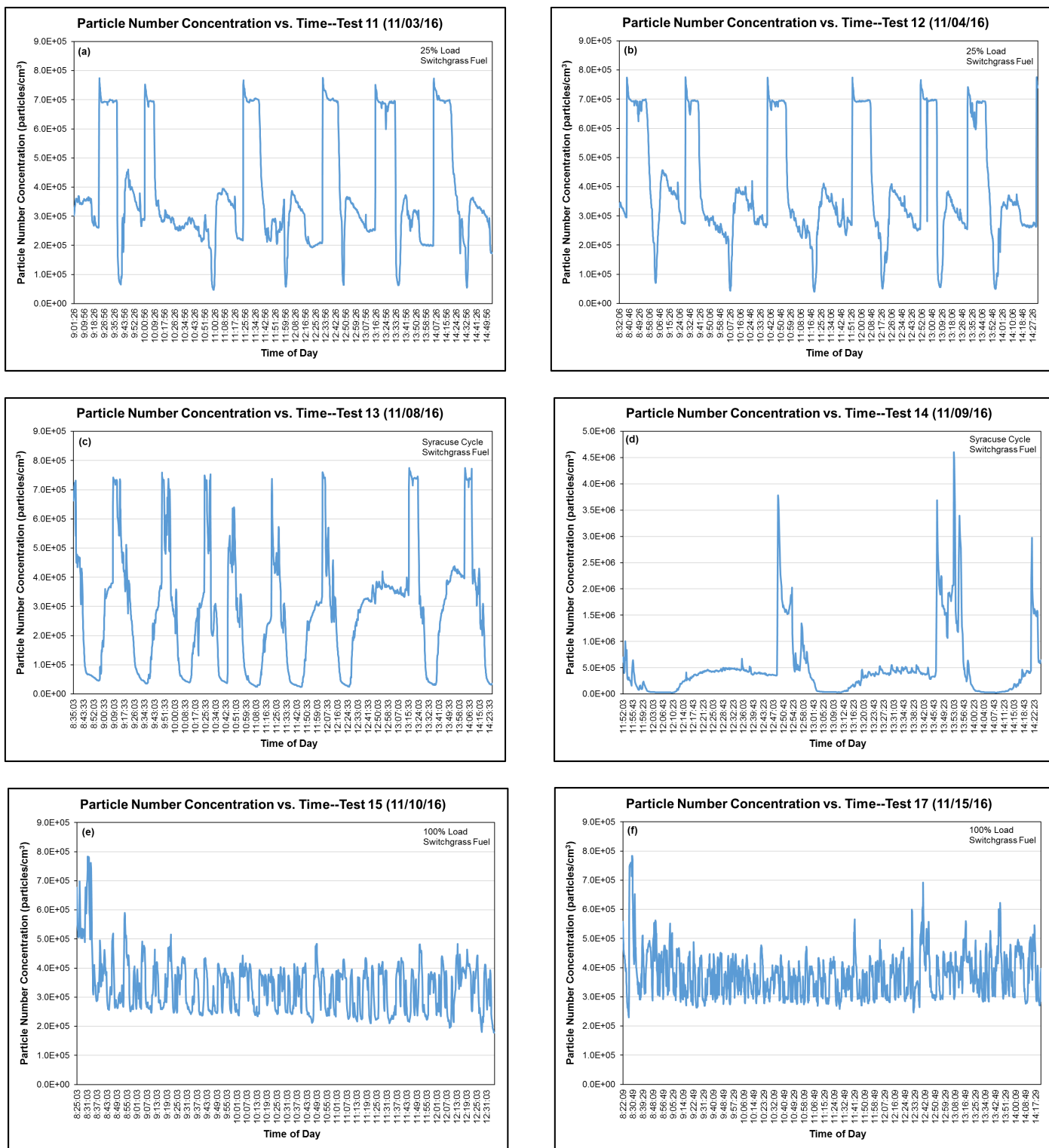
Figure 7-16. Total particle number concentration time histories for hardwood combustion at 25% load (a and b), during the Syracuse cycle (c and d), and 100% load (e and f)
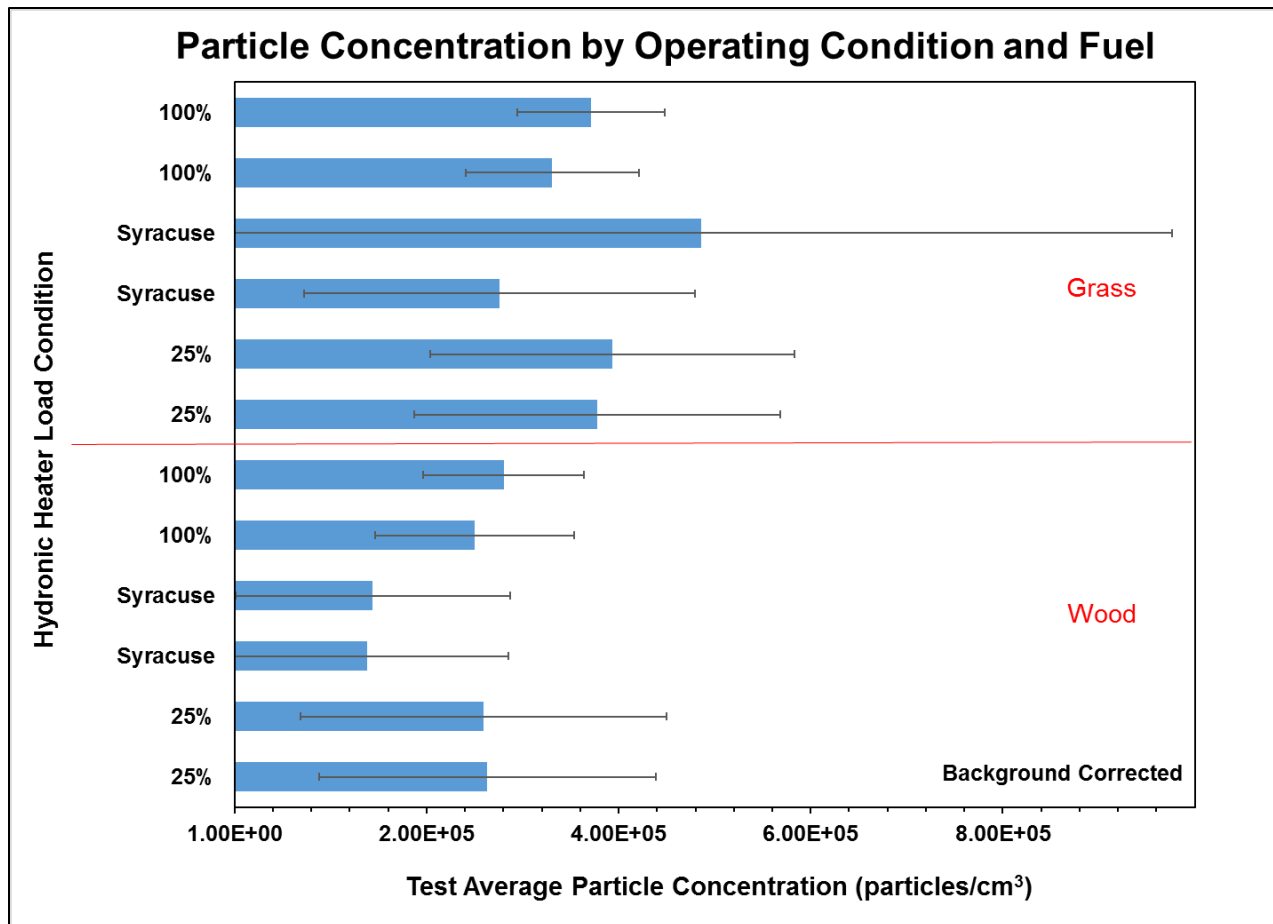
Figure 7-17. Background corrected test average particle number concentrations for both fuels.

As shown in Figure 7-19a, hardwood combustion generally produced fewer particles per fuel mass than switchgrass for all test conditions. This decrease varied from a factor of 1.1 at 100% load to a factor of greater than 1.9 for operation during the Syracuse cycle. Also, for both fuels, the total PM number emission factor dropped by about a factor of 3 with increasing load, similar to total PM mass. For hardwood, the number emission factor dropped from 2.07×10^{14} particles/kg fuel at 25% load to 6.78×10^{13} particles/kg fuel at 100%. In the case of switchgrass, the number emission factor was 2.3×10^{14} particles/kg fuel at 25% load and 7.18×10^{13} particles/kg fuel at 100% load.

Finally, it appears that the REKA unit tested under the Syracuse cycle using hardwood pellets has a substantially higher average particle number emission factor as compared to the appliance tested previously for NYSERDA in 2010 also under the Syracuse cycle. (Note that the European unit was operated using hardwood pellets only.) The European pellet heater had an average emission factor of 8.5×10^{10} particles/kg fuel whereas the REKA unit produced an emission factor of 7.65×10^{13} particles/kg fuel which is almost a 3 order-of-magnitude increase in particle number.

Table 7-9. Test Average Particle Number Emission Factors

Fuel Type	Load Condition	Value[b]	Average Particle Number Emissions[a]				
			particles/kg fuel	particles/MJ input	particles/MMBTU input	particles/MJ output	particles/MMBTU output
Hardwood	25%	Average	2.07E+14	1.15E+13	1.21E+16	1.47E+13	1.55E+16
		RPD	81.3	81.3		4.00	
	Syracuse Cycle	Average	7.65E+13	4.25E+12	4.48E+15	4.52E+12	4.77E+15
		RPD	19.5	19.5		6.19	
	100%	Average	6.78E+13	3.77E+12	3.97E+15	3.70E+12	3.90E+15
		RPD	13.8	13.8		11.7	
Switchgrass	25%	Average	2.30E+14	1.31E+13	1.39E+16	2.10E+13	2.22E+16
		RPD	13.3	13.3		4.31	
	Syracuse Cycle	Average	1.48E+14	8.45E+12	8.91E+15	1.18E+13	1.25E+16
		RPD	49.3	49.3		57.8	
	100%	Average	7.18E+13	3.77E+12	4.33E+15	5.03E+12	5.30E+15
		RPD	25.3	25.3		13.2	

[a] Three significant figures
[b] RPD = relative percent difference in emission factors for the two test runs conducted at each fuel/load condition; Three significant figures
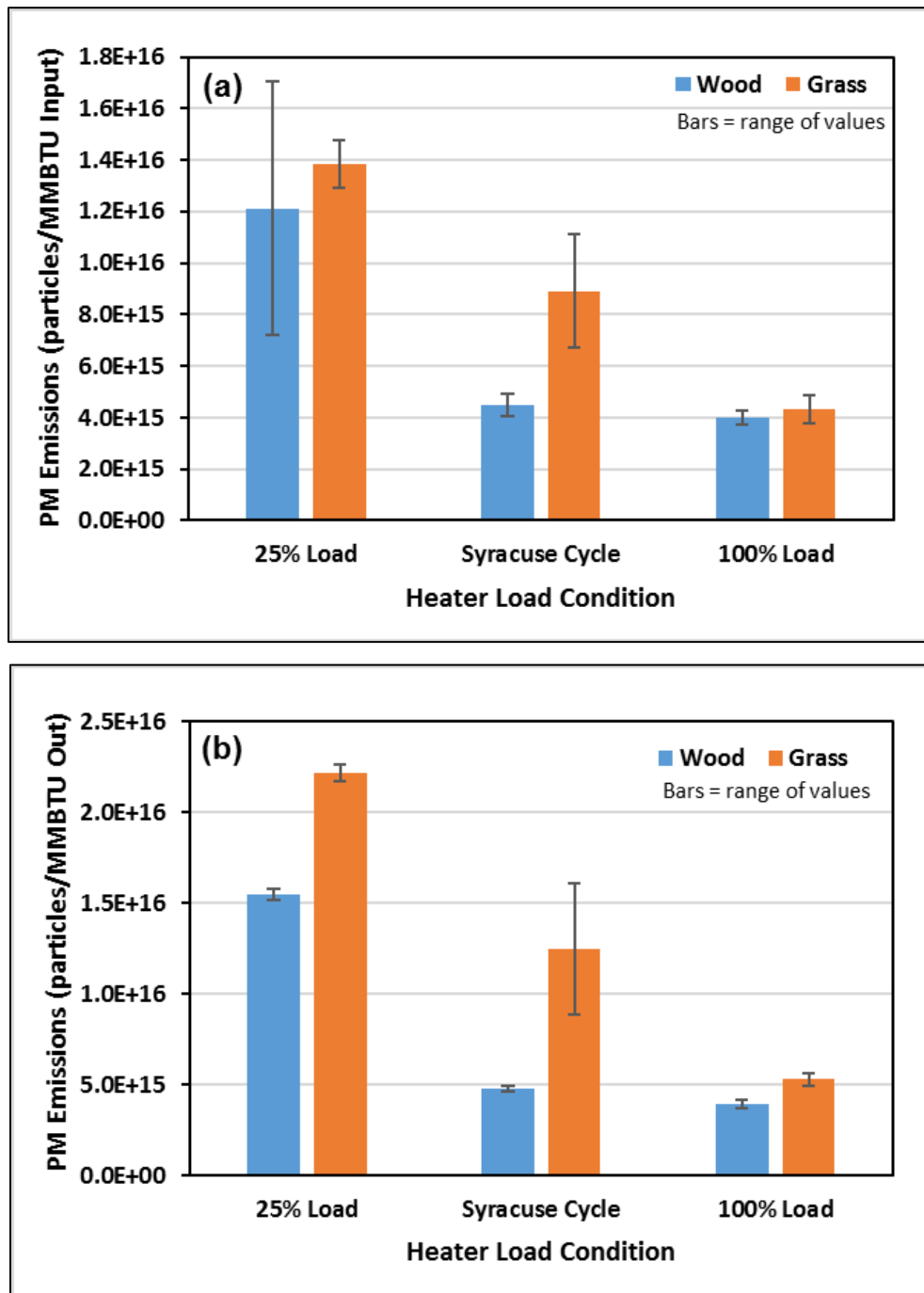
Figure 7-18. Total particle number emission factors (engineering units) in terms of: (a) particles per heat input; and (b) particles per heat output

70
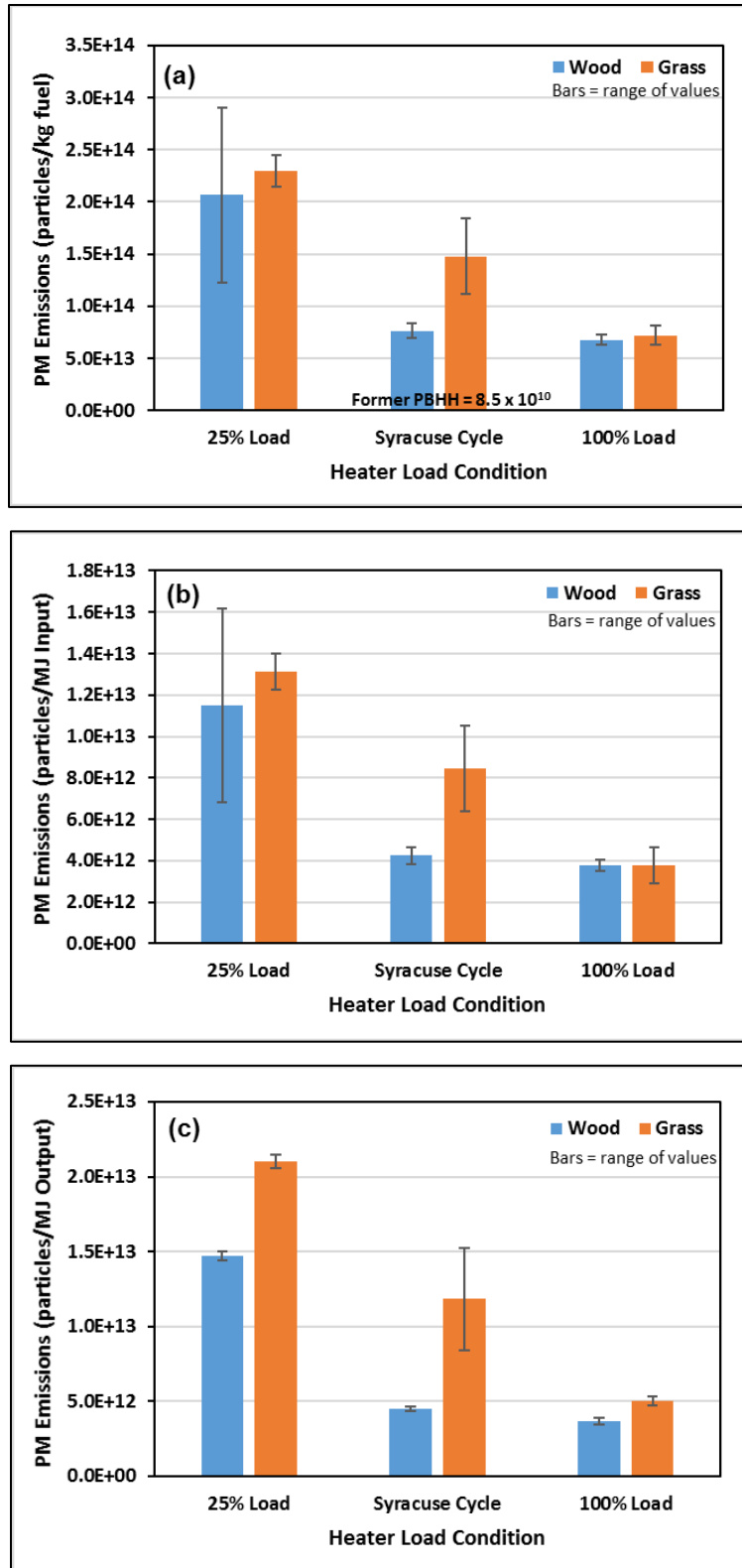
Figure 7-19. Total particle number emission factors (SI units) in terms of: (a) particles per mass of fuel burned; (b) particles per heat input; and (c) particles per heat output. Also shown in (a) is a similar factor for the European unit tested previously with hardwood during the Syracuse cycle.

7.3.3 Particle Size Distributions

The average differential number particle size distribution for each test conducted is shown in Figure 7-20 and Figure 7-21 for hardwood and switchgrass, respectively, as determined from the ELPI data. These data were then converted to a single equivalent lognormal PSD and summary statistics calculated in the form of the geometric mean particle diameter (GMD) and geometric standard deviation (GSD) of the distribution. These statistics are likewise shown in Figures 7-20 and 7-21 for each test run.

Looking at Figure 7-20 for hardwood, all the PSDs exhibited at least two modes, a major mode centered slightly greater or less than ~ 100 nm and a minor mode in the range of ~ 300 nm. For the 25% load condition, however, a third large particle mode centered around ~ 500 nm was also observed. The smaller 300 nm mode is likely the result of flame generated soot, and the larger 100 nm mode the result of condensed organic carbon formed post flame. The existence of two modes can be explained by high supersaturation vapor pressures caused by steep temperature profiles forcing homogeneous nucleation of new organic carbon particles rather than heterogeneous condensation of the organic carbon on existing soot particles. In addition, the shape of the PSDs was generally similar for the two tests conducted at each appliance operating condition except for 25% load. At 25% load, the particles were generally smaller and the distribution narrower during Test 6 (Figure 7-20b) compared to Test 4 (Figure 7-20a) which is reflected by differences in the GMD and GSD for the two tests. It should also be noted that a significant number of large particles > 1 μm were measured by the ELPI for all load conditions contributing to the relatively high mass emissions observed.

For the switchgrass PSDs shown in Figure 7-21, similar trends were observed as was the case for hardwood except that the number concentrations were generally higher, especially for the 25% load condition. Substantially differences in the PSD was also shown for the two tests conducted using the Syracuse cycle. For Test 14 (Figure 7-21d), the major mode was centered at ~ 300 nm rather than slightly less than 100 nm as was observed during Test 13 (Figure 7-21c). This is reflected by the shape of the PSD as well as the higher GMD for Test 14.

Finally, the PSDs generated for hardwood during the Syracuse cycle (Figures 7-20c and 7-20d) were compared to those determined for the European pellet burner tested previously (Kinsey et al., 2012). Figures 7-20c and 7-20d show a much broader bi-modal PSD as compared to the European unit which was narrower and mono-modal. This would, of course, indicate that combustion conditions inside the REKA hydronic heater were substantially different as also reflected by the higher particle number emission factors for the REKA discussed above.

7.3.4 Elemental and Organic Carbon (ECOC)

The averages emission factors for EC and OC determined from the time-integrated quartz filter sampling are provided in Table 7-10 along with the associated RPD for the two tests at each fuel and load condition. These data are also shown graphically in Figures 7-22 and 7-23 in terms of both engineering and SI units, respectively. Test-specific EC and OC emission factor data are provided in Appendix D.
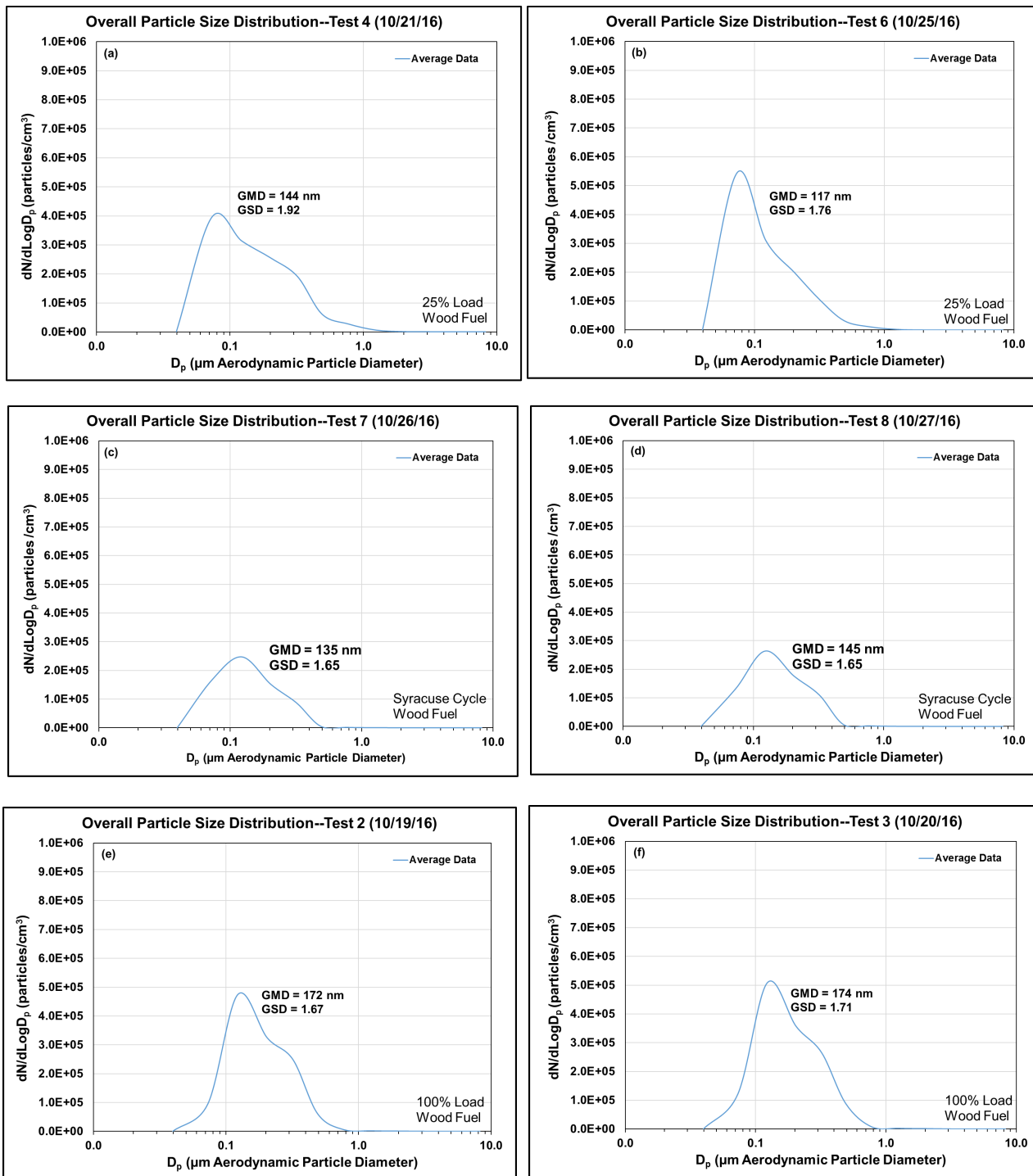
Figure 7-20. Differential number particle size distributions and summary statistics for tests burning hardwood pellets
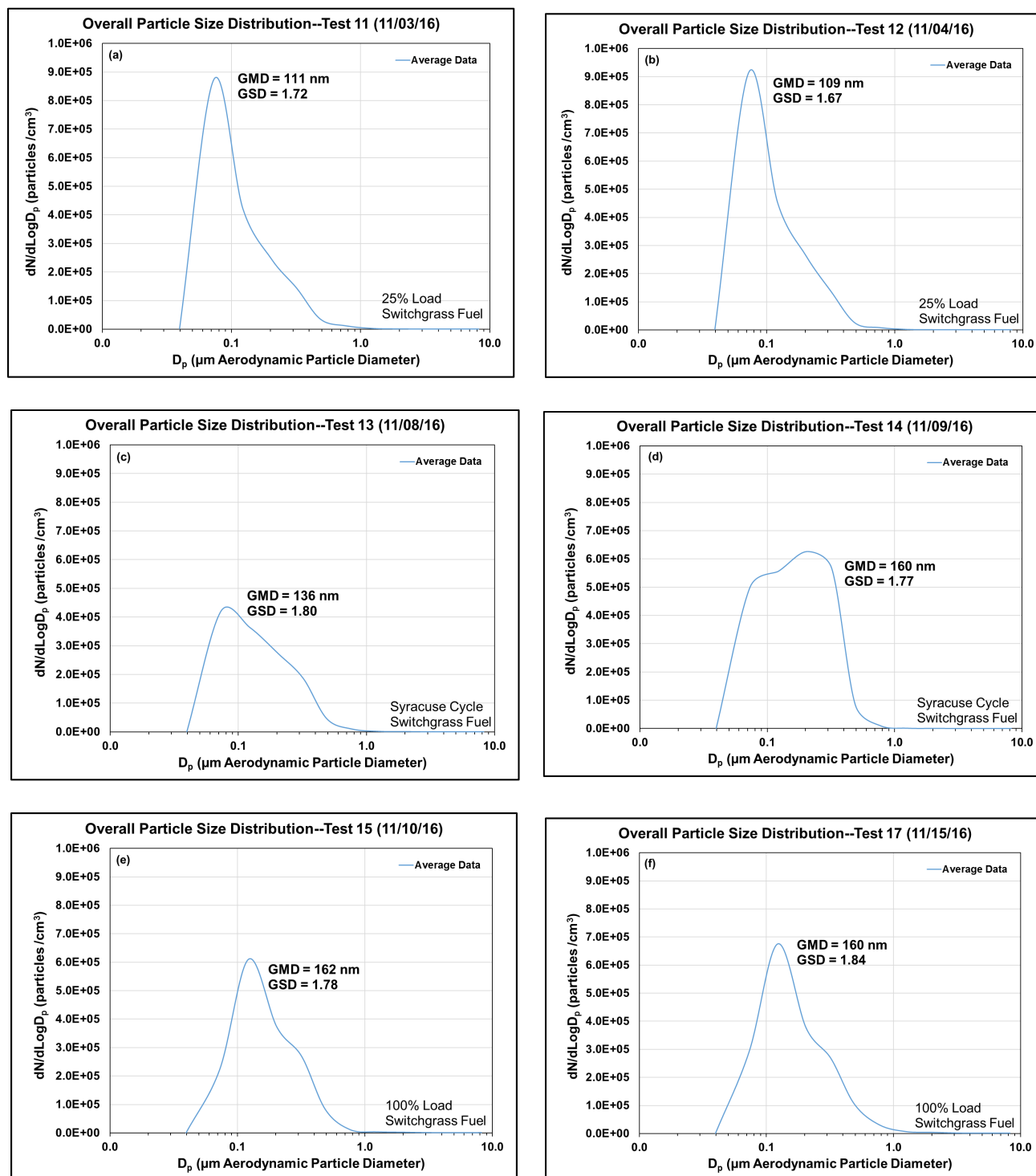
Figure 7-21. Differential number particle size distributions and summary statistics for tests burning switchgrass pellets

Table 7-10. Test Average ECOC Emission Factors[a]

Carbon Type	Fuel Type	Load Condition	Value	Average Carbon Emissions				
				mg/kg fuel	mg/MJ Input	lb/MMBTU Input	mg/MJ Output	lb/MMBTU Output
Elemental	Hardwood	25%	Average	20.0	1.11	0.00258	1.56	0.00362
			RPD	44.6	44.6		44.2	
		Syracuse Cycle	Average	10.2	0.568	0.00132	0.648	0.00150
			RPD	92.8	92.8		112	
		100%	Average	90.0	5.00	0.0116	4.66	0.0108
			RPD	95.5	95.5		74.6	
	Switchgrass	25%	Average	11.1	0.636	0.00148	1.01	0.00236
			RPD	23.5	23.5		5.91	
		Syracuse Cycle	Average	83.8	4.79	0.0111	6.53	0.0152
			RPD	60.5	60.5		52.0	
		100%	Average	292	16.7	0.0387	20.3	0.0472
			RPD	44.7	44.7		33.0	
Organic	Hardwood	25%	Average	1075	59.8	0.139	83.5	0.194
			RPD	45.7	45.7		43.1	
		Syracuse Cycle	Average	33.1	1.84	0.00427	1.83	0.00424
			RPD	122	122		105	
		100%	Average	1.78	0.0992	0.000230	0.0858	0.000199
			RPD	200	200		200	
	Switchgrass	25%	Average	572	32.7	0.0759	52.2	0.121
			RPD	20.2	20.2		2.58	
		Syracuse Cycle	Average	392	22.4	0.0520	30.7	0.0713
			RPD	38.4	38.4		29.5	
		100%	Average	62.8	3.59	0.00833	4.27	0.00993
			RPD	115	115		106	

[a] **Three significant figures. RPD = relative percent difference in emission factors for the two test runs at each fuel/load condition.**
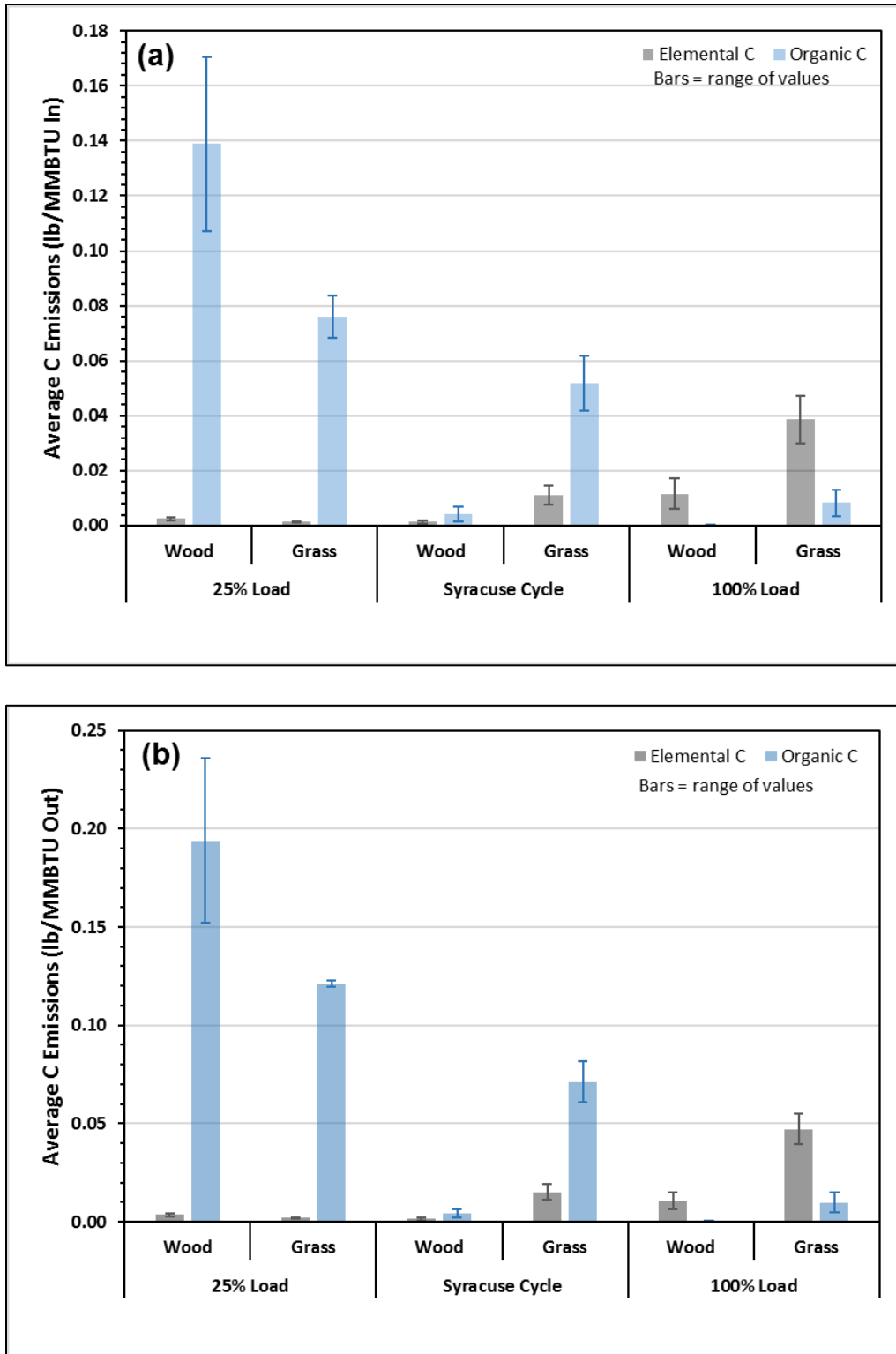
Figure 7-22. Elemental and organic carbon emission factors for all fuel and load conditions in terms of: (a) mass per heat input; and (b) mass per heat output (engineering units)

Figure 7-23. Elemental and organic carbon emission factors for all fuel and load conditions in terms of: (a) mass per mass fuel; (b) mass per heat input; and (c) mass per heat output (SI units)

Figure 7-23a shows that, except for wood at 25% load, the elemental carbon emissions generally increase with load for both fuel types whereas the organic carbon emissions decrease with increasing load. For wood, there was a factor of 4.5 increase in emissions between 25% and 100% load but for grass it was a 26x increase. The general trend is understandable since significant amounts of elemental carbon should only be produced at higher combustion temperatures whereas at lower temperatures, such as at 25% load, elemental carbon is generally minimized and greater amounts of organic carbon in the form of particle-phase semi-volatile organic compounds should be present which was indeed observed here. What cannot be explained is that the OC emission factors for hardwood combustion at 25% load is about twice that for switchgrass whereas just the opposite was the case at the other two appliance operating conditions where grass produced a factor of ~ 11-35x higher emissions. The same trend was also evident for EC. The EC emissions for grass were generally a factor of ~ 3 to 8x higher than wood except at 25% load where grass had about half the emissions of wood. It is obvious from these trends that the two fuels burn quite differently at minimal load as compared to higher, more stable load conditions. This is also consistent with the VOC and PAH emission factors discussed earlier, and suggest fundamental differences in the combustion of hardwood and switchgrass fuels perhaps related to fuel volatility.

In addition to the time-integrated filter data, ECOC was also measured using the Sunset Model 4 Semi-Continuous Carbon Analyzer. The test average emission factors from the semi-continuous instrument are compared to those derived from the manual filter sampling for both EC and OC in Figure 7-24. As shown by the linear regression results, the data from the two instruments appear to be well correlated with each other. However, the automated EC analyses provide 23% higher emission factors and a factor of 2x higher emission factors for OC as compared to the time-integrated data. One reason for the factor of 2 difference for OC is potentially one very high value for the semi-continuous instrument at 25% load using hardwood fuel drives the regression constant significantly upward. If this value was eliminated from the linear regression, the new regression constant would show the time-integrated analysis as being similar to that observed for EC.

It is not surprising, however, that the semi-continuous emission factors are always higher than the time-integrated filter results since the duration of each sample collection period is much shorter and thus more susceptible to the frequent excursions in emissions such as soot blowing which were characteristic of the REKA heater. These excursions were illustrated previously in Figures 7-15 and 7-16 where emission spikes of a factor of 2x or more in particle number concentration were oftentimes observed. It is recommended, therefore, that only the time-integrated filter OCEC emission factor results be used for reporting purposes since the longer sampling periods make them more representative of the entire test run.

7.3.5 Optical Black Carbon (OBC)

The test average OBC EFs determined by optical absorption using the Aethalometer are provided in Table 7-11 along with the associated RPD calculated for the two tests at each fuel and load condition. The EFs are also shown graphically in Figures 7-25 and 7-26 in terms of both engineering and SI units, respectively. More detailed OBC emission factor data are provided in Appendix D.

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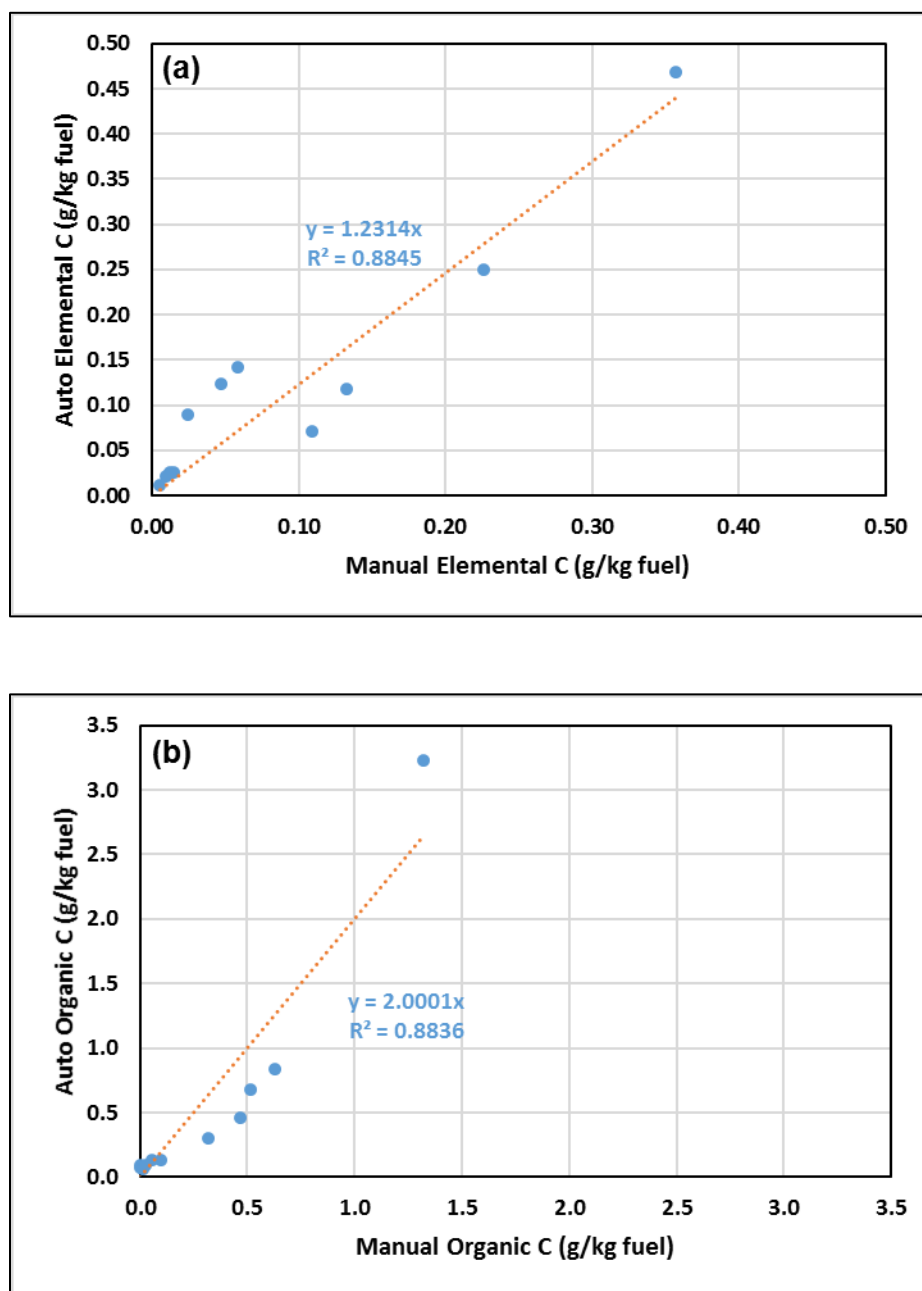
Figure 7-24. Comparison of manual filter results to those from the semi-continuous carbon analyzer for: (a) elemental carbon; and (b) organic carbon (all tests)

Table 7-11. Test Average Optical Black Carbon (BC) Emission Factors

Fuel Type	Load Condition	Value[b]	Average Optical BC Emissions[a]				
			mg/kg fuel	mg/MJ Input	lb/MMBTU Input	mg/MJ Output	lb/MMBTU Output
Hardwood	25%	Average	145	8.1	0.0188	7.2	0.0167
		RPD					
	Syracuse Cycle	Average	29.1	1.62	0.00375	1.66	0.00385
		RPD	72.2	72.2		48.8	
	100%	Average	180	10.0	0.0233	9.66	0.0224
		RPD	42.1	42.1		17.1	
Switchgrass	25%	Average	62.3	3.56	0.00827	5.71	0.0133
		RPD	9.94	9.94		7.72	
	Syracuse Cycle	Average	162	9.28	0.0215	12.8	0.0297
		RPD	21.2	21.2		12.1	
	100%	Average	420	24.0	0.0557	29.39	0.0683
		RPD	25.9	25.9		13.8	

[a] **Three significant figures. Numbers shown in red face type are a single test value**
[b] **RPD = relative percent difference in emission factors for the two test runs conducted at each load condition**

Looking at the data shown in Figure 7-26a, in a trend similar to EC, switchgrass produced a factor of 2-6x higher OBC as compared to hardwood except at 25% load where wood combustion gave a factor of ~ 3 higher emissions. Also, the OBC EF drops or stays about the same with increasing load for hardwood but increases with load for switchgrass. The drop in OBC for hardwood was between the 25% load condition and the Syracuse cycle where a factor of ~ 5 decrease in emissions was observed. In the case of switchgrass, the OBC emissions increased by almost a factor of ~ 7 at 100% load as compared to 25% load. This is a similar trend to that found for EC as discussed above.

Another interesting comparison is between the emissions of OBC and EC, as these two parameters are oftentimes used interchangeably. The OBC emission factors are compared to the manual EC results for all fuel and load conditions in Figure 7-27 along with a linear regression performed on the data. As shown by the regression constant, EC represented only about 63% of the OBC measured. Such results would indicate that, at least for the combustion of hardwood and switchgrass pellets in this study, the two parameters are not equivalent to each other and thus should not be used interchangeably.

Few studies on residential wood combustion have investigated black carbon emissions, and only one, to our knowledge, has investigated black carbon from a pellet stove. Bertrand et al. (2017) measured black carbon emissions from a 6-kW pellet stove operated on spruce/pine pellets and observed emission factors of 1.2 g/kg, which is nearly three times larger than the largest black carbon emissions observed in this study (0.4 g/kg, high load with the grass pellets).

80
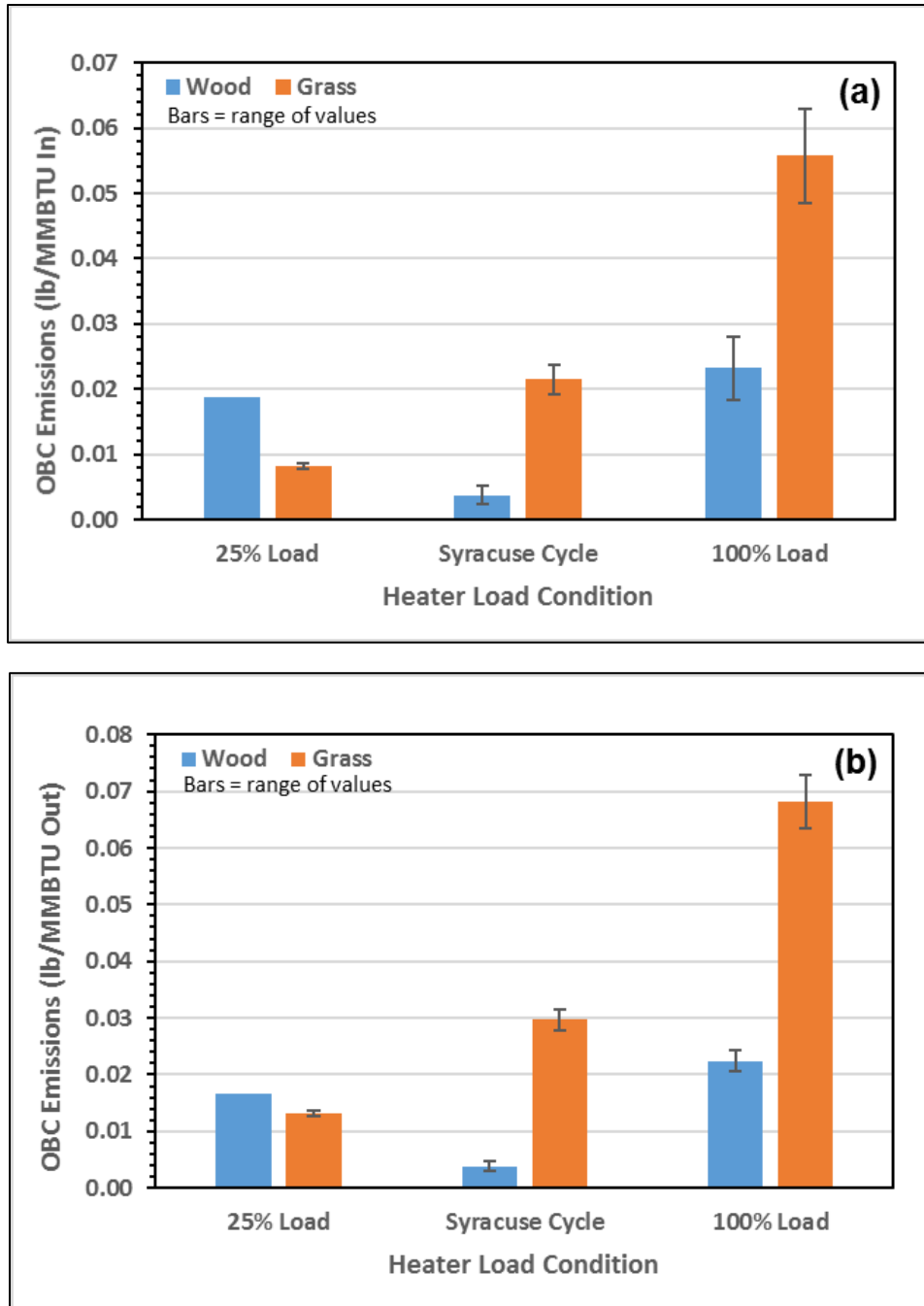
Figure 7-25. Optical black carbon emission factors for each fuel and load condition on the basis of (a) thermal input and (b) thermal output (engineering units)
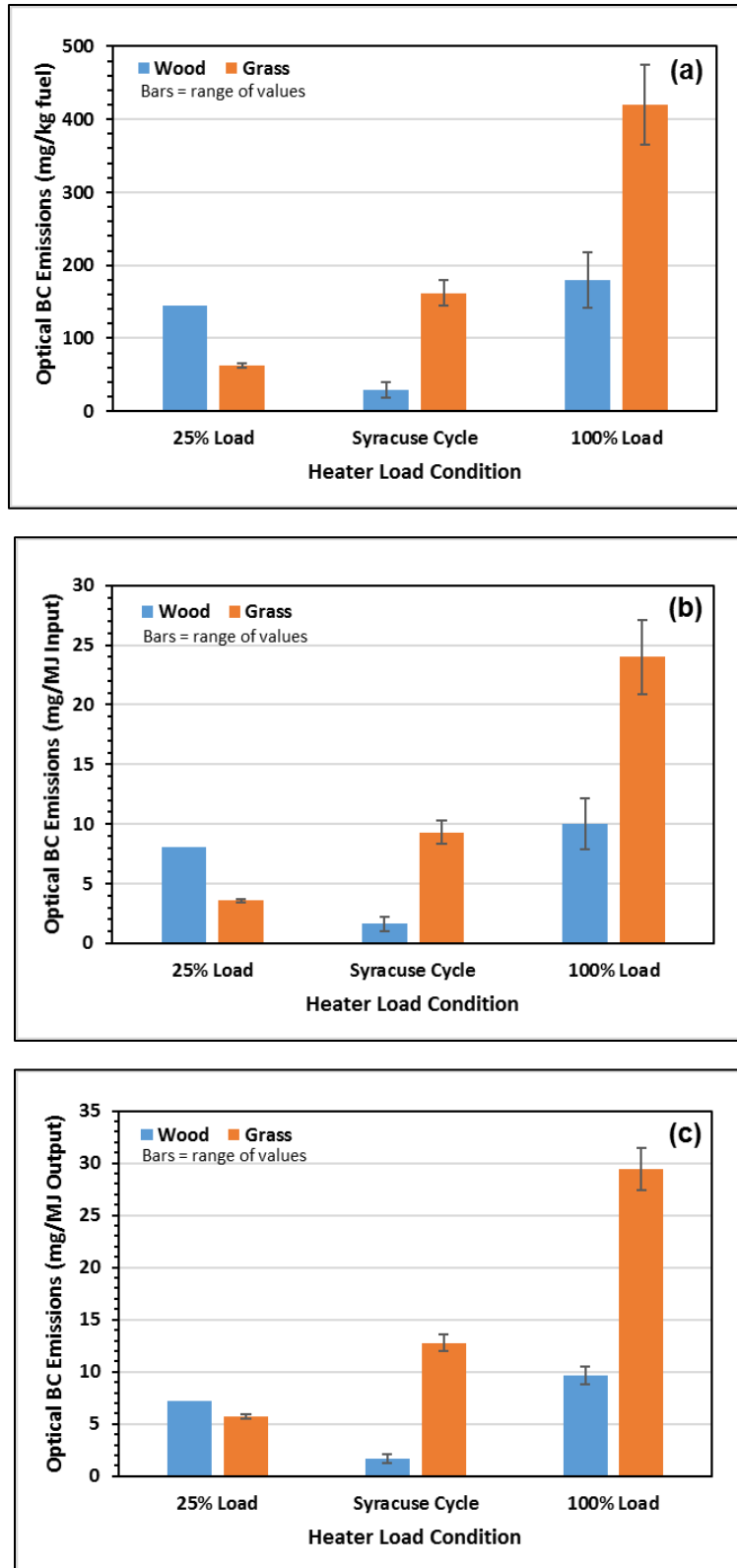
Figure 7-26. Optical black carbon emission factors for all fuel and load conditions in terms of: (a) mass per mass fuel; (b) mass per heat input; and (c) mass per heat output (SI units)
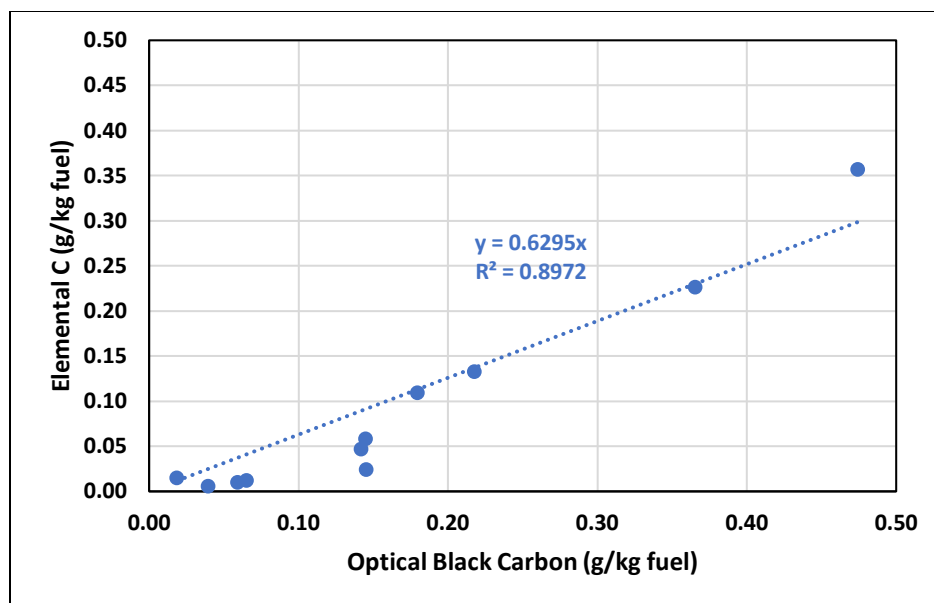
Figure 7-27. Comparison of optical black carbon to elemental C for all tests conducted

Many more studies have investigated elemental carbon emissions, but as was seen in our data, black carbon emissions can be substantial different from elemental carbon emissions, despite the high correlation between the two measures. Elemental carbon emissions have varied widely, depending on the type of appliance and on the feedstock for the pellets. Generally, grass and other agricultural residue pellets have led to higher emissions of elemental carbon than from wood pellets (Vicente et al. 2015). Likewise, in our study black carbon emissions were larger from grass pellets as compared to wood pellets.

7.3.6 *PM Elemental Composition*

PM elemental composition was determined by XRF analysis of the Teflon filter samples. From the analyses conducted, EFs were developed for those elements listed in the Clean Air Act as hazardous air pollutants which were found within the limits of detection plus sulfur and chlorine. Sulfur and chlorine were also selected since these elements represent precursors to other pollutants measured in the program. The EFs determined in terms of elemental mass per mass of fuel are summarized in Table 7-12 and shown graphically in Figure 7-28. More detailed XRF results are provided in Appendix D. Note that the EFs were not corrected for ambient background and thus represent worst case. It would be expected, however, that the background for these 5 elements would be negligible.

For the toxic metals shown in Figure 7-28a, only trace amounts of Cr, Mn, and Pb emissions were produced by both fuels during the Syracuse cycle and at 100% load. At 25% load, however, significant quantities of all three were present in the PM emissions from the burning of hardwood but switchgrass only produced trace emissions at this load condition. There is no apparent reason for this observation except the different combustion conditions occurring at low load. Pb was the

most prevalent element found for the Syracuse cycle and at 100% load where the EFs for grass were a factor of 1.8 to 2.5x higher than for wood. No significant levels of Pb were found in the two fuels.

Table 7-12. Emission Factors for Air Toxic and Other Selected Elements[a]

	Hardwood			Switchgrass		
	25% Load	Syracuse Cycle	100% Load	25% Load	Syracuse Cycle	100% Load
Element	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel
Cr	1.85E-03	3.94E-05	1.53E-05	6.05E-04	4.08E-04	2.00E-05
Mn	2.87E-03	2.19E-04	9.51E-05	1.45E-04	5.34E-05	2.89E-05
Pb	6.25E-03	2.55E-04	2.03E-04	1.38E-04	6.26E-04	3.68E-04
S	1.50E-01	1.13E-02	2.03E-02	6.40E-03	1.06E-02	5.80E-03
Cl	1.32E-01	9.05E-03	1.49E-02	9.38E-03	3.00E-02	3.81E-02

[a] Three significant figures; Values represent the average of all valid Teflon filter samples collected for both tests at each fuel and load condition; Not corrected for ambient background
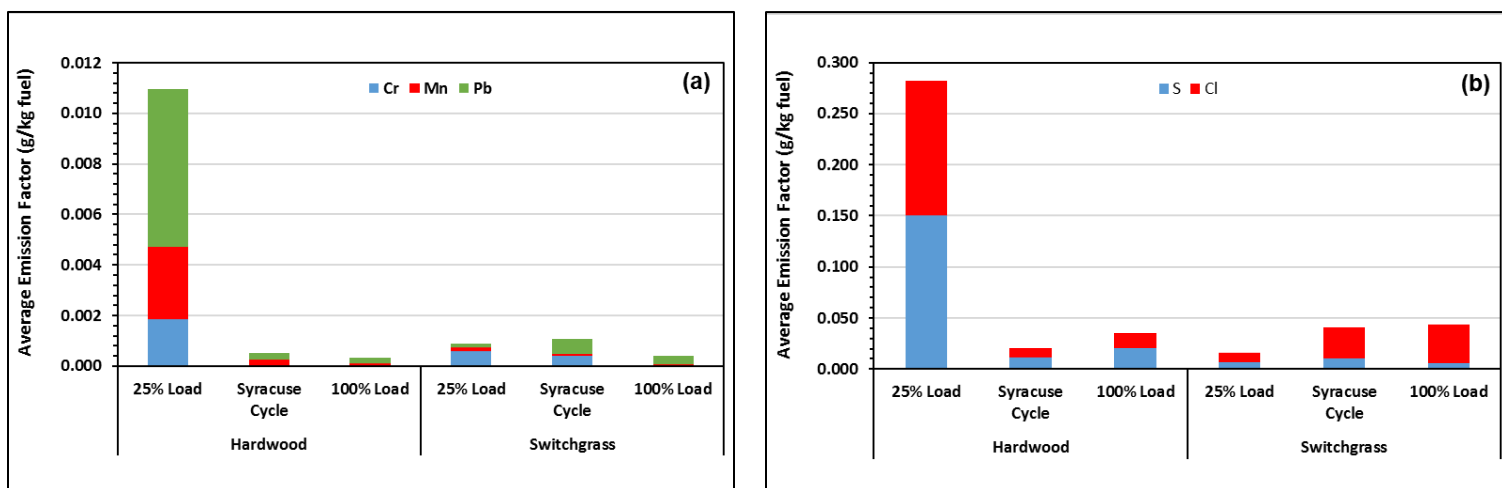
Figure 7-28. Average emissions factors for: (a) toxic metals; and (b) sulfur and chlorine as derived from XRF analysis of the Teflon filter sample

The same general trend was also seen for S and Cl as illustrated in Figure 7-28b. However, the magnitude of the EFs were much larger than for the 3 toxic metals discussed above. At 25% load for wood combustion, significant quantities of both S and Cl were found with much smaller amounts determined for grass combustion at the same load condition. For S during the Syracuse cycle and at 100% load, wood had EFs which were a factor of ~ 2x higher than grass. This is not consistent with the fuel analysis which shows that grass had a higher S content than wood. In the case of Cl at these load conditions, grass exhibited a factor of 2-3x higher emissions than wood. This is consistent with the fuel analysis which showed a similar difference in Cl content between the two fuels as discussed below.

7.3.7 Particle Morphology

Particles emitted from wood pellet combustion were mostly soot, i.e. aggregated carbonaceous primary particles. The primary particles were approximately 30 nm in diameter. These particles also had some electron dense inclusions that exhibited an EDS spectrum with K, S, and O (Figure 7-29). This composition is consistent with the XRF analysis of the bulk PM from wood pellets from the Syracuse cycle, which had 26% K and 6% S. These particles are consistent with the general understanding of biomass combustion in which inorganic compounds in the fuel are vaporized during combustion and rapidly condense forming alkali salts, which often serve as the nuclei for other particles (Torvala et al. 2014). The inclusions are likely KSO_4 particles that have aggregated with carbonaceous soot.
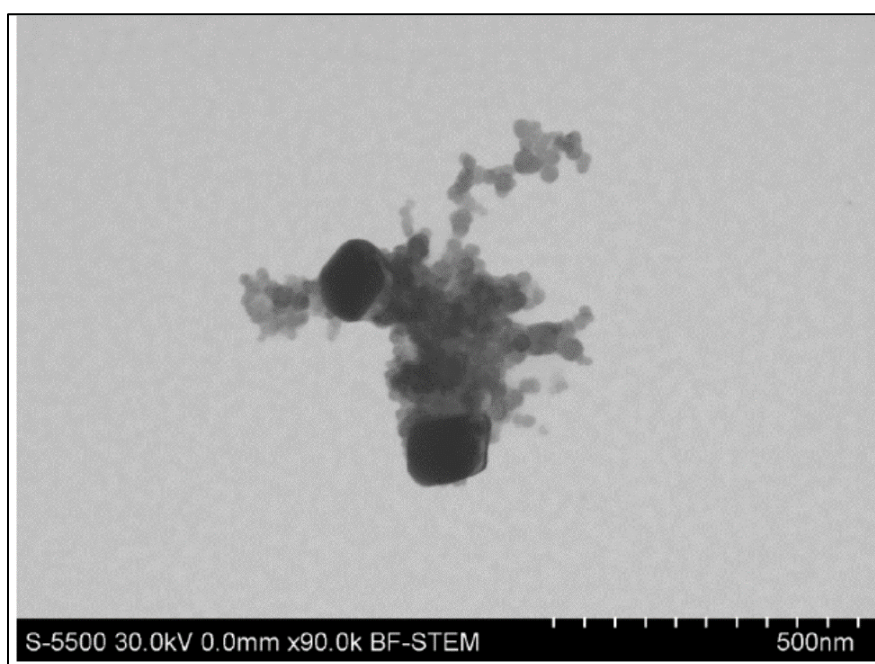
Figure 7-29. Soot aggregate with K inclusions emitted from wood pellet combustion

The particles from grass pellet combustion also exhibited a high carbon content and the typical soot structure seen in Figure 7-29. However, some particles had a more compact morphology and varying elemental composition. The particle in Figure 7-30a was typical of many of the collected particles from grass pellet combustion, exhibiting very small primary particles (< 10 nm) that are composed of C, Fe, and O. Figure 7-30b shows an example of an ash particle composed primarily of P, Ca, O and Mg in lesser amounts. This particle is an aggregate of several large primary particles (Dp ~ 50 – 100 nm), surrounded by a coating composed mostly of carbon. This carbonaceous coating unlike the carbonaceous aggregate in Figure 7-29, is likely very low volatility organic carbon that can persist in the high vacuum in the microscope and the electron bombardment.
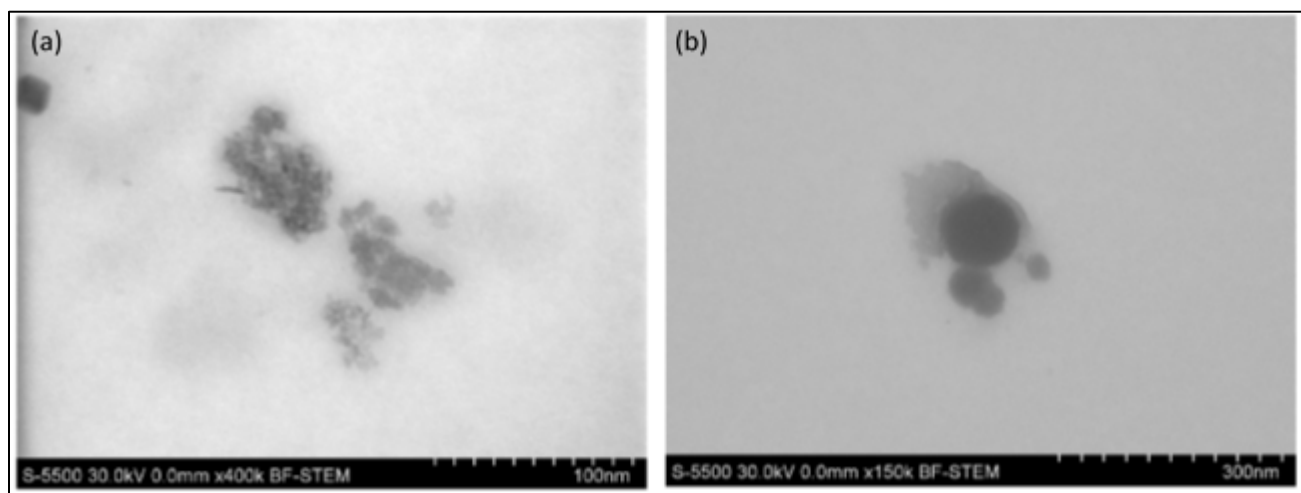
Figure 7-30. (a) C, Fe, O particle; and (b) ash particle emitted from grass pellet combustion

7.3.8 PM Semi-Volatile Organic Compounds

Total SVOC Emissions. Speciated SVOCs were determined by GC/MS analysis of extracts from the 47-mm quartz filters after determination of the total OC content. As such, the total SVOCs represent a component of the total OC with the remainder being an unresolved complex mixture. The test average total SVOC EFs are provided in Table 7-13 along with the RPD calculated for the two tests at each fuel and load condition. Table 7-14 shows the EFs for both the speciated and unresolved portions of the total OC. The EFs are also shown graphically in Figure 7-31 in SI units. More detailed results for total SVOCs are provided in Appendix D.

As shown in Figure 7-31, the highest EF determined for total SVOCs was for hardwood at 25% load followed by switchgrass at 25% load. For the Syracuse cycle and 100% load, wood had little total OC emissions and thus the speciated SVOCs were very low. In the case of grass, the SVOC content of the OC emission decreased with increasing load by a factor of up to ~ 18 at 100% load.

Table 7-13. Average Total SVOC Emission Factors

Fuel Type	Load Condition	Value[b]	Average Total SVOC Emissions[a]				
			mg/kg fuel	mg/MJ Input	lb/MMBTU Input	mg/MJ Output	lb/MMBTU Output
Hardwood	25%	Average	439	24.4	0.0567	34.4	0.0799
		RPD	41.8	41.8		46.9	
	Syracuse Cycle	Average	3.70	0.206	0.000478	0.210	0.000487
		RPD	82.6	82.6		60.2	
	100%	Average	0.640	0.0356	0.0000826	0.0000715	0.000000166
		RPD					
Switchgrass	25%	Average	124	7.10	0.0165	11.4	0.0265
		RPD	8.21	8.21		9.45	
	Syracuse Cycle	Average	79.4	4.54	0.0105	6.21	0.0144
		RPD	44.5	44.5		35.8	
	100%	Average	9.16	0.524	0.00122	0.624	0.00145
		RPD	116.00	116		107	

[a] **Three significant figures**
[b] **RPD = relative percent difference in emission factors for the two test runs conducted at each load condition**

Table 7-14. Average OC Emission Factor Components

Fuel Type	Load Condition	OC Emission Factor Components[a]					
		mg/MJ Input		mg/MJ Output		mg/kg fuel	
		Speciated SVOCs	Unresolved OC	Speciated SVOCs	Unresolved OC	Speciated SVOCs	Unresolved OC
Hardwood	25%	24.4	35.4	34.4	49.1	439	636
	Syracuse Cycle	0.206	1.63	0.210	1.62	3.70	29.4
	100%	0.0356	0.0637	0.0000715	0.0858	0.640	1.14
Switchgrass	25%	7.10	25.6	11.4	40.8	124	447
	Syracuse Cycle	4.54	17.8	6.21	24.5	79.4	312
	100%	0.524	3.06	0.624	3.65	9.16	53.6

[a] **Three significant figures**

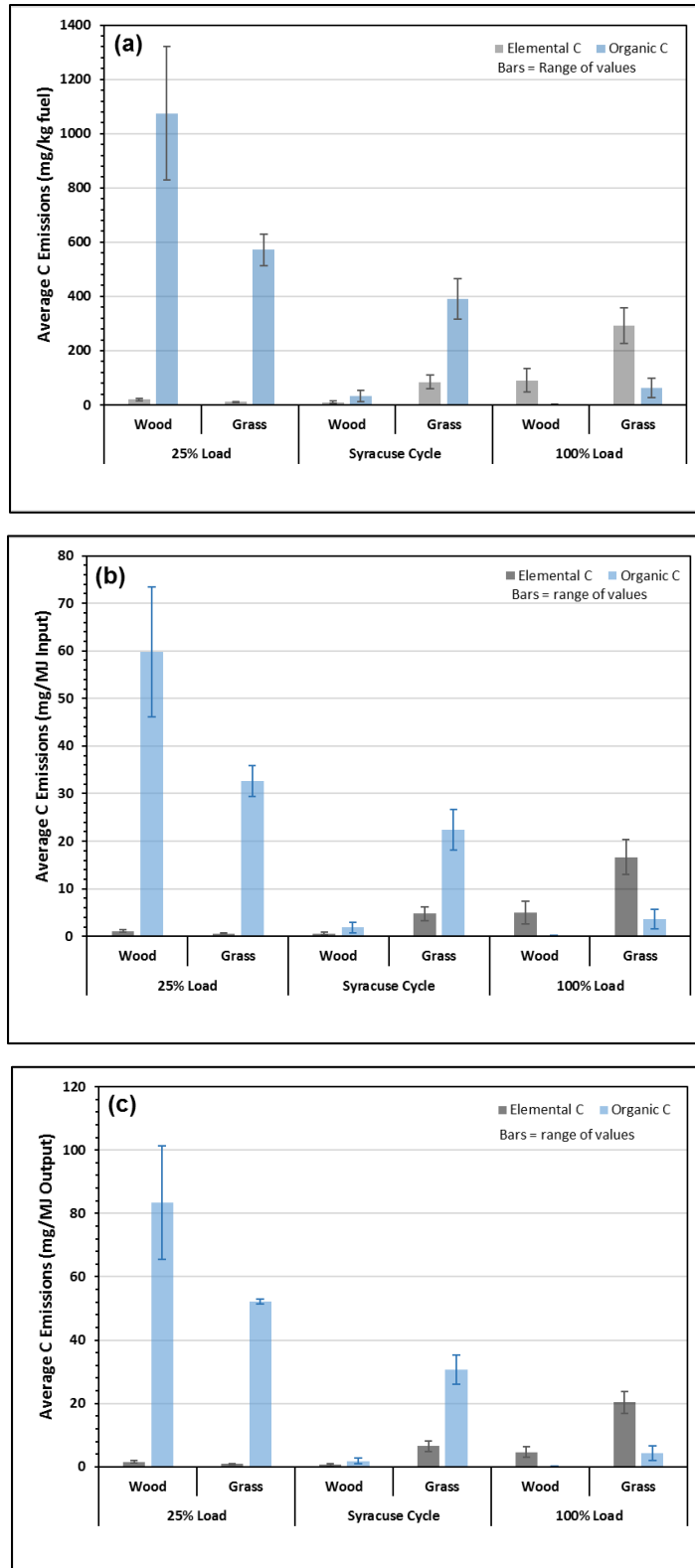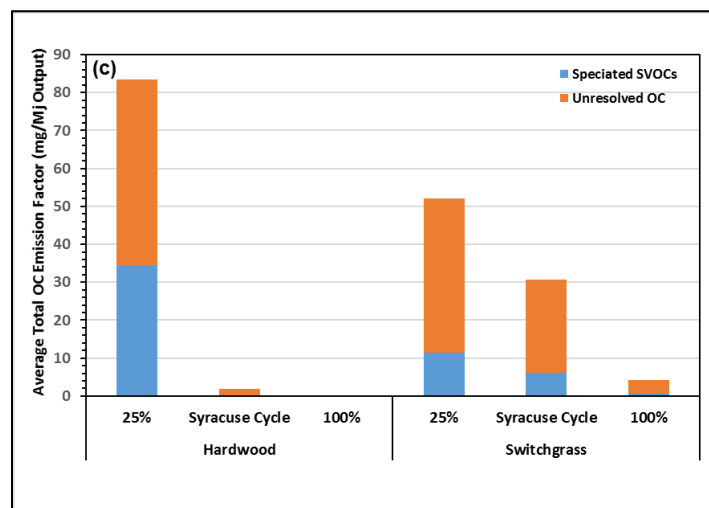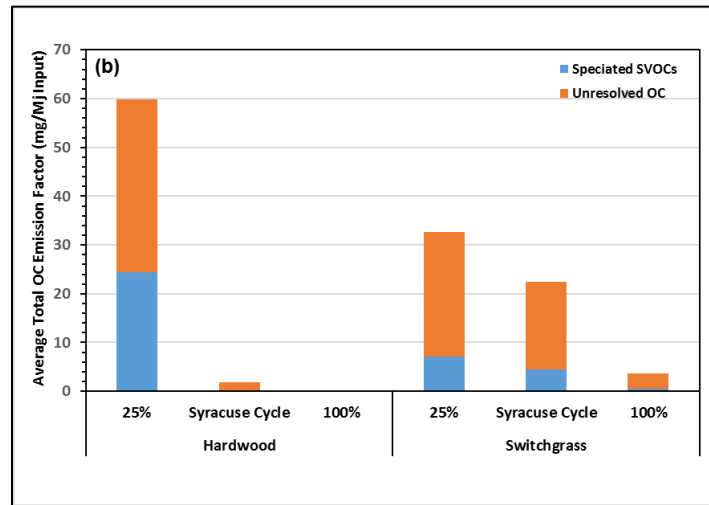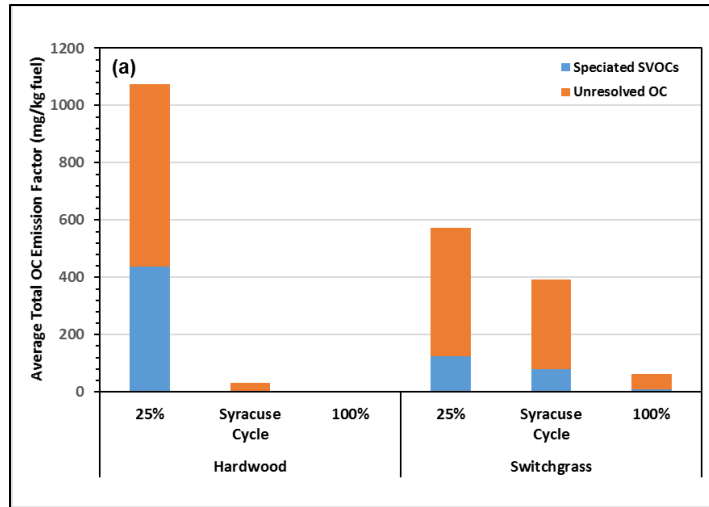**Figure 7-31.** SVOC and unresolved OC emission factors for all fuel and load conditions in terms of: (a) mass per mass fuel; (b) mass per heat input; and (c) mass per heat output (SI units)

Speciated SVOCs. Results of the laboratory-based thermal-optical measurements were used to determine organic carbon loadings on the filters. Composite filter OC loads ranged from 27 µg to 1455 µg. On average, 569 µg of filter OC was composited and extracted. For the laboratory-based thermal-optical instrument, an overall test composite mean and standard deviation for OC and EC was determined to be 669.5 ±309.0 µg m^{-3} and 696.2 ±482.1 µg m^{-3}, respectively. All filter-based OC and EC values being reported were corrected for artifact and background. Figure 7-32 shows the OC-EC ratios for each fuel and load condition. Full load testing produced significantly more EC in filter PM than either Syracuse or low loads. Although test load composites show no significant influence on the OC-EC ratio due to pellet type, OC-EC ratios produced from burning hardwood (HW) and switchgrass (SwG) pellets were significantly different at full- and low-load conditions. Generally, the low load and Syracuse load cycles produced more OC than EC irrespective of the fuel type used. It is interesting to note that the OC-EC ratio for switchgrass at full load is consistently higher that for hardwood.
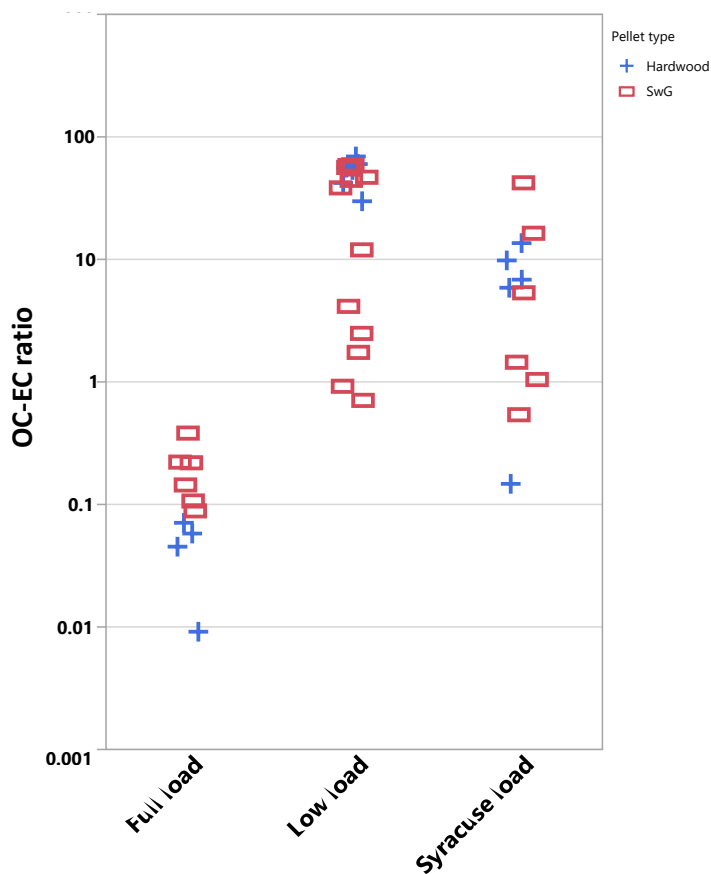
Figure 7-32. Filter-based OC-EC ratios in PM for individual tests sorted by load conditions. SwG = switchgrass

A total of 1325 individual compound concentrations survived detection limit and background subtraction criteria; 138 of which are injection replicates. Table 7-15 provides the data population (*N*) and the concentration data range grouped by compound class. We assumed an OC to OM ratio of 1.7 and determined on average that 12% w/w ±5.8% of the organic matter on the filters was identified using the GC-MS technique. The anhydrosugar, levoglucosan—a cellulose pyrolysis product sometimes used as an atmospheric tracer of biomass burning—exhibited the greatest relative concentration at 7.1% w/w of the organic matter. Additionally, the alkanoic acid, methoxy-phenol, and PAH compound classes accounted for 2.0% w/w, 1.6% w/w, and 0.89% w/w of the organic matter in the boiler particle emissions; whereas, the saturated hydrocarbons accounted for less than 0.4% w/w. In general, oxygenated compounds were detected and quantified at higher concentrations compared with the hydrocarbons; median concentrations were 436 µg/g OC and 108 µg/g OC for these respective chemical categories.

Table 7-15. Data Population and Concentration Range by Compound Class

Compound class	N	Min	Max
		µg/g OC	
Aliphatic diacid	93	2.685	3638
Alkanoic acid	182	40.75	61161
Anhydrosugars	17	11265	320299
Aromatic acid	117	0.2910	3417
Branched-alkane	32	2.336	461.2
Fatty acid	56	10.13	2019
Methoxy-phenol	94	51.55	38283
Normal-alkane	320	3.173	2962
PAH	370	0.4370	16590
Resin acid	44	13.30	4303

Figure 7-33 presents mean concentrations (µg of compound/g OC) of the individual organic compounds in the boiler fine PM emissions. Concentration ranges representing all test conditions are indicated by error bars and varied by greater than 3 orders of magnitude for nearly half of the compounds. The vast majority of compound concentration means was within 10-1000 µg/g OC. Figure 7-34 pools these individual compound concentrations by compound class and shows the relative enrichment of the methoxy-phenols and organic acids.
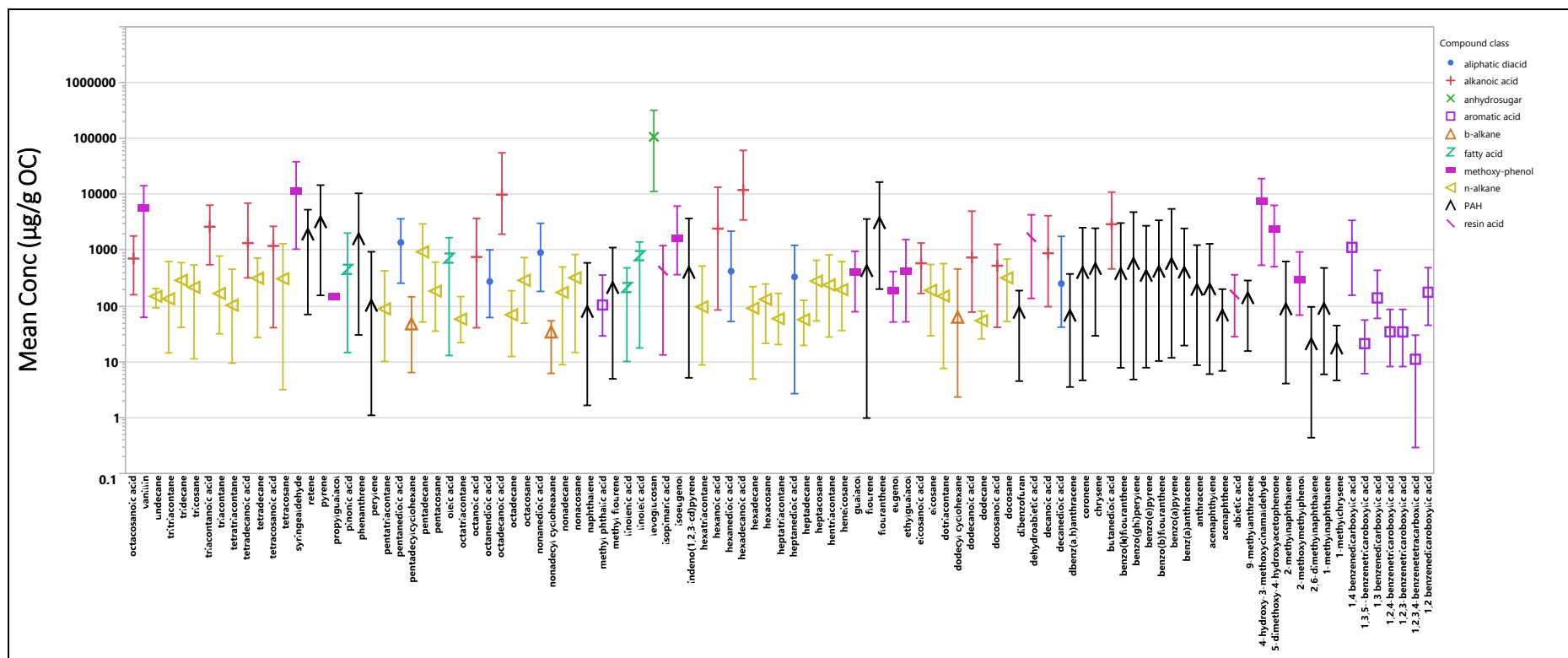
Figure 7-33. Individual mean SVOC concentrations in PM emitted from boiler testing. Concentrations are given in units of g/g OC. Error bars indicate the concentration range. The y-axis is log scale. Symbols and colors are coded by compound class.
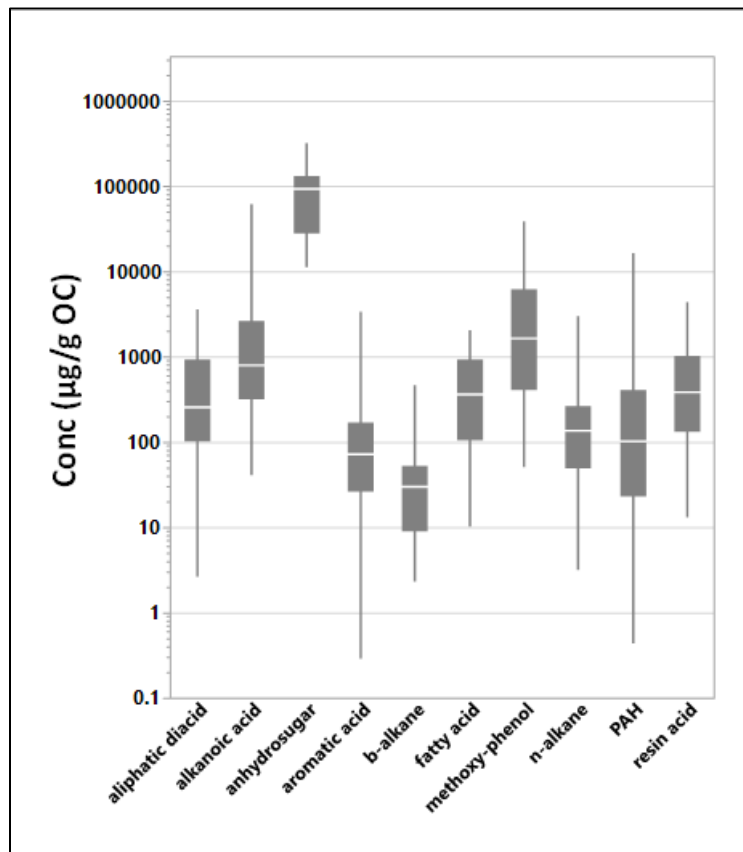
Figure 7-34. Quantile box plots of individual SVOC concentrations pooled by compound class. Levoglucosan is the anhydrosugar

Individual compounds remained pooled within their respective classes in order to further examine the effects of pellet type and test load conditions on the organic matter emissions. Figure 7-35 shows the concentration sums differentiated by individual test, compound class, test load conditions (full, low, and Syracuse), and fuel type (H-hardwood and SwG-switchgrass pellets). Test pairs were also examined using the Tukey-Kramer honestly significant difference test (α = 0.05). Mean concentrations of resin acids, fatty acids, and methoxy-phenols, showed no significant difference under the different test load conditions. However, for several cases (aliphatic diacids, alkanoic acids, *n*-alkanes, and PAH) the full load conditions produced significantly higher mean concentrations (μg/g OC) than both Syracuse and low load conditions. Moreover, compared with full load testing, low load tests produced significantly higher levoglucosan and lower aromatic acid concentrations in the organic aerosol particles. The effect of pellet fuel on the emissions also varied by compound class. SwG pellets produced significantly lower average aliphatic diacid, alkanoic acid, and methoxy-phenol concentrations. Although, oddly enough, use of SwG showed significantly higher PAH in the OC fraction of PM. Pellet type had no significant effect on levoglucosan, aromatic, resin and fatty acids, and *b*- and *n*-alkanes concentrations in the particle emissions. Finally, a one-way analysis using a data pool that considered all measured organic

compounds irrespective of class showed no significant difference among pairs of means representing test load conditions and pellet type.
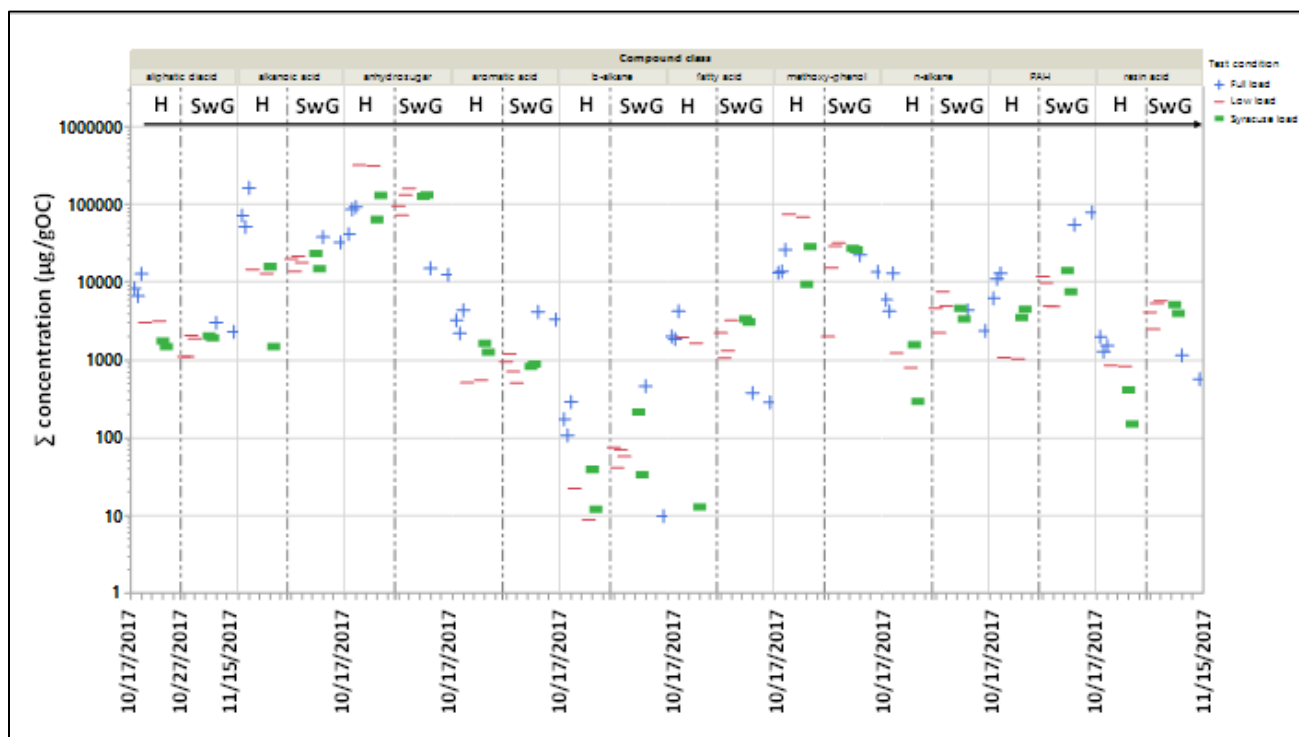
Figure 7-35. Concentration sums (µg/gOC) sorted by individual test, compound class, test load conditions, and fuel type (H- hardwood pellet; SwG – switch grass pellet)

7.3.9 Fuel and Ash

The results of the fuel analyses are provided in Table 7-16. These results represent a composite sample of fuel added to the heater during testing. Parameters of interest are shown in red face type. As shown in Table 7-16, there was about 4 times as much ash and about twice the chlorine in the grass pellets as compared to the wood pellets. The sulfur content of the grass pellets was also slightly higher than for wood. Finally, trace levels of Hg were found in both fuels but were not in the PM emissions.

Similar results for the bottom ash are presented in Table 7-17 and graphically in Figure 7-34 which represent averages of the two tests conducted. With regards to loss-on-ignition (LOI) in Figure 7-34a, the amount of unburned fuel generally increased with increasing load for both fuels. For wood, the LOI about doubled from 25% to 100% load and for grass, the LOI increased by a factor of ~ 8 from low to high load. These results are not unexpected since the appearance of the ash samples as they were collected showed a similar trend. There appeared to be a great deal of unburned carbon left in the ash samples especially at high load. This is likely the result of the unit's auger and automatic feeding system moving fuel more quickly through the firebox during high load conditions. The LOI for grass was about double that for wood except at 25% load where the grass LOI was slightly more than half that of wood. This is at least partially consistent with the lower

thermal efficiency of the unit for switchgrass as compared to wood and may also be related to higher emissions for switchgrass at high loads.

Table 7-16. Results of Fuel Analyses[a]

Parameter	PFI-Certified Wood Pellets		Switchgrass Pellets	
	As-Received	Dry	As-Received	Dry
Moisture (Weight %)	4.66		10.41	
Volatiles (Weight %)	80.34	84.27	72.62	81.06
Fixed Carbon (Weight %)	14.00	14.68	12.71	14.18
Ash (Weight %)	**1.00**	**1.05**	**4.26**	**4.76**
Sulfur (Weight %)	**0.09**	**0.09**	**0.12**	**0.13**
Carbon (Weight %)	47.91	50.25	42.79	47.76
Hydrogen (Weight %)	5.79	6.08	5.44	6.08
Nitrogen (Weight %)	0.31	0.32	0.82	0.92
Oxygen (Weight %)	40.24	42.21	36.16	40.35
Heat Content (BTU/lb)	7736	8115	7526	8401
Chlorine (ppmw)[b]	**66**	**69**	**134**	**150**
SiO_2 (%)	0.2657	0.2790	2.6834	2.9785
AlO (%)	0.0240	0.0252	0.3233	0.3589
FeO (%)	0.0489	0.0513	0.1546	0.1716
TiO_2 (%)	0.0027	0.0028	0.0026	0.0028
PO_5 (%)	0.0080	0.0084	0.0426	0.0473
CaO (%)	0.3663	0.3846	0.4511	0.5008
MgO (%)	0.0258	0.0271	0.1555	0.1726
NaO (%)	0.0044	0.0046	0.0601	0.0667
KO (%)	0.1176	0.1235	0.2735	0.3036
SO_3 (%)	0.1391	0.1461	0.0988	0.1097
Hg (ppb)	**5.5**		**12.38**	
Pb (ppm)	< 0.10		< 0.10	

[a] **Results from the analysis of composite sample of each fuel type. Particularly important parameters are shown in bold face type**
[b] **ppmw = parts per million by weight**

Table 7-17. Results of Bottom Ash Analyses[a]

Parameter	Hardwood Pellets			Switchgrass Pellets		
	25% Load (weight %)	Syracuse Cycle (weight %)	100% Load (weight %)	25% Load (weight %)	Syracuse Cycle (weight %)	100% Load (weight %)
SiO_2	21.5	23.2	15.5	56.3	45.8	28.0
Al_2O_3	1.32	1.76	1.00	6.72	5.35	3.27
Fe_2O_3	1.91	1.97	1.66	2.90	2.47	1.47
TiO_2	0.199	0.206	0.092	0.494	0.287	0.304
P_4O_{10}	0.374	0.391	0.392	0.877	0.772	0.428
CaO	36.6	38.0	30.5	12.1	9.2	4.6
MgO	2.02	2.42	1.94	3.37	2.52	1.42
Na_2O	0.361	0.383	0.360	1.38	1.12	0.649
K_2O	18.1	18.0	13.4	6.71	4.80	2.61
SO_3	0.968	1.05	0.530	1.22	0.539	0.527
LOI	17.1	12.95	34.43	7.70	27.16	57.18

[a] **Average of both test runs at each fuel and load condition. LOI = loss-on-ignition**
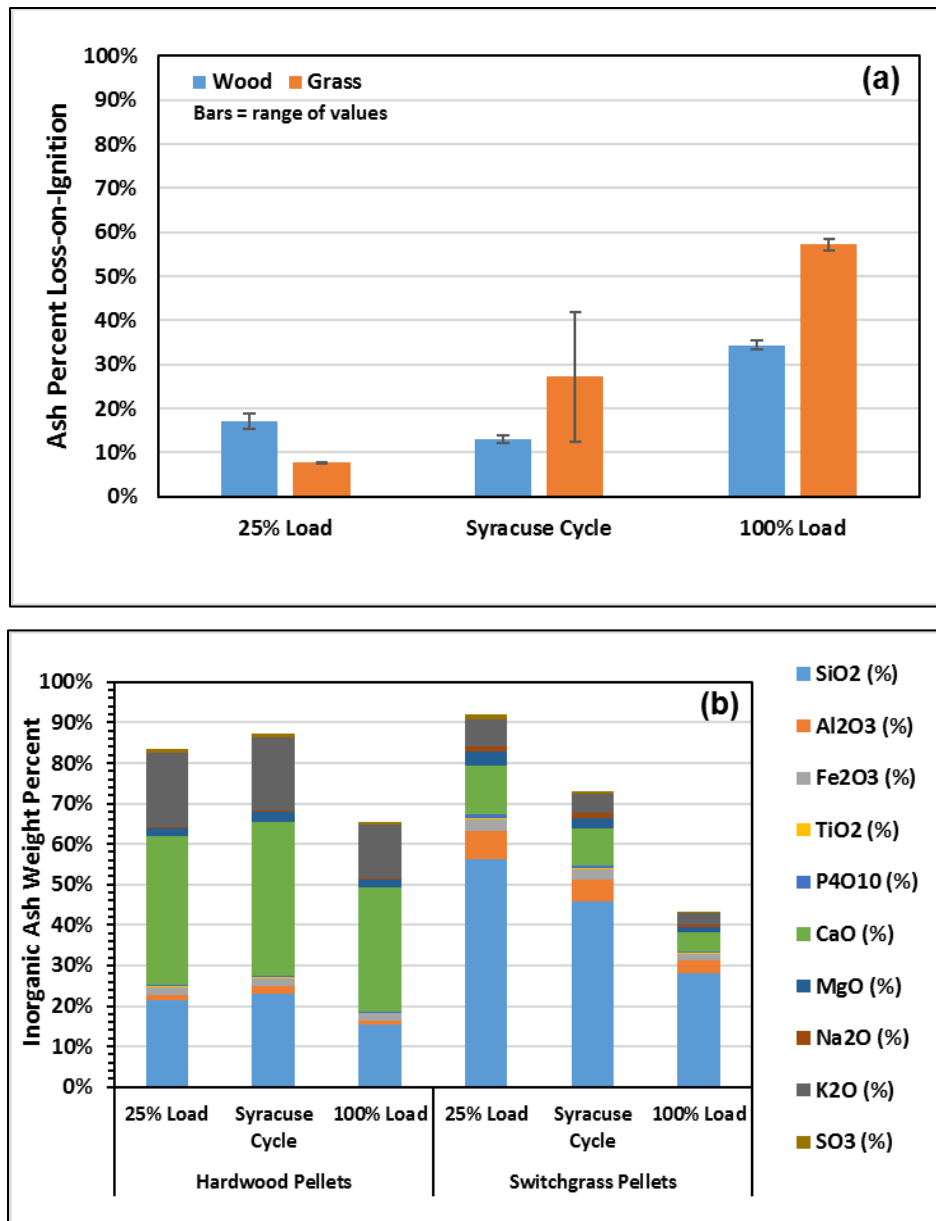
Figure 7-36. Bottom ash analyses in terms of: (a) loss-on-ignition; and (b) metal oxides. Data in weight percent

Finally, for the metal oxide data shown in Figure 7-34b, oxides of silicon, calcium, and potassium appear to be most abundant in the samples analyzed. The proportion of all the metal oxides was generally consistent over all load conditions for wood but silica dominated the ash composition for grass. This is also expected due to characteristics of the biological feedstock used for production of the two fuels, and consistent with the fuel analyses.

8   Summary and Conclusions

8.1   Effect of Fuel Type

The main objective of the program was to fully characterize the thermal efficiency and emissions of particulate matter (PM) and other pollutants from a hydronic heater using non-woody pellets as compared to combustion of premium wood pellets. The results of the individual measurements are extensive and presented in detail in Section 7 and will not be repeated here. Instead, the difference between the combustion of switchgrass and hardwood pellets was determined for the various measured parameters as shown in Table 8-1. In this table, the percent difference is shown assuming that the non-woody fuel produces higher values for each parameter measured. A negative value in Table 8-1 indicates that hardwood combustion exhibited the higher value instead of switchgrass.

Table 8-1. Percent Difference Between Switchgrass and Hardwood

Measured Parameter	Grass-Wood Difference in Average Emissions		
	25% Load	**Syracuse Cycle**	**100% Load**
Thermal efficiency	**-25.4%**	**-30.6%**	**-9.88%**
Total PM	**-123%**	182%	65.2%
PM number	11.2%	93.3%	5.97%
Elemental carbon	**-79.6%**	720%	224%
Organic carbon	**-88.1%**	1080%	3417%
Optical BC	**-133%**	458%	133%
Total particle-phase SVOCs	**-253%**	2045%	1333%
CO	**-12.5%**	3.61%	**-404%**
CH$_4$	**-118%**	175%	83.1%
NH$_3$	4520%	468%	**-186%**
N$_2$O	172%	500%	110%
NO$_x$	1780%	**-102%**	NA
SO$_2$	NA	NA	12.3%
Total VOCs and carbonyls	**-65.2%**	544%	314%
Total gaseous PAHs	**-869**	1990	761
Total PCDD/PCDFs	41.2	389	**-205**

[a] **Based on emission factors in mass/mass fuel burned**
[b] **Negative values (indicated in bold face type) show when the measured parameter for wood is greater than grass**

As Table 8-1 shows, hardwood combustion always results in higher thermal efficiency as compared to switchgrass at all load conditions. It also indicates that at 25% load, hardwood generally had the higher particle phase emission factors (i.e., 5 out of 6 pollutants) whereas for

operation during the Syracuse cycle and at 100% load switchgrass always had the highest emissions. More specifically, compared to wood at the two high load conditions, switchgrass had:

- 65-182% higher total PM emissions;
- 6-93% higher PM number emissions;
- 224-720% higher EC emissions;
- 341-1080% higher OC emissions;
- 133-458% higher OBC; and
- 1333-2045% higher total SVOC emissions.

At 25% load, compared to switchgrass, hardwood had:

- 123% higher total PM emissions;
- 80% higher EC emissions;
- 88% higher OC emissions;
- 133% higher OBC emissions; and
- 253% higher total PM SVOC emissions

In the case of criteria and related gas-phase contaminants, the results were more mixed. For CO, wood had higher emissions (13-404%) at 25% load and 100% load as compared to the Syracuse cycle where the emissions for wood and grass were about the same. In the case of CH_4, switchgrass had 83-175% more emissions for the Syracuse cycle and at 100% load whereas hardwood exhibited 118% higher emissions at 25% load. Switchgrass had 468-4520% higher NH_3 emissions at 25% load and for the Syracuse cycle whereas at 100% load, hardwood had 186% higher emissions. The N_2O emissions were always highest (110-500%) for the combustion of switchgrass at all load conditions whereas for NOx, grass had 1780% higher emissions at 25% load but for the Syracuse cycle wood exhibited 102% higher emissions.

Finally, for the speciated gases, the emission factor results were again mixed. In the case of total VOCs and carbonyls, grass pellet emissions were 314-255% higher than wood for the Syracuse cycle and at 100% load but at 25% load wood had 65% higher emissions. For total PAHs, grass combustion produced 761-1990% higher emissions for the Syracuse cycle and at 100% load whereas at 25% load wood had 869% higher emissions. In the case of the PCDD/PCDF emission factors, grass produced 41-389% higher emissions for 25% load and the Syracuse cycle while wood provided 205% higher emissions at 100% load.

8.2   Comparison to Historical Emissions Data

There were a few studies found in the literature pertaining to either the burning of switchgrass pellets in hydronic heaters or the emissions from other REKA models (Winther, 2006; Chandrasekaran et al., 2013a; Chandrasekaran et al., 2013a; Valente et al., 2014). Of these, the

most applicable to the current work is the study conducted by Chandrasekaran et al. (2013a). Although this study did not use a dilution tunnel and ASTM 2515 for collection and sampling of the emissions and only reports PM-10 rather than total PM, it did use EPA Conditional Test Method 039 (EPA, 2004) which employs another type of stack gas dilution system. Of the six units tested in the Chandrasekaran et al. study, Appliance D appears to be the most similar to the appliance described here and thus will be used for comparison purposes.

Figure 8-1 compares the emissions of total PM, OC, and CO from the REKA appliance at 25% and 100% load to Appliance D at "low" and "high" load. Looking at Figure 8-1a for total PM, at low load the REKA appliance produced a factor of 2-12x higher emissions than Appliance D whereas for high load the two units produced comparable emissions. In the case of OC in Figure 8-1b, the same general trend was observed but here the REKA emitted a factor of 22-260 higher OC emissions at low load as compared to Appliance D. Finally, Figure 8-1c shows that the REKA produced substantially higher CO while burning wood pellets at both low and high load as compared to Appliance D. For grass combustion at low load, the CO from both units were comparable whereas at high load the REKA produced a factor of ~ 4 lower emissions.

From the above comparison, it appears that for some fuel and load conditions the emissions from the two appliances were similar whereas for other fuel/load combinations the emissions can be substantially different. There are several possible explanations for these results including differences in fuel composition and sampling strategy as well as the lack of definition for high and low load in the Chandrasekaran et al. study as compared to the current work. It should also be noted that a direct comparison of the current results to those from the previous NYSERDA study (Kinsey et al., 2012) described in Section 7 showed good agreement for hardwood combustion while operating under the Syracuse cycle, with the exception of particles per kilograms fuel which differed by several orders of magnitude. Based on this analysis, it was concluded that the results presented here are generally comparable to the emissions from units of a similar type tested by others.
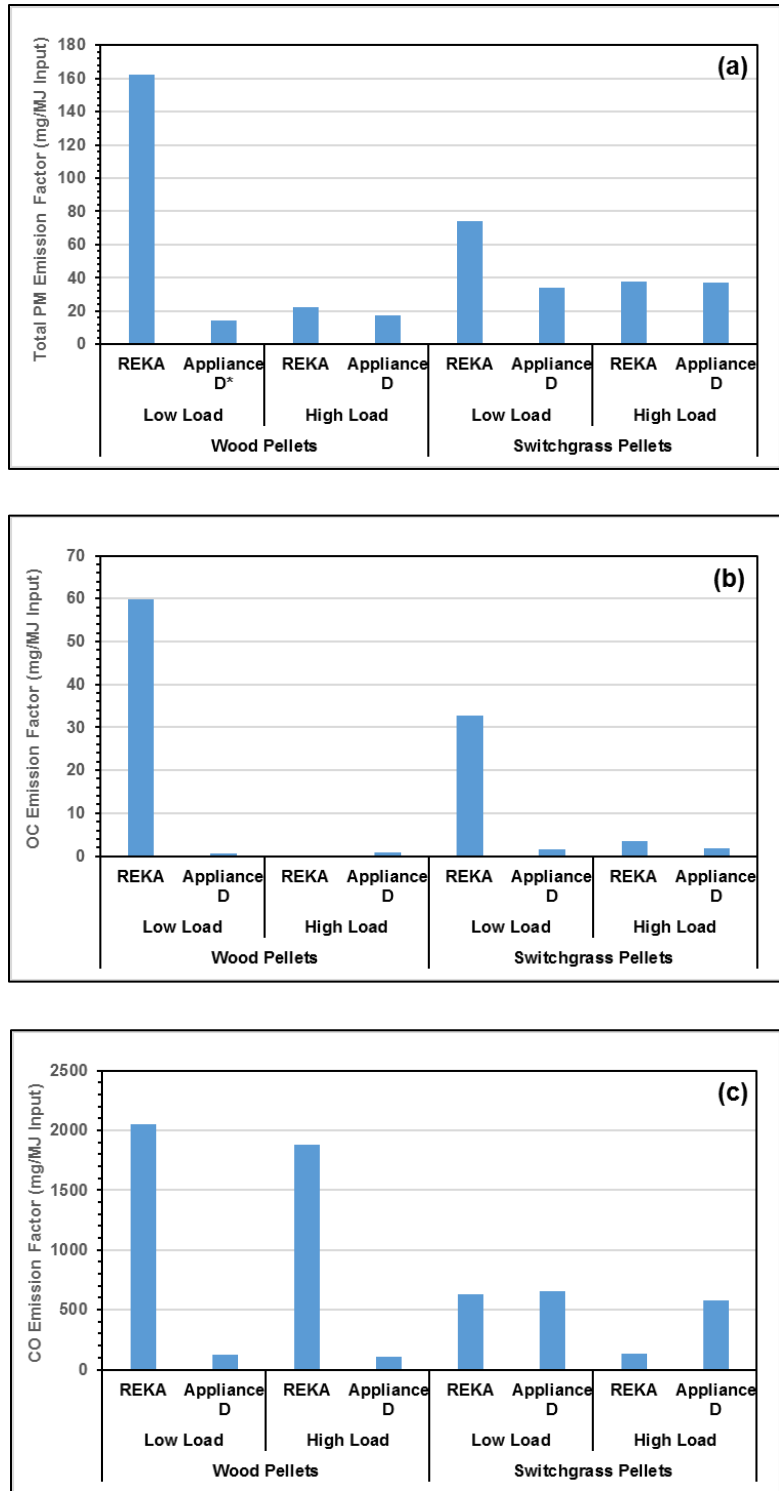
Figure 8-1. Comparison of REKA to Appliance D from the Chandrasekaran et al. study (2013a) for all fuel and load conditions for: (a) total PM; (b) OC; and (c) CO.

8.3 Conclusions

Based on the results presented in Section 7, the following conclusions were reached:

1. The combustion of hardwood exhibited the highest thermal efficiency at all load conditions. Of the three loads tested with hardwood, the highest efficiency was for operation during the Syracuse cycle which was the most indicative of "real world" conditions.

2. With respect to reduced and oxidized carbonaceous gases, the same general trend was observed as was the case for the particle-phase constituents namely, hardwood produced higher emissions at 25% load and switchgrass had the highest emissions during the Syracuse cycle and at 100% load.

3. For reduced and oxidized nitrogen compounds, grass combustion generally had the highest gaseous emissions as compared to hardwood.

4. For the speciated gas-phase VOCs, carbonyls, PAHs, and total PCDD/PCDFs, the combustion of hardwood generally produced the highest emissions at 25% load whereas during the Syracuse cycle and 100% load, switchgrass exhibited the higher emissions.

5. For particle-phase air pollutants, the combustion of hardwood produced the highest emissions at 25% load whereas during the Syracuse cycle and 100% load switchgrass exhibited the higher emissions.

6. Comparing the current results to historical data for similar hydronic heaters, the data reported here were at least generally comparable to the unit tested for NYSERDA in 2010 using hardwood pellets during the Syracuse cycle and to a similar appliance tested by Chandrasekaran et al. (2013a) burning both fuel types depending on load.

7. The lack of U. S. technical support severely hampered operation and testing of the REKA appliance evaluated in this study.

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APPENDIX A

Hydronic Heater Operating Parameters

Table A-1. REKA Unit Operating Parameters

Internal Computer Operating Parameter	Hardwood (100% & 25% Load)* Program 1 Set Points	Hardwood (Syracuse Cycle) Program 1 Set Points	Switchgrass (25% Load) Program 2 Set Points	Switchgrass (Syracuse Cycle) Program 2 Set Points	Switchgrass (100% Load) Program 2 Set Points
Boiler recirculation water temperature (°C)	167	150	167	150	167
Pause (min)	5	5	20	20	20
Oxy	5	5	0	0	0
Manual/Auto (sec)	0	0	0	0	0
Moving grate on (sec)	1.00	1.00	20	20	20
Moving grate off (min)	1.00	1.00	1.00	1.00	1.00
Ash screw on (sec)	1.0	1.0	10	10	10
Ash screw off (min)	30	30	20	20	20
Fuel step 0 (sec)	0.16	0.16	0.10	0.50	0.50
Fuel step 1 (sec)	0.50	0.50	0.23	0.70	0.70
Fuel step 2 (sec)	1.00	1.00	0.50	1.4	1.4
Fuel step 3 (sec)	1.6	1.6	0.83	2.0	2.0
Fan step 0	8	8	8	8	8
Fan step 1	10	10	10	10	10
Fan step 2	20	20	20	20	20
Fan step 3	80	80	80	80	80
Oxy step 0 (%)	11	11	11	11	11
Oxy step 1 (%)	10	10	10	10	10
Oxy step 2 (%)	9	9	9	9	9
Oxy step 3 (%)	8	8	8	8	8
Start up time (min)	15	15	15	15	15
Start up oxy (%)	0	0	0	0	0
Start up fan	40	40	40	40	40
High oxy level (%)	15	15	15	15	15
Pause fan	5	5	5	5	5
Pause fan time (sec)	10	10	10	10	10
Pause fuel (sec)	1.00	1.00	1.00	1.00	1.00
Pause airing (%)	8	8	8	8	8
Start fuel (sec)	4.00	4.00	4.00	4.00	4.00
After run (sec)	1	1	1	1	1
Boiler temperature hysterisis	3	3	3	3	3
Oxy blower down (%)	0	0	0	0	0
Motor 3 (%)	100	100	100	100	100
RSM	0	0	0	0	0
Step 3 always	0	0	0	0	0
Auto ignition (min)	0	0	0	0	0
VP2	0	0	0	0	0
Draft fan select	0	0	0	0	0

* Second test at 25% load used recirculating water temperature of 150 °C.

Survey: Display and Menu

Nr	Text in Display	Menu. Description of Adjustments	(Minimum – Maximum)
1	OPERATION TIME	Shows the number of operation hours	
2	DANSK DK	Language options	
3	FUEL TYPE	Selection of fuel	
4	BOILER TEMP	Selection of boiler temperature	(5 – 90)
5	PAUSE TIME	Selection of Interval time. Interval between operation in Interval mode	(3 – 99)
6	OXY %	Higher oxygen for fuels with high moisture content	(addition 0 – 3 %)
7	MAN / AUT	0 = automatic operation with Lambda probe 1-29 = manual operation without Lambda probe. The figures 1-29 determine the operation interval (f.inst. 20 = 20 seconds between manual stoking. (Please note: No operation at 30 and 50)	(0 – 99)
8	MAN / OUTPUT	0 = All outlets stopped 1 = Transport screw/silo screw 2 = Overdraught blower (main blower) Blower up 3 = Under draught blower (spare blower) Blower down (Small I. draft fan R2A 150) 4 = Moving grate 5 = Ash screw 6 = Draft fan 7 = Clearance (Stoker screw / cell sluice) 8 = Ash screw/I. draft fan. (Cleaning of boiler.)	(0 – 8)
9	MOVING GRATE ON	Selection of operating time of the moving grate	(0 – 52)
10	MOVING GRATE OFF	Selection of interval operating time of the moving grate	(0 – 255)
11	ASH SCREW ON	Selection of operating time of the ash screw	(0 – 52)
12	ASH SCREW OFF	Selection of interval operating time of the ash screw	(0 – 255)
13	FUEL STEP 0	Selection of fuel quantity at stage 0	(0.00 – 52)
14	FUEL STEP 1	Selection of fuel quantity at stage 1	(0.00 – 52)
15	FUEL STEP 2	Selection of fuel quantity at stage 2	(0.00 – 52)
16	FUEL STEP 3	Selection of fuel quantity at stage 3	(0.00 – 52)
17	Stop or press	"START-UP and ▼"	
18	FAN STEP 0	Selection of blower speed in stage 0	(0 – 80)
19	FAN STEP 1	Selection of blower speed in stage 1	(0 – 80)
20	FAN STEP 2	Selection of blower speed in stage 2	(0 – 80)
21	FAN STEP 3	Selection of blower speed in stage 3	(0 – 80)

22	OX % STEP 0	Selection of set point for oxygen content in stage 0	(7 – 14)
23	OXY % STEP 1	Selection of set point for oxygen content in stage 1	(7 – 12)
24	OXY % STEP 2	Selection of set point for oxygen content in stage 2	(7 – 11)
25	OXY % STEP 3	Selection of set point for oxygen content in stage 3	(7 – 10)
26	START-UP TIME	Selection of operation time in start-up mode	(0 – 99)
27	START-UP OXY	Oxygen content below "high oxygen level" before shift to operation (f. inst. 3 minus 15 = 12 %)	(0 – 5)
28	START-UP FAN	Blower speed during start-up	(0 - 80)
29	HIGH OXY LEVEL	Oxygen level during start-up	(10 – 21)
30	PAUSE FAN	Blower speed during interval operation	(0 – 80)
31	PAUSE FAN TIME	Time (sec.) the blower has to operate after interval firing	(0 – 255)
32	PAUSE FUEL	Fuel quantity during interval firing	(0 – 52)
33	PAUSE AIRING	Level for stop of interval ventilation	(6 – 21)
34	START FUEL	Fuel quantity by start after interval operation / start-up	(0.00 – 52)
35	AFTER RUN	Seconds. Empties the stoker screw at stop or interval	(0 – 255)
36	BOILER TEMP HYS.	Starting point for operation after interval (number of degrees below the boiler temperature)	(0 – 16)
37	OXY BLOWER DOWN	Oxygen level for stop of under draught	(0 – 16)
38	MOTOR 3	This function is used together with after run function. If setting = 150 then Stoker Screw and Cell sluice is running 50% longer than Transport Screw and Silo Screw. If setting = 180 then Stoker Screw and Celle sluice is running 80% longer then Transport Screw and Silo Screw. If setting = 205 then Stoker Screw and Celle sluice is running 2,5 sec. longer than Transport Screw and Silo Screw. If setting = 210 then Stoker Screw and Cell sluice is running 5 sec. longer than Transport Screw and Silo Screw. This will mean that every no. larger than 200 = 0,5 sec.(0 – 255)	
39	RSM	Available	
40	DISP.	Available	
41	STEP 3 ALWAYS	**On/off.** Always high output or interval (no low output) (0 – 1)	
42	AUT IGNITION	0 = no electric ignition /Electric ignition is active at numbers between 1 and 6) (0 – 6) 2 = 2 minutes between fuel feeding (start portion)	
43	VP2	Show time between the fuel steps at the display. Time in seconds when doses screw stands still.(0 – 1)	
44	DRAFT FAN SELECT	0 = Normal operation (0 – 3) 1 = Pulsates with draft fan 2 = Pulsates 3 seconds every 90 seconds (In interval operation) 3 = 1 + 2 mixed operation	

Factory Adjustments

Nr	Text in Display	Type 1: REKA 10 kW			Type 2: Reka 20 – 30 - 60 kW		
1	OPERATION TIME	00000			00000		
2	DANSK DK	DK			DK		
3	FUEL TYPE	Pellets Programme 1	Chipwood Programme 2	Various Fuels Programme 3	Pellets Programme 1	Chipwood Programme 2	Various Fuels Programme 3
4	BOILER TEMP	75°C	75°C	75°C	75°C	75°C	75°C
5	PAUSE TIME	30 m	20 m	15 m	30 m	20 m	15 m
6	OXY %	000	000	000	000	000	000
7	MAN / AUT	000	000	000	000	000	000
8	MAN / OUTPUT	000	000	000	000	000	000
9	MOVING GRATE ON	1.00s	1.00s	1.00s	1.00s	1.00s	1.00s

#							
10	MOVING GRATE OFF	001 m	001 m	001 m	001 m	001 m	001 m
11	ASH SCREW ON	0.50 s	0.50 s	0.50 s	1.00 s	1.00 s	1.00 s
12	ASH SCREW OFF	030 m	030 m	030 m	030 m	030 m	030 m
13	FUEL STEP 0	0.03s	0.10s	0.06s	0.16s- 0,50s	1.20s- 2,00s	0.60s- 1,00s
14	FUEL STEP 1	0.06s	0.30s	0.13s	0.50s- 1,00s	2.40s- 4,00s	1.20s- 2,00s
15	FUEL STEP 2	0.13s	0.60s	0.26s	1.00s- 2,00s	4.80s- 8s	2.40s- 4s
16	FUEL STEP 3	0.26s	1.00s	0.50s	1.60s- 3,00s	7 s- 12s	3,50 s- 6s
17	Stop or press "Start-up and ▼"						
18	FAN STEP 0	025	025	025	008	008	008
19	FAN STEP 1	025	025	025	010	010	010
20	FAN STEP 2	040	040	040	020	020	020
21	FAN STEP 3	080	080	080	080	080	080
22	OX % STEP 0	011 %	011 %	011 %	011 %	011 %	011 %
23	OXY % STEP 1	010 %	010 %	010 %	010 %	010 %	010 %
24	OXY % STEP 2	009 %	009 %	009 %	009 %	009 %	009 %
25	OXY % STEP 3	008 %	008 %	008 %	008 %	008 %	008 %
26	START-UP TIME	015 m	015 m	015 m	015 m	015 m	015 m
27	START-UP OXY	000 %	000 %	000 %	000 %	000 %	000 %
28	START-UP FAN	050	050	050	040	040	040
29	HIGH OXY LEVEL	015 %	015 %	015 %	015 %	015 %	015 %
30	PAUSE FAN	020	020	020	005	005	005
31	PAUSE FAN TIME	010s	010s	010s	010s	010s	010s
32	PAUSE FUEL	1.00s	1.00s	1.00s	1.00s	1.00s	1.00s
33	PAUSE AIRING	008 %	008 %	008 %	008 %	008 %	008 %
34	START FUEL	2.50s	2.50s	2.50s	4.00s	4.00s	4.00s
35	AFTER RUN	~~001~~	~~001~~	~~001~~	~~001~~	~~001~~	~~001~~
36	BOILER TEMP HYS.	003°C	003°C	003°C	003°C	003°C	003°C
37	OXY BLOWER DOWN	~~000~~	~~000~~	~~000~~	~~000~~	~~000~~	~~000~~
38	MOTOR 3	~~100~~	~~100~~	~~100~~	~~100~~	~~100~~	~~100~~
39	RSM	000	000	000	000	000	000
40	DISP.						
41	STEP 3 ALWAYS	000	000	000	000	000	000

42	AUT IGNITION	000	000	000	000	000	000
43	VP2	000	000	000	000	000	000
44	DRAFT FAN SELECT	001	001	001	000	000	000

APPENDIX B

Labview Temperatures

PBHH Load - Hardwood/100% Load

PBHH Load - Hardwood/ 100% Load

PBHH Load - Hardwood/25% Load

PBHH Load - Hardwood/25% Load

PBHH Load - Hardwood/Syracuse Cycle

Test Load — Planned Load

26-Oct-16

PBHH Load - Hardwood/Syracuse Cycle

Test Load — Target Load

27-Oct-2016

PBHH Load - Switchgrass/25% Load

PBHH Load - Switchgrass/25% Load

PBHH Load - Switchgrass/Syracuse Cycle

Test Load — Target Load

Heat Load, Btu/h

8-Nov-16

PBHH Load - Switchgrass/Syracuse Cycle

Test Load — Target Load

Heat Load, Btu/h

9-Nov-16

PBHH Load - Switchgrass/100% Load

Test Load   Target Load

Heat Load, Btu/h

10-Nov-16

PBHH Load - Switchgrass/100% Load

Test Load   Target Load

Heat Load, Btu/h

15-Nov-16

APPENDIX C

Gas-Phase Emission Factors

Table C-1. Test Average Emission Factors for Criteria and Related Gases

Fuel/Load Condition	Test Date	Average CO emissions			Average CH4 emissions			Average NH3 emissions		
		g/kg fuel	g/MJ Input	g/MJ Output	g/kg fuel	g/MJ Input	g/MJ Output	g/kg fuel	g/MJ Input	g/MJ Output
Hardwood - Full Load	10/19/2016	1.30E+01	7.21E-01	6.24E-01	9.69E-02	5.39E-03	3.61E-02	3.05E-02	1.70E-03	1.14E-02
Hardwood - Full Load	10/20/2016	9.75E+00	5.43E-01	6.06E-01	5.34E-02	2.97E-03	2.57E-02	2.07E-02	1.15E-03	9.95E-03
Hardwood - Low Load	10/21/2016	2.50E+01	1.39E+00	3.07E+00	1.65E+00	9.19E-02	1.56E+00	5.19E-04	2.89E-05	4.91E-04
Hardwood - Low Load	10/25/2016	4.87E+01	2.71E+00	2.42E+00	2.27E+00	1.26E-01	8.70E-01	9.28E-03	5.16E-04	3.56E-03
Hardwood - Syracuse	10/26/2016	2.19E+01	1.22E+00	1.14E+00	2.66E-01	1.48E-02	1.08E-01	1.05E-02	5.82E-04	4.22E-03
Hardwood - Syracuse	10/27/2016	1.51E+01	8.39E-01	1.02E+00	3.43E-01	1.91E-02	1.79E-01	ND	ND	ND
Switchgrass - Low Load	11/3/2016	3.30E+01	1.89E+00	2.77E+00	9.47E-01	5.42E-02	5.99E-01	2.80E-01	1.60E-02	1.77E-01
Switchgrass - Low Load	11/4/2016	3.26E+01	1.86E+00	3.27E+00	8.52E-01	4.88E-02	6.43E-01	1.72E-01	9.87E-03	1.30E-01
Switchgrass - Syracuse	11/8/2016	2.04E+01	1.17E+00	1.54E+00	9.69E-01	5.54E-02	5.51E-01	8.33E-02	4.76E-03	4.74E-02
Switchgrass - Syracuse	11/9/2016	1.79E+01	1.02E+00	1.48E+00	7.09E-01	4.06E-02	4.42E-01	3.55E-02	2.03E-03	2.21E-02
Switchgrass - Full Load	11/10/2016	1.52E+00	8.70E-02	1.14E-01	7.80E-02	4.46E-03	4.40E-02	1.01E-02	5.76E-04	5.68E-03
Switchgrass - Full Load	11/15/2016	2.98E+00	1.71E-01	1.98E-01	1.97E-01	1.13E-02	9.84E-02	7.81E-03	4.47E-04	3.90E-03

Fuel/Load Condition	Test Date	Average NOx emissions (as NO2)			Average SO2 Emissions			Average N2O Emissions		
		g/kg fuel	g/MJ Input	g/MJ Output	g/kg fuel	g/MJ Input	g/MJ Output	g/kg fuel	g/MJ Input	g/MJ Output
Hardwood - Full Load	10/19/2016	ND	ND	ND	4.53E-01	2.52E-02	1.69E-01	2.66E-02	1.48E-03	9.92E-03
Hardwood - Full Load	10/20/2016	ND	ND	ND	3.27E-01	1.82E-02	1.57E-01	1.41E-02	7.85E-04	6.79E-03
Hardwood - Low Load	10/21/2016	ND	ND	ND	ND	ND	ND	ND	ND	ND
Hardwood - Low Load	10/25/2016	9.90E-03	5.51E-04	3.80E-03	1.17E-01	6.51E-03	4.49E-02	7.69E-02	4.28E-03	2.95E-02
Hardwood - Syracuse	10/26/2016	2.05E-01	1.14E-02	8.29E-02	2.53E-02	1.41E-03	1.02E-02	3.36E-02	1.87E-03	1.36E-02
Hardwood - Syracuse	10/27/2016	ND	ND	ND	ND	ND	ND	2.22E-02	1.24E-03	1.16E-02
Switchgrass - Low Load	11/3/2016	1.33E-01	7.62E-03	8.43E-02	ND	ND	ND	2.39E-01	1.37E-02	1.51E-01
Switchgrass - Low Load	11/4/2016	2.38E-01	1.36E-02	1.80E-01	ND	ND	ND	1.80E-01	1.03E-02	1.36E-01
Switchgrass - Syracuse	11/8/2016	1.55E-01	8.89E-03	8.83E-02	ND	ND	ND	1.66E-01	9.51E-03	9.45E-02
Switchgrass - Syracuse	11/9/2016	4.84E-02	2.77E-03	3.02E-02	ND	ND	ND	1.69E-01	9.68E-03	1.05E-01
Switchgrass - Full Load	11/10/2016	1.02E-02	5.85E-04	5.77E-03	4.47E-01	2.56E-02	2.52E-01	4.20E-02	2.40E-03	2.37E-02
Switchgrass - Full Load	11/15/2016	ND	ND	ND	4.29E-01	2.45E-02	2.14E-01	4.36E-02	2.50E-03	2.18E-02

Table C-2. Test Average Speciated VOC Emission Factors (Mass/Mass Fuel Burned)[a]

Compound	Analysis	Hardwood Pellets 25% Load (mg/kg) AVG	RPD	Syracuse (mg/kg) AVG	RPD	100% Load (mg/kg) AVG	RPD	Switchgrass Pellets 25% Load (mg/kg) AVG	RPD	Syracuse (mg/kg) AVG	RPD	100% Load (mg/kg) AVG	RPD
Propylene	TO15	202	51%	11.0	61%	ND		155	29%	118	23%	0.161	110%
Propane	TO15	108	47%	4.94	64%	ND		84.4	30%	55.2	33%	ND	
Dichlorodifluoromethane	TO15	0.542	156%	0.0622	45%	0.0149	200%	0.470	10%	0.298	23%	ND	
Chloromethane	TO15	8.81	59%	0.877	8%	1.34	28%	5.92	29%	3.87	22%	0.885	13%
Isobutane	TO15	20.3	51%	1.22	40%	0.0905	66%	18.6	31%	11.6	21%	0.122	37%
Dichlorotetrafluoroethane	TO15	ND		ND		ND		ND		ND		ND	
VinylChloride	TO15	ND		ND		ND		ND		0.0208	200%	0.0115	200%
1-Butene	TO15	60.3	46%	2.58	73%	0.264	132%	55.8	31%	37.8	31%	1.07	6%
1,3-Butadiene	TO15	28.5	57%	1.94	51%	0.0542	8%	18.9	34%	16.4	27%	0.321	93%
Butane	TO15	16.2	37%	1.12	47%	0.00512	200%	18.00	39%	10.7	34%	ND	
trans-2-butene	TO15	22.6	44%	0.800	79%	ND		18.3	30%	11.1	34%	0.0229	200%
Bromomethane	TO15	ND		0.0125	200%	0.0376	12%	0.428	19%	0.267	25%	0.0779	0%
cis-2-butene	TO15	15.5	39%	0.571	84%	ND		13.7	27%	8.38	34%	ND	
Chloroethane	TO15	ND		0.00596	200%	0.0130	34%	ND		ND		0.0141	200%
Ethanol	TO15	12.2	55%	0.856	122%	0.505	25%	6.63	36%	4.08	3%	0.312	27%
VinylBromide	TO15	ND		ND		ND		ND		ND		ND	
Acetonitrile	TO15	12.4	81%	1.35	9%	0.320	37%	48.2	33%	31.9	33%	1.36	15%
Acrolein	TO15	168	59%	10.4	42%	0.622	51%	81.5	27%	66.8	1%	0.977	32%
Acetone	TO15	219	49%	10.3	58%	0.799	24%	164	31%	113	18%	0.0915	200%
iso-Pentane	TO15	16.8	90%	1.20	41%	0.0591	40%	18.4	37%	11.7	22%	ND	
Trichlorofluoromethane	TO15	ND		0.0134	174%	0.00233	200%	ND		ND		ND	
IsopropylAlcohol	TO15	1.14	40%	0.806	151%	0.128	28%	1.15	8%	0.773	22%	0.053	10%
1-Pentene	TO15	13.2	84%	0.332	99%	ND		6.99	22%	4.81	36%	0.00843	200%
Acrylonitrile	TO15	2.85	50%	0.379	5%	0.0828	24%	12.2	30%	9.55	19%	0.532	52%
n-Pentane	TO15	4.2	38%	0.220	36%	ND		6.82	38%	3.97	42%	ND	
Isoprene	TO15	9.49	50%	0.566	77%	0.201	6%	6.39	42%	4.26	27%	ND	
trans-2-pentene	TO15	6.96	45%	0.228	82%	0.0112	49%	6.26	34%	3.60	36%	0.0229	56%
cis-2-pentene	TO15	3.54	48%	0.138	62%	0.00466	200%	2.92	28%	1.84	36%	0.0118	200%
Tert-Butanol	TO15	48.1	34%	1.21	80%	0.103	49%	12.7	39%	7.99	35%	0.345	6%
1,1-Dichloroethene	TO15	ND		ND		ND		ND		0.0380	200%	ND	
MethyleneChloride	TO15	ND		0.0849	86%	0.0430	30%	0.00296	200%	ND		ND	
3-Chloro-1-Propene	TO15	0.919	79%	0.0364	200%	ND		ND		ND		ND	
1,1,2-Trichloro-1,2,2-trifluoroethane	TO15	ND		0.0574	200%	0.0573	200%	ND		ND		ND	
CarbonDisulfide	TO15	ND		ND		0.00460	200%	ND		ND		0.0415	200%
2,2-Dimethylbutane	TO15	ND		0.0205	50%	ND		ND		ND		ND	
trans-1,2-Dichloroethene	TO15	ND		ND		ND		ND		ND		ND	
Cyclopentane	TO15	43.3	45%	2.24	67%	0.0930	89%	32.8	38%	22.1	16%	0.0442	44%
2,3-Dimethylbutane	TO15	3.35	39%	0.206	17%	ND		3.41	44%	1.59	71%	ND	
1,1-Dichloroethane	TO15	ND		ND		ND		ND		ND		ND	
Methyl-t-Butyl-Ether	TO15	0.228	200%	ND		ND		0.203	200%	ND		ND	
VinylAcetate	TO15	111	46%	6.03	123%	0.486	96%	77.4	10%	45.8	24%	0.0999	200%
2-Methylpentane	TO15	2.69	38%	0.236	1%	0.0111	200%	2.44	76%	1.22	88%	ND	
2-Butanone	TO15	107	42%	3.57	70%	0.0683	62%	81.7	32%	49.1	29%	0.0597	200%
3-Methylpentane	TO15	0.132	103%	0.0699	114%	0.00329	170%	0.331	54%	0.185	11%	ND	
2-Chloroprene	TO15	ND		ND		ND		ND		ND		ND	
1-Hexene	TO15	3.61	42%	0.161	63%	0.0194	10%	5.22	31%	3.93	29%	0.0721	43%
cis-1,2-Dichloroethene	TO15	1.25	68%	0.0306	200%	ND		0.501	200%	0.158	200%	ND	
Diisopropylether	TO15	ND		ND		ND		ND		ND		ND	
EthylAcetate	TO15	ND		ND		ND		ND		ND		ND	
n-Hexane	TO15	1.27	23%	0.236	121%	0.0354	122%	2.24	43%	1.23	45%	ND	
Chloroform	TO15	0.52	28%	0.0210	70%	0.00885	42%	0.248	62%	0.0736	195%	0.000906	200%
Tetrahydrofuran	TO15	5.90	21%	0.167	54%	ND		4.93	39%	2.93	57%	ND	
EthylTert-ButylEther	TO15	2.08	27%	0.0478	108%	ND		ND		0.237	200%	ND	
Methylcyclopentane	TO15	0.230	101%	0.071	167%	ND		0.142	200%	0.0391	200%	ND	
1,2-Dichloroethane	TO15	ND		0.0086	11%	0.0000062	200%	ND		ND		ND	
2,4-Dimethylpentane	TO15	0.245	50%	0.0181	55%	ND		ND		ND		ND	
1,1,1-Trichloroethane	TO15	ND		ND		ND		ND		ND		ND	
Benzene	TO15	124	48%	25.6	25%	6.84	96%	84.6	13%	102	43%	54.6	56%
CarbonTetrachloride	TO15	0.0251	200%	0.0152	64%	0.0078	102%	0.0218	40%	0.0170	0%	0.00146	200%
Cyclohexane	TO15	0.673	59%	ND		ND		0.309	200%	0.282	47%	ND	
2-Methylhexane	TO15	6.75	21%	0.286	200%	ND		0.0824	61%	0.0658	200%	ND	
2,3-Dimethylpentane	TO15	ND		0.00866	200%	ND		ND		ND		ND	
TertAmylMethylEther	TO15	ND		ND		ND		ND		ND		ND	
3-methylhexane	TO15	0.115	200%	ND		0.00308	200%	0.109	200%	0.0307	200%	ND	
1,2-Dichloropropane	TO15	ND		ND		ND		ND		ND		ND	
Bromodichloromethane	TO15	ND		ND		ND		ND		ND		ND	
1,4-Dioxane	TO15	ND		ND		ND		ND		ND		ND	

Table C-2 (continued)

| | | Hardwood Pellets | | | | | | Switchgrass Pellets | | | | | |
| | | 25% Load mg/kg | | Syracuse mg/kg | | 100% Load mg/kg | | 25% Load mg/kg | | Syracuse mg/kg | | 100% Load mg/kg | |
Compound	Analysis	AVG	RPD	AVG	RPD	AVG	RPD	AVG	RPD	AVG	RPD	AVG	RPD
Trichloroethene	TO15	ND		ND		ND		ND		ND		ND	
Isooctane	TO15	ND		0.00937	146%	ND		ND		ND		ND	
MethylMethacrylate	TO15	ND		ND		ND		ND		ND		ND	
Heptane	TO15	0.915	37%	0.00735	200%	ND		2.34	31%	1.15	75%	ND	
cis-1,3-Dichloropropene	TO15	ND		ND		ND		ND		ND		ND	
4-Methy-2-Pentanone	TO15	0.323	200%	ND		ND		0.672	17%	0.547	46%	ND	
Methylcyclohexane	TO15	0.0367	200%	ND		ND		0.128	77%	0.0968	68%	ND	
trans-1,3-Dichloropropene	TO15	ND		ND		ND		ND		ND		ND	
1,1,2-Trichloroethane	TO15	ND		ND		ND		ND		ND		ND	
2,3,4-Trimethylpentane	TO15	ND		0.00675	73%	ND		ND		ND		ND	
Toluene	TO15	56.8	43%	4.36	35%	0.0709	23%	59.5	28%	45.8	47%	0.776	73%
2-Methylheptane	TO15	0.152	200%	ND		ND		0.202	200%	0.140	200%	ND	
2-Hexanone	TO15	ND		ND		ND		ND		ND		ND	
Dibromochloromethane	TO15	ND		ND		ND		ND		ND		ND	
3-Methylheptane	TO15	0.159	200%	ND		ND		ND		ND		ND	
1,2-Dibromoethane	TO15	ND		ND		ND		ND		ND		ND	
Octane	TO15	0.204	200%	ND		ND		0.779	40%	0.380	66%	ND	
Tetrachloroethene	TO15	ND		0.0180	49%	0.00850	200%	ND		ND		ND	
1,1,1,2-Tetrachloroethane	TO15	ND		ND		ND		ND		ND		ND	
Chlorobenzene	TO15	ND		ND		0.0415	20%	ND		ND		0.0393	200%
Ethylbenzene	TO15	3.57	38%	0.202	70%	ND		6.05	33%	4.07	50%	ND	
m-Xylene	TO15	4.91	21%	0.254	84%	ND		4.33	26%	3.71	62%	ND	
p-Xylene	TO15	4.14	28%	0.211	64%	ND		3.06	21%	2.57	57%	ND	
Bromoform	TO15	ND		ND		ND		ND		ND		ND	
Styrene	TO15	3.42	35%	0.302	28%	ND		4.8	31%	4.59	51%	0.236	111%
1,1,2,2-Tetrachloroethane	TO15	ND		ND		ND		ND		ND		ND	
o-Xylene	TO15	2.70	33%	0.160	85%	ND		2.46	30%	1.94	57%	ND	
Nonane	TO15	ND		ND		ND		0.168	200%	0.132	200%	ND	
Cumene	TO15	ND		ND		ND		ND		ND		ND	
Chlorotoluenes	TO15	ND		ND		ND		ND		ND		ND	
n-Propylbenzene	TO15	0.112	200%	ND		ND		0.390	35%	0.266	58%	ND	
m-Ethyltoluene	TO15	0.484	200%	ND		ND		0.647	48%	0.493	60%	ND	
1,3,5-Trimethylbenzene	TO15	ND		ND		ND		ND		0.199	200%	ND	
1,2,4-Trimethylbenzene	TO15	1.67	1%	0.0349	200%	ND		1.86	36%	1.16	45%	ND	
Tert-ButylBenzene	TO15	ND		ND		ND		0.105	200%	0.0954	200%	ND	
1-Ethyl-4-MethylBenzene	TO15	ND		ND		ND		0.456	200%	ND		ND	
o-Ethyltoluene	TO15	0.238	200%	ND		ND		0.728	45%	0.470	63%	ND	
1,3-Dichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
1,4-Dichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
n-Decane	TO15	ND		ND		ND		0.195	200%	0.123	200%	ND	
Sec-ButylBenzene	TO15	ND		ND		ND		ND		ND		ND	
1,2,3-Trimethylbenzene	TO15	0.28	200%	ND		ND		0.858	41%	0.411	60%	ND	
1,2-Dichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
o-Cymene	TO15	ND		ND		ND		ND		ND		ND	
1,3-Diethylbenzene	TO15	ND		ND		ND		0.225	33%	0.0671	200%	ND	
1,2-Diethylbenzene	TO15	0.277	200%	ND		ND		0.685	58%	0.370	50%	ND	
n-ButylBenzene	TO15	0.382	200%	ND		ND		0.585	58%	0.307	73%	ND	
Undecane	TO15	ND		ND		ND		0.525	53%	0.210	200%	ND	
1,2,4-Trichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
Naphthalene	TO15	21.0	53%	4.55	44%	1.01	127%	9.26	16%	11.7	65%	8.18	31%
Dodecane	TO15	0.162	200%	ND		0.0233	200%	0.918	90%	0.346	61%	ND	
Hexachlorobutadiene	TO15	ND		ND		ND		ND		ND		ND	
Formaldehyde	TO11A	586	17%	76.2	55%	7.14	51%	232	6%	216	5%	15.8	67%
Acetaldehyde	TO11A	358	17%	20.5	84%	0.735	27%	232	22%	159	26%	1.30	42%
Propanal	TO11A	142	31%	ND		ND		72.3	27%	42.1	24%	0.288	200%
Crotonaldehyde	TO11A	23.7	19%	ND		ND		14.00	54%	10.1	51%	ND	
Butyraldehyde	TO11A	40.5		ND		ND		0.139	200%	ND		ND	
Benzaldehyde	TO11A	28.2	200%	3.13	200%	ND		20.3	66%	19.2	4%	0.763	200%
Isovaleraldehyde	TO11A	4.78	200%	ND		ND		15.2	22%	10.2	1%	ND	
Valeraldehyde	TO11A	0.612	200%	ND		ND		0.116	200%	ND		0.00287	200%
o-Tolualdehyde	TO11A	4.56	200%	2.18	200%	ND		ND		2.95	200%	ND	
m-Tolualdehyde	TO11A	ND		ND		ND		ND		ND		ND	
p-Tolualdehyde	TO11A	178	200%	ND		ND		ND		ND		ND	
Hexaldehyde	TO11A	54.3	200%	ND		ND		32.4	22%	ND		ND	
2,5-Dimethylbenzaldehyde	TO11A	ND		ND		ND		ND		6.68	60%	ND	
TOTAL VOCs		2940	22%	205	45%	21.4	61%	1780	24%	1320	24%	88.7	54%

a ND=not detected. RPD=relative percent difference.

Table C-3. Test Average Speciated VOC Emission Factors (Mass/Heat Input)[a]

Compound	Analysis	Hardwood Pellets 25% Load mg/MJ input AVG	RPD	Syracuse mg/MJ input AVG	RPD	100% Load mg/MJ input AVG	RPD	Switchgrass Pellets 25% Load mg/MJ input AVG	RPD	Syracuse mg/MJ input AVG	RPD	100% Load mg/MJ input AVG	RPD
Propylene	TO15	11.2	51%	0.613	61%	ND		8.89	29%	6.74	23%	0.0092	110%
Propane	TO15	5.99	47%	0.274	64%	ND		4.83	30%	3.15	33%	ND	
Dichlorodifluoromethane	TO15	0.0302	156%	0.00346	45%	0.000827	200%	0.0269	10%	0.017	23%	ND	
Chloromethane	TO15	0.490	59%	0.0488	8%	0.0746	28%	0.338	29%	0.221	22%	0.0506	13%
Isobutane	TO15	1.13	51%	0.0679	40%	0.00503	66%	1.07	31%	0.660	21%	0.00700	37%
Dichlorotetrafluoroethane	TO15	ND		ND		ND		ND		ND		ND	
VinylChloride	TO15	ND		ND		ND		ND		0.00119	200%	0.000655	200%
1-Butene	TO15	3.35	46%	0.144	73%	0.0147	132%	3.19	31%	2.16	31%	0.0614	6%
1,3-Butadiene	TO15	1.58	57%	0.108	51%	0.00301	8%	1.08	34%	0.938	27%	0.0183	93%
Butane	TO15	0.901	37%	0.0622	47%	0.000285	200%	1.03	39%	0.613	34%	ND	
trans-2-butene	TO15	1.26	44%	0.0445	79%	ND		1.05	30%	0.636	34%	0.00131	200%
Bromomethane	TO15	ND		0.000693	200%	0.00209	12%	0.0245	19%	0.0153	25%	0.00445	0%
cis-2-butene	TO15	0.859	39%	0.0317	84%	ND		0.780	27%	0.479	34%	ND	
Chloroethane	TO15	ND		0.000331	200%	0.000725	34%	ND		ND		0.000808	200%
Ethanol	TO15	0.679	55%	0.0476	122%	0.0281	25%	0.379	36%	0.233	3%	0.0178	27%
VinylBromide	TO15	ND		ND		ND		ND		ND		ND	
Acetonitrile	TO15	0.690	81%	0.0752	9%	0.0178	37%	2.75	33%	1.83	33%	0.0779	15%
Acrolein	TO15	9.37	59%	0.577	42%	0.0346	51%	4.66	27%	3.82	1%	0.0559	32%
Acetone	TO15	12.2	49%	0.574	58%	0.0445	24%	9.39	31%	6.44	18%	0.00523	200%
iso-Pentane	TO15	0.932	90%	0.0668	41%	0.00328	40%	1.05	37%	0.667	22%	ND	
Trichlorofluoromethane	TO15	ND		0.000745	174%	0.000129	200%	ND		ND		ND	
IsopropylAlcohol	TO15	0.0636	40%	0.0448	151%	0.00709	28%	0.0658	8%	0.0442	22%	0.00303	10%
1-Pentene	TO15	0.735	84%	0.0185	99%	ND		0.399	22%	0.275	36%	0.000482	200%
Acrylonitrile	TO15	0.159	50%	0.0211	5%	0.00460	24%	0.697	30%	0.546	19%	0.0304	52%
n-Pentane	TO15	0.233	38%	0.0122	36%	ND		0.390	38%	0.227	42%	ND	
Isoprene	TO15	0.528	50%	0.0315	77%	0.0112	6%	0.365	42%	0.243	27%	ND	
trans-2-pentene	TO15	0.387	45%	0.0127	82%	0.000625	49%	0.358	34%	0.206	36%	0.00131	56%
cis-2-pentene	TO15	0.197	48%	0.00767	62%	0.000259	200%	0.167	28%	0.105	36%	0.000675	200%
Tert-Butanol	TO15	2.67	34%	0.0672	80%	0.00573	49%	0.727	39%	0.457	35%	0.0197	6%
1,1-Dichloroethene	TO15	ND		ND		ND		ND		0.00217	200%	ND	
MethyleneChloride	TO15	ND		0.00472	86%	0.00239	30%	0.000169	200%	ND		ND	
3-Chloro-1-Propene	TO15	0.0511	79%	0.00202	200%	ND		ND		ND		ND	
1,1,2-Trichloro-1,2,2-trifluoroethane	TO15	ND		0.00319	200%	0.00319	200%	ND		ND		ND	
CarbonDisulfide	TO15	ND		ND		0.000256	200%	ND		ND		0.00237	200%
2,2-Dimethylbutane	TO15	ND		0.00114	50%	ND		ND		ND		ND	
trans-1,2-Dichloroethene	TO15	ND		ND		ND		ND		ND		ND	
Cyclopentane	TO15	2.41	45%	0.125	67%	0.00517	89%	1.87	38%	1.27	16%	0.00252	44%
2,3-Dimethylbutane	TO15	0.186	39%	0.0114	17%			0.195	44%	0.0908	71%	ND	
1,1-Dichloroethane	TO15	ND		ND		ND		ND		ND		ND	
Methyl-t-Butyl-Ether	TO15	0.0127	200%	ND		ND		0.0116	200%	ND		ND	
VinylAcetate	TO15	6.19	46%	0.335	123%	0.0270	96%	4.43	10%	2.62	24%	0.00571	200%
2-Methylpentane	TO15	0.15	38%	0.0131	1%	0.000619	200%	0.139	76%	0.0695	88%	ND	
2-Butanone	TO15	5.95	42%	0.199	70%	0.0038	62%	4.67	32%	2.80	29%	0.00341	200%
3-Methylpentane	TO15	0.00736	103%	0.00389	114%	0.000183	170%	0.0189	54%	0.0106	11%	ND	
2-Chloroprene	TO15	ND		ND		ND		ND		ND		ND	
1-Hexene	TO15	0.201	42%	0.00893	63%	0.00108	10%	0.298	31%	0.225	29%	0.00412	43%
cis-1,2-Dichloroethene	TO15	0.0697	68%	0.0017	200%	ND		0.0287	200%	0.00905	200%	ND	
Diisopropylether	TO15	ND		ND		ND		ND		ND		ND	
EthylAcetate	TO15	ND		ND		ND		ND		ND		ND	
n-Hexane	TO15	0.0709	23%	0.0131	121%	0.00197	122%	0.128	43%	0.0702	45%	ND	
Chloroform	TO15	0.0289	28%	0.00117	70%	0.000492	42%	0.0142	62%	0.00421	195%	0.0000518	200%
Tetrahydrofuran	TO15	0.328	21%	0.0093	54%	ND		0.282	39%	0.167	57%	ND	
EthylTert-ButylEther	TO15	0.116	27%	0.00266	108%	ND		ND		0.0135	200%	ND	
Methylcyclopentane	TO15	0.0128	101%	0.00395	167%	ND		0.00809	200%	0.00223	200%	ND	
1,2-Dichloroethane	TO15	ND		0.000479	11%	3.45E-07	200%	ND		ND		ND	
2,4-Dimethylpentane	TO15	0.0136	50%	0.00101	55%	ND		ND		ND		ND	
1,1,1-Trichloroethane	TO15	ND		ND		ND		ND		ND		ND	
Benzene	TO15	6.87	48%	1.43	25%	0.38	96%	4.84	13%	5.81	43%	3.12	56%
CarbonTetrachloride	TO15	0.00140	200%	0.000845	64%	0.000434	102%	0.00125	40%	0.000971	0%	0.0000832	200%
Cyclohexane	TO15	0.0375	59%	ND		ND		0.0177	200%	0.0161	47%	ND	
2-Methylhexane	TO15	0.376	21%	0.0159	200%	ND		0.00471	61%	0.00376	200%	ND	
2,3-Dimethylpentane	TO15	ND		0.000482	200%	ND		ND		ND		ND	
TertAmylMethylEther	TO15	ND		ND		ND		ND		ND		ND	
3-methylhexane	TO15	0.00638	200%	ND		0.000171	200%	0.00620	200%	0.00175	200%	ND	
1,2-Dichloropropane	TO15	ND		ND		ND		ND		ND		ND	
Bromodichloromethane	TO15	ND		ND		ND		ND		ND		ND	
1,4-Dioxane	TO15	ND		ND		ND		ND		ND		ND	

Table C-3 (continued)

Compound	Analysis	Hardwood Pellets						Switchgrass Pellets					
		25% Load mg/MJ input		Syracuse mg/MJ input		100% Load mg/MJ input		25% Load mg/MJ input		Syracuse mg/MJ input		100% Load mg/MJ input	
		AVG	RPD	AVG	RPD	AVG	RPD	AVG	RPD	AVG	RPD	AVG	RPD
Trichloroethene	TO15	ND		ND		ND		ND		ND		ND	
Isooctane	TO15	ND		0.000521	146%	ND		ND		ND		ND	
MethylMethacrylate	TO15	ND		ND		ND		ND		ND		ND	
Heptane	TO15	0.0509	37%	0.000409	200%	ND		0.134	31%	0.0660	75%	ND	
cis-1,3-Dichloropropene	TO15	ND		ND		ND		ND		ND		ND	
4-Methy-2-Pentanone	TO15	0.018	200%	ND		ND		0.0384	17%	0.0312	46%	ND	
Methylcyclohexane	TO15	0.00204	200%	ND		ND		0.00730	77%	0.00553	68%	ND	
trans-1,3-Dichloropropene	TO15	ND		ND		ND		ND		ND		ND	
1,1,2-Trichloroethane	TO15	ND		ND		ND		ND		ND		ND	
2,3,4-Trimethylpentane	TO15	ND		0.000375	73%	ND		ND		ND		ND	
Toluene	TO15	3.16	43%	0.243	35%	0.00394	23%	3.40	28%	2.62	47%	0.0444	73%
2-Methylheptane	TO15	0.00847	200%	ND		ND		0.0116	200%	0.00798	200%	ND	
2-Hexanone	TO15	ND		ND		ND		ND		ND		ND	
Dibromochloromethane	TO15	ND		ND		ND		ND		ND		ND	
3-Methylheptane	TO15	0.00887	200%	ND		ND		ND		ND		ND	
1,2-Dibromoethane	TO15	ND		ND		ND		ND		ND		ND	
Octane	TO15	0.0113	200%	ND		ND		0.0445	40%	0.0217	66%	ND	
Tetrachloroethene	TO15	ND		0.00100	49%	0.000473	200%	ND		ND		ND	
1,1,1,2-Tetrachloroethane	TO15	ND		ND		ND		ND		ND		ND	
Chlorobenzene	TO15	ND		ND		0.00231	20%	ND		ND		0.00224	200%
Ethylbenzene	TO15	0.199	38%	0.0112	70%	ND		0.346	33%	0.233	50%	ND	
m-Xylene	TO15	0.273	21%	0.0141	84%	ND		0.247	26%	0.212	62%	ND	
p-Xylene	TO15	0.230	28%	0.0118	64%	ND		0.175	21%	0.147	57%	ND	
Bromoform	TO15	ND		ND		ND		ND		ND		ND	
Styrene	TO15	0.190	35%	0.0168	28%	ND		0.275	31%	0.262	51%	0.0135	111%
1,1,2,2-Tetrachloroethane	TO15	ND		ND		ND		ND		ND		ND	
o-Xylene	TO15	0.15	33%	0.00892	85%	ND		0.141	30%	0.111	57%	ND	
Nonane	TO15	ND		ND		ND		0.00961	200%	0.00753	200%	ND	
Cumene	TO15	ND		ND		ND		ND		ND		ND	
Chlorotoluenes	TO15	ND		ND		ND		ND		ND		ND	
n-Propylbenzene	TO15	0.00621	200%	ND		ND		0.0223	35%	0.0152	58%	ND	
m-Ethyltoluene	TO15	0.0269	200%	ND		ND		0.037	48%	0.0282	60%	ND	
1,3,5-Trimethylbenzene	TO15	ND		ND		ND		ND		0.0114	200%	ND	
1,2,4-Trimethylbenzene	TO15	0.0926	1%	0.00194	200%	ND		0.106	36%	0.0664	45%	ND	
Tert-ButylBenzene	TO15	ND		ND		ND		0.00598	200%	0.00546	200%	ND	
1-Ethyl-4-MethylBenzene	TO15	ND		ND		ND		0.0260	200%	ND		ND	
o-Ethyltoluene	TO15	0.0132	200%	ND		ND		0.0416	45%	0.0269	63%	ND	
1,3-Dichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
1,4-Dichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
n-Decane	TO15	ND		ND		ND		0.0112	200%	0.00704	200%	ND	
Sec-ButylBenzene	TO15	ND		ND		ND		ND		ND		ND	
1,2,3-Trimethylbenzene	TO15	0.0156	200%	ND		ND		0.0491	41%	0.0235	60%	ND	
1,2-Dichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
o-Cymene	TO15	ND		ND		ND		ND		ND		ND	
1,3-Diethylbenzene	TO15	ND		ND		ND		0.0129	33%	0.00384	200%	ND	
1,2-Diethylbenzene	TO15	0.0154	200%	ND		ND		0.0392	58%	0.0211	50%	ND	
n-ButylBenzene	TO15	0.0212	200%	ND		ND		0.0335	58%	0.0175	73%	ND	
Undecane	TO15	ND		ND		ND		0.0300	53%	0.0120	200%	ND	
1,2,4-Trichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
Naphthalene	TO15	1.17	53%	0.253	44%	0.0563	127%	0.530	16%	0.666	65%	0.468	31%
Dodecane	TO15	0.00901	200%	ND		0.00130	200%	0.0525	90%	0.0198	61%	ND	
Hexachlorobutadiene	TO15	ND		ND		ND		ND		ND		ND	
Formaldehyde	TO11A	32.6	17%	4.24	55%	0.397	51%	13.3	6%	12.3	5%	0.902	67%
Acetaldehyde	TO11A	19.9	17%	1.14	84%	0.0409	27%	13.3	22%	9.11	26%	0.0741	42%
Propanal	TO11A	7.88	31%	ND		ND		4.13	27%	2.40	24%	0.0164	200%
Crotonaldehyde	TO11A	1.32	19%	ND		ND		0.803	54%	0.576	51%	ND	
Butyraldehyde	TO11A	2.25	200%	ND		ND		0.00792	200%	ND		ND	
Benzaldehyde	TO11A	1.57	200%	0.174	200%	ND		1.16	66%	1.1	4%	0.0436	200%
Isovaleraldehyde	TO11A	0.266	200%	ND		ND		0.87	22%	0.584	1%	ND	
Valeraldehyde	TO11A	0.034	200%	ND		ND		0.0066	200%	ND		0.000164	200%
o-Tolualdehyde	TO11A	0.254	200%	0.121	200%	ND		ND		0.169	200%	ND	
m-Tolualdehyde	TO11A	ND		ND		ND		ND		ND		ND	
p-Tolualdehyde	TO11A	9.92	200%	ND		ND		ND		ND		ND	
Hexaldehyde	TO11A	3.02	200%	ND		ND		1.85	22%	ND		ND	
2,5-Dimethylbenzaldehyde	TO11A	ND		ND		ND		ND		0.382	60%	ND	
Total VOCs		163	22%	11.4	45%	1.19	61%	102	24%	75.2	24%	5.07	54%

[a] ND=not detected. RPD=relative percent difference.

Table C-4. Test Average Speciated VOC Emission Factors (Mass/Heat Output)[a]

Compound	Analysis	Hardwood Pellets 25% Load mg/MJ output AVG	RPD	Syracuse mg/MJ output AVG	RPD	100% Load mg/MJ output AVG	RPD	Switchgrass Pellets 25% Load mg/MJ output AVG	RPD	Syracuse mg/MJ output AVG	RPD	100% Load mg/MJ output AVG	RPD
Propylene	TO15	15.5	51%	0.685	61%	ND		14.1	29%	9.28	23%	0.0110	110%
Propane	TO15	8.35	47%	0.308	64%	ND		7.67	30%	4.33	33%	ND	
Dichlorodifluoromethane	TO15	0.0312	156%	0.00362	45%	0.000925	200%	0.0431	10%	0.0237	23%	ND	
Chloromethane	TO15	0.663	59%	0.0522	8%	0.0727	28%	0.538	29%	0.304	22%	0.0627	13%
Isobutane	TO15	1.55	51%	0.0749	40%	0.00478	66%	1.69	31%	0.909	21%	0.00874	37%
Dichlorotetrafluoroethane	TO15	ND		ND		ND		ND		ND		ND	
Vinyl Chloride	TO15	ND		ND		ND		ND		0.00172	200%	0.000858	200%
1-Butene	TO15	4.68	46%	0.162	73%	0.0157	132%	5.06	31%	2.97	31%	0.0759	6%
1,3-Butadiene	TO15	2.16	57%	0.120	51%	0.00300	8%	1.71	34%	1.29	27%	0.022	93%
Butane	TO15	1.28	37%	0.0690	47%	0.000318	200%	1.63	39%	0.842	34%	ND	
trans-2-butene	TO15	1.76	44%	0.0503	79%	ND		1.66	30%	0.873	34%	0.00172	200%
Bromomethane	TO15	ND		0.000842	200%	0.00205	12%	0.0391	19%	0.0213	25%	0.0055	0%
cis-2-butene	TO15	1.22	39%	0.0360	84%	ND		1.240	27%	0.658	34%	ND	
Chloroethane	TO15	ND		0.000402	200%	0.000703	34%	ND		ND		0.00106	200%
Ethanol	TO15	0.929	55%	0.0472	122%	0.0274	25%	0.601	36%	0.323	3%	0.0218	27%
Vinyl Bromide	TO15	ND		ND		ND		ND		ND		ND	
Acetonitrile	TO15	0.883	81%	0.0814	9%	0.0172	37%	4.37	33%	2.51	33%	0.0957	15%
Acrolein	TO15	12.7	59%	0.638	42%	0.0332	51%	7.41	27%	5.28	1%	0.0683	32%
Acetone	TO15	16.9	49%	0.641	58%	0.0434	24%	14.9	31%	8.87	18%	0.00685	200%
iso-Pentane	TO15	1.17	90%	0.0739	41%	0.00334	40%	1.67	37%	0.919	22%	ND	
Trichlorofluoromethane	TO15	ND		0.000892	174%	0.000145	200%	ND		ND		ND	
Isopropyl Alcohol	TO15	0.0900	40%	0.0436	151%	0.00691	28%	0.106	8%	0.0608	22%	0.00375	10%
1-Pentene	TO15	0.935	84%	0.0212	99%	ND		0.637	22%	0.377	36%	0.000631	200%
Acrylonitrile	TO15	0.219	50%	0.0227	5%	0.00450	24%	1.11	30%	0.752	19%	0.0369	52%
n-Pentane	TO15	0.332	38%	0.0135	36%	ND		0.618	38%	0.311	42%	ND	
Isoprene	TO15	0.730	50%	0.0356	77%	0.0110	6%	0.577	42%	0.335	27%	ND	
trans-2-pentene	TO15	0.542	45%	0.0144	82%	0.000639	49%	0.567	34%	0.282	36%	0.00159	56%
cis-2-pentene	TO15	0.273	48%	0.00858	62%	0.00029	200%	0.265	28%	0.145	36%	0.000884	200%
Tert-Butanol	TO15	3.83	34%	0.0761	80%	0.00585	49%	1.15	39%	0.627	35%	0.0244	6%
1,1-Dichloroethene	TO15	ND		ND		ND		ND		0.00287	200%	ND	
Methylene Chloride	TO15	ND		0.00537	86%	0.00241	30%	0.000249	200%	ND		ND	
3-Chloro-1-Propene	TO15	0.0657	79%	0.00246	200%	ND		ND		ND		ND	
1,1,2-Trichloro-1,2,2-trifluoroethane	TO15	ND		0.00388	200%	0.00356	200%	ND		ND		ND	
Carbon Disulfide	TO15	ND		ND		0.000286	200%	ND		ND		0.00311	200%
2,2-Dimethylbutane	TO15	ND		0.00127	50%	ND		ND		ND		ND	
trans-1,2-Dichloroethene	TO15	ND		ND		ND		ND		ND		ND	
Cyclopentane	TO15	3.37	45%	0.140	67%	0.00484	89%	2.97	38%	1.74	16%	0.00308	44%
2,3-Dimethylbutane	TO15	0.264	39%	0.0124	17%	ND		0.308	44%	0.124	71%	ND	
1,1-Dichloroethane	TO15	ND		ND		ND		ND		ND		ND	
Methyl-t-Butyl-Ether	TO15	0.0279	200%	ND		ND		0.0171	200%	ND		ND	
Vinyl Acetate	TO15	8.63	46%	0.389	123%	0.0252	96%	7.10	10%	3.60	24%	0.00748	200%
2-Methylpentane	TO15	0.213	38%	0.0141	1%	0.000535	200%	0.217	76%	0.0942	88%	ND	
2-Butanone	TO15	8.39	42%	0.223	70%	0.00362	62%	7.41	32%	3.86	29%	0.00447	200%
3-Methylpentane	TO15	0.0138	103%	0.00388	114%	0.000162	170%	0.0298	54%	0.0146	11%	ND	
2-Chloroprene	TO15	ND		ND		ND		ND		ND		ND	
1-Hexene	TO15	0.283	42%	0.0100	63%	0.00106	10%	0.474	31%	0.309	29%	0.00502	43%
cis-1,2-Dichloroethene	TO15	0.123	68%	0.00207	200%	ND		0.0421	200%	0.0131	200%	ND	
Diisopropyl ether	TO15	ND		ND		ND		ND		ND		ND	
Ethyl Acetate	TO15	ND		ND		ND		ND		ND		ND	
n-Hexane	TO15	0.104	23%	0.0130	121%	0.00180	122%	0.202	43%	0.0961	45%	ND	
Chloroform	TO15	0.042	28%	0.00131	70%	0.000501	42%	0.0222	62%	0.00608	195%	0.0000678	200%
Tetrahydrofuran	TO15	0.484	21%	0.0104	54%	ND		0.446	39%	0.229	57%	ND	
Ethyl Tert-Butyl Ether	TO15	0.169	27%	0.00306	108%	ND		ND		0.0179	200%	ND	
Methylcyclopentane	TO15	0.0156	101%	0.0038	167%	ND		0.0119	200%	0.00295	200%	ND	
1,2-Dichloroethane	TO15	ND		0.000511	11%	3.86E-07	200%	ND		ND		ND	
2,4-Dimethylpentane	TO15	0.0233	50%	0.00112	55%	ND		ND		ND		ND	
1,1,1-Trichloroethane	TO15	ND		ND		ND		ND		ND		ND	
Benzene	TO15	9.55	48%	1.51	25%	0.354	96%	7.75	13%	7.96	43%	3.79	56%
Carbon Tetrachloride	TO15	0.00124	200%	0.000947	64%	0.000458	102%	0.00197	40%	0.00134	0%	0.000109	200%
Cyclohexane	TO15	0.0507	59%	ND		ND		0.0259	200%	0.0221	47%	ND	
2-Methylhexane	TO15	0.607	21%	0.0193	200%	ND		0.00779	61%	0.00545	200%	ND	
2,3-Dimethylpentane	TO15	ND		0.000452	200%	ND		ND		ND		ND	
Tert Amyl Methyl Ether	TO15	ND		ND		ND		ND		ND		ND	
3-methylhexane	TO15	0.0140	200%	ND		0.000148	200%	0.00911	200%	0.00232	200%	ND	
1,2-Dichloropropane	TO15	ND		ND		ND		ND		ND		ND	
Bromodichloromethane	TO15	ND		ND		ND		ND		ND		ND	
1,4-Dioxane	TO15	ND		ND		ND		ND		ND		ND	

Table C-4 (continued)

Compound	Analysis	Hardwood Pellets						Switchgrass Pellets					
		25% Load mg/MJ output		Syracuse mg/MJ output		100% Load mg/MJ output		25% Load mg/MJ output		Syracuse mg/MJ output		100% Load mg/MJ output	
		AVG	RPD	AVG	RPD	AVG	RPD	AVG	RPD	AVG	RPD	AVG	RPD
Trichloroethene	TO15	ND		ND		ND		ND		ND		ND	
Isooctane	TO15	ND		0.000508	146%	ND		ND		ND		ND	
MethylMethacrylate	TO15	ND		ND		ND		ND		ND		ND	
Heptane	TO15	0.0848	37%	0.000496	200%	ND		0.212	31%	0.0898	75%	ND	
cis-1,3-Dichloropropene	TO15	ND		ND		ND		ND		ND		ND	
4-Methy-2-Pentanone	TO15	0.0395	200%	ND		ND		0.0614	17%	0.0428	46%	ND	
Methylcyclohexane	TO15	0.00449	200%	ND		ND		0.01140	77%	0.00754	68%	ND	
trans-1,3-Dichloropropene	TO15	ND		ND		ND		ND		ND		ND	
1,1,2-Trichloroethane	TO15	ND		ND		ND		ND		ND		ND	
2,3,4-Trimethylpentane	TO15	ND		0.000385	73%	ND		ND		ND		ND	
Toluene	TO15	4.44	43%	0.267	35%	0.00385	23%	5.41	28%	3.58	47%	0.0536	73%
2-Methylheptane	TO15	0.0186	200%	ND		ND		0.017	200%	0.0105	200%	ND	
2-Hexanone	TO15	ND		ND		ND		ND		ND		ND	
Dibromochloromethane	TO15	ND		ND		ND		ND		ND		ND	
3-Methylheptane	TO15	0.0195	200%	ND		ND		ND		ND		ND	
1,2-Dibromoethane	TO15	ND		ND		ND		ND		ND		ND	
Octane	TO15	0.025	200%	ND		ND		0.0704	40%	0.0296	66%	ND	
Tetrachloroethene	TO15	ND		0.00104	49%	0.000528	200%	ND		ND		ND	
1,1,1,2-Tetrachloroethane	TO15	ND		ND		ND		ND		ND		ND	
Chlorobenzene	TO15	ND		ND		0.00226	20%	ND		ND		0.00294	200%
Ethylbenzene	TO15	0.283	38%	0.0126	70%	ND		0.549	33%	0.318	50%	ND	
m-Xylene	TO15	0.403	21%	0.0160	84%	ND		0.394	26%	0.289	62%	ND	
p-Xylene	TO15	0.334	28%	0.0132	64%	ND		0.280	21%	0.201	57%	ND	
Bromoform	TO15	ND		ND		ND		ND		ND		ND	
Styrene	TO15	0.272	35%	0.0184	28%	ND		0.436	31%	0.359	51%	0.0161	111%
1,1,2,2-Tetrachloroethane	TO15	ND		ND		ND		ND		ND		ND	
o-Xylene	TO15	0.216	33%	0.0101	85%	ND		0.224	30%	0.151	57%	ND	
Nonane	TO15	ND		ND		ND		0.0141	200%	0.00995	200%	ND	
Cumene	TO15	ND		ND		ND		ND		ND		ND	
Chlorotoluenes	TO15	ND		ND		ND		ND		ND		ND	
n-Propylbenzene	TO15	0.0137	200%	ND		ND		0.0354	35%	0.0208	58%	ND	
m-Ethyltoluene	TO15	0.0592	200%	ND		ND		0.0583	48%	0.0385	60%	ND	
1,3,5-Trimethylbenzene	TO15	ND		ND		ND		ND		0.0150	200%	ND	
1,2,4-Trimethylbenzene	TO15	0.143	1%	0.00235	200%	ND		0.168	36%	0.0910	45%	ND	
Tert-ButylBenzene	TO15	ND		ND		ND		0.00879	200%	0.00721	200%	ND	
1-Ethyl-4-MethylBenzene	TO15	ND		ND		ND		0.0383	200%	ND		ND	
o-Ethyltoluene	TO15	0.0291	200%	ND		ND		0.0657	45%	0.0367	63%	ND	
1,3-Dichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
1,4-Dichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
n-Decane	TO15	ND		ND		ND		0.0164	200%	0.0093	200%	ND	
Sec-ButylBenzene	TO15	ND		ND		ND		ND		ND		ND	
1,2,3-Trimethylbenzene	TO15	0.0342	200%	ND		ND		0.0776	41%	0.0321	60%	ND	
1,2-Dichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
o-Cymene	TO15	ND		ND		ND		ND		ND		ND	
1,3-Diethylbenzene	TO15	ND		ND		ND		0.0204	33%	0.00506	200%	ND	
1,2-Diethylbenzene	TO15	0.0339	200%	ND		ND		0.0614	58%	0.0289	50%	ND	
n-ButylBenzene	TO15	0.0467	200%	ND		ND		0.0525	58%	0.0239	73%	ND	
Undecane	TO15	ND		ND		ND		0.0472	53%	0.0159	200%	ND	
1,2,4-Trichlorobenzene	TO15	ND		ND		ND		ND		ND		ND	
Naphthalene	TO15	2.01	53%	0.265	44%	0.0513	127%	0.847	16%	0.909	65%	0.572	31%
Dodecane	TO15	0.0198	200%	ND		0.00112	200%	0.0812	90%	0.027	61%	ND	
Hexachlorobutadiene	TO15	ND		ND		ND		ND		ND		ND	
Formaldehyde	TO11A	48.5	17%	4.72	55%	0.381	51%	21.3	6%	17.1	5%	1.09	67%
Acetaldehyde	TO11A	29.7	17%	1.29	84%	0.0398	27%	21.2	22%	12.5	26%	0.0903	42%
Propanal	TO11A	11.4	31%	ND		ND		6.58	27%	3.31	24%	0.0191	200%
Crotonaldehyde	TO11A	2.12	19%	ND		ND		1.26	54%	0.807	51%	ND	
Butyraldehyde	TO11A	4.96	200%	ND		ND		0.0116	200%	ND		ND	
Benzaldehyde	TO11A	1.40	200%	0.212	200%	ND		1.93	66%	1.52	4%	0.0506	200%
Isovaleraldehyde	TO11A	0.237	200%	ND		ND		1.39	22%	0.808	1%	ND	
Valeraldehyde	TO11A	0.0304	200%	ND		ND		0.0097	200%	ND		0.000215	200%
o-Tolualdehyde	TO11A	0.558	200%	0.113	200%	ND		ND		0.223	200%	ND	
m-Tolualdehyde	TO11A	ND		ND		ND		ND		ND		ND	
p-Tolualdehyde	TO11A	21.8	200%	ND		ND		ND		ND		ND	
Hexaldehyde	TO11A	2.70	200%	ND		ND		2.96	22%	ND		ND	
2,5-Dimethylbenzaldehyde	TO11A	ND		ND		ND		ND		0.522	60%	ND	
Total VOCs		241	66%	12.6	69%	1.13	37%	162	6%	104	15%	6.16	42%

[a] ND=not detected. RPD=relative percent difference.

Table C-5. Test Average Total PAH Emission Factors

Test Condition	Date	Test Average Total PAH Emission Factor				
		mg/kg fuel	mg/MJ Input	lb/MMBTU Input	mg/MJ Output	lb/MMBTU Out
Hardwood - Full Load	10/19/2016	4.69E+00	2.61E-01	6.06E-04	2.26E-01	5.24E-04
Hardwood - Full Load	10/20/2016	6.24E-01	3.47E-02	8.06E-05	3.88E-02	9.01E-05
Hardwood - Low Load	10/21/2016	1.52E+01	8.43E-01	1.96E-03	1.85E+00	4.31E-03
Hardwood - Low Load	10/25/2016	2.12E+02	1.18E+01	2.74E-02	1.05E+01	2.44E-02
Hardwood - Syracuse	10/26/2016	3.66E+00	2.03E-01	4.73E-04	1.91E-01	4.43E-04
Hardwood - Syracuse	10/27/2016	3.20E+00	1.78E-01	4.14E-04	2.16E-01	5.03E-04
Switchgrass - Low Load	11/3/2016	1.07E+01	6.12E-01	1.42E-03	8.99E-01	2.09E-03
Switchgrass - Low Load	11/4/2016	1.27E+01	7.29E-01	1.69E-03	1.28E+00	2.97E-03
Switchgrass - Syracuse	11/8/2016	6.49E+01	3.71E+00	8.62E-03	4.90E+00	1.14E-02
Switchgrass - Syracuse	11/9/2016	7.84E+01	4.48E+00	1.04E-02	6.49E+00	1.51E-02
Switchgrass - Full Load	11/10/2016	1.13E+01	6.47E-01	1.50E-03	8.47E-01	1.97E-03
Switchgrass - Full Load	11/15/2016	3.44E+01	1.97E+00	4.57E-03	2.28E+00	5.30E-03

Table C-6. Test Average Speciated PAH Emission Factors (Mass/Mass Fuel Burned)

PAH Compound	Hardwood Pellets						Switchgrass Pellets					
	25% Load		Syracuse Cycle		100% Load		25% Load		Syracuse Cycle		100% Load	
	10/21/2016	10/25/2016	10/26/2016	10/27/2016	10/19/2016	10/20/2016	11/3/2016	11/4/2016	11/8/2016	11/9/2016	11/10/2016	11/15/2016
	mg/kg fuel	mg/kg fuel	mg/kg fuel	mg/kg fuel	mg/kg fuel	mg/kg fuel	mg/kg fuel	mg/kg fuel	mg/kg fuel	mg/kg fuel	mg/kg fuel	mg/kg fuel
Naphthalene	1.05E+01	4.53E+00	2.26E+00	1.97E+00	2.83E+00	3.90E-01	7.35E+00	9.10E+00	3.94E+01	4.97E+01	5.15E+00	1.69E+01
Acenapthylene	1.29E+00	4.68E+01	2.10E-01	9.90E-02	1.98E-01	1.88E-02	5.27E-01	6.36E-01	7.36E+00	5.72E+00	1.93E+00	5.85E+00
Acenaphthene	6.44E-02	4.12E+00	2.06E-02	7.34E-03	4.28E-02	1.07E-03	8.17E-02	9.75E-02	2.64E-01	4.30E-01	3.48E-02	9.48E-02
Flourene	2.53E-01	1.67E+01	5.81E-02	4.49E-02	4.34E-02	3.80E-03	5.73E-01	6.24E-01	2.58E+00	2.36E+00	1.78E-01	6.16E-01
Phenanthrene	1.53E+00	7.03E+01	4.67E-01	4.63E-01	5.78E-01	7.10E-02	1.09E+00	1.23E+00	6.91E+00	9.21E+00	1.24E+00	3.70E+00
Anthracene	3.17E-01	1.66E+01	4.14E-02	3.10E-02	2.27E-02	2.87E-03	1.86E-01	1.98E-01	9.38E-01	1.12E+00	1.04E-01	3.41E-01
Fluoranthene	3.50E-01	1.98E+01	2.15E-01	2.40E-01	3.46E-01	5.25E-02	2.97E-01	2.84E-01	2.54E+00	3.64E+00	9.52E-01	2.43E+00
Pyrene	3.50E-01	1.82E+01	2.34E-01	2.53E-01	3.91E-01	5.42E-02	3.14E-01	2.67E-01	2.35E+00	3.17E+00	1.09E+00	2.66E+00
Benzo(a)Anthracene	6.83E-02	2.72E+00	1.44E-02	1.23E-02	2.07E-02	4.42E-03	5.98E-02	6.20E-02	4.19E-01	4.50E-01	5.76E-02	1.34E-01
Chrysene	1.08E-01	4.74E+00	2.60E-02	3.03E-02	3.88E-02	8.35E-03	1.15E-01	1.09E-01	5.25E-01	7.35E-01	8.91E-02	2.29E-01
Benzo(b)Flouranthene	6.17E-02	1.62E+00	1.80E-02	1.37E-02	2.88E-02	4.27E-03	3.14E-02	3.62E-02	3.49E-01	4.17E-01	8.18E-02	2.51E-01
Benzo(k)flouranthene	6.66E-02	1.58E+00	2.15E-02	1.40E-02	2.47E-02	3.86E-03	3.34E-02	3.80E-02	3.79E-01	4.85E-01	8.49E-02	2.72E-01
Benzo(a)pyrene	7.49E-02	1.73E+00	1.75E-02	4.26E-03	1.98E-02	1.17E-03	2.36E-02	3.04E-02	2.90E-01	3.16E-01	5.70E-02	2.30E-01
Indeno(1,2,3-cd)pyrene	6.96E-02	1.27E+00	1.95E-02	8.54E-03	3.46E-02	2.74E-03	1.36E-02	1.69E-02	2.64E-01	2.88E-01	8.43E-02	2.99E-01
Dibenz(a,h)anthracene	6.29E-03	1.88E-01	1.21E-03	8.10E-04	9.56E-04	1.16E-04	2.70E-03	3.82E-03	3.30E-02	3.81E-02	4.15E-03	1.53E-02
Benzo(g,h,i)perylene	7.95E-02	1.15E+00	3.66E-02	1.48E-02	6.44E-02	4.80E-03	1.36E-02	1.65E-02	3.24E-01	3.46E-01	1.63E-01	4.38E-01
Totals	1.52E+01	2.12E+02	3.66E+00	3.20E+00	4.69E+00	6.24E-01	1.07E+01	1.27E+01	6.49E+01	7.84E+01	1.13E+01	3.44E+01

Table C-7. Test Average Speciated PAH Emission Factors (Mass/Heat Input)

PAH Compound	Hardwood Pellets						Switchgrass Pellets					
	25% Load		Syracuse Cycle		100% Load		25% Load		Syracuse Cycle		100% Load	
	10/21/2016	10/25/2016	10/26/2016	10/27/2016	10/19/2016	10/20/2016	11/3/2016	11/4/2016	11/8/2016	11/9/2016	11/10/2016	11/15/2016
	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input
Naphthalene	5.83E-01	2.52E-01	1.26E-01	1.09E-01	1.58E-01	2.17E-02	4.20E-01	5.20E-01	2.25E+00	2.84E+00	2.95E-01	9.65E-01
Acenapthylene	7.17E-02	2.60E+00	1.17E-02	5.51E-03	1.10E-02	1.04E-03	3.01E-02	3.63E-02	4.20E-01	3.27E-01	1.10E-01	3.35E-01
Acenaphthene	3.58E-03	2.29E-01	1.15E-03	4.08E-04	2.38E-03	5.98E-05	4.67E-03	5.58E-03	1.51E-02	2.46E-02	1.99E-03	5.42E-03
Flourene	1.41E-02	9.29E-01	3.23E-03	2.49E-03	2.41E-03	2.11E-04	3.27E-02	3.57E-02	1.47E-01	1.35E-01	1.02E-02	3.52E-02
Phenanthrene	8.51E-02	3.91E+00	2.60E-02	2.57E-02	3.21E-02	3.95E-03	6.23E-02	7.03E-02	3.95E-01	5.26E-01	7.10E-02	2.11E-01
Anthracene	1.76E-02	9.22E-01	2.30E-03	1.72E-03	1.26E-03	1.59E-04	1.06E-02	1.13E-02	5.36E-02	6.40E-02	5.95E-03	1.95E-02
Fluoranthene	1.94E-02	1.10E+00	1.20E-02	1.33E-02	1.93E-02	2.92E-03	1.70E-02	1.62E-02	1.45E-01	2.08E-01	5.44E-02	1.39E-01
Pyrene	1.95E-02	1.01E+00	1.30E-02	1.41E-02	2.17E-02	3.02E-03	1.79E-02	1.53E-02	1.35E-01	1.81E-01	6.25E-02	1.52E-01
Benzo(a)Anthracene	3.80E-03	1.51E-01	8.02E-04	6.85E-04	1.15E-03	2.46E-04	3.42E-03	3.55E-03	2.40E-02	2.57E-02	3.29E-03	7.67E-03
Chrysene	6.01E-03	2.63E-01	1.44E-03	1.69E-03	2.16E-03	4.65E-04	6.59E-03	6.24E-03	3.00E-02	4.20E-02	5.09E-03	1.31E-02
Benzo(b)Flouranthene	3.43E-03	9.01E-02	1.00E-03	7.60E-04	1.60E-03	2.37E-04	1.79E-03	2.07E-03	1.99E-02	2.38E-02	4.68E-03	1.43E-02
Benzo(k)flouranthene	3.70E-03	8.81E-02	1.20E-03	7.77E-04	1.37E-03	2.15E-04	1.91E-03	2.17E-03	2.16E-02	2.77E-02	4.85E-03	1.56E-02
Benzo(a)pyrene	4.16E-03	9.60E-02	9.74E-04	2.37E-04	1.10E-03	6.49E-05	1.35E-03	1.74E-03	1.66E-02	1.81E-02	3.26E-03	1.31E-02
Indeno(1,2,3-cd)pyrene	3.87E-03	7.04E-02	1.08E-03	4.75E-04	1.92E-03	1.53E-04	7.76E-04	9.66E-04	1.51E-02	1.65E-02	4.82E-03	1.71E-02
Dibenz(a,h)anthracene	3.50E-04	1.05E-02	6.75E-05	4.51E-05	5.32E-05	6.43E-06	1.54E-04	2.18E-04	1.88E-03	2.18E-03	2.37E-04	8.73E-04
Benzo(g,h,i)perylene	4.42E-03	6.38E-02	2.04E-03	8.22E-04	3.58E-03	2.67E-04	7.80E-04	9.43E-04	1.85E-02	1.98E-02	9.32E-03	2.50E-02
Totals	8.43E-01	1.18E+01	2.03E-01	1.78E-01	2.61E-01	3.47E-02	6.12E-01	7.29E-01	3.71E+00	4.48E+00	6.47E-01	1.97E+00

Table C-8. Test Average Speciated PAH Emission Factors (Mass/Heat Output)

	Hardwood Pellets						Switchgrass Pellets					
	25% Load		Syracuse Cycle		100% Load		25% Load		Syracuse Cycle		100% Load	
	10/21/2016	10/25/2016	10/26/2016	10/27/2016	10/19/2016	10/20/2016	11/3/2016	11/4/2016	11/8/2016	11/9/2016	11/10/2016	11/15/2016
Isomer	mg/MJ Output	mg/MJ Output	mg/MJ Output	mg/MJ Output	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input	mg/MJ Input
Naphthalene	1.28E+00	2.25E-01	1.18E-01	1.33E-01	1.36E-01	2.43E-02	6.17E-01	9.12E-01	2.97E+00	4.11E+00	3.86E-01	1.12E+00
Acenapthylene	1.58E-01	2.32E+00	1.10E-02	6.69E-03	9.53E-03	1.17E-03	4.43E-02	6.37E-02	5.55E-01	4.73E-01	1.45E-01	3.88E-01
Acenaphthene	7.87E-03	2.04E-01	1.07E-03	4.96E-04	2.06E-03	6.68E-05	6.86E-03	9.77E-03	1.99E-02	3.56E-02	2.61E-03	6.28E-03
Flourene	3.10E-02	8.29E-01	3.03E-03	3.03E-03	2.09E-03	2.36E-04	4.81E-02	6.25E-02	1.95E-01	1.96E-01	1.33E-02	4.08E-02
Phenanthrene	1.87E-01	3.49E+00	2.44E-02	3.12E-02	2.78E-02	4.41E-03	9.15E-02	1.23E-01	5.21E-01	7.61E-01	9.30E-02	2.45E-01
Anthracene	3.88E-02	8.22E-01	2.16E-03	2.09E-03	1.09E-03	1.78E-04	1.56E-02	1.98E-02	7.08E-02	9.26E-02	7.79E-03	2.26E-02
Fluoranthene	4.28E-02	9.82E-01	1.12E-02	1.62E-02	1.67E-02	3.26E-03	2.49E-02	2.84E-02	1.92E-01	3.01E-01	7.13E-02	1.61E-01
Pyrene	4.28E-02	9.05E-01	1.22E-02	1.71E-02	1.88E-02	3.37E-03	2.63E-02	2.67E-02	1.78E-01	2.62E-01	8.18E-02	1.76E-01
Benzo(a)Anthracene	8.36E-03	1.35E-01	7.52E-04	8.32E-04	9.98E-04	2.75E-04	5.02E-03	6.21E-03	3.17E-02	3.73E-02	4.31E-03	8.90E-03
Chrysene	1.32E-02	2.35E-01	1.35E-02	2.05E-03	1.87E-03	5.19E-04	9.68E-03	1.09E-02	3.96E-02	6.08E-02	6.67E-03	1.52E-02
Benzo(b)Flouranthene	7.55E-03	8.04E-02	9.41E-04	9.23E-04	1.39E-03	2.65E-04	2.63E-03	3.63E-03	2.63E-02	3.45E-02	6.13E-03	1.66E-02
Benzo(k)flouranthene	8.15E-03	7.86E-02	1.12E-03	9.43E-04	1.19E-03	2.40E-04	2.80E-03	3.80E-03	2.86E-02	4.01E-02	6.36E-03	1.80E-02
Benzo(a)pyrene	9.16E-03	8.56E-02	9.14E-04	2.88E-04	9.52E-04	7.25E-05	1.98E-03	3.05E-03	2.19E-02	2.62E-02	4.27E-03	1.52E-02
Indeno(1,2,3-cd)pyrene	8.51E-03	6.28E-02	1.02E-03	5.77E-04	1.66E-03	1.71E-04	1.14E-03	1.69E-03	1.99E-02	2.39E-02	6.31E-03	1.98E-02
Dibenz(a,h)anthracene	7.69E-04	9.33E-03	6.33E-05	5.47E-05	4.60E-05	7.18E-06	2.27E-04	3.83E-04	2.49E-03	3.15E-03	3.11E-04	1.01E-03
Benzo(g,h,i)perylene	9.72E-03	5.69E-02	1.91E-03	9.98E-04	3.10E-03	2.98E-04	1.15E-03	1.65E-03	2.45E-02	2.86E-02	1.22E-02	2.90E-02
Totals	1.85E+00	1.05E+01	1.91E-01	2.16E-01	2.26E-01	3.88E-02	8.99E-01	1.28E+00	4.90E+00	6.49E+00	8.47E-01	2.28E+00

Table C-9. Composite Speciated PCDD/PCDF Emission Factors (Mass/Mass Fuel Burned)

Isomer	Hardwood Pellets			Switchgrass Pellets		
	25% Load	Syracuse Cycle	100% Load	25% Load	Syracuse Cycle	100% Load
	ng TEQ/kg fuel	ng TEQ/kg fuel	ng TEQ/kg fuel	ng TEQ/kg fuel	ng TEQ/kg fuel	ng TEQ/kg fuel
2,3,7,8 - TCDD	0.027	0.020	0.062	0.036	0.084	0.022
1,2,3,7,8 - PeCDD	0.042	0.019	0.063	0.089	0.168	0.024
1,2,3,4,7,8 - HxCDD	0.001	0.000	0.001	0.002	0.004	0.000
1,2,3,6,7,8 - HxCDD	0.003	0.001	0.001	0.011	0.013	0.001
1,2,3,7,8,9 - HxCDD	0.002	0.000	0.001	0.006	0.008	0.000
1,2,3,4,6,7,8 - HpCDD	0.002	0.000	0.000	0.005	0.006	0.000
1,2,3,4,6,7,8,9 - OCDD	0.000	0.000	0.000	0.001	0.001	0.000
2,3,7,8 - TCDF	0.039	0.026	0.088	0.029	0.079	0.031
1,2,3,7,8 - PeCDF	0.003	0.002	0.008	0.003	0.006	0.002
2,3,4,7,8 - PeCDF	0.030	0.020	0.079	0.026	0.064	0.019
1,2,3,4,7,8 - HxCDF	0.003	0.001	0.005	0.003	0.005	0.001
1,2,3,6,7,8 - HxCDF	0.004	0.002	0.006	0.003	0.007	0.002
1,2,3,7,8,9 - HxCDF	0.000	0.000	0.001	0.001	0.001	0.000
2,3,4,6,7,8 - HxCDF	0.002	0.001	0.005	0.003	0.006	0.001
1,2,3,4,6,7,8 - HpCDF	0.000	0.000	0.001	0.003	0.002	0.000
1,2,3,4,7,8,9 - HpCDF	0.000	0.000	0.000	0.000	0.000	0.000
1,2,3,4,6,7,8,9 - OCDF	0.000	0.000	0.000	0.001	0.001	0.000
Totals	0.158	0.093	0.320	0.223	0.455	0.105

Table C-10. Composite Speciated PCDD/PCDF Emission Factors (Mass/Heat Input)

	Hardwood Pellets						Switchgrass Pellets					
	25% Load		Syracuse Cycle		100% Load		25% Load		Syracuse Cycle		100% Load	
Isomer	ng TEQ/MJ	lb/MMBTU	ng TEQ/MJ	lb/MMBTU	ng TEQ/MJ	lb/MMBTU	ng TEQ/MJ	lb/MMBTU	ng TEQ/MJ	lb/MMBTU	ng TEQ/MJ	lb/MMBTU
2,3,7,8 - TCDD	1.50E-03	3.48E-12	1.09E-03	2.53E-12	3.44E-03	7.99E-12	2.05E-03	4.77E-12	4.78E-03	1.11E-11	1.23E-03	2.8636E-12
1,2,3,7,8 - PeCDD	2.35E-03	5.47E-12	1.08E-03	2.51E-12	3.51E-03	8.15E-12	5.11E-03	1.19E-11	9.62E-03	2.23E-11	1.40E-03	3.2474E-12
1,2,3,4,7,8 - HxCDD	5.35E-05	1.24E-13	1.39E-05	3.22E-14	4.12E-05	9.57E-14	1.25E-04	2.90E-13	2.07E-04	4.80E-13	2.03E-05	4.7234E-14
1,2,3,6,7,8 - HxCDD	1.57E-04	3.66E-13	2.85E-05	6.61E-14	8.15E-05	1.89E-13	6.04E-04	1.40E-12	7.56E-04	1.75E-12	4.32E-05	1.0037E-13
1,2,3,7,8,9 - HxCDD	9.40E-05	2.18E-13	1.67E-05	3.87E-14	4.53E-05	1.05E-13	3.58E-04	8.32E-13	4.70E-04	1.09E-12	2.16E-05	5.0186E-14
1,2,3,4,6,7,8 - HpCDD	1.10E-04	2.54E-13	8.19E-06	1.90E-14	1.87E-05	4.34E-14	3.01E-04	6.99E-13	3.41E-04	7.91E-13	1.28E-05	2.9817E-14
1,2,3,4,6,7,8,9 - OCDD	9.77E-06	2.27E-14	8.50E-07	1.97E-15	1.37E-06	3.19E-15	5.32E-05	1.24E-13	4.48E-05	1.04E-13	2.07E-06	4.809E-15
2,3,7,8 - TCDF	2.15E-03	5.00E-12	1.45E-03	3.36E-12	4.87E-03	1.13E-11	1.68E-03	3.91E-12	4.49E-03	1.04E-11	1.79E-03	4.1684E-12
1,2,3,7,8 - PeCDF	1.93E-04	4.48E-13	1.12E-04	2.61E-13	4.30E-04	9.99E-13	1.47E-04	3.42E-13	3.40E-04	7.90E-13	1.05E-04	2.4444E-13
2,3,4,7,8 - PeCDF	1.66E-03	3.86E-12	1.11E-03	2.57E-12	4.39E-03	1.02E-11	1.51E-03	3.51E-12	3.68E-03	8.54E-12	1.11E-03	2.5684E-12
1,2,3,4,7,8 - HxCDF	1.51E-04	3.50E-13	6.87E-05	1.60E-13	2.70E-04	6.28E-13	1.53E-04	3.55E-13	3.07E-04	7.12E-13	7.50E-05	1.7418E-13
1,2,3,6,7,8 - HxCDF	2.02E-04	4.69E-13	9.16E-05	2.13E-13	3.56E-04	8.27E-13	1.97E-04	4.58E-13	3.92E-04	9.10E-13	9.53E-05	2.2141E-13
1,2,3,7,8,9 - HxCDF	2.60E-05	6.04E-14	1.87E-05	4.35E-14	6.84E-05	1.59E-13	4.43E-05	1.03E-13	7.13E-05	1.66E-13	1.78E-05	4.133E-14
2,3,4,6,7,8 - HxCDF	1.10E-04	2.56E-13	7.08E-05	1.64E-13	2.61E-04	6.07E-13	1.81E-04	4.21E-13	3.28E-04	7.61E-13	6.99E-05	1.6237E-13
1,2,3,4,6,7,8 - HpCDF	2.24E-05	5.20E-14	1.05E-05	2.43E-14	3.02E-05	7.01E-14	1.96E-04	4.54E-13	1.01E-04	2.35E-13	1.04E-05	2.4208E-14
1,2,3,4,7,8,9 - HpCDF	2.45E-06	5.68E-15	1.46E-06	3.39E-15	3.22E-06	7.47E-15	9.66E-06	2.24E-14	1.07E-05	2.48E-14	1.53E-06	3.5426E-15
1,2,3,4,6,7,8,9 - OCDF	3.82E-06	8.87E-15	1.14E-06	2.64E-15	1.95E-06	4.54E-15	4.22E-05	9.80E-14	4.87E-05	1.13E-13	2.60E-06	6.0401E-15
Totals	8.80E-03	2.04E-11	5.17E-03	1.20E-11	1.78E-02	4.14E-11	1.28E-02	2.97E-11	2.60E-02	6.03E-11	6.01E-03	1.3958E-11

Table C-11. Composite Speciated PCDD/PCDF Emission Factors (Mass/Heat Output)

	Hardwood Pellets						Switchgrass Pellets					
	25% Load		Syracuse Cycle		100% Load		25% Load		Syracuse Cycle		100% Load	
Isomer	ng TEQ/MJ	lb/MMBTU	ng TEQ/MJ	lb/MMBTU	ng TEQ/MJ	lb/MMBTU	ng TEQ/MJ	lb/MMBTU	ng TEQ/MJ	lb/MMBTU	ng TEQ/MJ	lb/MMBTU
2,3,7,8 - TCDD	2.32E-03	5.38E-12	1.17E-03	2.72E-12	3.84E-03	8.93E-12	3.31E-03	7.68E-12	6.61E-03	1.53E-11	1.52E-03	3.54E-12
1,2,3,7,8 - PeCDD	3.64E-03	8.46E-12	1.17E-03	2.71E-12	3.92E-03	9.11E-12	8.23E-03	1.91E-11	1.33E-02	3.09E-11	1.73E-03	4.01E-12
1,2,3,4,7,8 - HxCDD	8.28E-05	1.92E-13	1.49E-05	3.47E-14	4.61E-05	1.07E-13	2.01E-04	4.67E-13	2.86E-04	6.64E-13	2.51E-05	5.83E-14
1,2,3,6,7,8 - HxCDD	2.44E-04	5.66E-13	3.06E-05	7.12E-14	9.10E-05	2.11E-13	9.72E-04	2.26E-12	1.05E-03	2.43E-12	5.34E-05	1.24E-13
1,2,3,7,8,9 - HxCDD	1.46E-04	3.38E-13	1.79E-05	4.17E-14	5.06E-05	1.17E-13	5.77E-04	1.34E-12	6.51E-04	1.51E-12	2.67E-05	6.20E-14
1,2,3,4,6,7,8 - HpCDD	1.70E-04	3.94E-13	8.82E-06	2.05E-14	2.09E-05	4.85E-14	4.85E-04	1.13E-12	4.71E-04	1.09E-12	1.59E-05	3.68E-14
1,2,3,4,6,7,8,9 - OCDD	1.51E-05	3.51E-14	9.15E-07	2.12E-15	1.53E-06	3.56E-15	8.57E-05	1.99E-13	6.19E-05	1.44E-13	2.56E-06	5.94E-15
2,3,7,8 - TCDF	3.33E-03	7.73E-12	1.56E-03	3.61E-12	5.44E-03	1.26E-11	2.71E-03	6.29E-12	6.21E-03	1.44E-11	2.22E-03	5.15E-12
1,2,3,7,8 - PeCDF	2.98E-04	6.93E-13	1.21E-04	2.81E-13	4.81E-04	1.12E-12	2.37E-04	5.51E-13	4.70E-04	1.09E-12	1.30E-04	3.02E-13
2,3,4,7,8 - PeCDF	2.57E-03	5.98E-12	1.19E-03	2.76E-12	4.90E-03	1.14E-11	2.43E-03	5.65E-12	5.09E-03	1.18E-11	1.37E-03	3.17E-12
1,2,3,4,7,8 - HxCDF	2.33E-04	5.41E-13	7.40E-05	1.72E-13	3.02E-04	7.02E-13	2.46E-04	5.72E-13	4.24E-04	9.85E-13	9.26E-05	2.15E-13
1,2,3,6,7,8 - HxCDF	3.12E-04	7.25E-13	9.86E-05	2.29E-13	3.98E-04	9.24E-13	3.18E-04	7.38E-13	5.42E-04	1.26E-12	1.18E-04	2.73E-13
1,2,3,7,8,9 - HxCDF	4.02E-05	9.34E-14	2.02E-05	4.69E-14	7.64E-05	1.77E-13	7.13E-05	1.66E-13	9.86E-05	2.29E-13	2.20E-05	5.10E-14
2,3,4,6,7,8 - HxCDF	1.70E-04	3.96E-13	7.62E-05	1.77E-13	2.92E-04	6.79E-13	2.92E-04	6.77E-13	4.54E-04	1.05E-12	8.63E-05	2.00E-13
1,2,3,4,6,7,8 - HpCDF	3.47E-05	8.05E-14	1.13E-05	2.62E-14	3.37E-05	7.83E-14	3.15E-04	7.32E-13	1.40E-04	3.25E-13	1.29E-05	2.99E-14
1,2,3,4,7,8,9 - HpCDF	3.79E-06	8.79E-15	1.57E-06	3.64E-15	3.60E-06	8.35E-15	1.56E-05	3.61E-14	1.48E-05	3.43E-14	1.88E-06	4.37E-15
1,2,3,4,6,7,8,9 - OCDF	5.91E-06	1.37E-14	1.22E-06	2.84E-15	2.18E-06	5.07E-15	6.79E-05	1.58E-13	6.74E-05	1.56E-13	3.21E-06	7.46E-15
Totals	1.36E-02	3.16E-11	5.56E-03	1.29E-11	1.99E-02	4.62E-11	2.06E-02	4.78E-11	3.59E-02	8.35E-11	7.42E-03	1.72E-11

APPENDIX D

Particle-Phase Emission Factors

Table D-1. Test Average Total PM Mass Emissions and Thermal Efficiency Summary (ASTM 2515)

Test Condition	Date	Average Efficiency	Total PM EF lb/MMBTU Input	Total PM EF g/MJ Input	Total PM EF lb/MMBTU Output	Total PM EF g/MJ Output	Total PM EF g/kg fuel
Hardwood - Full Load	10/19/2016	89.5%	5.46E-02	2.35E-02	4.72E-02	2.03E-02	4.23E-01
Hardwood - Full Load	10/20/2016		4.89E-02	2.11E-02	5.47E-02	2.35E-02	3.79E-01
Hardwood - Low Load	10/21/2016	78.8%	3.72E-01	1.60E-01	8.18E-01	3.52E-01	2.88E+00
Hardwood - Low Load	10/25/2016		3.80E-01	1.63E-01	3.39E-01	1.46E-01	2.94E+00
Hardwood - Syracuse	10/26/2016	94.5%	3.92E-02	1.69E-02	3.67E-02	1.58E-02	3.03E-01
Hardwood - Syracuse	10/27/2016		3.04E-02	1.31E-02	3.69E-02	1.59E-02	2.36E-01
Switchgrass - Low Load	11/3/2016	62.6%	2.03E-01	8.74E-02	2.98E-01	1.28E-01	1.53E+00
Switchgrass - Low Load	11/4/2016		1.43E-01	6.14E-02	2.50E-01	1.08E-01	1.07E+00
Switchgrass - Syracuse	11/8/2016	72.4%	1.13E-01	4.86E-02	1.49E-01	6.42E-02	8.50E-01
Switchgrass - Syracuse	11/9/2016		8.92E-02	3.84E-02	1.29E-01	5.56E-02	6.72E-01
Switchgrass - Full Load	11/10/2016	81.3%	7.04E-02	3.03E-02	9.23E-02	3.97E-02	5.31E-01
Switchgrass - Full Load	11/15/2016		1.05E-01	4.53E-02	1.22E-01	5.26E-02	7.93E-01

Table D-2. Test Average Total PM Mass Emissions Summary (Teflon Filters)

Test Condition	Date	Average TP Emission Factor		
		g/MJ Input	g/MJ Output	g/kg fuel
Hardwood - Full Load	10/19/2016	Void	Void	Void
Hardwood - Full Load	10/20/2016	9.90E-03	1.11E-02	1.78E-01
Hardwood - Low Load	10/21/2016	1.15E-01	2.53E-01	2.07E+00
Hardwood - Low Load	10/25/2016	2.18E-01	1.94E-01	3.92E+00
Hardwood - Syracuse	10/26/2016	1.10E-02	1.03E-02	1.98E-01
Hardwood - Syracuse	10/27/2016	8.90E-03	1.08E-02	1.60E-01
Switchgrass - Low Load	11/3/2016	5.50E-02	8.08E-02	9.63E-01
Switchgrass - Low Load	11/4/2016	9.47E-02	1.66E-01	1.66E+00
Switchgrass - Syracuse	11/8/2016	3.07E-02	4.05E-02	5.36E-01
Switchgrass - Syracuse	11/9/2016	5.45E-02	7.88E-02	9.53E-01
Switchgrass - Full Load	11/10/2016	2.42E-02	3.17E-02	4.24E-01
Switchgrass - Full Load	11/15/2016	5.53E-02	6.41E-02	9.67E-01

Table D-3. Test Average PM Number Emissions Summary (ELPI)

Test Condition	Date	Emission Factor part/MMBTU Input	Standard Deviation part/MMBTU Input	Emission Factor part/MJ Input	Standard Deviation part/MJ Input	Emission Factor part/MMBTU Out	Standard Deviation part/MMBTU Out	Emission Factor part/MJ Output	Standard Deviation part/MJ Output	Emission Factor part/kg fuel	Standard Deviation part/kg fuel
Hardwood - Full Load	10/19/2016	4.25E+15	1.76E+15	4.03E+12	1.67E+12	3.68E+15	1.52E+15	3.49E+12	1.44E+12	7.24E+13	1.61E+06
Hardwood - Full Load	10/20/2016	3.70E+15	1.10E+15	3.51E+12	1.05E+12	4.13E+15	1.23E+15	3.92E+12	1.17E+12	6.31E+13	4.23E+06
Hardwood - Low Load	10/21/2016	7.20E+15	4.80E+15	6.83E+12	4.55E+12	1.58E+16	1.06E+16	1.50E+13	1.00E+13	1.23E+14	2.33E+05
Hardwood - Low Load	10/25/2016	1.70E+16	1.25E+16	1.62E+13	1.19E+13	1.52E+16	1.12E+16	1.44E+13	1.06E+13	2.91E+14	1.45E+04
Hardwood - Syracuse	10/26/2016	4.92E+15	5.25E+15	4.67E+12	4.98E+12	4.62E+15	4.92E+15	4.38E+12	4.67E+12	8.39E+13	1.14E+05
Hardwood - Syracuse	10/27/2016	4.05E+15	4.02E+15	3.84E+12	3.81E+12	4.91E+15	4.88E+15	4.66E+12	4.62E+12	6.90E+13	2.51E+05
Switchgrass - Low Load	11/3/2016	1.48E+16	7.45E+15	1.40E+13	7.07E+12	2.17E+16	1.09E+16	2.06E+13	1.04E+13	2.45E+14	6.60E+04
Switchgrass - Low Load	11/4/2016	1.29E+16	6.23E+15	1.23E+13	5.91E+12	2.27E+16	1.09E+16	2.15E+13	1.03E+13	2.15E+14	1.11E+05
Switchgrass - Syracuse	11/8/2016	6.72E+15	4.95E+15	6.37E+12	4.69E+12	8.87E+15	6.54E+15	8.41E+12	6.20E+12	1.11E+14	2.54E+05
Switchgrass - Syracuse	11/9/2016	1.11E+16	1.12E+16	1.05E+13	1.06E+13	1.61E+16	1.62E+16	1.52E+13	1.54E+13	1.84E+14	1.30E+05
Switchgrass - Full Load	11/10/2016	3.78E+15	1.03E+15	3.59E+12	9.76E+11	4.95E+15	1.35E+15	4.70E+12	1.28E+12	6.27E+13	6.54E+06
Switchgrass - Full Load	11/15/2016	4.88E+15	1.01E+15	4.62E+12	9.58E+11	5.65E+15	1.17E+15	5.36E+12	1.11E+12	8.09E+13	5.18E+06

Table D-4. Test Average Elemental Carbon Emissions Summary (Manual NIOSH 5040)

Test Condition	Date	Test Average Elemental Carbon					
		Average EC lb/MMBTU Input	Standard Dev. lb/MMBTU Input	Average EC lb/MMBTU Out	Standard Dev. lb/MMBTU Out	Average EC mg/kg fuel	Standard Dev. mg/kg fuel
Hardwood - 100% Load	10/19/2016	1.72E-02	1.00E-02	1.49E-02	8.68E-03	1.33E+02	7.77E+01
Hardwood - 100% Load	10/20/2016	6.07E-03	1.41E-03	6.78E-03	1.57E-03	4.70E+01	1.09E+01
Hardwood - 25% Load	10/21/2016	2.01E-03	6.76E-04	4.41E-03	1.49E-03	1.55E+01	5.23E+00
Hardwood - 25% Load	10/25/2016	3.16E-03	1.08E-03	2.82E-03	9.67E-04	2.44E+01	8.39E+00
Hardwood - Syracuse	10/26/2016	7.07E-04	1.06E-04	6.63E-04	9.97E-05	5.48E+00	8.23E-01
Hardwood - Syracuse	10/27/2016	1.93E-03	2.06E-03	2.35E-03	2.50E-03	1.50E+01	1.60E+01
Switchgrass - 25% Load	11/3/2016	1.65E-03	2.40E-04	2.43E-03	3.53E-04	1.24E+01	1.81E+00
Switchgrass - 25% Load	11/4/2016	1.30E-03	2.32E-04	2.29E-03	4.06E-04	9.83E+00	1.75E+00
Switchgrass - Syracuse	11/8/2016	1.45E-02	1.54E-02	1.91E-02	2.04E-02	1.09E+02	1.16E+02
Switchgrass - Syracuse	11/9/2016	7.76E-03	4.05E-03	1.12E-02	5.86E-03	5.84E+01	3.05E+01
Switchgrass - 100% Load	11/10/2016	3.01E-02	8.14E-03	3.94E-02	1.07E-02	2.26E+02	6.13E+01
Switchgrass - 100% Load	11/15/2016	4.74E-02	3.34E-03	5.49E-02	3.87E-03	3.57E+02	2.51E+01

Table D-5. Test Average Organic Carbon Emissions Summary (Manual NIOSH 5040)

Test Condition	Date	Test Average Organic Carbon					
		Average OC	Standard Dev.	Average OC	Standard Dev.	Average OC	Standard Dev.
		lb/MMBTU Input	lb/MMBTU Input	lb/MMBTU Out	lb/MMBTU Out	mg/kg fuel	mg/kg fuel
Hardwood - 100% Load	10/19/2016	4.61E-04	NA	3.99E-04	NA	3.57E+00	
Hardwood - 100% Load	10/20/2016	ND		ND		ND	
Hardwood - 25% Load	10/21/2016	1.07E-01	5.68E-02	2.36E-01	1.25E-01	8.29E+02	4.40E+02
Hardwood - 25% Load	10/25/2016	1.70E-01	8.29E-02	1.52E-01	7.40E-02	1.32E+03	6.42E+02
Hardwood - Syracuse	10/26/2016	6.89E-03	1.35E-03	6.46E-03	1.27E-03	5.33E+01	1.05E+01
Hardwood - Syracuse	10/27/2016	1.66E-03	2.35E-03	2.01E-03	2.85E-03	1.28E+01	1.82E+01
Switchgrass - 25% Load	11/3/2016	8.35E-02	2.39E-02	1.23E-01	3.51E-02	6.29E+02	1.80E+02
Switchgrass - 25% Load	11/4/2016	6.82E-02	2.47E-02	1.20E-01	4.34E-02	5.14E+02	1.86E+02
Switchgrass - Syracuse	11/8/2016	6.20E-02	7.60E-02	8.18E-02	1.00E-01	4.67E+02	5.73E+02
Switchgrass - Syracuse	11/9/2016	4.20E-02	2.87E-02	6.08E-02	4.15E-02	3.16E+02	2.16E+02
Switchgrass - 100% Load	11/10/2016	3.55E-03	1.87E-03	4.66E-03	2.44E-03	2.68E+01	1.41E+01
Switchgrass - 100% Load	11/15/2016	1.31E-02	5.10E-03	1.52E-02	5.92E-03	9.87E+01	3.84E+01

Table D-6. Test Average Optical Black Carbon Summary (Aethalometer)

Test Condition	Date	Test Average Emission Factors					
		Average BC	Standard Deviation	Average BC	Standard Deviation	Average BC	Standard Deviation
		g/MJ Input	g/MJ Input	g/MJ Output	g/MJ Output	g/kg fuel	g/kg fuel
Hardwood - Full Load	10/19/2016	1.21E-02	1.54E-02	1.05E-02	1.34E-02	2.18E-01	2.78E-01
Hardwood - Full Load	10/20/2016	7.90E-03	7.60E-03	8.83E-03	8.50E-03	1.42E-01	1.37E-01
Hardwood - Low Load	10/21/2016	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Void	
Hardwood - Low Load	10/25/2016	8.08E-03	4.74E-02	7.21E-03	4.23E-02	1.45E-01	8.53E-01
Hardwood - Syracuse	10/26/2016	2.20E-03	1.20E-02	2.06E-03	1.13E-02	3.96E-02	2.16E-01
Hardwood - Syracuse	10/27/2016	1.03E-03	3.11E-03	1.25E-03	3.77E-03	1.86E-02	5.59E-02
Switchgrass - Low Load	11/3/2016	3.74E-03	1.23E-02	5.49E-03	1.80E-02	6.54E-02	2.14E-01
Switchgrass - Low Load	11/4/2016	3.38E-03	2.08E-02	5.93E-03	3.65E-02	5.92E-02	3.64E-01
Switchgrass - Syracuse	11/8/2016	1.03E-02	2.39E-02	1.35E-02	3.15E-02	1.79E-01	4.18E-01
Switchgrass - Syracuse	11/9/2016	8.30E-03	2.00E-02	1.20E-02	2.89E-02	1.45E-01	3.50E-01
Switchgrass - Full Load	11/10/2016	2.09E-02	2.96E-02	2.74E-02	3.87E-02	3.65E-01	5.17E-01
Switchgrass - Full Load	11/15/2016	2.71E-02	3.63E-02	3.14E-02	4.21E-02	4.74E-01	6.35E-01

Table D-7. Test Average Emission Factors for Selected and Toxic Metals (XRF)

Load	Fuel	Date	Sample No.	Element Mass/Mass Total PM (ug/ug)					Average Element Mass/Mass Total PM (ug/ug)									
									Sulfur		Chlorine		Chromium		Manganese		Lead	
				S	Cl	Cr	Mn	Pb	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
100%	Wood	10/19/2016	1	Void	Void	Void	Void	Void										
			2	Void	Void	Void	Void	Void										
			3	Void	Void	Void	Void	Void										
		10/20/2016	1	9.38E-02	1.11E-02	2.22E-05	5.74E-05	1.70E-04										
			2	1.30E-01	8.45E-03	2.68E-06	5.86E-05	1.00E-04										
			3	1.19E-01	1.58E-02	1.42E-05	1.05E-04	2.14E-04	1.14E-01	1.86E-02	8.35E-02	6.69E-02	8.61E-05	6.72E-05	5.34E-04	4.63E-04	1.14E-03	9.07E-04
25%	Wood	10/21/2016	1	1.98E-02	1.53E-03	3.83E-06	4.29E-05	0.00E+00										
			2	1.94E-04	1.76E-03	1.03E-05	5.09E-05	0.00E+00										
			3	3.09E-02	2.90E-04	1.15E-06	7.16E-05	0.00E+00	1.70E-02	1.55E-02	1.01E-02	1.20E-02	5.17E-05	7.50E-05	2.96E-04	3.42E-04	0.00E+00	
		10/25/2016	1	1.35E-01	4.90E-03	7.92E-05	9.76E-05	2.56E-04										
			2	8.78E-04	7.59E-04	2.68E-06	2.33E-05	3.37E-05										
			3	Void	Void	Void	Void	Void	6.77E-02	9.46E-02	6.19E-02	6.84E-02	9.16E-04	1.23E-03	1.31E-03	1.26E-03	3.19E-03	3.66E-03
Syracuse	Wood	10/26/2016	1	9.36E-02	7.78E-03	1.42E-05	1.52E-04	1.91E-04										
			2	5.46E-02	1.25E-03	2.68E-06	6.39E-05	6.24E-05										
			3	2.88E-02	9.46E-04	1.03E-05	7.69E-05	0.00E+00	5.90E-02	3.26E-02	6.39E-03	6.34E-03	5.08E-05	7.63E-05	4.54E-04	5.26E-04	1.08E-04	1.86E-04
		10/27/2016	1	9.34E-02	5.54E-03	1.15E-06	1.33E-04	1.13E-04										
			2	6.51E-02	1.05E-03	6.51E-05	7.54E-05	0.00E+00										
			3	4.73E-02	1.19E-02	3.90E-05	2.19E-04	3.80E-04	6.86E-02	2.33E-02	1.05E-01	1.27E-01	4.30E-04	4.03E-04	2.17E-03	2.12E-03	3.05E-03	4.28E-03
25%	Grass	11/3/2016	1	Void	Void	Void	Void	Void										
			2	4.04E-03	6.41E-04	4.82E-05	0.00E+00	0.00E+00										
			3	2.99E-03	3.58E-03	1.30E-05	1.04E-04	0.00E+00	3.51E-03	7.41E-04	5.22E-03	7.39E-03	1.90E-05	2.69E-05	1.52E-04	2.15E-04	0.00E+00	0.00E+00
		11/7/2016	1	8.22E-03	1.79E-02	5.59E-05	3.90E-05	3.50E-04										
			2	7.17E-03	1.30E-02	5.47E-05	8.84E-05	3.13E-04										
			3	1.68E-03	4.42E-03	3.25E-03	2.74E-04	5.59E-05	5.69E-03	3.51E-03	8.29E-03	5.81E-03	7.20E-04	1.18E-03	8.64E-05	7.83E-05	1.67E-04	1.24E-04
Syracuse	Grass	11/8/2016	1	5.34E-02	7.08E-03	2.40E-04	2.72E-05	1.83E-04										
			2	1.53E-02	3.17E-02	0.00E+00	1.84E-05	7.00E-04										
			3	2.06E-03	2.32E-03	0.00E+00	3.14E-05	0.00E+00	2.36E-02	2.66E-02	9.20E-02	1.55E-01	3.50E-05	6.06E-05	6.56E-05	7.94E-05	2.02E-03	3.43E-03
		11/9/2016	1	4.88E-03	3.37E-03	6.51E-06	0.00E+00	5.97E-05										
			2	2.09E-03	2.34E-02	1.34E-04	3.79E-05	4.22E-04										
			3	9.89E-04	2.14E-03	1.37E-03	1.07E-04	0.00E+00	8.94E-03	1.06E-02	1.11E-02	1.23E-02	8.37E-04	1.32E-03	7.51E-05	9.68E-05	1.78E-04	2.45E-04
100%	Grass	11/10/2016	1	9.01E-03	4.13E-02	1.31E-04	3.64E-05	4.41E-04										
			2	1.65E-02	4.28E-02	0.00E+00	4.29E-05	3.11E-04										
			3	1.07E-02	3.72E-02	1.19E-05	6.51E-06	3.15E-04	1.21E-02	3.94E-03	6.93E-02	4.95E-02	3.58E-05	3.46E-05	3.54E-05	2.65E-05	5.77E-04	4.03E-04
		11/15/2016	1	Void	Void	Void	Void	Void										
			2	Void	Void	Void	Void	Void										
			3	6.71E-03	4.41E-02	2.33E-05	4.02E-05	4.62E-04	6.71E-03		4.84E-02		2.57E-05		4.42E-05		5.08E-04	

Specific data for all elements measured are available electronically upon request.

Table D-8. Test Average Particle-Phase SVOC Summary (GC/MS)

Pellet Type	Test Condition	Date	Test Average SVOC Emission Factors				
			lb/MMBTU Input	mg/MJ Input	lb/MMBTU Output	mg/MJ Output	mg/kg fuel
Wood	Full load	10/19/2017	8.26E-05	3.56E-02	7.15E-05	3.08E-02	6.40E-01
	Full load	10/20/2017	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Wood	Low load	10/21/2017	4.48E-02	1.93E+01	9.86E-02	4.25E+01	3.47E+02
	Low load	10/25/2017	6.85E-02	2.95E+01	6.11E-02	2.63E+01	5.30E+02
Wood	Syracuse load	10/26/2017	6.75E-04	2.91E-01	6.34E-04	2.73E-01	5.23E+00
	Syracuse load	10/27/2017	2.80E-04	1.21E-01	3.41E-04	1.47E-01	2.17E+00
Grass	Low load	11/3/2017	1.72E-02	7.39E+00	2.52E-02	1.09E+01	1.29E+02
	Low load	11/4/2017	1.58E-02	6.81E+00	2.77E-02	1.19E+01	1.19E+02
Grass	Syracuse load	11/8/2017	1.29E-02	5.55E+00	1.70E-02	7.32E+00	9.70E+01
	Syracuse load	11/9/2017	8.19E-03	3.53E+00	1.19E-02	5.10E+00	6.17E+01
Grass	Full load	11/10/2017	5.12E-04	2.20E-01	6.70E-04	2.89E-01	3.85E+00
	Full load	11/15/2017	1.92E-03	8.27E-01	2.23E-03	9.59E-01	1.45E+01

Compound-specific emission factors are available electronically upon request.