Evaluation of the Energy and Emissions Performance of Commercial Scale Advanced Wood Combustion Systems

Final Report 10-15
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Evaluation of the Energy and Emissions Performance of Commercial Scale Advanced Wood Combustion Systems

Final Report

Prepared for the

New York State Energy Research and Development Authority

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NOTICE

Preface

The New York State Energy Research and Development Authority (NYSERDA) is pleased to publish the summary report, "Evaluation of the Energy, Emissions, and Performance from Commercial-Scale Advanced Wood Combustion Systems." The report was prepared by Clarkson University based on four research projects they conducted to evaluate the performance of staged-combustion biomass heating systems. One of these systems is the first made-in-NY commercial staged-combustion pellet boiler that was manufactured by Advanced Climate Technologies Bioenergy of Schenectady, NY under a separate NYSERDA contract. The Biomass Heating Program is a joint effort of the Environmental R&D and Buildings R&D Programs to develop a high-efficiency biomass heating market of technologies with acceptable emissions performance in New York State.

Acknowledgements

The research described in this report was supported by NYSERDA under contracts 10672, 10668, 11166, and 18127. NYSERDA gratefully acknowledges the technical insight and cooperation of David Dungate of Advanced Climate Technologies, Chris Rdzanek of The Wild Center/Natural History Museum of the Adirondacks, Lisa Rector of the Northeast States for Coordinated Air Use Management (NESCAUM), and Dr. Thomas Butcher of Brookhaven National Laboratory.

EXECUTIVE SUMMARY

Characterization of Three High Efficiency Wood Boilers

Gaseous and particle emission measurements were performed for two high-efficiency wood boilers manufactured by Hamont Consulting and Engineering, Austria, and one high-efficiency wood boiler manufactured domestically in New York based on designs purchased from Hamont. Emission measurements on a 150kW boiler burning premium wood pellets were conducted at Clarkson University's Walker Center between 2009 and 2010; another identical 150 kW boiler burning wood chips was tested at the Advanced Climate Technologies LLC plant in Schenectady during June 2009, and a 500 kW boiler burning premium wood pellets was tested at The Wild Center located in Tupper Lake, NY during April 2010.

The Hamont CATfire boilers (150 and 500 kW) use a triple air staging process that ensures complete combustion of the fuel. Figure ES1 shows an illustration of the fuel feed auger, ash auger and combustion zones of the Hamont boiler.

Air staging is accomplished by injecting primary air into the fuel bed at a low air to fuel ratio (λ) to de-volatilize but not combust the fuel. Secondary and tertiary air streams are injected at higher λ values to burn the pyrolysis gases and achieve complete combustion. In order to ensure optimum excess air delivery into the different combustion stages, the boiler was equipped with an accurate process control system that monitors pressure and oxygen levels in the combustion chamber and adjusts fuel feeding rate and various fan speeds to optimize combustion.

During the first stage, the fuel is heated to around 400ºC (750ºF), and in the second and third stages, air is tangentially injected into the combustion zone to reach temperatures up to 1100ºC (2000ºF). Because of good mixing of combustion air with pyrolysis gases, the boiler operates at low excess air levels, thus enabling the boiler to operate at higher temperatures in the combustion zone with high combustion efficiency (Nussbaumer 2003).

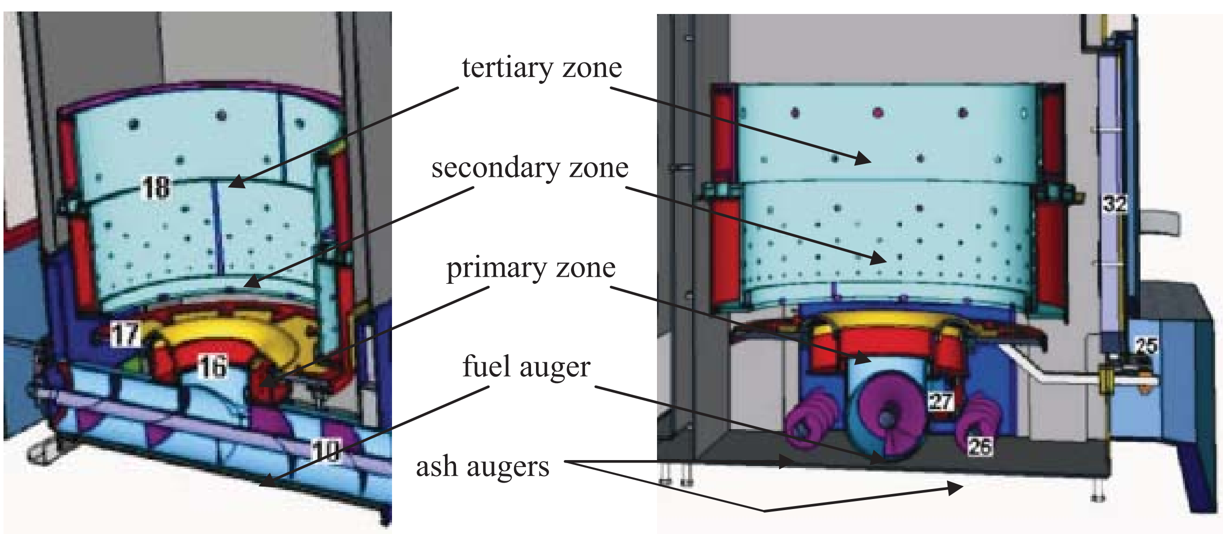

Figure ES1. Detailed view of fuel feed auger, ash augers, and combustion zones of a Hamont Boiler. (from Hamont European Operating Manual for CATfire 150-500 kW Wood Boilers).

Samples of combustion exhaust were drawn through a dilution stack sampling system conforming to EPA's conditional test method CTM-039 using a $PM_{2.5}$ cut-point cyclone. Diluted stack gas samples were drawn through the sampling ports to obtain semi-continuous measurements of carbon monoxide (CO), nitrogen oxides (NOx), sulphur dioxide (SO_2), and $PM_{2.5}$. Ultrafine particle size distributions were also measured in the stack emissions. $PM_{2.5}$ was collected on 142 mm baked quartz filters.

The average fuel feed rate into the 150 kW Walker Center boiler was 45 lbs hr^{-1} and the boiler was operated at 76% thermal capacity. CO, NOx, SO_2 and $PM_{2.5}$ emission factors were 0.27, 0.04, 0.001, and 0.06 lb $MMBTU^{-1}$, respectively. $PM_{2.5}$ mass was made up primarily of inorganic alkali salts (K^+ and SO_4^{2-}), with < 8 weight percent of organic carbon. The geometric mean diameter of the ultrafine particle size distribution was 89.3 nm. Total polycyclic aromatic hydrocarbons *(*PAHs) had an emissions factor of 7.43 x 10^{-5} lb $MMBTU^{-1}$. Potassium (K^+) and sulfate (SO_4^{2-}) combined made up 61% of total mass, while organic carbon (OC) made up 8% and EC was negligible. Sodium (Na^+), chloride (Cl^-), nitrate (NO_3^-), and zinc (Zn) were present at low levels. Figure ES2 shows the fine PM composition of Walker Center boiler stack emissions when burning wood pellets

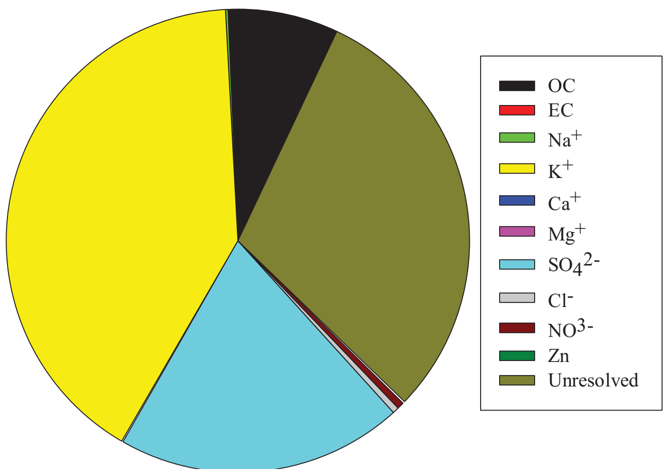

Figure ES2. Pie chart of fine PM composition from stack emission of Walker Center boiler when burning wood pellets.

The ACT Bioenergy150 kW wood chip boiler had an average fuel feed rate of 48 lbs hr^{-1} through the auger feed system. The nominal heat input rate during this measurement was 2.9 x 10^5 BTU hr^{-1}. The average emission factor for $PM_{2.5}$ measured during full load at steady state operation was 0.11 lb $MMBTU^{-1}$, while CO, SO_2 and NO_x were 0.35 lb $MMBTU^{-1}$, 0.004 lb $MMBTU^{-1}$ and 0.30 lb $MMBTU^{-1}$, respectively. The number average ultrafine particle diameter during steady state operation was 80.2 nm.

The measurements on The Wild Center 500 kW pellet boiler simultaneously tested emissions using EPA Method 5 for filterable particulate matter (FPM), OTM-28 for condensable particulate matter and dilution sampling with the CTM-039 for ultrafine particles, $PM_{2.5}$ and CO, CO_2, NOx and SO_2. Although loads of 25%, 50%, 75% and 100% were targeted, the boiler could only operate at 100% by constantly varying the temperature parameters because of the low heat demand in April 2010. Three measurements were conducted during this campaign. The boiler during the second and the third measurement was mostly operating in an unsteady state. The CTM-039 measurements during these periods were not included in the analysis and therefore, lower emission factors were estimated in comparison to the EPA Method 5 results (see Table 9). The emission factors during the boiler operation were 0.0007 lb $MMBTU^{-1}$ for SO_2, 0.07 lb $MMBTU^{-1}$ for NOx, 0.03 lb $MMBTU^{-1}$ for CO_2, 1.21 lb $MMBTU^{-1}$ for CO and 0.06 lb $MMBTU^{-1}$ for $PM_{2.5}$. The average fine PM concentration determined using EPA Method 5 was 0.087 lb $MMBTU^{-1}$, while the condensable particulate emission rate was 1.5 x 10^{-3} lb $MMBTU^{-1}$. Table ES1 summarizes the performance of the three boilers based on the measurements described in this report and measurements on other boilers made by Gammie and Snook.[1] The Hamont/ACT units were smaller than the other boilers but with just a single cyclone, they were able to achieve lower PM2.5 emissions than the others except the Chiptec closely-coupled gasifier with a multi-cyclone. The Messiersmith stoker boiler with multi-cyclone and bag house at the Crotched Mountain Rehabilitation Center was close at 0.07, but did require the bag house to achieve this low value. Nevertheless, none of these units would meet the requirements of the proposed National Emission Standards for Hazardous Air Pollutants for Area Sources: Industrial, Commercial, and Institutional Boilers.[2]

The thermal efficiency of the three Hamont boilers at the three locations ranged from a low of 61% and a high of 80% over a boiler thermal capacity at 50% to 101% yielding the average values provided int Table ES1. The lowest feed rate (57.1% of the maximum rate) was the manufacturer's recommended lowest feed rate. The efficiency ranged from 72-77% when the boiler was running at steady-state at Walker Center, and from 61-62% when the boiler was manipulated to run at 100% of the set fuel feed rate. During spring 2010, warmer than normal ambient temperatures were experienced producing low thermal demands on the boiler at both Walker and The Wild Center. To operate the boiler, it was necessary to force the system to operate under non-steady state conditions. The boiler normally operates to meet a set output water temperature (usually 90°C). Once this temperature is attained, the boiler automatically modulates the fuel feed rate to maintain that temperature. For the higher fuel feed rates, the boiler was easily reaching the set temperature and then reducing the fuel feed rate. In order to maintain the boiler running at 100% of the set feed rate, the output water temperature setting was manipulated to ~60°C, which effectively shut off the boiler. Once the water temperature dropped to 60°C, the required water temperature was raised to 90°C, at which point the boiler started feeding pellets at 100% of the set fuel feed rate. The boiler then ran at 100% of the set fuel feed rate until the output water temperature reached 90°C. The thermal efficiencies were estimated during this period of full feed rate operation.

Assessment of the collection characteristics of a model electrostatic precipitator (ESP) installed on the Walker Center boiler showed that the ESP efficiently captured particles under typical operating conditions. The estimated resistivity of the fly ash collected by the ESP was about $3x10^{10}$ ohm-cm at 120°C, indicating that ash resistivity is in an acceptable range for optimal ESP performance. The ESP exhibited an average collection efficiency of approximately 96 – 98% by mass at the different boiler load conditions tested, reducing the total mass emissions to about 3.0 mg/m^3. For example, the $PM_{2.5}$ emission factor for the 500 kW Wild Center boiler, is expected to reduce to about 2.64 x 10^{-3} lb $MMBTU^{-1}$, if an ESP is installed to the system. The total capital cost for installing ESPs on full-scale advanced wood combustion systems was estimated at about $93,000, excluding site preparation costs. Annual operating and maintenance costs were estimated at about $15,000 while the ESP power consumption over a period of five months was estimated at approximately 4,350 kWh.

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[1] Gammie, J. and Snook, S. 2009. Air Emissions Test Report: Small Biomass Energy System Particulate Matter Emissions Testing. State of Vermont Final Report. GamAir Project No.: 641-0712.
[2] 75 FR 31896

The measurements made in this study of high efficiency, low emissions European-designed wood boilers suggest that they represent a significant improvement over the stoker design wood boilers that were tested in the Vermont study. The stoker design represents the typically available commercial wood boiler in the U.S. If there is to be widespread use of renewable woody biofuels (pellets and chips obtained from sustainable forestry), then it is important that advanced gasification systems be used rather than conventional technologies to minimize emissions. From the available European literature, the staged combustion units in this study may not represent the state of the art in boiler design. Thus, there are additional opportunities to improve combustion efficiency with the potential of lower emissions and higher thermal efficiencies.

Table ES1. Comparison of PM emissions from ACT Bioenergy boilers with five wood fired boilers operating in Vermont, New Hampshire, and Rhode Island.

Boiler Location	**Boiler type**	**Particle control technology (removal%)**	**Fuel Type**	**EPA Test Method**	**Capacity (MMBTU/hr)**	**Filterable PM (lb $MMBTU^{-1}$)**	**Condensible PM (lb $MMBTU^{-1}$)**
ACT Bioenergy (this work) Schenectady, New York	Hamont, gasification	Cyclone	wood chip	CTM – 039	0.5	0.11*	-
Walker Center (this work) Potsdam, New York	Hamont, gasification	Cyclone	wood pellets	CTM – 039	0.5	0.06*	-
Wild Center Museum (this work) Tupper Lake, New York	ACT, gasification	Cyclone	wood pellets	CTM – 039	1.7	0.06*	-
Wild Center Museum (this work) Tupper Lake, New York	ACT, gasification	Cyclone	wood pellets	Method – 5 OTM – 28	1.7	0.09	0.004
Bennington College Bennington, Vermont[1]	AFS, (stoker)	Two multi-cyclones (61.1%)	whole tree hardwood chips	Method – 5 OTM – 28	16.8	0.35	0.031
Brattleboro High School Brattleboro, Vermont[1]	Messersmith, stoker	Core separator (57.2%)	millend wood chip	Method – 5 OTM – 28	10.0	0.16	0.011
Champlain Valley Union High School Hinesburg, Vermont[1]	Messersmith, stoker	Single cyclone (3.8)	millend wood chip	Method – 5 OTM – 28	6.5	0.17	0.012
Crotched Mountain Rehab. Center Greenfield, New Hampshire[1]	Messersmith, stoker	Baghouse and multi-cyclone (83.2%)	bolewood wood chip	Method – 5 OTM – 28	5.7	0.07	0.012
Ponaganset High School North Scituate, Rhode Island[1]	Chiptec closely-coupled gasifier	High-efficiency Multi-cyclone (22.5)	millend hardwood chip	Method – 5 OTM - 28	9.1	0.05	0.007

* - Particulate Matter less than 2.5 microns in size.
[1] – Data obtained from Gammie and Snook, 2009.

INTRODUCTION

There is a renewed interest in the use of biomass fuel combustion for residential and small to moderate scale commercial heating because of the fluctuating price of fossil fuels and the desire to use renewable energy. Still, conventional wood burning systems tend to have relatively low efficiency and high emissions of CO and particulate matter (Gammie and Snook 2009). In Europe, a number of advanced combustion systems have been developed that are reported to provide substantially higher thermal efficiency and lower emissions than conventional systems. These advanced systems use staged combustion that provides high thermal efficiency and also greatly reduced emissions of pollutants from the stack. Thus, in 2008, NYSERDA initiated a series of studies on both conventional and high-efficiency wood boiler systems. Clarkson University has evaluated three two-stage combustion systems that are described in the next section. Two of these units were imported from Austria, while the other was manufactured in the US. One 150 kW unit has been installed on the Clarkson campus to provide building heat for the Walker Center and has been subjected to continuous monitoring over multiple time periods. Clarkson has also conducted stack testing on the same model 150 kW wood chip boiler in Schenectady, NY. In addition, Clarkson has organized the stack testing of a 500 kW system with the same burner design but manufactured by Advanced Climate Technologies of Schenectady, NY, that was installed at The Wild Center in Tupper Lake, NY. Clarkson has also examined the potential problems that might be found with the use of conventional electrostatic precipitators (ESPs) on advanced wood burners given that these systems produce an ash that is essentially all inorganic salts. Such material could result in very high ash resistivity that could limit particle removal in an ESP.

BOILER CONFIGURATIONS

The Hamont CATfire boilers (150 and 500 kW) use a triple air staging process that ensures complete combustion of the fuel. Figure 1 shows an illustration of the fuel feed auger, ash auger, and combustion zones of the Hamont boiler.

Air staging is accomplished by injecting primary air into the fuel bed at a low air to fuel ratio (λ) to de-volatilize but not combust the fuel. Secondary and tertiary air streams are injected at higher λ values to burn the pyrolysis gases and achieve complete combustion. In order to ensure optimum excess air delivery into the different combustion stages, the boiler was equipped with an accurate process control system (CO/ λ control system) that varies the λ by measuring CO and λ using sensors in the combustion chamber.

During the first stage, the fuel is heated to around 400ºC (750ºF), and in the second and third stages, air is tangentially injected into the combustion zone to reach temperatures up to 1100ºC (2000ºF). Because of good mixing of combustion air with pyrolysis gases, the boiler operates at low excess air levels, thus enabling the boiler to operate at higher temperatures in the combustion zone with high combustion efficiency (Nussbaumer 2003).

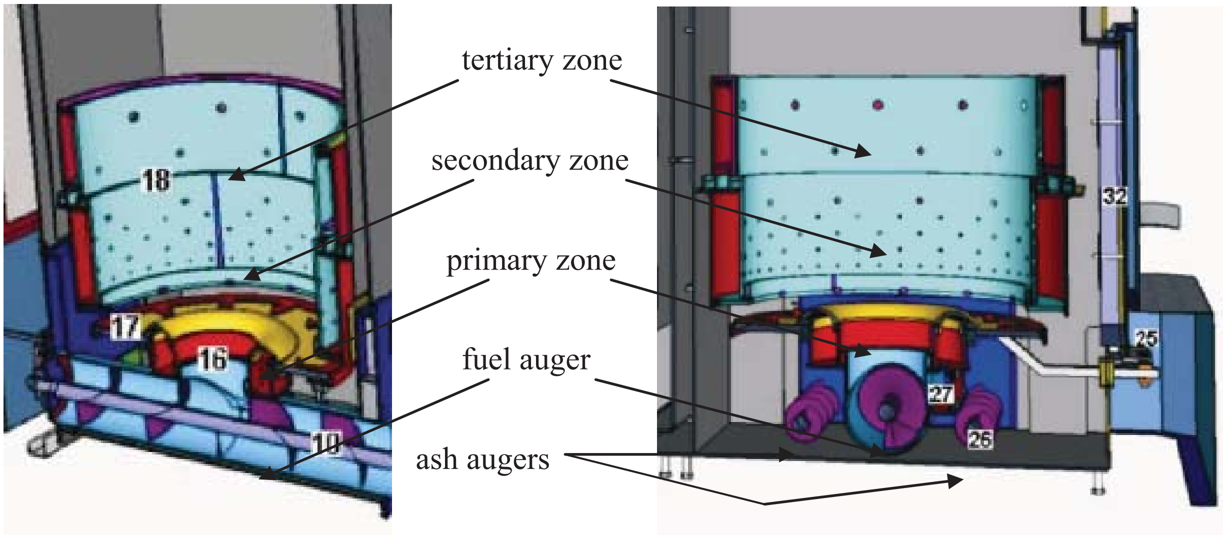

Figure 1. Detailed view of fuel feed auger, ash augers, and combustion zones of a Hamont Boiler. (from Hamont European Operating Manual for CATfire 150-500 kW Wood Boilers).

Walker Center Boiler

The 150 kW (514,000 BTU h^{-1}) Hamont CATfire, the150 kW boiler installed at the Walker Center was unpressurized since it was not ASME certified. The boiler uses a triple air staging combustion process, which can lower NOx and PM emissions (Nussbaumer 1998; Oser & Nussbaumer 2004). The wood pellets used during testing had a calorific value of 8052 BTU lb^{-1}, a moisture content of 4.8% and an ash content of 0.6%. During the Walker measurements, the boiler was tested for different feed rates between 260,000 BTU hr^{-1} and 630,000 BTU hr^{-1}or 50% to 122% of rated nominal load.

ACT Bioenergy Boiler

This boiler was identical to that installed at the Walker Center except this boiler was configured to burn wood chips with an operating range of 154,000-514,000 BTU hr^{-1} output or 30% and 100% of full load. The fuel for the project was urban wood waste comprised primarily of chipped wood pallets. Unlike virgin wood chips, these chips had visible dirt and paint contamination. The chips had a 27% moisture content and a heat content of 6111 BTU lb^{-1}.

The Wild Center Boiler

The boiler installed at The Wild Center was an ASME certified, 1.7 MMBTU hr^{-1}, boiler integrated with a solar hot water system. This system is expected to supply much of the hot water required to heat the 54,000-square-foot facility. The boiler used wood pellets supplied by Curran Renewable Energy, Massena, NY. Figure 2 is an illustration of a commercial size pellet boiler with solar thermal system at The Wild Center. The average fuel feed rate (wood pellets) through the auger feed system ranged between 160 and 416 lb hr^{-1}, and the heat input rate ranged between 1.3 and 3.4 MMBTU hr^{-1}. Although loads of 25%, 50%, 75% and 100% were targeted, due to very little heat demand during the testing in April 2010 we were able to run the boiler only at 100% by artificial manipulation. The measured gross calorific value of the pellet was 8059 BTU lb^{-1}.

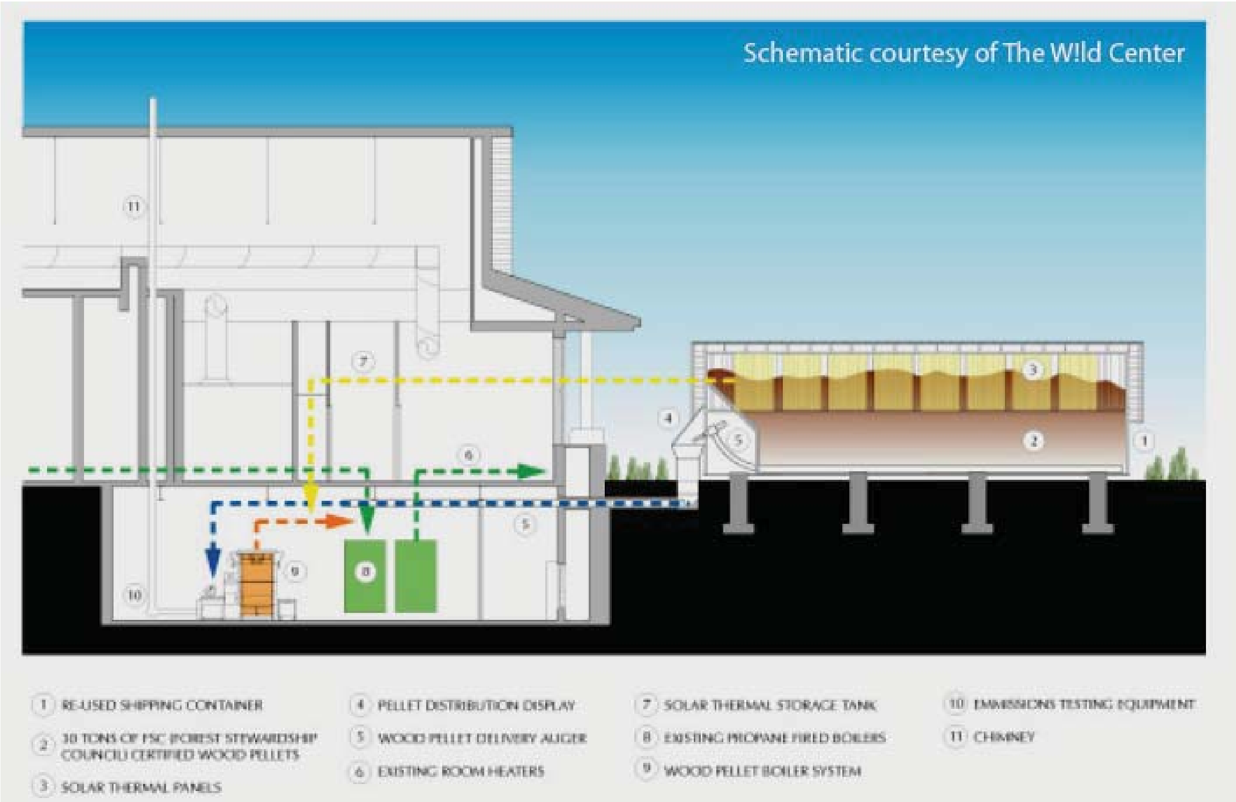

Figure 2. Schematics of commercial size pellet boiler with solar thermal system at The Wild Center. Obtained from www.**wildcenter**.org.

All of these boilers were configured to operate with a CO/ λ control system to optimize combustion air flows. This control adjusts the combustion air fan speed based on measured CO and O_2 levels in the flue gas. The target oxygen level was 8%. Nonetheless, during the test of the ACT Bioenergy boiler at Schenectady, NY, the oxygen levels ranged from 10 to 12% indicating that lambda control may have not been operating optimally and excess air was flowing through the combustion chamber. The boilers were generally operated at 100% load with the inlet and outlet water temperatures varying depending on the heat demand from the facility. When the heat demand from the building was low, the boiler input and output water set temperatures were varied to artificially force the boiler load to 100%.

Fuel Analysis

Table 1 summarizes the measured properties of fuel used in this work. Measurements were made using ASTM standard methods. Wood chips were slightly lower in terms of general fuel quality in comparison to wood pellets. Moisture content of wood pellets (about 5%) is lower than the moisture content present in woodchips (about 27%). Sulfur content in woodchips is more than two times the sulfur present in wood pellets. Similarly, nitrogen content in chips, although low, is more than two times the value present in pellets. The calorific value of woodchips is slightly lower than pellets, while Wild Center pellets show nearly the same heat content as the pellets used in Walker measurements.

Table 1. Analysis of fuel used in emissions measurement in the three boilers tested in this work.

Fuel Property	**Wood Pellets (Walker) – 150 kw**	**Wood Chips (ACT Bioenergy) – 150 kw**	**Curran Pellets (Wild Center) – 500 kw**
Heat Content (MJ/lbs)	8047	6369	8060
Moisture (%)	4.8	27	5.1
Ash (d.w. %)	0.6	1.79	0.6
Carbon (d.w. %)	51.5	45	48.74
Nitrogen (d.w. %)	0.13	0.37	0.15
Sulfur (d.w. ppm)	70.1	175	67.1

MEASUREMENT METHODS

CTM-39 Dilution Sampling System

Gaseous and $PM_{2.5}$ (particle matter <2.5 µm) concentrations were measured using a dilution tunnel sampling system obtained from Environmental Supply Co., Durham, NC conforming to EPA's conditional test method CTM-039. Stack gas was drawn isokinetically through an in-stack cyclone to remove particles larger than 2.5 µm and then into heated sample lines to prevent wall condensation. The heated sample gas was then mixed under turbulent conditions with dehumidified and HEPA filtered ambient air via a mixing cone. Dilution ratios of 20-60 were used. Sampling ports located at the end of the mixing chamber allowed for continuous measurements of carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), $PM_{2.5}$, and ultrafine particle number concentrations and size distributions.

Quartz filters, Telfon filters, and polyurethane foam plugs (PUFs) were collected for particle characterization and organic compound speciation. Continuous CO, NO_x and SO_2 measurements were taken using ambient gas monitors (Thermo Models 42i, 43i and 48i). Continuous $PM_{2.5}$ mass was determined using TEOM Filter Dynamics Measurement System (FDMS) (R&P Model 8500b), and ultrafine particle number concentrations and size distributions in the range from 5.6 to 560 nm were measured using a Fast Mobility Particle Sizer Spectrometer (FMPS) (TSI Model 3091).

The 142 mm quartz filters were analyzed for organic and elemental carbon (OC/EC) following the NIOSH 5040 method (Sunset Laboratories, Tigard, OR), and anions and cations by ion chromatography (IC). Organic artefacts from gas-phase adsorption onto quartz filters were corrected using a backup quartz filter. Teflon filters (47 mm) were analyzed for trace metals using inductively coupled plasma mass spectrometry (ICP-MS).

Quartz filters (142 mm) in series with PUFs were collected and analyzed for organic molecular markers, polycyclic aromatic hydrocarbons (PAHs) and polychlorinated dibenzodioxin and dibenzofurans (PCDD/Fs) using gas chromatography-mass spectrometry (GC/MS).

All emission factors and concentrations in this report are average emissions at full load during steady-state operation at dry gas standard state conditions (293.34 Kelvin temperature and 101.31 kPa pressure).

EPA Method 5 and OTM-28

At The Wild Center, additional measurements for particulate matter according to the EPA Method 5 and OTM-28 were conducted by CK Environmental under contract to Clarkson University. Briefly, particulate matter (PM) was withdrawn isokinetically from the stack gas, using a sampling apparatus obtained from Environmental Supply Company, Durham, NC. PM was collected on an out-of-stack glass fiber filter maintained at a constant temperature (248 ± 25°F) inside a heating box. The filter was heated to prevent condensation of moisture and gaseous compounds. The collected PM mass includes any material that condenses at or above the filtration temperature, and is determined gravimetrically. There are no specific load requirements for EPA Method 5 testing. Usually, the testing is done at loads between 90% and 100%, or the most probable boiler load.

After the particulate matter was removed from stack gas using the sampling apparatus described above, the stack gas sample stream was passed through dry impingers for measurement of condensable particulate matter (organic and inorganic fraction). In this method (OTM-28), the stack sample gas passes through a water jacketed coil condenser, a dry short stem moisture dropout impinger, and a dry regular impinger without a bubbler, and then through a Teflon® CPM filter. The sample gas is maintained at less than 85°F throughout this portion of the sampling system. Upon completion of sampling, the sampling train is purged with nitrogen for one hour and the components of the sampling train are rinsed with water and organic solvents. The organic and inorganic fractions are extracted in the lab, dried and weighed. The sum of these fractions is used to calculate the condensable PM mass concentration. The reported emission factors are at dry gas standard state conditions (293.34 K temperature and 101.31 kPa pressure).

Thermal Efficiency Measurement Methods

Boiler efficiency was determined using the direct method of dividing the useful heat output of the boiler by the energy input of the fuel (equation 1).

$$\eta = \frac{Q_w \rho c_p \Delta T}{C_v m_f} * 100 \qquad (1)$$

Where:

η – Boiler Thermal Efficiency
Q_w – Volumetric pipe flowrate (L/min)
ρ – Density of water (kg/L)
c_p – Specific heat capacity of water (MJ/kg°C)
ΔT – Water temperature difference (°C)
C_v – Gross calorific value of fuel (MJ/kg) m_f –
Fuel feed rate (kg/min)

Heat input was calculated from the gross calorific value (or higher heating value that takes into account the latent heat of vaporization of water) of the fuel and the fuel feed rate into the boiler. Gross calorific values were determined using oxygen bomb calorimetry according to STM E711 (Parr Oxygen Bomb Calorimeter and Calorimetric Thermometer Models 1341 and 6772).

Fuel feed rates into the Walker Center and the ACT Bioenergy boiler were determined by hand feeding a known quantity of pellets into the boiler’s feed bin and recording the time of consumption. The boiler fuel feed system is equipped with a display system to indicate the level of the fuel in the feeding bin. The initial fuel level was noted from the display and a known mass of pellets/woodchips were fed into the feed bin. The time elapsed for the fuel level to reach the initial level was noted and used to calculate the fuel feed rate. Several trials were conducted to yield better confidence in the estimated values. The Wild Center boiler had an automated reporting system where a binary value ‘1’ is reported every time the fuel feed system is activated and ‘0’ when the feeding system is inactive. Based on real-time measurements and fuel feed rate settings on the boiler control system, the fuel feed rate of The Wild Center boiler was determined.

Heat output from the boiler was determined by the temperature differences and flow rate in the output and return water pipe. Temperature was measured with thermocouples connected to a portable handheld data logger (Omega DAQPRO-5300). A handheld ultrasonic flow meter with type M1 transducers (Shenitch STUF-200H) was used to measure the water flow rate at the Walker Center and at The Wild Center. The water flow rate was not determined for ACT Bioenergy wood chip boiler, so the manufacturer reported flow rate of the pump was used. Figure 3. shows the boiler piping and the approximate positions of the thermocouple and flow meter used for direct thermal efficiency measurements

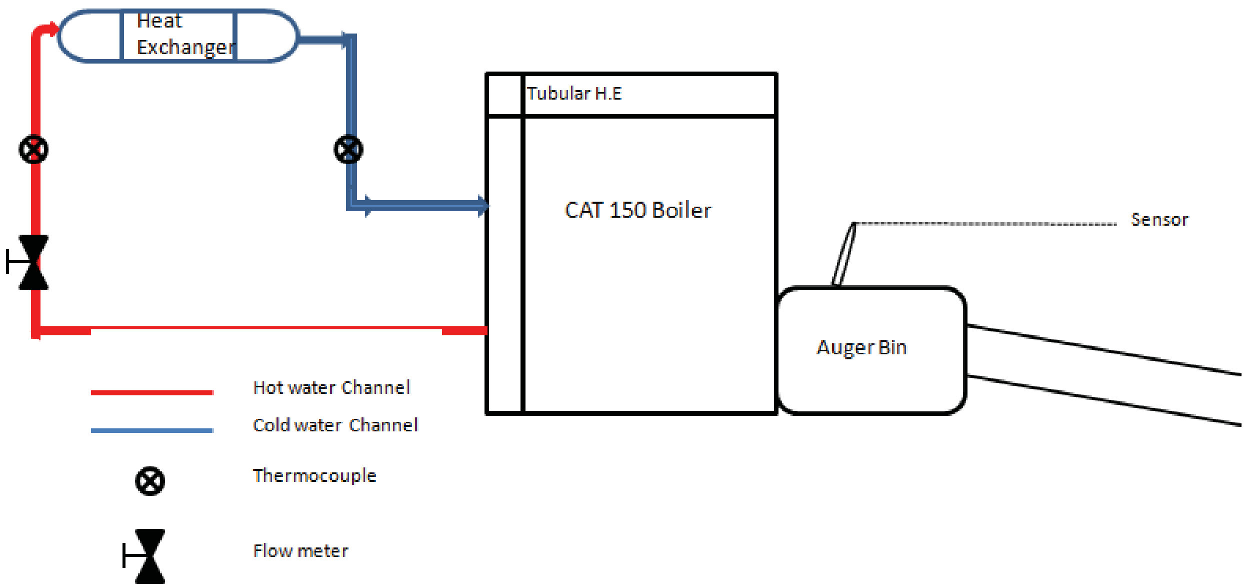

Figure 3. Illustration of boiler piping with approximate location of thermocouple and flowmeter.

MEASUREMENT RESULTS

Walker Center Boiler Measurements

Table 2 summarizes the emission concentrations and emission factors of CO, NO_x, SO_2, $PM_{2.5}$, and particle OC and EC from the 150 kW boiler at Clarkson while it was operating at steady state. All measurements were taken while the boiler was running at 72% of thermal capacity. The uncertainty values in Table 1 are 95% confidence intervals for the mean values. Figure 2 shows the concentration of criteria pollutants emitted by the Walker Center boiler when burning wood pellets.

The ultrafine particle number size distribution during steady state, in Figure 5, is log-normal with a peak in the accumulation mode (Figure 5). The geometric mean diameter (GMD) of the distribution was 89.3 nm, and count median diameter 80.6 nm. The average ultrafine particle number concentration for steady state operation was 2.66×10^7 # cm^{-3}. The emission factor was 1.71×10^{16} # $MMbtu^{-1}$.

Eight 142 mm quartz filters were analyzed for OC and EC by NIOSH Method 5040, and anions and cations by IC. Four 47 mm Teflon filters were analyzed for trace metals by ICP-MS

(Table 3). The particles were found to be composed primarily of inorganic salts (K^+ and SO_4^{2-}), which have been found to be much less toxic relative to organic based particles (Klippel and Nussbaumer, 2007). Potassium (K^+) and sulfate (SO_4^{2-}) combined made up 61% of total mass, while organic carbon (OC) made up 8% and EC was negligible. Sodium (Na^+), chloride (Cl^-), nitrate (NO_3^-), and zinc (Zn) were present at low levels. Figure 4 shows the fine PM composition of Walker Center boiler stack emissions when burning wood pellets

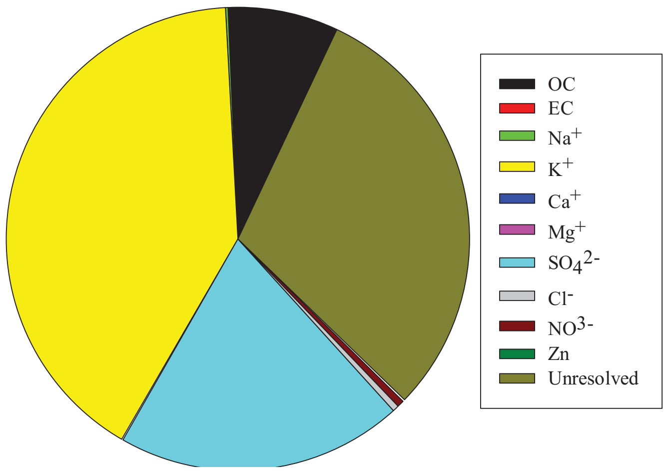

Figure 4. Pie chart of fine PM composition from stack emission of Walker Center boiler when burning wood pellets.

Particle and semi-volatile organic compounds were collected on the 142 mm quartz filter in series with a PUF plug. These samples were then analyzed by GC/MS. Eight quartz filters and six PUFs were collected (Table 4). Because of gas-phase adsorption of organic species onto the quartz filters, gas-particle partitioning could not be determined. Most of the n-alkane concentrations were low except for C29 and C30 compounds that had the highest concentrations of 240 µg m^{-3} and 160 µg m^{-3}, respectively. Levoglucosan, which has been used as a tracer for wood smoke, had the third highest concentration of 80 µg m^{-3}. Polychlorinated dioxins and dibenzofurans (PCDD/Fs) were below detection limits (< 22 pg m^{-3}).

Table 2. Emissions factors for a 150 kw Hamont staged combustion wood boiler during steady state operation using premium wood pellets tested at Walker Center, Clarkson University.

Emission Species	**mg m^{-3}**	**g/kg**	**lb $MMBtu^{-1}$**
CO	168 ± 1.76	2.16	0.27
NOx	25.7 ± 0.13	0.35	0.04
SO_2	0.47 ± 0.00	6.46	0.001
$PM_{2.5}$	37.2 ± 0.60	0.47	0.06
OC*	2.23 ± 0.62	0.02	0.004
EC*	0.10 ± 0.05	0.001	0.00

Note: Average emissions at steady state operation. Uncertainty indicated in this table represents the 95% confidence interval of the average value.
Results are based on eight aggregated filter samples.

Table 3. Chemical Composition of $PM_{2.5}$. for 150Kw pellet boiler at Walker Center

Elemental and Organic Carbon (wt % of $PM_{2.5}$)		
NIOSH 5040	OC	7.67 ± 1.69
NIOSH 5040	EC	0.00 ± 0.00
Ionic Species (wt % of $PM_{2.5}$)		
IC	Na^{+}	0.18 ± 0.03
IC	NH^{4+}	<0.05
IC	K^{+}	40.6 ± 7.22
IC	Mg^{+}	0.06 ± 0.04
IC	Ca^{+}	0.05 ± 0.07
IC	SO^{4-}	20.0 ± 0.58
IC	Cl^{-}	0.44 ± 0.2
IC	NO^{3-}	0.49 ± 0.07
Elemental Species (wt % of $PM_{2.5}$)		
ICP-MS	Al	$<8.57 \times 10^{-3}$
ICP-MS	As	$<6.30 \times 10^{-4}$
ICP-MS	Ba	$4.13 \times 10^{-3} \pm 5.15 \times 10^{-5}$
ICP-MS	Cd	$1.07 \times 10^{-3} \pm 1.39 \times 10^{-5}$
ICP-MS	Co	$<3.29 \times 10^{-4}$
ICP-MS	Cr	$8.69 \times 10^{-4} \pm 1.57 \times 10^{-5}$
ICP-MS	Cu	0.01 0.00
ICP-MS	Fe	<0.07
ICP-MS	Li	$4.11 \times 10^{-3} \pm 2.53 \times 10^{-5}$
ICP-MS	Mn	0.04 ± 0.00
ICP-MS	Ni	$<1.98 \times 10^{-3}$
ICP-MS	Pb	0.01 ± 0.00
ICP-MS	Rb	0.09 ± 0.00
ICP-MS	Tl	$1.27 \times 10^{-4} \pm 2.22 \times 10^{-6}$
ICP-MS	V	$6.93 \times 10^{-5} \pm 3.06 \times 10^{-6}$
ICP-MS	Zn	0.15 ± 0.00

Note: Uncertainty values indicated are the 95% confidence intervals

Table 5 shows the stack concentrations and emission factors for twenty-seven polycyclic aromatic hydrocarbons (PAHs) when using wood pellets as fuel. Total PAH emissions (34 ng BTU^{-1}) were lower than previous measurements of residential pellet stoves and burners during good combustion conditions (Boman et al. 2005; Johansson et al. 2004). The compounds with the highest emissions were phenanthrene, pyrene, acenaphthene, fluoranthene, indeno [1,2,3-cd] pyrene, and acenaphthylene.

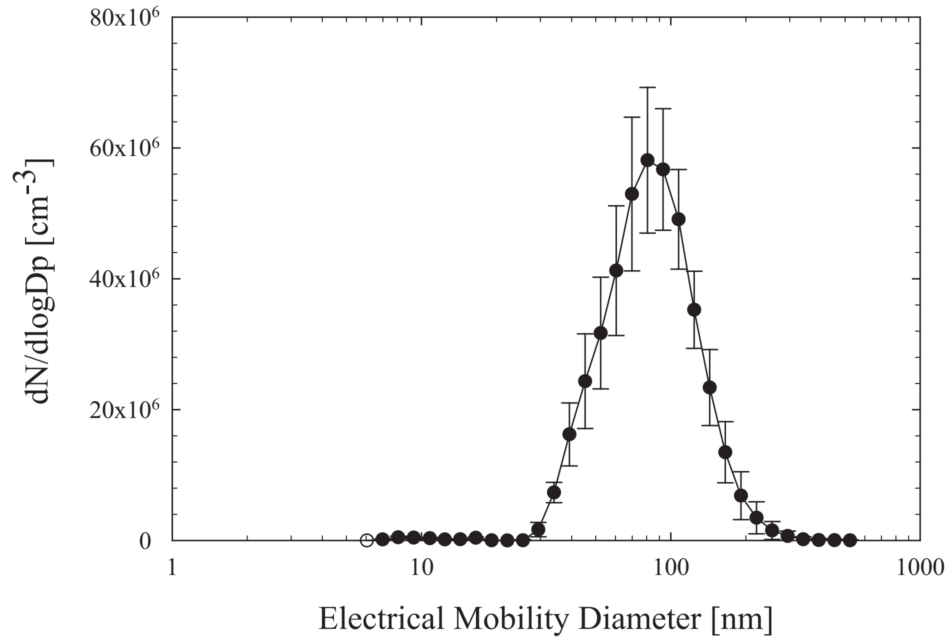

Figure 5. Ultrafine particle number size distribution during steady state of the boiler at Walker Center, Clarkson University. Error bars are one standard deviation.

Table 4. Emissions of total particle and semi-volatile organic functional groups and compounds when using wood pellets as fuel. The numbers in parentheses indicate the number of compounds analyzed in each functional group.

Functional Groups/Compounds	**Total (μg.m^{-3})**	**Total (ng.BTU^{-1})**
n-Alkanes (31)	539	398
PAHs (27)	48.6	33.7
Aromatic acids (5)	43.6	30.5
Alkanoic acids (22)	86.2	62.7
Dicarboxylic acids (12)	55.8	39.4
Pentacyclic triterpane (hopanes) (5)	64.4	41.3
Cholestane (sterols and cholestenes) (4)	0.64	0.48
Methyloxylated phenols (5)	23.6	16.5
Phytosterols (4)	0.52	0.37
Nonyl aldehyde	15.4	11.4
Squalene	3.44	2.20
cis-Pinonic acid	44.6	31.3
Levoglucosan	77.6	53.0
PCDD/Fs (17)	<0.02	<0.02

Note: Numbers in the parentheses represent the number of compounds in each functional group.
< b.d. – below detection limit
* - Value reported is the sum of species measured on the filter and the PUF plug.
Data based on three PUF and three filter samples.

Table 5. Total semi-volatile and particle polycyclic aromatic hydrocarbon (PAH) emission concentrations and emission factors for a 150 kW boiler burning wood pellets at the Walker Center.

PAHs	Total (μg.m^{-3})	Total (ng.BTU^{-1})
Naphthalene	1.63	1.11
Acenaphthylene	4.87	3.41
Phenanthrene	8.62	5.75
Fluoranthene	5.24	3.53
Pyrene	5.50	3.68
Benzo[a]anthracene	0.55	0.38
Benzo[k]fluoranthene	1.09	0.75
Dibenz[a,h]+[a,c]anthracene	N/F	N/F
Benzo[ghi]perylene	0.90	0.64
Anthracene	1.59	1.06
Benzo[b]fluoranthene	0.81	0.57
Indeno[1,2,3-cd]pyrene	4.58	3.42
Chrysene&Triphenylene	1.10	0.76
1-Methylnaphthalene	0.76	0.51
2,6-Dimethylnaphthalene	1.10	0.76
2-Methylanthrancene	0.69	0.45
Retene	1.34	0.96
Benzo[a]pyrene	1.19	0.86
Coronene	0.00	0.00
Benzo[e]pyrene	0.38	0.26
1-Methylpyrene	N/A	N/A
3-Methylchrysene	0.11	0.07
Indeno[1,2,3-cd]fluoranthene	N/F	N/F
4-H-cyclopenta[def]phenanthrene	1.17	0.77
Acenaphthene	4.71	3.54
Fluorene	0.71	0.48
Picene	N/F	N/F

Measurement Results of 150 kW Wood Chip-Fired Boiler

Figure 6 shows the concentrations of criteria pollutants measured during steady state operation at 100% load of boiler for 150 kW boiler burning wood chips and pellets. The data indicated for wood pellets was collected using the Walker Center boiler, while the data for woodchips was collected using the ACT Bioenergy boiler. The plot shows very stable concentration of the NO_x, SO_2, and $PM_{2.5}$ emitted during steady state operating conditions for woodchips and pellets. Carbon monoxide concentrations were more variable than the other pollutants for the woodchip boiler. Oxygen concentration (percent by volume) ranged between 10 and 12 percent during this measurement. Additional axis on the right shows the CO concentration converted to 7% oxygen concentration (volume basis). The CO varied between 140 and 200 ppm at 7% oxygen, for the ACT Bioenergy boiler, possibly as a result of the variability in the oxygen concentration during these measurements.

Figure 6 shows that the NO_x, SO_2 emission factors when using wood pellets (Walker Center boiler) were smaller than when burning wood chips (Cayuga boiler). This result is likely to be because the pellets were a cleaner fuel with less fuel-bound nitrogen and sulfur. The $PM_{2.5}$

emission factor was also lower when burning wood pellets compared with wood chips. This result may be due to the higher ash content of the wood chips, three times greater than the pellets. Previous studies have found that higher fuel ash content results in higher PM emissions (Johansson et al., 2004; Sippula et al., 2007; Wiinikka and Gebhart, 2005).

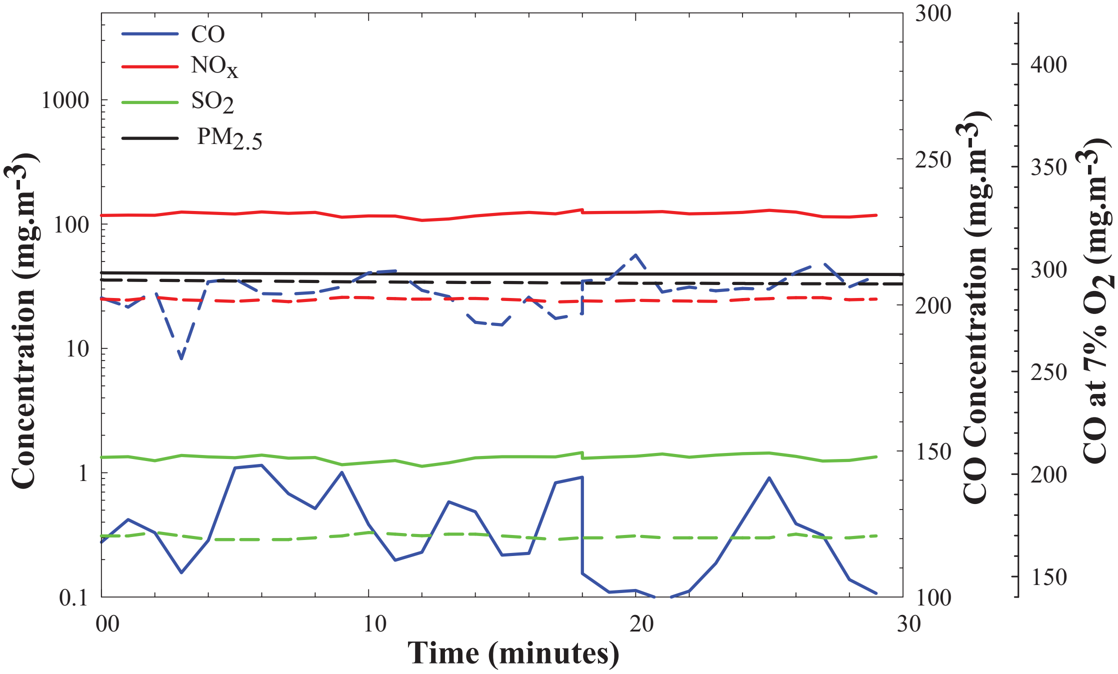

Figure 6. Concentration of criteria pollutants (CO, NO_x, SO_2 and $PM_{2.5}$) during steady state operation of 150 kW boiler (at full load). Dashed lines indicate data for wood pellets (Walker Center boiler) and solid line indicate data for wood chips (ACT Bioenergy boiler).

Table 6 summarize the measured average emission factors for NO_x, SO_2, CO, $PM_{2.5}$, and TOC. The uncertainty values in the table represent the 95% confidence interval of the average value. The CO/CO_2 ratio indicative of the extent of combustion in the boiler was 0.08%, this low percentage indicates that there was almost complete combustion of the fuel at 100% load. Total organic carbon (TOC) is the sum of organic carbon (OC) and elemental carbon (EC). Measurements of OC and EC revealed that there was negligible amounts of EC on the filters. Nevertheless, the EC concentration during shutdown operation was 5.8 mg m^{-3}, and the OC concentration was 20.3 mg m^{-3}.

Boiler shutdown operation was initiated at 17:30 hrs by stopping the feed of fuel (Figure 7). The $PM_{2.5}$ and CO concentration increased during boiler shutdown, while NO_x and SO_2 decreased. CO concentrations remained high (~725 $mg.m^{-3}$) for about 15 minutes even after the boiler was completely shut down. Emissions data during boiler shutdown is available only for the ACT Bioenergy boiler.

Average ultrafine particle size distributions during two trials at steady-state operation and during shutdown are shown in Figure 8. During both steady-state periods, the particle size distributions were fairly similar with a much higher mean value than during shutdown. The number average particle diameter during steady-state operation was 80.2 nm, while the number average particle diameter during shutdown was 17.1 nm.

Of the PAHs measured, phenanthrene and retene had the largest concentrations (1.0 and 2.6 μg/m^3, respectively, Table 7). As indicated earlier, there larger concentrations may be due to the incidental amounts of wood chips coated with paint. Most linear alkane concentrations are low except for the alkanes with chain length C15 to C20 and especially n-C16 and n-C17 (128 and 132 μg.m^{-3}, respectively). Table 8 shows the average emission factors of major polycyclic aromatic hydrocarbons from the Cayuga wood chip-fired boiler.

Table 6. Full load average emissions from a high efficiency 150 kW wood boiler using wood chips as fuel tested at Schenectady, NY.

Emission Species	Emission Factor (Fuel: Wood Chips)		
	mg m^{-3}	g kg^{-1}	lb $MMBTU^{-1}$
CO	138 ± 20.1 (76.7 – 516)	2.13 ± 0.29 (1.08 – 7.77)	0.35 ± 0.05 (0.18 – 1.27)
CO_2 (x 10^4)	18.0 ± 0.72 (15.2 – 21.4)	0.06 ± 0.00 (0.05 – 0.07)	0.01 ± 0.00 (0.008 – 0.011)
NO_x	119 ± 1.88 (106 – 155)	1.84 ± 0.05 (1.54 – 2.33)	0.30 ± 0.01 (0.25 – 0.38)
SO_2	1.30 ± 0.02 (1.13 – 1.65)	0.02 ± 0.00 (0.01 – 0.02)	0.004 ± 0.00 (0.003 – 0.006)
$PM_{2.5}$	38.4 ± 0.9 (35.8 – 41.3)	0.54 ± 0.05 (0.39 – 0.69)	0.11 ± 0.02 (0.06 – 0.16)
TOC*	0.97 ± 0.17 (0.70 – 1.16)	0.02 ± 0.00 (0.01 – 0.02)	0.003 ± 0.00 (0.002 – 0.003)

Note: Average emissions at steady state operation. Uncertainty indicated in this table represents the 95% confidence interval of the average value. Data in parenthesis indicate the range (minimum - maximum) measured during full load operation.
*- Data based on three aggregated filter samples.
TOC is OC plus EC

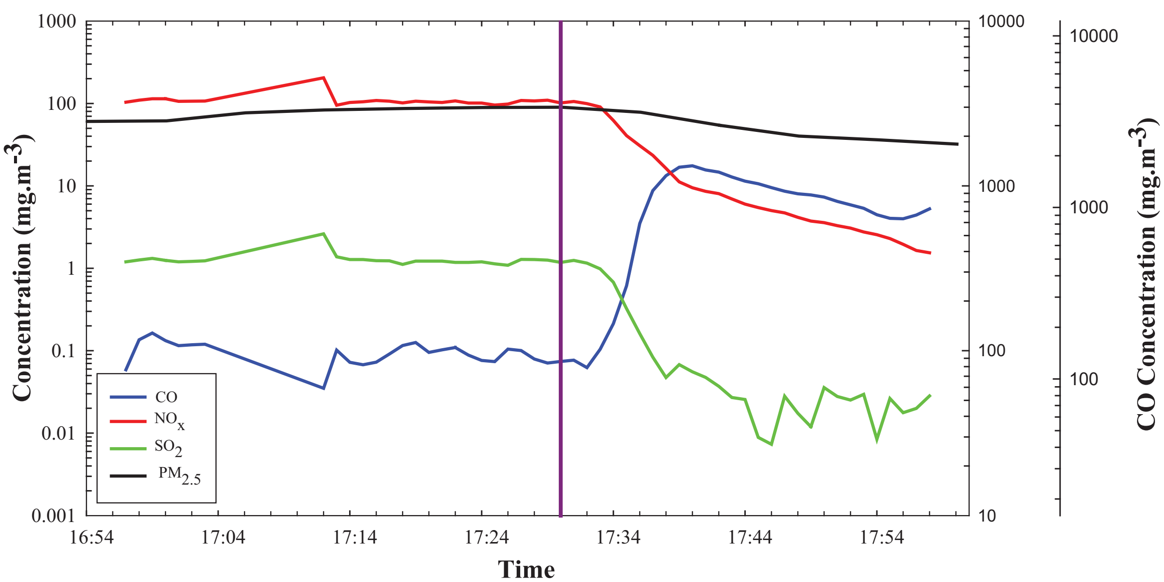

Figure 7. Concentration of criteria pollutants (CO, NO_x, SO_2 and $PM_{2.5}$) during shutdown of ACT Bioenergy boiler buring wood chips. Boiler shutdown was initiated at 17:30 hrs.

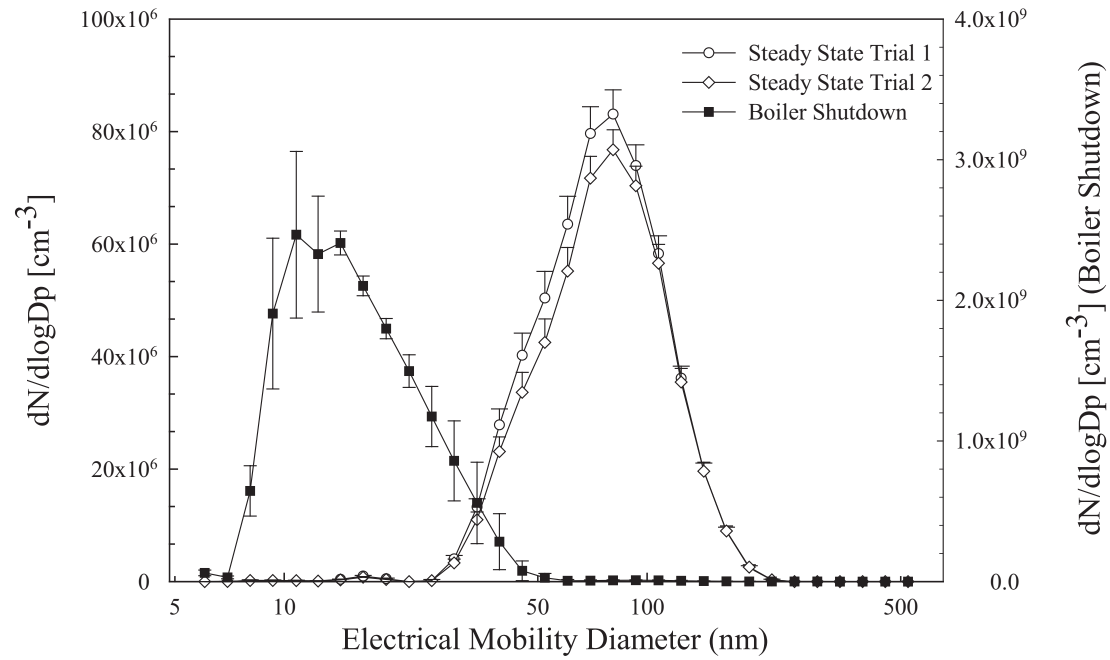

Figure 8. Average particle size distribution at full load during steady state operation and during boiler shutdown. Error bars in this figure are one standard deviation.

Table 7. Full load average emissions of selected aromatic compounds from a high efficiency wood boiler using wood chips as fuel.

Compound	**Total (µg m^{-3})**	**Total (ng BTU^{-1})**
n-Alkanes (31)	310	375
PAHs (27)	34.8	44.4
Aromatic acids (5)	N/F	N/F
Alkanoic acids (22)	41.3	49.6
Dicarboxylic acids (12)	5.06	6.07
Pentacyclic triterpane (hopanes) (5)	0.22	0.26
Cholestane (sterols and cholestenes) (4)	0.72	0.86
Methyloxylated phenols (5)	10.9	13.7
Phytosterols (4)	4.46	5.33
Nonyl aldehyde	0.01	0.02
Squalene	38.0	45.4
cis-Pinonic acid	0.13	0.15
Levoglucosan	38.0	45.4
PCDD/Fs (17)	<b.d.	<b.d.

< b.d. – below detection limit

* - Value reported here is the sum of species measured on the filter and the PUF plug. Data based on three PUF and three filter samples.

Table 8. Full load average emissions of selected aromatic compounds from a two-stage wood boiler using wood chips as fuel.

Compound	**Total*** **(µg m^{-3})**	**Total*** **(mg kg^{-1})**	**Total*** **(ng BTU^{-1})**
Phenanthrene	1.01	0.02	2.78
Fluoranthrene	0.33	0.01	0.93
Pyrene	0.3	0.01	0.85
Benzo[a]anthracene	0.00	0.00	0.01
Benzo[k]fluoranthrene	0.04	0.00	0.15
Dibenz[a,h]+[a,c]anthracene	0.00	0.00	0.00
Benzo[ghi]perylene	0.03	0.00	0.08
Anthracene	0.14	0.00	0.37
Benzo[b]fluoranthrene	0.09	0.00	0.29
Indeno[1,2,3-cd]pyrene	0.00	0.00	0.00
Chrysene&Triphenylene	0.07	0.00	0.23
1-Methylnaphthalene	0.65	0.01	1.84
2,6-Dimethylnaphthalene	0.30	0.01	0.84
2-Methylanthracene	0.36	0.01	1.07
Retene	2.63	0.05	7.91
Benzo[a]pyrene	0.00	0.00	0.00
coronene	0.00	0.00	0.00
Benzo[e]pyrene	0.04	0.00	0.12
1-Methylpyrene	0.05	0.00	0.14
3-Methylchrysene	< b.d.	< b.d.	< b.d.
Indeno[1,2,3-cd]fluoranthrene	0.00	0.00	0.00
4-H-cyclopenta[def]phenanthrene	0.05	0.00	0.12

< b.d. – below detection limit

* - Value reported here is the sum of species measured on the filter and the PUF plug. Data based on three PUF and three filter samples.

Measurement Results of The Wild Center Boiler

Figure 9 shows the concentration of criteria pollutants measured during operation at 100% load of boiler for 500 kW boiler burning wood pellets. Table 9 gives the full load average emission factors of the 500 kW boiler at The Wild Center. Table 10 compares the measurements conducted using EPA Method 5 using a glass fiber filter and the CTM-039 using a dilution sampling system. Comparison of particulate matter measurements from these two methods indicate that the EPA Method 5 measurements are about 11% higher than the CTM-039 dilution sampling measurement with measurements with Teflon filters.

Although loads of 25%, 50%, 75% and 100% were targeted, it was only possible to run the boiler at 100% by artificial manipulation because of the very low heat demand during April 2010. In order to force the system to operate, it was necessary to operate under non-steady state conditions. The boiler operates to meet a set output water temperature (usually 90°C). Once this temperature is attained, the boiler automatically modulates the fuel feed rate to maintain that temperature. For the higher fuel feed rates, the boiler was easily reaching the set temperature and then reducing the fuel feed rate. In order to maintain the boiler running at 100% of the set feed rate, the output water temperature setting was manipulated to ~60°C, which effectively shut off the boiler. Once the water temperature dropped to 60°C, the required water temperature was raised to 90°C, at which point the boiler started feeding pellets at 100% of the set fuel feed rate. The boiler then ran at 100% of the set fuel feed rate until the output water temperature reached 90°C. The thermal efficiencies were estimated during this period of full feed rate operation.

Method 5 captures total particulate matter, while CTM-039 was sampled using an in-stack 2.5 µm cyclone. The calorific value of the fuel obtained from the measurements at Clarkson was 8060 $BTU.lb^{-1}$ was used in the dilution method (CTM – 039) and EPA Method 5 calculations.

To quantify the mass of PM collected in the in-stack $PM_{2.5}$ cyclone during our CTM-039 measurements, the particles were dissolved in hexane, dried and weighed. The estimate PM concentration collected in the cyclone for the first measurement on 4/20/10 between 9:23 and 11:20 was 9.4 mg m^{-3}. Thus, the total PM collected during this measurement was 118.41 mg m^{-3} from the Teflon filter measurement and 100.9 mg m^{-3} from the TEOM FDMS measurement system. The difference in the result, therefore, is about 3.7 % and 17.9% from the Teflon filter and TEOM FDMS system, respectively.

The boiler during our second and the third measurement (in Table 9) was mostly operating in an unsteady state. Since the method (5) is an aggregated filter measurement, the operator was unable to turn off the Method 5 system during this unsteady boiler operation and, therefore, kept the measurement system running. The CTM-039 measurement system and the TEOM FDMS system was turned off temporarily to protect the instrument from these large fluctuations in the PM emissions. Therefore, the PM emissions during these fluctuations are not included in the reported values from the CTM-039 method, leading to the large discrepancy in the measured values.

Table 9. Full load average emissions from the ACT 500 kw wood boiler at The Wild Center using wood pellets as fuel.

Emission Species	**mg m^{-3}**	**lb $MMBTU^{-1}$**
CO	1182 ± 64.11	1.21 ± 0.09
CO_2	96.74 ± 13.82	0.03 ± 0.00
NO_x	72.06 ± 0.79	0.07 ± 0.00
SO_2	0.92 ± 0.01	0.0007 ± 0.00
$PM_{2.5}$	55.50 ± 5.55	0.06 ± 0.01
Condensable PM	5.22 ± 0.46	0.004 ± 0.00
TOC*	2.27 ± 0.29	0.01 ± 0.00

Note: Average emissions at steady state operation. Uncertainty indicated in this table represents the 95% confidence interval of the average value. Data in parenthesis indicate the range (minimum - maximum) measured during full load operation. Condensable PM was measured using EPA OTM -28.

*- Data based on three aggregated 142mm filter samples.

Table 10. Comparison of particulate matter concentration measurements by EPA Method 5 and Dilution Method CTM-039.

Sampling Date/Time	FPM ($mg\ m^{-3}$) Method 5	$PM_{2.5}$ ($mg\ m^{-3}$) CTM-039		FPM ($lb\ MMBTU^{-1}$) Method 5	$PM_{2.5}$ ($lb\ MMBTU^{-1}$) CTM-039	
4/20/10 09:23 – 11:20	123.0	109.01(1)	91.50(2)	0.07	0.07(1)	0.06(2)
4/20/10 13:23 – 14:29	121.6*	57.29(1)	45.30(2)	0.11	0.06(1)	0.05(2)
4/21/10 8:52 – 11:12	93.8	38.34(1)	58.04(2)	0.10	0.06(1)	0.08(2)

FPM – Filterable particulate matter, $PM_{2.5}$ – particulate matter with particles less than 2.5µm aerodynamic diameter.
*-Data collected using an in-stack $PM_{2.5}$ cyclone.
(1) – data collected using Teflon filter, averaging time was typically about one hour
(2) – data collected using TEOM FDMS system

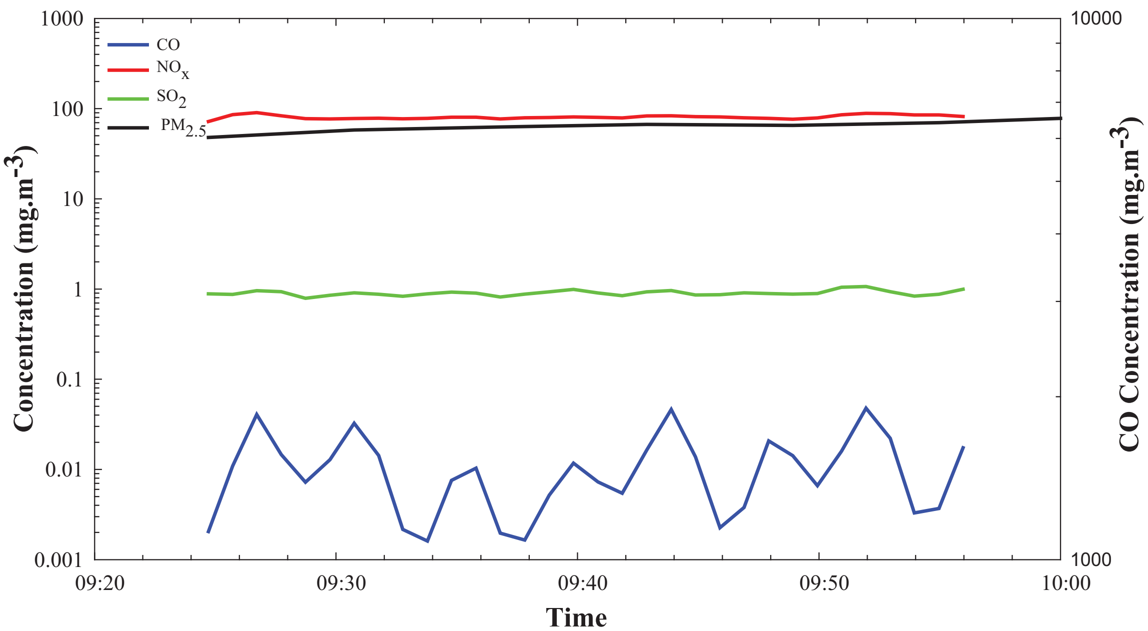

Figure 9. Concentration of criteria pollutants (CO, NO_x, SO_2 and $PM_{2.5}$) during steady state operation of 500 kW boiler (at full load).

Comparison of EPA Method 5, European EN303-5, and CTM–039 Measurements

Table 11 compares previously reported European emissions measurement results with all the results of the EPA test methods (CTM–039 and EPA Method 5) measurements. The CTM-039 is a dilution method, where the stack gas is diluted with HEPA filtered ambient air; where as the EPA Method 5 does not dilute the stack gas. The EN303-5 measurement method is typically conducted for boilers up to 300 kW load using solid fuels such woodchips, pellets, coal and coke. EN303-5 prescribes a maximum water temperature of 212°F and a maximum water pressure of 5.9 atmospheres. EN 303-5 Method includes 2 tests at nominal load and one test at 50% of nominal load. The EPA Method 5 measurements are typically done at 90% to 100% capacity of the boiler with no prescribed water temperature and pressure.

The European measurement results show much lower emissions of PM (reported as dust) and emissions gases such as CO, NOx and CO_2 in comparison to the emission measurement results from the EPA methods (CTM–039 and Method 5). The European emissions factors report dust as total PM (TSP).

Several possible reasons can be hypothesized for the higher emission factors for certain species reported here, in comparison to the European measurements. There could be differences in fuel quality for both wood chips and pellets between the US and Europe. Mill chips used in the European measurements did not include pine needles and wood bark that was present in the wood chips used in the ACT Bioenergy boiler tests. A small proportion of wood chips were found to be coated with paint. Moreover, measurements at The Wild Center were conducted in mid-April when there was little heat load on the system given relatively high ambient temperatures. In order to force the system to operate, it was necessary to operate under non-steady state conditions where the boiler load was modulating depending on the variability in the heat demand from The Wild Center facility.

Table 11. Comparison of European measurements with dilution tunnel CTM-039 and EPA Method.5

Pollutant	**European Measurements**			**CTM–039**[1]			**EPA Method 5**[2]
	150 kW (Pellets)	**150 kW (Woodchips)**	**500 kW (Pellets)**	**150 kW (Pellets)**	**150 kW (Woodchips)**	**500 kW (Pellets)**	**500 kW (Pellets)**
PM ($mg.m^{-3}$)	25	44	13	37	38	56	108
PM (lb/mmBTU)	–	–	–	0.06	0.11	0.07	0.07
CO ($mg.m^{-3}$)	42	111	140	168	138	1182	-
CO @ 7% O2(ppm)	182	113	143	224	168	1015.29	–
$\mathbf{NO_x}$ ($mg.m^{-3}$)	136	153	135	26	119	72	-
$\mathbf{n_{eff}}$ **(%)**	85	83	87	72	72	80	-

Note:
European measurements for PM indicated here was reported as dust by Hamont
O_2 concentration (percent by volume) was 10% for European measurements and was between 10 and 12% for CTM–039 and Method 5 measurements
1 - CTM–039 measurements are averages of at least eight hours of measurements
2 - EPM Method 5 are averages of about two hour aggregated filter measurements
Efficiency measurements based on higher heating value at 100% load.

The $PM_{2.5}$ mass concentrations reported here include non-volatile and condensed volatile species because of the dilution with filtered air. Dilution sampling may slightly increase the reported $PM_{2.5}$ concentration. Nevertheless, based on the TEOM FDMS measurements (Raja et al., 2009), and the condensable fraction obtained from OTM-28 for The Wild Center boiler, this process is not expected to increase the reported value by more than 3%. The ash content in wood chips was 1.6% and the moisture content was 30.4%. The ash content and the moisture content in the wood pellets being combusted at Clarkson were 0.6% and 4.6%, respectively. The fly ash had an OC content of 0.09 gram per gram of ash, while the fuel had average OC content of 0.28 gram per gram of wood pellet.

Carbon Monoxide as an Indicator of Polycyclic Organic Matter

As part of the US EPA's proposed National Emission Standards for Hazardous Air Pollutants for Area Sources: Industrial, Commercial, and Institutional Boilers (USEPA, 2010), EPA is trying to control mercury emissions from coal-fired area source boilers and the proposed emission standards for control of polycyclic organic matter (POM) emissions. The proposed emission standards for control of mercury emissions from biomass-fired and oil-fired area source boilers and for other hazardous air pollutants are based on EPA's proposed determination as to what constitutes the generally available control technology or management practices. However, the rules actually do not require measurement of POM in the emissions. EPA is proposing to regulate CO as a surrogate for the emission of POM based on seven specific POM species (benzo[a]anthracene, chrysene+triphenylene, benzo[b]fluoranthene, benzo[k]fluoranthene, indeno[1,2,3-cd]pyrene, dibenz[a,h]+[a,c]anthracene, benzo[a]pyrene) (USEPA, 2010). Measurements on conventional boilers suggest there is a reasonable correlation between CO and POM. Figure 10 shows the correlation between the sum of the 7 POMs with CO for the three high efficiency boilers tested in this study. It can be seen that there is no significant relationship among these values for these boilers.

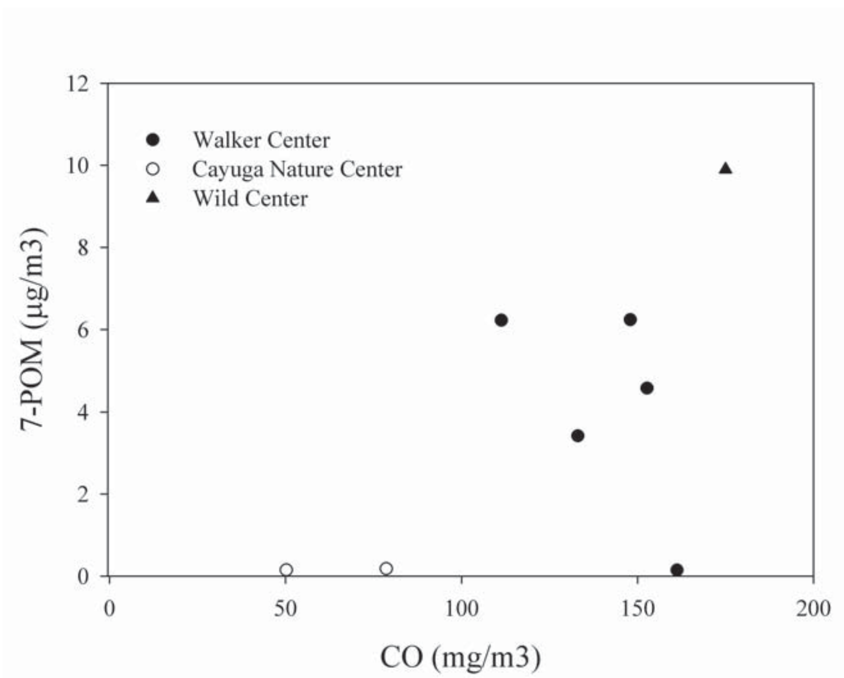

Figure 10. Relationship between seven selected POM compounds with CO in the stack emissions.

Thermal Efficiency Results

Table 12 shows the type of fuel used, energy input rate, energy output rate (by direct method calculation), boiler load capacity as percent of the input rate, and the calculated thermal efficiency for the three boilers tested between spring 2009 and spring 2010. The results are plotted in Figures 11 and 12.

The efficiency of the boilers at the three locations ranged from a low of 61% and a high of 80% over a boiler thermal capacity at 50% to 101% (Table 12). The lowest feed rate (57.1%) was the manufacturer's recommended lowest feed rate. Efficiency ranged from 72-77% when the boiler was running at steady-state at Walker Center, and from 61-62% when the boiler was manipulated to run at 100% of the set fuel feed rate (Figures 5 and 6).

Table 12. Thermal efficiency of the Walker, ACT Bioenergy, and Wild Center boilers at different heat inputs.

Testing Location	**Testing Period**	**Fuel**	**Input rate (kW)**	**Output rate (kW)**	**Boiler Capacity (%)**	$_{\text{thermal}}$ **(%)**
Wild Center	Spring 2010	pellets	620	409	82	66* ± 2
Wild Center	Spring 2010	pellets	379	303	61	80*# ± 2
Wild Center	Spring 2010	pellets	694	458	92	66* ± 1
Wild Center	Spring 2010	pellets	476	309	62	65* ± 6
Walker	Spring 2010	pellets	107	77.1	71	72* ± 4
Walker	Spring 2010	pellets	129	80.1	86	62* ± 4
Walker	Spring 2010	pellets	131	81.7	87	62* ± 4
Walker	Spring 2010	pellets	152	92.8	101	61* ± 4
Cayuga Nature	Spring 2009	chips	86	62.2	57	72# ± 5
Walker	Spring 2009	pellets	114	86.9	76	77# ± 7

Note: Uncertainties indicated here are the 95% confidence intervals.
* - Boiler manipulated to run at 100% of selected feed rate
# - Boiler operated at steady state conditions

Most of The Wild Center tests were run by manipulating the run as described above. However, this approach may have resulted in lower efficiencies than operating under actual steady-state conditions. The one steady-state run did result in a higher thermal efficiency value. Additional tests are recommended during the next heating season when the ambient temperatures are lower and there is a real load on the boiler.

Similarly, for the three highest fuel loads at Walker Center in the spring of 2010 (86%, 87% and 101% of boiler capacity), the boiler was also not operating at steady state and the procedure of manipulating the output water temperature setting outlined previously was employed.

The average difference in inlet and outlet water temperatures (ΔT) was about 8°F during Walker Center measurements, 10°F during the Cayuga boiler measurements, and 18°F during The Wild Center measurements. Although the ΔT (in °F) during the Wild Center measurements was nearly two times of the ΔT measured during the Walker Center measurements, the average estimated thermal efficiencies during these measurements were nearly the same (~ 64%). The larger ΔT in the Wild Center boiler is most likely due to the larger capacity of the boiler (500 kW) and a higher fuel intake rate.

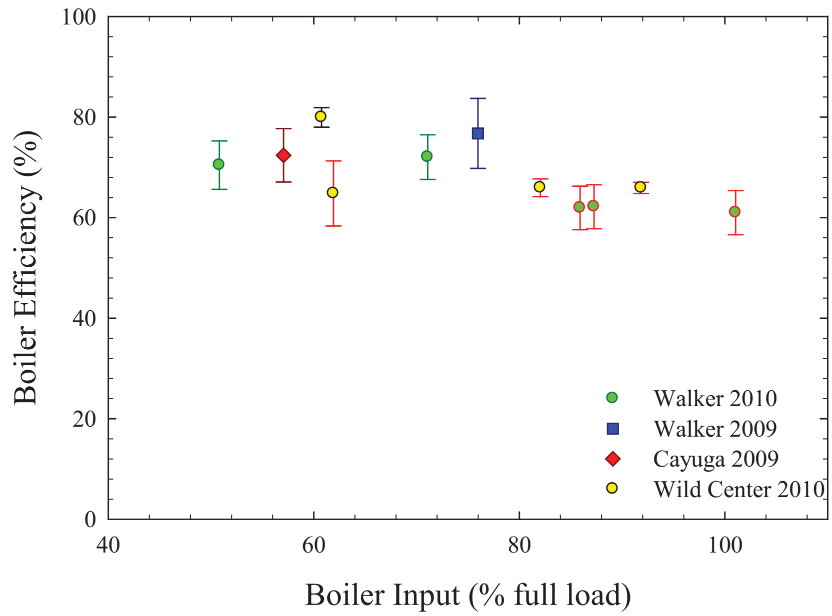

Figure 11. Thermal efficiency of the Walker Center, ACT Bioenergy and Wild Center boilers using the gross calorific value with 95% confidence intervals. The data points with red edges indicate data when the boiler was manipulated to run at 100% of the selected feed rate.

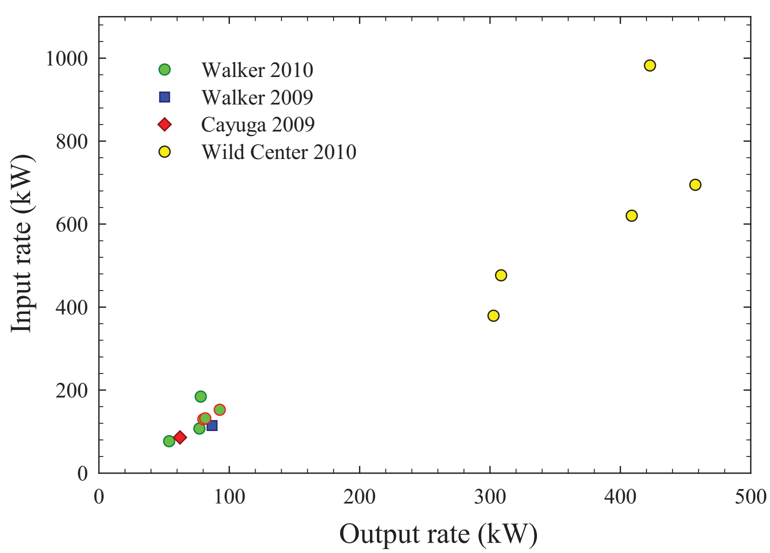

Figure 12. Comparison of thermal energy input rate and output rate of the Walker Center, ACT Bioenergy and Wild Center boilers (input rate calculated using the gross calorific value). The data points with red edges indicate data when the boiler was manipulated to run at 100% of the selected feed rate.

There could be several reasons to explain these estimated lower thermal efficiencies. The studies at The Wild Center in mid-April were at a time when there was little heat load on the system given relatively high ambient temperatures. Based on the available information, the estimated lower thermal efficiencies at The Wild Center are expected to be most likely due to lower heat demand. Low heat demand from The Wild Center facility may have also resulted in large fluctuations in boiler operations. Similar artificial manipulation of the boiler to run at 100% may be the most probable reason for lower estimated thermal efficiencies during the Walker Center measurements. Other factors, that may have contributed to lower thermal efficiencies, are currently being evaluated.

Comparison of Emissions from Other Wood Fired Boilers and Heating Equipment

Emissions from residential wood fire place and stoves, and other commercial boilers burning dry and wet wood residue are compared with the measurements from this study presented in Table 13. Emission factors for commercial boilers listed here burned wood residue generally in the form of hogged wood, bark, sawdust, shavings, chips, mill rejects, sander dust, or wood trim (EPA, 2008). Emissions measured in this study are lower than other commercial boilers and burners. Data from NESCAUM, (2008) show that PM emissions from a U.S. conventional wood chip boiler equipped with a cyclone has an emission factor of 0.20 lb $MMBTU^{-1}$ which is roughly 50% higher than the average $PM_{2.5}$ emissions from the boiler in the present study (0.11 lb $MMBTU^{-1}$).

Table 14 compares the emissions factors from England, 2004 for oil fired boilers and McDonald, 2009 for several pellet stoves, with the emissions determined in the present work. The $PM_{2.5}$ and NOx emission factors are higher than the emission factors reported in the measurements from the delta site reported by England, 2009, and from pellet stove emissions reported by McDonald, 2009. However, the 150 kW boiler burning pellets have somewhat similar NOx emissions as the pellet stove. The SO_2 emission factors, on the other hand, are lower from the present work in comparison to the oil fired boiler (England, 2009) and in pellet stoves (McDonald, 2009).

Table 14 also reports the thermal efficiencies of the boilers tested in the present work. These values were higher than the efficiency typically reported for other pellet stoves. In addition to the direct measurement of the efficiencies, it was possible to use an indirect method to assess the efficiency of The Wild Center boiler. The indirect method (BEE, 2008) is a theoretical estimation where the efficiency is calculated from the estimated total losses resulting from (1) dry flue gas, (2) moisture content of the fuel, (3) radiation and convection, and (4) partial conversion of C to CO and subtracting from 100% efficiency. It is calculated as:

$(\%\ \text{efficiency})_{indirect}$ = 100 – (loss due to Dry Flue gases + Loss due to Moisture in fuel + Loss due to Radiation and Convection + Loss due to Partial conversion of C to CO)

There was good agreement between the direct and indirect method estimates of The Wild Center 500 kW boiler efficiency.

Table 15 compares the particulate matter emissions from the two 150 kW and 500 kW boilers tested in this work with five wood fired boilers operating in Vermont, New Hampshire, and Rhode Island. The capacity of these boilers range between 5.7 and 16.8 MMBTU per hour, while the boilers tested here were two 0.5 and one 1.7 MMBTU per hour boilers. The particulate matter emission factors of the boilers tested in the present work are clearly lower than the high capacity boilers greater than 10 MMBTU per hour. The Ponaganset High School boiler (9.1 MMBTU/hr) is a closely-coupled gasifier system equipped with multiclones. It was the only boiler that had low emissions of PM compared to the other boilers tested in this work.

The Walker Center boiler emissions of carbonaceous derived species (CO, OC, EC, PAHs, and organic compounds) during steady-state operation were all relatively low due to near complete combustion. The emissions of all of these species were comparable to testing when using wood chips, so fuel quality does not seem to affect combustion conditions significantly. $PM_{2.5}$ was found to be comprised primarily of inorganic salts (K^+ and SO_4^{2-}), which have a lower toxicity than organic-based particles. NO_x, SO_2, and $PM_{2.5}$ were lower using wood pellets than wood chips, which is most likely due to the better quality of the fuel.

Table 13. Criteria emissions from various types of wood-fired burners and boilers.

Emission Species	Residential: Emission factors (Deangelis et al., 1980)		Commercial: Emission factors (EPA, 2008)		This study: 150 kW Wood Chips		This study: 150 kW Pellets		This study: 500 kW Pellets	
	Fireplace (g/kg)	Wood Stove (g/kg)	Wet Wood (lb/mmBTU)	Dry Wood (lb/mmBTU)	Wood Chips (g/kg)	Wood Chips (lb/mmBTU)	Wood Pellets (g/kg)	Wood Pellets (lb/mmBTU)	Wood Pellets (g/kg)	Wood Pellets (lb/mmBTU)
PM	13⁻	9.1⁻	0.350⁻	0.300⁻	0.54*	0.112*	0.47	0.060*	0.47	0.06*
SO_2	0.2	0.2	0.025	0.025	0.02	0.004	0.0065	0.001	0.005	0.001
NO_x	2.0	0.49	0.220	0.490	1.84	0.302	.35	0.040	0.42	0.07
CO	67	180	0.600	0.600	2.13	0.348	2.16	0.270	7.62	1.21

– measurements include only particles with diameters less than 2.5μm, cyclone used for PM control
– multiclones used in series for PM control
– no controls for PM

Table 14. Comparison of emission factors of criteria pollutants from No. 6 Oil fired boiler (Wien et al., 2004) and from advanced wood combustion systems (this work).

Emission Species	**Site: Delta (Oil) (England, 2004)**		**Pellet Stove (average) (McDonald, 2009)**		**150 kW (Wood Chips)**		**150 kW (Pellets)**		**500 kW (Pellets)**	
	lb/MMBTU	**mg/m^3**	**lb/MMBTU**	**ppm**	**lb/MMBTU**	**ppm**	**lb/MMBTU**	**ppm**	**lb/MMBTU**	**ppm**
$PM_{2.5}$	0.016	-	0.058	-	0.112	-	0.06	-	0.06	-
SO_2	0.033	-		2	0.004	0.7	0.001	0.3	0.001	0.3
NO_x	0.182	-		33	0.302	131	0.040	32	0.070	58
CO		-		128		149		224		1015
Efficiency(%) (Direct method)		-	69		72		72		80	
Efficiency (%) (Indirect method)			-		--		-		82	

Table 15. Comparison of PM emissions from ACT Bioenergy boilers with five wood fired boilers operating in Vermont, New Hampshire, and Rhode Island.

Boiler Location	Boiler type	Particle Control Technology (removal %)	Fuel Type	EPA Test Method	Capacity (MMBTU/hr)	Filterable PM (lb $MMBTU^{-1}$)	Condensable PM (lb $MMBTU^{-1}$)
ACT Bioenergy (this work) Ithaca, New York	Hamont, gasification	Cyclone	Wood chip	CTM – 039	0.5	0.11*	-
Walker Center (this work) Potsdam, New York	Hamont, gasification	Cyclone	Wood Pellets	CTM – 039	0.5	0.06*	-
Wild Center Museum (this work) Tupper Lake, New York	ACT, gasification	Cyclone	Wood Pellets	CTM – 039	1.7	0.06*	-
Wild Center Museum (this work) Tupper Lake, New York	ACT, gasification	Cyclone	Wood Pellets	Method – 5 OTM – 28	1.7	0.09	0.004
Bennington College Bennington, Vermont[1]	AFS, (stoker)	Two multi-cyclones (61%)	Whole tree Hardwood chips	Method – 5 OTM – 28	16.8	0.35	0.031
Brattleboro High School Brattleboro, Vermont[1]	Messersmith, stoker	Core separator (57%)	Millend Wood chip	Method – 5 OTM – 28	10.0	0.16	0.011
Champlain Valley Union High School Hinesburg, Vermont[1]	Messersmith, stoker	Single cyclone (38)	Millend Wood chip	Method – 5 OTM – 28	6.5	0.17	0.012
Crotched Mountain Rehab. Center Greenfield, New Hampshire[1]	Messersmith, stoker	Baghouse and multi-cyclone (83%)	Bolewood Wood chip	Method – 5 OTM – 28	5.7	0.07	0.012
Ponaganset High School North Scituate, Rhode Island[1]	Chiptec closely-coupled gasifier	High- efficiency Multi-cyclone (23%)	Millend Hardwood chip	Method – 5 OTM - 28	9.1	0.05	0.007

* - Particulate Matter less than 2.5 microns in size.
[1] – Data obtained from Gammie and Snook, 2009.

EVALUATION OF ADDITIONAL CONTROL TECHNOLOGY

Introduction

Given the potential impact of wood combustion on local air quality and public health, it may be desirable to control emissions from advanced wood combustion systems using conventional electrostatic precipitator (ESP) particularly in applications such as schools and other facilities where susceptible populations are exposed to the boiler effluent. The performance of an ESP in terms of its collection efficiency is significantly influenced by the process operating conditions. In particular, the resistivity of the fly ash to be collected, that is dependent on the chemical composition of the stack upstream of the ESP, is an important parameter that determines the ESP effectiveness. Ash resistivity is a measure of the resistance of the collected ash layer to the flow of electrical current. Particles with too high a resistivity (> 10^{11} ohm-cm) cause problems in the ESP as they build a layer of insulation over the collection plates inhibiting the effective collection of particles. On the other hand, particles with too low a resistivity (< 10^4 ohm-cm) may not get collected or quickly lose their charge after being collected, and potentially re-entrain into the effluent stream. ESPs operate effectively when the particle resistivity is within the range of 10^7 to 10^{11} ohm-cm. Ash resistivity may be problematic for ESPs installed on AWC boilers because:

(1) Particles in the stack are reportedly inorganic salts with essentially no organic material;
(2) Inorganic salts possess very high resistivity if they are devoid of water. However, combustion of the biomass fuel could produce varying relative humidity in the stack gas depending on the stack temperature. The inorganic particles could then deliquesce into high ionic strength solutions (low resistivity). In addition, the presence of liquids on the collection plates would be problematic because it can cause short circuits and corrosion;
(3) Wood pellets or wood chips used in advanced wood combustion systems are typically low sulfur fuels. Although these fuels provide low SO_2 emissions, the potential problem of high ash resistivity may be important since resistivity generally increases as the ratio of sulfur to ash content decreases.

Experimental Methods

The ESP used in this study is a two-stage device that was originally designed for the differential mass measurement of ambient particulate matter mass (Patashnick et al., 2001; Yi et al., 2004). The ESP unit was tested in the laboratory before installation on the wood pellet boiler. Stack gas sampling was performed using an EPA conditional test method (CTM-039) (EPA, 2004). Particle number concentrations and size distributions were measured using a scanning mobility particle sizer (SMPS) for particles with mobility diameters (d_m) in the size range of 0.01 – 0.64 µm. For particles with aerodynamic diameters (d_a) in the size range of 0.7 – 10 µm, an aerodynamic particle sizer (APS) was used. Different boiler load conditions representing high, medium and low thermal inputs were tested. High, medium, and low thermal inputs represented input rates of 147, 103, and 76 kW. The thermal input was determined as a function of the fuel-feeding rate and the fuel quality. During all the tests, the average stack gas temperature was 126 ± 6 ^oC while the exhaust gas temperature was 29.4 ± 2.5 ^oC. The average moisture fraction of the stack gas was about 3.5 ± 1.2 % H_2O (by volume).

The ESP was installed downstream of the dilution sampling train but before the particle measurement instruments. The ESP was alternately switched on (energized) and off (de-energized) to determine its collection efficiency. An estimate of the resistivity of the ash collected by the ESP was made based on the Bickelhaupt's model[5]. All test runs were conducted at an average exhaust relative humidity of about 7% and were repeated at least three times at each boiler load.

Results

Estimates of fly ash resistivity from the Bickelhaupt's model (Bickelhaupt, 1979) revealed that the resistivity of the fly ash was about 3 $x10^{10}$ ohm-cm at 120 ^oC (Figure 13). The Bickelhaupt's model predicts that the resistivity would be lower (~ 10^9 ohm-cm) at lower temperatures and highest (~ $2x10^{12}$ ohm-cm) at about 250 ^oC. The model results indicate that ash resistivity would not be a major problem for the ESP installed on the boiler, especially if the stack gas temperature is less than 200 ^oC.

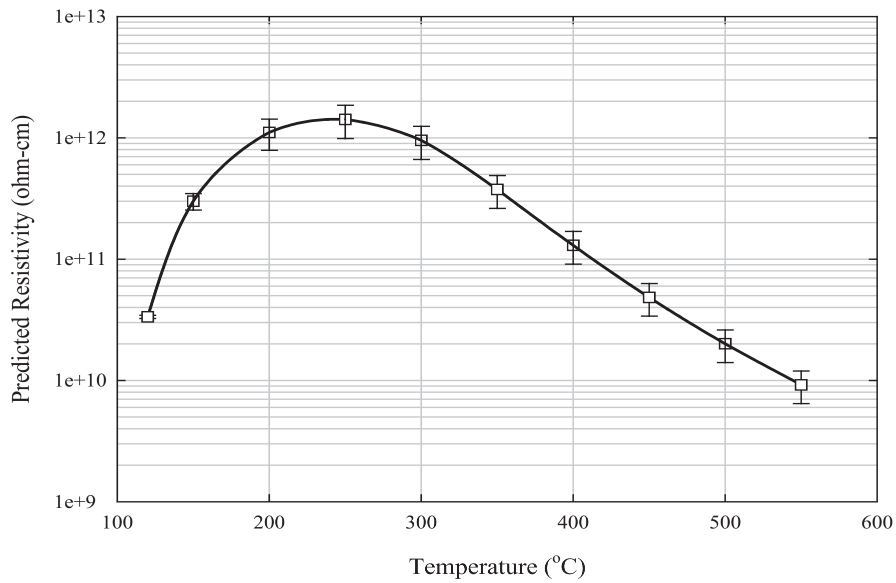

Figure 13. Ash resistivity as predicted from the Bickelhaupt's model

Table 16 shows the total number concentrations, the geometric mean diameters and the total collection efficiencies based on the number concentrations measured by the SMPS and the APS. The average collection efficiency of the ESP was approximately 98% for particles < 0.7 µm and 99% for particles in the size range of 0.7 – 10 µm. The total number concentration of the particulate matter emitted from the boiler was about $3*10^7$ #/Ncm^3 at low load and increased by about 40% when the boiler load was increased from low to high.

Table 17 shows the total mass concentrations as estimated from the SMPS and APS data assuming spherical particles and an effective particle density of 2 g/cm^3. The total mass concentration upstream of the ESP was between 160 – 285 mg/Nm^3 with particles of size 0.7 – 10 µm accounting for about 30 – 50% of the total mass. Downstream of the ESP (ESP energized), the particle mass was reduced by approximately 96 – 98% (particles < 0.7 µm) and 99% (particles > 0.7 µm), demonstrating excellent particle removal characteristics for particles emitted from the advanced wood combustion boiler.

Table 16. Total number concentrations, geometric mean diameters and number efficiencies for the ESP measured with the SMPS and APS instruments.

	High Load	Medium Load	Low Load
	SMPS ($0.01 < d_m < 0.64$ *μm*)		
Total number concentration (#/Ncm^3)[a]			
ESP de-energized	$4.81x10^7 \pm 1.27x10^5$	$3.26x10^7 \pm 1.27x10^5$	$2.93x10^7 \pm 9.65x10^4$
ESP energized	$6.96x10^5 \pm 2.43x10^3$	$6.53x10^5 \pm 8.50x10^3$	$4.62x10^5 \pm 1.40x10^3$
Geometric mean diameter (μm)			
- ESP de-energized	0.1105 ± 0.0050	0.1292 ± 0.0022	0.1220 ± 0.0016
- ESP energized	0.0981 ± 0.0015	0.1015 ± 0.0018	0.1051 ± 0.0011
Total number collection efficiency (%)	98.555 ± 0.0013	97.998 ± 0.0361	98.424 ± 0.0004
	APS ($0.7 < d_a < 10$ *μm*)		
Total number concentration (#/cm^3)[a]			
ESP de-energized	$9.70x10^4 \pm 1.34x10^3$	$9.14x10^4 \pm 2.96*10^3$	$8.88x10^4 \pm 0.96x10^3$
ESP energized	71.90 ± 35.56	160.96 ± 37.25	105.49 ± 31.11
Geometric mean diameter (μm)			
- ESP de-energized	0.8347 ± 0.0104	0.8387 ± 0.0123	0.8393 ± 0.0251
- ESP energized	0.8503 ± 0.0131	0.8351 ± 0.0212	0.8503 ± 0.0181
Total number collection efficiency (%)	99.923 ± 0.0357	99.825 ± 0.0351	99.923 ± 0.0357

Table 17. Total mass concentrations and particle collection efficiencies calculated from SMPS and APS data at the different boiler load conditions.

	High Load	Medium Load	Low Load
	SMPS ($0.01 < d_a < 0.64$ *μm*)		
Total mass concentration (mg/m^3)[b]			
ESP de-energized	184.70 ± 28.412	134.71 ± 33.102	83.90 ± 12.786
ESP energized	2.94 ± 0.995	3.46 ± 0.813	2.86 ± 0.618
Total mass collection efficiency (%)	98.454 ± 0.301	97.424 ± 0.029	96.625 ± 0.222
	APS ($0.7 < d_a < 10$ *μm*)		
Total mass concentration (mg/m^3)[b]			
ESP de-energized	100.65 ± 9.30	88.21 ± 6.55	78.51 ± 1.23
ESP energized	0.454 ± 0.0212	0.634 ± 0.1652	0 .416 ± 0.0198
Total mass collection efficiency (%)	99.566 ± 0.04	99.323 ± 0.165	99.471 ± 0.017

Cost Estimates for Adding ESPs to Full-Scale Advanced Wood Combustion Systems

The equipment cost of the ESP was estimated from the cost algorithm for ESPs as outlined in Chapter 6 of the OAQPS Control Cost Manual (EPA, 1996). For a boiler with a gas flow rate of 0.2 m^3/s (assuming a migration velocity of 10 cm/s and specific collection area ratio of 3), the equipment cost was estimated at $34,000. Estimates of direct and indirect costs showed a total capital cost of approximately $93,000 excluding site preparation costs.

For small-to-medium ESPs with an installed cost of approximately $100K or less, the total cost of maintenance is approximately 5% of the total capital cost; approximately $4,700. The operating cost will depend on several factors including labor costs, waste disposal and/or treatment, total hours of operation in a year, etc. A good estimate would be about $10,000 annually.

The operating power consumption in an ESP mainly comes from the corona power and pressure drop, with corona power being the main source. For an estimated total plate area of 600 ft^2, the ESP power consumption would be approximately 4,350 kWh assuming continuous operation for five months.

SUMMARY

The Walker Center boiler emissions of carbonaceous derived species (CO, OC, EC, PAHs, and organic compounds) during steady-state operation were all relatively low due to near complete combustion. Although, $PM_{2.5}$ and NOx emissions are higher than the emissions from oil fired boilers in comparison to the boilers tested in the present work, emissions of SO_2 were lower in comparison to oil fired boilers (England, 2004). The emissions of CO, OC, EC, PAHs and organic compounds were comparable to testing when using wood chips, so fuel quality does not seem to affect combustion conditions. $PM_{2.5}$ was found to be comprised primarily of inorganic salts (K^+ and SO_4^{2-}), which have a lower toxicity than organic-based particles. NO_x, SO_2, and $PM_{2.5}$ were lower using wood pellets than wood chips, which is most likely due to the better quality of the fuel.

The CO/CO_2 ratio of the ACT Bioenergy boiler tested in Schenectady, NY was about 0.08% indicating almost complete combustion of the fuel, while The Wild Center boiler had higher ratio of 12% due to unsteady boiler operation.

The slightly higher $PM_{2.5}$ emissions from the ACT Bioenergy boiler burning wood chips, in comparison to the Walker boiler burning pellets, are mostly attributed to the quality of the fuels. Therefore, the wood chip boiler would be expected to have lower emissions, if wood pellets are used, as they have lower moisture content and are a better fuel by quality and calorific heat value.

$PM_{2.5}$ and NOx emissions from The Wild Center boiler were higher than the smaller boilers burning woodchips and wood pellets. However, the SO_2 emissions were lower at The Wild Center in comparison to the two smaller boilers. The PM emission factors from Method 5 and CTM–039 for this boiler were in agreement, except when the boiler was operating in an unsteady manner.

The thermal efficiencies during steady-state operation calculated were between 70-77%, for both Walker Center and ACT Bioenergy boilers. The Wild Center boiler efficiency ranged between 61% and 85%. These efficiencies are lower than might be expected based on the reported European values reported by the vendor.

Assessment of the collection characteristics of a model ESP installed on a high efficiency, low emissions wood pellet boiler showed that the ESP efficiently captured the particles at the typical operating conditions. The estimated resistivity of the fly ash collected by the ESP was about 3×10^{10} ohm-cm at 120°C, indicating that ash resistivity was not a significant factor influencing the ESP performance. The ESP exhibited a high average collection efficiency of about 96 – 98% by mass at different boiler load conditions tested, reducing the total mass emissions to about 3.0 mg/m^3. The total capital cost for installing ESPs on full-scale advanced wood combustion systems was estimated at about $93,000, excluding site preparation costs. Annual operating and maintenance costs were estimated at about $15,000 while the ESP power consumption over a period of five months was estimated at approximately 4,350 kWh.

The measurements made in this study of high efficiency, low emissions European-designed wood boilers suggest that they represent a significant improvement over the stoker design wood boilers that were tested in the Vermont study. The stoker design represents the typically available commercial wood boiler in the U.S. If there is to be widespread use of renewable woody biofuels (pellets and chips obtained from sustainable forestry), then it is important that advanced gasification systems be used rather than conventional technologies to minimize emissions. From the available European literature, the staged combustion units in this study may not represent the state of the art in boiler design. Thus, there are additional opportunities to improve combustion efficiency with the potential of lower emissions and higher thermal efficiencies.

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Evaluation of the Energy and Emissions Performance of Commercial Scale Advanced Wood Combustion Systems

Final Report 10-15

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