New York State Energy Research and Development Authority

Evaluation of the Performance and Emission from Commercial Scale Advanced Wood Combustion Systems

Final Report

August 2010

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

Final Report

Prepared for the

New York State Energy Research and Development Authority

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NOTICE

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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. However, 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 provide high thermal efficiency and also greatly reduced emissions of pollutants from the stack.

In 2008, the New York State Energy Research and Development Authority (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 made by Hamont and imported from Austria, while Advanced Climate Technologies Bioenergy LLC (ACT) manufactured the other in the U.S. One 150 kW pellet-fired 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 at the ACT facility in Schenectady, NY prior to its installation at the Cayuga Nature Center. In addition, Clarkson has organized the stack testing of a 500 kW pellet system with the same burner design but manufactured by ACT, that was installed at the W!ld 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 and ACT boilers (150 and 500 kW) utilize 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 devolatilize 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).

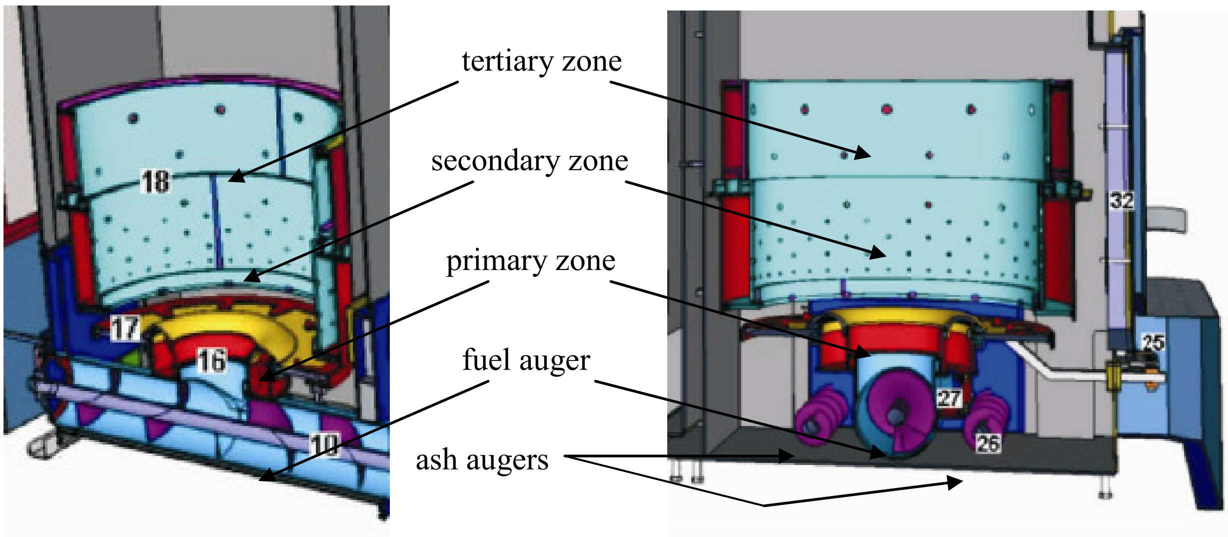

Figure 1. Detailed view of fuel feed auger, ash augers, and combustion zones of a Hamont Boiler. (Hamont European Operating Manual for CATfire 150-500 kW Wood Boilers).

Walker Center Boiler

The 150 kW (514,000 BTU h^{-1}) Hamont CATfire, installed at the Walker Center was unpressurized since it was not ASME certified. The boiler utilizes a triple air staging combustion process, which can lower NO_x 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 (45 lb h^{-1}) between 260,000 BTU hr^{-1} and 630,000 BTU hr^{-1}or 50% to 122% of rated nominal load.

Cayuga Nature Center Boiler

This 150 kW 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 fuel feed rate was at 48 lb h^{-1}.

W!ld Center Boiler

The boiler installed at the W!ld Center is the first ACT boiler made in the U.S. It is 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 energy required to heat the 54,000ft^2 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 W!ld 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 the boiler was run at 100% only by artificial manipulation. The measured gross calorific value of the pellet was 8059 BTU lb^{-1}.

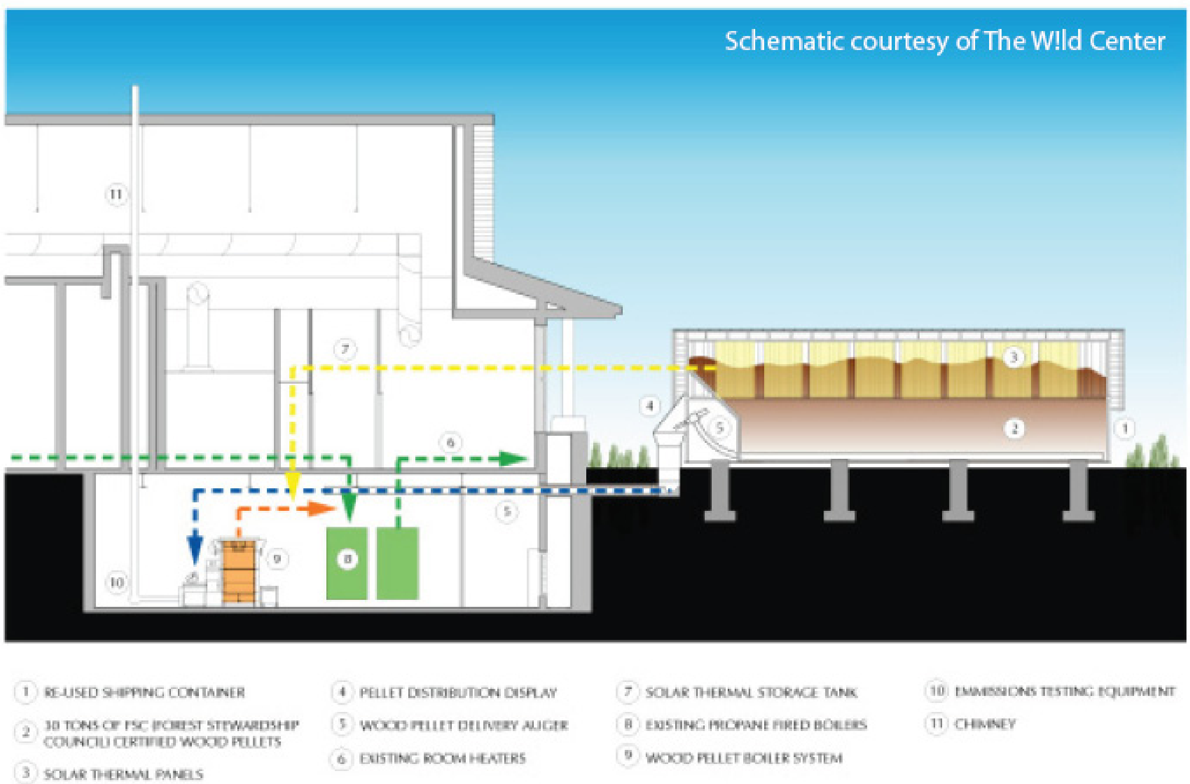

Figure 2. Schematics of commercial size pellet boiler with solar thermal system at the W!ld Center. Obtained from www.wildcenter.org.

All of these boilers were configured to operate with a CO/ λ control system to optimize combustion airflows. 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%. However, during the test of the 150 kW wood chip boiler, 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 much 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 W!ld Center pellets show nearly the same heat content as the pellets used in the 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	Pellets (W!ld 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 PM2.5 (particle matter <2.5 μm) concentrations were measured using a dilution tunnel sampling system obtained from Environmental Supply Co., Durham, NC conforming to Environmental Protection Agency's (EPA) 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 W!ld 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 150 kW pellet and chip boilers were determined by hand feeding a known quantity of pellets into each 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 was 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 W!ld 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 W!ld 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 W!ld Center. The water flow rate was not determined for the 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

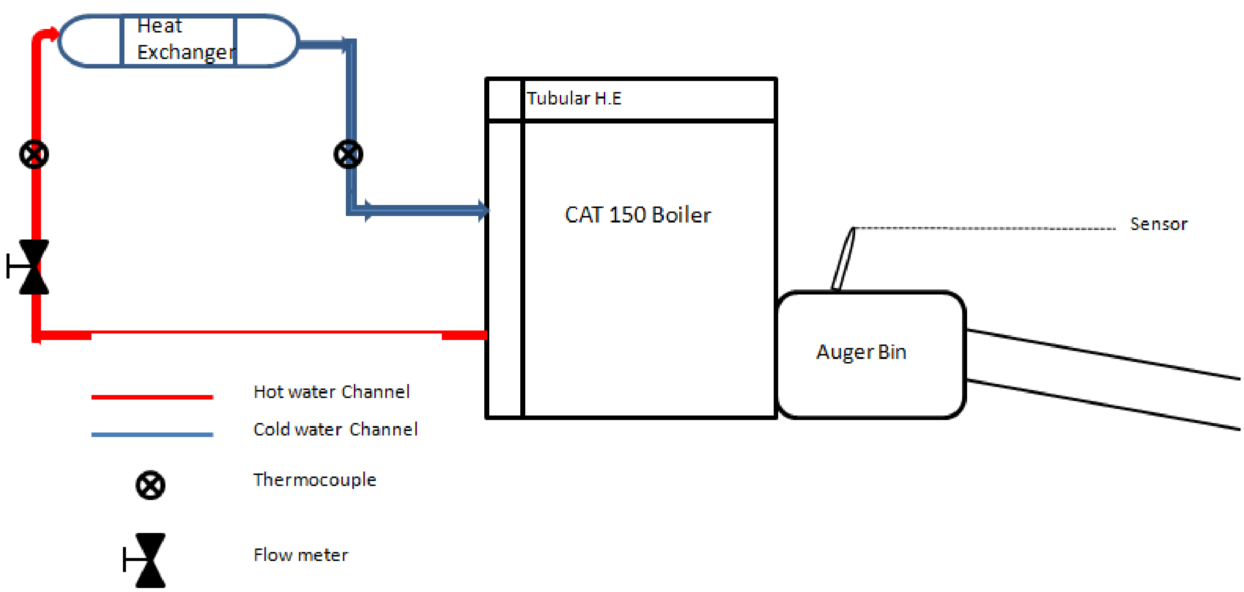

Figure 3. Illustration of boiler piping with approximate location of thermocouple and flowmeter.

MEASUREMENT RESULTS

150 kW Hamont wood pellet boiler at the Walker Center

The emission concentrations and emission factors of CO, NO_x, SO_2, $PM_{2.5}$, and particle OC and EC from the 150 kW pellet boiler at the Walker Center while it was operating at steady state are summarized in Table 2. All measurements were taken while the boiler was running at 72% of thermal capacity. The uncertainty values in Table 2 are 95% confidence intervals for the mean values. Figure 6 (solid lines) 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 lognormal with a peak in the accumulation mode. 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} # $MMBtu^{-1}$.

NIOSH Method 5040 analyzed eight 142 mm quartz filters for OC and EC, and IC analyzed anions and cations. 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 the Walker Center boiler stack emissions when burning wood pellets.

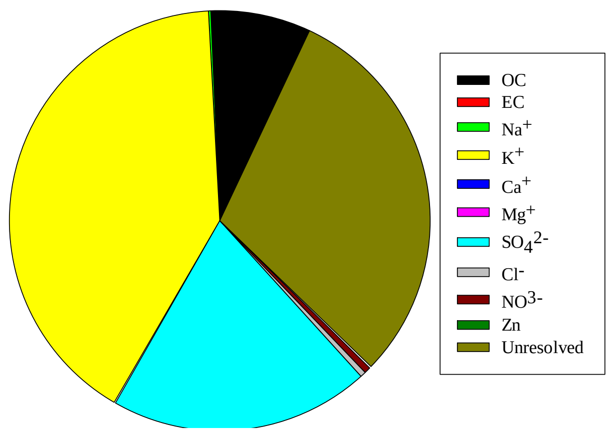

Figure 4. Pie chart of fine PM composition from stack emission of the Walker Center boiler when burning wood pellets at 72% of thermal capacity.

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 $\mu g\ m^{-3}$ and 160 $\mu g\ m^{-3}$, respectively. Levoglucosan, which has been used as a tracer for wood smoke, had the third highest concentration of 80 $\mu g\ m^{-3}$. 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 at 72% thermal capacity using premium wood pellets tested at the Walker Center, Clarkson University.

Emission Species	mg m^{-3}	g/kg	lb $MMBtu^{-1}$
CO	168 ± 1.76	2.16	0.27
NO_x	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 8 aggregated filter samples.

Table 3. Chemical Composition of $PM_{2.5}$. for 150Kw pellet boiler at the 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	± 0.00
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 27 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.

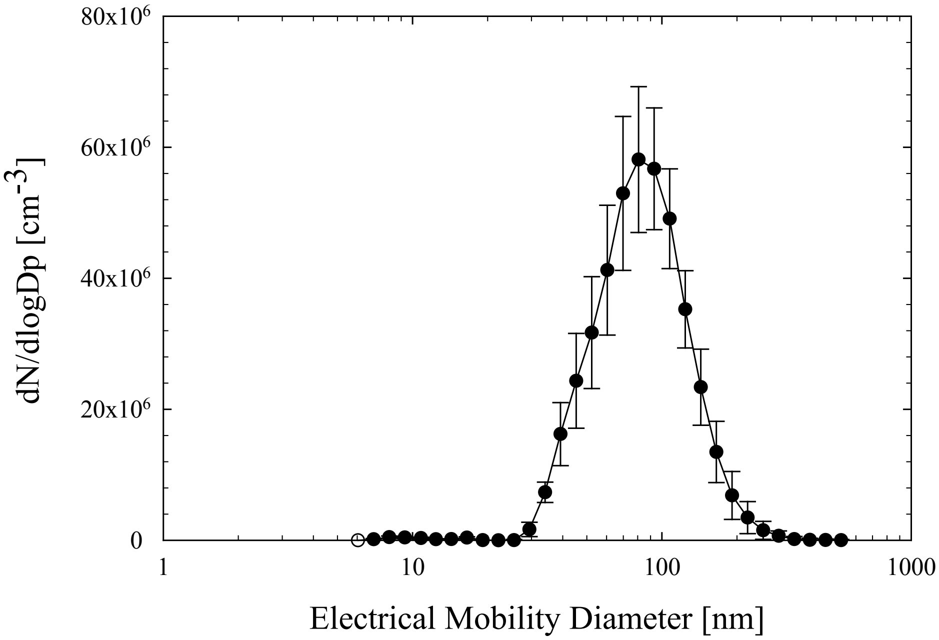

Figure 5. Ultrafine particle number size distribution during steady state of the boiler at the Walker Center, Clarkson University. Error bars are one standard deviation.

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 ($\mu g.m^{-3}$)	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 PAH emission concentrations and emission factors for a 150 kW boiler burning wood pellets at the Walker Center.

PAHs	Total ($\mu g.m^{-3}$)	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

150 kW Hamont Wood Chip-Fired Boiler (Cayuga Nature Center)

Table 6 summarizes the measured average emission factors for NO_x, SO_2, CO, $PM_{2.5}$, and total organic carbon (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. Figure 6 (dashed lines) shows the concentrations of criteria pollutants measured during steady state operation at 60 and 75% load of boiler for 150 kW boiler burning wood chips and pellets respectively. 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 boiler, possibly as a result of the variability in the oxygen concentration during these measurements.

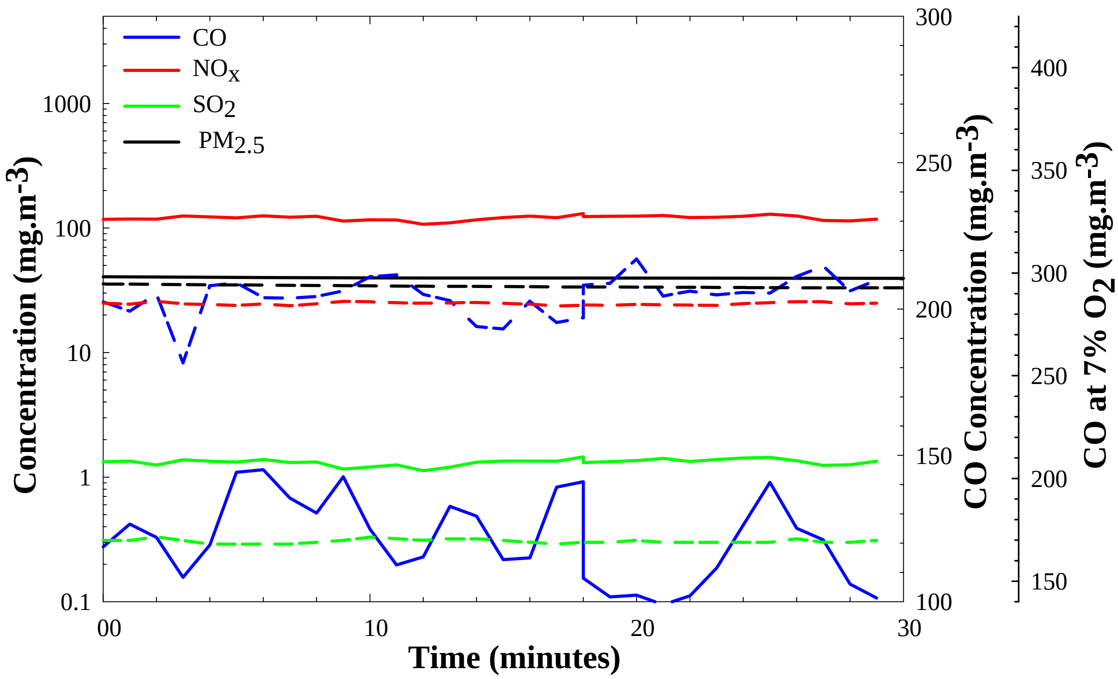

Figure 6. Concentration of criteria pollutants (CO, NO_x, SO_2 and $PM_{2.5}$) during steady state operation of 150 kW boiler (at full load). Dashed lines indicate data for wood pellets (Walker Center boiler) and solid line indicate data for wood chips (ACT Bioenergy boiler).

The NO_x, and SO_2 emission factors when using wood pellets were smaller than when burning wood chips. This result is likely 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).

Boiler shutdown operation was initiated at 17:30 hours by stopping the fuel feed (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 shutdown. Emissions data during boiler shutdown is available only for the 150 kW wood chip boiler.

In the particle phase, TOC is the sum of organic carbon (OC) and elemental carbon (EC). Measurements of OC and EC revealed that there were negligible amounts of EC on the filters. However, the EC concentration during shutdown operation was 5.8 mg m^{-3}, and the OC concentration was 20.3 mg m^{-3}.

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 $\mu g/m^3$, respectively, Table 7). As indicated earlier, the 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 $\mu g.m^{-3}$, respectively). Table 8 shows the average emission factors of major polycyclic aromatic hydrocarbons from the Cayuga wood chip-fired boiler.

Table 6. Average emissions from a high efficiency 150 kW Hamont boiler using wood chips as fuel at 60% boiler load.

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)	± 0.00 (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

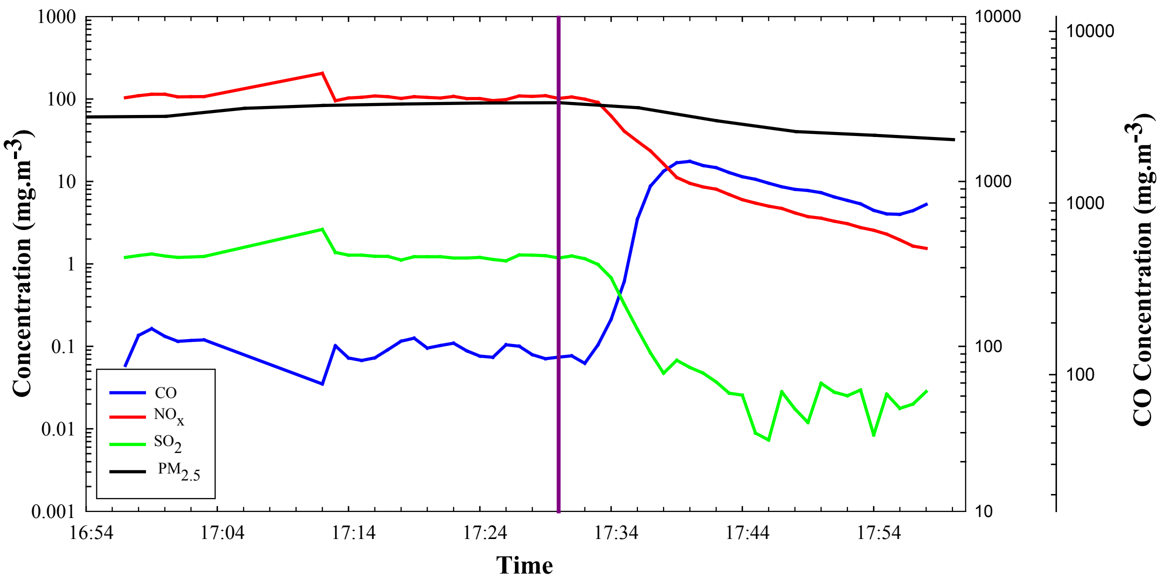

Figure 7. Concentration of criteria pollutants (CO, NO_x, SO_2 and $PM_{2.5}$) during shutdown of Hamont boiler burning wood chips. Boiler shutdown was initiated at 17:30 hours.

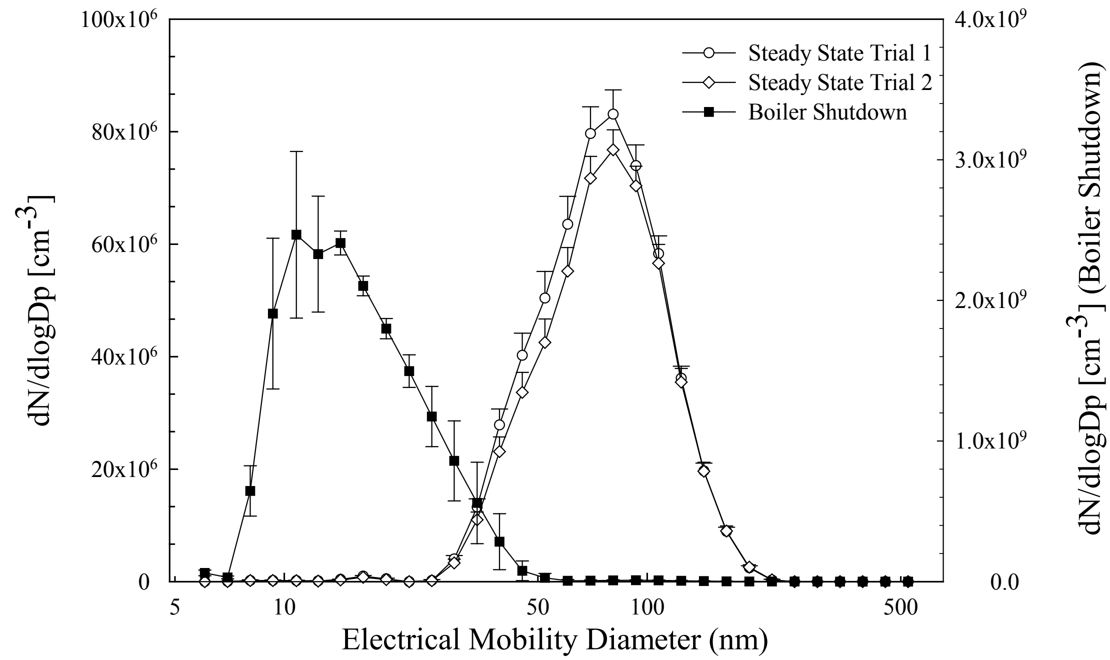

Figure 8. Average particle size distribution at full load during steady state operation and during boiler shutdown. Error bars in this figure are one standard deviation.

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-stagewood boiler using wood chips as fuel.

Compound	Total*	Total*	Total*
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.

500kW ACT pellet boiler at the W!ld Center

Figure 9 shows the concentration of criteria pollutants measured during operation at 100% load of boiler for a 500 kW boiler burning wood pellets. Table 9 gives the full load average emission factors of the 500 kW boiler at the W!ld 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 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 Btulb^{-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 the 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 April 20, 2010 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 10) was mostly operating in an unsteady state. Since Method 5 is an aggregated filter measurement, the operator was unable to turn off the system during this unsteady boiler operation and, therefore, kept the measurement system running. The CTM−039 measurement system and the TEOM FDMS system were 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 W!ld Center using wood pellets as fuel.

Emission Species	mg m^{-3}	g kg^{-1}	lb $MMBTU^{-1}$
CO	1182 ± 64.11	7.63± 0.58	1.21 ± 0.09
CO_2	96.74 ± 13.82	0.26±0.04	0.03 ± 0.00
NO_x	72.06 ± 0.79	0.421±0.015	0.07 ± 0.00
SO_2	0.92 ± 0.01	0.0049±0.0002	0.0007 ± 0.00
$PM_{2.5}$	55.50 ± 5.55	0.473±0.051	0.06 ± 0.01
Condensable PM	5.22 ± 0.46	0.044±0.04	0.004 ± 0.00
TOC*	2.27 ± 0.29	0.08±0.02	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. Condensable PM was measured using EPA OTM -28.
*- Data based on three aggregated 142 mm 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.
Data collected using Teflon filter, averaging time was typically about one hour.
Data collected using TEOM FDMS system.

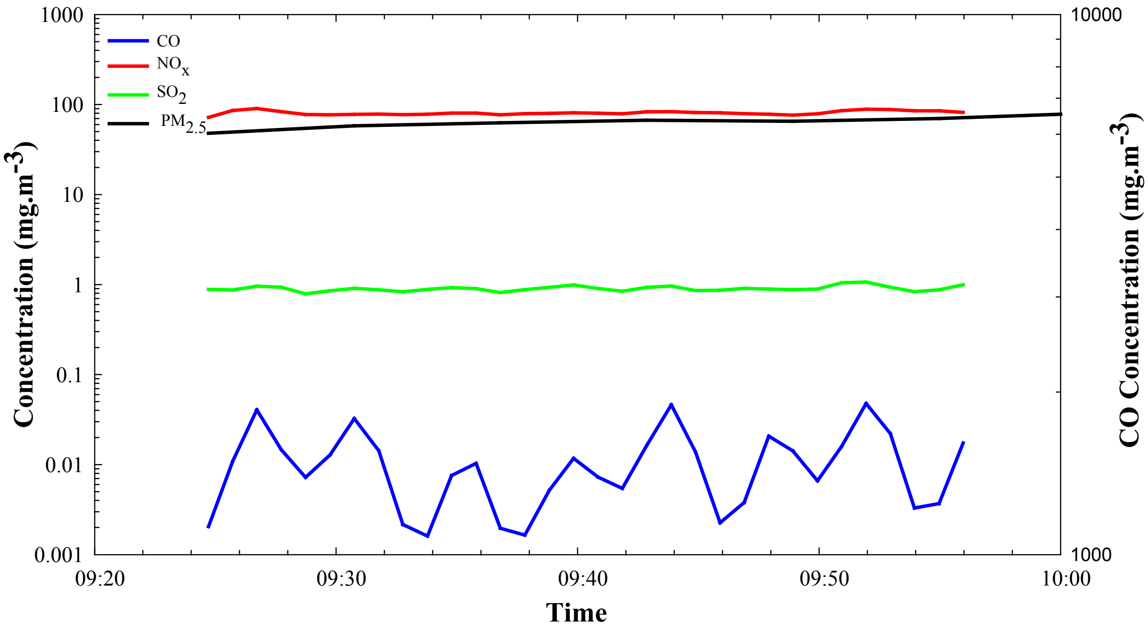

Figure 9. Concentration of criteria pollutants (CO, NO_x, SO_2 and $PM_{2.5}$) during steady state operation of 500 kW boiler (at full load).

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; whereas 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. EN303-5 method includes two 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, NO_x 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 U.S. 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 was found to be coated with paint. Moreover, measurements at the W!ld 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 W!ld 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	_
$\mathbf{NO_x}$ ($mg.m^{-3}$)	136	153	135	26	119	72	-
η_{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.
CTM–039 measurements are averages of at least 8 hours of measurements.
EPM Method 5 are averages of about 2 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. However, based on the TEOM FDMS measurements (Raja *et al.*, 2009), and the condensable fraction obtained from OTM-28 for W!ld 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 27%. The ash content and the moisture content in the wood pellets being combusted at Clarkson were 0.6% and 4.8%, 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 (EPA, 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. The 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) (EPA, 2010). Measurements on conventional boilers suggest there is a reasonable correlation between CO and POM. Figure 10 shows the correlation between the sums 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.

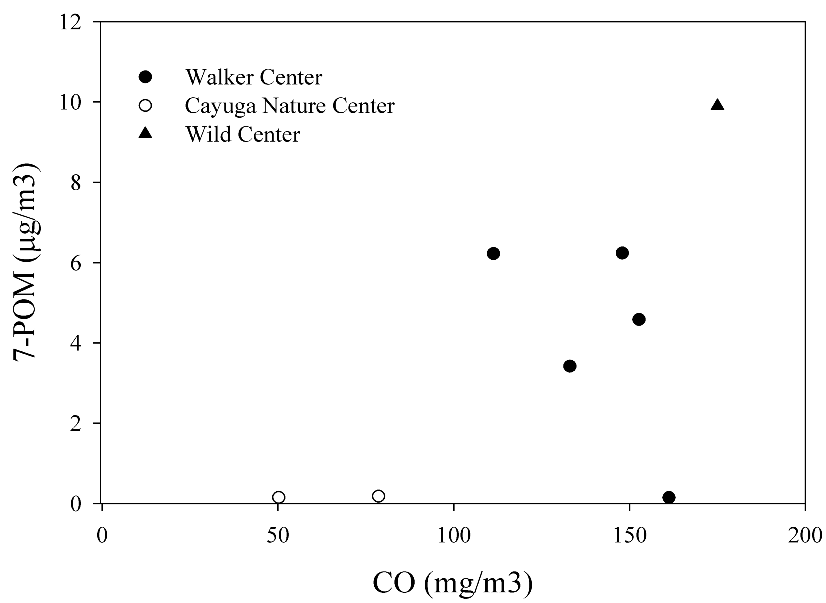

Figure 10. Relationship between seven selected POM compounds with CO in the stack emissions.

THERMAL EFFICIENCY RESULTS

Spring 2010 Measurements

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 91% 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 the Walker Center, and from 61−62% when the boiler was manipulated to run at 100% of the set fuel feed rate (Figures 11 and 12).

Most of the W!ld 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 the 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) were about 8°F during the Walker Center measurements, 10°F during the Cayuga boiler measurements, and 18°F during the W!ld Center measurements. Although the ΔT (in °F) during the W!ld 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 W!ld Center boiler is most likely due to the larger capacity of the boiler (500 kW) and a higher fuel intake rate.

Table 12. Thermal efficiency of the 150 kW Hamont and 500 kW ACT boilers at different heat inputs and with different fuels.

Test Period	Fuel	Input rate (kW)	Output rate (kW)	Boiler Capacity (%)	$\eta_{thermal}$ (%)
Spring 2011	pellets	182	125	36	$68^{\#} \pm 3$
Spring 2011	pellets	202	152	40	$75^{\#} \pm 1$
Spring 2011	pellets	271	212	54	$78^{\#} \pm 3$
Spring 2011	pellets	330	279	66	$84^{\#} \pm 2$
Spring 2011	pellets	404	360	81	$89^{\#} \pm 2$
Spring 2011	pellets	459	420	92	$91^{\#} \pm 1$
Spring 2011	pellets	88	77.1	59	$73^{\#} \pm 4$
Spring 2011	pellets	104	64	69	$79^{\#} \pm 3$
Spring 2011	pellets	122	77	81	$82^{\#} \pm 3$
Spring 2011	pellets	147	91	98	$86^{\#} \pm 2$
Spring 2010	pellets	620	448	-	66* ± 2
Spring 2010	pellets	379	303	76	$80^{*\#} \pm 2$
Spring 2010	pellets	694	458	-	$66^{*} \pm 1$
Spring 2010	pellets	476	309	95	$65^{*} \pm 6$
Spring 2010	pellets	107	77.1	71	$72^{*} \pm 4$
Spring 2010	pellets	129	80.1	86	62* ± 4
Spring 2010	pellets	131	81.7	87	62* ± 4
Spring 2010	pellets	152	92.8	101	61* ± 4
Spring 2009	chips	86	62.2	57	$72^{\#} \pm 5$
Spring 2009	pellets	114	86.9	76	$77^{\#} \pm 7$

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

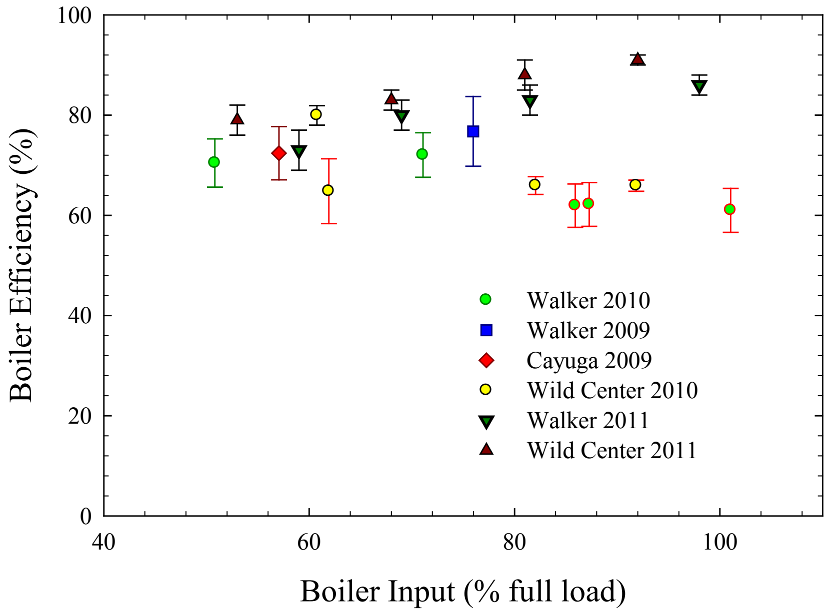

Figure 11. Thermal efficiency of the Walker Center, ACT Bioenergy and W!ld Center boilers using the gross calorific value with 95% confidence intervals. The data points with red edges indicate data when the boiler was manipulated to run at 100% of the selected feed rate.

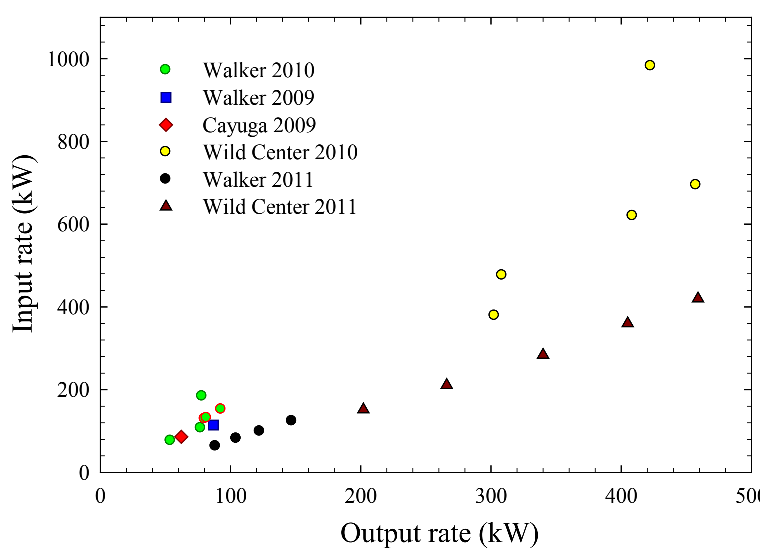

Figure 12. Comparison of thermal energy input rate and output rate of the Walker Center, ACT Bioenergy and W!ld Center boilers (input rate calculated using the gross calorific value). The data points with red edges indicate data when the boiler was manipulated to run at 100% of the selected feed rate.

There could be several reasons to explain these estimated lower thermal efficiencies. The studies at the W!ld 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 W!ld Center are expected to be most likely due to lower heat demand. Low heat demand from the W!ld 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.

Additional Measurements during the 2010-11 Heating Season

Over the 2010−2011 heating season, it was possible to collect additional thermal efficiency data on the Walker Center and W!ld Center boilers under normal operating conditions. The external heat exchanger for the boiler at the Walker Center was insulated to avoid the heat losses. Because of the continuous monitoring system at the W!ld Center, there was substantially more data available on hourly basis that was averaged for 24 hours, than was collected manually at the Walker Center which was an average of four hours at each load. Both the Walker Center (70−86%) and W!ld Center boilers (68%−91%) had similar thermal efficiency ranges at the various energy input rates (% full load) tested. Boiler input and output energy were linearly related (Figure 13) and efficiency increased with input rate (Figure 14). The maximum efficiency measured was about 86% for the 150 kW pellet boiler and 91% for the 500 kW pellet boiler (Figure 14). The measured efficiencies were in good agreement with European measurements of the same model boilers (Figure 14).

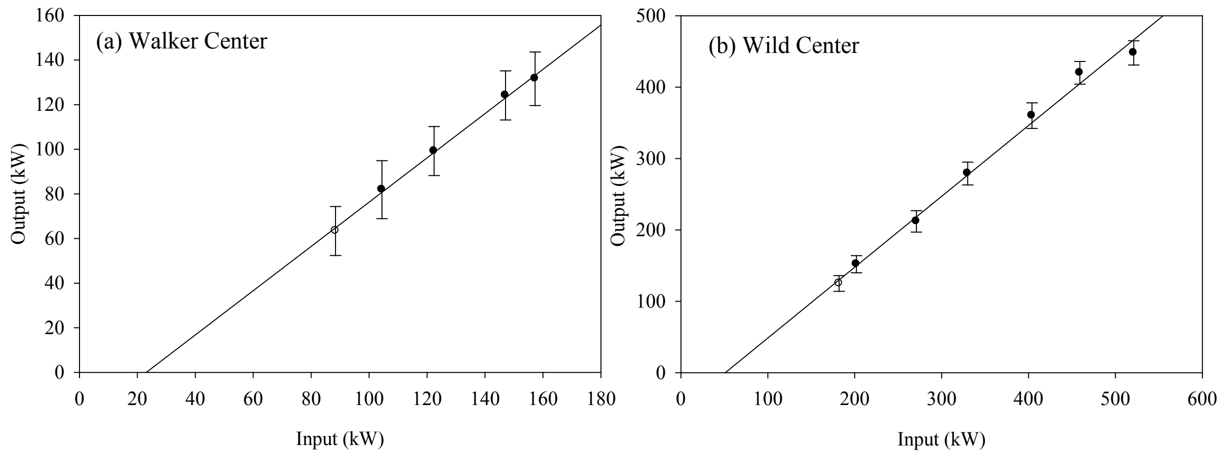

Figure 13. Thermal energy input rate and output rate of (a) the 150 kW pellet-fired boiler by Hamont tested at the Walker Center and (b) 500 kW ACT pellet-fired boiler tested at the W!ld Center (input rate calculated using the gross calorific value).

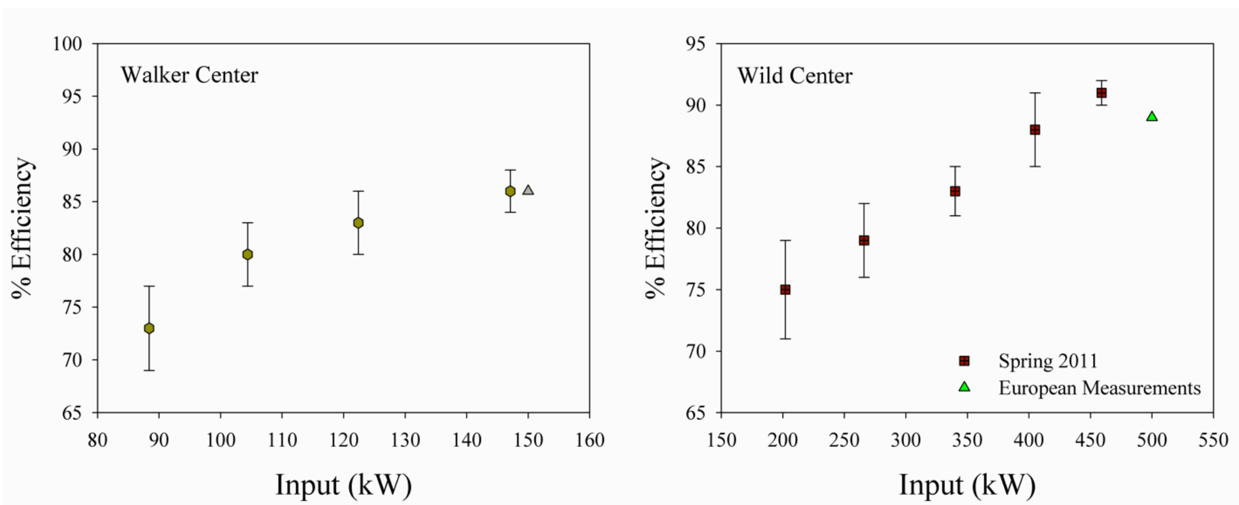

Figure 14. Thermal efficiency of (a) 150 kW Hamont pellet boiler tested at the Walker Center and (b) 500 kW ACT pellet boiler tested at the W!ld Center boilers for various energy inputs.

Thus, when these systems are operating in a normal fashion during the heating season, they show a much more consistent pattern of thermal efficiencies with the two boilers behaving similarly.

Comparison of Emissions from Other Wood Fired Boilers and Heating Equipment

Emissions from residential wood fireplace 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 $MMBTU^{-1}$).

Tables 14a and 14b 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 wood stove studies from McDonald, 2009 is mostly residential scale appliances, which is smaller when compared to the current study. The $PM_{2.5}$ and NO_x 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 NO_x 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 W!ld 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:

(% 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 W!ld 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 variability for the fuels used in this study 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 14a. Comparison of emission factors of criteria pollutants from No. 6 Oil fired boiler (England, 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 14b. Comparison of emissions from residential wood stoves and commercial size wood boiler.

	Appliance type	Scale	Over Feed	Drop down feed	Electric ignition	Gasification unit
			lbs/MMBtu			
PM2.5 Emissions	Stoves I*	Residential	0.065	0.09	0.056	-
	Stoves J*		0.047	0.056	0.051	-
	Stoves K*		0.056	0.052	0.049	-
	CAT 150kW	Commercial				0.06
	CAT 500kW					0.06

*BNL -91286-2009, Roger. J. McDonald

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*	-
W!ld Center Museum (this work) Tupper Lake, New York	ACT, Gasification	Cyclone	Wood Pellets	CTM – 039	1.7	0.06*	-
W!ld 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]	Messersmit h, 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]	Messersmit h, 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 (AWCs) 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 process operating conditions significantly influences the performance of an ESP in terms of its collection efficiency. 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:

Particles in the stack are reportedly inorganic salts with essentially no organic material;

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; and

Wood pellets or wood chips used in AWC 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°C while the exhaust gas temperature was 29.4 ± 2.5°C. 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 3×10^{10} ohm-cm at 120°C (Figure 13). The Bickelhaupt's model predicts that the resistivity would be lower (~ 10^9 ohm-cm) at lower temperatures and highest (~ 2×10^{12} ohm-cm) at about 250°C. 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°C.

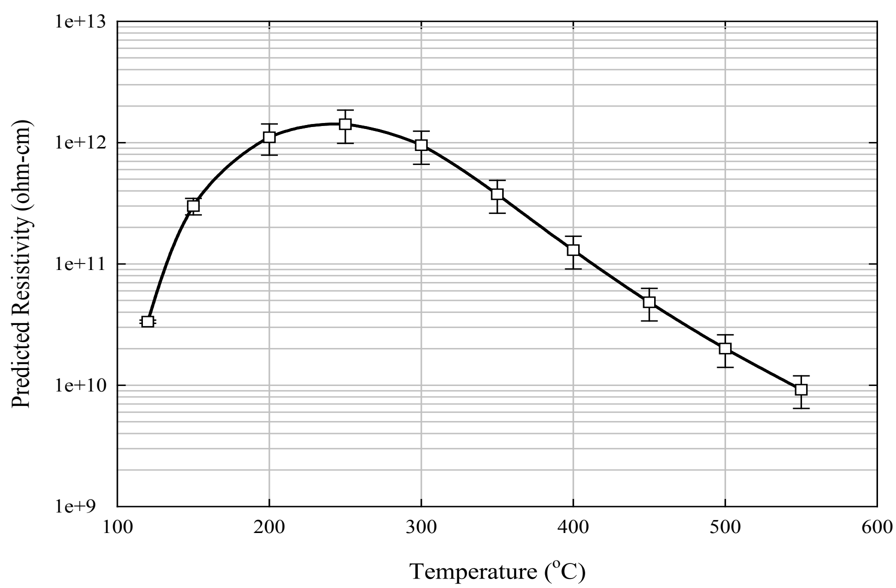

Figure 13. Ash resistivity as predicted from the Bickelhaupt's model

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 $3x10^7$ #/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 AWC 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 AWC 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 $100,000 or less, the total cost of maintenance is approximately 5% of the total capital cost. That is 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 NO_x 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 W!ld 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 NO_x emissions from the W!ld Center boiler were higher than the smaller boilers burning woodchips and wood pellets. However, the SO_2 emissions were lower at the W!ld 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 the Walker Center and ACT Bioenergy boilers. The W!ld Center boiler efficiency ranged between 61% and 91%. 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 $3x10^{10}$ 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 have been previously used in the U.S. 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. 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. Such improved performance will be necessary to make such systems more competitive with oil-fired boilers that currently represent boilers with similar efficiencies but lower emissions of pollutants particularly particulate matter.

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