Methods and Technologies for Demonstrating a Small Wood-Fired Boiler's Compliance with PM2.5 Air Quality Standards

Prepared For June 2008 Air & Waste Management Association's Annual Conference and Exhibition

Portland, Oregon

Paper #659

John A. Hinckley, QEP

Colin J. High, Ph.D., QEP

ABSTRACT

Concern for rising oil prices and global climate change has spawned a movement among institutions (high schools, colleges, universities, hospitals, etc.) to convert their building heat source from fossil fuel to woody biomass, specifically wood chips. While conversion to wood chips has alleviated some concerns, it has caused another concern, specifically a concern for health impacts from fine particulate matter (PM2.5) emissions. This is because wood chip combustion results in higher PM2.5 emissions than from combustion of liquid or gaseous fossil fuels. Consequently, consultants, engineers, equipment vendors, state pollution control officers, and others are working together to design wood-fired heating systems (wood-fired boilers) meeting National Ambient Air Quality Standards (NAAQS) and Prevention of Significant Deterioration (PSD) Requirements for PM2.5.

This paper will summarize a recent air quality study which helped identify a design for a wood-fired boiler for a new middle school meeting the newer, more stringent PM2.5 air quality standards. Air dispersion modeling determined a stack height and inside diameter that would provide the amount of atmospheric dispersion needed. A high efficiency multicyclone was identified as Best Available Control Technology (BACT) as information reviewed indicated significantly more PM2.5 can be controlled with a high efficiency multicyclone than a conventional multicyclone. The BACT analysis also found that a more effective technology, fabric filtration, was not technically feasible given the operating climate of a relatively small wood-fired boiler.

A small wood-fired boiler was defined for this study as a wood-fired boiler having a design heat input less than or equal to 10 MMBtu/hr. This paper will focus on methods and technologies identified for demonstrating a small wood-fired boiler's compliance with PM2.5 air quality standards.

INTRODUCTION

Concern for rising oil prices and global climate change is why many institutional facilities are converting their building heat source from fossil fuel to woody biomass, specifically wood chips. Conversion to wood chip fuel can mitigate economic, global climate, and national security concerns, but can cause health impacts from exposure to fine particulate matter (PM2.5) emissions and associated toxic air pollutants. This is because wood chip combustion can produce more PM2.5 emissions than liquid or gaseous fossil fuel combustion. In response to this concern, manufacturers, engineers, state pollution control agencies, and others have been working together to design wood heating systems (wood boilers) which can meet National Ambient Air Quality Standards (NAAQS) and Prevention of Significant Deterioration (PSD) Requirements for PM2.5.

This paper summarizes work recently completed for the first institutional wood boiler permitted in Rhode Island. The work involved developing a design for a wood boiler and associated air pollution control equipment for a new middle school that would meet the newer, more stringent PM2.5 air quality standards. Air dispersion modeling determined a stack height and inside diameter that would provide the amount of atmospheric dispersion needed. A Best Available Control Technology (BACT) evaluation determined the appropriate pollution control technology. A high efficiency multicyclone was identified as BACT as information reviewed indicated significantly more PM2.5 can be controlled with a high efficiency multicyclone than a conventional multicyclone. The BACT analysis also found that a more effective technology, fabric filtration, was not technically feasible for institutional wood-fired boilers having a heat input less than 10 MMBtu/hr.

The EPA strengthened the National Ambient Air Quality Standard (NAAQS) for PM2.5 in December 2006. In this, the 24-hour standard was lowered from 65 $\mu g/m^3$ to 35 $\mu g/m^3$ and the annual standard (15 $\mu g/m^3$) was not changed. EPA has also proposed PSD requirements and Significance Levels for PM2.5. In addition, a number of states have developed interim air dispersion modeling guidance. Given that there are a number of critical components of PM2.5 regulations which have not yet been finalized by EPA, the following questions had to be answered by the consultants (authors) and the permitting agency (Rhode Island Department of Environmental Management, or RI DEM) during the permitting process:

1) How should the PM2.5 background concentration be estimated?
2) What PM emission limit is applicable?
3) What pollution controls will ensure emission limits are met?
4) How should air dispersion models be configured to estimate 24-hour PM2.5 impacts?

A number of methods and technologies for demonstrating compliance with PM2.5 air quality standards were developed in answering these questions. These findings were incorporated into the design for a new wood boiler with a design heat input capacity of 4.6 million BTUs per hour (MMBtu/hr) at the Ponaganset Middle School in Glocester, Rhode Island.

STUDY AREA DESCRIPTION

The study area is located in Glocester, Rhode Island, which is located in northwest Rhode Island. The area is rural and has relatively hilly terrain. The site itself is relatively flat and is located near the top of a hill. The area immediately surrounding the site is composed mainly of forests, fields and is therefore not densely populated. There were no other air significant pollution sources near the site.

There is one contiguous school building composed of approximately four tiers ranging from 4.9 meters (16 feet) to 13.4 meters (44 feet). The wood boiler plant is included within the building envelope. The stack is located adjacent to the east side of the building and is near the tallest tier. The stack base elevation was assumed equal to the building's finished floor elevation; therefore, the stack would have to be at least 44 feet to reach the highest building elevation. There are no other significant buildings on the site.

WOOD BOILER DESCRIPTION

The wood boiler evaluated is a close-coupled gasifier manufactured by Chiptec®. The Chiptec system consists of two combustion chambers in series. In the first chamber, wood is heated in oxygen-deprived conditions to convert the wood to gas via a pyrolysis process. The gas is then ignited in a burner and combusted in the second chamber. The average flame temperature in the second chamber is between 2,100ºF and 2,300ºF for all operating capacities except pilot mode. The combustion process has a thermal efficiency of approximately 75%.[1]

This wood boiler's heat input capacity of 4.6 MMBtu/hour corresponds to a fuel consumption rate of 0.46 tons per hour, assuming a heat content of 5,013 Btus per pound of wood chips. This maximum fuel consumption rate does not occur every hour of a 24-hour period. The majority of wood boilers in New England operate at maximum load (high fire) for approximately 5% of a 24-hour period, even the coldest days of the year. This is because the operating capacity of institutional boilers is a function of building heat demand, which fluctuates significantly throughout the course of a 24-hour period. The system will therefore modulate between pilot, low-fire, and medium-fire modes throughout most of the course of a day. Despite operating load fluctuation, the air dispersion modeling, described later in this paper, reflects maximum load (high-fire) operating conditions for all hours in a 24-hour period.

Three size classes of wood boilers were identified by the BACT analysis. Small wood boilers are less than 10 MMBtu/hr (heat input), medium wood boilers are 10–30 MMBtu/hr, and large wood boilers are greater than 30 MMBtu/hr. 10 MMBtu/hr is the threshold level above which the New Source Performance Standard (NSPS) is applicable; 30 MMBtu/hr is the threshold level at which a stricter PM emission limit is required by the NSPS (0.030 lb/MMBtu compared to 0.10 lb/MMBtu).[2]

---

[1] www.chiptec.com

[2] US Code of Federal Regulations, Title 40, Part 60, Subpart Dc, Standards of Performance for Small Industrial-Commercial-Institutional Steam Generating Units.

The wood boiler being evaluated has a design heat input value of 4.6 MMBtu/hr and is therefore not subject to the NSPS. However, the Rhode Island permit applicability limit for solid fuel burning devices is 1.0 MMBtu/hr. Consequently, this wood boiler required a pre-construction permit from the RI DEM Air Resources Division.

BACKGROUND CONCENTRATION

The background concentration is the existing ambient air concentration of a given pollutant in a given area. Background concentrations are measured by state air pollution control agencies according to EPA methodology. Data from the ambient air monitoring station at the W. Alton Jones Campus of the University of Rhode Island in West Greenwich was used. The 98th percentile 24-hour averages for each year in a five-year period were averaged to calculate the 24-hour background concentration.[3] The 98th percentile concentration is typically exceeded 2% of all 24-hour periods in a given year; therefore, the 98th percentile value can be considered a relatively conservative estimate of background concentration. A 24-hour background concentration of 27.4 $\mu g/m^3$ was calculated based on the aforementioned method. Therefore, the study area is in attainment with the 24-hour NAAQS for PM2.5 of 35 $\mu g/m^3$.

The annual background concentration was the maximum annual average concentration for a five year period. This value, 8.1 $\mu g/m^3$, also meets the annual NAAQS for PM2.5.

PM EMISSIONS LIMIT

The total particulate matter (PM) emitted from wood boilers is the sum of filterable and condensable particles in the exhaust. PM2.5 and PM10 are the two size fractions of PM typically evaluated. PM10 is all particles having an aerodynamic diameter less than or equal to 10 microns. PM2.5 is all particles less than or equal to 2.5 microns. The fraction of PM2.5 in total PM varies with the type of wood combustion process. In general, approximately 50% and 90% of PM emissions are PM2.5 in stoker and close coupled gasification systems respectively.[4] Both these systems typically emit less than 0.25 lb/MMBtu of total PM, when controlled with a mechanical collector, such as a single-cyclone or multicyclone.

The PM2.5 emissions limit was a function of air dispersion modeling results, a BACT analysis, and choice of wood chip supply source. The air dispersion modeling and BACT analysis are described later in this paper. According to Rhode Island Air Pollution Control Regulations, a PM emission limit of 0.10 lb/MMBtu is mandatory for all wood boilers combusting wood residue from the pulp and paper industry.[5] If not, the emission limit is determined by other factors, such as the specifications of the proposed alternative wood fuel,

[3] Since completion of this study, it was learned that a number of states have decided to accept the average of the 98th percentile concentration from the last three years.

[4] BACT Report for Ponaganset Middle School. Resource Systems Group, Inc., White River Junction, Vermont. Prepared for the Foster-Glocester Regional School District, February 2007.

[5] Wood residue is defined in Rhode Island Regulation No. 13 as a “waste by-product of the pulp and paper industry which consists of bark, sawdust, slabs, chips, shavings, and mill trims.”

air dispersion modeling results, and BACT analysis results. It was decided not to purchase wood residue from the pulp and paper industry, so a higher emission limit became possible.

The PM limit identified for this project was 0.20 lb/MMBtu. The wood boiler proposed for this project was a close coupled gasifier; therefore, a PM2.5 emission limit of 0.18 lb/MMBtu was determined by multiplying the PM emission limit (0.20 lb/MMBtu) by the expected PM2.5 fraction (90%).

BACT ANALYSIS

A top-down BACT analysis was performed to identify necessary emission controls for the proposed wood boiler. The analysis considered "inherently lower emitting processes and practices" and add on emission controls. The following inherently lower emitting processes and practices were identified first:

1) *Cleanest available fuel*. Combustion of clean wood chips, having a moisture content between 25 and 45% and minimal bark content.
2) *Plume opacity observation*. Regular qualitative observations of exhaust plume opacity during normal operating conditions. Make adjustments to the wood boiler if excessive opacity is noted.
3) *Proper operation and maintenance*. Operation and maintenance according to the manufacturer's recommendations to promote safety and efficiency.
4) *Combustion efficiency testing*. In conjunction with regularly scheduled tune-ups, measure the carbon monoxide (CO) and carbon dioxide (CO_2) concentrations under normal operating conditions. Combustion efficiency must be 99% or greater according to the following equation:

   Combustion efficiency (%) = CO_2/ (CO_2 + CO) X 100

   Where:

   CO_2 = carbon dioxide concentration in the exhaust gas.

   CO = carbon monoxide concentration in the exhaust gas.

5) *Good combustion conditions*. High combustion chamber temperatures combined with a proper mix of air and fuel to promote complete combustion of pollutants.
6) *Staged combustion*. Spatially distribute the combustion process to promote an even mix of air, fuel and fire.
7) *Automated operating controls*. Automated controls ensure optimal fuel, air, and temperature management in real time. This is accomplished by equipping the wood boiler with sensors to measure oxygen concentration, fuel level and combustion chamber temperature. Information measured by the sensors is then incorporated in a computer operating program which regulates the air and fuel mixture and any other operating parameters.

8) *No fly ash re-injection*. Collection and reinjection of relatively large fly ash particles can break them into smaller particles thereby increasing PM2.5 emissions.

The following add on controls were considered:

1) *Mechanical collectors*. These devices use centrifugal forces to separate particulate matter from an exhaust gas stream. Multicyclones have higher collection efficiency than single cyclones because exhaust gas is routed through multiple cyclones in series or parallel. High-efficiency multicyclones have higher collection efficiency than multicyclones as their design typically includes more cyclones and a higher pressure drop.
2) *LSR core separator*. Similar in design to a high-efficiency multicyclone, but differs in that exhaust gas is recirculated to promote higher centrifugal separation at lower operating capacities. This was previously determined as BACT in a 2001 report written by Resource Systems Group, but was not commercially available at the time this study was performed.[6]
3) *Venturi scrubber*. Particles are absorbed by a liquid sprayed within a chamber. Often used in conjunction with a packed tower.
4) *Electrostatic precipitator (ESP)*. Based on the principle of electrostatic attraction between oppositely charged surfaces. Particles in the exhaust gas gravitate to an oppositely charged surface.
5) *Baghouse*. Exhaust gas is routed through an enclosed structure containing fabric filters, which retain particles and allow exhaust to pass through.

There were no demonstrated applications of ESPs, venturi scrubbers, or baghouses identified for the size wood boiler being considered. The LSR Core Separator was not commercially available at the time of the study so it was also ruled out. Therefore, mechanical collectors, specifically the high efficiency multicyclone was determined as BACT.

There has been significant interest as to whether a baghouse or mechanical collector is most appropriate for small wood boilers. The BACT analysis determined a baghouse was not technically feasible for this application due to a problem defined as filter bag clogging. In this, during periods of low operating capacity (pilot mode to low fire), exhaust gas temperature drops below the dew point, causing moisture to condense on fabric filter cake (dust which as accumulated on the fabric filter). The dust particles composing the cake are bound together by the moisture and form an impermeable surface, which cannot be removed by pulsing. These conditions cause significantly high pressure drops and ultimately lead to bag and overall system failure. For this reason, the baghouse vendor for this project could not guarantee that filter bag clogging would not occur.

Given the proposed wood boiler would operate for significant time periods at low operating capacity, such as weekends and holidays, when neither custodial nor technical staff are present, the filter bag clogging would be expected to occur. Therefore, a baghouse was deemed technically infeasible for the project.

---

[6] An Evaluation of Air Pollution Control Technologies for Small Wood-Fired Boilers. Resource Systems Group, 55 Railroad Row, White River Junction, Vermont 05001. September, 2001.

AIR DISPERSION MODELING

Air dispersion modeling was conducted to identify an exhaust stack height and diameter that would provide the plume dispersion needed to meet air quality standards. First, a Good Engineering Practice (GEP) stack height analysis was performed to determine what stack height is necessary to prevent impacts from building downwash, a condition which occurs when a pollution source's exhaust is drawn downward by turbulent air flow around buildings. The information from the GEP analysis was incorporated into AERMOD, an air dispersion model which predicts air quality impacts.

The U.S. EPA BPIP-Prime Model (Version 04274) was used. The GEP formula height was calculated using the dimensions of all buildings on site. Locations and dimensions of pertinent building geometry were derived from a USGS map, a digital orthophoto, and architectural plans. The information from these data sources was converted into the coordinates required as input to BPIP-Prime. The GEP equation height for this project was 34.2 meters (112.2 feet). The final height selected was 19.8 meters (65 feet).

AERMOD (version 07026) was used to estimate air quality impacts in all terrain regimes, including the building cavity (terrain adjacent to relevant buildings), simple terrain (terrain between stack base and stack top elevations), and complex terrain (terrain whose above the stack top). AERMOD is an EPA guideline model and includes the algorithms needed to evaluate all terrain regimes, including the prime downwash algorithm. This algorithm is especially useful because it can be used to estimate the extent of building downwash impacts for emissions from stacks below their GEP formula height. As stated above, the stack height selected for this project was below the GEP formula height.

A polar receptor grid was developed. Receptors (locations where the model calculates pollutant concentrations) were placed at 10º increments with the following spacing away from the wood boiler stack: 20-meter spacing to 200 meters, 50-meter spacing from 200 to 500 meters, 100-meter spacing from 500 meters, and 500-meter spacing from 1,000 meters to 5,000 meters. While not required by RI DEM, flagpole receptors were also placed over the building roof to determine if rooftop air handling units would be contaminated by wood boiler exhaust. As the name suggests, flagpole receptors are receptors at some determined height above ground (flagpole height).

Refined meteorology was obtained directly from RI DEM. Surface files correspond to Providence, RI. Profile (upper air) files correspond to Chatham, Massachusetts. These files were processed with AERMET according to RI DEM guidance. In particular, land use was modeled with one 360º sector and urban land use parameters. Land use parameters were derived from the AERMET User's Guide.[7]

[7] User's Guide for the AERMOD Meteorological Preprocessor (AERMET). EPA-454/B-03-002. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Emissions, Monitoring, and Analysis Division Research Triangle Park, North Carolina 27711. November 2004

Model output was configured as follows. For 24-hour results, the model was programmed to output sixth highest 24-hour average for each year modeled.[8] The model was programmed to output the annual average for each of the five years to model annual average concentrations.

According to RI DEM guidance, 100% load conditions were modeled for the 24-hour averaging period. Consumption of the entire proposed annual fuel cap was modeled for the annual averaging period. Air dispersion modeling results are compared with NAAQS and PSD requirements below. As shown, all standards are met.

Table 1: PM2.5 Modeling Results Compared with National Ambient Air Quality Standards

Averaging Period	Model Result (μg/m^3)	Background Concentration (μg/m^3)	Total Concentration (μg/m^3)	NAAQS (μg/m^3)
24 hour	6.0	27.4	33.4	35
Annual	0.4	8.1	8.5	15

Table 2: PM2.5 Modeling Results Compared with Proposed Prevention of Significant Deterioration Requirements

Averaging Period	Model Result (μg/m^3)	Proposed PSD Requirement (μg/m^3)
24 hour	6.0	9
Annual	0.4	5

CONCLUSION

Permitting work has been completed for the first institutional wood boiler in Rhode Island. Air dispersion modeling showed NAAQS and PSD requirements can be met with a stack that is 21 feet above the maximum building height and 47 below the GEP formula height, when the system is operating at maximum load at all times in a 24-hour period. The BACT analysis showed all add-on controls except mechanical collectors were technically infeasible. The high efficiency multicyclone was selected as BACT and will enable the wood boiler to meet a PM2.5 emission limit of 0.18 lb/MMBtu.

[8] Since this project was completed, other states have determined that a three-year average of each year's eighth highest 24-hour average is acceptable, assuming the highest eighth high values are derived from a five-year modeling period.