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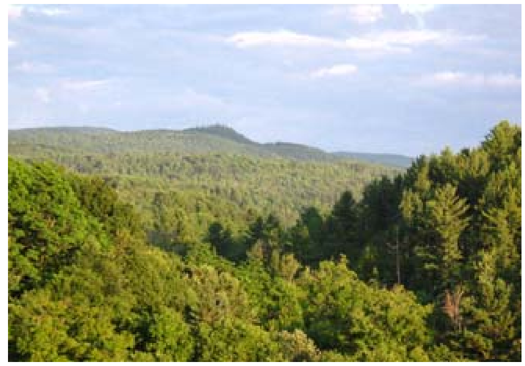

Emission Controls for Small Wood-Fired Boilers

Prepared for:

United States Forest Service,
Western Forestry Leadership Coalition

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DATA ■ ANALYSIS ■ SOLUTIONS

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GLOSSARY OF TERMS

Particulate matter (PM) - all sizes of filterable and condensable particles.

Filterable particulate matter – solid particles of all sizes (PM10, PM2.5, etc.) which can be collected on a filter.

Condensable particulate matter – particles which form as organic vapors in combustion exhaust cool and condense into liquid droplets or condense onto the surface of solid particles.

PM10 - particles equal to or less than ten micrometers in aerodynamic diameter, also referred to as "coarse particles" or "PM coarse." Can include filterable and condensable particles.

PM2.5 - particles less than or equal to 2.5 micrometers in aerodynamic diameter, also referred to as "fine particles" or "PM fine." Can include filterable and condensable particles.

CCG – close coupled gasifier or a combustion system which utilizes two separate combustion chambers in series.

SA – a stoker combustor where the fuel is fed to a grate in the combustor with an auger.

SP – a stoker combustor where the fuel is fed to a grate in the combustor pneumatically.

CS - core separator.™

HEMC – high efficiency multicylone.

MC – conventional multicyclone.

FF – fabric filter or baghouse.

ESP – electrostatic precipitator.

Whole tree chips – wood chips created by chipping the entire tree (stem, top, leaves/needles, branches).

Bole tree chips – wood chips created by chipping the tree stem.

Mill chips – wood chips from sawmill residue and contain no bark.

1.0 INTRODUCTION

In 2001, Resource Systems Group, Inc. (RSG) produced an emission control report for a consortium of northeastern government agencies called "An Evaluation of Air Pollution Control Technologies for Small Wood-Fired Boilers."[1] While the study identified and evaluated many ways to reduce emissions, it did select a single add-on control technology (the Core Separator™) as "BACT" or Best Available Control Technology for controlling particulate matter emissions. While the conclusions of this report were accepted by the consortium of northeastern state agencies, they did not translate into a formal BACT determination at the federal level.

According to the Environmental Protection Agency (EPA), "BACT is an emissions limitation which is based on the maximum degree of control that can be achieved. It is a case-by-case decision that considers energy, environmental, and economic impacts. BACT can be add-on control equipment or modification of the production processes or methods. This includes fuel cleaning or treatment and innovative fuel combustion techniques. BACT may be a design, equipment, work practice, or operational standard if imposition of an emissions standard is infeasible."[2]

For the purposes of this report, the best available control technology (BACT) may simply be defined as the highest performing control technology for a specific pollutant that is available commercially for a general class and size of emission source. This is usually defined as resulting in the lowest emission rate although differences in available fuel specifications may complicate the issue. Other environmental, health, safety and energy consumption factors should be considered in making a BACT determination. The operation of a specific control technology applied to a comparable source anywhere in the US is usually considered sufficient evidence that the technology is BACT. In principle, the search for BACT should be worldwide, although local conditions make comparability complicated and in practice, a control technology usually needs a US based customer support system to make it truly available.

Costs are also a consideration in defining BACT for a specific application. Total cost per unit of pollutant removed decline with increasing size of the facility; therefore, a technology may be BACT for a large plant but not for a smaller one. Wood-fired boilers in the size range of 3 to 10 MMBtu/hour have not been subject to formal federal BACT review for criteria pollutants given the comparatively high and therefore challenging cost of control technologies in this size range. However, state air pollution control permits are often required for this size range, which often require a number of technical analyses, including emissions estimation, air quality modeling and some degree of informal economic analysis for pollution control costs.

The EPA BACT process follows a top down procedure. It begins with the most effective control technology available that will result in the lowest emission rate and then reviewing that technology to determine if there are technical, safety, health or other environmental factors which would make it impractical or undesirable. If the technology is not rejected because of any of these factors, then a cost analysis is conducted to determine the absolute costs and per unit costs of implementation. The cost analysis follows guidelines established by EPA. If it is relevant, the analysis may include special costs associated with retrofitting the technology in an existing plant. The cost analysis is then reviewed to determine if the technology is economically feasible in the specific case. If the first technology choice is rejected for technical, environmental, safety or costs reasons, then the analysis proceeds to the second best performing technology and so on until a feasible technology is accepted or all available options are

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[1] An Evaluation of Air Pollution Control Technologies for Small Wood-Fired Boilers." Prepared for Vermont Department of Public Service; Vermont Department of Environmental Conservation, Air pollution Control Division; New Hampshire Governor's Office of Energy Resources and Community Services; and the Massachusetts Division of Energy Resources. Resource Systems Group, Inc., White River Junction, VT. Revised, September 2001.

[2] US EPA. http://www.epa.gov/nsr/psd.html

exhausted. This process may include not only add-on technology but combustion process modifications and changes in fuel specifications.

The study described by this report builds upon the 2001 report, but differs in that its goal was not to identify a single Best Available Control Technology (BACT). Rather, its goal was to identify multiple emission controls in order to provide more flexibility in the design process for biomass combustion systems. This is because there are many factors affecting the degree of control needed to meet the National Ambient Air Quality Standards (NAAQS), which were promulgated by EPA to protect human health and welfare.

Regarding the NAAQS, we note EPA significantly strengthened the NAAQS for PM2.5 (aka fine particulate matter or particles less than 2.5 micrometers in aerodynamic diameter) in 2006. PM2.5 consists of solid particles and liquid droplets less than 2.5 microns in aerodynamic diameter and is widely held to be the most critical pollutant resulting from biomass combustion. For comparison, the average period at the end of a sentence is approximately 500 microns in diameter.[1] Concern for health impacts from PM2.5 exposure coupled with the strengthened PM2.5 NAAQS has led to a much greater emphasis on emission control than in previous years.

The need to develop environmentally beneficial uses of low grade timber, improve forest health, mitigate climate change, offset rising fossil fuel oil prices and reduce foreign oil dependence have increased demand for biomass energy systems. Given frequent budget limitations, biomass developers are pressed to find cost-effective ways to reduce emissions of PM2.5 and other pollutants. In addition to being affordable, emission controls must be practical and easily implementable, otherwise they will not be effective. This study was commissioned by the U.S. Forest Service (USFS) to identify and evaluate such emission controls.

This report contains the following sections:

- Scope of study
- Emissions overview
- Best Management Practices (BMPs)
- Add-on pollution controls
- Summary of European emission control practices
- Capital costs for particulate matter control
- Cost effectiveness of add-on emission controls for particulate matter
- Overview of emission controls for other relevant pollutants
- Summary
- Conclusion
- Recommendations

The use of trade or firm names is for information only and does not imply endorsement by the authors or this study's sponsor.

[1] "Health Effects of Wood Smoke." Washington State Department of Ecology. http://www.ecy.wa.gov/biblio/92046.html

2.0 SCOPE OF STUDY

The scope of this study was to update and expand the RSG 2001 report as follows:

1) **Identify and Evaluate Best Management Practices (BMPs).** BMPs, also called "work practice standards" and "inherently lower emitting processes and practices," are used to control emissions upstream of add-on control technologies such as mechanical collectors (cyclones, multicyclones), baghouses (fabric filters), electrostatic precipitators (ESPs), etc. Attention is typically directed toward add-on emission control selection. These solutions are typically more costly. While not as effective as most add-on controls, BMPs can substantially reduce emissions, improve system efficiency and improve system performance; therefore, this report will focus on BMPs in addition to add-on controls. This said, BMPs alone will not likely satisfy the requirements for "LAER" or lowest achievable emission rate, which is typically required in non-attainment areas. Non-attainment areas are areas where one or more of the National Ambient Air Quality Standards (NAAQS) are not met.

2) **Expand the original size range evaluated from 3 MMBtu/hr - 10 MMBtu/hr to 3 MM Btu/hr - 30 MM Btu/hr (heat input).**[1] This report will still focus on small (less than 10 MMBtu/hr) wood boilers. However, there is new information available from recently constructed wood boilers smaller than 3MMBtu/hr and larger than 10 MMBtu/hr that can be extrapolated to the 3 to 10 MMBtu/hr size range. This information was evaluated for the purposes of this report.

3) **Include emissions control information for PM2.5 and a number of hazardous air pollutants (HAPs) including Mercury.** This is primarily in response to EPA's strengthening of the PM2.5 NAAQS and due to recent availability of stack emission test data for PM2.5 and HAPs.

4) **Include pellet boiler emission information.** Many new pellet boilers and pellet production plants (pellet mills) have been constructed in recent years in response to demand for this fuel. In addition, a number of stack emission tests have been completed for pellet boilers in the United States. This report will discuss this new information.

3.0 EMISSIONS OVERVIEW

When evaluating emission controls for biomass boilers, it is important to first develop an understanding of current actual emissions from biomass boilers. The most current and descriptive emissions information is obtained from exhaust stack emission tests performed according to EPA reference methods. These tests are typically performed to fulfill air pollution control permit requirements requiring a demonstration that emission limits are being met. In addition to compliance emission tests, many voluntary tests have been sponsored by interested parties given the level of interest in knowing actual emissions and effectiveness of emission controls. These tests were completed throughout the United States, with different fuel characteristics, different firing rates and different emission controls.

This study focused on particulate matter emissions. There are many terms used to characterize particulate matter. For the purposes of this report, the term particulate matter includes all sizes of solid particles and liquid particles (droplets). Solid particles are referred to as "filterable" particulate matter because they can be measured with a filter. Liquid particles are also called "condensable" particulate

[1] 30 MMBtu/hr is the threshold level at which the federal PM emission limit drops to 0.030 lb/MMBtu. This emission limit cannot be achieved with a mechanical collector. See 40 CFR Part 60, Subpart Dc. – Standards of Performance for Small Industrial-Commercial-Institutional Steam Generating Units.

matter because they are formed by vapors in the combustion exhaust which cool and condense into particles. These vapors can also condense onto the surface of solid particles.

Filterable and condensable particulate matter is grouped into three size classes. "Particulate matter" (PM) includes all sizes of filterable and condensable particles. The next smallest size class is PM10 or filterable and condensable particles equal to or less than ten micrometers in aerodynamic diameter. PM10 particles are also called "coarse particles." PM2.5 is the smallest particle size class currently regulated. PM2.5 particles, also called "fine particles," include all filterable and condensable particles less than or equal to 2.5 micrometers in aerodynamic diameter. For the purposes of this report, it was assumed all condensable particulate matter falls is less than 2.5 microns in diameter.

Condensable particulate matter is reported separately from filterable PM2.5 because it is controlled differently. Some of the "condensables" will condense on filterable particles. Hence, anything controlling filterable particulate matter will inherently control some portion of the total condensables. Good combustion practices are the primary means for controlling condensables from small wood boilers without add-on controls.

Unless stated otherwise, the terms PM10 and PM2.5 will refer to filterable particulate matter only. This is because the methods used to measure the PM10 and PM2.5 emissions listed in this report measured filterable particulate matter only.

RSG reviewed 24 recent stack emission tests to develop an understanding of existing emissions (see Appendix A for supporting stack test reports available for public consumption). All but one of these tests was completed after the 2001 RSG report. These stack tests were performed in Idaho, Montana, New Hampshire, North Dakota, Rhode Island and Vermont. Twenty-two of the tests were performed on wood chip boilers and two tests were performed on wood pellet boilers. All tests measured some form of particulate matter emissions (filterable PM10, filterable PM2.5 and condensable PM). Some of the tests included other pollutants such as carbon monoxide (CO) and a selected number of Hazardous Air Pollutants (HAPs). Fuels burned included sawmill residue chips, bole chips, whole tree chips, bark chips, sawdust and municipal vegetative waste combined with ground pallets. Add-on emission controls included cyclones, multicyclones, high efficiency multicyclones (HEMCs), core separators and baghouses.

This study did not identify any stack emission data for ESPs on small wood-fired boilers in the United States. However, according to the EPA "RACT-BACT-LAER Clearinghouse", the lowest emission limit listed for PM and PM10 for large wood-fired boilers controlled with ESPs is 0.02 lb/MMBtu (PM2.5 was not listed).[1] Given this limit is based on demonstrated technology, it is technically possible that small wood-fired boilers could meet this limit. However, the economic analysis on which this limit is based is for significantly larger systems (100 MMBtu/hour or greater), where the total cost per ton of pollutant removed is significantly lower. This is why the economic analysis performed for this report was based on outlet emissions not exceeding 0.045 lb/MMBtu of all filterable particulate matter.

It should also be noted that the larger facilities subject to the limit of 0.02 lb/MMBtu have the potential to emit more than an order magnitude more emissions and therefore must meet stringent emission limits in order to meet federal ambient air quality requirements.

Table 1 summarizes the 24 particulate matter stack test results. Emissions are grouped into the three categories: filterable PM10, filterable PM2.5 and condensable PM. Table 2 through Table 4 summarize emissions by the following heat input categories:

- Less than 30 MMBtu/hour and greater than 10 MMBtu/hour (based on seven stack tests).
- Less than or equal to 10 MMBtu/hour (based on 18 stack tests).
- Less than or equal to 5 MMBtu/hour (based on nine stack tests).

A more detailed summary of all 24 tests is shown in Table 5.

[1] This emission limit applies to a utility sized boiler whose heat input exceeds 100 MMBtu/hour.

As shown below in Table 1, there is a large difference between the maximum and minimum values measured. The difference was as much as two orders of magnitude for PM10. The maximum PM10 value of 0.506 lb/MMBtu resulted from a facility burning a low quality fuel - whole tree chips produced by a grinder and having notable quantities of dirt and rock. The fuel was burned in a stoker combustor with no add-on emission control. The lowest PM10 value of 0.06 lb/MMBtu resulted from burning a high quality mill chip (no bark and no soil/rock impurities) in a close-coupled gasifier controlled with a high efficiency multicyclone (HEMC).[1]

Table 1: Summary of all Stack Emission Test Results

Category	PM10 Emissions (lb/MMBtu)	PM2.5 Emissions (lb/MMBtu)	Condensable PM (lb/MMBtu)
Average[2]	0.178	0.111	0.021
Median	0.140	0.122	0.014
Maximum	0.506	0.267	0.039
Minimum	0.016	0.014	0.006

Table 2: Stack Test Summary for Heat Input Less than 30 MMBtu/hour and Greater than 10 MMBtu/hour

Category	PM10 Emissions (lb/MMBtu)	PM2.5 Emissions (lb/MMBtu)	Condensable PM Emissions (lb/MMBtu)
Average	0.230	0.164	0.011
Median	0.101	0.188	0.014
Maximum	0.382	0.267	0.014
Minimum	0.019	0.062	0.006

Table 3: Stack Test Summary for Heat Input Less Than or Equal to 10 MMBtu/hr

Category	PM10 Emissions (lb/MMBtu)	PM2.5 Emissions (lb/MMBtu)	Condensable PM Emissions (lb/MMBtu)
Average	0.175	0.107	0.018
Median	0.156	0.104	0.014
Maximum	0.506	0.179	0.039
Minimum	0.016	0.014	0.007

Table 4: Stack Test Summary for Heat Input Less Than or Equal to 5 MMBtu/hour

Category	PM10 Emissions (lb/MMBtu)	PM2.5 Emissions (lb/MMBtu)	Condensable PM Emissions (lb/MMBtu)
Average	0.231	0.114	0.025
Median	0.161	0.110	0.026
Maximum	0.506	0.179	0.039
Minimum	0.016	0.014	0.009

[1] The HEMC was determined to be BACT for small wood-fired boilers in Rhode Island in a 2006 BACT study completed by Resource Systems Group. BACT for PM10 and PM2.5 were determined to be 0.20 lb/MMBtu and 0.18 lb/MMBtu respectively.

[2] Average values represent the average of instances when both PM10 and PM2.5 were measured at the same site.

Table 5 provides more information for each stack test than the tables above. Information is provided in ascending order of measured PM10 emissions for each of the 24 tests. Table cells were left blank to represent instances when PM2.5 and condensable PM data were not available. Also shown is the type of fuel burned and type of emission control. The following combustion technologies are listed: close-coupled gasifier (CCG), auger fed stoker (SA), pneumatically fed stoker (SP).

Table 5: Summary of 24 Particulate Matter Stack Emission Tests

Location	Design Heat Input (MMBtu/hr)	Comb. Type	Fuel Burned	Emission Control	PM10 Emissions (lb/MMBtu)	PM2.5 Emissions (lb/MMBtu)	Condens. PM Emissions (lb/MMBtu)
Glocester, RI	4.6	CCG	Mill chips	HEMC	0.016	0.014	
Middlebury, VT	29.0	CCG	Bole chips	MC + FF	0.019		
Dillon, MT	19.0	CCG	Bole chips	MC	0.052		
N. Scituate, RI	9.1	CCG	Mill chips	HEMC	0.058	0.054	0.007
N. Scituate, RI	9.1	CCG	Mill chips	HEMC	0.066	0.066	
Thompson Falls, MT	2.2	CCG	Bole tree chips	Cyclone	0.070		
Brattleboro, VT	6.9	CCG	Wood chips	Core Sep.	0.078		
Greenfield, NH	5.7 & 11.4	SA	Bole chips	MC + FF	0.078	0.062	0.014
Newport, VT	15.6	CCG	Bole chips	MC	0.101		0.006
Peterborough, NH	2.8	SA	Pellets	MC	0.101		
Bennington, VT	16.8	SP	Whole tree chips	2 MC	0.140		
Darby, MT	3.3	SA	Bole chips	None	0.156		
Victor, MT	2.6	SA	Bole chips	None	0.166	0.098	0.009
Springfield, NH	15.5	SA	Sawdust	None	0.168		
Hinesburg, VT	6.5	SA	Bole chips	Cyclone	0.171	0.147	0.012
Brattleboro, VT	10.0	SA	Mill chips	Core Sep.	0.172	0.162	0.012
Burlington, VT	10.0	SA	Mill chips	MC	0.187		0.015
Darby, MT	3.3	SA	Bole chips	None	0.192	0.110	0.015
Bismarck, ND	1.0	SA	Muni. veg. & pallets	None	0.199	0.151	0.077
Burlington, VT	10.0	SA	Bole chips	MC	0.257		0.017
Townsend, MT	0.75	SA	Pellets	None	0.305	0.133	0.036
Bennington, VT	16.8	SP	Whole tree chips	2 MC	0.382	0.267	0.014
Council, ID	1.9	SA	Whole tree chips	None	0.506	0.179	0.039
Dillon, MT	19.0	CCG	Bole chips	MC		0.188	

The following were observed:

- Close-coupled gasifiers emitted the lowest levels of emissions. This may be due to less carry-over of filterable particles from the combustion chambers into the exhaust.
- There is limited PM2.5 emissions data. This is partially because PM2.5 is still not officially enforced by most state air quality agencies; therefore, state agencies are requiring compliance stack testing for PM10 only.
- The lowest PM10/PM2.5 emissions were produced by a close coupled gasifier burning a relatively high quality wood chip, with emissions controlled by a HEMC.
- PM10 emissions from baghouses were surprisingly not the lowest for all tests. They were the third and eighth lowest emissions of all tests. The lower than expected control efficiency for the

Greenfield, NH site is likely due to a portion of the boiler exhaust gases circumventing the bag house via a leaking damper into a bypass duct.

- PM10 emissions were equal to or less than 0.20 lb/MMBtu for 19 of the 24 tests (79%) and less than 0.10 lb/MMBtu for 10 of the 24 tests (41%).
- All but one of the PM2.5 tests was less than 0.20 lb/MMBtu. Five of the 13 PM2.5 tests were less than 0.10 lb/MMBtu.
- Bark can increase PM emissions. For example, the two results from Burlington, Vermont, where mill and bole chips were tested, indicate bark can increase PM emissions. PM10 emissions were 0.187 lb/MMBtu and 0.257 lb/MMBtu for mill and bole chips respectively.
- There are two stack test results for pellet fired systems. PM10 emissions from these systems ranged from 0.101 lb/MMBtu to 0.305 lb/MMBtu. The higher number corresponds to a much older system with no add-on emission controls. The lower number corresponds to a new system with a multicyclone. Average PM2.5 emissions from the older system were 0.133 lb/MMBtu. PM2.5 emissions were not measured for the newer system.

The EPA has developed emission factors for wood boilers. These emission factors are included in a document called "AP 42", which is a compilation of emission factors.[1] Comparable emission factors from the AP 42 are summarized for reference below. Note these emission factors represent an average for a group of emission tests. These emission factors were published in September, 2003 and likely correspond to systems larger than most of those considered for this report. The majority of the stack test data used to develop these emission factors was collected in the early to mid 1990's.

Table 6: Comparable EPA AP 42 Emission Factors

Fuel Type	Control Device	PM10 Emissions (lb/MMBtu)	PM2.5 Emissions (lb/MMBtu)	Condensable PM Emissions (lb/MMBtu)
Bark & wet wood	None	0.50	0.43	0.017
Bark & wet wood	Mechanical collector	0.32	0.19	0.017
Wet wood	None	0.29	0.25	0.017
Wet wood	Mechanical collector	0.20	0.12	0.017
All fuel types	Fabric filter (baghouse)	0.074	0.065	0.017
All fuel types	Electrostatic Precipitator (ESP)	0.04	0.035	0.017

3.1 Vermont APCD Emission Study

The Vermont Agency of Natural Resources (ANR) recently completed an emission study focusing on air pollutant control efficiency for a number of add-on pollution controls. The study evaluated inlet and outlet particulate matter emissions (or the emissions entering and exiting a given pollution control device) from five wood chip fired boilers in the Northeast. These boilers are located at Crochet Mountain Rehabilitation Center (Greenfield, NH), Bennington College (Bennington, VT), Brattleboro Union High School (Brattleboro, VT), Ponaganset High School (North Scituate, RI) and Champlain Valley Union High School (Hinesburg, VT). Emissions data and design heat inputs for these boilers are provided previously in Table 5.

[1] Can be accessed at http://www.epa.gov/ttn/chief/ap42/ch01/index.html

Table 7 shows approximate PM2.5, PM10 and PM control efficiency for the five sites.[1] The control efficiencies listed below refer to the percent of filterable particulate matter removed by the add-on pollution control device. Control efficiencies for different add-on pollution controls are further discussed later in this report.

Table 7: Vermont ANR Emission Study Approximate Control Efficiencies

Location	PM Control	PM2.5 Control Efficiency	PM10 Control Efficiency	PM Control Efficiency
Greenfield, NH	Multicyclone + baghouse	74%	74%	83%
Bennington, VT	Two multicyclones in series	14%	22%	61%
Brattleboro, VT	Core separator (24”)	24%	32%	60%
North Scituate, RI	High efficiency multicyclone	15%	21%	23%
Hinesburg, VT	Cyclone	3%	6%	4%

The following observations were made from these results:

- **Bennington and Brattleboro, VT.** The PM control efficiencies are typically significantly higher than the PM2.5 and PM10 efficiencies because there were significant quantities of particles larger than PM10 (ten microns in aerodynamic diameter) emitted during the stack tests.
- **Greenfield, NH.** The control efficiency is relatively low for a multicyclone followed by a baghouse. Baghouses are widely thought to achieve 99% control efficiency for PM2.5 and smaller filterable particles. As mentioned, the low control efficiency is suspected to be due to a portion of the boiler exhaust gases circumventing the bag house via a damper which was not closed completely. This allowed a small portion of the boiler exhaust into a bypass duct around the baghouse and into the stack.
- **Bennington, VT.** While this is the highest control efficiency value of all mechanical collectors tested, the actual emissions were higher than all other five sites (0.382 for PM10 and 0.267 lb/MMBtu for PM2.5). The higher emissions may be due to carry over of large particles from the combustion chamber caused by pneumatic feeding of fuel into the combustion chamber.

  It was discovered after this testing that some of the underfire air passages were obstructed by a buildup of boiler bottom ash. This ash was subsequently cleaned out, the boiler combustion air was adjusted and an improved ash management procedure was implemented. The retesting which occurred after these measures were implemented indicated the total PM emission rate dropped to 0.14 lb/MMBtu (approximately a 63% reduction).
- **Brattleboro, VT.** The PM collection efficiency was nearly the same as at Bennington, but the PM10 and PM2.5 collection efficiencies were higher. This shows the Core Separator™ is more effective at removing smaller particles than conventional multicyclones, even conventional multicyclones in series.

  The Core Separator™ operating at Brattleboro was designed for the exhaust volume from a 400 horsepower (hp) boiler. However, the boiler size was reduced to 332 hp during project development. So while a smaller “2-core” unit would have worked, a “3 core” unit was operating. The result is that during emission testing, the Core Separator™ was operating at half it's design pressure drop. A higher collection efficiency would likely have resulted if it was operating at its design pressure drop.

[1] The PM2.5 and PM10 control efficiencies were calculated using the inlet and outlet emission factors (in lb/MMBtu) from the control device. The PM control efficiency was taken directly from the study report.

- **North Scituate, RI.** The outlet emissions were the lowest of all sites (0.0662 MMBtu/hr for PM10 and 0.0660 MMBtu/hr for PM2.5) despite one of the lowest collection efficiencies measured (23%). Similar to the Brattleboro, this is because the system was operating at low capacity (30% load) which led to a low pressure drop (approximately 0.7 inches of WC). The design pressure drop for this system is 4" of WC. At this pressure drop it is conceivable that the collection efficiency would have been 75% or greater. Vendor calculations suggested a PM collection efficiency of 80% or greater at design load/pressure drop. It should also be noted that the vast majority of the inlet loading was PM2.5 (88.7%). Therefore, the control efficiency is relatively high for a mechanical collector operating at low pressure drop.
- **Hinesburg, VT.** Single cyclones have the lowest collection efficiency of all mechanical collectors. This is evidenced by the collection efficiency measured, which is due to a considerably higher portion of PM2.5 in the inlet exhaust. Despite the type of control device, the outlet emissions were relatively low (0.171 for PM10 and 0.147 lb/MMBtu for PM2.5). Similar to North Scituate, this boiler operated at relatively low load and consequently there was relatively low pressure drop across the cyclone.

3.2 Hazardous Air Pollutant Information

3.2.1 HAP Stack Emission Test Information

In addition to PM2.5, there is growing interest in Hazardous Air Pollutant (HAPs) emissions from wood combustion. The EPA publishes HAP emission factors in Section 1.6 of the AP 42, which was last updated in September, 2001 and, as mentioned, is based on emission tests conducted before that date. Since that time, there have been advances in combustion technology and practices, which suggest HAP emissions have and will likely continue to decline with time.

This study compared a number of AP 42 HAP emission factor values with measured emissions from five test sites. Both gaseous and particulate HAPs were evaluated. A full list of the HAPs evaluated is provided in the appendix. HAP emissions were not weighted according to their respective toxicity level.

The information provided in this report is intended to establish a starting point for understanding HAP emissions. Firm conclusions should not be drawn from the information provided as it is based on a limited number of stack emission tests.

Not all 188 federal HAPs were measured at each of the five test sites. Each HAP measured at each site was compared with its AP 42 equivalent.

The comparisons made showed actual emissions of individual HAPs were both higher and lower than AP 42 equivalents. They also showed total HAPs measured at each site were lower than the total AP 42 HAP equivalent for all but one site. The average actual total HAP emission from all sites was 68% lower than the AP 42 total HAP equivalent. The comparisons are summarized below. Detailed information is provided in the appendix.

Table 8: Summary of HAP Test Sites

Location	Design Heat Input (MMBtu/hr)	Combustion Type	Emission Control	Emission Test Date	Number of HAPs Compared	Total Measured HAP Percent of AP 42 Total HAP
North Scituate, RI	9.1	CCG	HEMC	2009	24	13%
Glocester, RI	4.6	CCG	HEMC	2009	24	8%
Council, ID	1.9	SA	Uncontrolled	2007	22	23%
Green Acres, VT	2.2	SA	Uncontrolled	1996	24	123%
Hazen Union, VT	2.8	CCG	MC	1996	24	26%

3.2.2 MERCURY EMISSIONS

Mercury emissions are typically considered with coal projects. Mercury emissions have been considered for wood combustion projects, but to a lesser extent. There is much information about mercury control from coal fired power plants via fuel and exhaust cleaning. Unlike NO_2 emissions, Mercury emissions are a function of fuel mercury content. Therefore, a fuel analysis provides a good indication of potential mercury emissions.

Mentz et al, describes work performed to measure mercury content of bark and stemwood in 30 locations throughout the country.[1] The average bark and stemwood concentrations at the 30 sites were 1.42 lb/10^{12} Btu and 0.28 lb/10^{12} Btu for bark and stemwood respectively. The mean mercury content for each of the 30 sites ranged from 0.57 lb/10^{12} Btu to 3.14 lb/10^{12} Btu in bark and from 0.12 lb/10^{12} Btu to 0.46 lb/10^{12} Btu in stemwood.

These numbers are based on the assumption that the entire quantify of mercury is released from the fuel into a vapor form and does not combine with any other constituents in the exhaust gas or is removed by some form of emission control.

Pease et al, describes research performed to evaluate the potential for flue gas cooling, flue gas humidification, pulsed energization, and sorbent injection in wet and dry ESPs to reduce mercury emissions. This study found that all of these measures are effective. It also found that some mercury will attach to fly ash thereby increasing the potential for mercury removal.

4.0 BEST MANAGEMENT PRACTICES (BMPS)

BMPs range from physical equipment such as oxygen sensors to operational practices such as visual observations of plume opacity. Properly implemented, BMPs will optimize combustion conditions thereby helping maximize energy efficiency and minimize emissions from any system.

4.1 Fuel Quality

The first step in implementing BMPs is to obtain the highest quality fuel possible. There are many factors affecting fuel quality. Fuel quality is an important consideration as improved fuel quality improves combustion conditions, increases efficiency and reduces emissions. Fuel quality is a function of fuel moisture content, bark content, uniformity, size, and purity. These factors are described in detail later in this report.

There are no formally established grades of wood chips. However, there are four basic types of wood chips, whose quality and corresponding emissions are fairly well understood. For the purposes of this report, the term "high quality" describes a chip which has minimal ash content, is of uniform and proper size and results in the least possible emissions.

1. **Sawmill residue chips (mill chips).** This chip is thought to be the highest quality in that it contains no bark. The availability of this chip is limited due to the decline in U.S. sawmills coupled with the demand for higher value products from those chips such as pulp, wood composite products and wood pellets.
2. **Bole tree chips (bole chips).** Are produced by chipping the tree stem (trunk). This is a moderate to high quality chip as it contains relatively minimal quantities of bark and are relatively uniform in size.

[1] Karen Mentz, John Pinkerton, and Jeff Louch."Potential Mercury and Hydrochloric Acid Emissions from Wood Fuels." Forest Products Journal, 55(2): 46-50. Received for publication in August, 2004. Article No. 9919.

3. **Whole tree chips.** Are produced by chipping the entire tree and therefore include the tops, leaves and branches/needles in addition to the trunk. This category would also include municipal vegetative waste in addition to trees removed from a given forest. These are a moderate to low quality chip as they are less uniform in size/shape and have higher ash content than bole tree chips.
4. **Bark chips.** These chips consist primarily of bark and are the lowest quality chip given the high ash content of bark. In addition to its mineral content, bark can have higher ash content because it may have impurities adhered to it from harvesting and transport.

Wood chips can be produced with chippers and grinders. Grinders can handle more dirt and rocks and therefore have greater potential for contaminating wood chips with those impurities. Grinders also produce chips with greater size variation than chippers. As is discussed later in this section, fuel homogeneity is important for effective fuel handling and combustion.

In 2007, the Biomass Energy Resource Center (BERC) published a report for the South Dakota Department of Agriculture, Resource Conservation & Forestry Division entitled "Woodchip Fuel Specifications and Procurement Strategies for the Black Hills."[1] While this document is intended for a specific geographic area, the overall principles can be applied throughout the United States. This document characterizes four grades of wood chip quality and provides guidelines for obtaining each of those four grades.

The information in the BERC report was combined with the author of this report's working knowledge to develop the fuel quality BMPs summarized in the table below below. Any number of these BMPs can be applied to planned as well as existing facilities.

Table 9: Summary of Fuel Quality BMPs for Wood Chips (Continued on Next Page)

BMP Category	Description	Fuel Quality Improvement	Combustion Improvements / Emission Reductions
Bark content	Minimize bark content. Mill chips and sawdust based pellets do not contain bark.	Reduces ash content.	Reduces clinker formation on grates thereby maintaining proper airflow through the grates. Reduces emissions associated with fly ash carry over. Increases combustion efficiency.
Moisture content	Moisture content must be within range meeting combustion system design requirements.	Ensures design fuel heat content met.	Energy loss occurs when excess moisture is vaporized. Fugitive dust and excess PM emissions occur when fuel is excessively dry.
Storage surface	Minimize/prevent storage on ground surfaces. Store on concrete or other type of clean paved surface.	Prevents transfer of soil, rocks, salts and other impurities from the ground surface to the fuel.	Improves combustion efficiency by reducing clinker and ash formation. Minimizes particulate matter emissions.
Storage time for trees with needles	When dry, needles fall off tree when fallen tree mechanically shaken.	Reduces ash content. Increases fuel uniformity.	Lower ash content and reduced potential for clinker formation and increases combustion efficiency. Reduced PM emissions from reduced fly ash carry over.

[1] Biomass Energy Resource Center (BERC). "Woodchip Fuel Specifications and Procurement Strategies for the Black Hills." Prepared for the South Dakota Department of Agriculture, Resource Conservation & Forestry Division. May 15, 2007. www.biomasscenter.org

BMP Category	Description	Fuel Quality Improvement	Combustion Improvements / Emission Reductions
Storage coverage	Store in covered area.	Ensures design moisture content met. Maximizes heat content of fuel.	Ensures design combustion efficiency met by preventing energy loss associated with excess moisture vaporization. This minimizes excess fuel consumption.
Method of chip production	Sharp and properly adjusted equipment is critical for grinders and chippers. Chipping typically produces better chip than grinder.	Maximizes wood chip uniformity. "Stringer" formation minimized.	Promotes uniform combustion thereby maximizing combustion efficiency. Prevents system interruptions (upset conditions) caused by stringers in metering bins.
Chipping/grinding equipment. Operation and maintenance.	Manufacturer's operation and maintenance requirements should be adhered to.	Ensures chip uniformity.	Promotes uniform combustion thereby maximizing combustion efficiency.
Uniformity of fuel input to chipper or grinder	Uniform size material fed to chipper or grinder.	Increases chip uniformity.	Promotes uniform combustion thereby maximizing combustion efficiency.
Chip screening	Mechanical screening (sizing) of chips.	Increases chip uniformity, removes oversized material and removes fines. Has potential to separate and remove some portion of bark from raw chips.	Promotes uniform combustion thereby maximizing combustion efficiency and reducing overall emissions. PM emissions potentially reduced as carry over of fines into exhaust eliminated. PM emissions reduced through reduced bark content.
Long term fuel supply contracts	Encourages investment in wood chip production equipment producing higher quality chip.	Optimal fuel characteristics developed.	Promotes optimal combustion conditions which maximizes energy efficiency and minimizes emissions.
Fuel supply testing	Visually inspect fuel geometry, uniformity, moisture content prior to fuel being dumped into storage bin. Retain grab samples if need for future fuel measurements anticipated.	Ensures design fuel specifications are met.	Ensures optimal combustion conditions.

There are a number of grades of wood pellets defined by the Pellet Fuel Institute (PFI). They are super premium, premium, standard and utility. As shown in Table 10, grades are a function of bulk density, diameter, pellet durability index, percent of fines, inorganic ash content, length, moisture content, chloride content, ash fusion and heating value. These categories are further described on the PFI Internet Site.[1] There are no legal factors necessitating use of any particular grade of wood pellets. However, it is useful to know the pellet grade for purposes of meeting air quality requirements for a given area.

[1] http://www.pelletheat.org/3/institute/standards/PFI%20Standards.pdf

While not depicted in the table below, the PFI is proposing standards for pellet manufacturers to disclose on the bag surface if non-natural additives were used to form the pellets. This is because additives have the potential to increase the relative toxicity of pellet combustion exhaust.

Table 10: Values used for Classifying Residential Grades of Pellets according to the Pellet Fuels Institute

Fuel Property	PFI Super Premium	PFI Premium	PFI Standard	PFI Utility
Bulk Density, lb./cubic foot	40.0-46.0	40.0-46.0	38.0-46.0	38.0-46.0
Diameter, inches	0.250- 0.285	0.250- 0.285	0.250- 0.285	0.250- 0.285
Diameter, mm	6.35-7.25	6.35-7.25	6.35-7.25	6.35-7.25
Pellet Durability Index	>97.5	>97.5	> 95.0	>95.0
Fines, % (at the mill gate)	<0.50	<0.50	<0.50	<0.50
Inorganic Ash, % - See Note 1	<0.50	< 1.0	<2.0	<6.0
Length, % greater than 1.50 inches	< 1.0	< 1.0	< 1.0	< 1.0
Moisture, %	<6.0	<8.0	<8.0	< 10.0
Chloride, ppm	< 300	< 300	< 300	< 300
Ash Fusion	NA	NA	NA	NA
Heating Value	As-Rec. ± 2SD	As-Rec. ± 2SD	As-Rec. ± 2SD	As-Rec. ± 2SD

4.2 Operation and Maintenance Plan

An operation and maintenance plan (O&M Plan) is a document describing the equipment and work practices that will take place to ensure optimal combustion conditions and compliance with applicable emission limits. These plans also specify the frequency that all work practices will be completed. Consequently, they may include daily, weekly, monthly and annual checklists to ensure all work practices (BMPs) are completed. Facilities are oftentimes required to record and maintain this information for a period of time as part of a permit condition. O&M plans are developed in concert by the boiler operator, wood boiler equipment vendor and state regulatory office. O&M plans should be flexible to allow for improved O&M measures if/when they are identified for a given facility. Ideally, all O&M plans are written and approved within a few months after start-up.

Here is a sample list of O&M components as specified in a Vermont air pollution control permit:

- Descriptions of routine maintenance and inspection procedures.
- Description of procedure for and frequency of ash removal from the boiler and the particulate matter emission control device.
- Provisions for maintaining records of maintenance and inspection procedures, including both routine activities and actions taken in response to observations of low combustion efficiency.
- Provisions for calibration and maintenance of any testing instruments and/or equipment used to measure the concentrations of CO_2 and CO in the boiler exhaust gases.

4.3 Boiler Operator Training

Boiler operator training is essential to proper operation and maintenance. This is typically provided by the vendor prior to and shortly after start-up. There are currently no standardized training programs for acquiring boiler operator certification.

There are occasions when the boiler operator who was trained by the vendor upon start-up leaves for a new job. In these situations, it is critical to ensure the replacement operator has sufficient training and experience.

4.4 Equipment Sensors

Many wood boilers are equipped with internal sensors that provide real time information about some aspect of the combustion process to an automated control system. Information from these sensors helps the system self-regulate with the intelligence they provide. Sensors are frequently used to measure pressure drop across a mechanical collector or baghouse, opacity in the exhaust stack (with smoke density meters), oxygen level in the combustion chamber and/or exhaust stack, and temperature in the combustion chamber and/or exhaust stack.

4.5 Automatic Ash Removal

Bottom ash, or ash collected at the bottom of the combustion chamber, can become re-suspended and carry over into the exhaust, thereby increasing particulate matter emissions. Automatic ash removal can ensure frequent bottom ash removal. This may be especially useful if burning a high ash content fuel.

4.6 Raking Grates as Needed

In most direct burn combustion systems, biomass is combusted on grates. Ash will accumulate on these grates. If left to accumulate, this can lead to clinker formation and limit under-fire airflow thereby reducing combustion efficiency. Raking the grates reduces this problem.

4.7 Combustion Efficiency Testing

Combustion efficiency testing is a way to quantify the degree of combustion completeness, not the overall thermal efficiency (heat input divided by heat output). One method for measuring combustion efficiency is by measuring carbon monoxide (CO) and carbon dioxide (CO_2) concentrations in the boiler exhaust with a hand-held portable analyzer.

CO is an indicator of the level of gaseous air toxics in boiler exhaust and therefore a good surrogate for gaseous air toxics. The relationship between CO and carbon dioxide (CO_2) concentrations provides an indication of the degree combustion completeness and is therefore appropriate for the levels of all emissions in boiler exhaust.

Vermont and Rhode Island implemented a permit condition requiring measurement of both CO and CO_2 in the exhaust gas to determine combustion efficiency. Combustion efficiency is determined using this equation, taken from a Vermont air pollution control permit:

Equation 1

$$CE(\%) = \frac{CO_2}{CO_2 + CO} \times 100$$

Where:

CE = Combustion efficiency,

CO_2 = % by volume of carbon dioxide in the flue gas, and

CO = % by volume of carbon monoxide in the flue gas.

Compliance is demonstrated when the combustion efficiency is calculated to be equal to or greater than 99%. A representative number of measurements should be taken given the broad range of operating conditions that can occur in a given biomass boiler.

4.8 Visual Plume Observations

Visually observing the exhaust plume is a way to confirm good combustion conditions are occurring. EPA publishes two methods for visually evaluating plume opacity. The first one, Method 22, is mostly qualitative and does not require formal training.[1] The second, Method 9, is more quantitative and requires the observer be re-certified every six months.[2] If the plume characteristics pass a Method 22 test, then the observation is complete. If the Method 22 test is not passed, then the observer can perform a Method 9 test to quantify the plume characteristics, if necessary. At minimum, steps should be taken to correct combustion conditions if a Method 22 test is not passed.

4.9 Recordkeeping

Consistent and thorough record keeping is another means to ensure ongoing optimal combustion conditions. Record keeping is therefore considered a means for demonstrating ongoing compliance with pollutant emission limits. Record keeping is required in the areas of fuel use, equipment maintenance and equipment monitoring. Record keeping has been required for the items below. These requirements listed are directly quoted or derived from recent permits issued in Vermont and New Hampshire.

- Track fuel use on a monthly basis if heat input equal to or greater than 10 MMBtu/hr. Track fuel use on an annual basis if heat input less than 10 MMBtu/hr.
- Measure and record oxygen in percent volume, in the exhaust gas and permanently record the output in a log book.
- Maintain records of the results of the combustion efficiency testing conducted on the Facility's boiler. These records shall at least include the test date, identification of boiler tested, a measurement of the load on the boiler (such as fuel feed rate or steam production rate), the concentrations of oxygen, carbon monoxide and carbon dioxide in the exhaust gas as well as the calculated combustion efficiency.
- Install and maintain a temperature sensor to measure the wood-fired boiler's exhaust exit temperature and permanently record the output in the log book.
- Observe visible emissions (via EPA Method 22) once a day on normal business days. Record the date, time, duration of excursion, and corrective actions taken if visible emissions are not typical of good operation.
- Inspect the differential pressure across the cyclone (once per shift).
- Visually inspect the cyclone shell, piping, and ducts for leaks; inspect the ash collection equipment and check for abnormal noise or hot spots (once per shift).
- Clean the boiler grates once a day on normal business days.
- Inspect the cyclone/multicyclone at least once per year or if conditions indicate it may need maintenance. Clean the boot and vanes if possible on the annual inspection.
- Empty the cyclone/multicyclone ash collection vessel as necessary, but not less than once per week, in accordance with the manufacturer's recommendations.[3]

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[1] More information can be accessed at http://www.epa.gov/ttn/emc/methods/method22.html

[2] More information can be accessed at http://www.epa.gov/ttn/emc/methods/method9.html

[3] This would also suffice for any other add-on control device.

4.10 Annual Tune Up

Annual tune ups are typically performed on wood boilers. The annual tune up includes a comprehensive inspection of the combustor, boiler and pollution control system components. Adjustments/improvements to system components are performed as needed. Combustion efficiency is typically measured when the annual tune up is performed.

5.0 ADD-ON POLLUTION CONTROLS

Add-on pollution controls are emission control devices which remove pollutants from the exhaust gas stream somewhere between the boiler combustion chamber and the exhaust stack. They are installed when the combustion equipment cannot reduce emissions to a desired level. In the absence of a fixed BACT requirement,[1] emission controls are determined on a case by case basis and are a function of the following: level of uncontrolled emissions, applicable state/federal emission limits, existing ambient pollutant concentrations (background concentrations), stack height and stack proximity of stack to sensitive populations. Potential add-on controls reviewed for this study include cyclones, multicyclones, high efficiency multicyclones (HEMCs), core separators, electrostatic precipitators (ESPs) and baghouses (fabric filters). The Core Separator™ was determined in the 2001 emission control report by Resource Systems Group as the Best Available Control Technology (BACT) for small wood-fired boilers burning a wood chip type fuel and capable of limiting PM10 emissions to 0.1 lb/MMBtu.[2] The Core Separator™ will be discussed in further detail later in this section. Again, the conclusions of this report were accepted by a consortium of New England states, they did not translate into a formal BACT determination at the federal level.

This section will focus on add-on controls for reducing filterable particulate matter because for the boiler size range considered in this study, combustion controls are used to limit emissions of other pollutants such as condensable particulate matter, nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOCs) and most hazardous air pollutants (HAPs or “air toxics”). Add-on controls are not discussed for sulfur dioxide (SO_2) given the low sulfur content of biomass. Combustion controls for pollutants other than particulate matter are summarized later in this report.

5.1 Mechanical Collectors

Mechanical collectors use centrifugal forces to separate particulate matter from an exhaust gas stream. Mechanical collectors include single cyclones, multicyclones, high efficiency multicyclones (HEMCs) and core separators. They are often used as exhaust gas pre-cleaners for other control devices, such as baghouses or ESPs.

The exhaust gas flow rate is directly proportional to the operating load of the boiler. Pressure drop, an indicator of centrifugal separation force which removes particles from exhaust, is directly proportional to the exhaust gas flow rate. Therefore, mechanical collectors work best when operating at their respective design (maximum) pressure drop.

[1] Massachusetts currently requires all wood boilers meeting the state permit applicability threshold meet a PM10 emission limit of 0.10 lb/MMBtu.

[2] An Evaluation of Air Pollution Control Technologies for Small Wood-Fired Boilers.” Prepared for Vermont Department of Public Service; Vermont Department of Environmental Conservation, Air pollution Control Division; New Hampshire Governor’s Office of Energy Resources and Community Services; and the Massachusetts Division of Energy Resources. Resource Systems Group, Inc., White River Junction, VT. Revised, September 2001.

5.1.1 Cyclones and Multicyclones

Single and multicyclones can remove a large percentage (approximately 90%) of large particles (PM10 and larger) and remove a small percentage (less than 10%) of fine particles (PM2.5). HEMCs and core separators will collect higher percentages of PM10 and PM2.5.

5.1.2 High Efficiency Multicyclones

The high efficiency multicyclone (HEMC) is similar to a conventional multicyclone, but has higher collection efficiency due to use of a higher pressure drop. Conversely, the additional pressure drop has a higher energy demand. The HEMC was found to be the Best Available Control Technology (BACT) in a 2006 permit application to the Rhode Island Department of Environmental Management (RI DEM) for new institutional wood boilers with heat input less than 10 MMBtu/hour. The BACT study translated into emission limits of 0.20 lb/MMBtu and 0.18 lb/MMBtu for PM10 and PM2.5 respectively (these limits include both filterable and condensable particulate matter).

Inlet-outlet testing was performed for the Vermont APCD study at the HEMC installed at the Ponaganset Middle School in North Scituate, RI. Two, one-hour tests were completed for a single wood boiler. The HEMC there is designed to operate most effectively at four inches of pressure drop. During testing, the wood boiler operated at low load (30% capacity) which created a pressure drop of approximately only 0.7 inches of water. The HEMC collected 23% of the particulate matter in the boiler exhaust despite the low pressure drop and a very high percentage of fine particles in the inlet exhaust gas stream (approximately 90%).

A collection efficiency of 23% is a relatively low number in comparison with other add-on controls. However, it is approximately 10% higher than what a conventional multicyclone can achieve for PM2.5 removal under design (maximum) pressure drop conditions. Furthermore, design calculations provided by the vendor indicate the PM2.5 collection efficiency would have been approximately four times higher at design pressure drop.

HEMC's can be designed to maintain a high pressure drop at low loads. This can be achieved by using valves to regulate the number of cyclones through which exhaust gas passes. For example, at high load, all valves would open thereby allowing exhaust gas to distribute among all the cyclones. As load decreased, valves would close causing exhaust gas to be distributed among a smaller number of cyclones.

5.1.3 Core Separator™

The Core Separator™ was previously determined as BACT for particulate mater, in a 2001 report written by Resource Systems Group.[1] This technology became commercially unavailable after the report was issued, when LSR Technologies stopped operating. Since that time, the rights to the patent were transferred to Easom Corporation, from whom core separators can currently be purchased.

Unlike conventional cyclone/multicyclones and the HEMCs in Rhode Island, the Core Separator™ design will maintain a relatively high pressure drop at all operating loads. Therefore, this technology's collection efficiency will not deteriorate with reduced operating loads. Stack test results indicate it has a PM collection efficiency of approximately 60% and outlet PM2.5 emissions of less than 0.1 lb/MMBtu with close coupled gasifiers and approximately 0.15 lb/MMBtu with stoker combustors.

5.2 Dry Electrostatic Precipitators

Dry Electrostatic precipitators (ESPs) work on the principle of electrostatic attraction. In this, particles in an exhaust gas stream are charged as they pass through the ESP and are pulled out of the exhaust gas stream by oppositely charged plates on the side of the ESP. This technology is widely used in Europe to

[1] 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.

control particulate emissions from biomass systems. The control efficiency of PM10 and PM2.5 appears to be 99% or greater, making this control technology very compelling.[1] There are no demonstrated applications of ESPs on small wood boilers in the United States. The pervasiveness of ESPs in Europe is due to stricter emission limits and higher subsidies.[2] There is one demonstrated ESP on a small coal fired boiler in North Carolina. At least two ESPs are slated for construction for small wood fired boilers in New England this year.

Until recently, it has been commonly held that ESPs have significantly higher capital costs than baghouses. Given changes in ESP design and recent cost analyses, it is now thought that ESPs have comparable capital costs to baghouses for certain boiler sizes as they require less ancillary equipment (such as insulated ductwork, multicyclone for exhaust pre-cleaning) than baghouses. This finding coupled with significantly lower operating costs and smaller spatial requirements than baghouses, have helped ESPs become especially attractive when advanced emission control is necessary.

Significant pressure drops do not occur in ESPs; therefore, they do not require the extra energy to run fans to overcome the pressure drop. This means ESPs potentially will have a lower energy demand than all other add-on controls.

5.3 Baghouses (Fabric Filters)

Baghouses utilize fabric filtration to remove particles from an exhaust gas stream. They are thought to provide the highest degree of control of all add-on controls (99%+ of filterable PM2.5 emissions).[3] This is higher than the control efficiency measured in Greenfield, NH or 74%. Again, this lower value was likely due to tramp air flowing through a bypass during the stack test there.

Cyclone/multicyclones are used to pre-clean exhaust gas upstream of baghouses to reduce fire hazard. As with mechanical collectors, there is pressure drop across this control device caused by the exhaust gas passing through fabric. Therefore, energy is required to draw exhaust through the fabric.

The 2001 RSG report determined baghouses were technically infeasible due to threat of fire. A 2006 RSG BACT study also found them technically infeasible due to fire hazard and due to potential for filter bag clogging, a condition which occurs when the exhaust gas cools to the dew point causing moisture to condense on the particulate “cake” on the side of the bag walls. The end product is impermeable and can cause bags to rupture.

It should be noted that filter clogging has the potential to occur in systems burning a wet fuel (approximately 25% to 50% moisture content) with variable firing rates. Filter clogging is not likely to occur in systems burning a dry fuel (approximately 15% or less moisture content) and operating consistently at a high firing rate, which prevents the exhaust from cooling and reaching its dew point.

Historically in New England, baghouses have not been selected for systems with design inputs less than 10 MMBtu/hour because the facilities which they would serve determined they did not have the financial or technical resources to purchase and service them. For example, this size boiler would serve a small school, which would typically not have a large and experienced facilities staff who could service the baghouse. In the absence of a significant subsidy, a small school would typically not have the financial resources to purchase a baghouse.

There are now three demonstrated applications of baghouses on relatively small wood fired boilers in New England. These installations are not experiencing filter bag clogging problem because the vendors developed a design to avoid this problem. However, there was one fire which occurred in one of the systems which required the bags to be replaced. A multicyclone was installed after the fire. No fires have been reported since that time. These systems are described below:

[1] Compilation of Emission Factors, AP 42, Chapter 1.6. US EPA, revised September, 2003

[2] Personal communication with Biomass Energy Resource Center. September, 2009.

[3] Compilation of Emission Factors. AP 42 Chapter 1.6. Revised September, 2003

- Mount Wachusett College, Gardiner, MA - 10 MMBtu/hour wood chip boiler.
- Crochet Mountain Rehabilitation Center, Greenfield, NH – 5.7 and 11.4 MMBtu/hour wood chip boilers.
- Middlebury College, Middlebury, VT – 29 MMBtu/hour wood chip boiler.

These applications indicate baghouses are technically feasible, provided they are designed to avoid fire and filter clogging.

Baghouses have the highest operating cost of all add on controls discussed in this report. This is largely due to the cost of replacement bags and to the amount of time required to keep baghouses in proper working order. At this time, it is not known exactly how frequently bags need to be replaced on small wood boilers. The rule of thumb is to replace a given bag every three years, which means replacing one third of all the bags every year. However, this may not be applicable to wood boilers operating only during the heating season. Bag replacement for these boilers could equate to approximately one sixth of the bags every year.

6.0 Summary of European Emission Control Practices

The Biomass Energy Resource Center (BERC) recently completed a research trip to Europe to learn more about their biomass facilities. Here is a synopsis of their findings.

- There are larger economic incentives for bioenergy in Europe as compared to the US. For example, electricity from biomass power plants can be sold to utilities for approximately 30 euro cents/kwh (40 US dollar cents/kWh), which is approximately three times higher than the price the utility will charge to its customer base. This means a subsidy of approximately 20 euro cents/kwh is paid to the utility. For comparison, in Vermont, biomass electricity is sold to utilities for approximately 12.5 cents/kwh and in turn sold by utilities for approximately 13 to 14 cents/kwh.
- Most of the biomass systems in Europe deploy the following energy efficiency measures (unless noted otherwise, the following list of energy efficiency measures are also used in the US):
    - High combustion temperature 1013°C (1855 F);
    - Low excess air (approximately 50 to 75%);
    - Continuous oxygen content monitoring (%O_2) to achieve target content in flue of approximately about 7 to 9%;
    - Setting target CO_2 exhaust content (not used in the US). The target of the CO_2 in the flue gas is 13%. If less than 10%, the secondary air is adjusted. Even for the small wood pellet boilers (residential scale) the O_2 % in the flue gases is monitored continuously and the excess air is modulated based on the % O_2 content;
    - Pre-heating of both the primary and the secondary air using an economizer;
    - A heat recovery system using the hot air from the upper level of the boiler room is used to dry the woodchips;
    - Water preheated using the flue gas, cooling the flue gases from 900°C (1652 °F) to 180°C (356°F)[1] before the ESP; and
    - Variable speed drives on the hot water distribution pumps.
- Emissions control equipment normally used is a multicyclone and ESP in series. ESP's are frequently installed outside of buildings.

[1] This temperature is maintained to prevent condensation.

- Some projects have condensers to remove the moisture from the flue gases simultaneously recovering some additional thermal energy.
- The average ash content is about 2-5% of the biomass and reflects burning lower quality biomass (in some cases). The ash streams are collected separately and utilized where appropriate. The ash from the multi-cyclone and the combustion chamber of the boiler may be used as fertilizer in farm operations. The ash from ESP (fine ash) is land filled, as it may contain heavy metals.
- The capital cost of a typical ESP for a new power plant of 5 to 10 MW capacity range was typically about 12-14% of the cost of the project. This percent may be more for smaller capacity plants producing only heat.
- The quality of woodchips is not considered to be very critical. This is likely attributable to the widespread use of ESPs.

7.0 Capital Costs of Emission Controls for Particulate Matter

Capital and operating costs were estimated with quotes from and personal communication with equipment vendors as well as the equations and methods presented in the "EPA Cost Control Manual."[1] Information used to generate costs is detailed in the appendix. In addition to the size of the biomass combustor, there are a number of other factors which cause variability in the capital costs. Here is a selected list of factors affecting price variability:

- **Change in the price of steel.** This change had a significant affect on the price of the Core Separator™ and other mechanical collectors.
- **Foreign exchange rates.** For equipment purchased overseas, specifically Europe, the cost is significantly affected by the exchange rate, which now increases price for US installations. The two high efficiency multicyclones featured in this report were purchased from a European vendor.
- **Pollution control device design.** Capital costs are also affected by the pollution control equipment design. For example, the price of electrostatic precipitators is sensitive to the size of the particle collection plates. Collection efficiency is related to collection plate size; therefore, projects requiring relatively high collection efficiency will result in larger collection plates and a more expenive electrostatic precipitator.
- **Fuel characteristics.** As mentioned systems having variable firing rates burning wet fuels are susceptible to filter clogging if a baghouse is installed. As a result, baghouses are now typically designed with additional components which mitigate the problem, but significantly increase price.
- **Space requirements.** The amount of horizontal and vertical space required for a given control can affect the installation cost. For examples, baghouses can require more space than electrostatic precipitators. The additional space required can increase the footprint and/or height of the building housing the equipment, thereby increasing construction costs.
- **Ancillary equipment.** For example, baghouses require more ancillary equipment, such as insulated ductwork and a mechanical collector (to reduce fire risk), than an ESP.

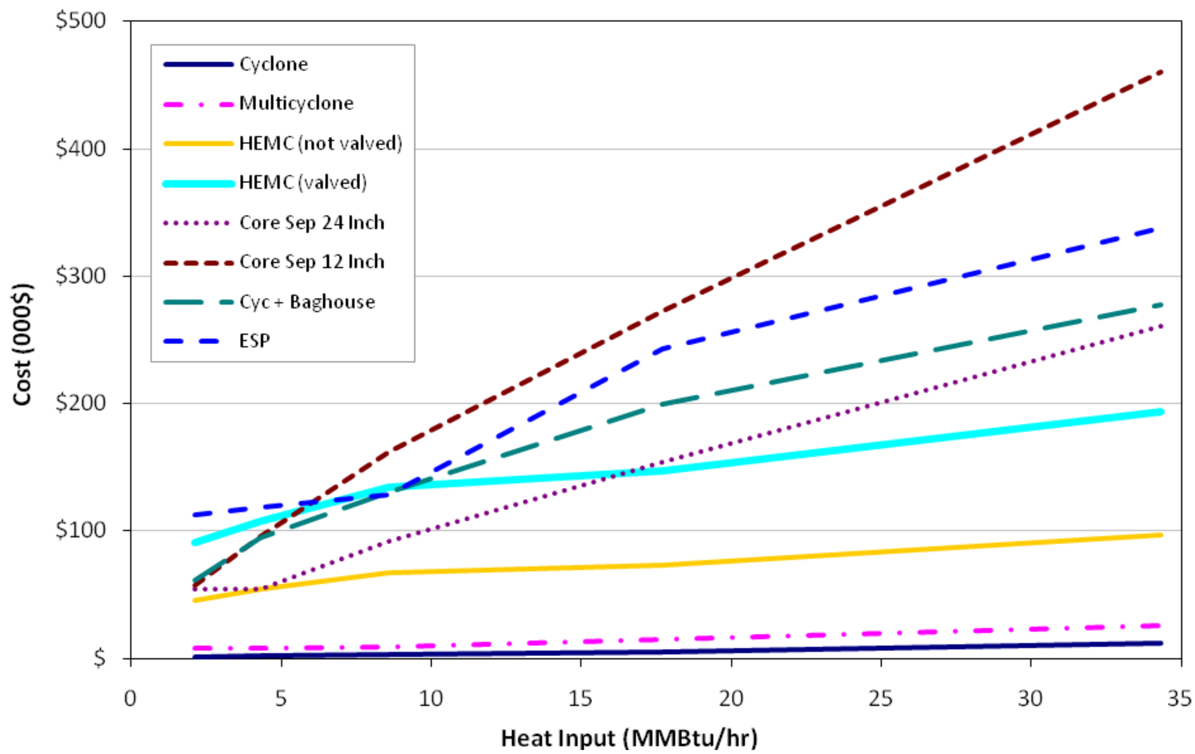
[1] EPA Cost Control Manual, Sixth Edition. U.S EPA report #EPA/452/B-02-001. January, 2002. Available at: http://www.epa.gov/ttn/catc/dir1/c_allchs.pdf.

- **Shipping costs.** The proximity of the location to major transportation hubs as well as the equipment production location can affect costs.
- **Duplicated equipment & services.** In some cases, the wood boiler vendor and emission control vendor may inadvertently include a number of similar equipment items and services in their quotes. This can significantly increase costs if overlapping equipment items are not identified and re-allocated.[1]

  Examples of duplicated equipment and services could include the support stand, draft fan, sensors, dampers, control panel with plc, vfd for draft fan, inlet and outlet expansion/isolation joints, rotary air lock, duct work, engineering services, assembling and commissioning.

Estimated capital costs for add-on particulate matter controls are shown below for a single cyclone, multicyclone, high efficiency multicyclone (not valved), high efficiency multicyclone (valved),[2] Core Separator™ (with 24 inch diameter separators), Core Separator™ (with 12 inch diameter separators), cyclone coupled with baghouse[3], and an electrostatic precipitator. Approximate costs are shown for systems from approximately 2 MMBtu/hour to 34 MMBtu/hour heat input in Figure 1. These costs are subject to the variability caused by the bulleted items discussed above. They are also a best estimate of installed cost.

Figure 1: Particulate Matter Add-On Emission Control Costs



[1] Duplicated costs were identified for a project RSG participated in which included an HEMC, and where it was determined that the price of the HEMC could be substantially reduced because the wood boiler vendor had already specified the equipment and services in its quote.

[2] As previously mentioned, the term "valved" refers to the use of valves to maintain pressure drop over a range of firing rates.

[3] Baghouse costs reflect baghouses with multiple cells to prevent filter clogging.

All capital costs shown above except those for "cyclone + baghouse" were derived exclusively with vendor quotes. This category was calculated by inputting the cost of the bags into an equation listed in Table 1.9 of the EPA Cost Control Manual, which calculated remaining costs based on the price of the bags. They are intended to represent all costs leading up to and including installation.

8.0 Cost Effectiveness of Particulate Matter Emission Controls

Cost effectiveness was estimated for the same particulate matter add-on controls. For the purposes of this report, the term "cost effectiveness" refers to the dollars spent to remove one ton of a given pollutant in a given year and are a function of the capital and operating costs. Costs were estimated using the methodology in the EPA Air Pollution Cost Control Manual and with price quotes and personal communication with equipment vendors and other technology experts.[1] Cost effectiveness is linearly related to the:

1) Design heat input of the system,
2) Annual fuel consumption rate (annual capacity factor),
3) Pollutant inlet loading of the pollution control device and
4) Size of particle being controlled (PM10 and PM2.5).

This means the cost effectiveness values listed later in this section can be scaled upward or downward, given the linear relationship of the aforementioned factors with cost effectiveness,

Cost effectiveness was estimated for PM10 and PM2.5. Table 11 summarizes the assumed parameter values used to model cost effectiveness. The values used are intended to help portray a small institutional wood boiler operating approximately half the year to provide heat and hot water. The inlet loading values were taken from AP 42 and correspond to the "wet wood" category. These values were deemed as being generally representative for a stoker combustion system. Actual numbers may be lower for "stokers" and are likely lower for close coupled gasifiers.

Table 11: Assumed Parameter Values for Cost Effectiveness Analysis

Wood boiler design heat input	5.0 MMBtu/hour
PM10 Inlet loading	0.31 lb/MMBtu
PM2.5 inlet loading	0.25 lb/MMBtu
Operating hours per year	4380 (half the year)
Average daily operating capacity	50%
Annual capacity factor	25%
Fuel heat content at 40% MC	5,013 btu/lb
Annual fuel consumption	1,095 tons/year
Annual uncontrolled PM10 emissions (tons/yr)	2.7
Annual uncontrolled PM2.5 emissions (tons/yr)	2.4

Table 12 and Table 13 show estimated cost effectiveness PM10 and PM2.5 removal respectively, from the system summarized in Table 11. A best estimate has been made to assign control efficiencies, capital costs and operating costs. Control efficiencies were estimated with the emission test information reviewed for this report, AP 42 uncontrolled and controlled emission factors, the RSG 2001 BACT report,

[1] EPA Air Pollution Control Cost Manual, Sixth Edition. EPA/452/B-02-001. United States Environmental Protection Agency, Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina. January, 2002

personal communication with equipment vendors, and a draft report written by the Northeast States for Coordinated Air Use Management (NESCAUM).[1] Assumed control efficiency values reflect optimal operating conditions are occurring for both the combustor and the control equipment. It should be noted that both HEMCs listed and only the 12" Core Separator control efficiencies are based on vendor calculations, not actual performance. Furthermore, as evidenced by the stack test in Rhode Island, actual control efficiency will be lower for "un-valved" HEMC's whose wood boiler is operating below full load.

As mentioned, there are many factors which cause variability in capital and operating costs. In addition, cost effectiveness (especially in mechanical collectors) is also affected by particle size distribution.[2] Therefore, actual costs could vary considerably from what is quoted below.

Table 12: Cost Effectiveness for Controlling PM10 Emissions[3]

Pollution Control Device	Control Efficiency	PM10 Emissions Removed (tons/year)	Installed Capital Cost of Equipment	Annual Operating Costs	Total Annual Costs	Total Cost per Ton Removed
Cyclone	50%	0.9	$2,243	$580	$791	$930
Multicyclone	75%	1.3	$9,424	$580	$1,469	$1,151
HE Multicyclone	99%	1.3	$62,878	$800	$6,980	$4,159
HE Multicyclone (valved)	99%	1.7	$125,756	$800	$12,915	$7,695
Core Separator (12")	94%	1.7	$111,709	$1,239	$12,350	$7,685
Core Separator (24")	72%	1.2	$63,337	$1,459	$8,004	$6,519
Cyclone + Baghouse	99%	1.7	$109,878	$3,920	$14,291	$8,483
ESP	95%	1.6	$138,005	$1,867	$14,894	$9,213

Table 13: Cost Effectiveness for Controlling PM2.5 Emissions[4]

Pollution Control Device	Control Efficiency	PM2.5 Emissions Removed (tons/year)	Installed Capital Cost of Equipment	Annual Operating Costs	Total Annual Costs	Total Cost per Ton Removed
Cyclone	5%	0.9	$ 2,243	$580	$791	$11,534
Multicyclone	10%	1.3	$9,424	$580	$1,469	$10,707
HE Multicyclone	86%	1.2	$65,478	$800	$6,980	$5,884
HE Multicyclone (valved)	86%	1.2	$128,356	$800	$12,915	$10,887
Core Separator (12")	56%	0.8	$117,709	$1,239	$12,350	$16,105
Core Separator (24")	29%	0.4	$69,337	$1,459	$8,004	$19,939
Cyclone + Baghouse	99%	1.7	$109,878	$3,920	$14,291	$10,519
ESP	90%	1.6	$138,005	$1,867	$14,894	$12,059

The total cost per ton of pollutant removed is calculated by dividing the total annual costs by the total amount of pollutant removed. Pollutant removal costs of PM2.5 with cyclones and multicyclones are significantly higher than for PM10 because the values for the tons of PM2.5 removed are less than one. This significant increase in pollutant removal cost demonstrates the relative ineffectiveness of conventional cyclones and multicyclones.

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[1] "Controlling Emissions from Wood Boilers." Northeast States for Coordinated Air Use Management (NESCAUM). October, 2008. Available at: http://www.nescaum.org/topics/commercial-wood-boilers.

[2] The particle size distribution corresponds to the collective percentages of each particle size.

[3] The quantity of emissions controlled is a function of the particle size distribution. The values in this table assume 100% of the inlet emissions are evenly distributed from 2.5 microns up to 10 microns.

[4] The quantity of emissions controlled is a function of the particle size distribution. The values in this table assume 100% of the inlet emissions are evenly distributed from 1 to 2.5 microns.

9.0 Overview of Emission Controls for Other Relevant Pollutants

9.1 Nitrogen Oxides (NOx)

There are two major sources of NOx emissions. The first, "fuel NOx" is NOx produced by the oxidation of fuel bound nitrogen during combustion. The second, "thermal NOx" is NOx produced by the oxidation of nitrogen in the combustion air. The latter is produced at temperatures typically much higher than those occurring during biomass combustion. Therefore, the total NOx is most influenced by the fuel nitrogen content.

Combustion controls are the only way NOx emissions are controlled apart from add-on controls such as selective catalytic reduction (SCR) or selective noncatalytic reduction (SNCR).

Increasing excess air can help control thermal NOx emissions by reducing flame temperature. Oxygen concentration is an indicator of the amount of excess air; therefore, monitoring oxygen concentration and linking oxygen measurements with automated controls establish the appropriate quantity of excess air on a continual basis and prevent excess thermal NOx emissions.

Staged combustion is another means for controlling thermal NOx emissions.

9.2 Sulfur Dioxide (SO_2)

SO_2 emissions from wood combustion are negligible given very low sulfur content in biomass.

9.3 Carbon Monoxide (CO)

Carbon monoxide emissions are minimized by good combustion conditions, specifically, maintaining the proper air to fuel ratio. Plume opacity observation, proper operation and maintenance, periodic combustion efficiency testing, and in-situ oxygen concentration monitoring are ways to ensure ongoing good combustion conditions. A combustion chamber designed with staged combustion increases the degree of combustion completeness and is therefore useful for minimizing CO emissions.

9.4 Volatile Organic Compounds (VOCs)

The same measures for minimizing CO emissions will minimize VOC emissions.

9.5 Hazardous Air Pollutants (HAPs)

Hazardous air pollutants include both gaseous and particulate based pollutants. The aforementioned controls for CO and are also effective at controlling HAPs, but most effective at controlling gaseous HAPs. Particulate HAPs are also controlled with an add-on control device.

10.0 CONCLUSIONS

The following conclusions were drawn from the study completed for this report:

1. New stack test emission information is providing additional insights into how fuel characteristics and add-on controls affect particulate emission levels.
2. Limited information is available for pellet combustion emissions, high efficiency multicyclone (HEMC) control efficiency, fabric filter, and electrostatic precipitator (ESPs) control efficiency for small wood boilers.
3. While the quantity of emissions information for wood boilers approximately 10 MMBtu/hour and smaller is growing to a level on which generally meaningful interpretations can be made, this quantity of information is not available to make meaningful interpretations for wood boilers smaller than 5.0 MMBtu/hour.
4. There are many Best Management Practices (BMPs), also called work practice standards, which can be implemented to characterize, enhance and preserve fuel quality. Implementing these measures improves fuel handling and combustion conditions, increases energy efficiency and reduces emissions.
5. The increased combustion completeness resulting from BMPs not only helps reduce particulate matter emissions, but also helps reduce emissions of gaseous pollutants, including carbon monoxide, nitrogen oxides, volatile organic compounds (VOCs) and hazardous air pollutants (HAPs).
6. BMPs help prevent upset combustion conditions which will reduce nuisance episodes accompanied by excessive plume opacity.
7. Particle size has a large affect on collection efficiency in <u>conventional</u> mechanical collectors (mechanical collectors with a relatively low pressure drop). Substantially smaller quantities of fine particles (PM2.5) than coarse particles (PM10) can be collected in conventional mechanical collectors.
8. Pressure drop has a large affect on mechanical collector collection efficiency. Core separators collect substantially larger quantities of fine particles than conventional mechanical collectors, at all firing rates, as they are designed to maintain a high pressure drop at all firing rates.
9. New baghouse designs are safer and technically feasible. These conclusions are demonstrated by three relatively new baghouse installations in the northeast.
10. Potential exists for implementing an HEMC design which maintains a relatively high pressure drop at a range of firing rates using valves.
11. The Core Separator™ was commercially unavailable, but is now commercially available. While not field tested, laboratory tests and engineering calculations indicate the 12” Core Separator has potential to collect more particulate matter than the 24” model.
12. ESPs and baghouses have near comparable capital costs for some system sizes. ESPs have lower operating costs and lower energy demand.
13. Recent experience in Europe indicates greater prevalence of ESPs due to greater financial incentives and stricter emission limits.
14. Baghouses and ESPs are the add-on controls providing the highest degree of control of PM2.5 for all firing rates.
15. For small systems less than 2.0 MMBtu/hr, the annual operating cost of all add-on emission controls except cyclones, multicyclones and “non-valved” high efficiency multicyclones are likely to be substantially higher than for larger systems.

11.0 Recommendations for Future Research

A number of factors affect emission rates, such as geographic location, type of fuel burned, firing rate characteristics, type of combustion technology, and type of add-on emission control. Additional emission tests will improve understanding of how these factors affect emission levels. Future emission tests could be structured for wood chip and wood pellet systems as follows:

1. Inlet-outlet testing for particulate emissions (PM10, PM2.5) controlled by ESPs, baghouses and HEMCs. Particle size distribution should also be measured at the inlet and outlet, in addition to measuring mass emission rates.
2. HAP emissions in concert with CO and PM2.5. Inlet and outlet testing should be performed for particulate HAPs. PM2.5 should be tested because it is considered a surrogate for particulate HAPs. CO should be tested (outlet testing only) because it is considered a surrogate for gaseous HAPs.
3. Stack testing for any given site should be expanded to include emissions from the following:
    a. Low, medium and high firing rates
    b. At least two fuels, such as, wood with bark (bole chips or whole tree chips) and wood without bark (mill chips).

Attention should also be given to the following:

1. Development of a voluntary universal boiler operator training program for obtaining boiler operator certification.
2. Further development of fuel quality specifications to further establish grades of wood fuels.

12.0 Summary

A number of emission controls for small wood-fired boilers have been evaluated. This study evaluated a number of Best Management Practices (BMPs – also called work practice standards) and add-on controls. While these controls are focused on particulate matter control, their implementation will control emissions of all types of pollutants, including carbon monoxide, sulfur dioxide, nitrogen oxides, volatile organic compounds and hazardous air pollutants. Maximizing fuel quality, optimizing combustion conditions and selecting a well designed add-on pollution control are the three main categories for controlling emissions. Control efficiency and cost effectiveness vary by boiler size, particle size distribution and type of add-on pollution control.

APPENDIX A

STACK TEST REPORTS

APPENDIX B

EMISSION CALCULATIONS

Hazardous Air Pollutant Synopsis

Pollutant Category	System Information / Pollutant	Ponaganset MS Result (lb/MMBtu)	Ponaganset HS Result (lb/MMBtu)	Council Result (lb/MMBtu)	Green Acres Result (lb/MMBtu)	Hazen Union Result (lb/MMBtu)	Overall Average Result (lb/MMBtu)	AP 42 Emission Factor (lb/MMBtu)	% of AP 42	Ponaganset % of Others
	Design Heat Input	9.1	4.6	1.9	2.2	2.8				
	Combustion type	CCG	CCG	SA	SA	CCG				
	Emission control	HEMC	HEMC	Uncontrolled	Uncontrolled	Multicyclone				
Metals	Arsenic	1.54E-06	8.40E-07	4.54E-06	2.66E-06	5.71E-07	2.03E-06	2.20E-05	9%	46%
	Cadmium			2.15E-05	1.78E-05	3.93E-06	1.44E-05	4.10E-06	352%	
	Chromium			2.34E-05	2.64E-05	6.51E-06	1.88E-05	2.10E-05	89%	
	Chromium VI	4.83E-06	1.31E-06		1.31E-06	8.37E-07	2.07E-06	3.50E-06	59%	286%
	Nickel	9.87E-06	3.29E-06	2.20E-05	2.11E-05	3.57E-06	1.20E-05	3.30E-05	36%	42%
	Manganese	9.58E-05	8.66E-05				9.12E-05	1.60E-03	6%	
	Phosporus	1.00E-04	1.29E-04				1.15E-04	2.70E-05	425%	
Organics	Formaldehyde	9.30E-04	4.77E-04	9.50E-04	1.05E-02	1.38E-03	2.84E-03	4.40E-03	65%	16%
	Benzene	1.50E-04	4.11E-06		4.49E-05	5.80E-05	6.43E-05	4.20E-03	2%	150%
PAHs	Acenapthene	4.27E-08	5.05E-08	0.00E+00	7.53E-07	4.65E-07	2.62245E-07	9.10E-07	29%	11%
	Acenapthylene	4.80E-06	4.81E-06	0.00E+00	3.33E-05	2.04E-04	4.93813E-05	5.00E-06	988%	6%
	Anthracene	1.82E-06	1.41E-06	0.00E+00	2.44E-06	1.42E-05	3.97491E-06	3.00E-06	132%	29%
	Benz(a)anthracene	2.38E-05	2.84E-05	0.00E+00	1.54E-06	1.63E-05	1.40124E-05	6.50E-08	21,558%	439%
	Benzo(b)fluoranthene	2.18E-05	1.83E-05	0.00E+00	3.66E-06	2.51E-05	1.37725E-05	1.00E-07	13,772%	209%
	Benzo(ghi)perylene	2.82E-06	2.57E-06	2.52E-07	1.93E-06	1.44E-05	4.39315E-06	9.30E-08	4,724%	49%
	Benzo(e)pyrene	1.50E-05	9.65E-06	0.00E+00	2.38E-06	1.57E-05	8.5388E-06	2.60E-09	328,416%	204%
	Benzo(a)pyrene	4.56E-06	5.50E-06	0.00E+00	9.91E-07	1.34E-05	4.88928E-06	2.60E-06	188%	105%
	Chrysene	4.91E-05	4.46E-05	0.00E+00	3.15E-06	2.43E-05	2.42272E-05	3.80E-08	63,756%	512%
	Dibenz(a,h)anthracene	3.73E-07	4.15E-07	0.00E+00	1.33E-07	6.97E-06	1.57829E-06	9.10E-09	17,344%	17%
	Fluoranthene	2.82E-05	9.15E-05	1.31E-06	1.08E-05	9.51E-05	4.53915E-05	1.60E-06	2,837%	168%
	Fluorene	1.17E-07	1.39E-07	1.43E-06	6.22E-07	2.90E-06	1.04166E-06	3.40E-06	31%	8%
	Ideno(1,2,3-cd)pyrene	2.22E-06	1.98E-06	0.00E+00	1.28E-06	2.77E-06	1.65057E-06	8.70E-08	1,897%	156%
	2-methylnapthalene	1.02E-06	9.51E-07	0.00E+00	1.32E-05	1.32E-05	5.67378E-06	1.60E-07	3,546%	11%
	Napthalene	2.85E-05	2.57E-05	6.55E-06	1.26E-04	7.47E-05	5.2285E-05	9.70E-05	54%	39%
	Phenanthrene	2.46E-05	2.05E-05	3.17E-06	2.67E-05	2.64E-04	6.77896E-05	7.00E-06	968%	23%
	Pyrene	3.05E-05	3.22E-05	4.69E-06	9.38E-06	8.12E-05	3.15871E-05	3.70E-06	854%	99%
AP 42 Comparison	Ponaganset Total HAPs	1.53E-03	9.91E-04					1.04E-02		
	Ponaganset % of AP 42	15%	10%							
	Council Total HAPs			1.04E-03				4.60E-03		
	Council % of AP 42			23%						
	Green Acres Total HAPs				1.08E-02			8.81E-03		
	Green Acres % of AP 42				123%					
	Hazen Total HAPs					2.32E-03		8.81E-03		
	Hazen % of AP 42					26%				
	Green Acres & Hazen Total HAPs						3.29E-03	8.81E-03		
	Green Acres & Hazen % of AP 42						37%			

Hazardous Air Pollutant Synopsis

Pollutant Category	System Information / Pollutant	Ponaganset MS Result (lb/MMBtu)	Ponaganset HS Result (lb/MMBtu)	Council Result (lb/MMBtu)	Green Acres Result (lb/MMBtu)	Hazen Union Result (lb/MMBtu)	Overall Average Result (lb/MMBtu)	AP 42 Emission Factor (lb/MMBtu)	% of AP 42	Ponaganset % of Others
	Design Heat Input	9.1	4.6	1.9	2.2	2.8				
	Combustion type	CCG	CCG	SA	SA	CCG				
	Emission control	HEMC	HEMC	Uncontrolled	Uncontrolled	Multicyclone				
Metals	Arsenic	1.54E-06	8.40E-07	4.54E-06	2.66E-06	5.71E-07	2.03E-06	2.20E-05	9%	46%
	Cadmium			2.15E-05	1.78E-05	3.93E-06	1.44E-05	4.10E-06	352%	
	Chromium			2.34E-05	2.64E-05	6.51E-06	1.88E-05	2.10E-05	89%	
	Chromium VI	4.83E-06	1.31E-06		1.31E-06	8.37E-07	2.07E-06	3.50E-06	59%	286%
	Nickel	9.87E-06	3.29E-06	2.20E-05	2.11E-05	3.57E-06	1.20E-05	3.30E-05	36%	42%
	Manganese	9.58E-05	8.66E-05				9.12E-05	1.60E-03	6%	
	Phosporus	1.00E-04	1.29E-04				1.15E-04	2.70E-05	425%	
Organics	Formaldehyde	9.30E-04	4.77E-04	9.50E-04	1.05E-02	1.38E-03	2.84E-03	4.40E-03	65%	16%
	Benzene	1.50E-04	4.11E-06		4.49E-05	5.80E-05	6.43E-05	4.20E-03	2%	150%
PAHs	Acenapthene	4.27E-08	5.05E-08	0.00E+00	7.53E-07	4.65E-07	2.62245E-07	9.10E-07	29%	11%
	Acenapthylene	4.80E-06	4.81E-06	0.00E+00	3.33E-05	2.04E-04	4.93813E-05	5.00E-06	988%	6%
	Anthracene	1.82E-06	1.41E-06	0.00E+00	2.44E-06	1.42E-05	3.97491E-06	3.00E-06	132%	29%
	Benz(a)anthracene	2.38E-05	2.84E-05	0.00E+00	1.54E-06	1.63E-05	1.40124E-05	6.50E-08	21,558%	439%
	Benzo(b)fluoranthene	2.18E-05	1.83E-05	0.00E+00	3.66E-06	2.51E-05	1.37725E-05	1.00E-07	13,772%	209%
	Benzo(ghi)perylene	2.82E-06	2.57E-06	2.52E-07	1.93E-06	1.44E-05	4.39315E-06	9.30E-08	4,724%	49%
	Benzo(e)pyrene	1.50E-05	9.65E-06	0.00E+00	2.38E-06	1.57E-05	8.5388E-06	2.60E-09	328,416%	204%
	Benzo(a)pyrene	4.56E-06	5.50E-06	0.00E+00	9.91E-07	1.34E-05	4.88928E-06	2.60E-06	188%	105%
	Chrysene	4.91E-05	4.46E-05	0.00E+00	3.15E-06	2.43E-05	2.42272E-05	3.80E-08	63,756%	512%
	Dibenz(a,h)anthracene	3.73E-07	4.15E-07	0.00E+00	1.33E-07	6.97E-06	1.57829E-06	9.10E-09	17,344%	17%
	Fluoranthene	2.82E-05	9.15E-05	1.31E-06	1.08E-05	9.51E-05	4.53915E-05	1.60E-06	2,837%	168%
	Fluorene	1.17E-07	1.39E-07	1.43E-06	6.22E-07	2.90E-06	1.04166E-06	3.40E-06	31%	8%
	Ideno(1,2,3-cd)pyrene	2.22E-06	1.98E-06	0.00E+00	1.28E-06	2.77E-06	1.65057E-06	8.70E-08	1,897%	156%
	2-methylnapthalene	1.02E-06	9.51E-07	0.00E+00	1.32E-05	1.32E-05	5.67378E-06	1.60E-07	3,546%	11%
	Napthalene	2.85E-05	2.57E-05	6.55E-06	1.26E-04	7.47E-05	5.2285E-05	9.70E-05	54%	39%
	Phenanthrene	2.46E-05	2.05E-05	3.17E-06	2.67E-05	2.64E-04	6.77896E-05	7.00E-06	968%	23%
	Pyrene	3.05E-05	3.22E-05	4.69E-06	9.38E-06	8.12E-05	3.15871E-05	3.70E-06	854%	99%
AP 42 Comparison	Ponaganset Total HAPs	1.53E-03	9.91E-04					1.04E-02		
	Ponaganset % of AP 42	15%	10%							
	Council Total HAPs			1.04E-03				4.60E-03		
	Council % of AP 42			23%						
	Green Acres Total HAPs				1.08E-02			8.81E-03		
	Green Acres % of AP 42				123%					
	Hazen Total HAPs					2.32E-03		8.81E-03		
	Hazen % of AP 42					26%				
	Green Acres & Hazen Total HAPs						3.29E-03	8.81E-03		
	Green Acres & Hazen % of AP 42						37%			

APPENDIX C

OPERATING COST CALCULATIONS

PM10 Operating Cost Calculation Values & References

GENERAL INPUTS

Category	Value	Notes
Interest rate (%)	0.07	Default value from EPA Cost Control Manual
Economic life (years)	20	Default value from EPA Cost Control Manual
Capital Recovery Factor (CRF)	9%	Equation 2.8a from EPA Cost Control Manual

CYCLONE / MULTICYCLONE OPERATING COSTS

Category	Value	Notes
total ash disposal cost	$0.00	all ash land applied for soil enhancement
electricity price ($/kwh)	0.1	av'g commercial elec. cost in 2009 (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html)
waste gas flow rate (acfm)	2562	from review of recent stack test reports in Vermont
static pressure drop (in wc)	2	based on project experience
combined fan-motor efficiency	60%	from EPA Cost Control Manual
hours per year	2,190	operating half the year at average operating capacity of 50% load
incremental electricity cost	$219.76	EPA Cost Control Manual, Equation 1.46.
labor hours per year	12	regular inspections, unexpected maintenance and annual inspection of the interior
labor rate	$30.00	personal communication with wood boiler vendor
labor costs	$360.00	
total annual costs	$579.76	

HIGH EFF MULTICYCLONE

Category	Value	Notes
total ash disposal cost	$0.00	all ash land applied for soil enhancement
electricity price ($/kwh)	0.1	av'g commercial elec. cost in 2009 (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html)
waste gas flow rate (acfm)	2,562	from review of recent stack test reports in Vermont
static pressure drop (in wc)	4	from vendor quote
combined fan-motor efficiency	60%	from EPA Cost Control Manual
hours per year	2,190	operating half the year at average operating capacity of 50% load
incremental electricity cost	$439.52	EPA Cost Control Manual, Equation 1.46.
labor hours per year	12	regular inspections, unexpected maintenance and annual inspection of the interior
labor rate	$30.00	personal communication with wood boiler vendor
labor costs	$360.00	
total annual costs	$799.52	

CORE SEPARATOR (24 INCH)

Category	Value	Notes
total ash disposal cost	$0.00	all ash land applied for soil enhancement
electricity price ($/kwh)	0.1	av'g commercial elec. cost in 2009 (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html)
waste gas flow rate (acfm)	2,562	from review of recent stack test reports in Vermont
static pressure drop (in wc)	8	personal communication with vendor
combined fan-motor efficiency	60%	from EPA Cost Control Manual
hours per year	2,190	operating half the year at average operating capacity of 50% load
incremental electricity cost	$879.03	EPA Cost Control Manual, Equation 1.46.
labor hours per year	12	regular inspections, unexpected maintenance and annual inspection of the interior
labor rate	$30.00	personal communication with wood boiler vendor
labor costs	$360.00	
total annual costs	$1,239.03	

CORE SEPARATOR (12 INCH)

Category	Value	Notes
total ash disposal cost	$0.00	all ash land applied for soil enhancement
electricity price ($/kwh)	0.1	av'g commercial elec. cost in 2009 (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html)
waste gas flow rate (acfm)	2,562	from review of recent stack test reports in Vermont
static pressure drop (in wc)	10	personal communication with vendor
combined fan-motor efficiency	60%	from EPA Cost Control Manual
hours per year	2,190	operating half the year at average operating capacity of 50% load
incremental electricity cost	$1,098.79	EPA Cost Control Manual, Equation 1.46.
labor hours per year	12	regular inspections, unexpected maintenance and annual inspection of the interior
labor rate	$30.00	personal communication with wood boiler vendor
labor costs	$360.00	
total annual costs	$1,458.79	

BAGHOUSE OPERATING COSTS

Category	Value	Notes
total ash disposal cost	$0.00	all ash land applied for soil enhancement
total bag cost	$4,250.00	vendor quote for coated bags
% of bags replaced annually	8%	1/12 of bags replaced every year assuming 50% annual capacity factor
bag replacement cost ($/yr)	$350.63	
electricity price ($/kwh)	0.1	av'g commercial elec. cost in 2009 (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html)
waste gas flow rate (acfm)	2,562	from review of recent stack test reports in Vermont
static pressure drop (in wc)	5	from permit application for new wood boiler in central Massachusetts
combined fan-motor efficiency	60%	from EPA Cost Control Manual
hours per year	2190	operating half the year at average operating capacity of 50% load
incremental electricity cost	$549.40	EPA Cost Control Manual, Equation 1.46.
labor rate	$30.00	personal communication with wood boiler vendor
labor hours per year	81	1 hr/wk general maint., 80 hours to replace all bags, 8 hours for black light testing at 2x per year
labor costs	$2,440.00	
total annual costs	$3,340.02	

ESP OPERATING COSTS

Category	Value	Notes
total ash disposal cost	$ -	all ash land applied for soil enhancement
pressure drop (in. water)	0.04	page 3-34 in EPA Cost Control Manual
operating time (h/yr)	2,190	operating half the year at average operating capacity of 50% load
system flow rate (acfm)	2,562	from review of recent stack test reports in Vermont
fan power req. (kWh/yr)	41	EPA Cost Control Manual, equation 3.46
electricity req. (kWh/yr)	2431	personal communication with vendor
electricity price ($/kwh)	0.1	av'g commercial elec. cost in 2009 (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html)
total electricity demand	569.4	sum of fan and other electricity requirements
total power cost	$ 247.20	
labor hours per year	8	personal communication with vendor. Open, inspect and clean ESP.
labor rate	$ 30.00	personal communication with wood boiler vendor
labor costs	$ 240.00	
maintenance costs	$ 1,021.59	page of EPA Cost Control Manual, equation 3-45
total annual costs	$ 1,508.79	

PM 2.5 Operating Cost Calculation Values & References

GENERAL INPUTS

Category	Value	Notes
Interest rate (%)	0.07	Default value from EPA Cost Control Manual
Economic life (years)	20	Default value from EPA Cost Control Manual
Capital Recovery Factor (CRF)	9%	Equation 2.8a from EPA Cost Control Manual

CYCLONE / MULTICYCLONE OPERATING COSTS

Category	Value	Notes
total ash disposal cost	$0.00	all ash land applied for soil enhancement
electricity price ($/kwh)	0.1	av'g commercial elec. cost in 2009 (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html)
waste gas flow rate (acfm)	2562	from review of recent stack test reports in Vermont
static pressure drop (in wc)	2	based on project experience
combined fan-motor efficiency	60%	from EPA Cost Control Manual
hours per year	2,190	operating half the year at average operating capacity of 50% load
incremental electricity cost	$219.76	EPA Cost Control Manual, Equation 1.46.
labor hours per year	12	regular inspections, unexpected maintenance and annual inspection of the interior
labor rate	$30.00	personal communication with wood boiler vendor
labor costs	$360.00	
total annual costs	$579.76	

HIGH EFF MULTICYCLONE

Category	Value	Notes
total ash disposal cost	$0.00	all ash land applied for soil enhancement
electricity price ($/kwh)	0.1	av'g commercial elec. cost in 2009 (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html)
waste gas flow rate (acfm)	2,562	from review of recent stack test reports in Vermont
static pressure drop (in wc)	4	from vendor quote
combined fan-motor efficiency	60%	from EPA Cost Control Manual
hours per year	2,190	operating half the year at average operating capacity of 50% load
incremental electricity cost	$439.52	EPA Cost Control Manual, Equation 1.46.
labor hours per year	12	regular inspections, unexpected maintenance and annual inspection of the interior
labor rate	$30.00	personal communication with wood boiler vendor
labor costs	$360.00	
total annual costs	$799.52	

CORE SEPARATOR (24 INCH)

Category	Value	Notes
total ash disposal cost	$0.00	all ash land applied for soil enhancement
electricity price ($/kwh)	0.1	av'g commercial elec. cost in 2009 (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html)
waste gas flow rate (acfm)	2,562	from review of recent stack test reports in Vermont
static pressure drop (in wc)	8	personal communication with vendor
combined fan-motor efficiency	60%	from EPA Cost Control Manual
hours per year	2,190	operating half the year at average operating capacity of 50% load
incremental electricity cost	$879.03	EPA Cost Control Manual, Equation 1.46.
labor hours per year	12	regular inspections, unexpected maintenance and annual inspection of the interior
labor rate	$30.00	personal communication with wood boiler vendor
labor costs	$360.00	
total annual costs	$1,239.03	

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Category	Value	Notes
total ash disposal cost	$0.00	all ash land applied for soil enhancement
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incremental electricity cost	$1,098.79	EPA Cost Control Manual, Equation 1.46.
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labor costs	$360.00	
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Category	Value	Notes
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waste gas flow rate (acfm)	2,562	from review of recent stack test reports in Vermont
static pressure drop (in wc)	5	from permit application for new wood boiler in central Massachusetts
combined fan-motor efficiency	60%	from EPA Cost Control Manual
hours per year	2190	operating half the year at average operating capacity of 50% load
incremental electricity cost	$549.40	EPA Cost Control Manual, Equation 1.46.
labor rate	$30.00	personal communication with wood boiler vendor
labor hours per year	81	1 hr/wk general maint., 80 hours to replace all bags, 8 hours for black light testing at 2x per year
labor costs	$2,440.00	
total annual costs	$3,340.02	

ESP OPERATING COSTS

Category	Value	Notes
total ash disposal cost	$ -	all ash land applied for soil enhancement
pressure drop (in. water)	0.04	page 3-34 in EPA Cost Control Manual
operating time (h/yr)	2,190	operating half the year at average operating capacity of 50% load
system flow rate (acfm)	2,562	from review of recent stack test reports in Vermont
fan power req. (kWh/yr)	41	EPA Cost Control Manual, equation 3.46
electricity req. (kWh/yr)	2431	personal communication with vendor
electricity price ($/kwh)	0.1	av'g commercial elec. cost in 2009 (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html)
total electricity demand	569.4	sum of fan and other electricity requirements
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