



■ Documentation for:

**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**

Massachusetts Division of Energy Resources

Revised September 2001

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EXECUTIVE SUMMARY

Resource Systems Group, Inc, has undertaken An Evaluation of Air Pollution Control Technologies for Small Wood-Fired Boilers. This is focused on boilers in the size range of approximately 3 to 10 MM Btu/hour heat output although reference is made to boilers slightly smaller and considerably larger in obtaining data for the analysis. The analysis is generic in that it is applicable to any manufacturer or type of wood-fired boiler in this size range for any location. Attention has been given to boilers in this size range manufactured by the companies that are active in marketing boilers in the northeastern states.

The conclusions of the study are that small wood-fired boilers using staged combustion or gasifier designs are able to achieve lower emission rates for particulate matter when compared to many larger wood-fired boilers and small units with older designs. However the analysis has demonstrated that lower PM10 emissions can be achieved with appropriate add on control systems at reasonable cost. The BACT for PM10 is an LSR Core Separator with an emission rate of less than 0.1 lb/MM Btu. This technology will also bring about some reduction in particulate toxic emissions.

A review of BACT for other criteria pollutants concluded that there was no practical control technology available that could bring about a reduction of emissions from wood-fired boilers in this size category especially when these boilers would be primarily used for space heating in institution or commercial situations.

A comparison of boiler emissions fired by wood, distillate oil, natural gas and propane shows that wood has lower sulfur dioxide and net greenhouse gas emissions than distillate oil. Nitrogen oxide emission rates from wood are close to the emission rates from distillate oil. Particulate matter, carbon monoxide and total organic compound emissions are higher than oil.



INTRODUCTION

Resource Systems Group, Inc. under contract to the Vermont Department of Public Service, the Vermont Department of Environmental Conservation, Air Pollution Control Division, the Massachusetts Division of Energy Resources and the New Hampshire Governor's Office of Energy Resources and Community Services, has undertaken "An Evaluation of Air Pollution Control Technologies for Small Wood-Fired Boilers." The study is intended for research and informational purposes by state agencies in Vermont, Massachusetts, New Hampshire and elsewhere and by energy planners and others with an interest in biomass energy systems. The conclusions and the opinions are those of the principal author Dr. Colin J. High and do not necessarily reflect the opinion of the sponsoring agencies. Although the study has been guided by the methods used in the EPA Best Available Control Technology (BACT) analysis process, it is not intended to define BACT for regulatory purposes or to imply that any of the sponsoring states intends to establish a BACT requirement for wood-fired boilers of this class. Reference to manufacturers names and the performance characteristics of specific equipment is for informational purposes. Neither the author nor the sponsoring agencies endorse these products or performance claims.

This study is focused on boilers in the size range of approximately 3 to 10 MM Btu/ hour heat output, although reference is made to boilers slightly smaller and considerably larger in obtaining data for the analysis. The analysis is generic in that it is applicable to any manufacturer or type of wood-fired boiler in this size range for any location. Attention has been given to boilers in this size range manufactured by companies that are active in marketing boilers in the northeastern states. The analysis is also guided by the regulatory requirements in the states of Massachusetts, New Hampshire and Vermont. The results are however, relevant beyond these specific terms of reference.

Formal BACT analysis for wood-fired boilers in this size range is somewhat uncharted territory because typically, smaller wood-fired boilers have not needed to demonstrate BACT, and they rarely use state-of-the-art control technologies. In consequence, the control engineering and costs for this size range are not well demonstrated. Therefore in some cases it has been necessary to use technology and cost information for somewhat larger systems and then use general engineering principles to scale the appropriate control systems to this size of boiler.

The second component of this study is to make a comparison between wood-fired systems and comparably sized systems burning fuel oil, natural gas or propane in terms of emissions and control technology for relevant pollutants. This comparison will provide the basis for making overall comparisons that may provide input to public policy decisions. It should be recognized that the second part of the analysis is inherently more difficult because it involves comparisons among pollutants that the existing regulatory frameworks do not consider.



METHOD AND SCOPE OF THE STUDY

The approach to the first part of this study has been to conduct the type of investigation that would normally be made in a control technology analysis. This involves collection of data from manufacturers, independent research sources, the EPA and state agencies on existing emission rates from actual equipment in the field and on the control technologies available commercially. The RACT/BACT/LAER Clearinghouse (RBLC) database was also searched for wood combustion systems in all sizes. This investigation covered US and Canadian sources of information in detail and in addition reviewed, as far as possible, information from European sources. North American importers of European and Japanese combustion systems and control technologies were also contacted.

The results of this research are described in the BACT analysis and summary tables that follow. In general European biomass combustion technologies and control systems are the same as those available in North America. Some of the wood combustion systems currently available in North America are based on European designs. Reported particulate emission rates for biomass-fired boilers in Denmark, where there is a well-developed biomass energy industry, are similar to comparable systems available in the North America. In the application of SCR systems to NO_x control, at least one European manufacturer has more experience with installations on smaller oil-fired boilers and internal combustion engines but none of this experience extends to wood fired combustion. None of the recommendations concerning BACT requires the import of technology or would be affected by technology exclusively in use in Europe.

BEST AVAILABLE CONTROL TECHNOLOGY ANALYSIS

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. In making the BACT determination other environmental, health, safety and energy consumption factors should be considered. The operation of a specific control technology applied to a comparable source anywhere in the US is usually considered to provide 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 and therefore a technology may be BACT for a large plant but not for a smaller one. Typically wood-fired boilers in the size range 3 – 10 MM Btu/hour have not been subject to formal BACT review for criteria pollutants in recognition of the comparatively high cost of most of the control technologies in this size range. Wood-fired boilers in this size range have



been subject to hazardous air emissions controls in Vermont¹ and therefore some have been subject to comparable technology review. In the federal BACT process and in Vermont's Hazardous Most Stringent Emission Rate (HMSER) process costs are taken into consideration.

An informal statement of the practice is that if the absolute costs are so high that they make the enterprise uncompetitive and therefore not viable and the costs per unit of pollutant removed are above the range that is typically paid by other enterprises, then a case can be made that the technology is not a realistically available option. Because the federal BACT decision process for criteria pollutants does not extend to wood-fired boilers of this size there are not specific precedents. In order to form opinions on what may be BACT this study has been guided by the EPA process.

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 the 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 exhausted. This process may include not only add-on technology but combustion process modifications and changes in fuel specifications. However, specifying a different fuel, such as gas to replace wood, is not considered here as part of the BACT analysis. The second part of the report makes comparisons between fuels to provide a comparative background in which to consider wood fuels.

In this study it is assumed that the boilers are new, not retrofitted and that there are no site-specific factors that increase or reduce costs. In addition it is assumed that the potential application for wood-fired boilers in this size range will include institutional and commercial, as well as small industrial uses. Therefore, environmental and safety issues associated with those applications need to be considered in a generic BACT analysis.

¹ Vermont Air Pollution Control Regulations, Section 5-261.



EMISSIONS FROM SMALL WOOD –FIRED BOILERS: AN OVERVIEW

Compared with distillate fuel oil, natural gas or propane, wood is a very variable fuel with respect to heat content, moisture content, density and combustion characteristics. In consequence emissions rates tend to be quite variable depending not only on the fuel but also on the conditions of combustion and the load of the boiler. Table 1: provides a range of emission factors for wood-fired boilers. The table includes boilers that span the size range of units as well as some larger and smaller units. Emission rates in this and other tables are standardized to lb/MM Btu for comparison. This removes the factor of moisture content and the differences between softwood and hardwood that affect emission rates reported on a volume or weight basis. These emission rates are for clean natural wood in the form of chips, hogged fuel or saw dust. Fuel that includes large quantities of bark will have different and generally less predictable emission rates¹. Fuel containing demolition material, painted or treated wood may have higher particulate and toxic air emissions.

Table 1: Emission Rates for Small Wood-Fired Boilers²

Manufacturer	Chiptec	Messersmith	BCS	KMW	AP 42	AP 42
Model	85-90T		2160	1800KW		
Heat Input MMBtu	2.2	2.8	16.3	6		
Control	Cyclone	None	Multiclone	Cyclone	None	Mechanical
Emissions	lb/MMBtu	lb/MMBtu	lb/MMBtu	lb/MMBtu	lb/MMBtu	lb/MMBtu
NOx	0.211	0.146			0.165	0.165
CO	0.902	2.123			1.496	1.496
Particulate PM10	0.097	0.12	0.113	0.12	0.968	0.286
SO2					0.00825	0.00825
TOC					0.0242	0.0242

As can be seen from Table 1 the variability of emissions in PM10 is very large especially when the

¹ US EPA, Compilation of Air Pollution Emission Factors Fifth Edition Revised. (AP42) Section 1.6

² The emission rates are provided by the manufacturers or other parties from actual tests. Chiptec and Messersmith tests are reported in CONEG Report "Wood-Chip Fired Furnaces Testing Project Air Analysis Testing and Public Health" April 1996, CONEG, Washington DC., BCS test were conducted by A & H Emissions Testing at Oak Hill Veneer Inc in a report dated June 6, 2001 submitted to Pennsylvania DEP to demonstrate compliance with PA DEP air permit plan approval No. 08-302-042., KMW tests are from Braaten, R.W., and T.G. Sellers, "Prince Edward Island Wood-Chip Fired Boiler Performance Report", Energy Research Laboratories, Ottawa, Ontario Canada April 1993. Mechanical or cyclone collectors only control particulate. The blanks indicate that no data are available. Chiptec, Messersmith, BCS and KMW are manufacturers of wood-fired combustion systems. AP42 emission rates are from the EPA reference (1) cited above.



uncontrolled AP42¹ emission rate is considered. The manufacturers emission rates are taken from field tests. These emission rates are not intended to be used to determine which manufacturer offers the lowest emissions equipment because they are field tests usually under full load and not guaranteed performance. In most cases the guaranteed emission rates are greater by a factor of 2 or 3. Emissions may increase considerably at low loads or under transient conditions. Furthermore the emission rates in three examples are after control by mechanical collectors such as cyclones or multicyclones.

PARTICULATE EMISSION CONTROL TECHNOLOGY INFORMATION

In order to compare the results of specific control technologies for the purpose of determining BACT it is necessary to determine what is the uncontrolled emission rate for particulate matter. The AP42 uncontrolled PM emission factor is 0.97 lb/MM Btu. The uncontrolled cumulative emission factor for PM10 is 0.71 lb/MM Btu². This is the emission rate used as the base for comparison in some of the tables that follow. However, some uncontrolled small wood-fired boilers of modern design with a gasifier³ or staged combustion have uncontrolled emission rates of between 0.1 and 0.2 lb/MM Btu.⁴ However, because of the variability of fuel and combustion conditions manufacturers will not guarantee these emission rates and therefore they cannot be used for regulatory purposes. It may be possible to obtain a guaranteed emission rate of 0.3 lb/MM Btu. The lower bound sets a comparison basis for incremental controls. In this study we have therefore chosen 0.3 lb/MM Btu as the lower bound and 0.71 lb/MM Btu as the upper bound of an uncontrolled emission rate as a basis for unit costs calculations for controlling PM10. Most commonly today's small wood-fired boilers may be expected to have uncontrolled emission rates between these limits but probably more commonly near the lower bound.

¹ US EPA, Compilation of Air Pollution Emission Factors Fifth Edition Revised. (AP42) Section 1.6, tables 1.6.1, 1.6.2, and 1.6.3

² AP42 table 1.6-7.

³ The term gasifier is used by Chiptec and some other manufacturers for a combustion system where the pyrolysis or gas generation stage is separate from the combustion chamber. This is essentially the same as staged combustion. Use of the term gasifier here differs from the way in which the term is used where gasifiers are used in the context of the production of wood derived liquid or gaseous fuels.

⁴ See the Messersmith boiler cited in Table 1 and a Hurst Boiler fitted with a Chiptec gasifier had uncontrolled emission rates for PM10 averaging 0.17 lb/MM Btu as reported in a Test Report for Allard Lumber Company of Brattleboro Vermont dated February 1997.



TOP DOWN BACT REVIEW FOR PM10

FABRIC FILTERS OR BAGHOUSES

Various types of fabric filters or bag houses have been successfully used for particulate control with solid and liquid fuels. With the correct design and choice of fabric, particulate control efficiencies of over 99% can be achieved even for very small particles (1 micrometer or less). The lowest emission rate for large wood-fired boilers controlled by fabric filters reported in the RACT/BACT/LAER (RBL) database is 0.01 lb/MM Btus. This is consistent with expected control efficiencies close to 99%. Operating experience with baghouses on larger wood-fired boilers indicates that there is a fire risk, due to caking of the filters with unburned wood dust. Although it is possible to control or manage this risk it is less practical in the small boilers being considered here. This is because small wood-fired boilers are used in small institutions such as schools and hospitals without full time boiler staff. In such situations the fire risk is unacceptable. A review of the RBL database shows only two fabric filter systems on wood-fired boilers and none in this size range. Therefore fabric filters are not recommended for the control of particulates in wood-fired boilers for safety reasons.

ELECTROSTATIC PRECIPITATORS (ESP)

Electrostatic precipitators (ESPs) are widely used for the control of particulates from a variety of combustion sources including wood combustion. An ESP is a particle control device that employs electric fields to collect particles from the gas stream on to collector plates from where they can be removed. There are a number of different designs that achieve very high overall control efficiencies. Control efficiencies typically average over 98% with control efficiencies almost as high for particle sizes of 1 micrometer or less. Overall ESPs are almost as good as the best fabric filters. The RBL database reports several large wood-fired boilers with PM10 emission rates in the range 0.02 to 0.03 lb/MM Btu. For small boilers two designs were considered; a dry electrostatic precipitator and a wet electrostatic precipitator. The systems are basically similar except that wet electrostatic precipitators use water to flush the captured particles from the collectors. The advantage of dry systems is that they may have a lower capital cost and reduced waste disposal problems. Wet systems may be less expensive to operate and are probably slightly more efficient at capturing very small particles that may include toxic metals.

Designs for both wet and dry systems were specified and estimates obtained for each system. The summary of costs for a wet ESP and a dry ESP for a boiler of 7.5 MM/Btu are included in tables 2 through 5. These are for boilers of 7.5 MM Btu heat input. There are four scenarios given.



Table 2: 30% annual capacity and uncontrolled emissions at 0.71 lb/MM Btu

Table 3: 75% annual capacity and uncontrolled emissions at 0.71 lb/MM Btu

Table 4: 30% annual capacity and uncontrolled emissions at 0.3 lb/MM Btu

Table 5: 75% annual capacity and uncontrolled emissions at 0.3 lb/MM Btu

Table 2: Particulate Control Systems Cost Analysis (ER =0.71 Lb MM Btu Cap Factor =30%)

Capital Cost	ESP Dry	ESP Wet	Core		
			Separator	Multiclone	Cyclone
Equipment	\$170,769	\$183,386	\$19,875	\$18,315	\$7,600
Site and Facilities	\$13,969	\$13,969	\$2,000	\$2,000	\$2,000
Installation	\$114,415	\$122,868	\$6,956	\$7,365	\$6,000
Total Direct Capital Cost	\$299,153	\$320,223	\$28,831	\$27,680	\$15,600
Annual Cost					
Total Direct	\$37,883	\$23,414	\$4,984	\$2,892	\$2,838
Capital recovery factor	0.15	0.15	0.15	0.15	0.15
Capital recovery	\$44,574	\$47,713	\$4,296	\$4,124	\$2,324
Total Annual Cost	\$82,457	\$71,127	\$9,280	\$7,017	\$5,162
PM10 Unit Cost of Control At 30% Annual Capacity Factor					
Control Efficiency PM10	99.0%	99.0%	90.0%	73.0%	50.0%
Emission Rate PM10 uncontrolled lb/MM Btu	0.71	0.71	0.71	0.71	0.71
Emission Rate PM10 controlled lb/MM Btu	0.0071	0.0071	0.071	0.1917	0.355
Annual Emissions PM10 uncontrolled tpy	6.997	6.997	6.997	6.997	6.997
Annual Emissions PM 10 after control tpy	0.070	0.070	0.700	1.889	3.499
Annual Emissions PM10 controlled tpy	6.927	6.927	6.297	5.108	3.499
Annual Cost per ton controlled	\$11,903.52	\$10,267.93	\$1,473.57	\$1,373.70	\$1,475.59



Table 3: Particulate Control Systems Cost Analysis (ER =0.71 Lb MM Btu Cap Factor =75%)

Capital Cost	Core				
	ESP Dry	ESP Wet	Separator	Multiclone	Cyclone
Equipment	\$170,769	\$183,386	\$19,875	\$18,315	\$7,600
Site and Facilities	\$13,969	\$13,969	\$2,000	\$2,000	\$2,000
Installation	\$114,415	\$122,868	\$6,956	\$7,365	\$6,000
Total Direct Capital Cost	\$299,153	\$320,223	\$28,831	\$27,680	\$15,600
Annual Cost					
Total Direct	\$94,707	\$58,534	\$12,459	\$7,231	\$7,095
Capital recovery factor	0.15	0.15	0.15	0.15	0.15
Capital recovery	\$44,574	\$47,713	\$4,296	\$4,124	\$2,324
Total Annual Cost	\$139,281	\$106,247	\$16,755	\$11,355	\$9,419
PM10 Unit Cost of Control At 75%% Annual Capacity Factor					
Control Efficiency PM10	99.0%	99.0%	90.0%	73.0%	50.0%
Emission Rate PM10 uncontrolled lb/MM Btu	0.71	0.71	0.71	0.71	0.71
Emission Rate PM10 controlled lb/MM Btu	0.0071	0.0071	0.071	0.1917	0.355
Annual Emissions PM10 uncontrolled tpy	17.493	17.493	17.493	17.493	17.493
Annual Emissions PM 10 after control tpy	0.175	0.175	1.749	4.723	8.746
Annual Emissions PM10 controlled tpy	17.318	17.318	15.743	12.770	8.746
Annual Cost per ton controlled	\$8,042.69	\$6,135.17	\$1,064.27	\$889.23	\$1,076.96

Table 4: Particulate Control Systems Cost Analysis (ER =0.3 Lb MM Btu Cap Factor =30%)

Capital Cost	Core				
	ESP Dry	ESP Wet	Separator	Multiclone	Cyclone
Equipment	\$170,769	\$183,386	\$19,875	\$18,315	\$7,600
Site and Facilities	\$13,969	\$13,969	\$2,000	\$2,000	\$2,000
Installation	\$114,415	\$122,868	\$6,956	\$7,365	\$6,000
Total Direct Capital Cost	\$299,153	\$320,223	\$28,831	\$27,680	\$15,600
Annual Cost					
Total Direct	\$37,883	\$23,414	\$4,984	\$2,892	\$2,838
Capital recovery factor	0.15	0.15	0.15	0.15	0.15
Capital recovery	\$44,574	\$47,713	\$4,296	\$4,124	\$2,324
Total Annual Cost	\$82,457	\$71,127	\$9,280	\$7,017	\$5,162
PM10 Unit Cost of Control At 30% Annual Capacity Factor					
Control Efficiency PM10	99.0%	99.0%	90.0%	73.0%	50.0%
Emission Rate PM10 uncontrolled lb/MM Btu	0.3	0.3	0.3	0.3	0.3
Emission Rate PM10 controlled lb/MM Btu	0.003	0.003	0.03	0.081	0.15
Annual Emissions PM10 uncontrolled tpy	2.957	2.957	2.957	2.957	2.957
Annual Emissions PM 10 after control tpy	0.030	0.030	0.296	0.798	1.478
Annual Emissions PM10 controlled tpy	2.927	2.927	2.661	2.158	1.478
Annual Cost per ton controlled	\$28,171.65	\$24,300.77	\$3,487.46	\$3,251.08	\$3,492.24



Table 5: Particulate Control Systems Cost Analysis (ER =0.3 Lb MM Btu Cap Factor =75%)

Capital Cost	Core				
	ESP Dry	ESP Wet	Separator	Multiclone	Cyclone
Equipment	\$170,769	\$183,386	\$19,875	\$18,315	\$7,600
Site and Facilities	\$13,969	\$13,969	\$2,000	\$2,000	\$2,000
Installation	\$114,415	\$122,868	\$6,956	\$7,365	\$6,000
Total Direct Capital Cost	\$299,153	\$320,223	\$28,831	\$27,680	\$15,600
Annual Cost					
Total Direct	\$94,707	\$58,534	\$12,459	\$9,641	\$7,095
Capital recovery factor	0.15	0.15	0.15	0.15	0.15
Capital recovery	\$44,574	\$47,713	\$4,296	\$4,124	\$2,324
Total Annual Cost	\$139,281	\$106,247	\$16,755	\$13,765	\$9,419
PM10 Unit Cost of Control At 75% Annual Capacity Factor					
Control Efficiency PM10	98.0%	98.0%	90.0%	73.0%	50.0%
Emission Rate PM10 uncontrolled lb/MM Btu	0.3	0.3	0.3	0.3	0.3
Emission Rate PM10 controlled lb/MM Btu	0.006	0.006	0.03	0.081	0.15
Annual Emissions PM10 uncontrolled tpy	7.391	7.391	7.391	7.391	7.391
Annual Emissions PM 10 after control tpy	0.148	0.148	0.739	1.996	3.696
Annual Emissions PM10 controlled tpy	7.243	7.243	6.652	5.396	3.696
Annual Cost per ton controlled	\$19,228.58	\$14,668.07	\$2,518.78	\$2,551.21	\$2,548.80

ESP control costs range from approximately \$6,000 to \$28,000 per ton controlled. Under all the scenarios in tables 2 to 5, the costs per ton removed using ESPs far exceed the normal range of costs for PM10 control. Costs for boilers of 3 MM Btu would be even higher. In addition there would be serious concerns about wastewater problems associated with wet ESPs at small commercial and institutional sites. Furthermore, the capital cost of the least expensive system is about 75% of the capital cost of the boiler. This makes the installation of an ESP economically infeasible. A search of the RBLIC reveals no ESP in use for wood-fired boilers in the 3 to 10 MM Btu size range. ESPs have been used on solid waste incinerators where they are needed for hazardous air pollutant control. Based on cost and lack of existing installations ESPs are not considered to be feasible for wood-fired boilers in this size range.



CORE SEPARATORS

The core separator is a relatively new mechanical collector system produced by LSR Technologies. It works on the same general principles as a cyclone but the processes of separation and collection are accomplished separately by two different components: a core separator and a cyclone collector. The exhaust gas is cleaned by being recirculated through the core separator by a recirculation fan until the particles are collected in the cyclone. The core separator has very high collection efficiency, comparable to an ESP, for particles above about 2.5 micrometers but collection efficiency falls to below 50% for particles below 1 micrometer. Its overall performance falls between an ESP or fabric filter and a cyclone. There are several units installed on wood and coal fired boilers and field test results are available for wood-fired applications. In tests on a boiler fired by a wood gasifier with uncontrolled total particulate emission rates that averaged 0.17 lb/MM Btu the core separator reduced the emissions to an average of 0.07 lb/MM Btu¹. The overall average collection efficiency was 56%. This collection efficiency reflects the low initial emission rate and resultant particle size distribution. The collection efficiency over the whole range of uncontrolled wood-fired boiler emissions may be as high as 90%

Based on the test results the core separator working on a boiler that is well controlled through good combustion practices can probably achieve controlled emission rates for total particulates of 0.07 lb MM Btu. over a wide range of load conditions. The capital cost and annual operating costs of a core separator are given in Tables 2 to 5. The unit cost for PM10 removed ranges from approximately \$1,000 per ton to \$3,500 per ton at 30% capacity factor. The cost for a 7.5 MM Btu boiler operating at 75% of annual capacity is about a \$1,000 per ton which is within the range of control cost acceptability. At 30 % of capacity the control cost of about \$3,500 are at the high end for control costs. If this same technology were to be applied to a 3 MM Btu size boiler then capital cost per ton controlled would further increase by at least 12 %.

The core separator when operating either on a well controlled or poorly controlled wood-fired boiler can be expected to control PM10 to below 0.1 lb/MM Btu. This would constitute BACT for at least boilers of 7.5 MM Btu and up. For smaller boilers at about 3 MM Btu being used for space heating and operating at an annual capacity factor of 30% or less the control costs rise. An argument could be made that a less expensive cyclone would be acceptable.

MULTICYCLONES

Multicyclones or multiple tube cyclones are mechanical separators that use the velocity differential across the cyclone to separate particles. A multicyclone uses several smaller diameter cyclones to improve efficiency. Overall efficiency ranges from 65% to 95% but multicyclones, like cyclones, are more efficient

¹ Particulate Emission Evaluation Boiler and Core Separator System Exhaust: Report of Tests at Allard Lumber Company Brattleboro Vermont, December 1996 and January 1997. LSR Technologies Inc. 898 Mains St, Acton MA 01720. 1997.



in collecting larger particles and their collection efficiency falls off at small particle sizes. The AP42 lists multicyclone controlled emission rates that indicate a control efficiency of 73% for PM₁₀ when the uncontrolled emission rate is 0.71 lb/MM Btus. The resulting multicyclone controlled emission rate is 0.19 lb/MM Btus. When the uncontrolled emission rate is as low as 0.1 to 0.2 lb/MM Btu the overall control efficiency will be lower. One set of test results for a well controlled Chiptec Gasifier and Hurst Boiler fired at 5.2 MM Btu with a Hurst multicyclone demonstrated emission rates of 0.17 to 0.2 lb/MM Btu. The lowest reported multicyclone controlled wood-fired boiler emission rate in the RBLC database, which was for a 48 MM Btu boiler, was 0.12 lb/MMBtu. Overall the multicyclone is slightly less efficient than the LSR Core Separator in controlling particulate matter, especially in the size range below 0.1 micrometer. This is a disadvantage because many of the hazardous air pollutants are in the very small size categories. On purely technical criteria the multicyclone is not BACT. When cost is taken in to consideration it can be seen from Table 2 that there is relatively little difference in cost between the core separator and the multicyclone. Therefore it should be concluded that the core separator is BACT at least for boilers in the upper part of this size range.

CYCLONES

Cyclones are less efficient collectors than multicyclone or the core separator and therefore simple cyclones are not BACT. A very well controlled multistage wood combustor or gasifier combined with a cyclone can achieve emission rates below 0.1 lb/MMBtu. However, in all cases we should expect that the same combustion unit would achieve lower emission rates with a core separator or multicyclone. Therefore, a cyclone equipped wood-fired boiler would not be BACT.

VENTURI AND WET SCRUBBERS.

Venturi and other wet scrubbers are more efficient than multicyclones especially in size fractions below 1 micrometer. The AP 42 indicates a control efficiency for wet scrubbers of 93% for PM₁₀. Overall performance across the particle size range is comparable to the LSR Core Separator. No wet scrubbers have been reported in use on wood-fired boilers in this size range. A venturi scrubber was installed on a 13.5 MM Btu wood-fired boiler in Hardwick MA. This had a design emission rate at full capacity of 0.13 lb/MM Btu. The best performing venturi scrubber on a wood-fired boiler listed in the RBLC database had an emission rate of 0.15 lb/MM Btu. Therefore a venturi scrubber is not BACT. A combined cyclone plus wet scrubber system on a wood-fired boiler of 35.5 MM Btu/hr capacity at Northampton MA had a design emission rate of 0.1 lb/MM Btu. This is no better than can be achieved by a Core Separator. A combined multicyclone followed by a Fischer Klosterman Spray Scrubber installed on a pair of wood-fired boilers with a combined capacity of 49 MM Btu/hr had a design emission rate of 0.01 lb/MM Btu. However, the Massachusetts DEP only set a permit condition emission rate at 0.15 lb/MM Btu so the lower number does not establish a BACT level even if the size range were comparable.



Combined multicyclones and wet scrubbers increase the cost well above that of multicyclones or an LSR Core Separator. In addition wet scrubbers are problematic in this size range because many applications are likely to be in small institutional or commercial buildings where it would be difficult to handle the waste-water in an environmentally sound manner.

Flue gas condensation systems designed for heat recovery purposes are in use on biomass-fired district heating boilers in Denmark. Claims for pollution control benefits have been made which we have been unable to substantiate. At best these condensation devices could not perform any better than a wet scrubber in which case they would remain as a less desirable option than a core separator for particulate control. The reported use in Denmark combines condensation with a multicyclone to control particulate emissions to less than 0.15 lb/MM Btu¹ which is comparable to the performance of a multicyclone alone. Condensation also suffers from some of the same problems of waste-water disposal described for wet scrubbers. Condensation has energy efficiency advantages and may remove some air toxics but it is not BACT for particulate.

SUMMARY

For wood-fired boilers in the size range of 3 to 10 MM Btu/hr heat output BACT for PM₁₀ is likely to be a well controlled multistage combustion unit or gasifier with an emission rate of less than 0.2 lb/ MM Btu controlled by an appropriately sized LSR Core Separator. The final emission rate is likely to be less than 0.1 lb/MM Btu. In order to allow for the variability of wood fuels the BACT emission rate should probably be set at 0.1 lb. MM Btu. Some combustion units could meet an emission level of 0.1 lb/MM Btu with a multicyclone. However, BACT is established by reference to technology and cost therefore the same combustion unit could achieve levels well below 0.1 lb/MM Btu controlled with a Core Separator. As the cost difference between an LSR Core Separator and a high efficiency multicyclone is small there are few disadvantages in choosing the Core Separator as BACT. The only technology consideration is that the LSR Core Separator is much newer than multicyclones and experience on wood-fired boilers is more limited.

PARTICULATE MATTER LESS THAN 2.5 MICROMETERS DIAMETER.

Particulate matter less than 2.5 micrometers diameter (PM_{2.5}) is more injurious to health and in consequence the EPA has proposed a new more stringent NAAQS for PM_{2.5}. It is currently unclear when the new standard will be implemented. When the new standard is implemented for fine particulate there will be implications for the control of most combustion sources of air pollutants. Approximately

¹ Biomass for Energy; Danish Solutions published by Energistyrelsen, Copenhagen, undated.



75% of the total particulate emissions from wood-fired boilers are below 2.5 micrometers and 67% are below 1 micrometer¹.

The recommendation made in this report concerning BACT for PM10 would also apply to a BACT determination for PM2.5. The only caveat is that because the Core Separator is better than a multicyclone at collecting particles below 2.5 micrometers the argument for the Core Separator is strengthened in the case of PM 2.5. Unless the generally accepted standards for economic feasibility are changed under new PM 2.5 rules ESPs would still be rejected on the grounds of cost.

NITROGEN OXIDES

Nitrogen oxide (NO_x) emissions from wood burning have two origins. First, is the fuel NO_x which is produced by the oxidation of the nitrogen in the fuel. The second is the thermal or flame NO_x, which is produced in the combustion flame from the oxidation of nitrogen in the air supplied to the boiler.

Fuel NO_x is dependent on the nitrogen content of the fuel, which is highly variable, but largely unaffected by combustion conditions. The thermal NO_x is strongly affected by combustion conditions but in rather complex ways. In wood-fired boiler combustion fuel NO_x is the dominant source of total NO_x. NO_x is one of the precursor pollutants for ozone and New England has many areas which are classified as non-attainment for the ozone standard therefore the New England states have State Implementation Plans targeted at NO_x reductions.

The AP42 reports a very wide range of NO_x emission rates for wood-fired boilers from 0.073 to 0.4 lbs/MM Btu for stoker boilers. The AP42 typical rate is 0.165 lb/MM Btu, which is close to the emission rate for several boilers in this size range (See Table 1). Higher and lower emission rates are also reported for other types of wood-fired boilers by the AP 42 and by boiler manufacturers. Two typical boilers in this size range given in Table 1 have NO_x emission rates ranging from 0.146 to 0.211 lb/MM Btu. However, these emission rates should not be considered as representative of a specific manufacturer's boiler as they could change if the fuel composition changes.

NITROGEN OXIDE BACT ANALYSIS

SELECTIVE CATALYTIC REDUCTION

Selective catalytic reduction (SCR) is a process whereby ammonia vapor is injected into the flue gas which then passes through a catalyst bed to convert nitric oxide to free nitrogen and water. The ammonia can

¹ EPA AP 42 section 1.6 table 1.6-7



be anhydrous (99.5%) or aqueous (25% to 30% in solution) in form. The latter is significantly safer to handle, store and transport than the anhydrous form.

SCR systems are now widely used on large utility scale coal and natural gas fired boilers in this country and on large oil-fired boilers in Europe and Japan. There are also a number of applications on diesel engines and a small number of installations on oil-fired boilers in the 50 to 100MM Btu size range. SCR systems can reduce NO_x emission by 85% to 95%. There are no installations on wood-fired boilers in North America, and no vendor in North America offering this system for wood-fired boilers. Siemens AG is offering its SINO_x SCR system for larger wood-fired boilers in Europe.

SCR systems are feasible if ammonia slip can be properly controlled. Apart from cost, the main problem is the temperature requirements of the catalyst. The optimal operating temperature for the catalyst is 675 F. The typical temperature of the flue gas in a small wood-fired boiler is between 300 and 500 degrees F. Therefore supplementary heating of the flue gas will be needed at all times that the boiler is operating with the firing rate increasing as the load decreases. In order to make SCR work effectively in a small wood-fired boiler with seasonal heat loads a propane fired duct heater will be needed after the boiler breaching and before SCR. It has not been possible to obtain costs on this system because none have been installed.

In addition to the need for supplementary heating with associated fuel cost and pollution problems, the SCR uses ammonia which can result in ammonia slip or increased ammonia emissions unless very carefully controlled. Such controls would be extremely difficult on a small wood-fired boiler. Therefore SCR cannot be considered a practical NO_x control system on wood-fired boilers of this size.

SELECTIVE NON-CATALYTIC REDUCTION

Selective non-catalytic reduction (SNCR) is a process where ammonia or urea is injected into the high temperature zone (1,600 – 2,000 degrees F) of the flue gas. The ammonia or urea reacts with the exhaust NO_x to form nitrogen, water and in the case of urea, carbon dioxide. If the temperature is too high or the ammonia/urea concentration too low then additional NO_x is formed. If the temperature is too low then the reaction is incomplete and ammonia slip occurs. In addition in urea reactions up to 30% of the N₂ can be converted into N₂O, a greenhouse gas. Using urea as a reagent SNCR systems are generally 50% to 60% efficient at removing NO_x from the flue gas. In order to avoid ammonia slip or poor NO_x removal SNCR needs to be closely controlled which is difficult in the variable flame combustion conditions associated with wood firing. As in the case of SCR there are also problems in handling ammonia in institutional and commercial settings without full-time boiler staff.

There is one SNCR system installed on a 150 MM Btu wood-fired boiler. There are none installed on small wood-fired boilers and no vendors offering system in that size range. Generally SNCR systems are considered inferior to SCR systems. For all these reasons therefore SNCR cannot be considered a practical NO_x control system on wood-fired boilers of this size.



OXIDATION CATALYSTS

Oxidation catalysts are used in automobiles, diesel engines and wood stoves to reduce emissions by oxidation in a catalyst bed. So called three way oxidation catalysts reduce NO_x, CO and hydrocarbons. In boilers they are not an optimal method for NO_x control but as multiple pollutant control systems they have demonstrated their value in some applications notably in automobiles. Oxidation catalysts are not used in wood-fired boilers in this size range for a number of reasons but notably because operating temperature for the catalyst is 1200 to 1600 degrees F where as the temperature in the exhaust stream of a small wood fire boiler is typically below 600 degrees F. Therefore oxidation catalysts are not practical for control of NO_x CO or hydrocarbons in small wood –fired boilers

SUMMARY

There are no cost effective or practical NO_x control systems for wood-fired boilers in this size range other than good combustion conditions. However, because most of the NO_x is fuel derived there is only so much that can be done. Furthermore some of the measures that might be taken to reduce thermal NO_x during the combustion process could lead to increasing CO, PM10 and volatile organic compounds.

The typical NO_x emission rates for wood-fired boilers in this size range shown in Table 1 are very close to the NO_x emission rates of distillate oil-fired commercial boilers of similar size (See table 6). There has been no attempt in New England or elsewhere to impose NO_x BACT requirements on small distillate oil-fired boilers.

CARBON MONOXIDE

Carbon monoxide (CO) is produced by all combustion processes. The CO emission rate for wood-fired boilers is highly variable. The AP42 emission rates vary by over an order of magnitude depending on boiler and fuel specific factors. Boiler data available for well controlled units as shown in Table 1 ranges from 0.9 to 2.1 lb/MM Btu. One of the lower reported CO emission rates for similar units is an average emission rate of 0.5 lb/MM Btu for a Chiptec unit with a regulatory limit of 0.9 lbs /MM Btu.

No post combustion control technology is practical for CO reduction in wood-fired boilers.



SULFUR DIOXIDE

Sulfur dioxide emissions from wood combustion are very low due to the low levels of sulfur in natural wood. The AP42 gives an emission rate of 0.0082 lb/MM Btu. There are no practical add on controls for SO₂ at these levels and therefore there is no BACT determination for SO₂.

ORGANIC COMPOUNDS

Organic compounds, usually referred to as volatile organic compounds (VOCs) or total organic compounds (TOCs), include a very wide range of organic compounds many of which are toxic or carcinogenic. There are more than 30 organic compounds widely recognized in wood boiler exhaust gas they include the aldehydes, benzene and several polycyclic organic compounds¹. The emission rate for TOCs is strongly affected by combustion conditions. Wood-fired boilers of modern design using staged combustion or gasification to insure complete combustion have lower TOC emissions. However, the variable characteristics of wood and the difficulty of controlling the firing rate make it difficult to control the TOC emissions. Control technologies for TOCs include thermal oxidizers, which are after burners using natural gas or propane, wet scrubbers and catalytic afterburners. No control systems specifically for TOC control are currently being used on wood-fired boilers of any size. Some organic compounds condense in the cooler regions of the stack gas and are deposited on particles. Therefore reducing the PM₁₀ emission rate by the use of the control systems described will also to some extent reduce the emissions of some but not all TOCs.

No BACT is proposed for TOC control. Most of the TOCs are listed as toxic substances by the states of Massachusetts, New Hampshire and Vermont. Vermont has a BACT like requirement, the Hazardous Most Stringent Emission Rate (HMSER) rule² which requires the use of BACT for control of air toxics above a threshold action level. Because there is no available control technology suitable for TOC control on small wood-fired boilers, a technical and cost analysis will likely conclude that HMSER is good combustion technology as demonstrated by CO and PM₁₀ control.

¹ EPA AP42: Compilation of Air Pollutant Emission Factors, Section 1.6, Table 1.6-4.

² Vermont Air Pollution Control Regulations Section 5-261.



TRACE ELEMENTS

Wood combustion releases 36 trace elements listed by the EPA AP42¹. These are metals that are released from wood in the combustion process. The emission rates are variable depending on the species and the environmental conditions under which the wood was grown. Most of the metals are listed as toxic air pollutants by the states of Massachusetts, New Hampshire and Vermont. As was the case with the TOCs Vermont has a BACT like requirement for toxic metals, the Hazardous Most Stringent Emission Rate (HMSER) rule, which requires the use of BACT for control of air toxics including metals above a threshold action level. Most of the metals with the exception of mercury and selenium are attached to particles and therefore they are controlled by particulate control systems. The use of a Core Separator is preferred over a multicyclone because it has better control efficiency in the small particle size classes where more of the toxic metals are concentrated. In order to control the trace metals effectively either ESPs or fabric filters will be needed. These technologies are not BACT for the reasons previously given. When considered specifically as a control technology for trace metals, which have very low emission rates, the cost of using ESPs increases to several million dollars per ton of toxic metals reduced². Therefore at this time BACT for PM10 is also BACT for trace metals.

COMPARISON OF BOILER EMISSIONS FIRED BY WOOD, DISTILLATE OIL, NATURAL GAS AND PROPANE

In evaluating BACT for small wood-fired boilers it is useful to compare the emission rates for wood with those of distillate oil, natural gas and propane in comparably sized boilers. Table 6 summarizes some of these emissions. Overall criteria pollutant emissions from wood-fired boilers are higher than oil and gas for all pollutants except sulfur dioxide. The PM10 emission rate even when controlled to 0.1 lb/MMBtu is still higher than other fuels used in boilers of this size. The sulfur dioxide emission rate for wood is less than for distillate oil with a sulfur content of 0.5 %, which is frequently specified as a permit limit for number 2 oil-fired commercial boilers. Number 2 distillate oil (transportation grade) with a sulfur content of 0.05% or 0.025% is available. The use of 0.025% sulfur oil would result in an emission rate of 0.025 lb/MM Btu, which would probably constitute BACT for SO₂ in distillate oil boilers if such a requirement were implemented. The SO₂ emission rate for wood at 0.0082 lb/MM Btu is below even the most stringent possible BACT for distillate oil-fired boilers in that size range.

¹ EPA AP42: Compilation of Air Pollutant Emission Factors, Section 1.6, Table 1.6-5.

² Vermont ANR Air Pollution Control Division Air Permit for Britton Limber Company Ely Vermont 1993.



The nitrogen oxide emission rate for wood is higher but very close to distillate oil. It is higher than natural gas but below propane. Some wood-fired boilers, depending on the nitrogen content of the wood burned, could be lower than distillate oil. Carbon monoxide and TOC emission rates are higher for wood also

In terms of greenhouse gas emissions wood has the highest gross carbon dioxide emission rate. However, wood is a renewable fuel, so that as long as the trees being used are being replaced either by planting or natural re-growth then there is no net release of carbon dioxide. As the New England forests are currently growing in volume it is reasonable to conclude that on average there is zero net release of carbon dioxide from wood burning.

In overall comparison with distillate oil wood is better in terms of sulfur dioxide and net greenhouse gas emissions. Wood is in the same general range for nitrogen oxide emissions. It is clearly worse for PM10, carbon monoxide and total organic compounds. Each of these pollutants has its own issues. The use of wood as it reduces sulfur dioxide helps to reduce the acid deposition problem. This is important in a region seriously impacted by acid deposition. The higher CO emissions are of relatively minor concern except in areas where there are high carbon monoxide levels, usually due to automobile exhaust. The relatively higher emissions of PM10 and TOCs are primarily a concern for public health especially because both PM10 and TOCs include toxic air pollutants.

Table 6: Comparison of Boiler Emissions Fired by Wood, Distillate Oil, Natural Gas and Propane¹

	Wood	Distillate Oil	Natural Gas	Propane
	lb/MM Btu	lb/MM Btu	lb/MM Btu	lb/MM Btu
PM 10	0.1	0.014	0.007	0.004
NOx	0.165	0.143	0.09	0.154
CO	0.73	0.035	0.08	0.021
SO2	0.0082	0.5	0.0005	0.016
TOC	0.0242	0.0039	0.01	0.005
CO2	gross 220 (net 0)	159	118	137

¹ All emission rates are without additional controls except the wood PM10 is controlled to BACT as discussed. The sulfur content of number 2 distillate oil is assumed to be at 0.5% by weight which is common. Other grades of oil are rarely used in boilers below 14 MM Btu heat input. Number 2 oil with a sulfur content as low as 0.025% is available but is rarely used. Propane is commercial grade with a heat content of 91,500 Btu/gal and a sulfur content of 15 gr/100 cf. The CO2 emission rate is gross except that the net emission rate is also given for wood.



There is no BACT requirement on small boilers using distillate oil, natural gas or propane. Based on the analysis undertaken for this report it is clear that add on controls on small wood-fired boilers can reduce PM10 at a reasonable cost and that a LSR Core Separator is BACT for this size of boiler. There appears to be no valid reason to require wood-fired boilers to employ add on controls for NOx reduction when they are not required for distillate oil-fired or propane-fired boilers with NOx emission rates in the same systems on any boilers in this size range, especially when used for space heating.

