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Aul, E. F. Jr., and K. W. Barnett

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Edward F. Aul, Jr., P.E.
Keith W. Barnett
Radian Corporation
Research Triangle Park, North Ca

INTRODUCTION

Wood-fired boilers have been used for many years in the United States by the paper and allied products industry, wood products industry, and furniture manufacturing industry. However, since 1973 these industries have significantly increased their purchases of new wood-fired boilers. Increasingly, plants with wood fuels available are finding that wood-fired boilers represent an economical alternative to boilers fired with gas, oil, or coal.

Many factors must be considered in choosing the most economical boiler fuel for any specific site. One of these factors is the cost associated with air pollution controls required to meet air pollution regulations. Wood-fired boilers may emit significant amounts of particulate matter into the atmosphere. By comparison, emissions of sulfur dioxide and nitrogen oxides are much lower and usually are less than the amounts produced by boilers fired with coal or oil. Boilers firing combinations of wood and fossil fuel may have to contend with State or Federal air pollution regulations requiring control of all three pollutants. However, boilers fired predominantly with wood will primarily have to contend with regulations requiring control of particulate emissions only.

This paper presents some highlights from an evaluation of the application of particulate emission controls to wood-fired boilers. This study, conducted by Radian Corporation for the U. S. Environmental Protection Agency (EPA), is one of several investigations of boilers and emission control systems undertaken by the EPA with the intent to develop air pollution standards. The EPA is required to develop standards of performance for new and modified stationary sources of air pollution under Section 111 of the Clean Air Act. A more detailed analysis of this study is available in the Nonfossil Fuel Fired Industrial Boilers - Background Information Document, available from EPA.

BACKGROUND INFORMATION

This paper first presents information on the increase in the use of wood as a boiler fuel. Then, the major factors affecting uncontrolled particulate emissions from wood-fired boilers, available technologies for controlling these emissions, and the performances of these technologies are identified and discussed. Cost impacts are not addressed here since they are adequately covered by other conference authors.

Sales of Wood-Fired Industrial Boilers

Wood-fired boilers are typically used in the paper and allied products industry, wood products industry, and the furniture industry. These boilers are fired with the wood wastes derived from industrial processes.

As shown in Figure 1, the sales of wood-fired boiler capacity in 1973 of 2.3 million kg/hr (5.1 million lb/hr) were more than double the 1972 sales of 0.8 million kg/hr (1.8 million lb/hr). Though wood-fired boiler sales have varied since 1973, they have consistently remained well above pre-1973 levels. These sales were mainly to the industries which have traditionally used wood-fired boilers, the paper and allied products industry, and the wood products industry. These two industries purchased over 95 percent of the wood-fired boilers sold from 1970 through 1980.

Annual sales of wood-fired boilers are expected to average 1.0 million kg/hr (2.3 million lb/hr) of steam capacity from 1984 through 1988.

EMISSIONS FROM INDUSTRIAL WOOD-FIRED BOILERS

In this section, uncontrolled emissions from wood-fired boilers and factors affecting these emissions are discussed. The pollutants discussed in this section are sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM). These pollutants are of interest because they are criteria pollutants which commonly require controls due to Federal and State emission regulations.

Sulfur Dioxide Emissions

Wood-fired boilers have very low emissions of SO_2. Uncontrolled SO_2 emissions are generally less than 9 ng/J (0.02 lb/10^6 BTU) of heat input, and in many cases, are below the detection limit of the applicable test methods.

The SO_2 emissions are low for two reasons:

(1) wood fuels have low sulfur contents (typically less than 0.1 percent); and

(2) most of the sulfur in the wood fuel (90 percent or more) remains with the ash residue of combustion.

Because of the low SO_2 emissions from wood combustion, SO_2 controls have not been applied to boilers exclusively firing wood fuels. However, if fossil fuels are fired in conjunction with wood, SO_2 controls may be required. EPA is currently developing SO_2 New Source Performance Standards (NSPS) for fossil and non-fossil (e.g., wood)-fired industrial boilers with heat input capacities above 100 million BTU/hr (typically about 65,000 lb/hr steam). According to the current schedule, these standards will be proposed in Fall, 1985. Until that time, wood-fired industrial boilers above 250 million BTU/hr input are subject to the Subpart D NSPS limiting SO_2 emissions to 516 ng/J

(1.2 lb/million BTU) for coal/wood mixtures and 344 ng/J (0.8 lb SO_2/million BTU) for oil/wood mixtures. EPA is also in the initial stages of reviewing the merits of an NSPS for SO_2, NO_x, and PM emissions for boilers below 100 million BTU/hr input.

Nitrogen Oxides Emissions

NO_x emissions from wood-fired boilers are lower than those from most fossil fuel-fired boilers. Wood-fired boilers generally have uncontrolled NO_x emission rates below 110 ng/J (0.25 lb/10^6 BTU) of heat input. Nitrogen oxide emissions come from two sources: conversion of nitrogen in the fuel to NO_x (fuel NO_x); and conversion of nitrogen in the combustion air (thermal NO_x).

Wood fuels have low nitrogen contents compared to some fossil fuels such as coal. This low nitrogen content reduces the amount of fuel NO_x formed. Also, the lower combustion temperatures of wood-fired boilers compared to fossil fuel-fired boilers reduce the formation of thermal NO_x. The lower combustion temperature is due to the generally higher moisture contents and excess air levels associated with wood firing. Emissions from boilers co-firing fossil and wood fuels approach the levels of emissions from fossil fuel boilers as the proportion of fossil fuel increases.

NSPS were proposed on June 19, 1984 for NO_x and PM emissions from industrial, commercial, and institutional boilers with heat input capacities above 100 million BTU/hr firing fossil and non-fossil fuels. No NO_x emission limits were proposed for boilers firing wood alone. However, for units buring mixtures of wood and fossil fuels where the boiler annual capacity factor (based on the fossil fuel) is greater than 30 percent, prorated emissions limits were proposed based on the fuel mixture. Table 1 summarizes the emission limits for the wood/fossil fuel mixtures covered. With the exception of wood/coal fired pulverized fuel boilers, the emissions limits are based on the use of low excess air combustion techniques. For pulverized fuel boilers, the limit is based on the use of staged combustion air.

Particulate Emissions

Wood-fired boilers can produce significant amounts of particulate matter emissions. There are two types of particulate matter produced by wood combustion: unburned combustible material (mostly carbon) and noncombustible ash. The noncombustible particulate fraction originates in two ways. First, wood and bark naturally contain some intrinsic mineral matter which is noncombustible. Combustion of entrained fuel particles releases this mineral matter or ash into the flue gas. And second, depending on the method of fuel preparation, varying quantities of dirt or sand may adhere to the fuel particles and be entrained in the flue gas along with the fuel.

Unburned combustibles result from particles of fuel being entrained in the flue gas and carried out of the furnace before combustion is complete. Emissions of unburned combustibles can be reduced either by reducing fuel entrainment or by improving the combustion efficiency of the entrained fuel particles. Unburned combustibles make up over 50 percent of the total particulate emissions from most wood-fired boilers.

Total uncontrolled particulate emissions generally range from 900 to 2600 ng/J (2 to 6 lb/10^6 BTU) of heat input for well designed, well operated wood-fired boilers. Uncontrolled emission levels are important because they affect the design and cost of emission control systems. The three major factors which affect uncontrolled emissions are the boiler firing method, fuel quality, and boiler operation. These factors will be discussed separately, although they are not necessarily independent of each other.

Effect of Boiler Firing Method on Emissions

As shown in Table 2, the most common firing method for wood-fired boilers sold from 1970 through 1978 is the spreader stoker. Other firing methods available for new wood-fired boilers are overfeed and underfeed stokers, suspension fired units, fuel cells, and fluidized bed combustors. Spreader stoker firing generally produces higher uncontrolled emissions than other firing methods. However, other factors such as steam demand variability, fuel type, and boiler efficiency may be more important than uncontrolled emissions in the selection of the boiler firing method.

In the spreader stoker, the fuel enters the furnace through a fuel chute and is mechanically or pneumatically spread across the furnace. The smaller fuel particles burn in suspension while the larger particles fall on a stationary or moving grate where combustion is completed. A portion of the combustion air is injected through the grate (underfire air) to drive off volatiles in the fuel and burn the char, while the rest of the combustion air is injected over the grate (overfire air) to complete combustion.

Spreader stoker boilers are currently the most common method of burning wood waste because of their ease of operation and relatively high thermal efficiency (typically 65-70 percent based on fuel energy). Spreader stokers can burn fuel with moisture contents up to 63-65 percent (wet basis). Above this level of moisture they cannot support stable combustion unless an auxiliary fossil fuel is used. One disadvantage of the spreader stoker over other boiler types is a higher emission rate resulting from the entrainment of unburned fuel particles and ash.

Overfeed and underfeed stokers are similar to spreader stokers. Overfeed stokers spread the fuel across the furnace by a moving grate, rather than throwing the fuel across the furnace by pneumatic or mechanical action of a fuel spreader. In underfeed stokers the wood fuel is placed on the grate by a ram or a screw. These methods of introducing the fuel reduce the amount of fuel burned in suspension and decrease the uncontrolled particulate matter emission rate, as compared to spreader stokers, since there is less chance for fuel particle entrainment.

Some stoker boilers have provisions to feed the smaller fuel particles in separate feed systems especially designed to handle these particles. These systems burn the smaller fuel particles in suspension above the grate. An example of this system is the firing of sanderdust in suspension above the grate of a spreader stoker firing bark. These types of systems are sometimes able to achieve better combustion of the smaller, more easily entrained fuel particles than is obtained by mixing them with the larger size fuel. Improved combustion of the smaller particles results in lower emissions of unburned particulate. These dual feed systems may also have an independent air supply to provide for better control of combustion air to the small fuel particles. Some types of wood fuel, such as sanderdust, burn rapidly and unless sufficient air is supplied in the right place, the fuel will not burn completely. This will result in a loss of boiler efficiency. Also, this unburned fuel will be entrained in the flue gas and increase uncontrolled particulate matter emissions.

In fuel cell boilers., wood fuel is piled on a stationary grate in a refractory lined cell. Forced draft air is supplied to drive off the volatiles in the wood and burn the carbon. The volatiles are mixed with secondary and tertiary combustion air above the fuel pile, and pass into a second chamber where combustion is completed. This two stage combustion process produces lower uncontrolled particulate matter emissions compared to spreader stoker boilers by reducing fuel entrainment.

Suspension-firing boilers differ from spreader stokers in that small-size fuel [normally smaller than 1.6 mm (0.06 in)] is blown into the boiler and combusted by supporting it in an air stream rather than on fixed grates. Rapid changes in combustion rate and steam generation rate are possible with this system because the finely divided fuel particles burn very quickly. Another advantage of suspension firing is that ash is easily removed from the furnace bottom. The disadvantages include:

1) restrictive requirements regarding fuel particle size and moisture content (30 percent or less on a wet basis); and

2) entrainment of most of the ash by the flue gas.

These boilers typically use a small size fuel (such as sanderdust) generated as a by-product of wood processing operations. These fuels are typically cleaner and drier than other types of wood fuels. Clean dry fuels result in increased combustion efficiency efficiency and lower uncontrolled particulate matter emissions.

A recent development in wood-firing is fluidized bed combustion (FBC). A fluidized bed consists of inert particles through which air is blown so that the bed behaves as a fluid. Wood waste enters in the space above the bed and burns both in suspension and in the bed. Fluidized beds can fire fuels with moisture contents up to 67 percent (wet basis), as compared with a maximum moisture content of 63-65 percent for a spreader stoker. Fluidized beds can also handle dirty fuels (up to 30 percent inert material on a dry basis). Because of its contact with the hot inert bed material, the wood fuel is pyrolyzed faster in a fluidized bed than on a grate. As a result, combustion is rapid and results in nearly complete combustion of the fuel, thereby minimizing emissions of unburned combustibles. Minimizing unburned combustibles should lower particulate matter emission rates for fluidized bed boilers compared to spreader stokers burning the same fuels, since the uncontrolled particulate matter emissions from spreader stokers are normally over 50 percent unburned combustibles.

The disadvantages of fluidized beds include lower thermal efficiency than stokers, higher pressure drops [10-15 kPa (40-60 inches of water)], higher operating costs, and larger requirements for excess air to keep the bed temperature lower than the ash fusion temperature. Over 30 fluidized beds are used currently. They are expected to become more common during the next decade, especially for low capacity units, because of their ability to burn fuels with high moisture and ash contents.

<u>Effect of Fuel Quality on Emissions</u>

Another factor influencing uncontrolled emissions from wood-fired boilers is fuel quality. Fuel quality is affected by the type of wood, the methods used for harvesting and storage of the wood, and its preparation before it is introduced into the fuel chute. The most important fuel quality parameters are moisture content, fuel size, and ash content.

Fuel moisture content is one of the most important measures of fuel quality. While most wood fuels show little variation in heating value on a dry basis, the variation in moisture content of wood waste, shown in Table 3, causes wide variations in heating value as fired. Higher fuel moisture content reduces the fuel heating value, reduces overall boiler thermal efficiency, and retards combustion. These effects of fuel moisture content mean that a higher fuel feed rate will be required for a given steam production rate when using wood with a higher fuel moisture content compared to another fuel with a lower fuel moisture content.

In addition, because the moisture in the fuel evaporates during combustion, it increases the gas velocity in the combustion zone. This increased gas velocity leads to the entrainment of more fuel particles and reduced residence time for combustion. For these reasons, the effect of an increase in fuel moisture content is usually an increase in particulate matter emissions.

Wide variability in fuel moisture content also makes control of combustion air difficult. The result may be less than optimum combustion conditions and increased unburned combustibles in the fly ash.

The effect of high moisture content on emissions from wood combustion (because of wood type or storage method) can be overcome by drying the fuel. One method of drying wood fuel is to use the heat discharged with the stack gases in a fuel dryer. The fuel can be dried to any degree desired. However, moisture levels below 25-30 percent (wet basis) may result in high combustion chamber temperatures and the possibility of grate damage. Other methods such as vibrating off water or pressing the fuel are only effective at moisture levels above 60 and 50 percent, respectively.

The initial fuel size distribution can be as important as the fuel moisture analysis in affecting PM emissions. Typical wood fuel is sized in a "hog" which reduces the size to less than four inches. The wood from the hog may be mixed with additional fuel which has already been reduced in size, such as sawdust and shavings. When fired, smaller fuel particles are entrained in the flue gas. As the average fuel size decreases, more particles become entrained. These particles may escape the boiler before burnout is complete, thereby increasing particulate matter emissions. The larger fuel particles tend to burn on the grate. By screening the fuel and hogging only those pieces too large for the fuel feed system, the average fuel size can be increased. This increased average fuel size should reduce fuel entrainment, and therefore particulate emissions.

High ash contents will increase particulate matter emissions. There are two types of ash in wood fuel. Inorganic compounds present in the wood structure represent intrinsic ash. Wood fuel may also be accompanied by "tramp" ash in the form of dirt and sand picked up during harvest or storage.

Harvesting and storage methods also affect fuel quality and thus, particulate matter emissions. In typical logging operations, dirt is picked up in the wood bark. The amount of dirt picked up is dependent on the type of soil and the weather conditions. This dirt may remain in the bark during processing of the raw wood and end up in the wood fuel. For this reason, bark will usually have a higher ash content than other types of wood fuels. Outside storage of wood fuel can also result in dirt mixed with the fuel. The dirt is then introduced into the combustion chamber.

In typical logging operations in the northwestern United States, logs are stored in salt water. Consequently, both bark and logs may have a salt content of approximately 1 percent (dry basis) and a moisture content near 60 percent (wet basis). Combustion of wood and bark waste from logs stored in this manner may result in uncontrolled particulate emissions containing about 20 percent salt. These salt particles are typically submicron in size.

<u>Effect of Boiler Operation on Emissions</u>

The third factor influencing uncontrolled emissions from wood-fired boilers is boiler operation. Several operational practices cause variations in boiler emissions. These practices are firing of fossil fuels in wood-fired boilers, fly ash re-injection, excess air levels, and boiler load.

Approximately 50 percent of wood-fired boilers have some type of fossil fuel-firing capability. Typically, the fuels used are coal, fuel oil, or natural gas. Fossil fuels may be fired during boiler startup or as an augmentation fuel, and may be fired alone or together with wood.

Startup operations vary with the operator and size of the boiler, but typically last no more than four hours. Augmentation of wood with fossil fuels may occur when steam demands exceed the boiler capacity on wood alone, when higher than normal moisture contents are encountered in the wood fuel, when the wood feed system is inoperative, or when enough wood fuel is not available.

The duration and frequency of the use of fossil fuels will vary depending on the situation. The majority of new wood-fired boilers are expected to obtain less than 25 percent of their total heat input from fossil fuels. The amount of fossil fuel fired at any specific time, however, may vary considerably.

The effect on particulate matter emissions of firing fossil fuels in wood-fired boilers will vary according to the fuel used. For a constant heat input, efficient oil or gas combustion results in smaller quantities of particulate matter emissions than wood combustion. Therefore, particulate matter emissions from combined fossil fuel/wood combustion will decrease with increased oil or gas firing in properly designed systems. With increased coal firing, particulate matter emissions may increase or decrease depending on the coal ash content and the extent to which coal affects the wood combustion efficiency.

Fly ash reinjection is the second operational factor which has a direct effect on particulate matter emissions from the boiler. Fly ash reinjection consists of taking the particulate matter collected in the mechanical collectors and injecting it back into the furnace, thereby recovering unburned carbon. Fly ash reinjection is done for two reasons:

1) to increase overall boiler efficiency (increases range from 1 to 4 percent); and

2) to reduce the amount of solid waste needing disposal.

The disadvantage of fly ash reinjection is that it increases the uncontrolled particulate matter emissions to the mechanical collector. New boiler installations typically separate the collected particulate mattter into large and small fractions in sand classifiers. The larger particles, which are mostly carbon, are reinjected into the furnace. The smaller particles, mostly inorganic ash and sand, are discarded.

Varying the excess air in wood-fired boilers also influences uncontrolled emissions. Excess air is necessary for proper combustion, but too much air can be detrimental to the combustion system. Optimum rates for new boilers usually range from 25 to 50 percent excess air depending on boiler design and fuel. The detrimental effects of too much combustion air include:

1) reducing combustion temperatures and retarding the combustion rate;

2) reducing thermal efficiency, thus requiring more fuel for a given steam output; and

3) increasing gas velocities in the furnace causing transport of fuel particles out of the furnace before combustion is complete.

The effects of too much combustion air on uncontrolled particulate matter emissions are most significant if the air is injected as undergrate air. Increasing undergrate air directly increases the upward furnace gas velocities both through the fuel bed on the grate and directly above the grate. This increases fuel entrainment.

The boiler load also affects emissions of particulate matter. If the load is increased, the fuel feed rate and combustion air feed rate also have to increase. Increasing the fuel feed rate and combustion air rates introduce more ash into the furnace and also increase furnace gas velocity, so more fuel is entrained in the flue gas.

CONTROLLING PARTICULATE EMISSIONS FROM WOOD-FIRED BOILERS

Even well designed and operated wood-fired boilers will require particulate control devices in most cases to meet current emission regulations. The NSPS for industrial, commercial, and institutional boilers proposed on June 19, 1984 sets a PM emission limit of 86 ng/J (0.2 lb/million

BTU) for wood-fired units in the range of 50 to 100 million BTU/hr heat input and 43 ng/J (0.10 lb/million BTU) for units above 100 million BTU/hr. If the boiler annual capacity factor is 30 percent or less (with an enforceable Federal, State, or local operating permit limiting the capacity factor to stated limits), the proposed PM emission limits are 129 ng/J (0.3 lb/million BTU) for boilers in the 50 to 100 million BTU/hr range and 86 ng/J (0.2 lb/million BTU) for boilers between 100 and 250 million BTU/hr. The opacity standard for these boilers is proposed at 20 percent (based on six minute averages).

There are several types of control devices available which are capable of reducing the particulate emissions to the levels required by these regulations. These devices include mechanical collectors, wet scrubbers, fabric filters, electrostatic precipitators, and electrostatic gravel-bed filters. This section discusses how these controls remove particulate matter from the gas. The major parameters affecting the performance of these control devices are discussed along with the applicability of these controls to various types of wood fuels. Finally, the results of performance tests on these controls are reviewed.

Table 4 presents an approximate distribution of emission control devices presently applied to wood-fired boilers. As shown in this table, mechanical collectors make up over 75 percent of the control devices presently installed on wood-fired boilers. However, recent sales data indicate that the more efficient controls, such as wet scrubbers and ESPs, are generally being applied to new boilers.

Mechanical Collectors

Devices using centrifugal separation to remove particulate matter from gas streams are called cyclones or mechanical collectors. At the entrance of the cyclone, a spin is imparted to the particle-laden gas. This spin creates a centrifugal force which causes the particulate matter to move away from the axis of rotation and towards the walls of the cyclone. Particles which contact the walls of the cyclone tube are directed to a dust collection hopper where they are deposited.

In a typical single cyclone, the gas enters tangentially to initiate the spinning motion. In a multitube cyclone, the gas approaches the entrance axially and has the spin imparted by a stationary "spin" vane that is in its path. This allows the use of many small, higher efficiency cyclone tubes, with a common inlet and outlet, in parallel to the gas flow stream.

The performance of mechanical collectors is primarily a function of the particle size distribution of the particulate matter to be collected. The collection efficiency of a mechanical collector increases as the percentage of larger particles increases. The most important design parameters affecting the performance of mechanical collectors are the inlet gas velocity, tube diameter, and the number and angle of the spin vanes. Higher gas velocities, smaller tube diameters, and increasing the numbers and angles of the spin vanes increase collector efficiency. However, for mechanical collectors applied to wood-fired boilers, there is a limit to the efficiency increases that can be obtained. The limit exists because the particulate matter from wood combustion will break up into smaller particles which are more difficult to collect if the centrifugal forces become too great.

Fly ash collection by multitube cyclones is a well established technology, and has been used for many years to control particulate emissions from all types of wood-fired boilers. Multitube cyclones were the most commonly used method for fly ash control before stricter emission regulations were enacted, and many are still in place on existing sources. For new wood-fired boilers in the larger sizes, mechanical collectors are now mainly used as precleaners, and/or for fly ash reinjection prior to a more efficient final control device. However, some of the smaller wood-fired boilers may still be able to meet current emissions regulations with mechanical collectors alone.

Wet Scrubbers

A wet scrubber is a collection device which uses an aqueous stream or slurry to remove particulates and/or gaseous pollutants. Scrubbers are usually classified by energy consumption (in terms of gas phase pressure drop). Medium-energy scrubbers such as impingement scrubbers have pressure drops of 1.3-3.7 kPa (5-15 inches of water). High-energy scrubbers such as high-pressure drop venturi scrubbers can have pressure drops exceeding 3.7 kPa (15 inches of water). The most common scrubbers used for "moderate" levels of particulate matter control are medium energy impingement and venturi scrubbers. Higher removal levels are usually accomplished with high energy venturi scrubbers.

Factors that affect the performance of typical wet scrubbers are:

1) contacting power (or gas phase pressure drop);

2) gas/liquid separation (mist elimination);

3) liquid-to-gas ratio (L/G);

4) particle size distribution; and

5) the amount of particulate matter present in the gas.

The major factor affecting the performance of a wet scrubber is the contacting power. In most scrubber applications, contacting power is indicated by the gas phase pressure drop. Removal efficiency usually increases with increasing gas phase pressure drop; greater pressure drops create greater turbulence in the gas-liquid contacting zone which results in more efficient particulate matter collection.

In some cases, wet scrubbers may show decreasing removal efficiency with increasing pressure drop above a certain level due to carryover of droplets of the particulate-laden scrubber liquid. These droplets which contain suspended particulate matter can evaportate, releasing the particulate matter back into the flue gas. Wet scrubbers should thus be equipped with mist eliminators to ensure adequate separation of gas and scrubbing liquid droplets. This misting problem, although still present, may not be as severe if once-through scrubbing liquid is used. Once-through liquid generally will have a lower solids content than recycled liquid.

If the liquid rate to the scrubber is sufficient to completely sweep the gas stream with droplets without flooding the scrubber, scrubber performance is relatively insensitive to variations in the liquid-to-gas ratio (L/G). Increases in the L/G generally increase scrubber efficiency, but the performance increases are usually small.

Scrubber performance also depends on the particle size distribution of the particulate matter to be collected. Collection efficiency varies directly with particle size, with larger particles collected at greater efficiency.

Scrubber performance also depends on the amount of particulate matter in the flue gas. If the amount of particulate matter exceeds the level the scrubber was designed for, the scrubber could become overloaded, resulting in reduced removal efficiency. In cases where the amount of particulate exceeds the design rate, scrubber efficiency may be improved by increasing the gas pressure drop and L/G. Alternatively, precleaners such as cyclones could be used upstream of the scrubber to reduce the particulate matter entering the scrubber.

Venturi scrubber applications generally include a variable throat system which allows a constant pressure drop to be maintained. A constant pressure drop enables a constant efficiency to be maintained at varying boiler loads.

Wet scrubbing is a well-established technology for wood-fired boilers and has been applied to most types of wood-fuels. However, wet scrubbers are not as effective on boilers firing salt-laden wood as they are on other types of wood fuels. This is because this fuel produces particulate emissions containing a significant fraction of submicron salt particles. These smaller size particles are difficult to collect with a wet scrubber.

<u>Fabric Filters</u>

In a typical fabric filter (baghouse), the inlet gas passes through the filter and the particulate matter is retained on the filter material by inertial impaction, diffusion, direct interception, and sieving. The first three processes prevail only briefly during the first few minutes of filtration with new or recently cleaned fabrics, while the sieving action of the dust layer accumulating on the fabric surface soon predominates. This sieving action is most predominant at dust loadings greater than 1 g/m^3 (0.4 gr/ft^3). The sieving mechanism leads to high efficiency collection unless defects such as pinhole leaks or cracks appear in the filter cake.

In fabric filtration, both the collection efficiency and the pressure drop across the bag surface increase as the dust layer on the bag builds up. Since the system cannot continue to operate with an increasing pressure drop, the bags are cleaned periodically. Cleaning typically occurs in one of three ways. In shaker cleaning, the bags are oscillated by a small electric motor. The oscillation shakes most of the collected dust into a hopper. In reverse flow cleaning, backwash air is introduced to the bags to collapse them and fracture the dust cake. Both shaker cleaning and reverse flow cleaning require a sectionalized baghouse to permit cleaning of one section while other sections are functioning normally. The third cleaning method, pulse jet cleaning, does not require sectionalizing. A short pulse of compressed air is introduced through venturi nozzles and directed from the top to the bottom of the bags. The primary pulse of air aspirates secondary air as it passes through the nozzles. The resulting air mass expands the bag and fractures the cake.

During baghouse operation, it is essential that baghouse temperatures be maintained above the water dewpoint of the gas so that condensation will not occur on the compartment walls and filter surfaces. In the latter case, resultant plugging or blinding may restrict gas flow and cause irreversible bag damage. Condensation is most likely to occur during transient operations such as startup, shutdown, or fluctuating loads. Bypassing or preheating the baghouse prior to system startup, continuous gas recirculation during brief shutdowns, and/or sufficient insulation on the baghouse and duct should minimize condensation problems.

The most important design factor for a baghouse is the air-to-cloth ratio (A/C). This parameter relates the volume of gas filtered (m^3/min or acfm) to the available filtering area (m^2 or ft^2). This parameter is, in effect, the superficial velocity of the gas through the filtering media. Air-to-cloth ratios for the pulse jet cleaning systems applied to wood-fired boilers range from 0.9-1.5 m/min (3-5 ft/min).

Baghouse outlet loading does not vary greatly as a result of changes in gas flowrate for a given boiler application. As the flowrate is reduced from the design rate (presumably the flow at rated capacity), the A/C decreases. Filtration generally improves with decreasing A/C, especially if the unit collects substantial quantities of small particles and the cleaning cycle is triggered by attainment of a predetermined pressure drop. Hence, a baghouse that meets specifications at the design flowrate should have equal or lower outlet grain loadings at reduced flowrates. Fabric filters can operate at efficiencies greater than 99.9 percent with pressure drops of 0.5 to 1.5 kPa (2 to 6 inches of water).

Fabric filters have had limited applications to wood-fired boilers. The principal drawback to fabric filtration, as perceived by potential users, is a fire danger arising from the collection of a combustible carbonaceous fly ash. Some factors which can reduce this fire hazard are:

1) water quenching the gas stream upstream of the baghouse;

2) minimizing the in-leakage of air to the hot carbonaceous fly ash;

3) establishing a filter cleaning sequence that prevents the build-up of a thick filter cake;

4) bypassing the baghouse during the intermittent operations, such as soot-blowing and cyclone cleaning, when sparks are likely to reach the baghouse; and

5) removing large burning particles of fly ash in multitube cyclone precleaners.

In addition to the steps taken above to reduce the fire hazard, a baghouse owner may add special fire protection measures. The baghouse can be fitted with a sprinkler system to quench the baghouse and bags when fire occurs. Although the bags will need to be replaced after a quench, major structural damage may be avoided. A special protection system may also be added to quench sparks before they reach the baghouse. Such a system consists of a flame detector and a supply of extinguishing agent such as water, steam, or carbon dioxide. The extinguishing agent is applied only long enough to quench sparks.

Of the seven baghouses applied to wood-fired boilers, two are applied to boilers firing salt-laden wood. This fuel produces particulates with a high salt content. This type of fly ash poses a smaller fire hazard due to the quenching effect of the salt.

Electrostatic Precipitators

An electrostatic precipitator (ESP) collects particulates in three steps: entering particles are given an electrical charge; the charged particles migrate to a collecting electrode of opposite polarity while subjected to a diverging electric field; and the collected particulate matter is dislodged from the collecting electrodes.

Charging of the particles to be collected is usually caused by ions produced in a high voltage d-c corona. The electric fields and the corona necessary for particle charging are provided by high voltage transformers and rectifiers. Removal of the collected particulate matter is accomplished mechanically by rapping or vibrating the collecting electrodes.

The performance of ESPs depends on the :

1) amount of available collecting surface;
2) gas flow rate;
3) particulate resistivity;
4) particle size distribution;
5) gas velocity distribution;
6) rapping intensity and frequency; and
7) electrical field strength.

Because the individual effects of these factors on ESP peformance are difficult to model, ESP performance has classically been predicted with the empirical three parameter Deutsch-Anderson equation:

$$\eta = 1 - \exp\left[- W_e(A/V)\right]$$

where η = collection efficiency;

W_e = average migration velocity, m/sec (ft/min);

V = gas flow rate, m^3/sec (ft^3/min); and

A = collection plate area, m^2(ft^2).

The ratio A/V is known as the specific collection area (SCA) and is usually expressed in $m^2/(m^3/sec)$ or $ft^2/1000$ acfm. Practical values of SCA range from 20 to 160 $m^2/(m^3/sec)$ (100 to 800 $ft^2/1000$ acfm) for the most field applications on boilers. Collection efficiency improves as SCA increases, but the ESP becomes larger and more expensive.

In many cases, field data indicate lower ESP efficiencies than predicted by the Deutsch-Anderson relationship. To account for this lower efficiency, the empirical relationship:

$$\eta = 1 - \exp\left[- W_k \, (A/V)^{0.5}\right]$$

is used as a more realistic predictor of particulate collection efficiency. The exponent, 0.5, is applicable when the ESP system is handling coal fly ash. The term W_k is an effective migration velocity determined from experimental measurements. Use of this equation results in a better estimate of SCA at high removal efficiencies.

The average migration velocity or precipitation rate is a function of particle size distribution and resistivity, gas velocity distribution, rapping intensity and frequency, and electrical field strength.

Wood fly ash is relatively easy to collect with an ESP. The suitability of particulate collection by electrostatic precipitators depends primarily on the resistivity of the particles. Particles with resistivities in the range of 5×10^3 to 2×10^{10} ohm-cm are the most suitable for electrostatic precipitation. Available data on wood-fired boiler particulates show resistivities in the range of 1.7×10^5 to 9.6×10^9 ohm-cm.

As shown in Table 4, ESPs have had limited applications to wood-fired boilers. Many of the applications have been to boilers firing wood/coal mixtures. However, more recently ESPs have also been successfully applied to boilers firing 100 percent wood fuels.

<u>Electrostatic Gravel-Bed Filters</u>

The electrostatic gravel-bed filter (EGB) consists of two concentric louvered cylindrical tubes contained in a cylindrical vessel. The annular space between the tubes is filled with pea-sized gravel media. Particulate-laden gas enters the filter through breeching and is distributed to the filter face by a plenum section formed by the outer louvered cylinder and the vessel wall. Particulate matter is removed from the gas stream by impaction with the media. An electrically charged grid within the gravel bed is used to augment collection by impaction. The particulate-laden media exits the bottom of the gravel-bed vessel and is pneumatically conveyed to a de-entrainment vessel through a verticle lift pipe. The particulate matter is removed from the gravel media by the abrasion of media as it is conveyed up the lift pipe, the scrubbing action of the air as it lifts the media, and a rattler section in the de-entrainment vessel. The gravel media falls from the conveyor air stream by gravity and is returned to the filter bed. The separated particulate matter is air conveyed to a storage silo where it is removed from the air stream by fabric filtration.

Very little data are available to assess the factors affecting the performance of gravel-bed filters and electrostatic gravel-bed filters. But the principal factors are expected to be:

1) the grid voltage;

2) the particle size of the particulate matter;

3) the air/media ratio;

4) the pressure drop across the media; and

5) the extent of particulate separation from the spent media.

Particle collection efficiency decreases with decreasing particle size and decreasing grid voltage. Particle collection efficiency should increase with decreasing air/media ratios and increasing gas-phase pressure drop based on theoretical considerations and on data for other particulate matter control devices.

Electrostatic gravel bed filters have been applied to several wood-fired boilers including those firing salt-laden wood. No limitations are known to exist at the present time that would prevent this device from being applied to any type of wood-fired boiler.

Performance of Particulate Matter Control Techniques

This section summarizes emission test data from many sources to illustrate the relative performance of various particulate matter control techniques. All the data used were obtained by approved EPA test methods. These test data came from industry emission tests, State and local environmental agency emission tests, and emission tests performed for the EPA. The emission test data shown in Figure 2 are grouped in five sets: medium-energy wet scrubbers, high-energy wet scrubbers, ESPs, fabric filters, and EGBs. For each set, the range of emission test results and the average is shown. Data for mechanical collectors are not shown because these devices are not generally used to meet stringent emission levels. However, all of the wood-fired boilers tested used mechanical collectors as precleaners and/or for fly ash reinjection before the final control device.

The first set of data, set A, show the results of nine emission tests at eight different facilities performed on medium-energy wet scrubbers with design pressure drops of 1.5 to 2 kPa (6 to 8 inches of water) applied to spreader stoker wood-fired boilers. These scrubbers show higher emissions than the other particulate emission controls tested, and also show a wider range of emissions. The range of emissions shown is most likely caused by differences in inlet emissions to the control devices due to differences in wood fuels and boiler operation. Such differences would result in a wider range of outlet emissions for lower efficiency control devices, such as the medium-energy scrubbers, than for higher efficiency controls.

Set B shows the results of four emission tests performed at three facilities on high pressure-drop scrubbers applied to wood-fired spreader stoker boilers. The scrubbers tested had pressure drops ranging from 3.7 to 6.5 kPa (15 to 26 inches of water). These scrubbers show lower emissions than the medium pressure drop scrubbers in set A.

Set C shows the results of six emission tests at five facilities on ESPs applied to wood-fired and wood/fossil fuel cofired boilers. At one facility an ESP is used to control emissions from the combined flue gases of a pulverized coal-fired boiler and a wood/coal cofired spreader stoker. The rest of the facilities have spreader stoker boilers. The average of these tests is lower than the wet scrubber test results. The range of emission rates shown is mainly due to the different specific collection areas (SCAs) during testing. These SCAs ranged from 45 to 120 $m^2/(m^3/sec)$ (230 to 600 $ft^2/1000$ acfm).

Set D shows emission test results for two facilities with wood-fired boilers controlled with fabric filters. Fabric filters showed the lowest average emissions of any of the control devices tested. At one facility the boiler was a spreader stoker; the other facility consisted of several oil pile-burning Dutch oven boilers. At the latter facility, the boiler was firing a wood fuel with a salt content of 0.4 percent (dry basis). The air-to-cloth ratios for these two fabric filters ranged from 0.9 to 1.1 m/min (3.0 to 3.7 ft/min).

The last group of emission test data, set E, came from tests performed on an EGB. All of these tests were performed on the same spreader stoker boiler and control system. One test for this set came from an emission test performed for the EPA. During this test, the boiler was operated under "typical" conditions for this facility. The remainder of the data came from a series of tests performed by the boiler owner at a range of steam production rates and with fuel of varying quality. The emission rates shown by the EGB were comparable to the emission rates shown by fabric filters and ESPs.

Comparison of the performance test results to the proposed NSPS levels shows that high-energy wet scrubbers, ESPs, fabric filters, and EGBs are all capable of meeting the 0.10 lb/million BTU limit. Medium-energy scrubbers may be capable of meeting the lower limit in some circumstances, but should be able to meet the upper limit (for 50-100 million BTU/hr boilers) in almost all cases.

SUMMARY

New wood-fired boilers are expected to be sold at an average rate of 1.8 million kg/hr (4.0 million lb/hr) per year in 1984 through 1990. These new wood-fired boilers will be required to meet State and Federal emission regulations at acceptable costs.

Emissions of sulfur dioxides and nitrogen oxides from wood-fired boilers are low compared to those from fossil fuels, and controls for these pollutants have not generally been applied to boilers fired exclusively with wood fuels.

Emissions of particulate matter are higher than SO_2 and NO_x emissions. In most cases the high level of these particulate matter emissions will require that particulate matter controls be applied to meet current and future emission regulations. The level of particulate emissions can be affected by several factors. These factors are boiler firing method, fuel quality, and boiler operation.

Current and future owners of wood-fired boilers should be aware of these factors and their effects on particulate emissions so that uncontrolled emissions can be maintained at the lowest practical level. Maintaining low uncontrolled particulate emissions may allow less expensive control devices to be used. Also, if the uncontrolled emission level increases over design levels, the control devices may become overloaded, and the required emission limit may be exceeded.

There are several types of control devices available which can achieve stringent emission levels. These include wet scrubbers, fabric filters, electrostatic precipitators, and electrostatic gravel-bed filters. Selection of the best particulate control system design depends on the emission level the boiler must meet, the boiler design, boiler size, and fuel type.

TABLE 2. WOOD-FIRED BOILERS SOLD BETWEEN 1970 AND 1978 BY FIRING METHOD AND SIZE CATEGORY

Firing Methods[a]	Steam Capacity - 10^3 kg/hr (10^3 lbs/hr) 7.3 - 45 (10 - 100)	46 - 113 (101 - 250)	114 - 227 (251 - 500)	Over 227 (Over 500)	Percent of Total Sales
Spreader Stoker - percent of size range[b]	20.6	67.8	100.0	100.0	65.9
Overfeed Stoker - percent of size range[b]	41.2	32.2	0	0	21.9
Underfeed Stoker - percent of size range[b]	1.9	0	0	0	0.6
Other[c] - percent of size range[b]	31.7	0	0	0	10.1
Suspension[d] - percent of size range[b]	4.6	0	0	0	1.5

[a]This table includes only boilers firing wood as the primary fuel. The firing method is for the wood fuel only. Many of the boilers, especially in the larger size ranges, co-fire wood and an auxiliary fossil fuel.

[b]Value is percent of total capacity sold in that size range.

[c]Includes fuel cells and fluidized bed combustion.

[d]Suspension boilers are defined as those which burn only small sized fuel (such as sanderdust) and the fuel is burned 100 percent in suspension.

TABLE 3. RANGE OF MOISTURE CONTENT OF TYPICAL WOOD FUELS

Fuel	Moisture Content, (%) Wet Basis
Bark	25-75
Coarse Wood Residues	30-60
Planer Shavings	16-40
Sawdust	25-40
Sanderdust	2-8
Reject "Mat Furnish"	4-8

TABLE 4. APPROXIMATE DISTRIBUTION OF EMISSION CONTROLS APPLIED TO WOOD-FIRED BOILERS[a]

Final Control Device	Wet Scrubber	Fabric Filter	ESPs	EGBs[b]	MC[c]	Other
Number	135	7	8	7	686	35
Percentage of Total	15	1	1	1	78	4

[a]Distribution is based on 1982 National Emissions Data System (NEDS), literature, and phone survey. Boilers co-firing wood and fossil fuels are included.

[b]Does not include the older type gravel bed filters without the electrostatic grid. These systems are included in "other". Some EGB units are applied in parallel to treat exhausts from single boilers. The number of EGB units is reported here.

[c]Includes dual mechanical collectors in series.

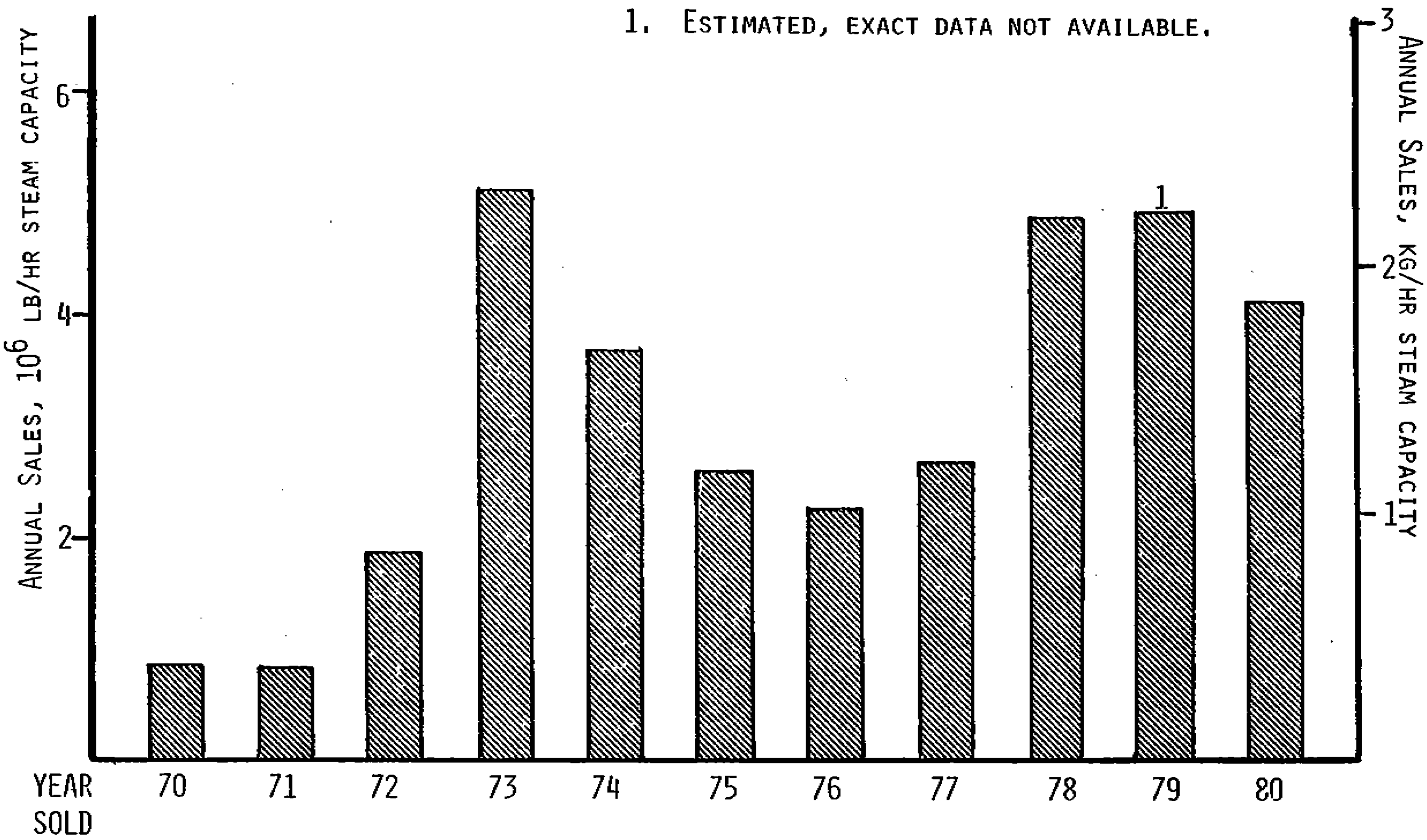

Figure 1. Sales of wood-fired boilers for 1970 through 1980.