AP-42
Section 1.6
Ref # 1

EMISSION FACTOR DOCUMENTATION FOR

AP-42 SECTION 1.6

WOOD WASTE COMBUSTION IN BOILERS

Prepared by:

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Contract No. 68-DO-0120
EPA Work Assignment Officer: Michael Hamlin

Office of Air Quality Planning and Standards
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1. INTRODUCTION

The document "Compilation of Air Pollutant Emission Factors" (AP-42) has been published by the U.S. Environmental Protection Agency (EPA) since 1972. Supplements to AP-42 have been routinely published to add new emission source categories and to update existing emission factors. The AP-42 is routinely updated by EPA to respond to new emission factor needs of EPA, State, and local air pollution control programs and industry.

An emission factor relates the quantity (weight) of pollutants emitted to a unit of activity of the source. The uses for the emission factors reported in AP-42 include:

1. Estimates of area-wide emissions;
2. Emission estimates for a specific facility; and
3. Evaluation of emissions relative to ambient air quality.

The purpose of this report is to provide background information from over 17 test reports to support revision of emission factors for wood waste combustion in boilers.

Including the introduction (Chapter 1), this report contains five chapters. Chapter 2 gives a description of the use of wood waste for combustion in boilers and furnaces. It includes a characterization of the industry, an overview of the different wood waste and boiler types, a description of emissions, and a description of the technology used to control emissions resulting from wood waste combustion. Chapter 3 is a review of emissions data collection and analysis procedures. It describes the literature search, the screening of emission data reports, and the quality rating system for both emission data and emission factors. It also describes particle size determination and particle size data analysis methodology. Chapter 4 details pollutant emission factor development. It includes the review of specific data sets, the results of data analysis, and the data base protocol. Chapter 5 presents the new AP-42 Section 1.6 for Wood Waste Combustion in Boilers.

2. INDUSTRY DESCRIPTION

The burning of wood waste in boilers is mostly confined to those industries where it is available as a byproduct.[1-3] It is burned both to obtain heat energy and to alleviate possible solid waste disposal problems. Generally, bark is the major type of wood waste burned in pulp mills, and either a varying mixture of wood and bark waste or wood waste alone are most frequently burned in the lumber, furniture, and plywood industries.

2.1 CHARACTERIZATION OF THE INDUSTRY[4]

As of 1980, there were approximately 1,600 wood-fired boilers in operation in the U.S. with a total capacity of over 30,000 MW (1.0×10^{11} Btu/hr). These boilers ranged in size from approximately 0.3 MW (1 million Btu/hr) to over 410 MW (1,400 million Btu/hr) heat input. In this report, MW refers to heat input to the boiler unless otherwise indicated. The largest numbers of wood-fired boilers are located in the states of forest-related industries: Oregon, Washington, Georgia, Florida, and Arkansas.

2.2 PROCESS DESCRIPTION[5]

Use of wood as a fuel occurs primarily where it is generated as a byproduct of a manufacturing operation. Some of the principal manufacturing operations which utilize significant quantities of wood waste are summarized below:

- Lumber and plywood manufacturing facilities use bark and other wood residues to fire boilers for energy production;
- Paper mills use only the white wood for paper manufacturing and must dispose of the undesirable bark. This bark can be burned in a boiler to generate plant steam;
- Particle board and hardboard manufacturing plants must dispose of trim, surface material, or other combustible wood waste. Most plants can

convert this dry, combustible fuel to energy more economically than they can burn oil or gas;

- Furniture manufacturing facilities may generate enough dry waste wood that it can be used economically for process steam generation or sold as a fuel to other users.

2.2.1 Wood Types

The type of wood to be combusted dictates the design of the wood handling and storage system. These factors, in turn, influence the combustion characteristics of the wood waste and emissions potential. The principal types of wood burned as boiler fuels are hogged wood, sawdust, shavings, chips, sanderdust, and particle board/hardwood residue and trim.

One of the most common forms of wood combusted in boilers is hogged wood. The usual way to reduce the size of wood and bark is with a "hog" -- a machine designed to reduce large pieces of wood to a smaller, nearly uniform size. The hog consists of rotating hammers which carve out small chunks of wood from larger pieces and allow them to drop from a discharge chute. Hogging of wood residue or bark is usually done at the point of generation because it is easier to handle and transport the hogged fuel than the large chunks of wood or bark. Hogged wood is generally stored in a pile outside the boiler house. Wood is transported by a reclaim conveyor from the storage pile to boiler overhead feed bins. Prolonged storage of hogged wood outside can reduce the wood's heating value due to deterioration and moisture accumulation.

Sawdust is the wood fiber removed by saws during cutting. The ash content is low because it is mostly white wood, not bark. Size of particles ranges from 1 to 10 millimeters (1/32 to 3/8 inch), depending on the saw, the wood species, the direction of cut, and other factors. Moisture content is the same as that of the original wood, typically 25 to 50 weight percent, but sawdust can be dried more readily because of its relatively high surface-to-volume ratio. Sawdust may be transported by mechanical conveyor systems or pneumatic systems. Although it can be fired separately, sawdust is usually blended with the hogged fuel either in the storage system or in the fuel feed system just ahead of the furnace.

Shavings are generated during the manufacture of dimension lumber when rough-sawed wood is planed to its final size. Since the wood is dried or seasoned before it is planed, the moisture content of shavings is low, near 10 to 20 weight percent. The shavings are nearly flat with dimensions of about 1 by 13 by 13 millimeters (1/32 by 1/2 by 1/2 inch). Thus, these particles also have a high surface-to-volume ratio. Shavings are transported almost exclusively by pneumatic system, usually terminating in a cyclone that drops the shavings into a bin or directly into the boiler feed system.

A paper mill wood chip is about 13 to 25 millimeters (1/2 to 1 inch) on a side and about 3 millimeters (1/8 inch) thick. Except for size, their properties are similar to those of hogged wood. Chips are nearly always transported by a pneumatic system with a cyclone as the terminal separation device. Wood chips are seldom used as fuel unless supplies of hogged wood and bark are not available.

Sanderdust is generated by high-speed sanding of plywood or particle board. Some is also generated by an abrasive planer that is used to finish dimension lumber. Sanderdust is extremely dry, and the particles are very small [less than 8 millimeters (1/32 inch)]. Moisture content ranges from 2 to 8 weight percent typically. Sanderdust is transported pneumatically and normally stored in a bin before firing.

Particle board and hardboard are made of wood fibers, usually mixed with resinous materials and pressed into the product form. Trim, sawdust, sanderdust, and reject fiber from these processes provide an excellent, dry fuel for wood-fired boilers. This material may be finely divided and must be handled with care to avoid explosions. This wood waste may contain various quantities of resin which should be considered in terms of possible effects on the boiler and boiler emissions. Particle board and hardboard residues are usually handled by pneumatic systems with surge bins ahead of the boiler feeding system.

Systems for predrying wood residue and bark may be used to improve the combustion characteristics of the fuel. One of the shortcomings of wood fuel is the variability in moisture content of hogged wood, sawdust, bark, and other "dry" fuels. The moisture content is affected by wood species, handling practices, storage conditions, and related factors. Drying the fuel outside the boiler allows boiler operators to deal with a more uniform fuel. The second reason for predrying of the fuel is to minimize the water content of the boiler fuel. This increases both the thermal efficiency and steam generating capacity of the boiler. Wood drying is normally accomplished using either hot flue gases from the boiler or process steam in a rotary dryer, classifier, or kiln.

2.2.2 Fuel Characteristics[4]

In addition to wood fuel size and moisture content, other fuel characteristics can affect boiler emission levels. Harvesting and storage methods can influence particulate matter (PM) 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 cause dirt to be mixed with the fuel and thus be introduced into the combustion chamber. In addition to directly increasing the ash and PM emissions, this dirt can cause a reduction in combustion temperature, resulting in incomplete combustion and higher emissions of carbon monoxide (CO) and organic compounds.

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

The analyses presented in Table 2-1 for a typical wood waste show that wood fuels have low quantities of sulfur (in comparison to the quantities normally present in coal). Wood fuel nitrogen contents can range from as low as 0.04 percent up to 0.77 percent (dry basis). However, on the average the nitrogen content is less than 0.22 percent. These low nitrogen and sulfur contents translate to low sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions from wood combustion compared to typical emissions from the firing of coal. Heating values for wood waste typically range from approximately 4,500 to 5,600 kcal/kg (8,000 to 10,000 Btu/lb) on a dry basis, or from 2,200 to 2,800 kcal/kg (4,000 to 5,000 Btu/lb) on a wet, as-received basis with a typical moisture content of 50 weight percent.

2.2.3 Boiler Types[4,5,6]

Various boiler firing configurations are used for burning wood waste. One common type in smaller operations is the Dutch oven. This unit is widely used because it can burn fuels with very high moisture. As shown in Figure 2-1, fuel is fed into the oven through an opening in the top of a refractory-lined furnace. The fuel accumulates in a cone-shaped pile on a flat or sloping grate through which underfire air is fed. Overfire air is introduced around the sides of the fuel pile and into the secondary combustion chamber. Combustion is accomplished in two stages: (1) drying and gasification, and (2) combustion of gaseous products. The first stage takes place in the primary furnace, which is separated from the secondary furnace chamber by a bridge wall. Combustion is completed in the secondary chamber before gases enter the boiler section. The large mass of refractory helps to stabilize combustion rates but also causes a slow response to fluctuating steam demands.

In another wood waste boiler type, the fuel cell oven, fuel is dropped onto suspended fixed grates and is fired in a pile. Unlike the Dutch oven, the refractory-lined fuel cell also uses combustion air preheating and positioning of secondary and tertiary air injection ports to improve combustion efficiency. Forced draft air is supplied to drive off the volatiles in the wood and to 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. Like the Dutch oven, this two-stage combustion process gives lower PM emissions compared to spreader stoker boilers by reducing fuel entrainment.

The most common firing method for wood-fired boilers larger than 45,000 kg steam/hr (100,000 lb steam/hr) is the spreader stoker. With this boiler, wood enters the furnace through a fuel chute and is spread either pneumatically or mechanically across the furnace, where small pieces of the fuel burn while in suspension. Simultaneously, larger pieces of fuel are spread in a thin, even bed on a stationary or moving grate. The flame over the grate radiates heat back to the fuel to aid combustion. The combustion area of the furnace is lined with heat exchange tubes (i.e., waterwalls). A representative spreader stoker is shown in Figure 2-2.

Although spreader stokers are the most common stokers for large wood-fired boilers, overfeed and underfeed stoker designs are also employed for smaller units. With the overfeed stoker, wood is fed from a hopper onto a moving grate and enters the furnace after passing under an adjustable grate that regulates the thickness of the fuel bed. Various types of underfeed stokers are used in industrial boiler applications. They vary depending on whether the wood is fed horizontally or by gravity, whether the ash is discharged from the end or the sides, and how many retorts (i.e., or channels through which the wood is fed) are contained in the boilers.

Another boiler type sometimes used for wood combustion is the suspension-firing boiler. This boiler differs from a spreader stoker in that small-sized fuel [normally less than 2 millimeters (1/16 inch)] is blown into the boiler and combusted by supporting it on air rather than on fixed grates. Rapid changes in combustion rate and therefore steam generation rate are possible because the finely divided fuel particles burn very quickly. Another advantage is that ash is easily removed from the furnace bottom. Disadvantages of this design include: (1) restrictive requirements regarding fuel particle size and moisture content (30 percent or less on a wet basis) and (2) most of the ash is entrained in the flue gas. These boilers typically use a small-size fuel, such as sanderdust.

A recent development in wood firing is the fluidized bed combustion (FBC) boiler. 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. Because of the large thermal mass represented by the hot inert bed particles, fluidized beds can handle fuels with moisture contents up to near 70 percent (total basis). Fluidized beds can also handle dirty fuels (up to 30 percent inert material).

Wood fuel is pyrolyzed faster in a fluidized bed than on a grate due to immediate contact with hot bed material. As a result, combustion is rapid and results in nearly complete combustion of the organic matter, thereby minimizing emission of unburned organic compounds. The disadvantages of fluidized beds include slightly lower thermal efficiency compared to spreader stokers, higher pressure drops, higher operating costs, and the larger amounts of excess air required for bed fluidization and to keep bed temperatures below ash fusion temperatures.

Wood-fired boilers can be of either the watertube or firetube design. In firetube boilers, the hot combustion gases flow through tubes and the water being heated circulates outside the tubes. In watertube boilers, just the opposite occurs. Firetube boilers are usually limited in size to less than 9 MW (30 million Btu/hr); they are commonly used in the furniture industry. Watertube boilers dominate among larger boilers.

2.3 EMISSIONS[4,5]

2.3.1 Combustion Theory

The complete combustion of wood waste can be thought of as occurring in two stages: primary and secondary combustion. Primary combustion refers to the physical and chemical changes occurring on the fuel bed. It consists of drying, devolatilization, ignition, and burning of the wood waste. Secondary combustion refers to the oxidation of the gases and particulate matter released by primary combustion. Secondary combustion is aided by high temperature, sufficient air and turbulence in the gas stream. The turbulence must be intense and last long enough to ensure adequate mixing at elevated temperatures.

Time, temperature, turbulence, and air require a delicate balance for complete combustion. A disturbance in one or more of these variables can reduce combustion efficiency and result in measurable increases in emissions of CO and other organic compounds (i.e., the products of incomplete combustion). As a class, these organic compound emissions are generally measured either as volatile organic compounds (VOCs) or total organic compounds (TOCs).

The principal characteristics of wood fuels are high contents of moisture, volatile matter, and oxygen. About 80 percent of the fuel (dry basis) evolves as volatile matter and must be burned in the furnace space above the grates. The remaining 20 percent is fixed carbon, which must be burned on the grate.

The material remaining after combustion is ash, a noncombustible material that must be disposed of. Some of the ash collects in the furnace, while the remainder is entrained as PM in the combustion gases.

2.3.2 Boiler Operating Procedures

In addition to boiler design type and fuel quality, a third factor which influences uncontrolled emissions from wood waste-fired boilers is boiler operations. Several operational practices cause variations in boiler emissions. The first involves firing fossil fuels in wood-fired boilers. 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 cofired with wood. The impact on emissions will depend on the sulfur, nitrogen, and ash contents of the fossil fuels and the extent to which cofiring influences combustion efficiency, peak flame temperature, gas velocities, and combustion zone turbulence.

Fly ash reinjection is the second operational factor which has a direct effect on PM emissions from wood-fired boilers. Fly ash reinjection consists of taking the PM collected in the mechanical collectors and injecting it back into the furnace. This 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 this technique is that it increases the particulate loading to the mechanical collector and, hence, increases controlled PM emissions to the atmosphere. More recent boiler installations typically separate the collected PM 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 sent to disposal.

Varying the excess air in wood-fired boilers also influences uncontrolled emissions. Excess air in necessary for proper combustion. However, too much excess air can increase uncontrolled PM emissions (due to increased furnace gas velocities) and organic compound emissions (due to lower combustion temperatures and reduced combustion efficiency).

2.4 CONTROL TECHNOLOGIES[4,7,8]

The major emission of concern from wood-fired boilers is particulate matter. Other pollutants, particularly CO and TOC, may be emitted in significant amounts under poor boiler operating conditions.

2.4.1 PM Control

Currently, there are four primary control devices used to reduce particulate emissions: (1) mechanical collectors (MCs), (2) wet scrubbers, (3) electrostatic precipitators (ESPs), and (4) fabric filters.

Mechanical collectors, or cyclones, use centrifugal separation to remove PM from flue gas streams. At the entrance of the cyclone, a spin is imparted to the particle-laden gas. This spin creates a centrifugal force which causes the PM 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 (or multiclone), 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 operating parallel to the gas flow stream, with a common inlet and outlet header.

One variation of the multitube cyclone is to place two similar mechanical collectors in series. This system is often referred to as a dual or double mechanical collector. The first collector removes the bulk of the dust and the second removes smaller particles. The efficiency of this arrangement varies from 65 to 95 percent. Single mechanical collectors have been reported to have PM collection efficiencies of 20 to 60 percent.

Particulate emissions from wood-fired boilers are considered to be abrasive and can cause erosion within the mechanical collector. Such erosion reduces PM collection efficiency over time unless corrective maintenance procedures are employed.

A wet scrubber is a collection device which uses an aqueous stream or slurry to remove particulate and/or gaseous pollutants. There are three basic mechanisms involved with collecting particulate matter in wet scrubbers: interception, inertial impaction, and diffusion of particles on droplets. The interception and inertial impaction effects dominate at large particle diameters; the diffusion effects dominate at small particle diameters.

Wet scrubbers are usually classified by energy consumption (in terms of gas-phase pressure drop). Low-energy scrubbers, represented by spray chambers and towers, have pressure drops of less than 1 kPa (5 inches of water). Medium-energy scrubbers such as impingement scrubbers have pressure drops of 1 to 4 kPa (5 to 15 inches of water). High-energy scrubbers such as high- pressure-drop venturi scrubbers have pressure drops exceeding 4 kPa (15 inches of water). Greater removals of PM are usually achieved with higher-energy scrubbers.

Currently the most widely used wet scrubbers for wood-fired boilers are venturi scrubbers. In a typical venturi scrubber, the particle-laden gas first contacts the liquor stream in the core and throat of the venturi section. The gas and liquid streams then pass through the annular orifice formed by the core and throat, atomizing the liquid into droplets which are impacted by particles in the gas stream. Impaction results mainly from the high differential velocity between the gas stream and the atomized droplets. The droplets are then removed from the gas stream by centrifugal action in a cyclone separator and (if present) a mist eliminator section.

Wet scrubbers have reported PM collection efficiencies of 90 percent or greater. Operational problems can occur with wet scrubbers due to clogged spray nozzles, sludge deposits, dirty recirculation water, improper water levels, and unusually low pressure drops.

Gaseous emissions (e.g., SO_2 and organics) may also be absorbed to a significant extent in a wet scrubber. In addition, alkali compounds are sometimes utilized in the scrubber to prevent low pH conditions. If CO_2-generating compounds (such as sodium carbonate or calcium carbonate) are used, CO_2 emissions will increase.

Particulate collection in an ESP occurs in three steps: suspended 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 PM is dislodged from the collecting electrodes.

Charging of the particles to be collected is usually caused by ions produced in a high voltage direct current corona. The electric fields and the corona necessary for particle charging are provided by high voltage transformers and rectifiers. Removal of the collected PM is accomplished mechanically by rapping or vibrating the collecting electrodes. When applied to wood-fired boilers, ESPs are often used downstream of mechanical collector precleaners which remove larger-sized particles. Collection efficiencies of 93 to 99.8 percent for PM have been reported for ESPs operating on wood-fired boilers.

A variation of the ESP which has been applied to wood-fired boilers is the electrostatic gravel-bed filter (EGBF). This device 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 augments collection by impaction. The PM-laden media exits the bottom of the gravel-bed vessel and is pneumatically conveyed to a de-entrainment vessel through a vertical lift pipe. The PM is removed from the gravel media by the abrasion of media as it is conveyed up the lift pipe, by the scrubbing action of the air as it lifts the media, and by 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 PM is air conveyed to a storage silo where it is removed from the air stream by fabric filtration. PM collection efficiencies of 95 percent were reported for one EGBF operating on a wood-fired boiler.

In fabric filters (also known as baghouses), particulate-laden dust passes through a set of filters mounted inside the collector housing. Dust particles in the inlet air are retained on the filters 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 filters, while the sieving action of the dust layer accumulating on the fabric surface soon predominates. The sieving mechanism leads to high efficiency PM collection unless defects such as pinhole leaks or cracks appear in the filter cake.

Cleaning of the bag filters 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 air cleaning, backwash air is introduced to the bags to collapse them and fracture the dust cake. Both shaker cleaning and reverse air 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.

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 combustible carbonaceous fly ash. Steps can be taken to reduce this hazard, including the installation of a mechanical collector upstream of the fabric filter to remove large burning particles of fly ash (i.e., "sparklers"). Despite complications, fabric filters are generally preferred for boilers firing salt-laden wood. This fuel produces fine particulates with a high salt content. Fabric filters are normally preferred for fine particulate collection and the salt content of the particles has a quenching effect, thereby reducing fire hazards. In two tests of fabric filters operating on salt-laden wood-fired boilers, PM collection efficiencies were near 98.5 percent.

2.4.2 NO_x Control

NO_x emissions from wood-fired boilers are lower than those from coal-fired boilers due to the lower nitrogen content of wood and the lower combustion temperatures which characterize wood-fired boilers. For stoker and FBC boilers, overfire air ports may be used to lower NO_x emissions by staging combustion reactions. In those areas of the U.S. where NO_x emissions must be reduced to their lowest levels, the application of selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) to waste wood-fired boilers has either been accomplished (SNCR) or is being contemplated (SCR). Both systems are post-combustion NO_x reduction techniques in which ammonia (or urea) is injected into the flue gas to selectively reduce NO_x to nitrogen and water. In the SCR process, a catalyst is used to allow the reaction to take place at a lower temperature. The ammonia is injected and mixed with flue gas before the stream comes into contact with the catalyst. The SCR process is designed to treat flue gases in the 300 to 425 °C (575 to 800 °F) temperature range.

In the SNCR process, ammonia (or urea) is injected into the upper regions of the boiler so that the NO_x-reduction reactions take place without a catalyst at temperatures of 870 to 1,100 °C (1,600 to 2,000 °F). In one application of SNCR to an industrial wood-fired boiler, NO_x reduction efficiencies varied between 35 and 75 percent as the ammonia:NO_x ratio increased from 0.4 to 3.2.

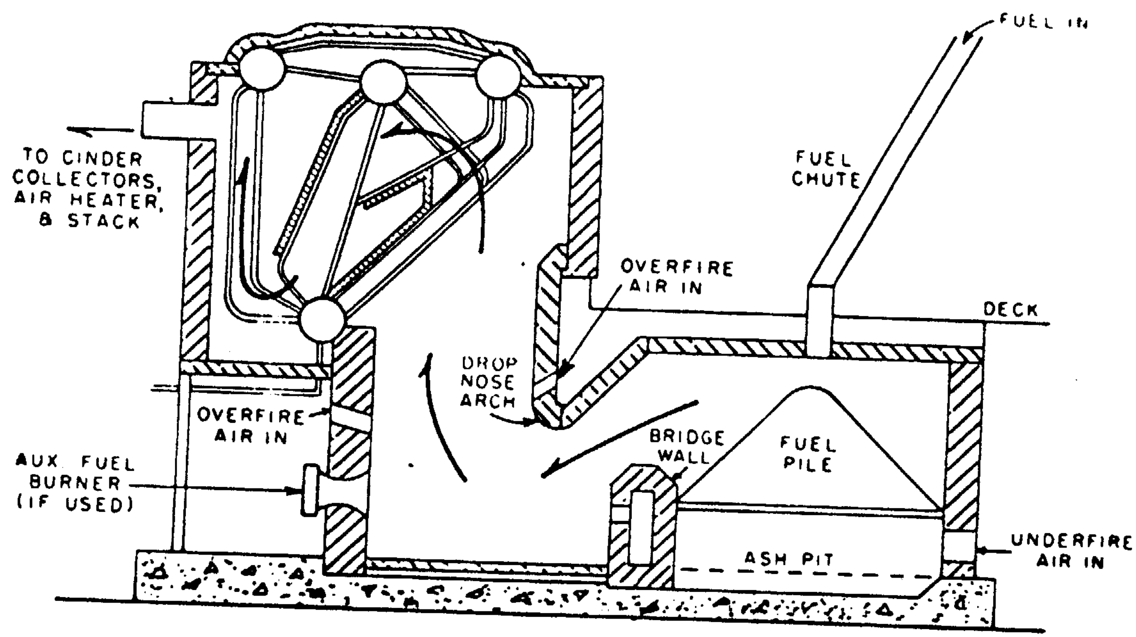

Figure 2-1. Cross-section for Dutch oven furnace and boiler.[5]

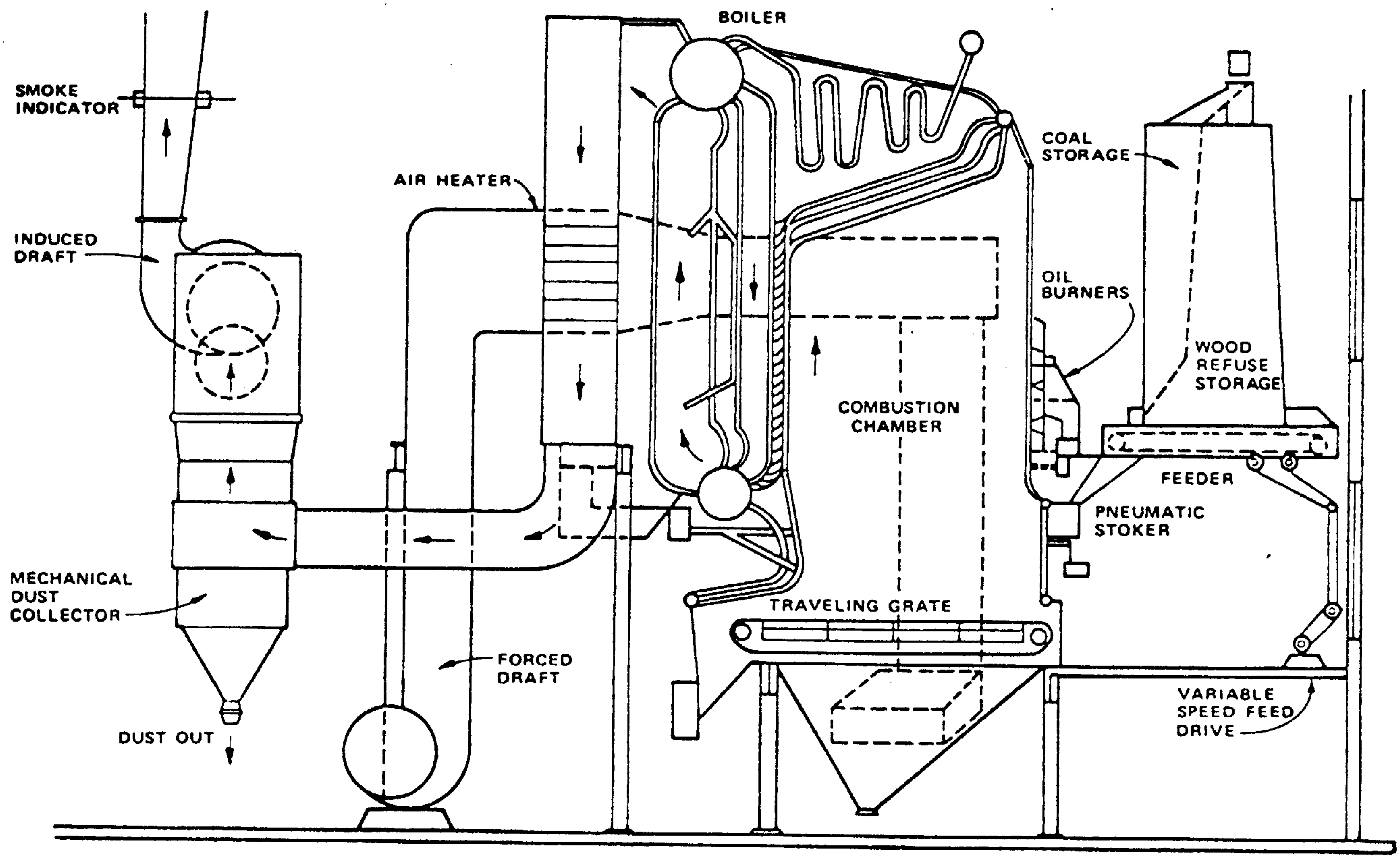

Figure 2-2. Typical spreader stoker boiler.[5]

TABLE 2-1. TYPICAL WOOD WASTE ANALYSES[4]

Parameter	Weight percent, as fired
Moisture	50.00
Ultimate Analysis	
Carbon	26.95
Hydrogen	2.85
Sulfur	0.02
Ash	1.00
Nitrogen	0.08
Oxygen	19.10
Heating Value	2,540 kcal/kg (4,560 Btu/lb)

REFERENCES FOR CHAPTER 2

1. Steam, 38th Edition, Babcock and Wilcox, New York, NY, 1972.

2. Atmospheric Emissions From the Pulp and Paper Manufacturing Industry, EPA-450/1-73-002, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1973.

3. C-E Bark Burning Boilers, C-E Industrial Boiler Operations, Combustion Engineering, Inc., Windsor, Connecticut, 1973.

4. Nonfossil Fuel Fired Industrial Boilers - Background Information, EPA-450/3-82-007, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1982.

5. Control of Particulate Emissions From Wood-Fired Boilers, EPA 340/1-77-026, U. S. Environmental Protection Agency, Washington, DC, 1977.

6. Background Information Document For Industrial Boilers, EPA 450/3-82-006a, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1982.

7. "Emission Control Technologies For Wood-Fired Boilers", E. Aul, Jr., and K. Barnett, Radian Corporation, Presented at the Wood Energy Conference, Raleigh, NC, October 1984.

8. "Noncatalytic Ammonia Injection For NO_x Reduction on a Waste Wood Fired Boiler", G. Moilanen, Sierra Environmental Engineers, Inc., Costa Mesa, California, and K. Price, C. Smith, and A. Turchina, Proctor & Gamble Company, Cincinnati, Ohio, Presented at the 80th Annual Meeting of the Air Pollution Control Association, New York, NY, June 1987.

3. GENERAL DATA REVIEW AND ANALYSIS PROCEDURES

3.1 LITERATURE SEARCH AND SCREENING

The first step of this investigation involved a search of available literature relating to criteria and noncriteria pollutant emissions associated with natural gas combustion. This search included the following sources:

- AP-42 background files;
- Files and dockets maintained by the Emission Standards Division (ESD) of the Office of Air Quality, Planning, and Standards (OAQPS) for relevant New Source Performance Standards (NSPSs) and National Emission Standards on Hazardous Air Pollutants (NESHAPs);
- "Locating and Estimating" reports available through EPA's Clearinghouse for Inventories and Emission Factors (CHIEF) bulletin board system;
- Particulate matter of less than ten microns in diameter (PM-10) "gap filling" documents in the OAQPS library;
- Publications available through EPA's Control Technology Center;
- Reports and project summaries from EPA's Office of Research and Development;
- Control Techniques Guideline documents generated by the ESD of OAQPS;
- Information in the Air Facility System (AFS) of EPA's Aerometric Information Retrieval System (AIRS);
- Handbook of Emission Factors, Parts I and II, Ministry of Health and Environmental Protection, The Netherlands;
- EPA's CHIEF and National Air Toxics Information Clearinghouse (NATICH);

- EPA databases, including SPECIATE, XATEF, and TSAR;
- Various EPA contractor reports; and
- Various files maintained by the Contractor.

To reduce the large amount of literature collected to a final group of references pertinent to this report, the following general criteria were used:

1. Emissions data must be from a primary reference:

a. Source testing must be from a referenced study that does not reiterate information from previous studies.

b. The document must constitute the original source of test data. For example, a technical paper was not included if the original study was contained in the previous document. If the exact source of the data could not be determined, the document was eliminated.

2. The referenced study must contain test results based on more than one test run.

3. The report must contain sufficient data to evaluate the testing procedures and source operating conditions (e.g., one-page reports were generally rejected).

A final set of reference materials was compiled after a thorough review of the pertinent reports, documents, and information according to these criteria.

3.2 EMISSION DATA QUALITY RATING SYSTEM[1]

As part of the Contractor's analysis of the emission data, the quantity and quality of the information contained in the final set of reference documents were evaluated. The following data were always excluded from consideration.

1. Test series averages reported in units that cannot be converted to the selected reporting units;

2. Test series representing incompatible test methods (i.e., comparison of EPA method 5 front-half with EPA method 5 front- and back-half);

3. Test series of controlled emissions for which the control device is not specified;

4. Test series in which the source process is not clearly identified and described; and

5. Test series in which it is not clear whether the emissions were measured before or after the control device.

Data sets that were not excluded were assigned a quality rating. The rating system used that specified by the OAQPS for the preparation of AP-42 sections. The data were rated as follows:

A--Multiple tests performed on the same source using sound methodology and reported in enough detail for adequate validation. These tests do not necessarily conform to the methodology specified in either the inhalable particulate (IP) protocol documents or the EPA reference test methods, although these documents and methods were certainly used as a guide for the methodology actually used.

B--Tests that were performed by a generally sound methodology but lack enough detail for adequate validation.

C--Tests that were based on an untested or new methodology or that lacked a significant amount of background data.

D--Tests that were based on a generally unacceptable method but may provide an order-of-magnitude value for the source.

The following criteria were used to evaluate source test reports for sound methodology and adaquate detail:

1. Source operation. The manner in which the source was operated was well documented in the report. The source was operating within typical parameters during the test.

2. Sampling procedures. The sampling procedures conformed to a generally acceptable methodology. If actual procedures deviated from accepted methods, the deviations are well documented. When deviations occurred, an evaluation was made of the extent such alternative procedures could influence the test results.

3. Sampling and process data. Adequate sampling and process data are documented in the report. Many variations can occur unnoticed and without warning during testing. Such variations can include wide deviations in sampling results. If a large spread between test results cannot be explained by information contained in the test report, the data are suspect and were given a lower rating.

4. Analysis and calculations. The test reports contain original raw data sheets. The nomenclature and equations used were compared to those (if any) specified by EPA to establish equivalency. The depth of review of the calculations was dictated by the reviewer's confidence in the ability and conscientiousness of the tester, which in turn was based on factors such as consistency of results and completeness of other areas of the test report.

3.3 PARTICLE SIZE DETERMINATION

There is no one method which is universally accepted for the determination of particle size. A number of different techniques can be used which measure the size of particles according to their basic physical properties. Since there is no "standard" method for particle size analysis, a certain degree of subjective evaluation was used to determine if a test series was performed using a sound methodology for particle sizing.

For pollution studies, the most common types of particle sizing instruments are cyclones and cascade impactors. Traditionally, cyclones have been used as a preseparator ahead of a cascade impactor to remove the larger particles. These cyclones are of the standard reverse-flow design whereby the flue gas enters the cyclone through a tangential inlet and forms a vortex flow pattern. Particles move outward toward the cyclone wall with a velocity that is determined by the geometry and flow rate in the cyclone and by their size. Large particles reach the wall and are collected. A series of cyclones with progressively decreasing cut-points can be used to obtain particle size distributions.

Cascade impactors used for the determination of particle size in process streams consist of a series of plates or stages containing either small holes or slits with the size of the openings decreasing from one plate to the next. In each stage of an impactor, the gas stream passes through the orifice or slit to form a jet that is directed toward an impaction plate. For each stage, there is a characteristic particle diameter that has a 50 percent probability of impaction. This characteristic diameter is called the cut-point (D_{50}) of the stage. Typically, commercial instruments have six to eight impaction stages with a backup filter to collect those particles which are either too small to be collected by the last stage or which are re-entrained off the various impaction surfaces by the moving gas stream.

3.4 EMISSION FACTOR QUALITY RATING SYSTEM

The quality of the emission factors developed from analysis of the test data was rated utilizing the following criteria:

A--Excellent: Developed only from A-rated test data taken from many randomly chosen facilities in the industry population. The source category is specific enough so that variability within the source category population may be minimized.

B--Above average: Developed only from A-rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industries. As in the A-rating, the source category is specific enough so that variability within the source category population may be minimized.

C--Average: Developed only from A- and B-rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. As in the A-rating, the source category is specific enough so that variability within the source category population may be minimized.

D--Below average: The emission factor was developed only from A- and B-rated test data from a small number of facilities, and there is reason to suspect that these facilities do not represent a random sample of the industry. There also may be evidence of variability within the source category population. Any limitations on the use of the emission factor are footnoted in the emission factor table.

E--Poor: The emission factor was developed from C- and D-rated test data, and there is reason to suspect that the facilities tested do not represent a random sample of the industry. There also may be evidence of variability within the source category population. Any limitations on the use of these factors are always clearly noted.

The use of these criteria is somewhat subjective and depends to an extent on the individual reviewer. Details of the rating of each candidate emission factor are provided in Chapter 4 of this report.

REFERENCES FOR CHAPTER 3

1. Technical Procedures for Developing AP-42 Emission Factors and Preparing AP-42 Sections (Draft), Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC, March 1992.

4. POLLUTANT EMISSION FACTOR DEVELOPMENT

This chapter describes the test data and methodology used to develop pollutant emission factors for wood waste combustion in boilers and furnaces.

4.1 REVIEW OF SPECIFIC DATA SETS

A total of 17 references were documented and reviewed during the literature search. These references are listed at the end of this chapter. The source data for this revision included emission data from the October 1986 version of AP-42 Section 1.6.

The following efforts were made to ensure that the selection and rating of the reference documents did not introduce bias in the data. One-half of references used (50 percent) were either compliance test reports or summaries of compliance test report results. Given the impetus for compliance testing, these reports would be expected to characterize facilities with various levels of maintenance, operation, and control. The other 50 percent of the references used in this report were classified as research or special study tests. In some cases, it could be reasoned that such studies would involve testing of facilities with above-average maintenance, operation, and control and would, therefore, not be representative of the industry. Rather than downgrade the ratings for these references, each reference was considered on its own merit.

The original group of 17 documents was reduced to a final set of 12 primary references utilizing the criteria outlined in Chapter 3. For the five reference documents not used, the reason(s) for rejection are summarized below:

Reference	Reason for rejection
13	Boiler modified after initial installation.
14	Averages could not be converted into selected reporting units.
15	Averages could not be converted into selected reporting units.
16	Wood co-fired with coal during test.
17	Wood co-fired with oil during test.

The following is a discussion of the data contained in each of the primary references used to develop candidate emission factors. Emission factors were developed in terms of weight of pollutant per megagram (or ton) of wood waste combusted, consistent with previous versions of AP-42 Section 1.6. It should be noted that the terms "controlled" and "uncontrolled" in this discussion are indicative of the location at which the measurements were made (i.e., downstream and upstream of an air pollution control device designed to remove the subject pollutant, respectively). If measurements were made downstream of a control device which was not specifically designed to remove the subject pollutant (e.g., trace organic compounds measured at the outlet of an electrostatic precipitator), the data are labelled as "after control device".

A summary of particulate matter (PM) and lead emissions data are contained in Table 4-1. Tables 4-2 and 4-3 present summaries of emissions data for NO_x, CO, CO_2, and TOC. Table 4-4 provides an overview of the data presented in Tables 4-1 through 4-3 that were used to develop corresponding emission factors. Tables 4-5 and 4-6 present overall summaries of the data used to develop emission factors for speciated organic compounds and trace elements (except lead), respectively.

4.1.1 Reference 1

This reference contained a summary of the results of testing on 11 wood- and bark-fired boilers. The testing was conducted in response to California Assembly Bill 25/88 to develop a test pool of air toxics data for wood-fired boilers. Particulate matter emission controls on tested boilers included cyclones, MCs, wet scrubbers, and ESPs. Emissions measured included PM, NO_x, CO, CO_2, total hydrocarbons (THC), speciated organic compounds, and trace elements. Sampling was conducted with EPA Method 5-front half for PM and trace elements. Other sampling and analysis was conducted according to the California Air Resources Board (CARB) Air Toxics Testing Manual. The data were consistent and complete but raw data sheets and other validation information were not included with the written communication transmitted; as a result, the data were assigned a B rating.

4.1.2 Reference 2

This reference reported the results of a study of CO emissions from wood-fired boilers. One of the boilers co-fired oil with wood during the test and hence was excluded from consideration for emission factor development. Of the other two boilers, one was controlled by a lime spray drying scrubber and the other by a variable throat venturi scrubber. The former scrubber used a slurry of lime to absorb SO_2 and hydrochloric acid (HCl) from combustion flue gases. Certified continuous emission monitors (CEMs) were used to collect the CO data. Due to a lack of raw data sheets and other validation information, the data were assigned a B rating.

4.1.3 Reference 3

Reference 3 contained the results of a study of VOC data from four wood-fired boilers. Particulate matter control equipment included MCs followed by venturi scrubbers and multiple sets of MCs in series. Collected data included methane, non-methane VOC, and CO. The VOC data were not used because they were collected using a reduction method that reported the VOC as total methane. Carbon monoxide data were used since they were obtained with an appropriate CEM; they were assigned an A rating.

4.1.4 Reference 4

This reference reported the results of a study of emissions of polycyclic organic matter (POM) from industrial wood-fired boilers. Seven boilers were tested; boilers were either uncontrolled or controlled for PM using MCs. Total PM and a variety of speciated organic compounds were measured. Analysis of speciated organics was performed by a non-standard gas chromatography (GC) method and by gas chromatography/mass spectroscopy (GC/MS). Only the data obtained via GC/MS were used for emission factor development. These were assigned a B rating due to a lack of complete documentation.

4.1.5 Reference 5

Reference 5 reported the results of a study of formaldehyde emissions from wood residue-fired boilers. Seven boilers were tested but the results from three sites were excluded from consideration for the following reasons: coal was co-fired with wood at Site 2; the boiler fuel at Site 4 was known to contain a formaldehyde-based resin; and all formaldehyde samples from Site 5 failed data acceptability criteria. Particulate matter controls on the remaining four boilers consisted of a wet scrubber and three ESPs. Data for CO were obtained using certified CEMs. Data for formaldehyde were collected using EPA Method 5 sampling methodology. Analyses of the water impinger catches were performed with the chromotropic acid, acetylacetone, and pararosaniline procedures. Where multiple procedures were used, the results were averaged. The results were generally complete and consistent but did not include raw data sheets and other validation information; as a result, the data were assigned a B rating.

4.1.6 Reference 6

Reference 6 was a compliance test report on a new wood-fired boiler operating with a MC for PM control (with flyash reinjection). Data collected for an older boiler operating at this site were not suitable for emission factor development due to a lack of supporting information. Emission test results reported for the "good combustion periods" were utilized. Testing results included CO, NO_x, CO_2, and THC measured by lab-certified CEMs. Particulate matter, trace elements, and speciated organics were collected by EPA Modified Method 5. Trace elements were analyzed by inductively-coupled argon plasma spectrometry (ICAP), except for arsenic and selenium which required graphite furnace absorption spectrometry (GF/AA). Formaldehyde was analyzed by EPA Method 8315. Benzene was collected on charcoal tubes and analyzed by GC/flame ionization detector (FID). Organic species were analyzed with EPA Method 8270. The data were assigned an A rating.

4.1.7 Reference 7

Reference 7 reported the results of a study of dioxin/furan emissions from a wood-fired boiler equipped with a MC and baghouse in series. Flyash was not reinjected into the test boiler but was injected into other boilers at the site. Test data for NO_x, CO, CO_2, and THC were collected via certified CEMs. Dioxins and furans were sampled using EPA Modified Method 5; analyses were performed via high resolution GC/MS. The data were assigned an A rating.

4.1.8 Reference 8

This reference contained the results of testing of a wood-fired boiler which originally was designed for coal feed but had been modified to burn wood chips. One test series was conducted while the boiler combusted dry wood chips and a second series was conducted with the boiler operating on green wood chips. The emissions data from the two test series were combined and averaged to yield an overall average emission factor for each pollutant measured. Air pollution control equipment on this boiler consisted of two sets of overfire air ports which were used for NO_x control and a mechanical collector for PM control. Certified CEMs were utilized to obtain NO_x and CO data. Particulate matter data were collected with EPA Modified Method 5. Speciated organic compounds were collected with a source assessment sampling system (SASS). Total organic compounds were measured on-site using gas chromatography; speciated organic compounds were analyzed using infrared spectroscopy (IR), GC/MS, and liquid chromatography (LC). Trace elements were collected via grab sample and analyzed using spark source mass spectroscopy (SSMS) and atomic absorption spectroscopy (AA). The data were consistent and complete with appropriate validation information; an A rating was assigned.

4.1.9 References 9 and 10

Reference 9 was a compliance test report for two parallel wood-fired boilers equipped with ESPs; after passing through the two ESPs, the flue gases from each boiler were joined and exhausted to a common stack where emissions data were collected. Compliance test data were reported in Reference 10 for a wood waste-fired boiler equipped with a MC and ESP for PM control and an ammonia injection system for NO_x control. Certified CEMs were used to obtain data for NO_x, CO, CO_2, and THC. Particulate matter data were collected with EPA Method 5 while trace element data were collected using EPA Modified Method 5. Speciated organic compounds were analyzed using GC/electron capture detector (ECD), GC/FID, and GC/PID. These methods provide reasonable detection limits but speciation is limited; GC/MS is the preferred method. As a result, the speciated organic compound data were assigned a B rating while all other reported data were assigned an A rating.

4.1.10 References 11 and 12

Reference 11 contained the results of an emissions test of a bark-fired boiler equipped with a MC and ESP operated in series. In Reference 12, a bark-fired boiler equipped with a cyclone (with flyash reinjection) and a variable throat venture scrubber was tested. The data in these reports were collected to support the development of new source performance standards for wood-fired boilers. Certified CEMs were used to obtain data for NO_x, CO, and CO_2. Selected trace elements were sampled using EPA Method 5 and analyzed using AA. The data were assigned an A rating.

4.2 RESULTS OF DATA ANALYSIS

This section discusses the development of emission factors for tested pollutants based on the data contained in the reference documents described above. In all cases, emission factors were developed using manual and computer spreadsheet manipulation of emission data and factors expressed in units other than the mass of pollutant per megagram (or ton) of wood waste combusted.

In some cases, new test data were not utilized if they did not improve the rating of an existing emission factor. In addition, no new data were located which could be used to revise the existing emission factors for the following source categories:

- For PM emissions from bark-fired boilers,
  - Uncontrolled boilers
  - Multiclone, with flyash reinjection (FR)
  - Multiclone, without FR
- For PM emissions from wood/bark-fired boilers,
  - Uncontrolled boilers
  - Multiclone, with FR
  - Multiclone, without FR

- For PM emissions from wood-fired boilers,
  - Uncontrolled boilers.

Thus, the same PM emission factors for these boilers (which have overall ratings or B and C) will continue to be used in this revision of AP-42 Section 1.6.

Summaries of developed emission factors for tested pollutants are shown in Tables 4-4, 4-5, and 4-6. All boiler size values discussed refer to output steam production.

4.2.1 Filterable Particulate Matter

Following the organization of PM emission factors specified in the 1986 version of AP-42 Section 1.6, the available new PM test data were categorized according to type of wood waste burned: bark, wood/bark mixture, and wood. This is a logical organization for PM emissions because bark may contain 70 weight percent moisture, sand, and other non-combustibles. As a result, bark-fired boilers may emit considerably greater amounts of particulate matter than wood-fired boilers, or boilers firing a mixture of bark and wood.

For wood/bark-fired boilers, new data were available for boilers controlled by wet scrubbers and by ESPs. New test data were also available for wood-fired boilers controlled by mechanical collectors and ESPs. These categories of controlled boilers were not included in the previous version of Section 1.6.

Test data for three wood/bark-fired boilers controlled by wet scrubbers were available from the emission test summaries in Reference 1. These included a Dutch oven boiler and two stoker boilers ranging in size from 17,000 to 53,000 kg steam/hr (37,000 to 118,000 lb steam/hr). Data for four boilers controlled by ESPs were available from the Reference 1 summary. Steam output from the three stoker boilers and one FBC boiler ranged from 41,000 to 75,200 kg/hr (92,000 to 167,000 lb/hr).

For the six wood-fired boilers controlled by mechanical collectors (either cyclones or multiclones), data were obtained from References 4, 6, and 8. Two boilers controlled with ESPs were evaluated in References 9 and 10. The size range for all wood-fired boilers was 11,000 to 94,000 kg steam/hr (25,000 to 209,000 lb steam/hr).

No condensible PM data were encountered during this update.

4.2.2 Particulate Matter Below 10 Microns (PM-10)

New PM-10 data were located for one wood-fired boiler controlled with a mechanical collector. As discussed in Reference 8, this was a stoker boiler rated at 11,200 kg steam/hr (25,000 lb steam/hr). The remaining PM-10 emission factors shown in Table 4-1 were derived from the PM emission factors and particle size distribution data presented in Reference 18.

4.2.3 Lead

Lead emission factors are included in the table with PM and PM-10 emission factors because they are a priority pollutant associated with the particulate fraction of flue gas emissions from boilers. Lead emissions data were obtained for one uncontrolled bark-fired boiler (Reference 11), one wood/bark-fired boiler controlled with a mechanical collector (Reference 11), one wood-fired boiler controlled with a mechanical collector (Reference 8), and two wood-fired boilers controlled with ESP (References 9 and 10). These boilers included both stoker and FBC boilers rated between 11,000 and 94,000 kg steam/hr (25,000 and 209,000 lb steam/hr).

4.2.4 Nitrogen Oxides

For NO_x, and other pollutants discussed below, boiler design type has more influence on emissions levels than the distinction between bark and wood fuels. Thus, NO_x and other pollutant emission factors have been organized according to the three major types of combustor designs encountered in the test data: fuel cell/Dutch oven (FC/DO), stoker (includes air suspension), and FBC. Fuel cells and Dutch ovens were combined into one category due to the similarity of their design and operating features, as discussed in Chapter 2. Spreader stoker and air suspension boilers were combined for the same reason.

For FC/DO boilers, two new sets of test data were combined with 7 sets of existing data in Reference 18. The nine boilers ranged in size from 2,000 to 45,000 kg steam/hr (4,000 to 100,000 lb steam/hr). None of the boilers were equipped with explicit NO_x control systems.

A total of 12 data sets were available for stoker boilers: two new data sets and ten existing data sets. None of these boilers were equipped with explicit NO_x control systems although nearly all were equipped with underfire and overfire air systems, which can be used to effect partially staged combustion and hence lower NO_x emissions. Since overfire and underfire air systems are integral to the design and operation of stoker boilers, they were not considered to be explicit NO_x control techniques. Rated boiler capacities ranged from 11,000 to 180,000 kg steam/hr (25,000 to 400,000 lb steam/hr).

Nitrogen oxide test data were available for two FBC boilers -- one controlled and one uncontrolled. The controlled boiler included an ammonia injection system designed to reduce NO_x emission levels in the boiler flue gases. These controlled test data came from a 94,000 kg steam/hr (209,000 lb steam/hr) boiler in Reference 10 which the uncontrolled test data were taken from a 16,000 kg steam/hr (36,000 lb steam/hr) boiler reported in Reference 18.

4.2.5 Carbon Monoxide

In almost all cases where NO_x test data were reported, data were also reported for CO. Although some NO_x control techniques may increase CO emissions, the only NO_x control system encountered in the test data was an ammonia injection system, which does not materially affect CO (nor CO_2 or THC) emissions. Thus all CO data were considered to be uncontrolled; measurements were taken downstream of a PM control device, however.

New test data were available from six FC/DO boilers (References 1,6, and 7); 19 stoker boilers (References 1, 2, 3, 5, 8, and 9); and two FBC boilers. Rated capacities ranged from 3,000 to 248,000 kg steam/hr (6,000 to 550,000 lb steam/hr).

4.2.6 Total Organic Compounds

In almost all cases, total organic compounds were measured as total hydrocarbons emissions using a CEM. Measurements were converted from a volume basis to a weight basis using the molecular weight of propane.

New test data were available from four FC/DO boilers (References 1 and 7) and seven stoker boilers (References 1, 9, and 10). Rated capacities ranged from 3,000 to 94,000 kg steam/hr (6,000 to 209,000 lb steam/hr).

4.2.7 Carbon Dioxide

New CO_2 test data were available for five FC/DO boilers (References 1 and 7);

nine stoker boilers (References 1, 9, 11, and 12); and two FBC boilers (References 1 and 10). These boilers ranged in size from 3,000 to 94,000 kg steam/hr (6,000 to 209,000 lb steam/hr). In general, CO_2 emissions are expected to vary with the amount of carbon in the wood fired, which changes slightly from location to location.

4.2.8 Speciated Organic Compounds

Speciated organic compounds are either present in the wood fed to the boiler or are formed as products of incomplete combustion within the boiler combustion and cooling zones. Thus, boiler design type might be expected to have an influence on emissions of speciated organics. When emissions data for various organic compounds were grouped by boiler design type, however, the data displayed considerable overlap, indicating poor correlation with boiler design type. For this reason, speciated organic compounds were not grouped by boiler design type but instead were averaged over all boiler types and fuel types for purposes of emission factor development. Emission factors for most speciated organic compounds span the range of boiler types and rated capacities discussed above.

4.2.9 Trace Elements

As with speciated organic compounds, attempts were made to correlate reported trace element emission levels with boiler design types and fuel types (i.e., bark and wood). As with speciated organic compounds, however, the data sets displayed such large overlaps and poor correlation that this type of categorization was abandoned. Instead, trace element emission factors were calculated based on all the test data available for a given element. As such, the factors for most elements spanned the range of boiler types and rated capacities discussed above.

4.3 PROTOCOL FOR DATA BASE

4.3.1 Engineering Methodology

The 17 references discussed in Section 4.1 were thoroughly reviewed to establish a data base for the pollutants discussed above. Data rating forms (see Appendix A) were created to facilitate the evaluation of exclusion criteria, methodology/detail criteria, and data rating criteria. These forms were completed for each reference to document the rationale for either excluding the reference from emission factor development consideration or for including the reference and assigning ratings to relevant source test data.

The emissions data from source test reports were averaged as the arithmetic mean of different sampling runs prior to inclusion in the data base. Test programs at most facilities consisted of at least three sampling runs conducted during distinct time periods under normal operating conditions for the systems tested.

Due to the variety of formats used to report units of measure at different wood waste combustors, the emission data required some processing to standardize the units of measure prior to calculation of emission factors. Average emission factors were then calculated in terms of kg/Mg (or lb/ton) of wood waste combusted for all pollutants based on the arithmetic average of collected data. A list of conversion factors used in the test data processing is included in Table 4-7.

In many cases it was necessary to convert data expressed in terms of lb pollutant/million Btu or parts per million by volume (ppmv) to kg pollutant /Mg wood waste (or lb pollutant/ton wood waste). Based on the information contained in References 1 through 12, this conversion was made using an average wood waste heating value of 2,500 kcal/kg (4,500 Btu/lb) wet fuel and average moisture content of 50 weight percent, except in cases where the fuel heating value and moisture content were specified in the reference. In addition, F-Factors of 9,240 dry standard ft^3/million Btu (dscf/10^6 Btu) for wood-fired boilers and 9,600 dscf/10^6 Btu for wood/bark-fired boilers were utilized.[19] These factors were adjusted from 0 percent O_2 to other O_2 flue gas concentrations using the equations:

$$F_{wood} = 9{,}240 \text{ dscf}/10^6 \text{ Btu } [20.9/(20.9\text{-}\%O_{2d})]$$

and

$$F_{bark} = 9{,}600 \text{ scf}/10^6 \text{ Btu } [20.9/(20.9\text{-}\%O_{2d})]$$

where $\%O_{2d}$ is the flue gas O_2 content measured on a dry basis.

Determinations of emission factors were made only when wood waste feed rates were documented or derivable from plant records.

Quality control and quality assurance procedures were used to assure that the data base accurately reflected the reported test data. Each data rating form was checked by a second reviewer to assure accurate documentation of reference exclusion or emission data rating criteria. In addition, manual and spreadsheet calculations were spot checked by a second reviewer to assure accurate documentation of reported emission and process data prior to calculation of overall average emission factors. After emission tables were generated, a final comparison was made between randomly selected test reports, their associated data rating forms, and the produced emission table to assure the quality of the data acquisition and associated calculations.

TABLE 4-1. SUMMARY OF EMISSION FACTORS FOR PM, PM-10, AND LEAD

Source category	Filterable PM[a], kg/Mg (lb/ton)/ rating/reference	PM-10, kg/Mg (lb/ton)/ rating/reference	Lead, kg/Mg (lb/ton/ rating/reference
Bark-fired boilers			
Uncontrolled		8.4 (16.8),b,20	1.5E-3 (2.9E-3),a,11
Controlled			
MC with FR		5.5 (11.0),b,20	
MC without FR		1.6 (3.2),b,20	
Wet scrubber		1.3 (2.5),b,20	
Wood/bark-fired boilers			
Uncontrolled		3.3 (6.5),d,18	
Controlled			
MC with FR		2.8 (5.5),d,20	1.7E-04 (3.4E-4),a,11
MC without FR		0.9 (1.7),d,20	1.5E-5 (3.0E-5),b,1 3.9E-4 (7.7E-4),b,1 6.5E-5 (1.3E-4),b,1
Wet scrubber	0.38 (0.75),b,1 0.14 (0.27),b,1 0.22 (0.43),b,1	0.22 (0.43),d,20	2.9E-4 (5.8E-4),b,1 1.8E-4 (3.5E-4),b,1 6.5E-5 (1.3E-4),b,1
ESP	0.01 (0.02),b,1 0.01 (0.02),b,1 0.01 (0.02),b,1 0.04 (0.08),b,1		0.7E-6 (1.4E-5),b,1 8.0E-6 (1.5E-5),b,1 8.0E-6 (1.5E-5),b,1 1.0E-5 (2.0E-5),b,1
Wood-fired boilers			
Controlled			
MC without FR	2.2 (4.3),a,4 1.6 (3.2),b,4 1.3 (2.6),b,4 1.8 (3.6),a,6 3.6 (7.2),a,8	2.2 (4.4),a,8	1.6E-4 (3.1E-4),a,8
ESP	0.11 (0.21),a,9 0.06 (0.12),a,10		3.2E-5 (6.4E-5),a,9 1.1E-3 (2.1E-3),a,10

[a]Filterable PM is that particulate collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.
MC = Mechanical collector
FR = Flyash reinjection
ESP = Electrostatic precipitator

TABLE 4-1. SUMMARY OF EMISSION FACTORS FOR PM, PM-10, AND LEAD

Source category	Filterable PM[a], kg/Mg (lb/ton)/ rating/reference	PM-10, kg/Mg (lb/ton)/ rating/reference	Lead, kg/Mg (lb/ton/ rating/reference
Bark-fired boilers			
Uncontrolled		8.4 (16.8),b,20	1.5E-3 (2.9E-3),a,11
Controlled			
MC with FR		5.5 (11.0),b,20	
MC without FR		1.6 (3.2),b,20	
Wet scrubber		1.3 (2.5),b,20	
Wood/bark-fired boilers			
Uncontrolled		3.3 (6.5),d,18	
Controlled			
MC with FR		2.8 (5.5),d,20	1.7E-04 (3.4E-4),a,11
MC without FR		0.9 (1.7),d,20	1.5E-5 (3.0E-5),b,1 3.9E-4 (7.7E-4),b,1 6.5E-5 (1.3E-4),b,1
Wet scrubber	0.38 (0.75),b,1 0.14 (0.27),b,1 0.22 (0.43),b,1	0.22 (0.43),d,20	2.9E-4 (5.8E-4),b,1 1.8E-4 (3.5E-4),b,1 6.5E-5 (1.3E-4),b,1
ESP	0.01 (0.02),b,1 0.01 (0.02),b,1 0.01 (0.02),b,1 0.04 (0.08),b,1		0.7E-6 (1.4E-5),b,1 8.0E-6 (1.5E-5),b,1 8.0E-6 (1.5E-5),b,1 1.0E-5 (2.0E-5),b,1
Wood-fired boilers			
Controlled			
MC without FR	2.2 (4.3),a,4 1.6 (3.2),b,4 1.3 (2.6),b,4 1.8 (3.6),a,6 3.6 (7.2),a,8	2.2 (4.4),a,8	1.6E-4 (3.1E-4),a,8
ESP	0.11 (0.21),a,9 0.06 (0.12),a,10		3.2E-5 (6.4E-5),a,9 1.1E-3 (2.1E-3),a,10

[a]Filterable PM is that particulate collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.
MC = Mechanical collector
FR = Flyash reinjection
ESP = Electrostatic precipitator

TABLE 4-2. EMISSION FACTORS FOR NO_x AND CO

›urce category	NO_x[a] kg/Mg (lb/ton)/ rating/reference	CO, kg/Mg (lb/ton)/ rating/reference
‹/DO boilers[b]		
	0.47 (0.94),a,6	1.9 (3.9),a,6
	0.0017 (0.0033),a,7	1.0 (2.1),a,7
	0.10 (0.20),a,18	0.32 (0.65),b,1
	0.10 (0.20),a,18	10.5 (21.1),b,1
	0.10 (0.20),a,18	1.8 (3.6),b,1
	0.8 (1.5),a,18	4.1 (8.3),b,1
	0.10 (0.20),a,18	
	0.04 (0.08),a,18	
	0.04 (0.08),a,18	
›ker boilers[b]		
	1.8 (3.6),a,8	40.2 (80.4),a,8
	0.7 (1.3),a,9	8 (16),a,9
	0.6 (1.1),a,18	0.9 (1.9),b,1
	0.6 (1.2),a,18	6.2 (12.4),b,1
	0.33 (0.66),a,18	4.8 (9.7),b,1
	0.6 (1.2),a,18	2.4 (4.8),b,1
	0.9 (1.9),a,18	1.3 (2.6),b,1
	0.8 (1.5),a,18	13.5 (27.1),b,1
	0.8 (1.5),a,18	2.2 (4.5),b,2
	0.49 (0.97),a,18	1.9 (3.9),b,2
	0.8 (1.7),a,18	14.6 (29.3),a,3
	0.9 (1.9),a,18	9.7 (19.4),a,3
		5.0 (10.0),a,3
		4.2 (8.5),a,3
		1.7 (3.4),b,5
		3.2 (6.5),b,5
		4.5 (9.0),b,5
		3.0 (6.1),b,5
		1.3 (2.6),b,5
‹ boilers		
›controlled	1.0 (2.0),a,18	1.19 (2.39),b,1

O_2.
ntrolled boilers.
) = Fuel cell/Dutch oven
Fluidized bed combustion

TABLE 4-4. SUMMARY OF WOOD WASTE COMBUSTION EMISSION DATA FOR PM, PM-10, LEAD, NO_x, CO, TOC, AND CO_2

Pollutant/source	No. of data points	Data ratings	Emission factor range		Average emission factor		Emission factor rating	Reference number
			kg/Mg	lb/ton	kg/Mg	lb/ton		
<u>Filterable PM</u>								
Wood/bark-fired boilers								
Controlled								
Wet scrubber	3	b	0.13-0.37	0.27-0.75	0.24	0.48	D	1
ESP	4	b	0.01-0.04	0.02-0.08	0.02	0.04	D	1
Wood-fired boilers								
Controlled								
MC without FR	5	a,b	1.8-3.6	3.6-7.2	2.1	4.2	C	6,8
ESP	2	a	0.6-0.10	0.12-0.21	0.08	0.17	D	9,10
<u>PM-10</u>								
Bark-fired boilers								
Uncontrolled	1	b		-	8.5	17	D	20
Controlled								
MC with FR	1	b		-	5.5	11	D	20
MC without FR	1	b		-	1.6	3.2	D	20
Wet scrubber	1	b		-	1.3	2.5	D	20
Wood/bark-fired boilers								
Uncontrolled	1	d		-	3.2	6.5	E	20

TABLE 4-4. SUMMARY OF WOOD WASTE COMBUSTION EMISSION DATA FOR PM, PM-10, LEAD, NO_x, CO, TOC, AND CO_2 (Continued)

Pollutant/source	No. of data points	Data ratings	Emission factor range		Average emission factor		Emission factor rating	Reference number
			kg/Mg	lb/ton	kg/Mg	lb/ton		
Controlled								
MC with FR	1	d		-	2.7	5.5	E	20
MC without FR	1	d		-	0.8	1.7	E	20
Wet scrubber	1	d		-	0.23	0.47	E	20
Wood-fired boilers								
Controlled								
MC without FR	1	a		-	1.3	2.6	D	8
<u>Lead</u>								
Bark-fired boilers								
Uncontrolled	1	a		-	1.4E-3	2.9E-3	D	11
Wood/bark-fired boilers								
Controlled								
MC	4	a,b	1.3E-5-3.9E-4	2.5E-5-7.7E-4	1.6E-4	3.2E-4	D	1,11
Wet scrubber	3	b	7.0E-5-2.9E-4	1.3E-4-5.8E-4	1.8E-4	3.5E-4	D	1
ESP	4	b	7.0E-6-1.0E-5	1.4E-5-2.0E-5	8.0E-6	1.6E-5	D	1
Wood-fired boilers								
Controlled								
MC without FR	1	a		-	1.5E-4	3.1E-4	D	8
ESP	2	a	3.2E-5-1.0E-03	6.4E-5-2.1E-3	5.5E-4	1.1E-3	D	9,10

TABLE 4-4. SUMMARY OF WOOD WASTE COMBUSTION EMISSION DATA FOR PM, PM-10, LEAD, NO_x, CO, TOC, AND CO_2 (Continued)

Pollutant/source	No. of data points	Data ratings	Emission factor range		Average emission factor		Emission factor rating	Reference number
			kg/Mg	lb/ton	kg/Mg	lb/ton		
Nitrogen oxides								
FC/DO boilers After PM control device	9	a	0.0016-0.7	0.0033-1.5	0.19	0.38	C	6,7,18
Stoker boilers After PM control device	12	a	0.33-1.8	0.66-3.6	0.7	1.5	C	8,9,18
FBC boilers After PM control device	1	a		-	1.0	2.0	D	18
Carbon monoxide								
FC/DO boiler After PM control device	6	a,b	0.32-10.5	0.65-21.1	3.3	6.6	C	1,6,7
Stoker boiler After PM control device	19	a,b	0.9-40.2	1.9-80.4	6.8	13.6	C	1,2,3,5,8,9
FBC boiler After PM control device	2	a,b	0.23-1.19	0.47-2.39	0.7	1.4	D	1,10
Total organic compounds								
FC/DO boilers After PM control device	4	a,b	0.011-0.23	0.023-0.46	0.9	0.18	C	1,7
Stoker After PM control device	7	a,b	0.009-0.33	0.019-0.67	0.11	0.22	C	1,9,10

TABLE 4-4. SUMMARY OF WOOD WASTE COMBUSTION EMISSION DATA FOR PM, PM-10, LEAD, NO_x, CO, TOC, AND CO_2 (Continued)

Pollutant/source	No. of data points	Data ratings	Emission factor range		Average emission factor		Emission factor rating	Reference number
			kg/Mg	lb/ton	kg/Mg	lb/ton		
Carbon dioxide								
FC/DO boilers								
After PM control device	5	a,b	715-1080	1430-2160	950	1900	B	1,10
Stoker boilers								
After PM control device	9	a,b	850-1175	1700-2350	1000	2000	B	1,9,11,12
FBC boilers								
After PM control device	2	b	780-985	1560-1970	900	1800	B	1,10

MC = Mechanical collector
FR = Flyash reinjection
ESP = Electrostatic precipitator
FC/DO = Fuel cell/Dutch oven
FBC = Fluidized bed combustion

TABLE 4-5. SUMMARY OF WOOD WASTE COMBUSTION EMISSION DATA FOR SPECIATED ORGANIC COMPOUNDS

Organic compound[a]	No. of data points	Data ratings	Emission factor range, kg/Mg (lb/ton)	Average emission factor, kg/Mg (lb/ton)	Emission factor rating	Reference number
Formaldehyde	15	a,b	1.1E-4-1.6E-2 (2.3E-4-3.3E-2)	3.3E-3 (6.6E-3)	C	1,5,6
Acetaldehyde	12	a,b	3.0E-5-1.2E-2 (6.1E-5-2.4E-2)	1.5E-3 (3.0E-3)	C	1,6,9
Benzene	11	a,b	4.3E-5-7.0E-3 (8.6E-5-1.4E-2)	1.8E-3 (3.6E-3)	C	1,6
Phenols	4	a,b	3.2E-5-6.0E-5 (6.4E-5-1.2E-4)	1.9E-4 (3.9E-4)	C	1,8
Naphthalene	12	a,b	2.5E-5-2.9E-3 (5.0E-5-5.8E-3)	1.2E-3 (2.3E-3)	C	1,4,8,10
Acenaphthene	7	a,b	4.3E-8-2.1E-6 (8.6E-8-4.3E-6)	1.7E-6 (3.4E-6)	C	1,8
Flourene	10	a,b	9.0E-8-1.4E-5 (1.7E-7-2.8E-5)	4.8E-6 (9.6E-6)	C	1,8
Phenanthrene	11	a,b	1.0E-6-9.0E-5 (2.0E-6-1.8E-4)	2.8E-5 (5.7E-5)	C	1,8
Anthracene	10	a,b	4.3E-8-1.7E-4 (8.6E-8-3.5E-4)	1.9E-5 (3.8E-5)	C	1,4,8
Fluoranthene	14	a,b	4.3E-8-4.3E-4 (8.6E-8-8.6E-4)	4.5E-5 (9.0E-5)	C	1,4,8
Pyrene	10	b	2.1E-7-2.9E-5 (4.3E-7-5.9E-5)	8.5E-6 (1.7E-5)	C	1
Benzo (a)anthracene	4	b	4.3E-8-3.2E-6 (8.6E-8-6.4E-6)	9.0E-7 (1.8E-6)	C	1
Benxo (b+k)fluoranthene	7	a,b	1.7E-7-9.5E-5 (3.4E-7-1.9E-4)	1.4E-5 (2.9E-5)	C	1,4,8
Benzo (a)pyrene	2	a,b	4.3E-8-1.5E-7 (8.6E-8-3.0E-7)	9.5E-8 (1.9E-7)	D	1,12
Benzo (g,h,i)perylene	4	b	4.3E-8-1.7E-6 (8.6E-8-3.5E-6)	6.0E-7 (1.2E-6)	C	1
Chrysene	7	a,b	4.3E-8-1.5E-4 (8.6E-8-3.0E-4)	2.1E-5 (4.3E-5)	C	1,4,8
Indeno (1,2,3,c,d)pyrene	2	b	4.3E-8-3.0E-7 (8.6E-8-6.0E-7)	1.7E-7 (3.4E-7)	D	1
2,3,7,8-Tetrachlorodibenzo-p-dioxin	2	a,b	1.1E-11-2.6E-11 (2.1E-11-5.1E-11)	1.8E-11 (3.6E-11)	D	1,10
Polychlorinated dibenzo-p-dioxins	6	a,b	1.5E-9-1.7E-8 (3.0E-9-3.3E-8)	6.0E-9 (1.2E-8)	C	1,9
Polychlorinated dibenzo-p-furans	8	a,b	2.3E-9-1.2E-7 (4.6E-9-2.3E-7)	2.7E-8 (5.3E-8)	C	1,7,9,10
Acenaphthylene	10	a,b	3.0E-7-3.4E-5 (6.0E-7-6.8E-5)	2.2E-5 (4.4E-5)	C	1,8
Pyrene	1	a	-	4.5E-6 (9.0E-6)	D	8

TABLE 4-5. SUMMARY OF WOOD WASTE COMBUSTION EMISSION DATA FOR SPECIATED ORGANIC COMPOUNDS (Continued)

Organic compound[a]	No. of data points	Data ratings	Emission factor range, kg/Mg (lb/ton)	Average emission factor, kg/Mg (lb/ton)	Emission factor rating	Reference number
Methyl anthracene	1	b	-	7.0E-5 (1.4E-4)	D	4
Acrolein	1	a	-	2.0E-6 (4.0E-6)	D	6
Solicyladehyde	1	a	-	1.1E-5 (2.3E-5)	D	6
Benzoaldehyde	1	a	-	6.0E-6 (1.2E-5)	D	6

[a] After PM control device.

TABLE 4-6. SUMMARY OF WOOD WASTE COMBUSTION EMISSION DATA FOR TRACE ELEMENTS

Trace element[a]	No. of data points	Data ratings	Emission factor range, kg/Mg (lb/ton)	Average emission factor, kg/Mg (lb/ton)	Emission factor rating	Reference number
Arsenic	11	a,b	7.0E-7-1.2E-4 (1.4E-6-2.4E-4)	4.4E-5 (8.8E-5)	C	1,6,9,10
Beryllium	11	b	-	BDL	-	1
Cadmium	12	a,b	1.3E-6-2.7E-4 (2.7E-6-5.4E-4)	8.5E-6 (1.7E-5)	C	1,8,10
Chromium	14	a,b	3.0E-6-2.3E-4 (6.0E-6-4.6E-4)	6.5E-5 (1.3E-4)	C	1,8,9,10
Chromium (VI)	3	b	1.5E-5-2.9E-5 (3.1E-5-5.9E-5)	2.3E-5 (4.6E-5)	D	1
Copper	13	a,b	7.0E-6-6.0E-4 (1.4E-5-1.2E-3)	9.5E-5 (1.9E-4)	C	1,6,8
Manganese	14	a,b	1.5E-4-2.6E-2 (3.0E-4-5.2E-2)	4.4E-3 (8.9E-3)	C	1,6,9,10
Mercury	7	a,b	1.3E-6-1.0E-5 (2.6E-6-2.1E-5)	3.2E-6 (6.5E-6)	C	1
Nickel	13	a,b	1.7E-5-2.9E-3 (3.4E-5-5.8E-3)	2.8E-4 (5.6E-4)	C	1,6,8,10
Selenium	2	a,b	8.5E-6-9.0E-6 (1.7E-5-1.8E-5)	8.8E-6 (1.8E-5)	D	6,8
Zinc	12	a,b	4.9E-5-1.2E-2 (9.9E-5-2.3E-2)	2.2E-3 (4.4E-3)	C	1,6
Barium	1	a	-	2.2E-3 (4.4E-3)	D	6
Potassium	1	a	-	3.9E-1 (7.8E-1)	D	6
Sodium	1	a	-	9.0E-3 (1.8E-2)	D	6
Iron	2	a	4.3E-4-4.3E-2 (8.6E-4-8.7E-2)	2.2E-2 (4.4E-2)	D	9,10
Lithium	1	a	-	3.5E-5 (7.0E-5)	D	8
Boron	1	a	-	4.0E-4 (8.0E-4)	D	8
Chlorine	1	a	-	3.9E-3 (7.8E-3)	D	8
Vanadium	1	a	-	6.0E-5 (1.2E-4)	D	8
Cobalt	1	a	-	6.5E-5 (1.3E-4)	D	8
Thorium	1	a	-	8.5E-5 (1.7E-5)	D	8
Tungsten	1	a	-	5.5E-6 (1.1E-5)	D	8
Dysprosium	1	a	-	6.5E-6 (1.3E-5)	D	8
Samarium	1	a	-	1.0E-5 (2.0E-5)	D	8

TABLE 4-6. SUMMARY OF WOOD WASTE COMBUSTION EMISSION DATA FOR TRACE ELEMENTS (Continued)

Trace element[a]	No. of data points	Data ratings	Emission factor range, kg/Mg (lb/ton)	Average emission factor, kg/Mg (lb/ton)	Emission factor rating	Reference number
Neodymium	1	a	-	1.3E-5 (2.6E-5)	D	8
Praeseodymium	1	a	-	1.5E-5 (3.0E-5)	D	8
Iodine	1	a	-	9.0E-6 (1.8E-5)	D	8
Tin	1	a	-	1.5E-5 (3.1E-5)	D	8
Molybdenum	1	a	-	9.5E-5 (1.9E-4)	D	8
Niobium	1	a	-	1.7E-5 (3.5E-5)	D	8
Zirconium	1	a	-	1.7E-4 (3.5E-4)	D	8
Yttrium	1	a	-	2.8E-5 (5.6E-5)	D	8
Rubidium	1	a	-	6.0E-4 (1.2E-3)	D	8
Bromine	1	a	-	1.9E-4 (3.9E-4)	D	8
Germanium	1	a	-	1.7E-6 (2.5E-6)	D	8

[a]After PM control device.
BDL = Below detection limit.

TABLE 4-7. LIST OF CONVERSION FACTORS

Multiply	By	To obtain
mg/dscm	4.37E-4	gr/dscf
m^2	10.764	ft^2
acm/min	35.31	acfm
m/s	3.281	ft/s
kg/h	2.205	lb/h
kPa	4.0	in. of H_2O
lpm	0.264	gal/min
kg/Mg	2.0	lb/ton

Temperature conversion equations

F = (9/5)*C+32

C = (5/9)*(F-32)

REFERENCES FOR CHAPTER 4

1. Written communication from G. Murray, California Forestry Association, Sacramento, California to E. Aul, Edward Aul & Associates, Inc., Chapel Hill, NC, Transmittal of Wood Fired Boiler Emission Test, April, 24, 1992.

2. Carbon Monoxide Emissions From Selected Combustion Sources Based on Short-Term Monitoring Records, NCASI Technical Bulletin No. 416, National Council of the Paper Industry For Air and Stream Improvement, New York, NY, January 1984.

3. Volatile Organic Carbon Emissions From Wood Residue Fired Power Boilers in the Southeast, NCASI Technical Bulletin No. 455, National Council of the Paper Industry For Air and Stream Improvement, New York, NY, April 1985.

4. A Polycyclic Organic Materials Study For Industrial Wood-Fired Boilers, NCASI Technical Bulletin No. 400, National Council of the Paper Industry For Air and Stream Improvement, New York, NY, May 1983.

5. A Study of Formaldehyde Emissions From Wood Residue-Fired Boilers, NCASI Technical Bulletin No. 622, National Council of the Paper Industry For Air and Stream Improvement, New York, NY, January 1992.

6. Hazardous Air Emissions Potential From a Wood-Fired Furnace (and Attachments), A. J. Hubbard, Wisconsin Department of Natural Resources, Madison, WI, July 1991 (Attachments).

7. National Dioxin Study Tier 4, Combustion Sources: Final Test Report, Site 7, Wood Fired Boiler WFB-A, EPA-450/4-84-014p, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1987.

8. Environmental Assessment of a Wood-Waste-Fired Industrial Watertube Boiler, EPA Contract No. 68-02-3188, Acurex Corporation, Mountain View, CA, March 1984.

9. Evaluation Test on a Wood Waste Fired Incinerator at Pacific Oroville Power Inc., Test Report No. C-88-050, California Air Resources Broad, Sacramento, CA, May 1990.

10. Evaluation Test on Twin Fluidized Bed Wood Waste Fueled Combustors Located in Central California, Test Report No. C-87-042, California Air Resources Board, Sacramento, CA, February, 1990.

11. Emission Test Report, Owens-Illinois Forest Products Division, Big Island, Virginia, EMB Report 80-WFB-2, U. S. Environmental Protection Agency, Research Triangle Park, NC, February 1980.

12. Emission Test Report, St. Joe Paper Company, Port St. Joe, Florida, EMB Report 80-WFB-5, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1980.

13. Source Test Report, Woodtech, Inc., Bluefield, Virginia, Environmental Quality Management, Inc., Durham, NC, January 1992.

14. Evaluation Test on a Wood Fired Incinerator at Koppers Company, Oroville, California, Test Report No. C-88-065, California Air Resources Board, Sacramento, CA, May 1990.

15. Evaluation Test on a Wood Waste Fired Incinerator at Louisiana Pacific Hardboard Plant, Oroville, California, Test Report No. C-88-066, California Air Resources Board, Sacramento, CA, May 1990.

16. Results of the July 30, 1986 Air Emission Tests Performed in Conjunction With the Railroad Tie Test Burn on the No. 5 Boiler at the Blandin Paper Company Plant in Grand Rapids, Minnesota, Interpoll, Inc., Circle Pines, MN, August 1986.

17. Environmental Assessment of a Waste-to-Energy Process, Burlington Electric's Wood and Oil Co-fired Boiler, EPA-600/7-80-148, U. S. Environmental Protection Agency, Research Triangle Park, NC, August 1980.

18. Emission Factor Documentation for Section 1.6 Wood/Bark Waste Combustion in Boilers, EPA Contract No. 68-02-3511, Pacific Environmental Services, Inc., Durham, NC, August 1982.

19. 40 Code of Federal Regulations Chapter I, Part 60, Appendix A, Method 19, U. S. Environmental Protection Agency, July 1991 Edition.

20. Compilation of Air Pollutant Emission Factors, Supplement A, Section 1.6, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1986.

5. AP-42 SECTION 1.6: WOOD WASTE COMBUSTION IN BOILERS

The revision to Section 1.6 of AP-42 is presented in the following pages as it would appear in the document. A marked-up copy of the 1986 version of this section is included in Appendix B.

1.6 WOOD WASTE COMBUSTION IN BOILERS

1.6.1 General[1-5]

The burning of wood waste in boilers is mostly confined to those industries where it is available as a byproduct. It is burned both to obtain heat energy and to alleviate possible solid waste disposal problems. In boilers, wood waste is normally burned in the form of hogged wood, sawdust, shavings, chips, sanderdust, or wood trim. Heating values for this waste range from about 2,200 to 2,700 kcal/kg (4,000 to 5,000 Btu/lb) of fuel on a wet, as-fired basis. The moisture content of as-fired wood is typically near 50, weight percent but may vary from 5 to 75 weight percent depending on the waste type and storage operations.

Generally, bark is the major type of waste burned in pulp mills; either a mixture of wood and bark waste or wood waste alone is burned most frequently in the lumber, furniture, and plywood industries. As of 1980, there were approximately 1,600 wood-fired boilers operating in the U.S., with a total capacity of over 30 GW (1.0×10^{11} Btu/hr).

1.6.2 Firing Practices[5-7]

Various boiler firing configurations are used for burning wood waste. One common type of boiler used in smaller operations is the Dutch oven. This unit is widely used because it can burn fuels with very high moisture content. Fuel is fed into the oven through an opening in the top of a refractory-lined furnace. The fuel accumulates in a cone-shaped pile on a flat or sloping grate. Combustion is accomplished in two stages: (1) drying and gasification, and (2) combustion of gaseous products. The first stage takes place in the primary furnace, which is separated from the secondary furnace chamber by a bridge wall. Combustion is completed in the secondary chamber before gases enter the boiler section. The large mass of refractory helps to stabilize combustion rates but also causes a slow response to fluctuating steam demand.

In another boiler type, the fuel cell oven, fuel is dropped onto suspended fixed grates and is fired in a pile. Unlike the Dutch oven, the refractory-lined fuel cell also uses combustion air preheating and positioning of secondary and tertiary air injection ports to improve boiler efficiency. Because of their overall design and operating similarities, however, fuel cell and Dutch oven boilers have comparable emission characteristics.

The most common firing method employed for wood-fired boilers larger than 45,000 kg/hr (100,000 lb/hr) steam generation rate is the spreader stoker. With this boiler, wood enters the furnace through a fuel chute and is spread either pneumatically or mechanically across the furnace, where small pieces of the fuel burn while in suspension. Simultaneously, larger pieces of fuel are spread in a thin, even bed on a stationary or moving grate. The burning is accomplished in three stages in a single chamber: (1) moisture evaporation; (2) distillation and burning of volatile matter; and (3) burning of fixed carbon. This type of operation has a fast response to load changes, has improved combustion control, and can be operated with multiple fuels. Natural gas or oil is often fired in spreader stoker boilers as auxiliary fuel. This is done to maintain constant steam when the wood waste supply fluctuates and/or to provide more steam than can be generated from the waste supply alone. Although spreader stokers are the most common stokers among larger wood-fired boilers, overfeed and underfeed stokers are also utilized for smaller units.

Another boiler type sometimes used for wood combustion is the suspension-firing boiler. This boiler differs from a spreader stoker in that small-sized fuel (normally less than 2 mm) is blown into the boiler and combusted by supporting it in air rather than on fixed grates. Rapid changes in combustion rate and, therefore, steam generation rate are possible because the finely divided fuel particles burn very quickly.

A recent development in wood firing is the fluidized bed combustion (FBC) boiler. 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. Because of the large thermal mass represented by the hot inert bed particles, fluidized beds can handle fuels with moisture contents up to near 70 percent (total basis). Fluidized beds can also handle dirty fuels (up to 30 percent inert material). Wood fuel is pyrolyzed faster in a fluidized bed than on a grate due to its immediate contact with hot bed material. As a result, combustion is rapid and results in nearly complete combustion of the organic matter, thereby minimizing emission of unburned organic compounds.

1.6.3 Emissions And Controls[6-11]

The major emission of concern from wood boilers is particulate matter (PM), although other pollutants, particularly carbon monoxide (CO) and organic compounds, may be emitted in significant quantities under poor operating conditions. These emissions depend on a number of variables, including (1) the composition of the waste fuel burned, (2) the degree of flyash reinjection employed and (3) furnace design and operating conditions.

The composition of wood waste depends largely on the industry from which it originates. Pulping operations, for example, produce great quantities of bark that may contain more than 70 weight percent moisture, sand, and other non-combustibles. As a result, bark boilers in pulp mills may emit considerable amounts of particulate matter to the atmosphere unless they are well controlled. On the other hand, some operations, such as furniture manufacturing, generate a clean, dry wood waste (e.g., 2 to 20 weight percent moisture) which produces relatively low particulate emission levels when properly burned. Still other operations, such as sawmills, burn a varying mixture of bark and wood waste that results in PM emissions somewhere between these two extremes.

Furnace design and operating conditions are particularly important when firing wood waste. For example, because of the high moisture content that may be present in wood waste, a larger than usual area of refractory surface is often necessary to dry the fuel before combustion. In addition, sufficient secondary air must be supplied over the fuel bed to burn the volatiles that account for most of the combustible material in the waste. When proper drying conditions do not exist, or when secondary combustion is incomplete, the combustion temperature is lowered, and increased PM, CO, and organic compound emissions may result. Short term emissions can fluctuate with significant variations in fuel moisture content.

Flyash reinjection, which is commonly used with larger boilers to improve fuel efficiency, has a considerable effect on PM emissions. Because a fraction of the collected flyash is reinjected into the boiler, the dust loading from the furnace and, consequently, from the collection device increase significantly per unit of wood waste burned. More recent boiler installations typically separate the collected particulate 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 sent to ash disposal.

Currently, the four most common control devices used to reduce PM emissions from wood-fired boilers are mechanical collectors, wet scrubbers, electrostatic precipitators (ESPs), and fabric filters. The use of multitube cyclone (or multiclone) mechanical collectors provides particulate control for many hogged boilers. Often, two multiclones are used in series, allowing the first collector to remove the bulk of the dust and the second to remove smaller particles. The efficiency of this arrangement is from 65 to 95 percent. The most widely used wet scrubbers for wood-fired boilers are venturi scrubbers. With gas-side pressure drops exceeding 4 kPa (15 inches of water), particulate collection efficiencies of 90 percent or greater have been reported for venturi scrubbers operating on wood-fired boilers.

Fabric filters (i.e., baghouses) and ESPs are employed when collection efficiencies above 95 percent are required. When applied to wood-fired boilers, ESPs are often used downstream of mechanical collector precleaners which remove larger-sized particles. Collection efficiencies of 93 to 99.8 percent for PM have been observed for ESPs operating on wood-fired boilers.

A variation of the ESP is the electrostatic gravel bed filter. In this device, PM in flue gases is removed by impaction with gravel media inside a packed bed; collection is augmented by an electrically charged grid within the bed. Particulate collection efficiencies are typically near 95 percent.

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 combustible carbonaceous fly ash. Steps can be taken to reduce this hazard, including the installation of a mechanical collector upstream of the fabric filter to remove large burning particles of fly ash (i.e., "sparklers"). Despite complications, fabric filters are generally preferred for boilers firing salt-laden wood. This fuel produces fine particulates with a high salt content. Fabric filters are capable of high fine particle collection efficiencies; in addition, the salt content of the particles has a quenching effect, thereby reducing fire hazards. In two tests of fabric filters operating on salt-laden wood-fired boilers, particulate collection efficiencies were above 98 percent.

Emissions of nitrogen oxides (NO_x) from wood-fired boilers are lower than those from coal-fired boilers due to the lower nitrogen content of wood and the lower combustion temperatures which characterize wood-fired boilers. For stoker and FBC boilers, overfire air ports may be used to lower NO_x emissions by staging the combustion process. In those areas of the U.S. where NO_x emissions must be reduced to their lowest levels, the application of selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) to waste wood-fired boilers has either been accomplished (SNCR) or is being contemplated (SCR). Both systems are post-combustion NO_x reduction techniques in which ammonia (or urea) is injected into the flue gas to selectively reduce NO_x to nitrogen and water. In one application of SNCR to an industrial wood-fired boiler, NO_x reduction efficiencies varied between 35 and 75 percent as the ammonia:NO_x ratio increased from 0.4 to 3.2.

Emission factors and emission factor ratings for wood waste boilers are summarized in Tables 1.6-1 through 1.6-7. Emission factors are for uncontrolled combustors, unless otherwise indicated.

Cumulative particle size distribution data and associated emission factors are presented in Tables 1.6-8 and 1.6-9. Uncontrolled and controlled size-specific emission factors are plotted in Figures 1.6-1 and 1.6-2. All emission factors presented are based on the feed rate of wet, as-fired wood with average properties of 50 weight percent moisture and 2,500 kcal/kg (4,500 Btu/lb) higher heating values.

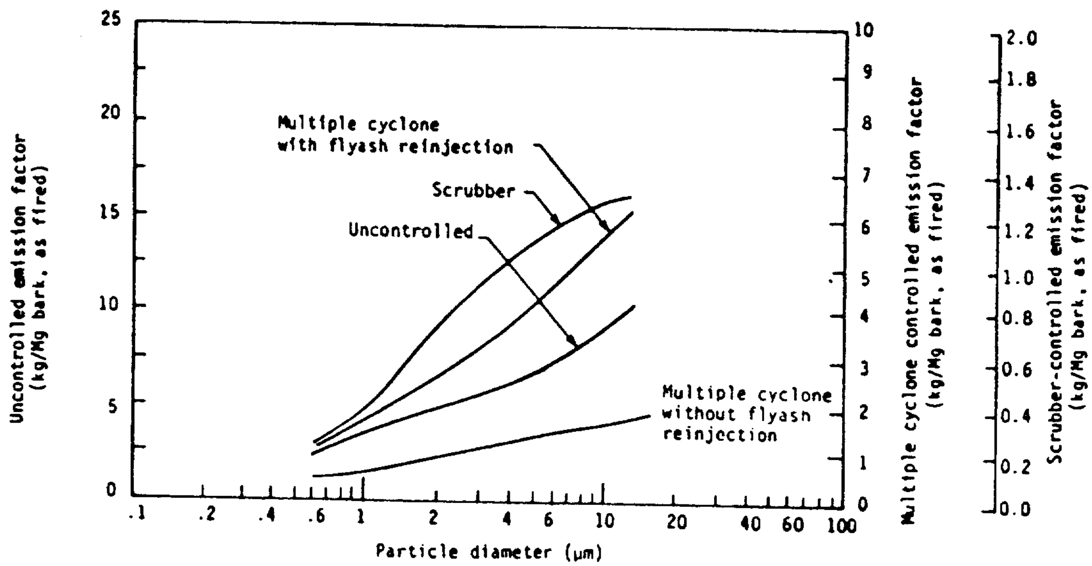

Figure 1.6-1. Cumulative size specific particulate matter emission factors for bark-fired boilers.

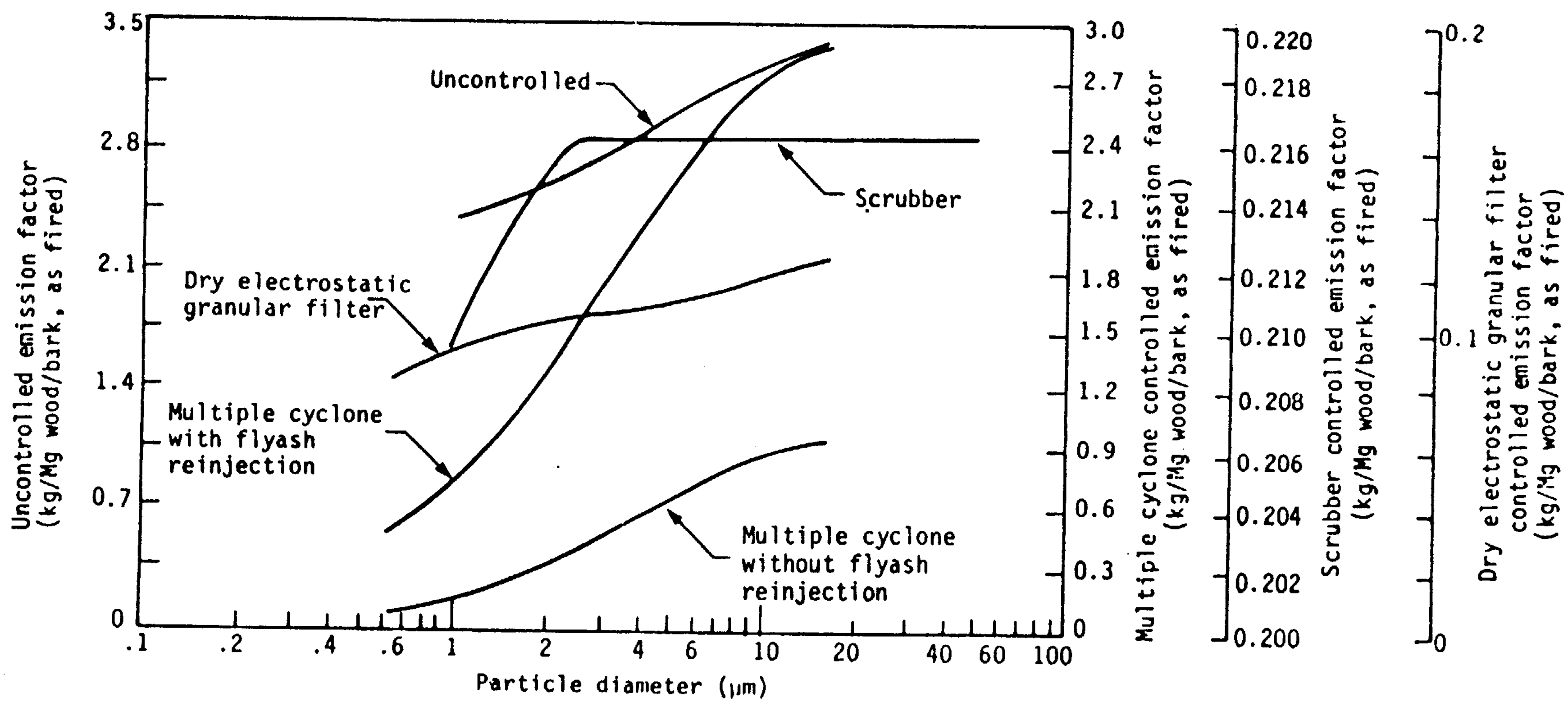

Figure 1.6-2. Cumulative size specific particulate matter emission factors for wood/bark-fired boilers.

Table 1.6-1. EMISSION FACTORS FOR PARTICULATE MATTER (PM), PARTICULATE MATTER LESS THAN 10 MICRONS (PM-10), AND LEAD FROM WOOD WASTE COMBUSTION[a]

Source Category (SCC)[b]	PM[c]			PM-10[d]			Lead[e]		
	kg/Mg	lb/ton	Rating	kg/Mg	lb/ton	Rating	kg/Mg	lb/ton	Rating
Bark-fired boilers (10100901, 10200901, 10200904, 10300901)									
Uncontrolled	23.5	47	B	8.4	17	D	1.4E-03	2.9E-03	D
Mechanical collector									
with flyash reinjection	7	14	B	5.5	11	D	ND[f]	ND	
without flyash reinjection	4.5	9.0	B	1.6	3.2	D			
Wet scrubber	1.5	2.9	D	1.3	2.5	D	ND	ND	
Wood/bark-fired boilers (10100902, 10200902, 10200905, 10300902)									
Uncontrolled	3.6	7.2	C	3.2	6.5	E	ND	ND	
Mechanical collector									
with flyash reinjection	3.0	6.0	C	2.7	5.5	E	1.6E-04[g]	3.2E-04[g]	D
without flyash reinjection	2.7	5.3	C	0.08	1.7	E	1.6E-04[g]	3.2E-04[g]	
Wet scrubber	0.24	0.48	D	0.23	0.47	E	1.8E-04	3.5E-04	D
Electrostatic precipitator	0.02	0.04	D	ND	ND		8.0E-05	1.6E-05	D
Wood-fired boilers (10100903, 10200903, 10200906, 10300903)									
Uncontrolled	4.4	8.8	C	ND	ND		ND	ND	
Mechanical collector									
without flyash reinjection	2.1	4.2	C	1.3[h]	2.6[h]	D	1.5E-04	3.1E-04	D
Electrostatic precipitator	0.08	0.17	D	ND	ND		5.5E-03	1.1E-03	D

[a]Units are kg of pollutant/Mg of wood waste burned and lbs. of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2,500 kcal/kg (4,500 Btu/lb) higher heating value.
[b]SCC = Source Classification Code.
[c]References 11-15.
[d]References 13, 16.
[e]References 11, 13-15, 17.
[f]ND = No data.
[g]Due to lead's relative volatility, it is assumed that flyash reinjection does not have a significant effect on lead emissions following mechanical collectors.
[h]Based on one test in which 61 percent of emitted PM was less than 10 micrometer in size.

Table 1.6-2. EMISSION FACTORS FOR NITROGEN OXIDES (NO_x), SULFUR OXIDES (SO_x), AND CARBON MONOXIDE (CO) FROM WOOD WASTE COMBUSTION[a]

Source Category (SCC)[b]	NO_x[c]			SO_x[d]			CO[e]		
	kg/Mg	lb/ton	Rating	kg/Mg	lb/ton	Rating	kg/Mg	lb/ton	Rating
Fuel cell/Dutch oven boiler (no SCC)	0.19 (0.0017-0.75)	0.38 (0.0033-1.5)	C	0.37 (0.005-0.1)	0.075 (0.01-0.2)	B	3.3 (0.33-11)	6.6 (0.65-21)	C
Stoker boilers (no SCC)	0.75 (0.33-1.8)	1.5 (0.66-3.6)	C	0.37 (0.005-0.1)	0.075 (0.01-0.2)	B	6.8 (0.95-40)	13.6 (1.9-80)	C
FBC boilers[f] (no SCC)	1.0	2.0	D	0.37 (0.005-0.1)	0.075 (0.01-0.2)	B	0.7 (0.24-1.2)	1.4 (0.47-2.4)	D

[a] Units are kg of pollutant/Mg of wood waste burned and lbs. of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2,500 kcal/kg (4,500 Btu/lb) higher heating value.
[b] SCC = Source Classification Code.
[c] References 12-14, 18-20. NO_x formation is primarily a function of wood nitrogen content. Higher values in the range (parentheses) should be used for wood nitrogen contents above a typical value of 0.08 weight percent, as fired.
[d] Reference 23. Lower limit of the range (in parentheses) should be used for wood and higher values for bark.
[e] References 11-15, 18, 24-26. Higher values in the range (in parentheses) should be used if combustion conditions are less than adequate, such as unusually wet wood or high air-to-fuel ratios.
[f] FBC = Fluidized bed combustion.

TABLE 1.6-3 EMISSION FACTORS FOR TOTAL ORGANIC COMPOUNDS (TOC) AND CARBON DIOXIDE (CO_2) FROM WOOD WASTE COMBUSTION[a]

Source Category (SCC)[b]	TOC[c]			CO_2[d]		
	kg/Mg	lb/ton	Rating	kg/Mg	lb/ton	Rating
Fuel cell/Dutch oven boilers (no SCC)	0.09	0.18	C	1100	2100	B
Stoker boilers (no SCC)	0.11	0.22	C	1100	2100	B
FBC boilers[e] (no SCC)	ND[f]	ND		1100	2100	B

[a]Units are kg of pollutant/Mg of wood waste burned and lbs. of pollutant/ton of wood waste burned. Emission factros are b ased on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2500 kcal/kg (4500 Btu/lb) higher heating value.
[b]SCC = Source Classification Code.
[c]References 11, 14-15, 18. Emissions measured as total hydrocarbons, converted to kg carbon/Mg fuel (lb carbon/ton fuel).
[d]References 11, 14-15, 17, 27.
[e]FBC = Fluidized bed combustion.
[f]ND = No data.

Table 1.6-4 (Metric Units). EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM WOOD WASTE COMBUSTION[a]

Organic Compound[b]	Emission Factor Range[c] kg/Mg	Average Emission Factor kg/Mg	Emission Factor Rating
Phenols	3.2E-05-6.0E-05	1.9E-04	C
Acenaphthene	4.3E-08-2.1E-06	1.7E-06	C
Fluorene	8.5E-08-1.4E-05	4.8E-06	C
Phenanthrene	1.0E-06-9.0E-05	2.8E-05	C
Anthracene	4.3E-08-1.7E-04	1.9E-05	C
Fluoranthene	4.3E-08-4.3E-04	4.5E-05	C
Pyrene	2.1E-07-2.9E-05	8.5E-06	C
Benzo(a)anthracene	4.3E-08-3.2E-06	9.0E-07	C
Benzo(b+k)fluoranthene	1.7E-07-9.5E-05	1.9E-05	C
Benzo(a)pyrene	4.3E-08-1.5E-07	9.5E-08	D
Benzo(g,h,i)perylene	4.3E-08-1.7E-06	6.0E-07	C
Chrysene	4.3E-08-1.5E-04	2.1E-05	C
Indeno(1,2,3,c,d)pyrene	4.3E-08-3.0E-07	1.7E-07	D
Polychlorinated dibenzo-p-dioxins	1.5E-09-1.7E-08	6.0E-09[d,e]	C
Polychlorinated dibenzo-p-furans	2.3E-09-3.6E-08	1.5E-08[d,f]	C
Acenaphthylene	3.0E-07-3.4E-05	2.2E-05	C
Pyrene		4.5E-06[g]	D
Methyl anthracene		7.0E-05[g]	D
Acrolein		2.0E-06[g]	D
Solicyladehyde		1.1E-05[g]	D
Benzaldehyde		6.0E-06[g]	D
Formaldehyde	1.2E-04-1.6E-02	3.3E-03	C
Acetaldehyde	3.0E-05-1.2E-02	1.5E-03	C
Benzene	4.3E-05-7.0E-03	1.8E-03	C
Naphthalene	2.5E-05-2.9E-03	1.1E-03	C
2,3,7,8-Tetrachlorodibenzo-p-dioxin	1.1E-011-2.6E-011	1.8E-11	D

[a]Units are kg of pollutant/Mg of wood waste burned and lbs. of pollutant/ton wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2500 kcal/kg higher heating value. Source Classification Codes are 10100901/02/03, 10200901/02/03/04/05/06/07, and 10300901/02/03.
[b]Pollutants in this table represent organic species measured for wood waste combustors. Other organic species may also have been emitted but were either not measured or were present at concentrations below analytical limits.
[c]References 11-15, 18, 26-28.
[d]Emission factors are for total dioxins and furans, not toxic equivalents.
[e]Excludes data from combustion of salt-laden wood. For salt-laden wood, emission factor is 6.5E-07 kg/Mg with a D rating.
[f]Excludes data from combustion of salt-laden wood. For salt-laden wood, emission factor is 2.8E-07 kg/Mg with a D rating.
[g]Based on data from one source test.

Table 1.6-5 (English Units). EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM WOOD WASTE COMBUSTION[a]

Organic Compound[b]	Emission Factor Range[c] lb/ton	Average Emission Factor lb/ton	Emission Factor Rating
Phenols	6.4E-05-1.2E-04	3.9E-04	C
Acenaphthene	8.6E-08-4.3E-06	3.4E-06	C
Fluorene	1.7E-07-2.8E-05	9.6E-06	C
Phenanthrene	2.0E-06-1.8E-04	5.7E-05	C
Anthracene	8.6E-08-3.5E-04	3.8E-05	C
Fluoranthene	8.6E-08-8.6E-04	9.0E-05	C
Pyrene	4.3E-07-5.9E-05	1.7E-05	C
Benzo(a)anthracene	8.6E-08-6.4E-06	1.8E-06	C
Benzo(b+k)fluoranthene	3.4E-07-1.9E-04	2.9E-05	C
Benzo(a)pyrene	8.6E-08-3.0E-07	1.9E-07	D
Benzo(g,h,i)perylene	8.6E-08-3.5E-06	1.2E-06	C
Chrysene	8.6E-08-3.0E-04	4.3E-05	C
Indeno(1,2,3,c,d)pyrene	8.6E-08-6.0E-07	3.4E-07	D
Polychlorinated dibenzo-p-dioxins	3.0E-09-3.3E-08	1.2E-08[d,e]	C
Polychlorinated dibenzo-p-furans	4.6E-09-7.2E-08	2.9E-08[d,f]	C
Acenaphthylene	6.0E-07-6.8E-05	4.4E-05	C
Pyrene		9.0E-06[g]	D
Methyl anthracene		1.4E-04[g]	D
Acrolein		4.0E-06[g]	D
Solicyladehyde		2.3E-05[g]	D
Benzaldehyde		1.2E-05[g]	D
Formaldehyde	2.3E-04-3.3E-02	6.6E-03	C
Acetaldehyde	6.1E-05-2.4E-02	3.0E-03	C
Benzene	8.6E-05-1.4E-02	3.6E-03	C
Naphthalene	5.0E-05-5.8E-03	2.3E-03	C
2,3,7,8-Tetrachlorodibenzo-p-dioxin	2.12E-011-5.11E-011	3.6E-11	D

[a]Units are kg of pollutant/Mg of wood waste burned and lbs. of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 4500 Btu/lb higher heating value. Source Classification Codes are 10100901/02/03, 10200901/02/03/04/05/06/07, and 10300901/02/03.

[b]Pollutants in this table represent organic species measured for wood waste combustors. Other organic species may also have been emitted but were either not measured or were present at concentrations below analytical limits.

[c]References 11-15, 18, 26-28.

[d]Emission factors are for total dioxins and furans, not toxic equivalents.

[e]Excludes data from combustion of salt-laden wood. For salt-laden wood, emission factor is 1.3E-06 lb/ton with a D rating.

[f]Excludes data from combustion of salt-laden wood. For salt-laden wood, emission factor is 5.5E-07 lb/ton with a D rating.

[g]Based on data from one source test.

Table 1.6-6 (Metric Units). EMISSION FACTORS FOR SPECIATED METALS FROM WOOD WASTE COMBUSTION[a]

Trace Element[b]	Emission Factor Range[c] kg/Mg	Average Emission Factor kg/Mg	Emission Factor Rating
Chromium (VI)	1.5E-05-2.9E-05	2.3E-05	D
Copper	7.0E-06-6.0E-04	9.5E-05	C
Zinc	4.9E-05-1.1E-02	2.2E-03	C
Barium		2.2E-03[d]	D
Potassium		3.9E-01[d]	D
Sodium		9.0E-03[d]	D
Iron	4.3E-04-3.3E-02	2.2E-02	D
Lithium		3.5E-05[d]	D
Boron		4.0E-04[d]	D
Chlorine		3.9E-03[d]	D
Vanadium		6.0E-05[d]	D
Cobalt[b]		6.5E-05[d]	D
Thorium		8.5E-06[d]	D
Tungsten		5.5E-06[d]	D
Dysprosium		6.5E-06[d]	D
Samarium		1.0E-05[d]	D
Neodymium		1.3E-05[d]	D
Praeseodymium		1.5E-05[d]	D
Iodine		8.0E-06[d]	D
Tin		1.5E-05[d]	D
Molybdenum		9.5E-05[d]	D
Niobium		1.7E-05[d]	D
Zirconium		1.7E-04[d]	D
Yttrium		2.8E-05[d]	D
Rubidium		6.0E-04[d]	D
Bromine		1.8E-04[d]	D
Germanium		1.7E-06[d]	D
Arsenic	7.0E-07-1.2E-04	4.4E-05	C
Cadmium	1.3E-06-2.7E-04	8.5E-06	C
Chromium (Total)	3.0E-06-2.3E-04	6.5E-05	C
Manganese	1.5E-04-2.6E-02	4.4E-03	C
Mercury	1.3E-06-1.0E-05	3.7E-06	C
Nickel	1.7E-05-2.9E-03	2.8E-04	C
Selenium	8.5E-06-9.0E-06	8.8E-06	D

[a] Units are kg of pollutant/Mg of wood waste burned and lbs. of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2500 kcal/kg higher heating value. Source Classification Codes are 10100901/02/03, 10200901/02/03/04/05/06/07, and 10300901/02/03.

[b] Pollutants in this table represent metal species measured for wood waste combustors. Other metal species may also have been emitted but were either not measured or were present at concentrations below analytical limits.

[c] References 11-15.

[d] Based on data from one source test.

Table 1.6-7 (English Units). EMISSION FACTORS FOR SPECIATED METALS FROM WOOD WASTE COMBUSTION[a]

Trace Element[b]	Emission Factor Range[c] lb/ton	Average Emission Factor lb/ton	Emission Factor Rating
Chromium (VI)	3.1E-05-5.9E-05	4.6E-05	D
Copper	1.4E-05-1.2E-03	1.9E-04	C
Zinc	9.9E-05-2.3E-02	4.4E-03	D
Barium		4.4E-03[d]	D
Potassium		7.8E-01[d]	D
Sodium		1.8E-02[d]	D
Iron	8.6E-04-8.7E-02	4.4E-02	D
Lithium		7.0E-05[d]	D
Boron		8.0E-04[d]	D
Chlorine		7.8E-03[d]	D
Vanadium		1.2E-04[d]	D
Cobalt		1.3E-04[d]	D
Thorium		1.7E-05[d]	D
Tungsten		1.1E-05[d]	D
Dysprosium		1.3E-05[d]	D
Samarium		2.0E-05[d]	D
Neodymium		2.6E-05[d]	D
Praeseodymium		3.0E-05[d]	D
Iodine		1.8E-05[d]	D
Tin		3.1E-05[d]	D
Molybdenum		1.9E-04[d]	D
Niobium		3.5E-05[d]	D
Zirconium		3.5E-04[d]	D
Yttrium		5.6E-05[d]	D
Rubidium		1.2E-03[d]	D
Bromine		3.9E-04[d]	D
Germanium		2.5E-06[d]	D
Arsenic	1.4E-06-2.4E-04	8.8E-05	C
Cadmium	2.7E-06-5.4E-04	1.7E-05	C
Chromium (Total)	6.0E-06-4.6E-04	1.3E-04	C
Manganese	3.0E-04-5.2E-02	8.9E-03	C
Mercury	2.6E-06-2.1E-05	6.5E-06	C
Nickel	3.4E-05-5.8E-03	5.6E-04	C
Selenium	1.7E-05-1.8E-05	1.8E-05	D

[a]Units are kg of pollutant/Mg of wood waste burned and lbs. of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 4500 Btu/lb higher heating value. Source Classification Codes are 10100901/02/03, 10200901/02/03/04/05/06/07, and 10300901/02/03.

[b]Pollutants in this table represent metal species measured for wood waste combustors. Other metal species may also have been emitted but were either not measured or were present at concentrations below analytical limits.

[c]References 11-15.

[d]Based on data from one source test.

Table 1.6-8. CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE SPECIFIC EMISSION FACTORS FOR BARK-FIRED BOILERS[a]

EMISSION FACTOR RATING: D

Particle Size[b] (μm)	Cumulative Mass % ≤ stated size				Cumulative Emission Factor[c] [kg/Mg (lb/ton) bark, as fired]			
	Uncontrolled	Controlled			Uncontrolled	Controlled		
		Multiple Cyclone[d]	Multiple Cyclone[e]	Scrubber[f]		Multiple Cyclone[d]	Multiple Cyclone[e]	Scrubber[f]
15	42	90	40	92	10.1 (20.2)	6.3 (12.6)	1.8 (3.6)	1.32 (2.64)
10	35	79	36	87	8.4 (16.8)	5.5 (11.0)	1.62 (3.24)	1.25 (2.50)
6	28	64	30	78	6.7 (13.4)	4.5 (9.0)	1.35 (2.7)	1.12 (2.24)
2.5	21	40	19	56	5.0 (10.0)	2.8 (5.6)	0.86 (1.72)	0.81 (1.62)
1.25	15	26	14	29	3.6 (7.2)	1.8 (3.6)	0.63 (1.26)	0.42 (0.84)
1.00	13	21	11	23	3.1 (6.2)	1.5 (3.0)	0.5 (1.0)	0.33 (0.66)
0.625	9	15	8	14	2.2 (4.4)	1.1 (2.2)	0.36 (0.72)	0.20 (0.40)
TOTAL	100	100	100	100	24 (47)	7 (14)	4.5 (9.0)	1.44 (2.88)

[a]Reference 16. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2,500 kcal/kg (4,500 Btu/lb) higher heating value. Source Classification Codes are 10100901, 10200901, 10200904, and 10300901.
[b]Expressed as aerodynamic equivalent diameter.
[c]Units are kg of pollutant/Mg of wood waste burned and lbs. of pollutant/ton of wood waste burned. Data limited to spreader stoker boilers.
[d]With flyash reinjection.
[e]Without flyash reinjection.
[f]Assumed control efficiency for scrubber is 94%.

Table 1.6-9. CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE SPECIFIC EMISSION FACTORS FOR WOOD/BARK-FIRED BOILERS[a]

EMISSION FACTOR RATING: E

Particle Size[b] (µm)	Cumulative Mass % ≤ stated size					Cumulative Emission Factor[c] [kg/Mg (lb/ton) bark, as fired]				
	Uncontrolled[d]	Controlled				Uncontrolled[c]	Controlled			
		Multiple Cyclone[d]	Multiple Cyclone[e]	Scrubber[f]	DEGF		Multiple Cyclone[g]	Multiple Cyclone[e]	Scrubber[f]	DEGF[g]
15	94	96	35	98	77	3.38 (6.77)	2.88 (5.76)	0.95 (1.90)	0.216 (0.431)	0.123 (0.246)
10	90	91	32	98	74	3.24 (6.48)	2.73 (5.46)	0.86 (1.72)	0.216 (0.432)	0.118 (0.236)
6	86	80	27	98	69	3.10 (6.20)	2.40 (4.80)	0.73 (1.46)	0.216 (0.432)	0.110 (0.220)
2.5	76	54	16	98	65	2.74 (5.47)	1.62 (3.24)	0.43 (0.86)	0.216 (0.432)	0.104 (0.208)
1.25	69	30	84	96	61	2.48 (4.97)	0.90 (1.80)	0.22 (0.44)	0.211 (0.422)	0.098 (0.196)
1.00	67	24	6	95	58	2.41 (4.82)	0.72 (1.44)	0.16 (0.32)	0.209 (0.418)	0.093 (0.186)
0.625	ND	16	3	ND	51	ND	0.48 (0.96)	0.081 (0.162)	ND	0.082 (0.164)
TOTAL	100	100	100	100	100	3.6 (7.2)	3.0 (6.0)	2.7 (5.4)	0.24 (0.48)	0.16 (0.32)

[a] Reference 16. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2500 kcal/kg (4500 Btu/lb) higher heating value. Source Classification Codes are 10100902, 10200902, 10200905, and 10300902.
[b] Expressed as aerodynamic equivalent diameter.
[c] Units are kg of pollutant/Mg of wood/bark burned and lbs. of pollutant/ton of wood/bark burned.
[d] From data on underfeed stokers. May also be used as size distribution for wood-fired boilers.
[e] From data on spreader stokers without flyash reinjection.
[f] From data on Dutch ovens. Assumed control efficiency is 94%.
[g] From data on spreader stokers with flyash reinjection.
[h] ND = No data.

References for Section 1.6

1. *Emission Factor Documentation for AP-42 Section 1.6--Wood Waste Combustion in Boilers*, Technical Support Division, Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1993.

2. *Steam*, 38th Edition, Babcock and Wilcox, New York, NY, 1972.

3. *Atmospheric Emissions From the Pulp and Paper Manufacturing Industry*, EPA-450/1-73-002, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1973.

4. *C-E Bark Burning Boilers*, C-E Industrial Boiler Operations, Combustion Engineering, Inc., Windsor, CT, 1973.

5. *Nonfossil Fuel Fired Industrial Boilers - Background Information*, EPA-450/3-82-007, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1982.

6. *Control of Particulate Emissions From Wood-Fired Boilers*, EPA 340/1-77-026, U. S. Environmental Protection Agency, Washington, DC, 1977.

7. *Background Information Document For Industrial Boilers*, EPA 450/3-82-006a, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1982.

8. E. F. Aul, Jr. and K. W. Barnett, "Emission Control Technologies For Wood-Fired Boilers", Presented at the Wood Energy Conference, Raleigh, NC, October 1984.

9. G. Moilanen, K. Price, C. Smith, and A. Turchina, "Noncatalytic Ammonia Injection For NO_x Reduction on a Waste Wood Fired Boiler", Presented at the 80th Annual Meeting of the Air Pollution Control Association, New York, NY, June 1987.

10. "Information on the Sulfur Content of Bark and Its Contribution to SO_2 Emissions When Burned as a Fuel", H. Oglesby and R. Blosser, *Journal of the Air Pollution Control Agency*, 30(7):769-772, July 1980.

11. Written communication from G. Murray, California Forestry Association, Sacramento, CA to E. Aul, Edward Aul & Associates, Inc., Chapel Hill, NC, Transmittal of Wood Fired Boiler Emission Test, April, 24, 1992.

12. *Hazardous Air Emissions Potential From a Wood-Fired Furnace (and Attachments)*, A. J. Hubbard, Wisconsin Department of Natural Resources, Madison, WI, July 1991.

13. *Environmental Assessment of a Wood-Waste-Fired Industrial Watertube Boiler*, EPA Contract No. 68-02-3188, Acurex Corporation, Mountain View, CA, March 1984.

14. *Evaluation Test on a Wood Waste Fired Incinerator at Pacific Oroville Power Inc.*, Test Report No. C-88-050, California Air Resources Broad, Sacramento, CA, May 1990.

15. *Evaluation Test on Twin Fluidized Bed Wood Waste Fueled Combustors Located in Central California*, Test Report No. C-87-042, California Air Resources Board, Sacramento, CA, February, 1990.

References for Section 1.6 (Continued)

16. *Inhalable Particulate Source Category Report for External Combustion Sources*, EPA Contract No. 68-02-3156, Acurex Corporation, Mountain View, CA, January 1985.

17. *Emission Test Report, Owens-Illinois Forest Products Division, Big Island, Virginia*, EMB Report 80-WFB-2, U. S. Environmental Protection Agency, Research Triangle Park, NC, February 1980.

18. *National Dioxin Study Tier 4, Combustion Sources: Final Test Report, Site 7, Wood Fired Boiler WFB-A*, EPA-450/4-84-014p, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1987.

19. *Air Pollutant Emission Factors*, APTD-0923, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1970.

20. *A Study of Nitrogen Oxides Emissions From Wood Residue Boilers*, Technical Bulletin No. 102, National Council of the Paper Industry for Air and Stream Improvement, New York, NY, November 1979.

21. R. A. Kester, *Nitrogen Oxide Emissions From a Pilot Plant Spreader Stoker Bark Fired Boiler*, Department of Civil Engineering, University of Washington, Seattle, WA, December 1979.

22. A. Nunn, *NO_x Emission Factors For Wood Fired Boilers*, EPA-600/7-79-219, U. S. Environmental Protection Agency, September 1979.

23. H. S. Oglesby and R. O. Blosser, "Information on the Sulfur Content of Bark and Its Contribution to SO_2 Emissions When Burned as a Fuel", *Journal of the Air Pollution Control Agency*, 30(7):769-772, July 1980.

24. *Carbon Monoxide Emissions From Selected Combustion Sources Based on Short-Term Monitoring Records*, Technical Bulletin No. 416, National Council of the Paper Industry For Air and Stream Improvement, New York, NY, January 1984.

25. *Volatile Organic Carbon Emissions From Wood Residue Fired Power Boilers in the Southeast*, Technical Bulletin No. 455, National Council of the Paper Industry For Air and Stream Improvement, New York, NY, April 1985.

26. *A Study of Formaldehyde Emissions From Wood Residue-Fired Boilers*, Technical Bulletin No. 622, National Council of the Paper Industry For Air and Stream Improvement, New York, NY, January 1992.

27. *Emission Test Report, St. Joe Paper Company, Port St. Joe, Florida*, EMB Report 80-WFB-5, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1980.

28. *A Polycyclic Organic Materials Study For Industrial Wood-Fired Boilers*, Technical Bulletin No. 400, National Council of the Paper Industry For Air and Stream Improvement, New York, NY, May 1983.

APPENDIX A

EMISSION SOURCE DATA RATING FORMS

SOURCE CATEGORY:____________________

EXCLUSION CRITERIA CHECKLIST

REFERENCE____

____

CRITERIA	YES	NO
1. Test series averages are reported in units that can be converted to the selected reporting units?		
2. Test series represent compatible test methods?		
3. In tests in which emission control devices were used, the control devices are fully specified?		
4. Is it clear whether or not the emissions were controlled (or not controlled)?		

Form filled out by____

Date ____________________

INDICATE WHETHER ANSWER IS YES OR NO WITH AN "X" IN APPROPRIATE BOX.

IF ALL ANSWERS ARE "YES" PROCEED TO METHODOLOGY/DETAIL CRITERIA CHECKLIST.

SOURCE CATEGORY_______________________________

METHODOLOGY/DETAIL CRITERIA CHECKLIST

REFERENCE___________________________________

CRITERIA	YES	NO	COMMENTS
1. Is the manner in which the source was operated well documented in the report?			
Was the source operating within typical parameters during the test?			
2. Did sampling procedures deviate from standard methods?			
If so, were the deviations well documented?			
Were the deviations appropriate?			
Comment on how any alterations in sampling procedure may have influenced the results.			
3. Were there wide variations in the results?			
If yes, can the variations be adequately explained by information in the report?			
If the variations are not well explained, should the data be considered of poor quality?			
4. Do the test reports contain the raw data sheets?			
Are the nomenclature and equations used equivalent to those specified by the EPA?			
Comment on the consistency and completeness of the results.			

Form filled out by___________________________

Date ___________________________

INDICATE YES OR NO WITH AN "X" IN THE APPROPRIATE BOX. FILL IN COMMENTS.

IF, BASED ON ABOVE ANSWERS, THE SOURCE REPORT PROVIDES ADEQUATE DETAIL AND DEMONSTRATES SOUND METHODOLOGY, PROCEED TO RATING THE DATA IN THE RATING CRITERIA CHECKLIST.

SOURCE CATEGORY____________________
RATING CRITERIA CHECKLIST

Reference____________________

	RATING CRITERIA	YES	NO
A	Tests performed by a sound methodology and reported in enough detail for adequate validation?		
B	Tests were performed by a generally sound methodology, but not enough detail for adequate validation?		
C	Were tests based on untested or new methodology that lacks significant amount of background data?		
D	Were tests based on generally unacceptable methods, but may provide order-of-magnitude values for the source?		

COMMENTS

Form filled out by____________________
Date____________________

BASED ON ANSWERS AND COMMENTS ABOVE, ASSIGN A RANK TO THIS LITERATURE SOURCE:

RANK ASSIGNED TO EMISSION SOURCE DATA

APPENDIX B

MARKED-UP 1986 AP-42 SECTION 1.6

When burned in boilers, wood waste is normally in the form of hogged wood, sawdust, shavings, chips, sanderdust, or wood trim.

The moisture content of as-fired wood is typically near 50 weight percent but may vary from 5 to 75 weight percent depending on waste type and handling/storage operations

on a wet, or as-fired, basis.

1.6 WOOD WASTE COMBUSTION IN BOILERS

1.6.1 General[1-5]

The burning of wood waste in boilers is mostly confined to those industries where it is available as a byproduct. It is burned both to obtain heat energy and to alleviate possible solid waste disposal problems. ~~Wood waste may include large pieces like slabs, logs and bark strips, as well as cuttings, shavings, pellets and sawdust, and~~ heating values for this waste range from about ~~4,400~~ 2,200 to ~~5,000~~ kilocalories per kilogram of fuel ~~dry weight~~ (~~7,940~~ to ~~9,131~~ Btu/lb). ~~However, because of typical moisture contents of 40 to 75 percent, the heating values for many wood waste materials as actually fired are as low as 2,200 to 3,300 kilocalories per kilogram of fuel.~~ Generally, bark is the major type of waste burned in pulp mills, ~~and~~ either a ~~varying~~ mixture of wood and bark waste or wood waste alone ~~are~~ is most frequently burned in the lumber, furniture, and plywood industries. As of 1980, there were approximately 1,600 wood-fired boilers operating in the U.S., with a total capacity of over 30 GW (1.0×10^{11} Btu/hr).

1.6.2 Firing Practices[1-3 5-7]

Various boiler firing configurations are used ~~in~~ when burning wood waste. One common type of boiler used in smaller operations is the dutch oven~~, or extension type of furnace with a flat grate~~. This unit is widely used because it can burn fuels with very high moisture content. Fuel is fed into the oven through ~~apertures atop a firebox and is fired in a cone shaped pile on a flat grate.~~ an opening in the top of a refractory-lined furnace. The fuel accumulates in a cone-shaped pile on a flat or sloping grate. ~~The burning~~ Combustion is ~~done~~ accomplished in two stages, (1) drying and gasification, and (2) combustion of gaseous products. The first stage takes place in ~~a cell~~ the primary furnace, which is separated from the ~~boiler section~~ secondary furnace chamber by a bridge wall. ~~The combustion stage takes place in the main boiler section. The dutch oven is not responsive to changes in steam load, and it provides poor combustion control.~~ Combustion is completed in the secondary chamber before gases enter the boiler section. The large mass of refractory helps to stabilize combustion rates but also causes a slow response to fluctuating steam demands.

In another type, the fuel cell oven, fuel is dropped onto suspended fixed grates and is fired in a pile. Unlike the dutch oven, the fuel cell also uses combustion air preheating and repositioning of ~~the~~ secondary and tertiary air injection ports to improve boiler efficiency.

refractory-lined

Insert A

~~In many large operations, more conventional boilers have been modified to burn wood waste.~~ These units may include spreader ~~stokers~~ with traveling grates, vibrating grate ~~stokers, etc., as well as~~ tangentially fired or cyclone fired boilers. ~~The most widely used of these configurations is the spreader stoker.~~ Fuel is dropped in front of an air jet which casts the fuel out over ~~a moving grate, spreading it in an even thin blanket~~. The burning is ~~done~~ accomplished in three stages in a single chamber, (1) ~~drying~~ moisture evaporation, (2) distillation and burning of volatile matter and (3) burning of carbon. This type of operation has a fast response to load changes, has improved combustion control and can be operated with multiple fuels. Natural gas or oil are often fired in spreader stoker boilers as auxiliary fuel. This is done to maintain constant steam when the wood waste supply fluctuates and/or to provide more steam than ~~is possible~~ can be generated from the waste supply alone. Although spreader stokers are the most common stokers for large wood-fired boilers, overfeed and underfeed designs are also employed for smaller units.

TABLE 1.6-1. EMISSION FACTORS FOR WOOD AND BARK COMBUSTION IN BOILERS

Pollutant/Fuel type	kg/Mg	lb/ton	Emission Factor Rating
Particulate[a]			
Bark[b]			
Multiclone, with flyash reinjection[c]	7	14	B
Multiclone, without flyash reinjection[c]	4.5	9	B
Uncontrolled	24	47	B
Wood/bark mixture[d]			
Multiclone, with flyash reinjection[c,e]	3	6	C
Multiclone, without flyash reinjection[c,e]	2.7	5.3	C
Uncontrolled[f]	3.6	7.2	C
Wood[g]			
Uncontrolled	4.4	8.8	C
Sulfur dioxide[h]	0.075 (0.01 - 0.2)	0.15 (0.02 - 0.4)	B
Nitrogen oxides (as NO_2)[j]			
50,000 - 400,000 lb steam/hr	1.4	2.8	B
<50,000 lb steam/hr	0.34	0.68	B
Carbon monoxide[k]	2 - 24	4 - 47	C
VOC			
Nonmethane[m]	0.7	1.4	D
Methane[n]	0.15	0.3	E

[a]References 2, 4, 9, 17-18, 20. With gas or oil as auxiliary fuel, all particulate assumed to result from only wood waste fuel. May include condensible hydrocarbons of pitches and tars, mostly from back half catch of EPA Method 5. Tests indicate condensible hydrocarbons about 4% of total particulate weight.

[b]Based on fuel moisture content about 50%.

[c]References 4,7-8. After control equipment, assuming an average collection efficiency of 80%. Data indicate that 50% flyash reinjection increases dust load at cyclone inlet 1.2 to 1.5 times, and 100% flyash reinjection increases the load 1.5 to 2 times.

[d]Based on fuel moisture content of 33%.

[e]Based on large dutch ovens and spreader stokers (avg. 23,430 kg steam/hr) with steam pressures 20 - 75 kps (140 - 530 psi).

[f]Based on small dutch ovens and spreader stokers (usually ≤9075 kg steam/hr), with steam pressures 5 - 30 kpa (35 - 230 psi). Careful air adjustments and improved fuel separation and firing sometimes used, but effects can not be isolated.

[g]References 12-13, 19, 27. Wood waste includes cuttings, shavings, sawdust and chips, but not bark. Moisture content ranges 3 - 50 weight %. Based on small units (≤3000 kg steam/hr).

[h]Reference 23. Based on dry weight of fuel. From tests of fuel sulfur content and SO_2 emissions at 4 mills burning bark. Lower limit of range (in parentheses) should be used for wood, and higher values for bark. Heating value of 5000 kcal/kg (9000 Btu/lb) is assumed.

[j]References 7, 24-26. Several factors can influence emission rates, including combustion zone, temperature, excess air, boiler operating conditions, fuel moisture and fuel nitrogen content.

[k]Reference 30.

[m]References 20, 30. Nonmethane VOC reportedly consists of compounds with high vapor pressure, such as alpha pinene.

[n]Reference 30. Based on approximation of methane/nonmethane ratio, quite variable. Methane, expressed as % total VOC, varied 0 - 74 weight %.

See new emission factor tables

Sander dust is often burned in various boiler types at plywood, particle board and furniture plants. Sander dust contains fine wood particles with low moisture content (less than 20 weight percent). It is fired in a flaming horizontal torch, usually with natural gas as an ignition aid or supplementary fuel.

1.6.3 Emissions And Controls[4-28]

The major emission of concern from wood boilers is particulate matter, although other pollutants, particularly carbon monoxide, may be emitted in significant amounts under poor operating conditions. These emissions depend on a number of variables, including (1) the composition of the waste fuel burned, (2) the degree of flyash reinjection employed and (3) furnace design and operating conditions.

The composition of wood waste depends largely on the industry whence it originates. Pulping operations, for example, produce great quantities of bark that may contain more than 70 weight percent moisture and sand and other noncombustibles. Because of this, bark boilers in pulp mills may emit considerable amounts of particulate matter to the atmosphere unless they are well controlled. On the other hand, some operations, such as furniture manufacturing, produce a clean, dry wood waste, 5 to 50 weight percent moisture, with relatively little particulate emission when properly burned. Still other operations, such as sawmills, burn a varying mixture of bark and wood waste that results in particulate emissions somewhere between these two extremes.

Furnace design and operating conditions are particularly important when firing wood waste. For example, because of the high moisture content that can be present in this waste, a larger than usual area of refractory surface is often necessary to dry the fuel before combustion. In addition, sufficient secondary air must be supplied over the fuel bed to burn the volatiles that account for most of the combustible material in the waste. When proper drying conditions do not exist, or when secondary combustion is incomplete, the combustion temperature is lowered, and increased particulate, carbon monoxide and hydrocarbon emissions may result. Lowering of combustion temperature generally means decreased nitrogen oxide emissions. Also, short term emissions can fluctuate with significant variations in fuel moisture content.

Flyash reinjection, which is common in many larger boilers to improve fuel efficiency, has a considerable effect on particulate emissions. Because a fraction of the collected flyash is reinjected into the boiler, the dust loading from the furnace and consequently from the collection device increases significantly per unit of wood waste burned. It is reported that full reinjection can cause a tenfold increase in the dust loadings of some systems, although increase of 1.2 to 2 times are more typical for boilers using 50 to 100 percent reinjection. A major factor affecting this dust loading increase is the extent to which the sand and other noncombustibles can be separated from the flyash before reinjection to the furnace.

Although reinjection increases boiler efficiency from 1 to 4 percent and reduces emissions of uncombusted carbon, it increases boiler maintenance requirements, decreases average flyash particle size and makes collection more difficult. Properly designed reinjection systems should separate sand and char

TABLE 1.6-2. CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE SPECIFIC EMISSION FACTORS FOR BARK FIRED BOILERS[a]

EMISSION FACTOR RATING: D

Particle size[b] (μm)	Cumulative mass % ≤ stated size				Cumulative emission factor [kg/Mg (lb/ton) bark, as fired]			
	Uncontrolled	Controlled			Uncontrolled	Controlled		
		Multiple cyclone[c]	Multiple cyclone[d]	Scrubber[e]		Multiple cyclone[c]	Multiple cyclone[d]	Scrubber[e]
15	42	90	40	92	10.1 (20.2)	6.3 (12.6)	1.8 (3.6)	1.32 (2.64)
10	35	79	36	87	8.4 (16.8)	5.5 (11.0)	1.62 (3.24)	1.25 (2.50)
6	28	64	30	78	6.7 (13.4)	4.5 (9.0)	1.35 (2.7)	1.12 (2.24)
2.5	21	40	19	56	5.0 (10.0)	2.8 (5.6)	0.86 (1.72)	0.81 (1.62)
1.25	15	26	14	29	3.6 (7.2)	1.8 (3.6)	0.63 (1.26)	0.42 (0.84)
1.00	13	21	11	23	3.1 (6.2)	1.5 (3.0)	0.5 (1.0)	0.33 (0.66)
0.625	9	15	8	14	2.2 (4.4)	1.1 (2.2)	0.36 (0.72)	0.20 (0.40)
TOTAL	100	100	100	100	24 (48)	7 (14)	4.5 (9.0)	1.44 (2.88)

[a]Reference 31. All spreader stoker boilers.
[b]Expressed as aerodynamic equivalent diameter.
[c]With flyash reinjection.
[d]Without flyash reinjection.
[e]Estimated control efficiency for scrubber, 94%.

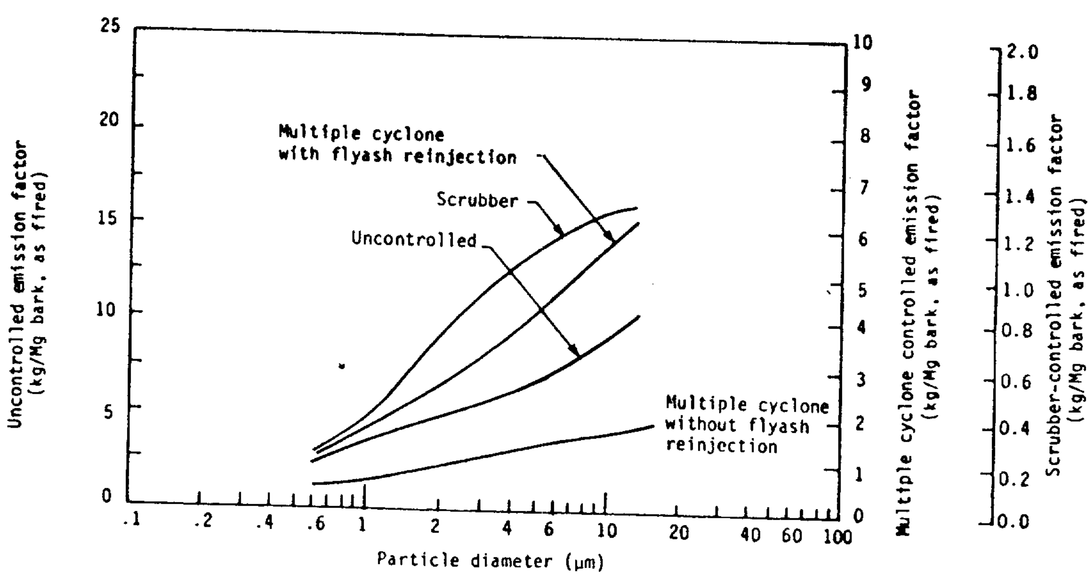

Figure 1.6-1. Cumulative size specific emission factors for bark fired boilers.

from the exhaust gases, to reinject the larger carbon particles to the furnace and to divert the fine sand particles to the ash disposal system.

Several factors can influence emissions, such as boiler size and type, design features, age, load factors, wood species and operating procedures. In addition, wood is often cofired with other fuels. The effect of these factors on emissions is difficult to quantify. It is best to refer to the references for further information.

The use of multitube cyclone mechanical collectors provides particulate control for many hogged boilers. Usually, two multicyclones are used in series, allowing the first collector to remove the bulk of the dust and the second to remove smaller particles. The efficiency of this arrangement is from 65 to 95 percent. Low pressure drop scrubbers and fabric filters have been used extensively for many years, and pulse jets have been used in the western U. S.

Emission factors and emission factor ratings for wood waste boilers are presented in Table 1.6-1, except for cumulative size distribution data, size specific emission factors for particulate, and emission factor ratings for the cumulative particle size distribution, all presented in Tables 1.6-2 through 1.6-8. Uncontrolled and controlled size specific emission factors are in Figures 1.6-1 and 1.6-2.

TABLE 1.6-~~3~~7. CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE SPECIFIC EMISSION FACTORS FOR WOOD/BARK FIRED BOILERS[a]

EMISSION FACTOR RATING: E (A for dry electrostatic granular filter [DEGF])

Particle size[b] (μm)	Cumulative mass % ≤ stated size					Cumulative emission factors [kg/Mg (lb/ton) wood/bark, as fired]				
	Uncontrolled[c]	Controlled				Uncontrolled[c]	Controlled			
		Multiple cyclone[d]	Multiple cyclone[e]	Scrubber[f]	DEGF		Multiple cyclone[d]	Multiple cyclone[e]	Scrubber[f]	DEGF[d]
15	94	96	35	98	77	3.38 (6.77)	2.88 (5.76)	0.95 (1.90)	0.216 (0.431)	0.123 (0.246)
10	90	91	32	98	74	3.24 (6.48)	2.73 (5.46)	0.86 (1.72)	0.216 (0.432)	0.118 (0.236)
6	86	80	27	98	69	3.10 (6.20)	2.40 (4.80)	0.73 (1.46)	0.216 (0.432)	0.110 (0.220)
2.5	76	54	16	98	65	2.74 (5.47)	1.62 (3.24)	0.43 (0.86)	0.216 (0.432)	0.104 (0.208)
1.25	69	30	8	96	61	2.48 (4.97)	0.90 (1.80)	0.22 (0.44)	0.211 (0.422)	0.098 (0.196)
1.00	67	24	6	95	58	2.41 (4.82)	0.72 (1.44)	0.16 (0.32)	0.209 (0.418)	0.093 (0.186)
0.625	-	16	3	-	51	-	0.48 (0.96)	0.081 (0.162)	-	0.082 (0.164)
TOTAL	100	100	100	100	100	3.6 (7.2)	3.0 (6.0)	2.7 (5.4)	0.22 (0.44)	0.16 (0.32)

[a] Reference 31. Dash = insufficient data.
[b] Expressed as aerodynamic equivalent diameter.
[c] From data on underfeed stokers. May also be used as size distribution for wood fired boilers.
[d] From data on spreader stokers. With fly ash reinjection.
[e] From data on spreader stokers. Without fly ash reinjection.
[f] From data on dutch ovens. Estimated control efficiency, 94%.

SECTION 1.6 - INSERTS

INSERT A

The most common firing method for wood-fired boilers larger than 100,000 lb steam/hr is the spreader stoker. With this boiler, wood enters the furnace through a fuel chute and is spread either pneumatically or mechanically across the furnace, where small pieces of the fuel burn while in suspension. Simultaneously, larger pieces of fuel are spread in a thin, even bed on a stationary or moving grate.

INSERT B

Another boiler type sometimes used for wood combustion is the suspension-firing boiler. This boiler differs from a spreader stoker in that small-sized fuel (normally less than 2 mm) is blown into the boiler and combusted by supporting it on air rather than on fixed grates. Rapid changes in combustion rate and therefore steam generation rate are possible because the finely divided fuel particles burn very quickly.

A recent development in wood firing is the fluidized bed combustion (FBC) boiler. 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. Because of the large thermal mass represented by the hot inert bed particles, fluidized beds can handle fuels with moisture contents up to near 70 percent (total basis). Fluidized beds can also handle dirty fuels (up to 30 percent inert material). Wood fuel is pyrolyzed faster in a fluidized bed than on a gate due to immediate contact with hot bed material. As a result, combustion is rapid and results in nearly complete combustion of the organic matter, thereby minimizing emission of unburned organic compounds.

INSERT C

More recent boiler installations typically separate the collected particulate 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 sent to disposal.

INSERT D

The most widely used wet scrubbers for wood-fired boilers are venturi scrubbers. With gas-side pressure drops exceeding 4 kPa (15 inches of water), particulate collection efficiencies of 90 percent or greater have been reported.

Fabric filters (i.e., baghouses) and ESPs are employed when collection efficiencies above 95 percent are required. When applied to wood-fired boilers, ESPs are often used downstream of mechanical collector precleaners which remove larger-sized particles. Collection efficiencies of 93 to 99.8 percent for PM have been reported for ESPs operating on wood-fired boilers.

A variation of the ESP is the electrostatic gravel bed filter. In this device, particulate matter in flue gases is removed by impaction with gravel media inside a packed bed; collection is augmented by an electrically charged grid within the bed. Particulate collection efficiencies of 95 percent have been measured.

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 combustible carbonaceous fly ash. Steps can be taken to reduce this hazard, including the installation of a mechanical collector upstream of the fabric filter to remove large burning particles of fly ash (i.e., "sparklers"). Despite complications, fabric filters are generally preferred for boilers firing salt-laden wood. This fuel produces fine particulates with a high salt content. Fabric filters are normally preferred for fine particulate collection and the salt content of the particles has a quenching effect, thereby reducing fire hazards. In two tests of fabric filters operating on salt-laden wood-fired boilers, particulate collection efficiencies were above 98 percent.

NO_x emissions from wood-fired boilers are lower than those from coal-fired boilers due to the lower nitrogen content of wood and the lower combustion temperatures which characterize wood-fired boilers. In those areas of the U.S. where NO_x emissions must be reduced to their lowest levels, the application of selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) to waste wood-fired boilers has either been accomplished (SNCR) or is being contemplated (SCR). Both systems are post-combustion NO_x reduction techniques in which ammonia (or urea) is injected into the flue gas to selectively reduce NO_x to nitrogen and water. In one application of SNCR to an industrial wood-fired boiler, NO_x reduction efficiencies varied between 35 and 75 percent as the ammonia:NO_x ratio increased from 0.4 to 3.2.

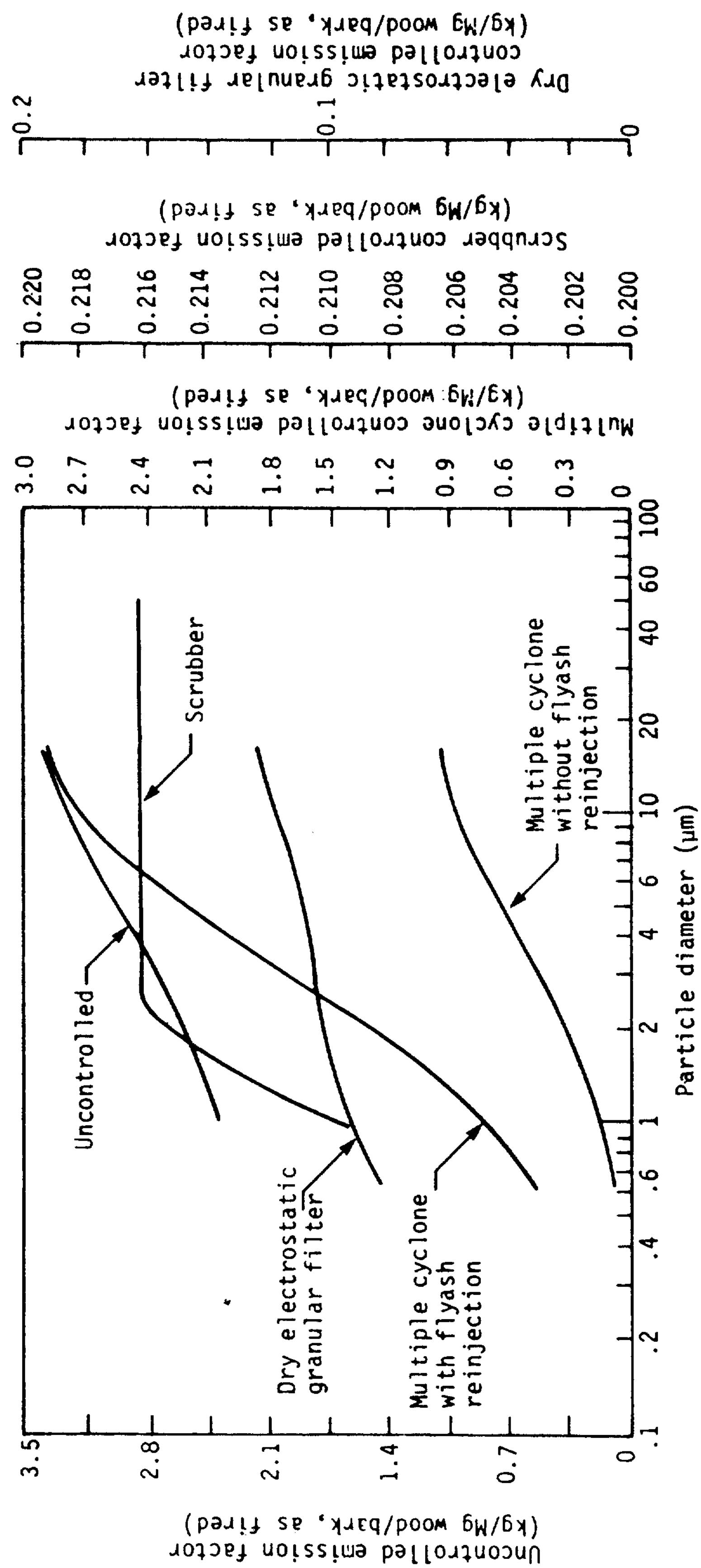

Figure 1.6-2. Cumulative size specific emission factors for wood/bark fired boilers.

References for Section 1.6

1. Wood Waste EFD

2 1. Steam, 38th Edition, Babcock and Wilcox, New York, NY, 1972.

3 2. Atomspheric Emissions from the Pulp and Paper Manufacturing Industry, EPA-450/1-73-002, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1973.

4 3. C-E Bark Burning Boilers, C-E Industrial Boiler Operations, Combustion Engineering, Inc., Windsor, CT, 1973.

4. A. Barron, Jr., "Studies on the Collection of Bark Char throughout the Industry", Journal of the Technical Association of the Pulp and Paper Industry, 53(8):1441-1448, August 1970.

5. H. Kreisinger, "Combustion of Wood Waste Fuels", Mechanical Engineering, 61:115-120, February 1939.

6. P. L. Magill (ed.), Air Pollution Handbook, McGraw-Hill Book Co., New York, NY, 1956.

7. Air Pollutant Emission Factors, APTD-0923, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1970.

8. J. F. Mullen, A Method for Determining Combustible Loss, Dust Emissions, and Recirculated Refuse for a Solid Fuel Burning System, Combustion Engineering, Inc., Windsor, CT, 1966.

9. Source test data, Alan Lindsey, U. S. Environmental Protection Agency, Atlanta, GA, May 1973.

10. H. K. Effenberger, et al., "Control of Hogged Fuel Boiler Emissions: A Case History", Journal of the Technical Association of the Pulp and Paper Industry, 56(2):111-115, February 1973.

11. Source test data, Oregon Department of Environmental Quality, Portland, OR, May 1973.

12. Source test data, Illinois Environmental Protection Agency, Springfield, IL, June 1973.

13. J. A. Danielson (ed.), Air Pollution Engineering Manual, Second Edition, AP-40, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1973. Out of Print.

14. H. Droege and G. Lee, "The Use of Gas Sampling and Analysis for the Evaluation of Teepee Burners", presented at the Seventh Conference on the Methods in Air Pollution Studies, Los Angeles, CA, January 1967.

15. D. C. Junge and K. Kwan, "An Investigation of the Chemically Reactive Constituents of Atmospheric Emissions from Hog-fuel Boilers in Oregon", Northwest International Section of the Air Pollution Control Association, November 1973.

See new references

16. S. F. Galeano and K. M. Leopold, "A Survey of Emissions of Nitrogen Oxides in the Pulp Mill", Journal of the Technical Association of the Pulp and Paper Industry, 56(3):74-76, March 1973.

17. P. B. Bosserman, "Wood Waste Boiler Emissions in Oregon State", presented at the Annual Meeting of the Pacific Northwest International Section of the Air Pollution Control Association, September 1976.

18. Source test data, Oregon Department of Environmental Quality, Portland, OR, September 1975.

19. Source test data, New York State Department of Environmental Conservation, Albany, NY, May 1974.

20. P. B. Bosserman, "Hydrocarbon Emissions from Wood Fired Boilers", presented at the Annual Meeting of the Pacific Northwest International Section of the Air Pollution Control Association, November 1977.

21. Control of Particulate Emissions from Wood Fired Boilers, EPA-340/1-77-026, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1978.

22. Wood Residue Fired Steam Generator Particulate Matter Control Technology Assessment, EPA-450/2-78-044, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1978.

23. H. S. Oglesby and R. O. Blosser, "Information on the Sulfur Content of Bark and Its Contribution to SO_2 Emissions When Burned as a Fuel", Journal of the Air Pollution Control Association, 30(7):769-772, July 1980.

24. A Study of Nitrogen Oxides Emissions from Wood Residue Boilers, Technical Bulletin No. 102, National Council of the Paper Industry for Air and Steam Improvement, New York, NY, November 1979.

25. R. A. Kester, Nitrogen Oxide Emissions from a Pilot Plant Spreader Stoker Bark Fired Boiler, Department of Civil Engineering, University of Washington, Seattle, WA, December 1979.

26. A. Nunn, NO_x Emission Factors for Wood Fired Boilers, EPA-600/7-79-219, U. S. Environmental Protection Agency, September 1979.

27. C. R. Sanborn, Evaluation of Wood Fired Boilers and Wide Bodied Cyclones in the State of Vermont, U. S. Environmental Protection Agency, Boston, MA, March 1979.

28. Source test data, North Carolina Department of Natural Resources and Community Development, Raleigh, NC, June 1981.

29. Nonfossil Fueled Boilers - Emission Test Report: Weyerhaeuser Company, Longview, Washington, EPA-80-WFB-10, Office Of Air Quality Planning And Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1981.

30. A Study of Wood Residue Fired Power Boiler Total Gaseous Nonmethane Organic Emissions in the Pacific Northwest, Technical Bulletin No. 109, National Council of the Paper Industry for Air and Steam Improvement, New York, NY, September 1980.

31. Inhalable Particulate Source Category Report for External Combustion Sources, EPA Contract No. 68-02-3156, Acurex Corporation, Mountain View, CA, January 1985.