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Guide to Low-Emission Boiler and Combustion Equipment Selection

C. B. Oland

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GUIDE TO LOW-EMISSION BOILER AND COMBUSTION EQUIPMENT SELECTION

C. B. Oland

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ACRONYMS

ABMA	American Boiler Manufacturers Association
AEL	Alternative Emission Limit
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATW	Air Toxics Web site
BACM	Best Available Control Measures
BACT	Best Available Control Technology
BF	bias firing
BOOS	burners out of service
BT	burner tuning
CAA	Clean Air Act
CAAA	Clean Air Act Amendments of 1990
CATC	Clean Air Technology Center
CEM	continuous emission monitoring
CFR	*Code of Federal Regulations*
CHIEF	Clearinghouse for Inventories and Emission Factors
CIBO	Council of Industrial Boiler Owners
CO	carbon monoxide
CO_2	carbon dioxide
DOE	U.S. Department of Energy
EMC	Emission Measurement Center
ESP	electrostatic precipitator
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
FBC	fluidized-bed combustion
FGD	flue-gas desulfurization
FGR	flue gas recirculation
FIR	fuel-induced recirculation and forced-internal recirculation
FR	*Federal Register*
HAP	hazardous air pollutant
HCN	hydrogen cyanide
HRT	horizontal return tubular
ICI	industrial/commercial/institutional
IFGR	induced flue-gas recirculation
LAER	Lowest Achievable Emission Rate
LEA	low excess air
LNB	low-NO_x burner
LP	liquefied petroleum
MACT	Maximum Achievable Control Technology
MCR	maximum continuous rating
MOU	Memorandum of Understanding
MSW	municipal solid waste
NAA	nonattainment area
NAAQS	National Ambient Air Quality Standards
NESCAUM	Northeast States for Coordinated Air Use Management
NESHAPs	National Emissions Standards for Hazardous Air Pollutants
NFPA	National Fire Protection Association

NGR	natural gas reburning
NO_x	nitrogen oxides
NSPS	New Source Performance Standards or Standards of Performance for New Stationary Sources
NSR	New Source Review
OAR	Office of Air and Radiation
OFA	overfire air
OIT	Office of Industrial Technologies
ORNL	Oak Ridge National Laboratory
OT	oxygen trim
OTAG	Ozone Transport Assessment Group
OTR	Ozone Transport Region
OTC	Ozone Transport Commission
PC	pulverized coal
PM	particulate matter
PSD	prevention of significant deterioration
RACM	Reasonably Available Control Measure
RACT	Reasonably Available Control Technology
RAP	reducing air preheat
RBLC	RACT/BACT/LAER Clearinghouse
RDF	refuse-derived fuel
SCA	staged combustion air
SCRAM	Support Center for Regulatory Air Models
SCR	selective catalytic reduction
SI	steam injection
SIP	State Implementation Plan
SNCR	selective noncatalytic reduction
SO_2	sulfur dioxide
T-BACT	Best Available Control Technology for Toxics
TDF	tire-derived fuel
TTN	Technology Transfer Network
UHC	unburned hydrocarbon
UL	Underwriters Laboratories
ULNB	ultra low-NO_x burner
VOC	volatile organic compound
WI	water injection

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EXECUTIVE SUMMARY

Boiler owners and operators who need additional generating capacity face a number of legal, political, environmental, economic, and technical challenges. Their key to success requires selection of an adequately sized low-emission boiler and combustion equipment that can be operated in compliance with emission standards established by state and federal regulatory agencies.

Recognizing that many issues are involved in making informed selection decisions, the U.S. Department of Energy (DOE), Office of Industrial Technologies (OIT) sponsored efforts at the Oak Ridge National Laboratory (ORNL) to develop a guide for use in choosing low-emission boilers and combustion equipment. To ensure that the guide covers a broad range of technical and regulatory issues of particular interest to the commercial boiler industry, the guide was developed in cooperation with the American Boiler Manufacturers Association (ABMA), the Council of Industrial Boiler Owners (CIBO), and the U.S. Environmental Protection Agency (EPA).

The guide presents topics pertaining to industrial, commercial, and institutional (ICI) boilers. Background information about various types of commercially available boilers is provided along with discussions about the fuels that they burn and the emissions that they produce. Also included are discussions about emissions standards and compliance issues, technical details related to emissions control techniques, and other important selection considerations. Although information in the guide is primarily applicable to new ICI boilers, it may also apply to existing boiler installations.

Use of the guide is primarily intended for those involved in either expanding current steam or hot water generating capacity or developing new capacity. Potential users include owners, operators, plant managers, and design engineers who are involved in selecting low-emission boilers and combustion equipment that comply with established emissions requirements. Regulatory authorities who deal with emission issues and boiler permit applications may also find useful information in the guide.

The guide is organized into topics that address many of the fundamental concerns encountered in planning a new steam or hot water boiler system. An overview of boilers, fuel feed systems, fuels, and emissions, which are fundamental considerations in the planning process, is presented in the first part of the guide. Discussions about firetube, watertube, cast iron, and tubeless boilers that burn fossil or nonfossil fuels are presented in Chap. 2. Technical terms and emission control techniques introduced in the overview provide a foundation for following discussions.

Issues pertaining to solid, liquid, and gaseous fuels commonly fired in ICI boilers are presented in the first part of Chap. 3. Characteristics of fossil and nonfossil fuels are included with emphasis on coal, oil, natural gas, biomass, and refuse-derived fuels (RDFs). For completeness, other materials such as heavy residuals from petroleum-cracking processes, coal tar pitch, and pulp mill sludge, which are sometimes used as boiler fuel, are briefly described. Following the fuel discussions, emphasis shifts to solid and gaseous emissions that are regulated under the Clean Air Act (CAA). The four principle emissions from combustion boilers that are regulated under this act include nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM), and carbon monoxide (CO). Mechanisms by which these emissions are formed are briefly described as an aid in understanding the various control techniques for reducing emissions.

The legal basis for regulating emissions from combustion boilers is contained in the CAA. This piece of environmental legislation addresses concerns about ground-level ozone, the accumulation of fine particles in the atmosphere, and acid rain. It also authorizes EPA to establish performance-based emissions standards for certain air pollutants including NO_x, SO_2, PM, and CO. A summary of emission limitations that are applicable to combustion boilers is presented in Appendix A. These limitations are specified as (1) maximum emission rates or (2) required reductions in potential combustion concentrations. Although the mandated emission limitations are a function of boiler type and size, the amount of each emission that may be released is strongly influenced by the type of fuel or fuel mixture being burned, the method of combustion, and the geographical location of the installation. In addition to discussions about the CAA, other topics covered in Chap. 4 include information sources, permitting issues, and lessons learned.

Techniques that are effective in reducing NO_x, SO_2, and PM emissions are subdivided into three general categories, depending on which stage in the combustion process they are applied. The categories include precombustion, combustion, and postcombustion emission control techniques. Table ES.1 shows the various techniques that may be applied to reduce these emissions. Descriptions of each technique are presented in Chap. 5.

As an aid in boiler and combustion equipment selection, emission control options for 14 of the most popular boiler and fuel combinations are identified and discussed in Chap. 6. These options reflect combustion of coal, fuel oil, natural gas, biomass, and RDF in watertube and firetube boilers. Figure ES.1 presents the general format used to identify the various emission control options that are available for a particular boiler and fuel combination. Use of information presented in the tables will help ensure that the best available control technologies are identified.

Although many factors must be considered when selecting a low-emission boiler and combustion equipment, the final choice should not be made until the performance of the complete system is evaluated and understood. Evaluations of different emission control equipment arranged in various configurations

Table ES.1. Emission control techniques discussed in the guide

Emission	Control technique		
	Precombustion	**Combustion**	**Postcombustion**
Nitrogen oxide (NO_x)	Switch to fuel with a low nitrogen content	Operational modifications: • oxygen trim (OT) • burner tuning (BT) • low excess air (LEA) Staged combustion air (SCA): • burners out of service (BOOS) • biased firing (BF) • overfire air (OFA) Steam or water injection (SI/WI) Flue gas recirculation (FGR) Fuel-induced recirculation (FIR) Low-NO_x burner (LNB) Ultra low-NO_x burner (ULNB) Natural gas reburning (NGR) Reducing air preheat (RAP)	Selective catalytic reduction (SCR) Selective noncatalytic reduction (SNCR)
Sulfur dioxide (SO_2)	Switch to fuel with a low-sulfur content Perform beneficiation	For fluidized-bed combustion (FBC) boilers, use limestone or dolomite as a sulfur-capture sorbent	Flue gas desulfurization (FGD): • nonregenerative techniques • regenerative techniques
Particulate matter (PM)	Switch to fuel with a low-ash content Perform beneficiation	Make operational modifications to reduce unburned carbon	Cyclone separator Wet scrubber Electrostatic precipitator (ESP) Fabric filter (baghouse)

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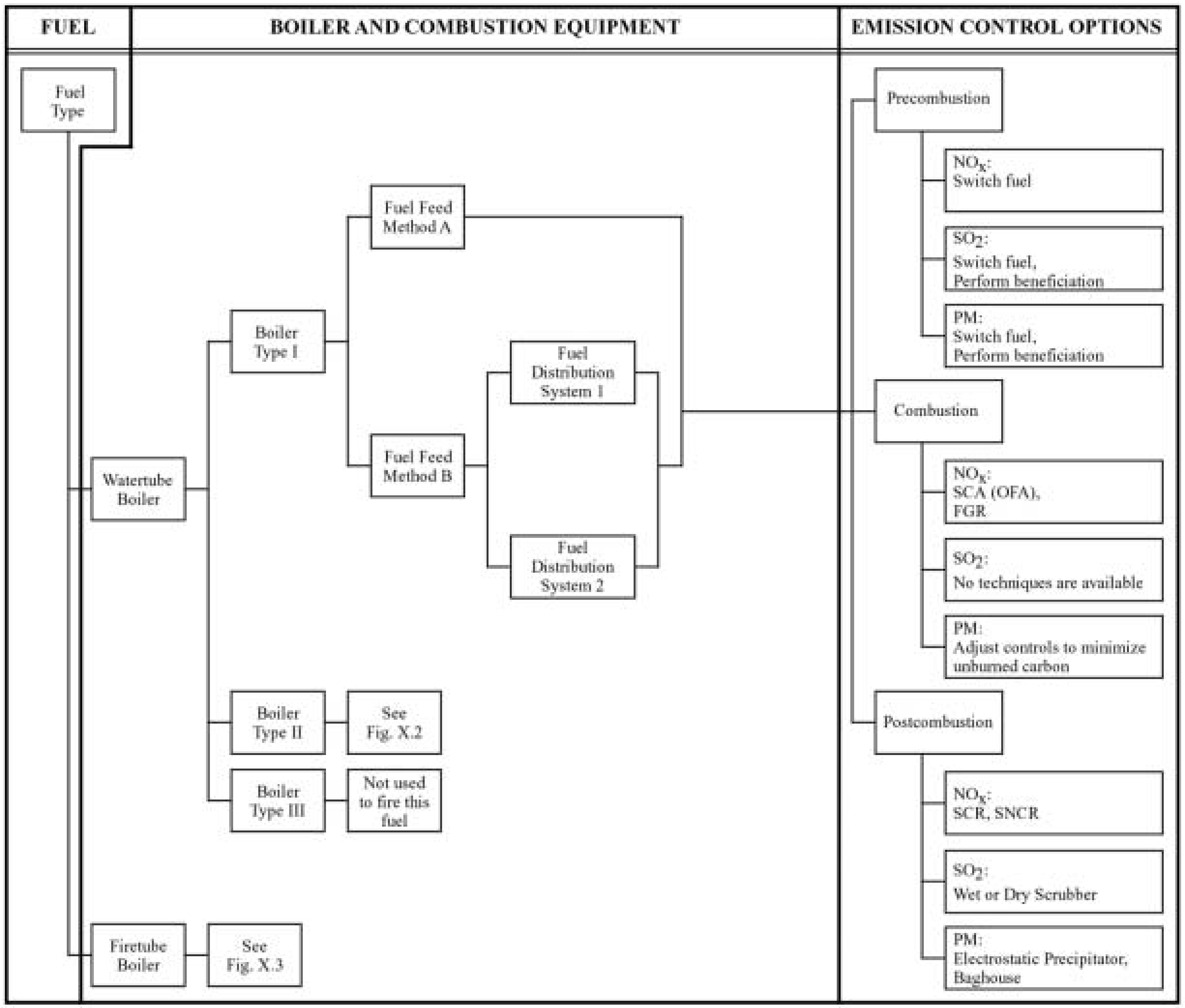

Fig. ES.1. Format used to present emission control options for various fuel and boiler combinations.

are technically complex. However, results of these evaluations are now an essential element of the permitting process. Details of the evaluations often establish the technical basis for permit applications submitted to regulatory authorities as part of the permitting process. Unless these evaluations are accurate and complete and unless currently accepted techniques for controlling emissions are adequately taken into consideration, it is unlikely that the regulatory authority will act favorably on the application. Information presented in this guide is intended to help owners and operators prepare permit applications that address the principal concerns and legal requirements of the regulatory authority.

References cited throughout the guide are listed for each chapter and also compiled in a bibliography. Information from these references was used to develop the text and tables that appear in the guide. The bibliography is provided to help identify useful resources for acquiring knowledge or technical details about a specific subject.

1. INTRODUCTION

Boiler owners and operators who need additional generating capacity face a number of legal, political, environmental, economic, and technical challenges. Their key to success requires selection of an adequately sized low-emission boiler and combustion equipment that can be operated in compliance with emission standards established by state and federal regulatory agencies. This guide presents a broad overview of technical and regulatory issues that may be encountered at various points in the selection process.

Information in the guide is primarily applicable to new industrial, commercial, and institutional (ICI) boilers and combustion equipment that must comply with emission requirements in the Clean Air Act (CAA).[1] These boilers are designed to use the chemical energy in fuel to raise the energy content of water so that it can be used for heating and power applications. Industrial boilers are used extensively in the chemical, food processing, paper, and petroleum industries. Commercial and institutional boilers are used in many other applications, including commercial businesses, office buildings, apartments, hotels, restaurants, hospitals, schools, museums, government buildings, and airports.

Use of the guide is primarily intended for those involved in either expanding current steam or hot water generating capacity or developing new capacity. Potential users include owners, operators, plant managers, and design engineers who are involved in the selection process. Regulatory authorities that deal with emission issues and boiler permit applications may also find the guide useful.

The guide was prepared at the Oak Ridge National Laboratory (ORNL) for the U.S. Department of Energy (DOE) through the Office of Industrial Technologies (OIT). To ensure that the guide covers a broad range of technical and regulatory issues of particular interest to the commercial boiler industry, the guide was developed in cooperation with the American Boiler Manufacturers Association (ABMA), the Council of Industrial Boiler Owners (CIBO), and the U.S. Environmental Protection Agency (EPA).

1.1 SCOPE AND OBJECTIVES

Information is presented for a broad class of steam and hot-water generating units known as ICI boilers. General discussions about commercially available ICI boilers are provided as well as information about the fuels that they burn and the emissions that they release. Discussions on environmental regulations, including emissions standards and compliance issues, technical details related to emission control techniques, and important considerations for combustion equipment selection, are also presented.

Emissions from ICI boilers that are currently regulated under the CAA are addressed in detail. These emissions, which include nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), and particulate matter (PM), are released whenever certain fossil and nonfossil fuels are burned. For discussion purposes, techniques for reducing these emissions from ICI boilers are subdivided into three categories: precombustion, combustion, and postcombustion emission control techniques. Although emission requirements for toxic air pollutants, which are also regulated under the CAA, have only been established for large municipal waste combustion units, a brief discussion about these pollutants is provided because emissions from combustion boilers may soon be regulated. Other important topics such as selection of process control instrumentation and emissions monitoring systems, which are key functional elements in new low-emission boiler installations, are not specifically addressed in this guide.

The primary objectives of the guide are to (1) present a broad range of issues that should be considered during the selection of new low-emission ICI boilers and combustion equipment and (2) identify information sources that contain relevant technical details. The guide is not intended to serve as a step-by-step design, procurement, or operations manual, nor is it considered a state-of-the-art report on combustion technology. Although information in the guide is primarily applicable to new ICI boilers, it may also apply to existing boiler installations. Issues pertaining to the selection of heat recovery steam generators or gas turbines are beyond the scope of the guide. Additional discussions about important boiler topics are presented in documents prepared by ABMA, CIBO, and DOE.[2–5]

1.2 APPROACH

Information is organized into topics that address many of the fundamental concerns encountered in planning a new steam or hot water boiler system that must comply with established emission standards. An overview of boilers, fuels, and emissions, which are fundamental considerations in the planning process, is presented immediately after the introduction. Terms and emission control concepts introduced in the overview provide a foundation for following discussions.

Chapter 2 focuses on the various types of ICI boilers that are commercially available. Emphasis is placed on firetube and watertube boilers although some discussion about other types of boilers, including cast iron and tubeless boilers, is also provided. Descriptions of solid, liquid, and gaseous fuels commonly fired in ICI boilers are presented in the first part of Chap. 3. Characteristics of fossil and nonfossil fuels are included with emphasis on coal, oil, natural gas, biomass, and refuse-derived fuels (RDFs). For completeness, other materials such as heavy residuals from petroleum-cracking processes, coal tar pitch, and pulp mill sludge, which are sometimes used as boiler fuel, are briefly described. Following the fuel discussions, emphasis shifts to solid and gaseous emissions that are regulated under the CAA.[1] Mechanisms by which these emissions are formed are briefly described as an aid in understanding the various emission control techniques that can be used to reduce emissions. Finally, the topic of efficiency is discussed. Efficiency is an important selection consideration because extracting as much energy from the fuel as possible is an effective way to reduce the total amount of emissions that are released.

The legal basis for regulating emissions from combustion boilers is contained in the CAA.[1] Discussions in Chap. 4 focus on this complex piece of environmental legislation that addresses concerns about ground-level ozone, the accumulation of fine particles in the atmosphere, hazardous air pollutants (HAPs), and acid rain. It also authorizes EPA to establish performance-based emissions standards for a broad list of pollutants. Federal emission limitations that are currently applicable to combustion boilers are tabulated in Appendix A. These limitations are specified as (1) maximum emission rates or (2) required reductions in potential combustion concentrations. Although the mandated emission limitations are a function of boiler type and size, the amount of each emission that may be released is strongly influenced by the type of fuel or fuel mixture being burned, the method of combustion, and the geographical location of the installation.

Techniques for reducing emissions before, during, and after combustion are presented in Chap. 5. Emission reductions can sometimes be achieved by switching to a different fuel or treating the fuel prior to combustion. As an example, SO_2 emissions from coal combustion can often be reduced by using low-sulfur instead of high-sulfur coal or by removing materials such as pyrites from the coal before it is fed into the boiler. Although these two precombustion emission control techniques are sometimes very effective, meaningful reductions generally require outfitting a boiler with special combustion equipment designed to implement a particular emissions control strategy. Reductions can be achieved by using an emission control technique that keeps the emission from forming during combustion or removes it after combustion has occurred.

These approaches to emissions reduction are reflected in the guidelines for selecting low-emission boilers and combustion equipment presented in Chap. 6. Discussions in this chapter focus on ICI boilers that burn various types of fuel and identify precombustion, combustion, and postcombustion emission control techniques that should be considered. As an aid in boiler and combustion equipment selection, emission control options for 14 of the most popular boiler and fuel combinations are identified. These options reflect combustion of coal, fuel oil, natural gas, biomass, and RDF in watertube and firetube boilers. Use of this information will help ensure that the best available control technologies (BACTs) are identified.

References cited throughout the guide are listed for each chapter and also compiled in a bibliography. Information from these references was used to develop the text and tables that appear in the guide. The bibliography represents another resource that may be useful in acquiring knowledge or technical details about a specific subject.

1.3 REFERENCE

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2. *Combustion Control Guidelines for Single Burner Firetube and Watertube Industrial/ Commercial/Institutional Boilers*, American Boiler Manufacturers Association, Arlington, Virginia, 1999.
3. *Combustion Control Guidelines for Multiple Burner Boilers*, American Boiler Manufacturers Association, Arlington, Virginia, 2002.
4. *Energy Efficiency Handbook*, ed. R. A. Zeitz, Council of Industrial Boiler Owners, Burke, Virginia, November 1997.
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2. INDUSTRIAL, COMMERCIAL, AND INSTITUTIONAL BOILERS

Combustion boilers are designed to use the chemical energy in fuel to raise the energy content of water so that it can be used for heating and power applications. Many fossil and nonfossil fuels are fired in boilers, but the most common types of fuel include coal, oil, and natural gas. During the combustion process, oxygen reacts with carbon, hydrogen, and other elements in the fuel to produce a flame and hot combustion gases. As these gases are drawn through the boiler, they cool as heat is transferred to water. Eventually the gases flow through a stack and into the atmosphere. As long as fuel and air are both available to continue the combustion process, heat will be generated.

Boilers are manufactured in many different sizes and configurations depending on the characteristics of the fuel, the specified heating output, and the required emissions controls. Some boilers are only capable of producing hot water, while others are designed to produce steam. Various studies have been conducted to estimate the number of boilers in the United States, but no data source provides a complete representation of the existing boiler population.[1]

In the United States, boilers are typically designed and constructed as either power or heating boilers in accordance with applicable requirements adopted by the American Society of Mechanical Engineers (ASME). Rules for power boilers are provided in Sect. I of the *ASME Boiler and Pressure Vessel Code*.[2] These rules apply to steam boilers that operate above 15 psig and hot water boilers that operate above 160 psig or 250°F. Common design pressures are 150, 200, 250, and 300 psig, but higher pressures are possible. [3] For example, boilers for certain pulp and paper industry applications are now designed for pressures as high as 1,500 psig. Corresponding rules for heating boilers are provided in Sect. IV.[4] According to these rules, heating boilers that produce hot water are not allowed to operate above 160 psig or at temperatures above 250°F at or near the boiler outlet. Additional rules limit heating boilers that produce steam to a maximum operating pressure of 15 psig.

Many boilers with heat input capacities more than 250 million British thermal units per hour (MBtu/h) are classified as utility boilers because they are used at power plants to produce electricity. Some boilers of this size are also used at paper mills and institutions and for other industrial applications. Smaller boilers with less capacity are categorized as ICI boilers. Industrial boilers are used extensively by the chemical, food processing, paper, and petroleum industries. They have heat input capacities up to and sometimes more than 250 MBtu/h. Commercial and institutional boilers are used in many other applications including commercial businesses, office buildings, apartments, hotels, restaurants, hospitals, schools, museums, government buildings, and airports.

In the past when emissions were less regulated, choosing the right boiler and combustion equipment for a particular application generally involved matching the process requirements with the boiler's output capacity. Proper sizing and selection required knowledge of the peak process requirements and an understanding of the load profile. This boiler selection philosophy emphasized energy conversion at the lowest possible cost. Reduced emphasis was placed on controlling emissions. Public concerns about air and water quality and enactment of federal, state, and local regulations have shifted this emphasis. The current design objective is to provide low-cost energy with an acceptable impact on the environment. As discussed in an engineering manual published by ABMA, control of PM, NO_x, CO, and SO_2 emissions is now a significant consideration in the overall boiler and combustion equipment design and selection process.[3]

2.1 TYPES OF ICI BOILERS

Information in this guide focuses primarily on a broad class of steam and hot water generating units known as ICI boilers. Because of differences in their features and characteristics, ICI boilers can be classified in at least three ways.

- Boilers are commonly subdivided into watertube or firetube units. These designations reflect the way the water and combustion gases are designed to pass through the unit.
- Boilers are sometimes classified by their heat sources. For example, boilers are often referred to as oil-fired, gas-fired, coal-fired, or solid fuel-fired boilers. Coal-fired boilers can be further divided based on the equipment used to fire the boiler. The three major coal-fired boiler subclasses are pulverized-coal (PC) fired, stoker-fired, and fluidized-bed combustion (FBC) boilers.
- Boilers are occasionally distinguished by their method of fabrication. Packaged boilers are assembled in a factory, mounted on a skid, and transported to the site as one package ready for hookup to auxiliary piping. Shop-assembled boilers are built up from a number of individual pieces or subassemblies. After these parts are aligned, connected, and tested, the entire unit is shipped to the site in one piece. Field-erected boilers are too large to transport as an entire assembly. They are constructed at the site from a series of individual components. Sometimes these components require special transportation and lifting considerations because of their size and weight.

The basic purpose of any ICI boiler is to convert the chemical energy in fuel into thermal energy that can be used to generate steam or hot water. Inside the combustion chamber, two fundamental processes must occur to achieve this objective. First, the fuel must be mixed with sufficient oxygen to allow sustained combustion. The heated gases produced by the combustion process must then transfer the thermal energy to a fluid such as water or steam. Various components inside the boiler are required to promote efficient combustion and heat transfer. Their design depends on factors such as the type of fuel and the method selected to transfer thermal energy.

The ICI boilers are manufactured in a wide range of sizes to burn coal, oil, natural gas, biomass, and RDFs as well as other fuels and fuel combinations. Most ICI boilers are classified as either watertube or firetube boilers, but other designs such as cast iron, coil-type, and tubeless (steel shell) boilers are also produced. Descriptions of some of the more typical boiler designs are presented below. Additional details about ICI boilers and their design, construction, and operation are available from other sources.[3,5–7]

2.1.1 Firetube Boilers

Firetube boilers consist of a series of straight tubes that are housed inside a water-filled outer shell. The tubes are arranged so that hot combustion gases flow through the tubes. As hot gases flow through the tubes, they heat the water that surrounds the tubes. The water is confined by the outer shell of the boiler. To avoid the need for a thick outer shell, firetube boilers are used for lower-pressure applications. Generally, the heat input capacities for firetube boilers are limited to 50 MBtu/h or less,[5] but in recent years the size of firetube boilers has increased.

Firetube boilers are subdivided into three groups. Horizontal return tubular (HRT) boilers typically have horizontal, self-contained firetubes with a separate combustion chamber. Scotch, Scotch marine, or shell boilers have the firetubes and combustion chamber housed within the same shell. Firebox boilers have a water-jacketed firebox and employ, at most, three passes of combustion gases. Boiler configurations for each type are shown in Figs. 2.1–2.3, respectively.

Most modern firetube boilers have cylindrical outer shells with a small round combustion chamber located inside the bottom of the shell. Depending on construction details, these boilers have tubes configured in either one, two, three, or four pass arrangements. Because the design of firetube boilers is simple, they are easy to construct in a shop and can be shipped fully assembled as a package unit. Table 2.1 identifies various types of firetube boilers and the associated fuels that they typically burn.

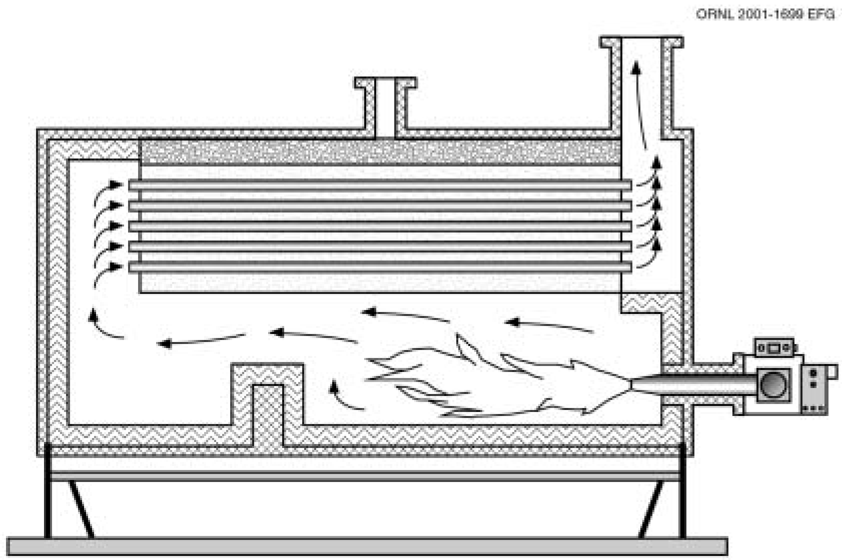

Fig. 2.1. Configuration of HRT firetube boiler.

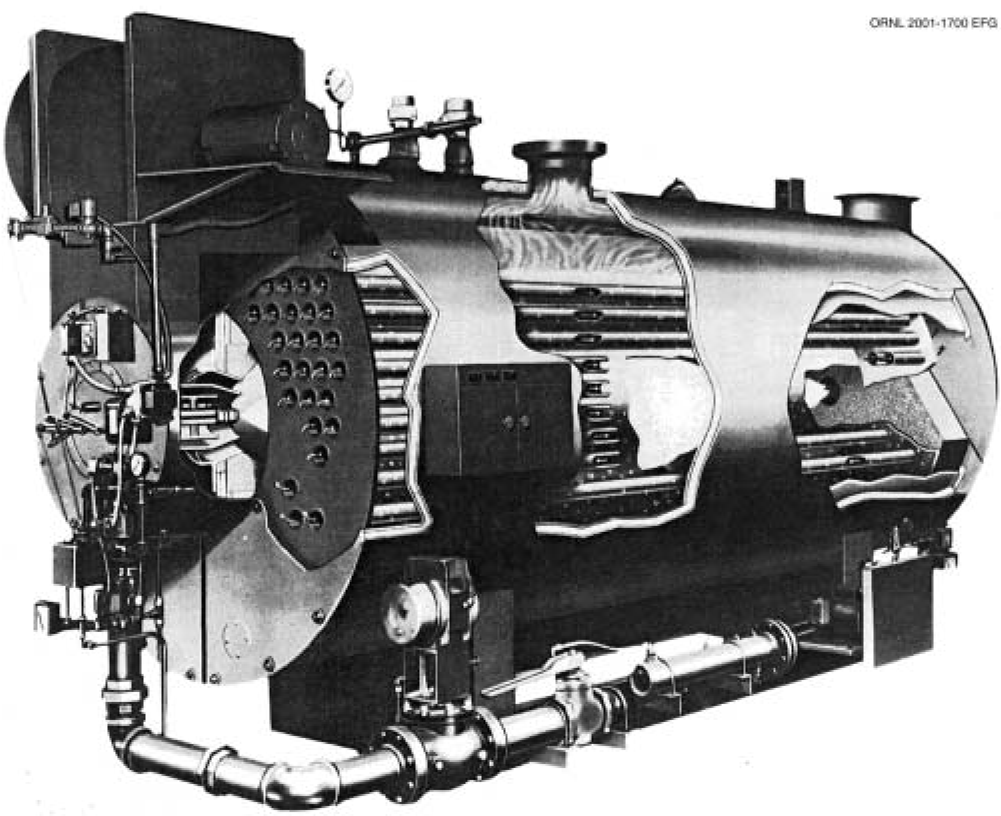

Fig. 2.2. Configuration of Scotch package firetube boiler. *Source*: Reprinted from Ref. 6.

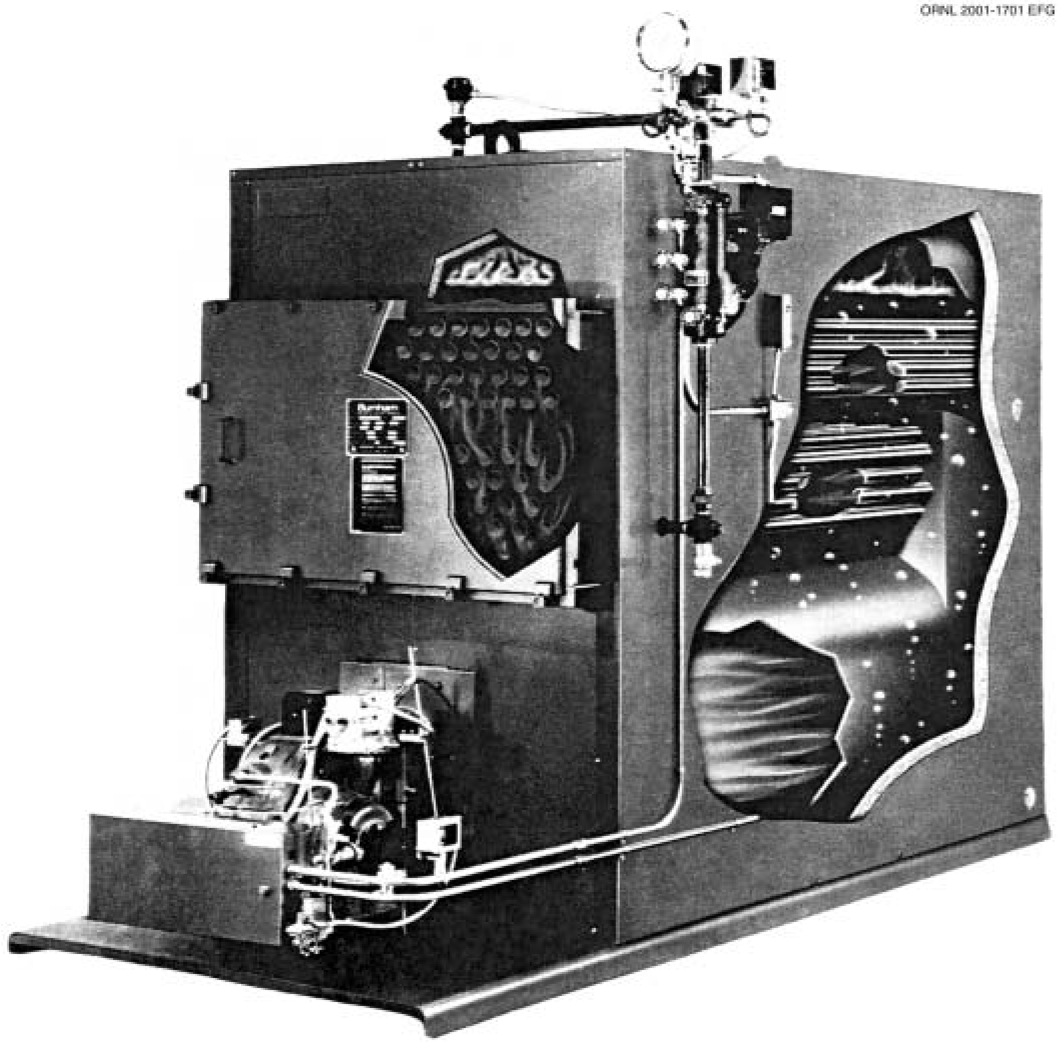

Fig. 2.3. Configuration of firebox firetube boiler. *Source*: Reprinted from Ref. 6.

Table 2.1. Fuels typically fired in ICI firetube boilers

Firetube boiler type	Fuel				
	Coal	Fuel oil	Natural gas	Biomass	Refuse-derived
HRT boilers	Yes	Yes	Yes	Yes	Yes
Scotch boilers	Yes	Yes	Yes	No	No
Firebox boilers	Yes	Yes	Yes	Yes	Yes

2.1.2 Watertube Boilers

Watertube boilers are designed to circulate hot combustion gases around the outside of a large number of water-filled tubes.[8] The tubes extend between an upper header, called a steam drum, and one or more lower headers or drums. In older designs, the tubes are either straight or bent into simple shapes. Newer boilers have tubes with complex and diverse bends. Because the pressure is confined inside the tubes, watertube boilers can be fabricated in larger sizes and used for higher-pressure applications. Small watertube boilers, which have one and sometimes two burners, are generally fabricated and supplied as packaged units. Because of their size and weight, large watertube boilers are often fabricated in pieces and assembled in the field. Configurations for packaged and field-erected watertube boilers are shown in Figs. 2.4 and 2.5, respectively.

Almost any solid, liquid, or gaseous fuel can be burned in a watertube boiler. Common fuels include coal, oil, natural gas, biomass, and other solid fuels such as municipal solid waste (MSW), tire-derived fuel (TDF), and RDF. Designs of watertube boilers that burn these fuels can be significantly different. Various watertube boilers and the fuels that they commonly burn are identified in Table 2.2. Configurations of boilers for burning RDF, MSW, and other solid fuel are shown in Figs. 2.6–2.8 (Ref. 9).

Coal-fired watertube boilers are classified into three major categories: stoker-fired units, PC-fired units, and FBC boilers.

Stoker-fired boilers include a mechanical system that is designed to feed solid fuel into the boiler. These stokers are designed to support the combustion process and to remove the ash as it accumulates. All stokers operate similarly. They use both undergrate and overfire air to burn fuel located on a grate. Different designs for stokers are described in Sect. 2.2.1.

The PC-fired boilers are generally large field-erected units such as the one shown in Fig. 2.9. During operation, finely ground coal is mixed with primary combustion air and fed to the burner or burners where it ignites. Secondary combustion air is then supplied to complete the combustion process. Depending on the location of the burners and the direction of coal injection, PC-fired boilers can be classified as single- or opposed-wall, tangential (corner), or cyclone boilers. Discussions about burners for PC-fired boilers are provided in Sect. 2.2.2. Depending on whether the ash is removed in a solid or

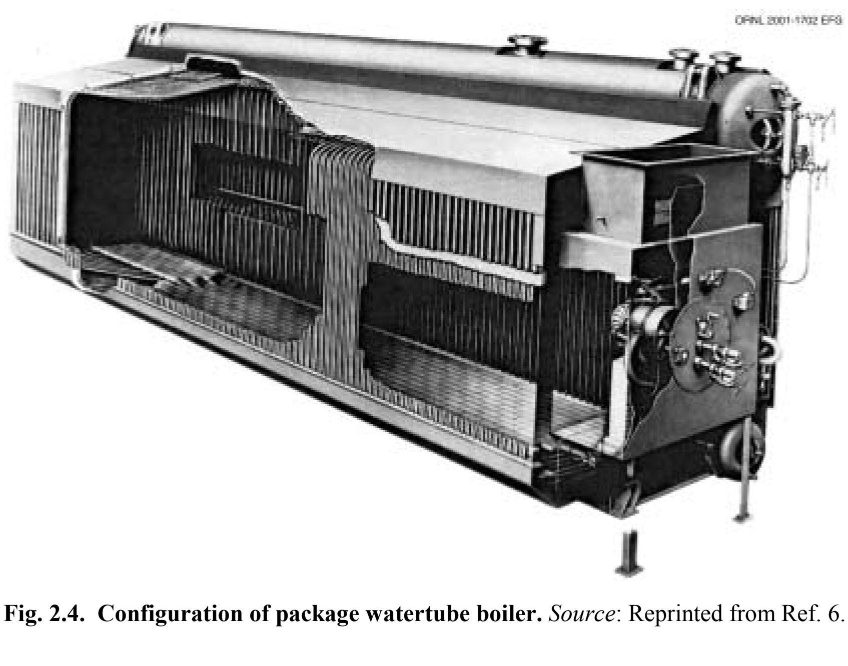

Fig. 2.4. Configuration of package watertube boiler. *Source*: Reprinted from Ref. 6.

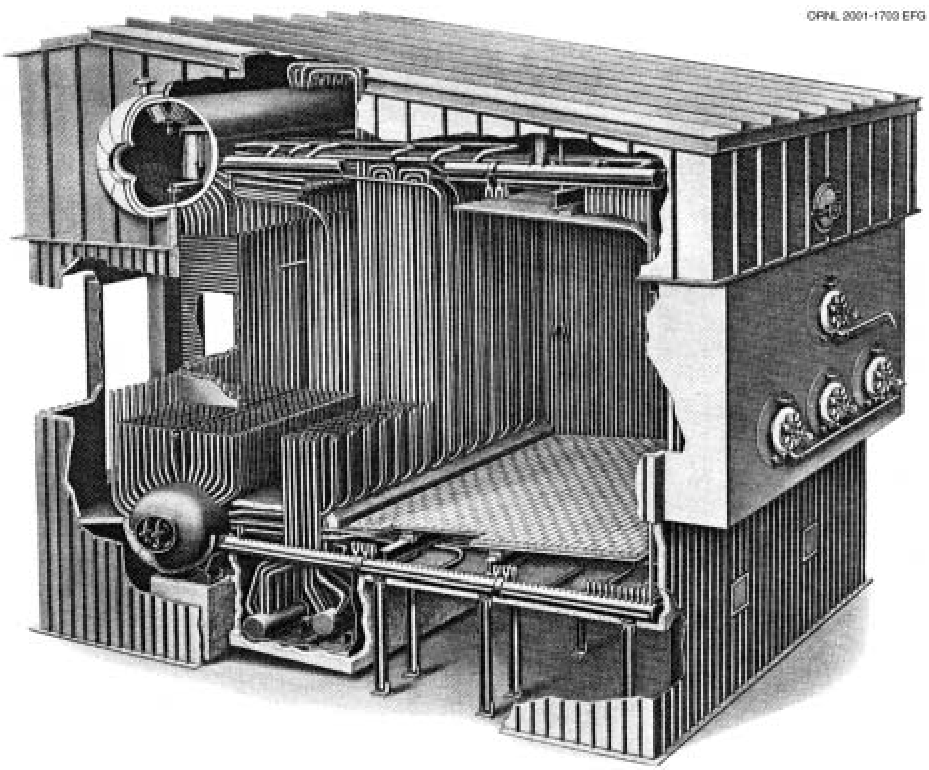

Fig. 2.5. Configuration of field-erected watertube boiler. *Source*: Reprinted from Ref. 6.

Table 2.2. Fuels typically fired in ICI watertube boilers

Watertube boiler	Fuel				
	Coal	**Fuel oil**	**Natural gas**	**Biomass**	**Refuse-derived**
Stoker-fired boilers	Yes for boilers with the following types of stokers	No	No	Yes for boilers with the following types of stokers	Yes for boilers with the following types of stokers
Underfeed stokers • Horizontal feed side-ash discharge • Gravity feed rear-ash discharge Overfeed stokers • Mass feed ✓ Water-cooled vibrating grate ✓ Moving (chain and traveling) grate • Spreader ✓ Traveling grate ✓ Air-cooled vibrating grate ✓ Water-cooled vibrating grate					
PC-fired boilers • Single or opposed-wall • Tangential (corner) • Cyclone	Yes for the following types of PC-fired boilers	*a*	*a*	No	No
FBC boilers • Atmospheric ✓ Bubbling ✓ Circulating • Pressurized	Yes for the following types of FBC boilers	*a*	*a*	Yes for the following types of FBC boilers	Yes for the following types of FBC boilers
Package boilers • "A" • "D" • "O"	No	Yes for the following types of package boilers	Yes for the following types of package boilers	No	No

[a]Gas or oil is often used at start-up.

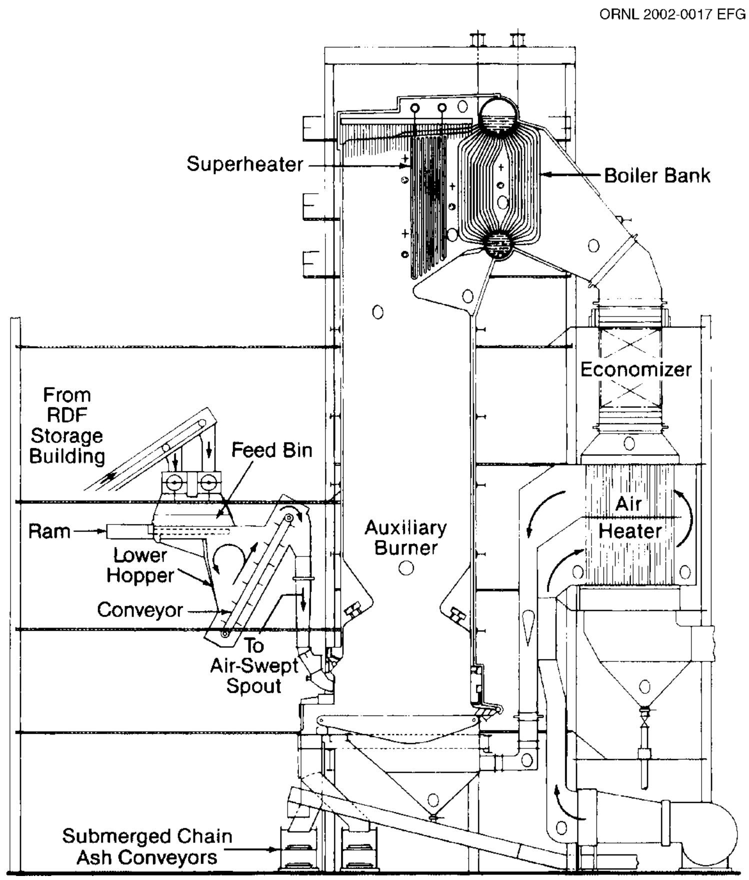

Fig. 2.6. Configuration of watertube boiler for burning RDF. *Source:* Reprinted from Ref. 9.

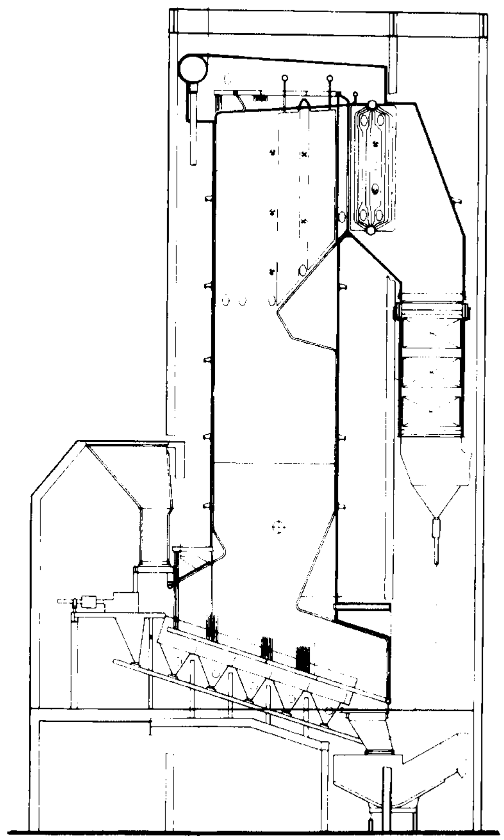

Fig. 2.7. Configuration of watertube boiler for burning MSW. *Source:* Reprinted from Ref. 9.

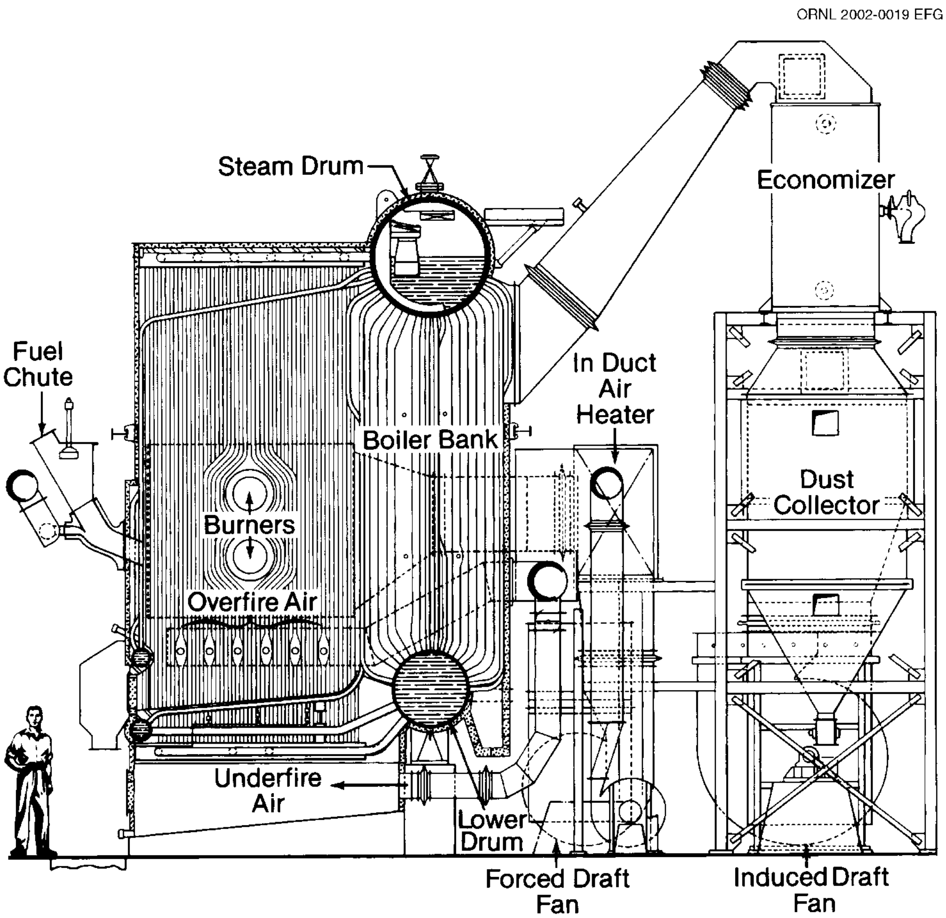

Fig. 2.8. Configuration of watertube boiler for burning solid fuel such as wood, biomass, or stoker coal. *Source:* Reprinted from Ref. 9.

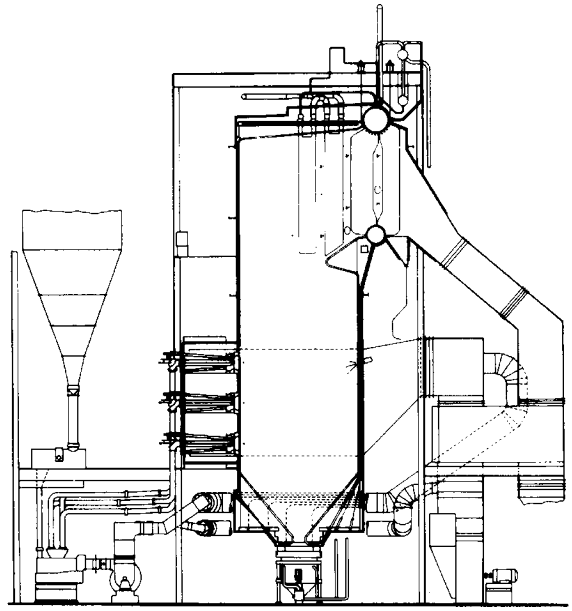

Fig. 2.9. Configuration of watertube boiler for burning PC. *Source:* Reprinted from Ref. 9.

molten state, PC-fired boilers are also classified as dry or wet bottom. Opposed-wall boilers are usually much larger than 250-MBtu/h heat input capacity. They are used primarily for utility but may be suitable for certain industrial applications. Coal burned in cyclone boilers is crushed rather than pulverized.

The FBC boilers are capable of burning a wide range of solid fuels. In this method of combustion, fuel is burned in a bed of hot incombustible particles suspended by an upward flow of fluidizing gas such as air. Fuels that contain a high concentration of ash, sulfur, and nitrogen can be burned efficiently while meeting stringent emission limitations. When sulfur capture is not required, inert materials such as alumina may be added to supplement the fuel ash and maintain the bed. In applications where sulfur capture is required, limestone is incorporated into the bed and used as the sorbent.[10] The FBC boilers are categorized as either atmospheric or pressurized units. Atmospheric FBC boilers are further divided into bubbling-bed and circulating-bed units; the fundamental difference between these two is the fluidization velocity. Coal is often burned in FBC boilers, but it is also possible to burn biomass and other solid fuels. Natural gas or fuel oil is used primarily as a start-up fuel to preheat the fluidized bed or as an auxiliary fuel when additional heat is required. Configurations of various types of FBC boilers are shown in Figs. 2.10–2.12.

Combustion of other solid fuels, including MSW and RDF, is often accomplished in a boiler with a stoker system. Fuels of this type generally have specially designed feed systems for supplying and distributing the fuel particles. Boilers that burn these fuels are also specially designed to interface with the fuel feed system and to burn the fuel as efficiently as possible. Many boilers that burn solid nonfossil fuels have some type of fossil fuel firing capability. These auxiliary fuels are used during start-up operations, as a supplementary fuel, or alone when the primary fuel is unavailable.

Nonfossil gaseous fuels that are rich in CO and hydrogen can also be burned in watertube boilers. These fuels can be generated by the partial combustion of biomass using gasification or pyrolysis techniques.

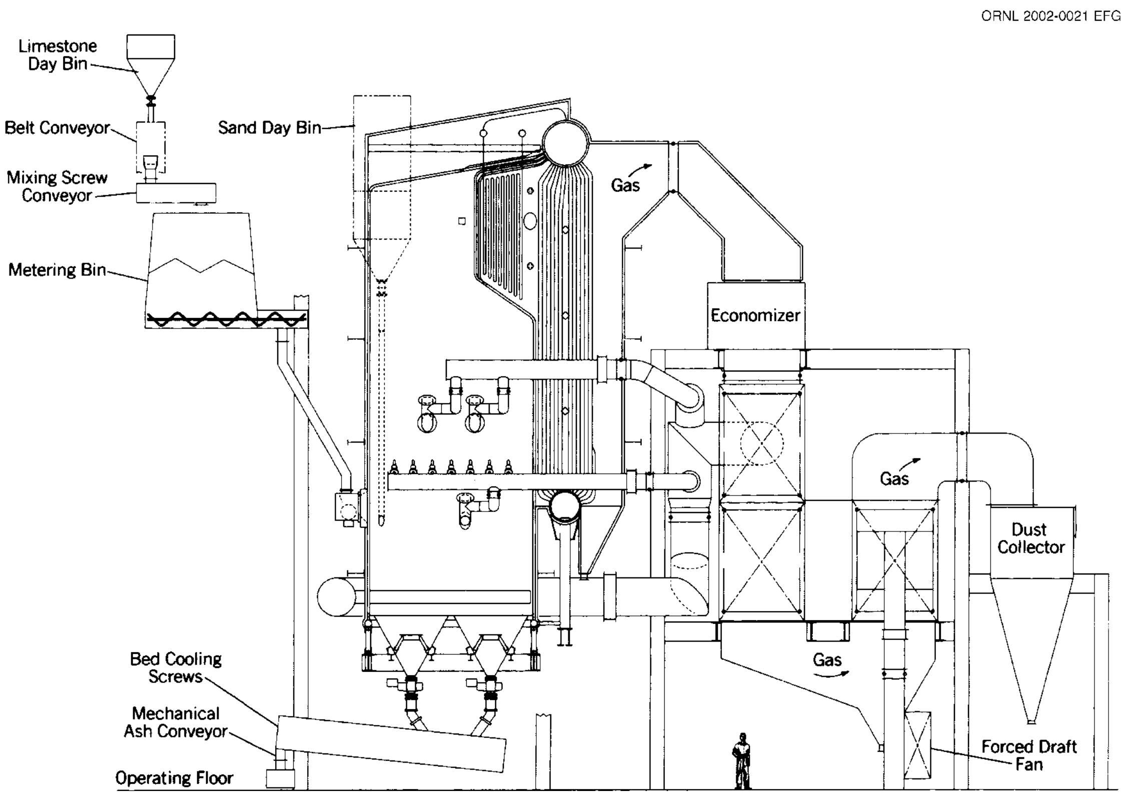

Fig. 2.10. Configuration of bubbling FBC watertube boiler. *Source:* Reprinted from Ref. 9.

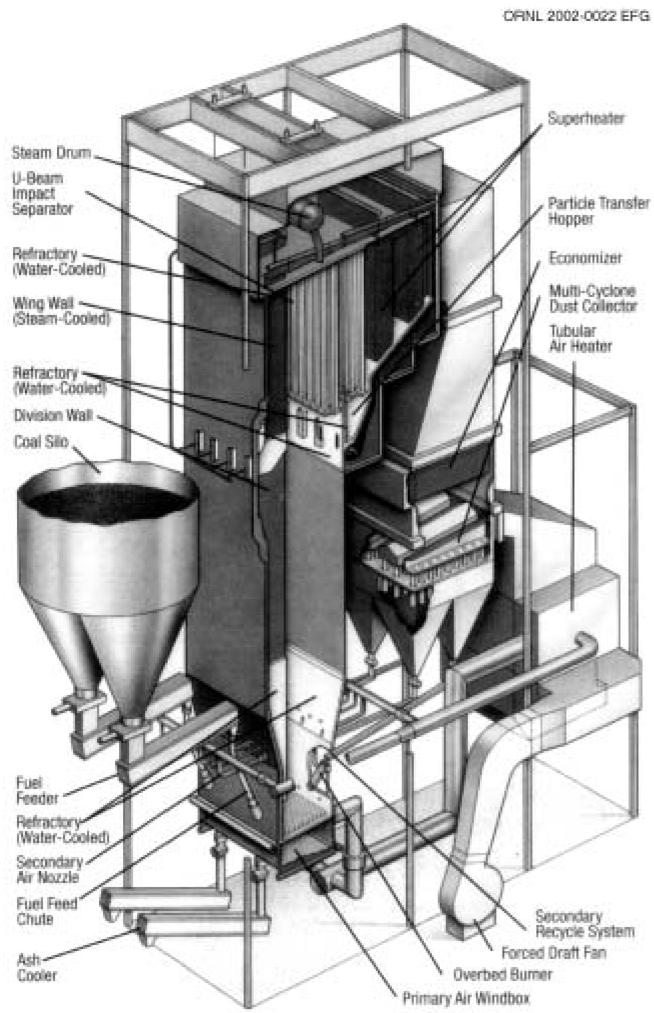

Fig. 2.11. Configuration of circulating FBC watertube boiler. *Source*: Reprinted from Ref. 9.

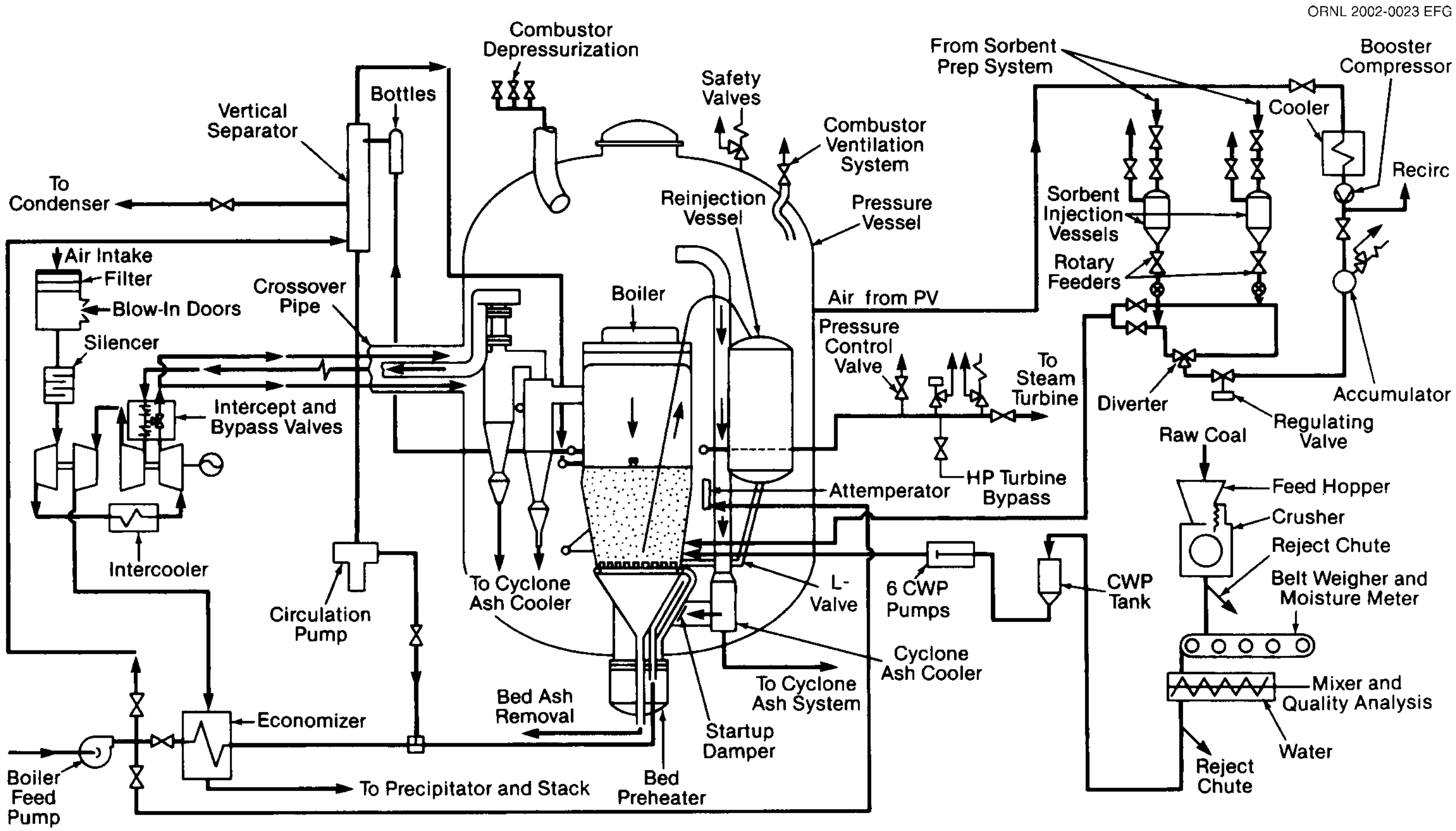

Fig. 2.12. Configuration of pressurized FBC boiler system. *Source:* Reprinted from Ref. 9.

Fuel oil-fired and natural gas-fired watertube package boilers are subdivided into three classes based on the geometry of the tubes. The "A" design has two small lower drums and a larger upper drum for steam-water separation. In the "D" design, which is the most common, the unit has two drums and a large-volume combustion chamber. The orientation of the tubes in a "D" boiler creates either a left- or right-handed configuration. For the "O" design, the boiler tube configuration exposes the least amount of tube surface to radiant heat. Rental units are often "O" boilers because their symmetry is a benefit in transportation. Figures 2.13–2.15 show tube configurations for each of these watertube package boiler designs.

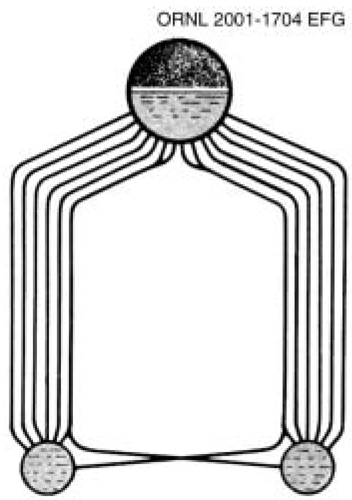

Fig. 2.13. Configuration of tubes for "A" package watertube boiler. *Source*: Reprinted from Ref. 11.

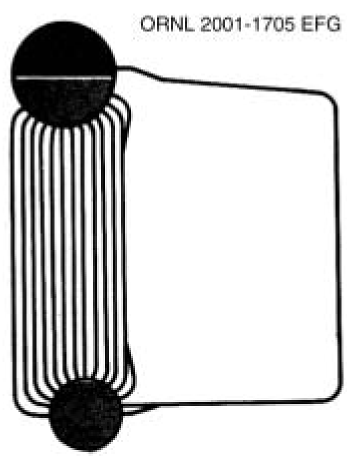

Fig. 2.14. Configuration of tubes for "D" package watertube boiler. *Source*: Reprinted from Ref. 11.

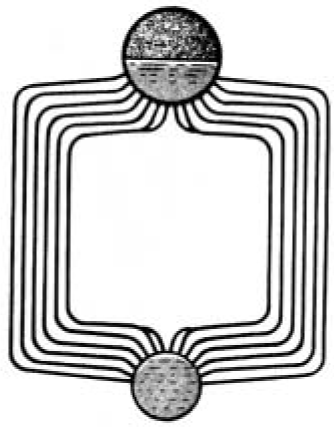

Fig. 2.15. Configuration of tubes for "O" package watertube boiler. *Source*: Reprinted from Ref. 11.

2.1.3 Other Combustion Boilers

Cast iron boilers are fabricated from a number of cast iron sections that are bolted together. The design of each section includes integral water and combustion gas passages. When fully assembled, the interconnecting passages create chambers where heat is transferred from the hot combustion gases to the water. These boilers generally produce low-pressure steam (15 psig) or hot water (30 psig) and burn either oil or natural gas. Only about 12% of the cast iron boilers in the United States are fired by coal.

Because of their construction, cast iron boilers are limited to smaller sizes. Only 37% have heat input capacities greater than 0.4 MBtu/h (Ref. 5). Because the components of these boilers are relatively small and easy to transport, they can be assembled inside a room with a conventional-size doorway. This feature means that cast iron boilers are often used as replacement units, which eliminate the need for temporary wall removal to provide access for larger package units. Cast iron boilers represent only about 10% of the ICI boiler capacity in the United States. The configuration of a cast iron boiler is shown in Fig. 2.16.

Another boiler that is sometimes used to produce steam or hot water in known as a tubeless boiler. The design of tubeless boilers incorporates nested pressure vessels with water located between the shells.[5] Combustion gases are fired into the inner vessel where heat is transferred to water located between the outside surface of the inner shell and the inside surface of the outer shell. For oil-fired and natural-gas-fired vertical tubeless boilers, the burner is typically located at the bottom of the boiler and fires into the inner pressure vessel. The configuration of a vertical tubeless boiler is shown in Fig. 2.17.

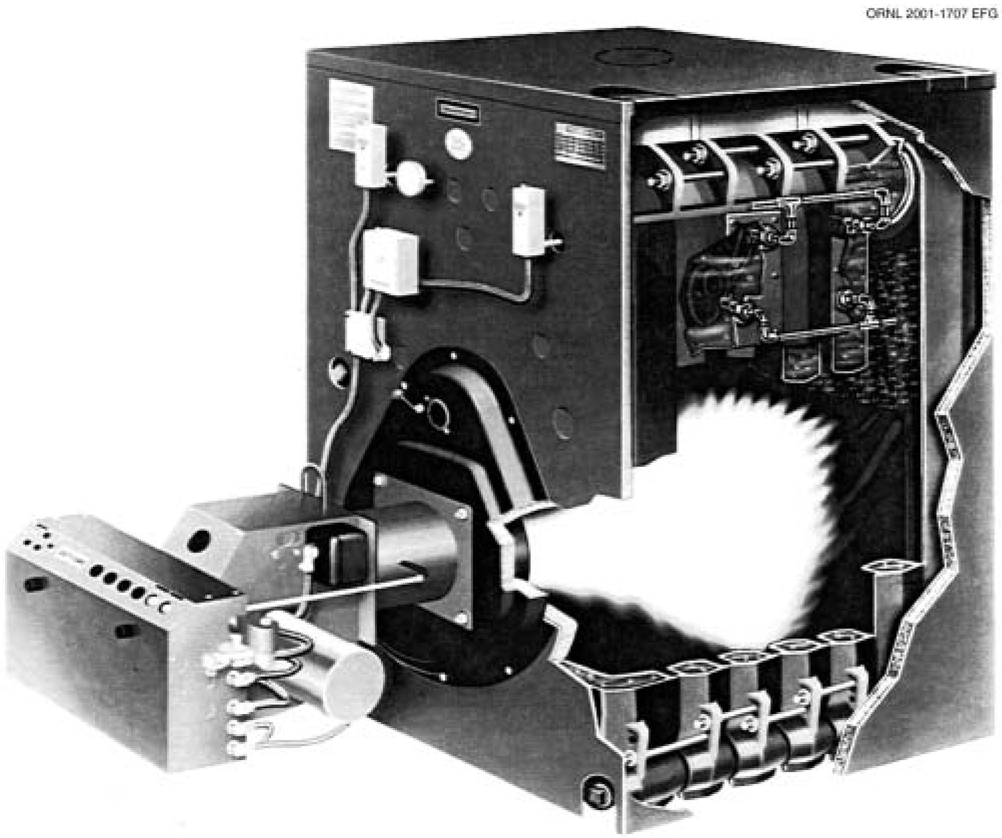

Fig. 2.16. Configuration of cast iron boiler. *Source*: Reprinted from Ref. 6.

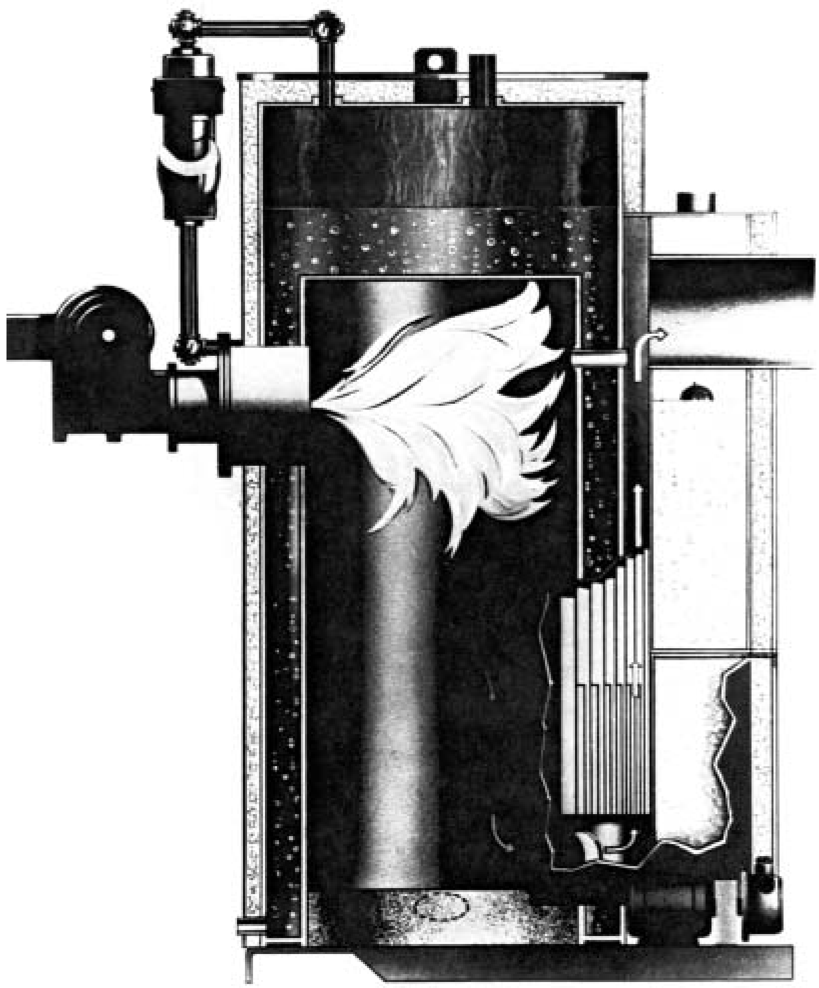

Fig. 2.17. Configuration of vertical tubeless boiler. *Source*: Reprinted from Ref. 6.

2.2 FUEL FEED SYSTEMS

Fuel feed systems play a critical role in the performance of low-emission boilers. Their primary functions include (1) transferring the fuel into the boiler and (2) distributing the fuel within the boiler to promote uniform and complete combustion. The type of fuel and whether the fuel is a solid, liquid, or gas influences the operational features of a fuel feed system.

Gaseous fuels are relatively easy to transport and handle. Any pressure difference will cause gas to flow, and most gaseous fuels mix easily with air. Because on-site storage of gaseous fuel is generally not feasible, boilers must be connected to a fuel source such as a natural gas pipeline. Flow of gaseous fuel to a boiler can be precisely controlled using a variety of control systems. These systems generally include automatic valves that meter gas flow through a burner and into the boiler based on steam or hot water demand. The purpose for the burner is to increase the stability of the flame over a wide range of flow rates by creating a favorable condition for fuel ignition and establishing aerodynamic conditions that ensure good mixing between the primary combustion air and the fuel. Burners are the central elements of an effective combustion system. Other elements of their design and application include equipment for fuel preparation and air-fuel distribution as well as a comprehensive system of combustion controls.

Like gaseous fuels, liquid fuels are also relatively easy to transport and handle by using pumps and piping networks that link the boiler to a fuel supply such as a fuel oil storage tank. To promote complete combustion, liquid fuels must be atomized to allow thorough mixing with combustion air. Atomization by air, steam, or pressure produces tiny droplets that burn more like gas than liquid. Control of boilers that burn liquid fuels can also be accomplished using a variety of control systems that meter fuel flow.

Solid fuels are much more difficult to handle than gaseous and liquid fuels. Preparing the fuel for combustion is generally necessary and may involve techniques such as crushing or shredding. Before combustion can occur, the individual fuel particles must be transported from a storage area to the boiler. Mechanical devices such as conveyors, augers, hoppers, slide gates, vibrators, and blowers are often used for this purpose. The method selected depends primarily on the size of the individual fuel particles and the properties and characteristics of the fuel. Stokers are commonly used to feed solid fuel particles such as crushed coal, TDF, MSW, wood chips, and other forms of biomass into boilers. Mechanical stokers evolved from the hand-fired boiler era and now include sophisticated electromechanical components that respond rapidly to changes in steam demand. The design of these components provides good turndown and fuel-handling capability. In this context, turndown is defined as the ratio of maximum fuel flow to minimum fuel flow. Although stokers are used for most solid fuels, PC combustion, which consists of very fine particles, does not involve a stoker. Coal in this form can be transported along with the primary combustion air through pipes that are connected to specially designed burners.

The following discussions about stokers and burners are only intended to provide background information about these devices. Because the characteristics of stokers and burners are very complex and highly technical, the information does not address detailed issues associated with their design, construction, theory of operation, or performance. Because of concerns about revealing proprietary information, these discussions are intentionally generic in nature. Specific details about a particular product or design should be obtained from the manufacturer.

2.2.1 Stokers

Firing systems that involve stokers must be integrated into the overall boiler design to optimize combustion and heat recovery while minimizing unburned fuel and atmospheric emissions. Modern mechanical stokers consist of (1) a fuel admission system, (2) a stationary or moving grate assembly that supports the burning fuel and provides a pathway for the primary combustion air, (3) an overfire air (OFA) system that supplies additional air to complete combustion and minimize atmospheric emissions, and (4) an ash discharge system.[12] Stoker-firing systems are typically categorized as either underfeed or overfeed stokers.

2.2.1.1 Underfeed stokers

Underfeed stokers supply both fuel and primary combustion air from beneath the grate. The fuel is moved into a hopper and onto the grate by either a screw or ram-driven mechanism. As the fuel moves out over the grate where it is exposed to air and radiant heat, it begins to burn. During the combustion process, ash accumulates. To reduce the tendency for clinker formation, it is sometimes necessary to use moving grates that agitate the burning fuel bed. The two basic types of underfeed stokers are the (1) horizontal-feed, side-ash discharge type and (2) the less popular gravity-feed, rear-ash discharge type.[12] The cross section of an underfeed, side-ash discharge stoker is shown in Fig. 2.18. Because of cost and environmental considerations, the demand for underfeed stokers has diminished.

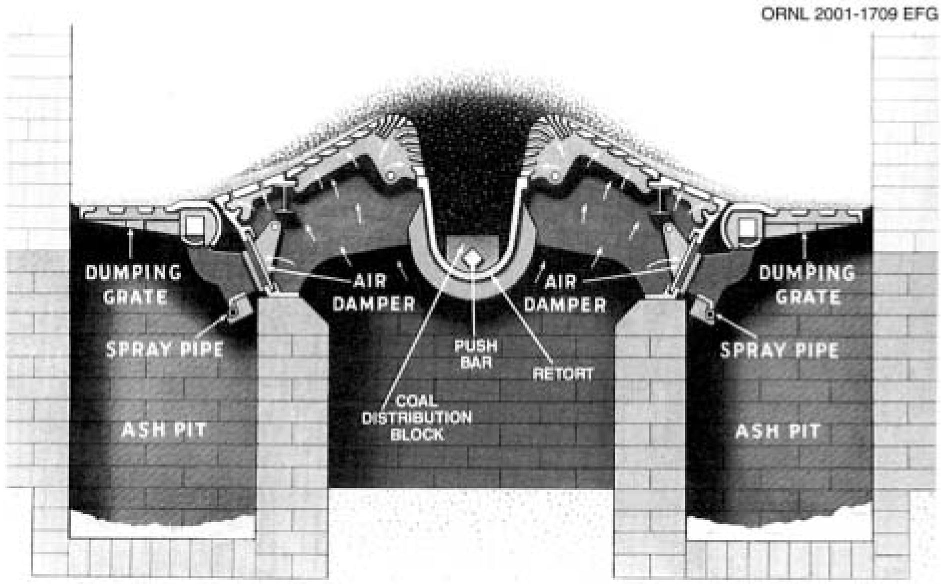

Fig. 2.18. Cross section of underfeed, side-ash discharge stoker. *Source*: Reprinted from Ref. 11.

2.2.1.2 Overfeed stokers

Overfeed stokers are generally classified as either mass-feed or spreader stokers. These designations reflect the way that the fuel is distributed and burned within the boiler.

Mass-feed stokers introduce fuel continuously at one end of a grate. As the fuel moves into the boiler, it falls onto the grate by gravity. The height of the fuel bed is controlled in two ways. A gate can be moved up or down to regulate the amount of fuel that is allowed to enter the boiler, and the speed at which the fuel moves beneath the gate can be adjusted. Inside the boiler, the fuel burns as it travels along the grate. Ash that forms and remains on the grate is discharged at the opposite end. Primary combustion air flows upward from beneath the grate and through the burning bed of fuel. The two primary mass-feed stokers are (1) water-cooled vibrating grate and (2) moving (chain and traveling) grate stokers.[12] Cross sections of (1) an overfeed, water-cooled, vibrating-grate, mass-feed stoker and (2) an overfeed, water-cooled, traveling-grate, mass-feed stoker are shown in Figs. 2.19 and 2.20, respectively.

Spreader stokers are very versatile and the most commonly used stoker. They are capable of distributing fuel evenly and to a uniform depth over the entire grate surface by using a device that propels the individual fuel particles into the air above the grate. Methods used to propel the fuel particles include air injection and underthrow and overthrow rotors. As the fuel is thrown into the boiler, fines ignite and burn in suspension. Because of suspension burning, response time of spreader stokers is better than mass-feed or underfeed stokers. The coarser particles fall onto the grate and burn in a thin bed. Primary combustion air is supplied from an air plenum located beneath the grate. The OFA ports supply the additional air that is needed to complete the combustion process. Grates for spreader stokers are generally designed to move rather than remain stationary. Traveling grates, air-cooled vibrating grates, and water-cooled vibrating grates are designs that have been used successfully. Cross sections of (1) an overfeed, traveling-grate, spreader stoker; (2) an overfeed air-cooled, vibrating-grate, spreader stoker;

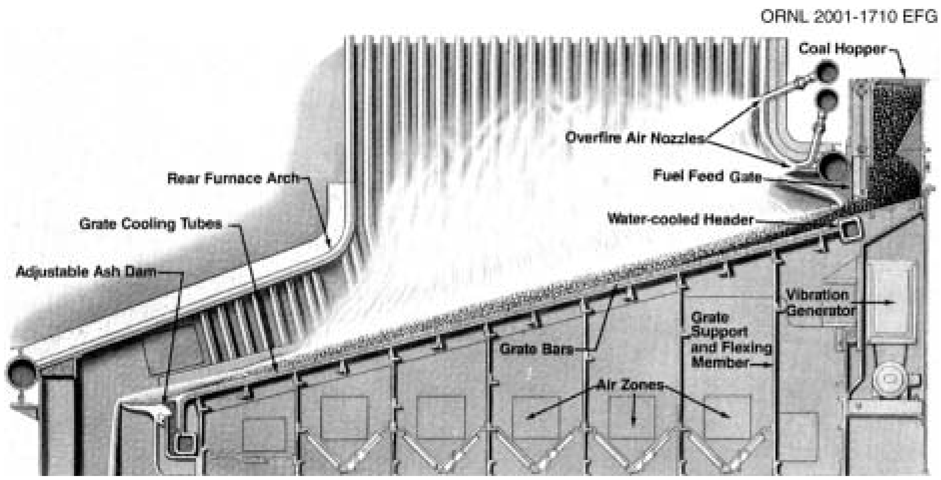

Fig. 2.19. Cross section of overfeed, water-cooled, vibrating-grate, mass-feed stoker. *Source*: Reprinted from Ref. 11.

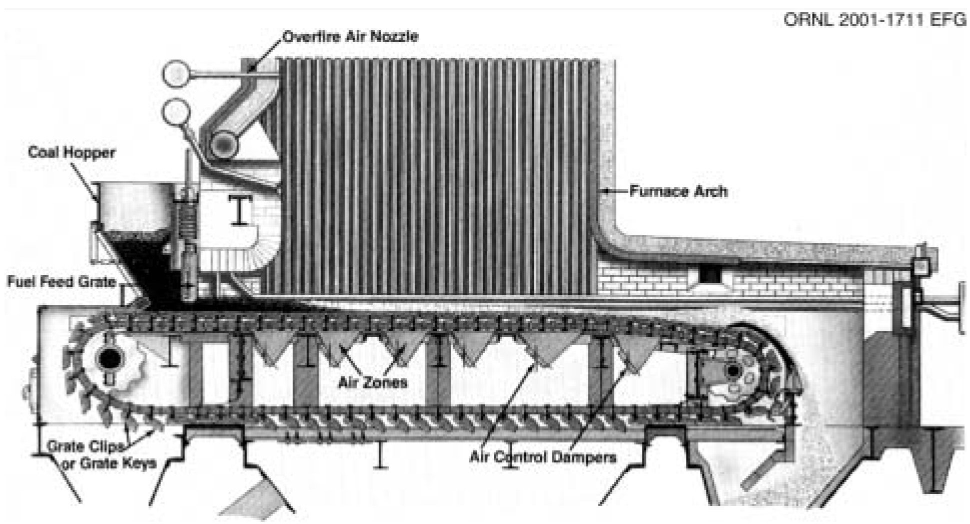

Fig. 2.20. Cross section of overfeed, traveling-grate, mass-feed stoker. *Source*: Reprinted from Ref. 11.

and (3) an overfeed water-cooled, vibrating-grate, spreader stoker are shown in Figs. 2.21–2.23, respectively. Spreader stokers with stationary water-cooled grates are used primarily in the sugar industry to burn bagasse. Modern boilers with spreader stokers consist of

- units that distribute fuel uniformly over the grate,
- specially designed air-metering grates,
- dust collection and reinjection equipment,
- blowers for OFA,
- forced draft fans for both undergrate and OFA, and
- combustion controls to coordinate fuel and air supply with steam demand.[12]

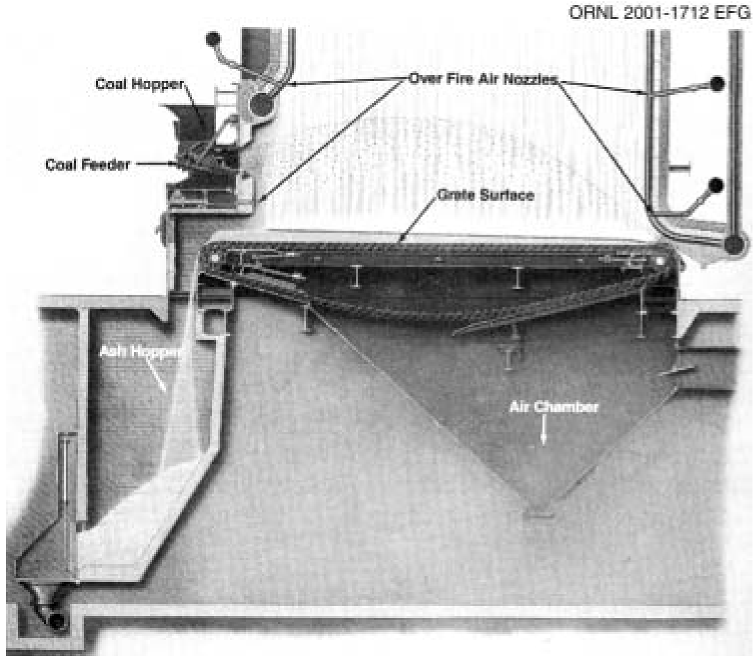

Fig. 2.21. Cross section of overfeed, traveling-grate, spreader stoker. *Source*: Reprinted from Ref. 11.

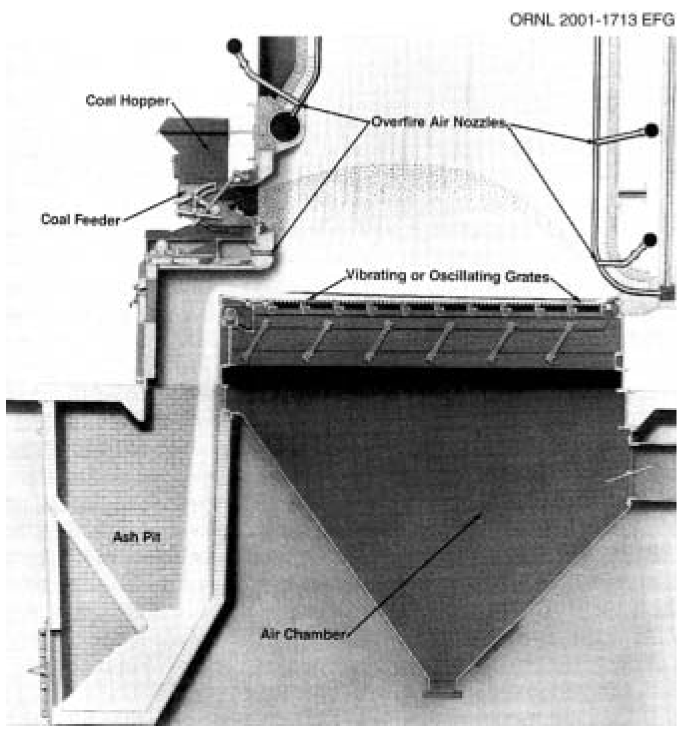

Fig. 2.22. Cross section of overfeed air-cooled, vibrating-grate, spreader stoker. *Source*: Reprinted from Ref. 11.

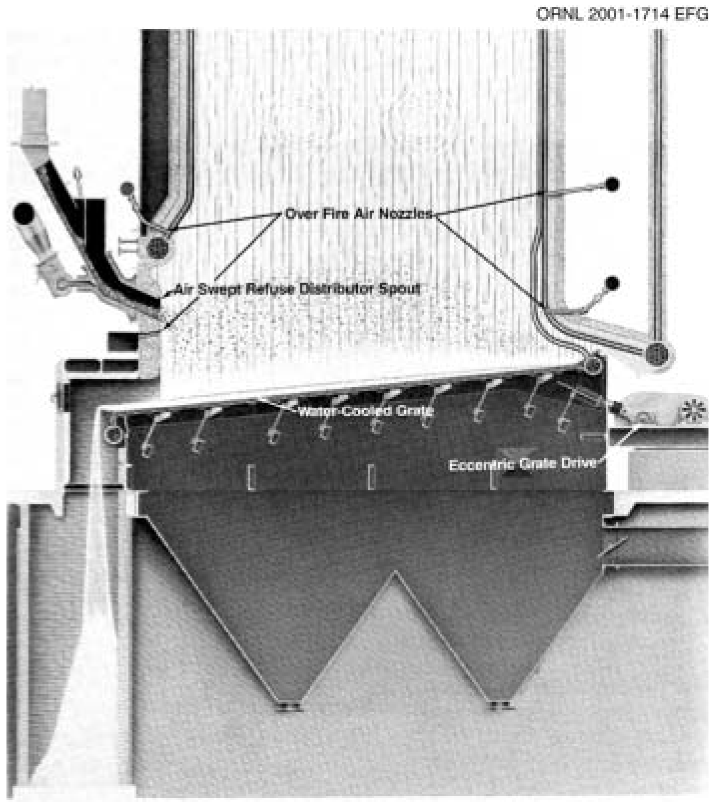

Fig. 2.23. Cross section of overfeed, water-cooled, vibrating-grate, spreader stoker. *Source*: Reprinted from Ref. 11.

2.2.2 Burners

A burner is defined as a device or group of devices for the introduction of fuel and air into a furnace at the required velocities, turbulence, and concentration to maintain ignition and combustion of fuel within the furnace. Burners for gaseous fuels are less complex than those for liquid or solid fuels because mixing of gas and combustion air is relatively simple compared to atomizing liquid fuel or dispersing solid fuel particles.

There is no formal classification system for burners, but attempts to combine desirable burner characteristics have given rise to a rich diversity in burner designs.[13] Terminology used to identify burners that have been in existence for a long time as well as advanced burners that are based on emerging technology is listed in Table 2.3.

The ability of a burner to mix combustion air with fuel is a measure of its performance. A good burner mixes well and liberates a maximum amount of heat from the fuel. The best burners are engineered to liberate the maximum amount of heat from the fuel and limit the amount of pollutants such as CO, NO_x, and PM that are released. Burners with these capabilities are now used routinely in boilers that must comply with mandated emission limitations. Emission control techniques that are effective in reducing NO_x, CO, SO_2, and PM emissions are described in Chap. 5.

An effective way to minimize NO_x emissions is to use a low-NO_x burner (LNB). These burners employ various strategies for mixing the fuel with combustion air to reduce the formation of NO_x. Two

Table 2.3. Terminology used to identify burners

Air-atomizing oil burner
Atmospheric gas burner
Dual-fuel burner
Forced internal recirculation (FIR) burner
Low-NO_X burner (LNB)
Modulating gas power burner
Modulating pressure-atomizing oil burner
Multistage pressure-atomizing oil burner
On-off burner
Premix burner
Premix radiant burner
Premix surface burner
Premix surface-stabilized burner
PC burner
Rapid-mix burner
Rotary cup oil burner
Single-stage gas power burner
Single-stage pressure-atomizing oil burner
Staged gas power burner
Steam-atomizing oil burner
Ultra low-NO_X burner (ULNB)

techniques often used for this purpose include (1) introducing the fuel and air at different stages, and (2) recirculating flue gas with fresh combustion air. The LNBs that can be retrofitted to existing boilers have been developed and are currently being marketed. Complete systems that integrate LNBs into new and efficient boiler designs are also available.

Ultra low-NO_X burners (ULNBs) use emerging technology to reduce NO_X and CO emissions to extremely low levels. These burners are specifically designed to burn clean gaseous fuels such as natural gas that are essentially free of fuel-bound nitrogen. Discussions about ULNBs and the techniques used to minimize thermal and prompt NO_X formation are presented in Sect. 5.2.1.6.

Many vendors of conventional LNBs and ULNBs are members of the ABMA. This organization represents the manufacturers of commercial, industrial, and utility steam-generating and fuel-burning equipment, as well as suppliers to the industry. In general, technical information about the design of a particular LNB and its in-service performance can only be obtained from the manufacturer.

2.3 EMISSION RATES

Use of boilers for steam and hot water production is not limited to any particular geographic location. Consequently, atmosphere emissions resulting from fuel combustion can affect the human and natural environment over a wide area.[14] In the United States, emissions of air pollutants from boilers are regulated under the CAA.[15] This federal legislation was amended in 1990 to address specific concerns about ground-level ozone, the accumulation of fine particles in the atmosphere, the development of acid rain, the acidification of aquatic systems, HAPs, and visibility limitations. To effectively achieve national ambient air quality goals, EPA is authorized to establish maximum emission rates for selected pollutants from new and existing steam-generating units. This action ensures that some level of emission control is applied in all areas, irrespective of ambient air quality considerations. The degree of emissions limitation is achieved through the application of the best system of emission reduction, which has been adequately demonstrated. Such systems are referred to as Best Available Control Technology (BACT). Conditions under which reasonably available control technology (RACT), BACT, and lowest achievable emissions rate (LAER) must be applied are discussed in Chap. 4. State and local governments are also authorized to establish emission limits that are more stringent than federal requirements.

Major emissions from combustion boilers include NO_x, SO_2, CO, and PM. The amount of each pollutant discharged into the atmosphere is influenced by factors such as the fuel consumed and the method by which it is fired, the design features of the boiler, the way the boiler is operated, and the completeness of combustion. Achieving the required emissions reductions involves the use of precombustion, combustion, or postcombustion emission control techniques, or a combination of techniques. Emissions limitations that have been established by EPA for electric utility and ICI steam-generating units are summarized in Appendix A.

One of the main reasons for selecting and installing low-emission boilers and combustion equipment is to reduce NO_x, SO_2, CO, and PM emissions. As discussed in Sect. 4.1, it may also be necessary in the near future to reduce HAP emissions from certain combustion boilers. Although suitable control techniques for reducing emissions vary from one unit to another, assessing the effectiveness of a particular technique requires knowledge about uncontrolled and controlled emission rates. From a regulatory viewpoint, maximum allowable emissions rates are typically specified in units of pounds per million British thermal units of heat input or as a percent of theoretical emissions.

2.3.1 Uncontrolled Emissions

Theoretical or uncontrolled emissions are defined as emissions that would result from combustion of a fuel in an uncleaned state without emission controls. The term used by EPA to quantify uncontrolled emissions is potential combustion concentration.[16] For utility boilers with at least 250-MBtu/h heat input capacity, EPA has defined the following potential combustion concentrations for specific types of fuel.

For PM:
- 7.0-lb/MBtu heat input for solid fuels
- 0.17-lb/MBtu heat input for liquid fuels

For NO_x:
- 0.67-lb/MBtu heat input for gaseous fuels
- 0.72-lb/MBtu heat input for liquid fuels
- 2.30-lb/MBtu heat input for solid fuels

Currently, there are no corresponding potential combustion concentrations for NO_x and PM emissions from ICI boilers. However, EPA has developed emission factors for a variety of pollutants emitted from external combustion sources, including SO_2 and HAPs.[17] External combustion sources include steam-generating plants for electricity, industrial boilers, and commercial and domestic combustion units. These emission factors are cited in numerous EPA publications and appear in various electronic databases. The process details and supporting reference materials on which these data are based have been compiled and published.[17] Uncontrolled emissions from combustion sources depend on the composition of the fuel and the type of boiler. For example, for SO_2, the emission factor representing uncontrolled emissions from a spreader stoker-fired boiler that burns bituminous coal is 38S lb/ton of coal, where S is the weight percent sulfur content of coal as fired.

Ranges of uncontrolled NO_x emissions are reported in ABMA and EPA publications.[5,6,17] Data reported in these sources provide valuable insight into the level of emissions that can be expected from different types of boilers and combustion equipment. Although NO_x emission factors for many boiler and fuel combinations are listed, it is not always possible to make meaningful data comparisons. Variations in reporting methods, presentation formats, and boiler classification schemes account for some of the uncertainty. Accurate determinations of NO_x emissions are most reliably obtained using standardized testing methods designed to minimize the influence of boiler design, method of firing, condition of combustion equipment, operational characteristics, fuel composition, and various other site-specific parameters on the test results. Test methods for determining NO_x emissions are published by ASTM and EPA.[18–25] These methods describe analytical techniques and procedures that are suitable for specific applications.

Uncontrolled emissions of SO_2 are directly influenced by the amount of sulfur contained in the fuel. Natural gas contains essentially no sulfur, while other fuels such as coal and fuel oil often contain significant amounts of sulfur-bearing compounds. Test methods for determining the sulfur content of coal, fuel oil, and liquefied petroleum (LP) gas are referenced in applicable fuel specifications published by ASTM.[26–28] Results of sulfur-content testing are useful in evaluating potential SO_2 emissions because any sulfur in fuel that is not removed along with the ash oxidizes to SO_2. Test methods for determining SO_2 emissions are published by EPA.[25,29–32]

The PM emissions are a function of the noncombustible material or ash contained in the fuel. As with SO_2, test methods for determining the ash content of coal, fuel oil, and LP gas are referenced in applicable fuel specifications published by ASTM.[26–28] Results of ash-content testing are useful in evaluating potential PM emissions because all noncombustible materials that enter the boiler and are not removed as ash become PM emissions. Test methods for determining PM emissions are published by EPA.[25,33–35]

2.3.2 Controlled Emissions

In the United States, emissions of NO_x, SO_2, and PM from most utility and ICI boilers must be controlled by the application of one or more emission control techniques. Because there is no practical way to totally eliminate all emissions from fuel combustion, emission limits have been established to address a variety of concerns about atmospheric pollution on the human and natural environment. These limits, which are specified in units of pounds per million British thermal units or as a percent of potential combustion concentration, are based on federal and, in certain cases, more stringent state emissions standards. Discussions about emission limits in federal regulations are presented in Chap. 4. Descriptions of emission control techniques are presented in Chap. 5.

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3. FUELS, EMISSIONS, AND EFFICIENCY

Conversion of water to steam requires sufficient heat to cause the water to boil. Although a variety of energy sources, including nuclear energy and solar radiation, can produce the required amount of heat, combustion of a fuel in the presence of oxygen is the most common source. Combustion is a rapid chemical reaction between oxygen and a solid, liquid, or gaseous fuel. Oxygen required for this reaction is readily available in the air. As air and fuel are mixed at elevated temperatures, the oxygen reacts with carbon, hydrogen, and other elements in the fuel to produce heat. As long as fuel and air are both available, combustion will continue, and heat will be generated.

Heat produced during combustion is useful for a wide variety of applications; however, atmospheric emissions, which are also generated as by-products of the combustion process, must be controlled. Common gaseous emissions include SO_2, NO_x, water vapor, carbon dioxide (CO_2), and CO. The principle solid by-product of combustion is ash, the inorganic residue remaining after ignition of combustible materials.

Discussions that follow focus on fuels commonly fired in boilers to generate steam or hot water, atmospheric emissions associated with fuel combustion, and factors that influence how effectively the energy content of the fuel is transferred into usable heat.

3.1 FUELS

Many different solid, liquid, and gaseous fuels are fired in boilers. Sometimes, combinations of fuels are used to reduce emissions or improve boiler performance. Fuels commonly fired in boilers include fossil, biomass, and RDFs as well as other types of fuels and fuel combinations.

Coal, petroleum-based oils, and natural gas are fossil fuels commonly fired in ICI boilers. However, other forms of solid, liquid, or gaseous fuel derived from these fossil fuels are sometimes included in this category. One of these fuels, which is referred to as tire-derived fuel (TDF), consists of shredded vehicle tires.

Another boiler fuel is referred to as biomass. Biomass is renewable organic matter. Examples of biomass include fast-growing trees and plants, wood and wood waste, agricultural crops and residue, aquatic plants and algae, animal wastes, and organic municipal and industrial wastes.

RDF is a potentially valuable energy source. It consists of MSW that has been processed using size reduction and material recovery techniques to eliminate materials such as aluminum, steel, glass, plastic, and rock.

Common types of fuels fired in boilers are listed in Table 3.1 with key properties provided in Table 3.2. Additional information about some of the more common fuels is presented in the remainder of this section.

3.1.1 Coal

Coal is a brown-to-black combustible, sedimentary rocklike material composed primarily of consolidated and chemically altered plant material that grew in prehistoric forests.[1] The chemical composition of coal varies from one location to another, depending on the vegetation from which it was formed and the environmental conditions (such as temperature and pressure) to which the formation was exposed. In addition to its major chemical constituents of carbon, hydrogen, nitrogen, and oxygen, coal also contains some water and impurities of which ash, mercury, and sulfur are major concerns from an emissions viewpoint.