

1.1 Bituminous And Subbituminous Coal Combustion

1.1.1 General

Coal is a complex combination of organic matter and inorganic mineral matter formed over eons from successive layers of fallen vegetation. Coals are classified by rank according to their progressive alteration in the natural metamorphosis from lignite to anthracite. Coal rank depends on the volatile matter, fixed carbon, inherent moisture, and oxygen, although no single parameter defines a rank. Typically, coal rank increases as the amount of fixed carbon increases and the amount of volatile matter and moisture decreases.

Bituminous coals are by far the largest group and are characterized as having lower fixed carbon and higher volatile matter than anthracite. The key distinguishing characteristics of bituminous coal are its relative volatile matter and sulfur content as well as its slagging and agglomerating characteristics. Subbituminous coals have higher moisture and volatile matter and lower sulfur content than bituminous coals and may be used as an alternative fuel in some boilers originally designed to burn bituminous coals.¹ Generally, bituminous coals have heating values of 10,500 to 14,000 British thermal units per pound (Btu/lb) on a wet, mineral-matter-free basis.² As mined, the heating values of typical U.S. bituminous coals range from 10,720 to 14,730 Btu/lb.³ The heating values of subbituminous coals range from 8,300 to 11,500 Btu/lb on a wet, mineral-matter-free basis², and from 9,420 to 10,130 Btu/lb on an as-mined basis.³ Formulae and tables for classifying coals are given in Reference 2.

1.1.2 Firing Practices⁴

Coal-fired boilers can be classified by type, fuel, and method of construction. Boiler types are identified by the heat transfer method (watertube, firetube, or cast iron), the arrangement of the heat transfer surfaces (horizontal or vertical, straight or bent tube), and the firing configuration (suspension, stoker, or fluidized bed). The most common heat transfer method for coal-fired boilers is the watertube method in which the hot combustion gases contact the outside of the heat transfer tubes, while the boiler water and steam are contained within the tubes.

Coal-fired watertube boilers include pulverized coal, cyclone, stoker, fluidized bed, and handfed units. In stoker-fired systems and most handfed units, the fuel is primarily burned on the bottom of the furnace or on a grate. In a fluidized bed combustor (FBC), the coal is introduced to a bed of either sorbent or inert material (usually sand) which is fluidized by an upward flow of air. In pulverized coal-fired (PC-fired) boilers, the fuel is pulverized to the consistency of talcum powder (i.e., at least 70 percent of the particles will pass through a 200-mesh sieve) and pneumatically injected through the burners into the furnace. Combustion in PC-fired units takes place almost entirely while the coal is suspended in the furnace volume. PC-fired boilers are classified as either dry bottom or wet bottom (also referred to as slag tap furnaces), depending on whether the ash is removed in a solid or molten state. In dry bottom furnaces, coals with high fusion temperatures are burned, resulting in dry ash. In wet bottom furnaces, coals with low fusion temperatures are used, resulting in molten ash or slag.

Depending upon the type and location of the burners and the direction of coal injection into the furnace, PC-fired boilers can also be classified into two different firing types, including wall, and tangential. Wall-fired boilers can be either single wall-fired, with burners on only one wall of the furnace firing horizontally, or opposed wall-fired, with burners mounted on two opposing walls. Tangential (or corner-fired) boilers have burners mounted in the corners of the furnace. The fuel and air are injected tangent to an imaginary circle in the plane of the boilers. Cyclone furnaces are often

categorized as PC-fired systems even though the coal is crushed to a maximum size of about 4-mesh. The coal is fed tangentially, with primary air, into a horizontal cylindrical furnace. Smaller coal particles are burned in suspension while larger particles adhere to the molten layer of slag on the combustion chamber wall. Cyclone boilers are high-temperature, wet-bottom type systems.

Stoker-fired systems account for the vast majority of coal-fired watertube boilers for industrial, commercial, and institutional applications. Most packaged stoker units designed for coal firing are small and can be divided into three groups: underfeed stokers, overfeed stokers, and spreader stokers. Underfeed stokers are generally either the horizontal-feed, side-ash-discharge type or the gravity-feed, rear-ash-discharge type. An overfeed stoker uses a moving grate assembly in which coal is fed from a hopper onto a continuous grate which conveys the fuel into the furnace. In a spreader stoker, mechanical or pneumatic feeders distribute coal uniformly over the surface of a moving grate. The injection of the fuel into the furnace and onto the grate combines suspension burning with a thin, fast-burning fuel bed. The amount of fuel burned in suspension depends primarily on fuel size and composition, and air flow velocity. Generally, fuels with finer size distributions, higher volatile matter contents, and lower moisture contents result in a greater percentage of combustion and corresponding heat release rates in suspension above the bed.

FBCs, while not constituting a significant percentage of the total boiler population, have nonetheless gained popularity in the last decade, and today generate steam for industries, cogenerators, independent power producers, and utilities. There are two major categories of FBC systems: (1) atmospheric, operating at or near ambient pressures, and (2) pressurized, operating from 4 to 30 atmospheres (60 to 450 pounds per square inch gauge). At this time, atmospheric FBCs are more advanced (or commercialized) than pressurized FBCs. The two principal types of atmospheric FBCs are bubbling bed and circulating bed. The feature that varies most fundamentally between these two types is the fluidization velocity. In the bubbling bed design, the fluidation velocity is relatively low in order to minimize solids carryover or elutriation from the combustor. Circulating FBCs, however, employ high fluidization velocities to promote the carryover or circulation of the solids. High-temperature cyclones are used in circulating FBCs and in some bubbling FBCs to capture the solid fuel and bed material for return to the primary combustion chamber. The circulating FBC maintains a continuous, high-volume recycle rate which increases the residence time compared to the bubbling bed design. Because of this feature, circulating FBCs often achieve higher combustion efficiencies and better sorbent utilization than bubbling bed units.

Small, coal-fired boilers and furnaces are found in industrial, commercial, institutional, or residential applications and are sometimes capable of being hand-fired. The most common types of firetube boilers used with coal are the horizontal return tubular (HRT), Scotch, vertical, and the firebox. Cast iron boilers are also sometimes available as coal-fired units in a handfed configuration. The HRT boilers are generally fired with gas or oil instead of coal. The boiler and furnace are contained in the same shell in a Scotch or shell boiler. Vertical firetube boilers are typically small singlepass units in which the firetubes come straight up from the water-cooled combustion chamber located at the bottom of the unit. A firebox boiler is constructed with an internal steel-encased, water-jacketed firebox. Firebox firetube boilers are also referred to as locomotive, short firebox, and compact firebox boilers and employ mechanical stokers or are hand-fired.

1.1.3 Emissions⁴

Emissions from coal combustion depend on the rank and composition of the fuel, the type and size of the boiler, firing conditions, load, type of control technologies, and the level of equipment maintenance. The major pollutants of concern from bituminous and subbituminous coal combustion are particulate matter (PM), sulfur oxides (SO_x), and nitrogen oxides (NO_x). Some unburned combustibles, including carbon monoxide (CO) and numerous organic compounds, are generally emitted even under proper boiler operating conditions.

1.1.3.1 Particulate Matter⁴ -

PM composition and emission levels are a complex function of boiler firing configuration, boiler operation, pollution control equipment, and coal properties. Uncontrolled PM emissions from coal-fired boilers include the ash from combustion of the fuel as well as unburned carbon resulting from incomplete combustion. In pulverized coal systems, combustion is almost complete; thus, the emitted PM is primarily composed of inorganic ash residues.

Coal ash may either settle out in the boiler (bottom ash) or entrained in the flue gas (fly ash). The distribution of ash between the bottom ash and fly ash fractions directly affects the PM emission rate and depends on the boiler firing method and furnace type (wet or dry bottom). Boiler load also affects the PM emissions as decreasing load tends to reduce PM emissions. However, the magnitude of the reduction varies considerably depending on boiler type, fuel, and boiler operation.

Soot blowing is also a source of intermittent PM emissions in coal-fired boilers. Steam soot and air soot blowing is periodically used to dislodge ash from heat transfer surfaces in the furnace, convective section, economizer, and air preheater.

Particulate emissions may be categorized as either filterable or condensable. Filterable emissions are generally considered to be the particles that are trapped by the glass fiber filter in the front half of a Reference Method 5 or Method 17 sampling train. Vapors and particles less than 0.3 microns pass through the filter. Condensable particulate matter is material that is emitted in the vapor state which later condenses to form homogeneous and/or heterogeneous aerosol particles. The condensable particulate emitted from boilers fueled on coal or oil is primarily inorganic in nature.

1.1.3.2 Sulfur Oxides⁴ -

Gaseous SO_x from coal combustion are primarily sulfur dioxide (SO₂), with a much lower quantity of sulfur trioxide (SO₃) and gaseous sulfates. These compounds form as the organic and pyritic sulfur in the coal are oxidized during the combustion process. On average, about 95 percent of the sulfur present in bituminous coal will be emitted as gaseous SO_x, whereas somewhat less will be emitted when subbituminous coal is fired. The more alkaline nature of the ash in some subbituminous coals causes some of the sulfur to react in the furnace to form various sulfate salts that are retained in the boiler or in the flyash.

1.1.3.3 Nitrogen Oxides⁵⁻⁶ -

NO_x emissions from coal combustion are primarily nitric oxide (NO), with only a few volume percent as nitrogen dioxide (NO₂). Nitrous oxide (N₂O) is also emitted at a few parts per million. NO_x formation results from thermal fixation of atmospheric nitrogen in the combustion flame and from oxidation of nitrogen bound in the coal. Experimental measurements of thermal NO_x formation have shown that the NO_x concentration is exponentially dependent on temperature and is proportional to nitrogen concentration in the flame, the square root of oxygen concentration in the flame, and the gas residence time.⁷ Cyclone boilers typically have high conversion of nitrogen to NO_x. Typically, only 20 to 60 percent of the fuel nitrogen is converted to NO_x. Bituminous and subbituminous coals usually

contain from 0.5 to 2 weight percent nitrogen, mainly present in aromatic ring structures. Fuel nitrogen can account for up to 80 percent of total NO_x from coal combustion.

1.1.3.4 Carbon Monoxide -

The rate of CO emissions from combustion sources depends on the fuel oxidation efficiency of the source. By controlling the combustion process carefully, CO emissions can be minimized. Thus, if a unit is operated improperly or is not well-maintained, the resulting concentrations of CO (as well as organic compounds) may increase by several orders of magnitude. Smaller boilers, heaters, and furnaces typically emit more CO and organics than larger combustors. This is because smaller units usually have less high-temperature residence time and, therefore, less time to achieve complete combustion than larger combustors. Combustion modification techniques and equipment used to reduce NO_x can increase CO emissions if the modification techniques are improperly implemented or if the equipment is improperly designed.

1.1.3.5 Organic Compounds -

As with CO emissions, the rate at which organic compounds are emitted depends on the combustion efficiency of the boiler. Therefore, combustion modifications that change combustion residence time, temperature, or turbulence may increase or decrease concentrations of organic compounds in the flue gas.

Organic emissions include volatile, semivolatile, and condensable organic compounds either present in the coal or formed as a product of incomplete combustion (PIC). Organic emissions are primarily characterized by the criteria pollutant class of unburned vapor-phase hydrocarbons. These emissions include alkanes, alkenes, aldehydes, alcohols, and substituted benzenes (e.g., benzene, toluene, xylene, and ethyl benzene).^{8,9}

Emissions of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/PCDF) also result from the combustion of coal. Of primary interest environmentally are tetrachloro- through octachloro- dioxins and furans. Dioxin and furan emissions are influenced by the extent of destruction of organics during combustion and through reactions in the air pollution control equipment. The formation of PCDD/PCDF in air pollution control equipment is primarily dependent on flue gas temperature, with maximum potential for formation occurring at flue gas temperatures of 450 degrees to 650 degrees Fahrenheit.

The remaining organic emissions are composed largely of compounds emitted from combustion sources in a condensed phase. These compounds can almost exclusively be classed into a group known as polycyclic organic matter (POM), and a subset of compounds called polynuclear aromatic hydrocarbons (PNA or PAH). Polycyclic organic matter is more prevalent in the emissions from coal combustion because of the more complex structure of coal.

1.1.3.6 Trace Metals-

Trace metals are also emitted during coal combustion. The quantity of any given metal emitted, in general, depends on:

- the physical and chemical properties of the metal itself;
- the concentration of the metal in the coal;
- the combustion conditions; and

- the type of particulate control device used, and its collection efficiency as a function of particle size.

Some trace metals become concentrated in certain particle streams from a combustor (e.g., bottom ash, collector ash, and flue gas particulate) while others do not.¹⁰ Various classification schemes have been developed to describe this partitioning behavior.¹⁰⁻¹² These classification schemes generally distinguish between:

- Class 1: Elements that are approximately equally concentrated in the fly ash and bottom ash, or show little or no small particle enrichment. Examples include manganese, beryllium, cobalt, and chromium.
- Class 2: Elements that are enriched in fly ash relative to bottom ash, or show increasing enrichment with decreasing particle size. Examples include arsenic, cadmium, lead, and antimony.
- Class 3: Elements which are emitted in the gas phase (primarily mercury and, in some cases, selenium).

Control of Class 1 metals is directly related to control of total particulate matter emissions, while control of Class 2 metals depends on collection of fine particulate. Because of variability in particulate control device efficiencies, emission rates of these metals can vary substantially. Because of the volatility of Class 3 metals, particulate controls have only a limited impact on emissions of these metals.

1.1.3.7 Acid Gases-

In addition to SO₂ and NO_x emissions, combustion of coal also results in emissions of chlorine and fluorine, primarily in the form of hydrogen chloride (HCl) and hydrogen fluoride (HF). Lesser amounts of chlorine gas and fluorine gas are also emitted. A portion of the chlorine and fluorine in the fuel may be absorbed onto fly ash or bottom ash. Both HCl and HF are water soluble and are readily controlled by acid gas scrubbing systems.

1.1.3.8 Fugitive Emissions -

Fugitive emissions are defined as pollutants which escape from an industrial process due to leakage, materials handling, inadequate operational control, transfer, or storage. The fly ash handling operations in most modern utility and industrial combustion sources consist of pneumatic systems or enclosed and hooded systems which are vented through small fabric filters or other dust control devices. The fugitive PM emissions from these systems are therefore minimal. Fugitive particulate emissions can sometimes occur during fly ash transfer operations from silos to trucks or rail cars.

1.1.3.9 Greenhouse Gases¹³⁻¹⁸ -

Carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions are all produced during coal combustion. Nearly all of the fuel carbon (99 percent) in coal is converted to CO₂ during the combustion process. This conversion is relatively independent of firing configuration. Although the formation of CO acts to reduce CO₂ emissions, the amount of CO produced is insignificant compared to the amount of CO₂ produced. The majority of the fuel carbon not converted to CO₂ is entrained in bottom ash. CO₂ emissions for coal vary with carbon content, and carbon content varies between the classes of bituminous and subbituminous coals. Further, carbon content also varies within each class of coal based on the geographical location of the mine.

Formation of N₂O during the combustion process is governed by a complex series of reactions and its formation is dependent upon many factors. Formation of N₂O is minimized when combustion

temperatures are kept high (above 1575°F) and excess air is kept to a minimum (less than 1 percent). N₂O emissions for coal combustion are not significant except for fluidized bed combustion (FBC), where the emissions are typically two orders of magnitude higher than all other types of coal firing due to areas of low temperature combustion in the fuel bed.

Methane emissions vary with the type of coal being fired and firing configuration, but are highest during periods of incomplete combustion, such as the start-up or shut-down cycle for coal-fired boilers. Typically, conditions that favor formation of N₂O also favor emissions of CH₄.

1.1.4 Controls⁴

Control techniques for criteria pollutants from coal combustion may be classified into three broad categories: fuel treatment/substitution, combustion modification, and postcombustion control. Emissions of noncriteria pollutants such as particulate phase metals have been controlled through the use of post combustion controls designed for criteria pollutants. Fuel treatment primarily reduces SO₂ and includes coal cleaning using physical, chemical, or biological processes; fuel substitution involves burning a cleaner fuel. Combustion modification includes any physical or operational change in the furnace or boiler and is applied primarily for NO_x control purposes, although for small units, some reduction in PM emissions may be available through improved combustion practice. Postcombustion control employs a device after the combustion of the fuel and is applied to control emissions of PM, SO₂, and NO_x for coal combustion.

1.1.4.1 Particulate Matter Control⁴ -

The principal control techniques for PM are combustion modifications (applicable to small stoker-fired boilers) and postcombustion methods (applicable to most boiler types and sizes). Uncontrolled PM emissions from small stoker-fired and hand-feed combustion sources can be minimized by employing good combustion practices such as operating within the recommended load ranges, controlling the rate of load changes, and ensuring steady, uniform fuel feed. Proper design and operation of the combustion air delivery systems can also minimize PM emissions. The postcombustion control of PM emissions from coal-fired combustion sources can be accomplished by using one or more of the following particulate control devices:

- Electrostatic precipitator (ESP),
- Fabric filter (or baghouse),
- Wet scrubber,
- Cyclone or multiclone collector, or
- Side stream separator.

Electrostatic precipitation technology is applicable to a variety of coal combustion sources. Because of their modular design, ESPs can be applied to a wide range of system sizes and should have no adverse effect on combustion system performance. The operating parameters that influence ESP performance include fly ash mass loading, particle size distribution, fly ash electrical resistivity, and precipitator voltage and current. Other factors that determine ESP collection efficiency are collection plate area, gas flow velocity, and cleaning cycle. Data for ESPs applied to coal-fired sources show fractional collection efficiencies greater than 99 percent for fine (less than 0.1 micrometer) and coarse particles (greater than 10 micrometers). These data show a reduction in collection efficiency for particle diameters between 0.1 and 10 micrometers.

Fabric filtration has been widely applied to coal combustion sources since the early 1970s and consists of a number of filtering elements (bags) along with a bag cleaning system contained in a main shell structure incorporating dust hoppers. The particulate removal efficiency of fabric filters is

dependent on a variety of particle and operational characteristics. Particle characteristics that affect the collection efficiency include particle size distribution, particle cohesion characteristics, and particle electrical resistivity. Operational parameters that affect fabric filter collection efficiency include air-to-cloth ratio, operating pressure loss, cleaning sequence, interval between cleanings, cleaning method, and cleaning intensity. In addition, the particle collection efficiency and size distribution can be affected by certain fabric properties (e. g., structure of fabric, fiber composition, and bag properties). Collection efficiencies of fabric filters can be as high as 99.9 percent.

Wet scrubbers, including venturi and flooded disc scrubbers, tray or tower units, turbulent contact absorbers, or high-pressure spray impingement scrubbers are applicable for PM as well as SO₂ control on coal-fired combustion sources. Scrubber collection efficiency depends on particle size distribution, gas side pressure drop through the scrubber, and water (or scrubbing liquor) pressure, and can range between 95 and 99 percent for a 2-micron particle.

Cyclone separators can be installed singly, in series, or grouped as in a multicyclone or multiclone collector. These devices are referred to as mechanical collectors and are often used as a precollector upstream of an ESP, fabric filter, or wet scrubber so that these devices can be specified for lower particle loadings to reduce capital and/or operating costs. The collection efficiency of a mechanical collector depends strongly on the effective aerodynamic particle diameter. Although these devices will reduce PM emissions from coal combustion, they are relatively ineffective for collection of particles less than 10 micron (PM-10). The typical overall collection efficiency for mechanical collectors ranges from 90 to 95 percent.

The side-stream separator combines a multicyclone and a small pulse-jet baghouse to more efficiently collect small-diameter particles that are difficult to capture by a mechanical collector alone. Most applications to date for side-stream separators have been on small stoker boilers.

Atmospheric fluidized bed combustion (AFBC) boilers may tax conventional particulate control systems. The particulate mass concentration exiting AFBC boilers is typically 2 to 4 times higher than pulverized coal boilers. AFBC particles are also, on average, smaller in size, and irregularly shaped with higher surface area and porosity relative to pulverized coal ashes. The effect is a higher pressure drop. The AFBC ash is more difficult to collect in ESPs than pulverized coal ash because AFBC ash has a higher electrical resistivity and the use of multiclones for recycling, inherent with the AFBC process, tends to reduce exit gas stream particulate size.

1.1.4.2 Sulfur Oxides Control⁴ -

Several techniques are used to reduce SO_x emissions from coal combustion. Table 1.1-1 presents the techniques most frequently used. One way is to switch to lower sulfur coals, since SO_x emissions are proportional to the sulfur content of the coal. This alternative may not be possible where lower sulfur coal is not readily available or where a different grade of coal cannot be satisfactorily fired. In some cases, various coal cleaning processes may be employed to reduce the fuel sulfur content. Physical coal cleaning removes mineral sulfur such as pyrite but is not effective in removing organic sulfur. Chemical cleaning and solvent refining processes are being developed to remove organic sulfur.

Post combustion flue gas desulfurization (FGD) techniques can remove SO₂ formed during combustion by using an alkaline reagent to absorb SO₂ in the flue gas. Flue gases can be treated using wet, dry, or semi-dry desulfurization processes of either the throwaway type (in which all waste streams are discarded) or the recovery/regenerable type (in which the SO₂ absorbent is regenerated and reused). To date, wet systems are the most commonly applied. Wet systems generally use alkali slurries as the SO₂ absorbent medium and can be designed to remove greater than 90 percent of the incoming SO₂. Lime/limestone scrubbers, sodium scrubbers, and dual alkali scrubbers are among the commercially

proven wet FGD systems. The effectiveness of these devices depends not only on control device design but also on operating variables. Particulate reduction of more than 99 percent is possible with wet scrubbers, but fly ash is often collected by upstream ESPs or baghouses, to avoid erosion of the desulfurization equipment and possible interference with FGD process reactions.¹⁸ Also, the volume of scrubber sludge is reduced with separate fly ash removal, and contamination of the reagents and by-products is prevented.

The lime and limestone wet scrubbing process uses a slurry of calcium oxide or limestone to absorb SO₂ in a wet scrubber. Control efficiencies in excess of 91 percent for lime and 94 percent for limestone over extended periods are possible. Sodium scrubbing processes generally employ a wet scrubbing solution of sodium hydroxide or sodium carbonate to absorb SO₂ from the flue gas. Sodium scrubbers are generally limited to smaller sources because of high reagent costs and can have SO₂ removal efficiencies of up to 96.2 percent. The double or dual alkali system uses a clear sodium alkali solution for SO₂ removal followed by a regeneration step using lime or limestone to recover the sodium alkali and produce a calcium sulfite and sulfate sludge. SO₂ removal efficiencies of 90 to 96 percent are possible.

1.1.4.3 Nitrogen Oxide Controls⁴ -

Several techniques are used to reduce NO_x emissions from coal combustion. These techniques are summarized in Table 1.1-2. The primary techniques can be classified into one of two fundamentally different methods—combustion controls and postcombustion controls. Combustion controls reduce NO_x by suppressing NO_x formation during the combustion process, while postcombustion controls reduce NO_x emission after their formation. Combustion controls are the most widely used method of controlling NO_x formation in all types of boilers and include low excess air (LEA), burners out of service (BOOS), biased burner firing, overfire air (OFA), low NO_x burners (LNBS), and reburn. Postcombustion control methods are selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR). Combustion and postcombustion controls can be used separately or combined to achieve greater NO_x reduction from fluidized bed combustors in boilers.

Operating at LEA involves reducing the amount of combustion air to the lowest possible level while maintaining efficient and environmentally compliant boiler operation. NO_x formation is inhibited because less oxygen is available in the combustion zone. BOOS involves withholding fuel flow to all or part of the top row of burners so that only air is allowed to pass through. This method simulates air staging, or OFA conditions, and limits NO_x formation by lowering the oxygen level in the burner area. Biased burner firing involves more fuel-rich firing in the lower rows of burners than in the upper row of burners. This method provides a form of air staging and limits NO_x formation by limiting the amount of oxygen in the firing zone. These methods may change the normal operation of the boiler and the effectiveness is boiler-specific. Implementation of these techniques may also reduce operational flexibility; however, they may reduce NO_x by 10 to 20 percent from uncontrolled levels.

OFA is a technique in which a percentage of the total combustion air is diverted from the burners and injected through ports above the top burner level. OFA limits NO_x by (1) suppressing thermal NO_x by partially delaying and extending the combustion process resulting in less intense combustion and cooler flame temperatures and (2) suppressing fuel NO_x formation by reducing the concentration of air in the combustion zone where volatile fuel nitrogen is evolved. OFA can be applied for various boiler types including tangential and wall-fired, turbo, and stoker boilers and can reduce NO_x by 20 to 30 percent from uncontrolled levels.

LNBS limit NO_x formation by controlling the stoichiometric and temperature profiles of the combustion process in each burner zone. The unique design of features of an LNBS may create (1) a reduced oxygen level in the combustion zone to limit fuel NO_x formation, (2) a reduced flame

temperature that limits thermal NO_x formation, and/or (3) a reduced residence time at peak temperature which also limits thermal NO_x formation.

LNBs are applicable to tangential and wall-fired boilers of various sizes but are not applicable to other boiler types such as cyclone furnaces or stokers. They have been used as a retrofit NO_x control for existing boilers and can achieve approximately 35 to 55 percent reduction from uncontrolled levels. They are also used in new boilers to meet New Source Performance Standards (NSPS) limits. LNBs can be combined with OFA to achieve even greater NO_x reduction (40 to 60 percent reduction from uncontrolled levels).

Reburn is a combustion hardware modification in which the NO_x produced in the main combustion zone is reduced in a second combustion zone downstream. This technique involves withholding up to 40 percent (at full load) of the heat input to the main combustion zone and introducing that heat input above the top row of burners to create a reburn zone. Reburn fuel (natural gas, oil, or pulverized coal) is injected with either air or flue gas to create a fuel-rich zone that reduces the NO_x created in the main combustion zone to nitrogen and water vapor. The fuel-rich combustion gases from the reburn zone are completely combusted by injecting overfire air above the reburn zone. Reburn may be applicable to many boiler types firing coal as the primary fuel, including tangential, wall-fired, and cyclone boilers. However, the application and effectiveness are site-specific because each boiler is originally designed to achieve specific steam conditions and capacity which may be altered due to reburn. Commercial experience is limited; however, this limited experience does indicate NO_x reduction of 50 to 60 percent from uncontrolled levels may be achieved.

SNCR is a postcombustion technique that involves injecting ammonia (NH₃) or urea into specific temperature zones in the upper furnace or convective pass. The ammonia or urea reacts with NO_x in the flue gas to produce nitrogen and water. The effectiveness of SNCR depends on the temperature where reagents are injected; mixing of the reagent in the flue gas; residence time of the reagent within the required temperature window; ratio of reagent to NO_x; and the sulfur content of the fuel that may create sulfur compounds that deposit in downstream equipment. There is not as much commercial experience to base effectiveness on a wide range of boiler types; however, in limited applications, NO_x reductions of 25 to 40 percent have been achieved.

SCR is another postcombustion technique that involves injecting NH₃ into the flue gas in the presence of a catalyst to reduce NO_x to nitrogen and then water. The SCR reactor can be located at various positions in the process including before an air heater and particulate control device, or downstream of the air heater, particulate control device, and flue gas desulfurization systems. The performance of SCR is influenced by flue gas temperature, fuel sulfur content, ammonia-to-NO_x ratio, inlet NO_x concentration, space velocity, and catalyst condition. Although there is currently very limited application of SCR in the U.S. on coal-fired boilers, NO_x reductions of 75 to 86 percent have been realized on a few pilot systems.

1.1.5 Emission Factors

Emission factors for SO_x, NO_x, and CO are presented in Table 1.1-3. Tables in this section present emission factors on both a weight basis (lb/ton) and an energy basis (lb/Btu). To convert from lb/ton to lb/MMBtu, divide by a heating value of 26.0 MMBtu/ton. Because of the inherently low NO_x emission characteristics of FBCs and the potential for in-bed SO₂ capture by calcium-based sorbents, uncontrolled emission factors for this source category were not developed in the same sense as with other source categories. For NO_x emissions, the data collected from test reports were considered to be baseline (uncontrolled) if no additional add-on NO_x control system (such as ammonia injection) was operated.

For SO₂ emissions, a correlation was developed from reported data on FBCs to relate SO₂ emissions to the coal sulfur content and the calcium-to-sulfur ratio in the bed.

Filterable particulate matter and particulate matter less than, or equal to, 10 micrometers in diameter (PM-10) emission factors are presented in Table 1.1-4. Condensable particulate matter emission factors are presented in Table 1.1-5. Cumulative particle size distributions and particulate size-specific emission factors are given in Tables 1.1-6, 1.1-7, 1.1-8, 1.1-9, 1.1-10, and 1.1-11. Particulate size-specific emission factors are also presented graphically in Figures 1.1-1, 1.1-2, 1.1-3, 1.1-4, 1.1-5, and 1.1-6.

Controlled emission factors for PCDD/PCDF and PAHs are provided in Tables 1.1-12 and 1.1-13, respectively. Controlled emission factors for other organic compounds are presented in Table 1.1-14. Emission factors for hydrogen chloride and hydrogen fluoride are presented in Table 1.1-15.

Table 1.1-16 presents emission factor equations for nine trace metals from controlled and uncontrolled boilers. Table 1.1-17 presents uncontrolled emission factors for seven of the same metals, along with mercury, POM and formaldehyde. Table 1.1-18 presents controlled emission factors for 13 trace metals and includes the metals found in Tables 1.1-16 and 1.1-17. The emission factor equations in Table 1.1-16 are based on statistical correlations among measured trace element concentrations in coal, measured fractions of ash in coal, and measured particulate matter emission factors. Because these are the major parameters affecting trace metals emissions from coal combustion, it is recommended that the emission factor equations be used when the inputs to the equations are available. If the inputs to the emission factor equations are not available for a pollutant, then the emission factors provided in Table 1.1-17 and 1.1-18 for the pollutant should be used.

Greenhouse gas emission factors, including CH₄, non-methane organic compounds (NMOC), and N₂O are provided in Table 1.1-19. In addition, Table 1.1-20 provides emission factors for CO₂.

1.1.6 Updates Since the Fifth Edition

The Fifth Edition was released in January 1995. Revisions to this section since that date are summarized below. For further detail, consult the memoranda describing each supplement or the background report for this section. These and other documents can be found on the EFIG home page (<http://www.epa.gov/oar/oaqps/efig/>).

Supplement A, February 1996

- SCC's were corrected from 1-01-002-17, 1-02-002-17, and 1-03-002-17, to 1-01-002-18, 1-02-002-18, and 1-03-002-18 in the tables with SO_x, NO_x, CO, and PM/PM10 emission factors.
- For SO_x factors, clarifications were added to the table footnotes to clarify that "S" is a weight percent and not a fraction. Similar clarification was added to the footnote for the CO₂ factor.
- For fluidized bed combustors (bubbling bed and circulating bed), the PM10 factors were replaced with footnote "m." The revised footnote "m" directs the user to the emission factor for spreader stoker with multiple cyclones and no flyash reinjection.
- In the table with filterable PM factors, the misspelling of "filterable" was corrected.
- In the cumulative particle size distribution table, text was added to the table footnotes to clarify that "A" is a weight percent and not a fraction.
- In the cumulative particle size distribution for spreader stokers, all of the factors were corrected.
- The N₂O emission factor for bubbling bed was changed from 5.9 lb/ton to 5.5 lb/ton.

Supplement B, October 1996

- Text was added concerning coal rank/classification, firing practices, emissions, and controls.
- The table for NO_x control technologies was revised to include controls for all types of coal-fired boilers.
- SO_x, NO_x, and CO emission factors were added for cell burners.
- The PM table was revised to recommend using spreader stoker PM factors for FBC units.
- Tables were added for new emission factors for polychlorinated toxics, polynuclear aromatics, organic toxics, acid gas toxics, trace metal toxics, and controlled toxics.
- N₂O emission factors were added.
- Default CO₂ emission factors were added.

Supplement E, September 1998

- The term "Filterable" was added to the PM-10 column heading of Table 1.1-4.

- Reference to condensable particulate matter was deleted from footnote b of Table 1.1-4.
- Emission factors for condensable particulate matter were added (Table 1.1-5).
- Table 1.1-7 was revised to correct a typographical errors in the ESP column.
- The zeros in Table 1.1-8 appeared to be in error. Engineering judgement was used to determine a conservative estimate.
- NO_x emission factors were updated based on data from the Acid Rain program.

Table 1.1-1. POSTCOMBUSTION SO₂ CONTROLS FOR COAL COMBUSTION SOURCES

Control Technology	Process	Typical Control Efficiencies	Remarks
Wet scrubber	Lime/limestone	80 - 95+%	Applicable to high sulfur fuels, wet sludge product
	Sodium carbonate	80 - 98%	5-430 million Btu/hr typical application range, high reagent costs
	Magnesium oxide/hydroxide	80 - 95+%	Can be regenerated
	Dual alkali	90 - 96%	Uses lime to regenerate sodium-based scrubbing liquor
Spray drying	Calcium hydroxide slurry, vaporizes in spray vessel	70 - 90%	Applicable to low and medium sulfur fuels, produces dry product
Furnace injection	Dry calcium carbonate/hydrate injection in upper furnace cavity	25 - 50%	Commercialized in Europe, several U. S. demonstration projects are completed
Duct injection	Dry sorbent injection into duct, sometimes combined with water spray	25 - 50+%	Several research and development, and demonstration projects underway, not yet commercially available in the United States.

Table 1.1-2. NO_x CONTROL OPTIONS FOR COAL-FIRED BOILERS^a

Control Technique	Description of Technique	Applicable Boiler Designs	NO _x Reduction Potential ^b (%)	Commercial Availability/R & D Status	Comments
Combustion Modifications					
Load reduction	Reduction of coal and air	Stokers	Minimal	Available	Applicable to stokers that can reduce load without increasing excess air; may cause reduction in boiler efficiency; NO _x reduction varies with percent load reduction.
Operational modifications (BOOS, LEA, BF, or combination)	Rearrangement of air or fuel in the main combustion zone	Pulverized coal boilers (some designs); Stokers (LEA only)	10 - 20	Available	Must have sufficient operational flexibility to achieve NO _x reduction potential without sacrificing boiler performance.
Overfire Air	Injection of air above main combustion zone	Pulverized coal boilers and stokers	20 - 30	Available	Must have sufficient furnace height above top row of burners in order to retrofit this technology to existing boilers.
Low NO _x Burners	New burner designs controlling air-fuel mixing	Pulverized coal boilers	35 - 55	Available	Available in new boiler designs and can be retrofit in existing boilers.
LNB with OFA	Combination of new burner designs and injection of air above main combustion zone	Pulverized coal boilers	40 - 60	Available	Available in new boiler designs and can be retrofit in existing boilers with sufficient furnace height above top row of burners.
Reburn	Injection of reburn fuel and completion air above main combustion zone	Pulverized coal boilers, cyclone furnaces	50 - 60	Commercially available but not widely demonstrated	Reburn fuel can be natural gas, fuel oil, or pulverized coal. Must have sufficient furnace height to retrofit this technology to existing boilers.

Table 1.1-2 (cont.).

Control Technique	Description of Technique	Applicable Boiler Designs	NO _x Reduction Potential ^b (%)	Commercial Availability/R & D Status	Comments
Post-Combustion Modifications					
SNCR	Injection of NH ₃ or urea in the convective pass	Pulverized coal boilers, cyclone furnaces, stokers, and fluidized bed boilers	30 - 60	Commercially available but not widely demonstrated	Applicable to new boilers or as a retrofit technology; must have sufficient residence time at correct temperature (1,750°±90°F); elaborate reagent injection system; possible load restrictions on boiler; and possible air preheater fouling by ammonium bisulfate.
SCR	Injection of NH ₃ in combination with catalyst material	Pulverized coal boilers, cyclone furnaces	75 - 85	Commercially offered, but not yet demonstrated	Applicable to new boilers or as a retrofit technology provided there is sufficient space; hot-side SCR best on low-sulfur fuel and low fly ash applications; cold-side SCR can be used on high-sulfur/high-ash applications if equipped with an upstream FGD system.
LNB with SNCR	Combination of new burner designs and injection of NH ₃ or urea	Pulverized coal boilers	50-80	Commercially offered, but not widely demonstrated as a combined technology	Same as LNB and SNCR alone.
LNB with OFA and SCR	Combination of new burner design, injection of air above combustion zone, and injection of NH ₃ or urea	Pulverized coal boiler	85-95	Commercially offered, but not widely demonstrated as a combined technology	Same as LNB, OFA, and SCR alone.

^a References 20-21.

^b NO_x reduction potential from uncontrolled levels.

Table 1.1-3. EMISSION FACTORS FOR SO_x, NO_x, AND CO
FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

Firing Configuration	SCC	SO _x ^b		NO _x ^c		CO ^{d,e}	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
PC, dry bottom, wall-fired ^f , bituminous Pre-NSPS ^g	1-01-002-02 1-02-002-02 1-03-002-06	38S	A	22	A	0.5	A
PC, dry bottom, wall-fired ^f , bituminous Pre-NSPS ^g with low-NO _x burner	1-01-002-02 1-02-002-02 1-03-002-06	38S	A	11	A	0.5	A
PC, dry bottom, wall-fired ^f , bituminous NSPS ^g	1-01-002-02 1-02-002-02 1-03-002-06	38S	A	12	A	0.5	A
PC, dry bottom, wall-fired ^f , sub-bituminous Pre-NSPS ^g	1-01-002-22 1-02-002-22 1-03-002-22	35S	A	12	C	0.5	A
PC, dry bottom, wall fired ^f , sub-bituminous NSPS ^g	1-01-002-22 1-02-002-22 1-03-002-22	35S	A	7.4	A	0.5	A
PC, dry bottom, cell burner ^h fired, bituminous	1-01-002-15	38S	A	31	A	0.5	A
PC, dry bottom, cell burner fired, sub-bituminous	1-01-002-35	35S	A	14	E	0.5	A

Table 1.1-3 (cont.).

Firing Configuration	SCC	SO _x ^b		NO _x ^c		CO ^{d,e}	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
PC, dry bottom, tangentially fired, bituminous, Pre-NSPS ^g	1-01-002-12 1-02-002-12 1-03-002-16	38S	A	15	A	0.5	A
PC, dry bottom, tangentially fired, bituminous, Pre-NSPS ^g with low-NO _x burner	1-01-002-12 1-02-002-12 1-03-002-16	38S	A	9.7	A	0.5	A
PC, dry bottom, tangentially fired, bituminous, NSPS ^g	1-01-002-12 1-02-002-12 1-03-002-16	38S		10	A	0.5	A
PC, dry bottom, tangentially fired, sub-bituminous, Pre-NSPS ^g	1-01-002-26 1-02-002-26 1-03-002-26	35S	A	8.4	A	0.5	A
PC, dry bottom, tangentially fired, sub-bituminous, NSPS ^g	1-01-002-26 1-02-002-26 1-03-002-26	35S	A	7.2	A	0.5	A
PC, wet bottom, wall-fired ^f , bituminous, Pre-NSPS ^g	1-01-002-01 1-02-002-01 1-03-002-05	38S	A	31	D	0.5	A
PC, wet bottom, tangentially fired, bituminous, NSPS ^g	1-01-002-11	38S	A	14	E	0.5	A
PC, wet bottom, wall-fired sub-bituminous	1-01-002-21 1-02-002-21 1-03-002-21	35S	A	24	E	0.5	A

Table 1.1-3 (cont.).

Firing Configuration	SCC	SO _x ^b		NO _x ^c		CO ^{d,e}	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
Cyclone Furnace, bituminous	1-01-002-03 1-02-002-03 1-03-002-03	38S	A	33	A	0.5	A
Cyclone Furnance, sub-bituminous	1-01-002-23 1-02-002-23 1-03-002-23	35S	A	17	C	0.5	A
Spreader stoker, bituminous	1-01-002-04 1-02-002-04 1-03-002-09	38S	B	11	B	5	A
Spreader Stoker, sub-bituminous	1-01-002-24 1-02-002-24 1-03-002-24	35S	B	8.8	B	5	A
Overfeed stoker ⁱ	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	38S (35S)	B	7.5	A	6	B
Underfeed stoker	1-02-002-06 1-03-002-08	31S	B	9.5	A	11	B
Hand-fed units	1-03-002-14	31S	D	9.1	E	275	E

Table 1.1-3 (cont.).

Firing Configuration	SCC	SO _x ^b		NO _x ^c		CO ^{d,e}	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
FBC, circulating bed	1-01-002-18 1-02-002-18 1-03-002-18	— ^j	E	5.0	D	18	E
FBC, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	— ^j	E	15.2	D	18	D

^a Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code. To convert from lb/ton to kg/Mg, multiply by 0.5.

^b Expressed as SO₂, including SO₂, SO₃, and gaseous sulfates. Factors in parentheses should be used to estimate gaseous SO_x emissions for subbituminous coal. In all cases, S is weight % sulfur content of coal as fired. Emission factor would be calculated by multiplying the weight percent sulfur in the coal by the numerical value preceding S. For example, if fuel is 1.2% sulfur, then S = 1.2. On average for bituminous coal, 95% of fuel sulfur is emitted as SO₂, and only about 0.7% of fuel sulfur is emitted as SO₃ and gaseous sulfate. An equally small percent of fuel sulfur is emitted as particulate sulfate (References 22-23). Small quantities of sulfur are also retained in bottom ash. With subbituminous coal, about 10% more fuel sulfur is retained in the bottom ash and particulate because of the more alkaline nature of the coal ash. Conversion to gaseous sulfate appears about the same as for bituminous coal.

Table 1.1-3. (cont.)

- ^c Expressed as NO₂. Generally, 95 volume % or more of NO_x present in combustion exhaust will be in the form of NO, the rest NO₂ (Reference 6). To express factors as NO, multiply factors by 0.66. All factors represent emissions at baseline operation (i. e., 60 to 110% load and no NO_x control measures).
- ^d Nominal values achievable under normal operating conditions. Values 1 or 2 orders of magnitude higher can occur when combustion is not complete.
- ^e Emission factors for CO₂ emissions from coal combustion should be calculated using $\text{lb CO}_2/\text{ton coal} = 72.6C$, where C is the weight % carbon content of the coal. For example, if carbon content is 85%, then C equals 85.
- ^f Wall-fired includes front and rear wall-fired units, as well as opposed wall-fired units.
- ^g Pre-NSPS boilers are not subject to any NSPS. NSPS boilers are subject to Subpart D or Subpart Da. Subpart D boilers are boilers constructed after August 17, 1971 and with a heat input rate greater than 250 million Btu per hour (MMBtu/hr). Subpart Da boilers are boilers constructed after September 18, 1978 and with a heat input rate greater than 250 MMBtu/hr.
- ^h References 24-27.
- ⁱ Includes traveling grate, vibrating grate, and chain grate stokers.
- ^j SO₂ emission factors for fluidized bed combustion are a function of fuel sulfur content and calcium-to-sulfur ratio. For both bubbling bed and circulating bed design, use: $\text{lb SO}_2/\text{ton coal} = 39.6(S)(\text{Ca}/S)^{-1.9}$. In this equation, S is the weight percent sulfur in the fuel and Ca/S is the molar calcium-to-sulfur ratio in the bed. This equation may be used when the Ca/S is between 1.5 and 7. When no calcium-based sorbents are used and the bed material is inert with respect to sulfur capture, the emission factor for underfeed stokers should be used to estimate the SO₂ emissions. In this case, the emission factor ratings are E for both bubbling and circulating units.

Table 1.1-4. UNCONTROLLED EMISSION FACTORS FOR PM AND PM-10
FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

Firing Configuration	SCC	Filterable PM ^b		Filterable PM-10	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
PC-fired, dry bottom, wall-fired	1-01-002-02/22	10A	A	2.3A	E
	1-02-002-02/22				
	1-03-002-06/22				
PC-fired, dry bottom, tangentially fired	1-01-002-12/26	10A	B	2.3A ^c	E
	1-02-002-12/26				
	1-03-002-16/26				
PC-fired, wet bottom	1-01-002-01/21	7A ^d	D	2.6A	E
	1-02-002-01/21				
	1-03-002-05/21				
Cyclone furnace	1-01-002-03/23	2A ^d	E	0.26A	E
	1-02-002-03/23				
	1-03-002-03/23				
Spreader stoker	1-01-002-04/24	66 ^e	B	13.2	E
	1-02-002-04/24				
	1-03-002-09/24				
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24	17	B	12.4	E
	1-02-002-04/24				
	1-03-002-09/24				
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24	12	A	7.8	E
	1-02-002-04/24				
	1-03-002-09/24				

Table 1.1-4 (cont.).

Firing Configuration	SCC	Filterable PM ^b		Filterable PM-10	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
Overfeed stoker ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	16 ^g	C	6.0	E
Overfeed stoker, with multiple cyclones ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	9 ^h	C	5.0	E
Underfeed stoker	1-02-002-06 1-03-002-08	15 ⁱ	D	6.2	E
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	11 ^h	D	6.2 ^j	E
Hand-fed units	1-03-002-14	15 ^m	E	6.2 ^k	E
FBC, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	^m	E	^m	E
FBC, circulating bed	1-01-002-18 1-02-002-18 1-03-002-18	^m	E	^m	E

^a Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. To convert from lb/ton to kg/Mg, multiply by 0.5. SCC = Source Classification Code.

Table 1.1-4 (cont.).

- ^b Based on EPA Method 5 (front half catch) as described in Reference 28. Where particulate is expressed in terms of coal ash content, A, factor is determined by multiplying weight % ash content of coal (as fired) by the numerical value preceding the A. For example, if coal with 8% ash is fired in a PC-fired, dry bottom unit, the PM emission factor would be 10 x 8, or 80 lb/ton.
- ^c No data found; emission factor for PC-fired dry bottom boilers used.
- ^d Uncontrolled particulate emissions, when no fly ash reinjection is employed. When control device is installed, and collected fly ash is reinjected to boiler, particulate from boiler reaching control equipment can increase up to a factor of 2.
- ^e Accounts for fly ash settling in an economizer, air heater, or breaching upstream of control device or stack. (Particulate directly at boiler outlet typically will be twice this level.) Factor should be applied even when fly ash is reinjected to boiler from air heater or economizer dust hoppers.
- ^f Includes traveling grate, vibrating grate, and chain grate stokers.
- ^g Accounts for fly ash settling in breaching or stack base. Particulate loadings directly at boiler outlet typically can be 50% higher.
- ^h See Reference 4 for discussion of apparently low multiple cyclone control efficiencies, regarding uncontrolled emissions.
- ^j Accounts for fly ash settling in breaching downstream of boiler outlet.
- ^k No data found; emission factor for underfeed stoker used.
- ^m No data found; use emission factor for spreader stoker with multiple cyclones and reinjection.

Table 1.1-5. CONDENSABLE PARTICULATE MATTER EMISSION FACTORS FOR BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

Firing Configuration ^b	Controls ^c	SCC	CPM - TOT ^{d,e}		CPM - IOR ^{d,e}		CPM - ORG ^{d,e}	
			Emission Factor (lb/MMBtu)	EMISSION FACTOR RATING	Emission Factor (lb/MMBtu)	EMISSION FACTOR RATING	Emission Factor (lb/MMBtu)	EMISSION FACTOR RATING
All pulverized coal-fired boilers	All PM controls (without FGD controls)	1-01-002-01/21	0.1S-0.03 ^{f,g}	B	80% of CPM-TOT emission factor ^e	E	20% of CPM-TOT emission factor ^e	E
		1-01-002-02/22						
		1-01-002-12/26						
		1-02-002-01/21						
		1-02-002-02/22						
		1-02-002-12/26						
		1-03-002-05/06						
		1-03-002-16						
		1-03-002-21/22						
		1-03-002-26						
All pulverized coal-fired boilers	All PM controls combined with an FGD control	1-01-002-01/21	0.02 ^h	E	ND		ND	
		1-01-002-02/22						
		1-01-002-12/26						
		1-02-002-01/21						
		1-02-002-02/22						
		1-02-002-12/26						
		1-03-002-05/06						
		1-03-002-16						
		1-03-002-21/22						
		1-03-002-26						
Spreader stoker, travelling grate overfeed stoker, underfeed stoker	All PM controls, or Uncontrolled	1-01-002-04/24	0.04 ⁱ	C	80% of CPM-TOT emission factor ^e	E	20% of CPM-TOT emission factor ^e	E
		1-01-002-05/25						
		1-02-002-04/24						
		1-02-002-05/25						
		1-02-002-06						
		1-03-002-07/08						
		1-03-002-09/11						
		1-03-002-16						
		1-03-002-24/25						

Table 1.1-5 (cont.).

- ^a All condensable PM is assumed to be less than 1.0 micron in diameter.
- ^b No data are available for cyclone boilers (SCCs 1-01-002-03/23, 1-02-002-03/23, 1-03-002-23) or for atmospheric fluidized bed combustion (AFBC) boilers (SCCs 1-01-002-17, 1-02-002-17, 1-03-002-17). For cyclone boilers, use the factors provided for pulverized coal-fired boilers and applicable control devices. For AFBC boilers, use the factors provided for pulverized coal-fired boilers with PM and FGD controls.
- ^c FGD = flue gas desulfurization.
- ^d CPM-TOT = total condensable particulate matter.
CPM-IOR = inorganic condensable particulate matter.
CPM-ORG = organic condensable particulate matter.
ND = No data.
- ^e Factors should be multiplied by fuel rate on a heat input basis (MMBtu), as fired. To convert to lb/ton of bituminous coal, multiply by 26 MMBtu/ton. To convert to lb/ton of subbituminous coal, multiply by 20 MMBtu/ton.
- ^f S = coal sulfur percent by weight, as fired. For example, if the sulfur percent is 1.04, then S = 1.04. If the coal sulfur percent is 0.4 or less, use a default emission factor of 0.01 lb/MMBtu rather than the emission equation.
- ^g References 78-94.
- ^h References 95 and 96.
- ⁱ References 97-104.

Table 1.1-6. CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR DRY BOTTOM BOILERS BURNING PULVERIZED BITUMINOUS AND SUBBITUMINOUS COAL^a

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size					Cumulative Emission Factor ^c (lb/ton)				
	Uncontrolled	Controlled				Uncontrolled ^d	Controlled ^e			
		Multiple Cyclones	Scrubber	ESP	Baghouse		Multiple Cyclones ^f	Scrubber ^g	ESP ^g	Baghouse ^f
15	32	54	81	79	97	3.2A	1.08A	0.48A	0.064A	0.02A
10	23	29	71	67	92	2.3A	0.58A	0.42A	0.054A	0.02A
6	17	14	62	50	77	1.7A	0.28A	0.38A	0.024A	0.02A
2.5	6	3	51	29	53	0.6A	0.06A	0.3A	0.024A	0.01A
1.25	2	1	35	17	31	0.2A	0.02A	0.22A	0.01A	0.006A
1.00	2	1	31	14	25	0.2A	0.02A	0.18A	0.01A	0.006A
0.625	1	1	20	12	14	0.10A	0.02A	0.12A	0.01A	0.002A
TOTAL	100	100	100	100	100	10A	2A	0.6A	0.08A	0.02A

^a Reference 33. Applicable Source Classification Codes are 1-01-002-02, 1-02-002-02, 1-03-002-06, 1-01-002-12, 1-02-002-12, and 1-03-002-16. To convert from lb/ton to kg/Mg, multiply by 0.5. Emission Factors are lb of pollutant per ton of coal combusted, as fired. ESP = Electrostatic precipitator.

^b Expressed as aerodynamic equivalent diameter.

^c A = coal ash weight percent, as fired. For example, if coal ash weight is 8.2%, then A = 8.2.

^d EMISSION FACTOR RATING = C.

^e Estimated control efficiency for multiple cyclones is 80%; for scrubber, 94%; for ESP, 99.2%; and for baghouse, 99.8%.

^f EMISSION FACTOR RATING = E.

^g EMISSION FACTOR RATING = D.

Table 1.1-7. CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR WET BOTTOM BOILERS BURNING PULVERIZED BITUMINOUS COAL^a

EMISSION FACTOR RATING: E

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size			Cumulative Emission Factor ^c (lb/ton)		
	Uncontrolled	Controlled		Uncontrolled	Controlled ^d	
		Multiple Cyclones	ESP		Multiple Cyclones	ESP
15	40	99	83	2.8A	1.38A	0.046A
10	37	93	75	2.6A	1.3A	0.042A
6	33	84	63	2.32A	1.18A	0.036A
2.5	21	61	40	1.48A	0.86A	0.022A
1.25	6	31	17	0.42A	0.44A	0.01A
1.00	4	19	8	0.28A	0.26A	0.004A
0.625	2	— ^e	— ^e	0.14A	— ^e	— ^e
TOTAL	100	100	100	7.0A	1.4A	0.056A

^a Reference 33. Applicable Source Classification Codes are 1-01-002-01, 1-02-002-01, and 1-03-002-05. To convert from lb/ton to kg/Mg, multiply by 0.5. Emission factors are lb of pollutant per ton of coal combusted as fired. ESP = Electrostatic precipitator.

^b Expressed as aerodynamic equivalent diameter.

^c A = coal ash weight %, as fired. For example, if coal ash weight is 2.4%, then A = 2.4.

^d Estimated control efficiency for multiple cyclones is 94%, and for ESPs, 99.2%.

^e Insufficient data.

Table 1.1-8. CUMULATIVE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR CYCLONE FURNACES BURNING BITUMINOUS COAL^a

EMISSION FACTOR RATING: E

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size			Cumulative Emission Factor ^c (lb/ton)		
	Uncontrolled	Controlled		Uncontrolled	Controlled ^d	
		Multiple Cyclones	ESP		Multiple Cyclones	ESP
15	33	95	90	0.66A	0.114A	0.013A
10	13	94	68	0.26A	0.112A	0.011A
6	8	93	56	0.16A	0.112A	0.009A
2.5	5.5	92	36	0.11A ^e	0.11A	0.006A
1.25	5	85	22	0.10A ^e	0.10A	0.004A
1.00	5	82	17	0.10A ^e	0.10A	0.003A
0.625	0	— ^f	— ^f	0	— ^f	— ^f
TOTAL	100	100	100	2A	0.12A	0.016A

^a Reference 33. Applicable Source Classification Codes are 1-01-002-03, 1-02-002-03, and 1-03-002-03. To convert from lb/ton to kg/Mg, multiply by 0.5. Emissions are lb of pollutant per ton of coal combusted, as fired.

^b Expressed as aerodynamic equivalent diameter.

^c A = coal ash weight %, as fired. For example, if coal ash weight is 2.4%, then A = 2.4.

^d Estimated control efficiency for multiple cyclones is 94%, and for ESPs, 99.2%.

^e These values are estimates based on data from controlled source.

^f Insufficient data.

Table 1.1-9. CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR SPREADER STOKERS BURNING BITUMINOUS COAL^a

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size					Cumulative Emission Factor (lb/ton)				
	Uncontrolled	Controlled				Uncontrolled ^c	Controlled			
		Multiple Cyclones ^c	Multiple Cyclones ^d	ESP	Baghouse		Multiple Cyclones ^{c,f}	Multiple Cyclones ^{d,e}	ESP ^{f,g}	Baghouse ^{e,g}
15	28	86	74	97	72	18.5	14.6	8.8	0.46	0.086
10	20	73	65	90	60	13.2	12	7.8	0.44	0.072
6	14	51	52	82	46	9.2	8.6	6.2	0.40	0.056
2.5	7	8	27	61	26	4.6	1.4	3.2	0.30	0.032
1.25	5	2	16	46	18	3.3	0.4	2.0	0.22	0.022
1.00	5	2	14	41	15	3.3	0.4	1.6	0.20	0.018
0.625	4	1	9	— ^h	7	2.6	0.2	1.0	— ^h	0.006
TOTAL	100	100	100	100	100	66.0	17.0	12.0	0.48	0.12

^a Reference 33. Applicable Source Classification Codes are 1-01-002-04, 1-02-002-04, 1-03-002-09. To convert from lb/ton to kg/Mg, multiply by 0.5. Emissions are lb of pollutant per ton of coal combusted, as fired.

^b Expressed as aerodynamic equivalent diameter.

^c With flyash reinjection.

^d Without flyash reinjection.

^e EMISSION FACTOR RATING = C.

^f EMISSION FACTOR RATING = E.

^g Estimated control efficiency for ESP is 99.22%; and for baghouse, 99.8%.

^h Insufficient data.

Table 1.1-10. CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR OVERFEED STOKERS BURNING BITUMINOUS COAL^a

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size		Cumulative Emission Factor (lb/ton)			
	Uncontrolled	Multiple Cyclones Controlled	Uncontrolled		Multiple Cyclones Controlled ^c	
			Emission Factor	EMISSION FACTOR RATING	Emission Factor	EMISSION FACTOR RATING
15	49	60	7.8	C	5.4	E
10	37	55	6.0	C	5.0	E
6	24	49	3.8	C	4.4	E
2.5	14	43	2.2	C	3.8	E
1.25	13	39	2.0	C	3.6	E
1.00	12	39	2.0	C	3.6	E
0.625	— ^d	16	— ^d	C	1.4	E
TOTAL	100	100	16.0	C	9.0	E

^a Reference 33. Applicable Source Classification Codes are 1-01-002-05, 1-02-002-05, and 1-03-002-07. To convert from lb/ton to kg/Mg, multiply by 0.5. Emissions are lb of pollutant per ton of coal combusted, as fired.

^b Expressed as aerodynamic equivalent diameter.

^c Estimated control efficiency for multiple cyclones is 80%.

^d Insufficient data.

Table 1.1-11. CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR UNDERFEED STOKERS BURNING BITUMINOUS COAL^a

EMISSION FACTOR RATING: C

Particle Size ^b (μm)	Cumulative Mass % ≤ Stated Size	Uncontrolled Cumulative Emission Factor ^c (lb/ton)
15	50	7.6
10	41	6.2
6	32	4.8
2.5	25	3.8
1.25	22	3.4
1.00	21	3.2
0.625	18	2.7
TOTAL	100	15.0

^a Reference 33. Applicable Source Classification Codes are 1-02-002-06 and 1-03-002-08. To convert from lb/ton to kg/Mg, multiply by 0.5. Emission factors are lb of pollutant per ton of coal combusted, as fired.

^b Expressed as aerodynamic equivalent diameter.

^c May also be used for uncontrolled hand-fired units.

Table 1.1-12 EMISSION FACTORS FOR POLYCHLORINATED DIBENZO-P-DIOXINS AND POLYCHLORINATED DIBENZOFURANS FROM CONTROLLED BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION

Controls	FGD-SDA with FF ^a		ESP or FF ^b	
Congener	Emission Factor ^c (lb/ton)	EMISSION FACTOR RATING	Emission Factor ^c (lb/ton)	EMISSION FACTOR RATING
2,3,7,8-TCDD	No data	---	1.43E-11	E
Total TCDD	3.93E-10	E	9.28E-11	D
Total PeCDD	7.06E-10	E	4.47E-11	D
Total HxCDD	3.00E-09	E	2.87E-11	D
Total HpCDD	1.00E-08	E	8.34E-11	D
Total OCDD	2.87E-08	E	4.16E-10	D
Total PCDD ^d	4.28E-08	E	6.66E-10	D
2,3,7,8-TCDF	No data	---	5.10E-11	D
Total TCDF	2.49E-09	E	4.04E-10	D
Total PeCDF	4.84E-09	E	3.53E-10	D
Total HxCDF	1.27E-08	E	1.92E-10	D
Total HpCDF	4.39E-08	E	7.68E-11	D
Total OCDF	1.37E-07	E	6.63E-11	D
Total PCDF ^d	2.01E-07	E	1.09E-09	D
TOTAL PCDD/PCDF	2.44E-07	E	1.76E-09	D

^a Reference 34. Factors apply to boilers equipped with both flue gas desulfurization spray dryer absorber (FGD-SDA) and a fabric filter (FF). SCCs = pulverized coal-fired, dry bottom boilers, 1-01-002-02/22, 1-02-002-02/22, and 1-03-002-06/22.

^b References 35-37. Factors apply to boilers equipped with an electrostatic precipitator (ESP) or a fabric filter. SCCs = pulverized coal-fired, dry bottom boilers, 1-01-002-02/22, 1-02-002-02/22, 1-03-002-06/22; and, cyclone boilers, 1-01-002-03/23, 1-02-002-03/23, and 1-03-002-03/23.

^c Emission factor should be applied to coal feed, as fired. To convert from lb/ton to kg/Mg, multiply by 0.5. Emissions are lb of pollutant per ton of coal combusted.

^d Total PCDD is the sum of Total TCDD through Total OCDD. Total PCDF is the sum of Total TCDF through Total OCDF.

Table 1.1-13 EMISSION FACTORS FOR POLYNUCLEAR AROMATIC HYDROCARBONS (PAH) FROM CONTROLLED COAL COMBUSTION^a

Pollutant	Emission Factor ^b (lb/ton)	EMISSION FACTOR RATING
Biphenyl	1.7E-06	D
Acenaphthene	5.1E-07	B
Acenaphthylene	2.5E-07	B
Anthracene	2.1E-07	B
Benzo(a)anthracene	8.0E-08	B
Benzo(a)pyrene	3.8E-08	D
Benzo(b,j,k)fluoranthene	1.1E-07	B
Benzo(g,h,i)perylene	2.7E-08	D
Chrysene	1.0E-07	C
Fluoranthene	7.1E-07	B
Fluorene	9.1E-07	B
Indeno(1,2,3-cd)pyrene	6.1E-08	C
Naphthalene	1.3E-05	C
Phenanthrene	2.7E-06	B
Pyrene	3.3E-07	B
5-Methyl chrysene	2.2E-08	D

^a References 35-45. Factors were developed from emissions data from six sites firing bituminous coal, four sites firing subbituminous coal, and from one site firing lignite. Factors apply to boilers utilizing both wet limestone scrubbers or spray dryers with an electrostatic precipitator (ESP) or fabric filter (FF). The factors also apply to boilers utilizing only an ESP or FF. Bituminous/subbituminous SCCs = pulverized coal-fired dry bottom boilers, 1-01-002-02/22, 1-02-002-02/22, 1-03-002-06; pulverized coal, dry bottom, tangentially-fired boilers, 1-01-002-12/26, 1-02-002-12/26, 1-03-002-16/26; and, cyclone boilers, 1-01-002-03/23, 1-02-002-03/23, and 1-03-002-03/23.

^b Emission factor should be applied to coal feed, as fired. To convert from lb/ton to kg/Mg, multiply by 0.5. Emissions are lb of pollutant per ton of coal combusted.

Table 1.1-14 EMISSION FACTORS FOR VARIOUS ORGANIC COMPOUNDS
FROM CONTROLLED COAL COMBUSTION^a

Pollutant ^b	Emission Factor ^c (lb/ton)	EMISSION FACTOR RATING
Acetaldehyde	5.7E-04	C
Acetophenone	1.5E-05	D
Acrolein	2.9E-04	D
Benzene	1.3E-03	A
Benzyl chloride	7.0E-04	D
Bis(2-ethylhexyl)phthalate (DEHP)	7.3E-05	D
Bromoform	3.9E-05	E
Carbon disulfide	1.3E-04	D
2-Chloroacetophenone	7.0E-06	E
Chlorobenzene	2.2E-05	D
Chloroform	5.9E-05	D
Cumene	5.3E-06	E
Cyanide	2.5E-03	D
2,4-Dinitrotoluene	2.8E-07	D
Dimethyl sulfate	4.8E-05	E
Ethyl benzene	9.4E-05	D
Ethyl chloride	4.2E-05	D
Ethylene dichloride	4.0E-05	E
Ethylene dibromide	1.2E-06	E
Formaldehyde	2.4E-04	A
Hexane	6.7E-05	D
Isophorone	5.8E-04	D
Methyl bromide	1.6E-04	D
Methyl chloride	5.3E-04	D
Methyl ethyl ketone	3.9E-04	D
Methyl hydrazine	1.7E-04	E
Methyl methacrylate	2.0E-05	E

Table 1.1-14 (cont.).

Pollutant ^b	Emission Factor ^c (lb/ton)	EMISSION FACTOR RATING
Methyl tert butyl ether	3.5E-05	E
Methylene chloride	2.9E-04	D
Phenol	1.6E-05	D
Propionaldehyde	3.8E-04	D
Tetrachloroethylene	4.3E-05	D
Toluene	2.4E-04	A
1,1,1-Trichloroethane	2.0E-05	E
Styrene	2.5E-05	D
Xylenes	3.7E-05	C
Vinyl acetate	7.6E-06	E

^a References 35-53. Factors were developed from emissions data from ten sites firing bituminous coal, eight sites firing subbituminous coal, and from one site firing lignite. The emission factors are applicable to boilers using both wet limestone scrubbers or spray dryers and an electrostatic precipitator (ESP) or fabric filter (FF). In addition, the factors apply to boilers utilizing only an ESP or FF. SCCs = pulverized coal-fired, dry bottom boilers, 1-01-002-02/22, 1-02-002-02/22, 1-03-002-06/22; pulverized coal, dry bottom, tangentially-fired boilers, 1-01-002-12/26, 1-02-002-12/26, 1-03-002-16/26; cyclone boilers, 1-01-002-03/23, 1-02-002-03/23, 1-03-002-03/23; and, atmospheric fluidized bed combustors, circulating bed, 1-01-002-18/38, 1-02-002-18, and 1-03-002-18.

^b Pollutants sampled for but not detected in any sampling run include: Carbon tetrachloride- 2 sites; 1,3-Dichloropropylene- 2 sites; N-nitrosodimethylamine- 2 sites; Ethylidene dichloride- 2 sites; Hexachlorobutadiene- 1 site; Hexachloroethane- 1 site; Propylene dichloride- 2 sites; 1,1,2,2-Tetrachloroethane- 2 sites; 1,1,2-Trichloroethane- 2 sites; Vinyl chloride- 2 sites; and, Hexachlorobenzene- 2 sites.

^c Emission factor should be applied to coal feed, as fired. To convert from lb/ton to kg/Mg, multiply by 0.5.

Table 1.1-15. EMISSION FACTORS FOR HYDROGEN CHLORIDE (HCl) AND HYDROGEN FLUORIDE (HF) FROM COAL COMBUSTION^a

EMISSION FACTOR RATING: B

Firing Configuration	SCC	HCl	HF
		Emission Factor (lb/ton)	Emission Factor (lb/ton)
PC-fired, dry bottom	1-01-002-02/22	1.2	0.15
	1-02-002-02/22		
	1-03-002-06/22		
PC-fired, dry bottom, tangential	1-01-002-12/26	1.2	0.15
	1-02-002-12/26		
	1-03-002-16/26		
PC-fired, wet bottom	1-01-002-01/21	1.2	0.15
	1-02-002-01/21		
	1-03-002-05/21		
Cyclone Furnace	1-01-002-03/23	1.2	0.15
	1-02-002-03/23		
	1-03-002-03/23		
Spreader Stoker	1-01-002-04/24	1.2	0.15
	1-02-002-04/24		
	1-03-002-09/24		
Overfeed Stoker	1-01-002-05/25	1.2	0.15
	1-02-002-05/25		
	1-03-002-07/25		
Underfeed Stoker	1-02-002-06	1.2	0.15
	1-03-002-08		
FBC, Bubbling Bed	1-01-002-17	1.2	0.15
	1-02-002-17		
	1-03-002-17		
FBC, Circulating Bed	1-01-002-18/38	1.2	0.15
	1-02-002-18		
	1-03-002-18		
Hand-fired	1-03-002-14	1.2	0.15

^a Reference 54. The emission factors were developed from bituminous coal, subbituminous coal, and lignite emissions data. To convert from lb/ton to kg/Mg, multiply by 0.5. The factors apply to both controlled and uncontrolled sources.

Table 1.1-16. EMISSION FACTOR EQUATIONS FOR TRACE ELEMENTS FROM COAL COMBUSTION^a

EMISSION FACTOR EQUATION RATING: A^b

Pollutant	Emission Equation (lb/10 ¹² Btu) ^c
Antimony	$0.92 * (C/A * PM)^{0.63}$
Arsenic	$3.1 * (C/A * PM)^{0.85}$
Beryllium	$1.2 * (C/A * PM)^{1.1}$
Cadmium	$3.3 * (C/A * PM)^{0.5}$
Chromium	$3.7 * (C/A * PM)^{0.58}$
Cobalt	$1.7 * (C/A * PM)^{0.69}$
Lead	$3.4 * (C/A * PM)^{0.80}$
Manganese	$3.8 * (C/A * PM)^{0.60}$
Nickel	$4.4 * (C/A * PM)^{0.48}$

^a Reference 55. The equations were developed from emissions data from bituminous coal combustion, subbituminous coal combustion, and from lignite combustion. The equations may be used to generate factors for both controlled and uncontrolled boilers. The emission factor equations are applicable to all typical firing configurations for electric generation (utility), industrial, and commercial/industrial boilers firing bituminous coal, subbituminous coal, and lignite. Thus, all SCCs for these boilers are assigned to the factors.

^b AP-42 criteria for rating emission factors were used to rate the equations.

^c The factors produced by the equations should be applied to heat input. To convert from lb/10¹² Btu to kg/joules, multiply by 4.31 x 10⁻¹⁶.

C = concentration of metal in the coal, parts per million by weight (ppmwt).

A = weight fraction of ash in the coal. For example, 10% ash is 0.1 ash fraction.

PM = Site-specific emission factor for total particulate matter, lb/10⁶ Btu.

Table 1.1-17. EMISSION FACTORS FOR TRACE ELEMENTS, POM, AND HCOH FROM UNCONTROLLED BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

EMISSION FACTOR RATING: E

Firing Configuration (SCC)	Emission Factor, lb/10 ¹² Btu									
	As	Be	Cd	Cr	Pb ^b	Mn	Hg	Ni	POM	HCOH
Pulverized coal, configuration unknown (no SCC)	ND	ND	ND	1922	ND	ND	ND	ND	ND	112 ^c
Pulverized coal, wet bottom (1-01-002-01/21, 1-02-002-01/21, 1-03-002-05/21)	538	81	44-70	1020-1570	507	808-2980	16	840-1290	ND	ND
Pulverized coal, dry bottom (1-01-002-02/22, 1-02-002-06/22, 1-03-002-06/22)	684	81	44.4	1250-1570	507	228-2980	16	1030-1290	2.08	ND
Pulverized coal, dry bottom, tangential (1-01-002-12/26, 1-02-002-12/26, 1-03-002-16/26)	ND	ND	ND	ND	ND	ND	ND	ND	2.4	ND
Cyclone furnace (1-01-002-03/23, 1-02-002-03/23, 1-03-002-03/23)	115	<81	28	212-1502	507	228-1300	16	174-1290	ND	ND
Stoker, configuration unknown (no SCC)	ND	73	ND	19-300	ND	2170	16	775-1290	ND	ND
Spreader stoker (1-01-002-04/24, 1-02-002-04/24, 1-03-002-09/24)	264-542	ND	21-43	942-1570	507	ND	ND	ND	ND	221 ^d
Overfeed stoker, traveling grate (1-01-002-05/25, 1-02-002-05/25, 1-03-002-07/25)	542-1030	ND	43-82	ND	507	ND	ND	ND	ND	140 ^e

^a References 56-61. The emission factors in this table represent the ranges of factors reported in the literature. If only 1 data point was found, it is still reported in this table. To convert from lb/10¹² Btu to pg/J, multiply by 0.43. SCC = Source Classification Code. ND = no data.

^b Lead emission factors were taken directly from an EPA background document for support of the National Ambient Air Quality Standards.

^c Based on 2 units; 133 x 10⁶ Btu/hr and 1550 x 10⁶ Btu/hr.

^d Based on 1 unit; 59 x 10⁶ Btu/hr.

Table 1.1-18 EMISSION FACTORS FOR TRACE METALS FROM CONTROLLED COAL COMBUSTION^a

Pollutant	Emission Factor (lb/ton) ^b	EMISSION FACTOR RATING
Antimony	1.8E-05	A
Arsenic	4.1E-04	A
Beryllium	2.1E-05	A
Cadmium	5.1E-05	A
Chromium	2.6E-04	A
Chromium (VI)	7.9E-05	D
Cobalt	1.0E-04	A
Lead	4.2E-04	A
Magnesium	1.1E-02	A
Manganese	4.9E-04	A
Mercury	8.3E-05	A
Nickel	2.8E-04	A
Selenium	1.3E-03	A

^a References 35-53, 62-70. The emission factors were developed from emissions data at eleven facilities firing bituminous coal, fifteen facilities firing subbituminous coal, and from two facilities firing lignite. The factors apply to boilers utilizing either venturi scrubbers, spray dryer absorbers, or wet limestone scrubbers with an electrostatic precipitator (ESP) or Fabric Filter (FF). In addition, the factors apply to boilers using only an ESP, FF, or venturi scrubber. SCCs = pulverized coal-fired, dry bottom boilers, 1-01-002-02/22, 1-02-002-02/22, 1-03-002-06/22; pulverized coal, dry bottom, tangentially-fired boilers, 1-01-002-12/26, 1-02-002-12/26, 1-03-002-16/26; cyclone boilers, 1-01-002-03/23, 1-02-002-03/23, 1-03-002-03/23; and, atmospheric fluidized bed combustors, circulating bed, 1-01-002-18/38, 1-02-002-18, and 1-03-002-18.

^b Emission factor should be applied to coal feed, as fired. To convert from lb/ton to kg/Mg, multiply by 0.5.

Table 1.1-19. EMISSION FACTORS FOR CH₄, TNMOC, AND N₂O FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

Firing Configuration	SCC	CH ₄ ^b		TNMOC ^{b,c}		N ₂ O ^d	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
PC-fired, dry bottom, wall fired	1-01-002-02/22	0.04	B	0.06	B	0.03	B
	1-02-002-02/22						
	1-03-002-06/22						
PC-fired, dry bottom, tangentially fired	1-01-002-12/26	0.04	B	0.06	B	0.08	B
	1-02-002-12/26						
	1-03-002-16/26						
PC-fired, wet bottom	1-01-002-01/21	0.05	B	0.04	B	0.08	E
	1-02-002-01/21						
	1-03-002-05/21						
Cyclone furnace	1-01-002-03/23	0.01	B	0.11	B	0.09 ^e	E
	1-02-002-03/23						
	1-03-002-03/23						
Spreader stoker	1-01-002-04/24	0.06	B	0.05	B	0.04 ^f	D
	1-02-002-04/24						
	1-03-002-09/24						
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24	0.06	B	0.05	B	0.04 ^f	E
	1-02-002-04/24						
	1-03-002-09/24						
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24	0.06	B	0.05	B	0.04 ^f	E
	1-02-002-04/24						
	1-03-002-09/24						

Table 1.1-19 (cont.).

Firing Configuration	SCC	CH ₄ ^b		TNMOC ^{b,c}		N ₂ O ^d	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
Overfeed stoker ^g	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	0.06	B	0.05	B	0.04 ^f	E
Overfeed stoker, with multiple cyclones ^g	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	0.06	B	0.05	B	0.04 ^f	E
Underfeed stoker	1-02-002-06 1-03-002-08	0.8	B	1.3	B	0.04 ^f	E
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	0.8	B	1.3	B	0.04 ^f	E
Hand-fed units	1-03-002-14	5	E	10	E	0.04 ^f	E
FBC, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	0.06 ^h	E	0.05 ^h	E	3.5 ^h	B
FBC, circulating bed	1-01-002-18 1-02-002-18 1-03-002-18	0.06	E	0.05	E	3.5	B

^a Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code. To convert from lb/ton to kg/Mg, multiply by 0.5.

^b Reference 32. Nominal values achievable under normal operating conditions; values 1 or 2 orders of magnitude higher can occur when combustion is not complete.

^c TNMOC are expressed as C₂ to C₁₆ alkane equivalents (Reference 71). Because of limited data, the effects of firing configuration on TNMOC emission factors could not be distinguished. As a result, all data were averaged collectively to develop a single average emission factor for pulverized coal units, cyclones, spreaders, and overfeed stokers.

^d References 14-15.

Table 1.1-20. DEFAULT CO₂ EMISSION FACTORS FOR U. S. COALS^a

EMISSION FACTOR RATING: C

Coal Type	Average %C ^b	Conversion Factor ^c	Emission Factor ^d (lb/ton coal)
Subbituminous	66.3	72.6	4810
High-volatile bituminous	75.9	72.6	5510
Medium-volatile bituminous	83.2	72.6	6040
Low-volatile bituminous	86.1	72.6	6250

^a This table should be used only when an ultimate analysis is not available. If the ultimate analysis is available, CO₂ emissions should be calculated by multiplying the %carbon (%C) by 72.6. This resultant factor would receive a quality rating of "B".

^b An average of the values given in References 2,76-77. Each of these references listed average carbon contents for each coal type (dry basis) based on extensive sampling of U.S. coals.

^c Based on the following equation:

$$\frac{44 \text{ ton CO}_2}{12 \text{ ton C}} \times 0.99 \times 2000 \frac{\text{lb CO}_2}{\text{ton CO}_2} \times \frac{1}{100\%} = 72.6 \frac{\text{lb CO}_2}{\text{ton \%C}}$$

Where:

- 44 = molecular weight of CO₂,
- 12 = molecular weight of carbon, and
- 0.99 = fraction of fuel oxidized during combustion (Reference 16).

^d To convert from lb/ton to kg/Mg, multiply by 0.5.

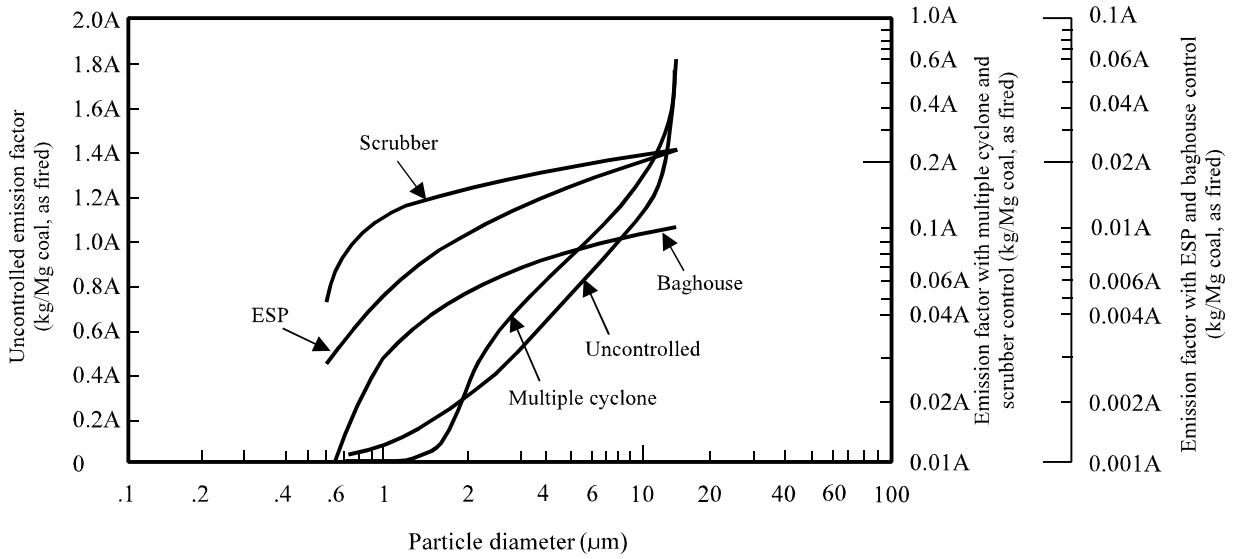


Figure 1.1-1. Cumulative size-specific emission factors for an example dry bottom boiler burning pulverized bituminous coal.

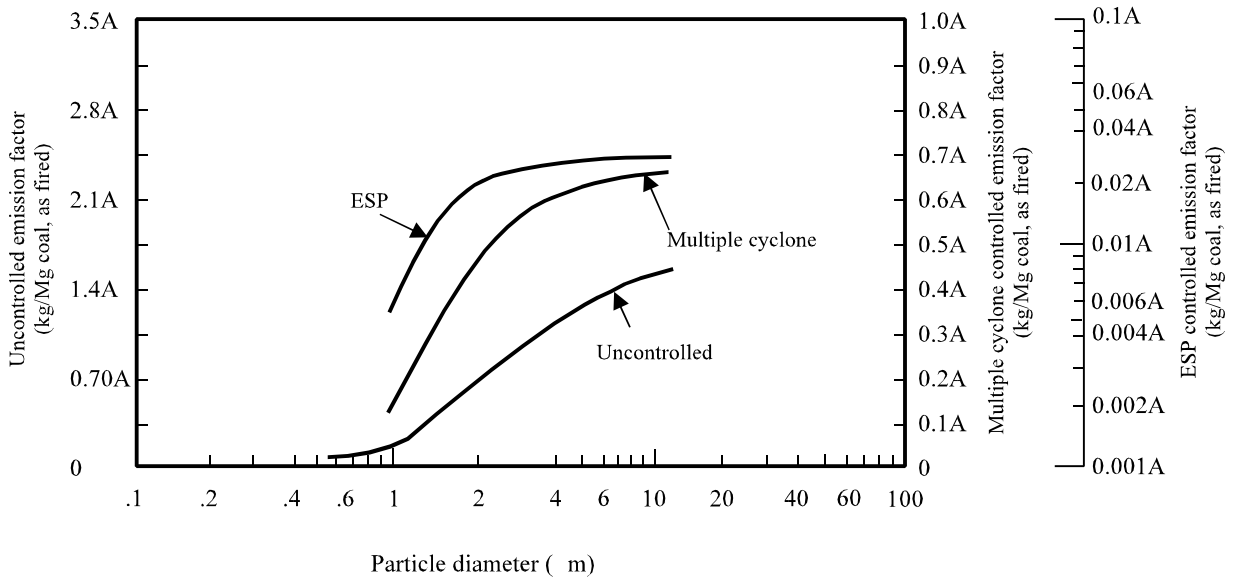


Figure 1.1-2. Cumulative size-specific emission factors for an example wet bottom boiler burning pulverized bituminous coal.

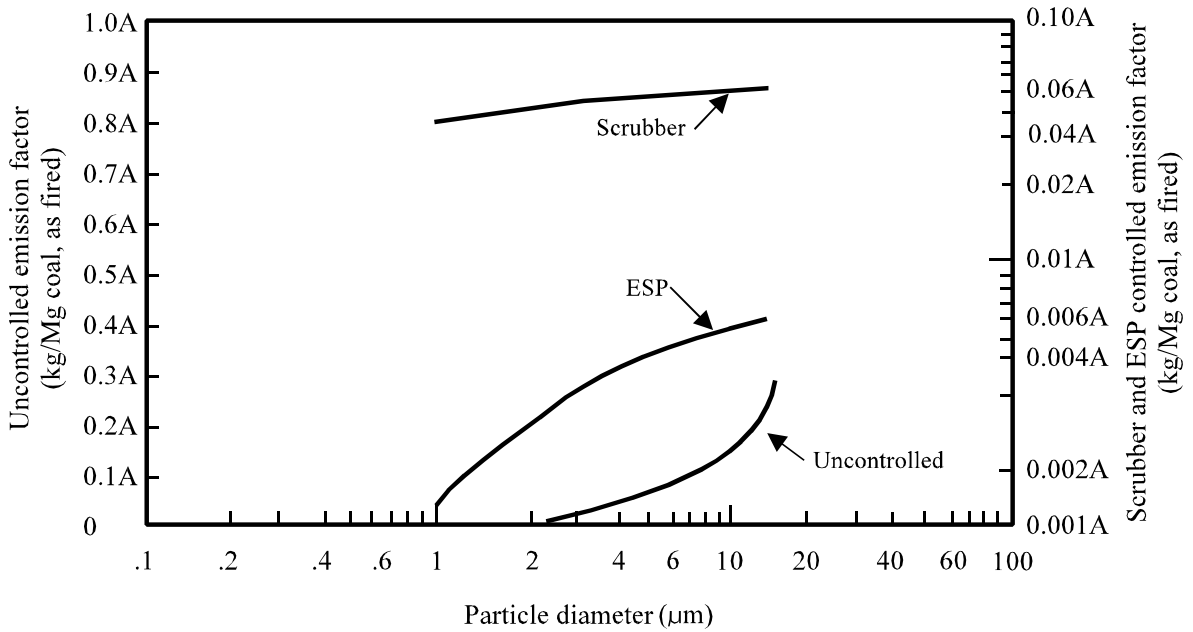


Figure 1.1-3. Cumulative size-specific emission factors for an example cyclone furnace burning bituminous coal.

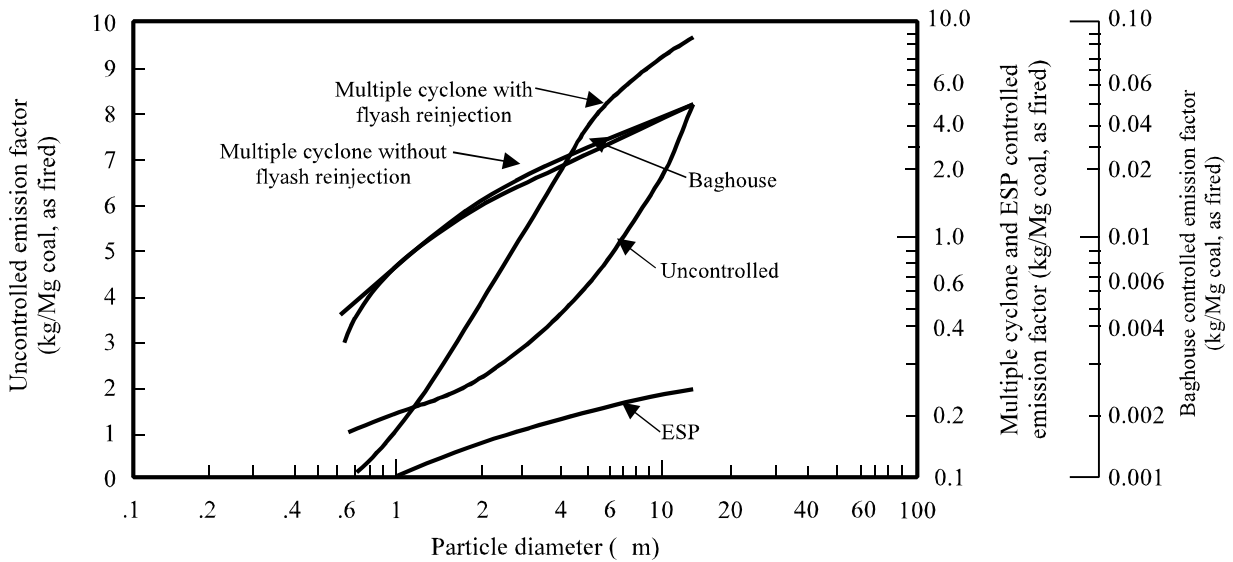


Figure 1.1-4. Cumulative size-specific emission factors for an example spreader stoker burning bituminous coal.

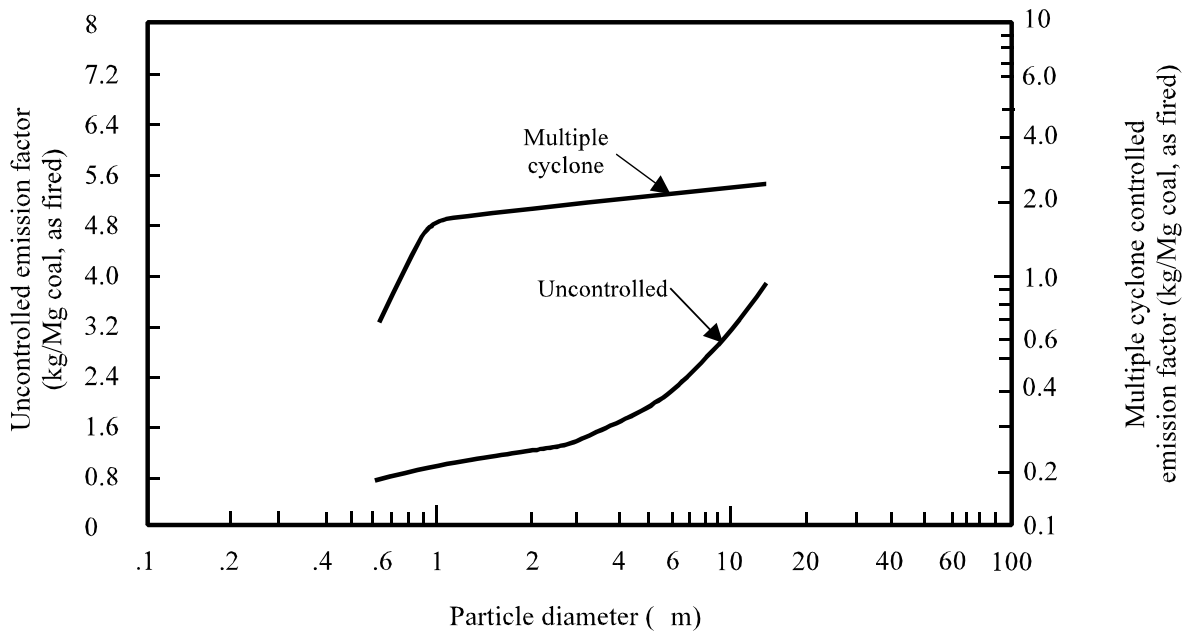


Figure 1.1-5. Cumulative size-specific emission factors for an example overfeed stoker burning bituminous coal.

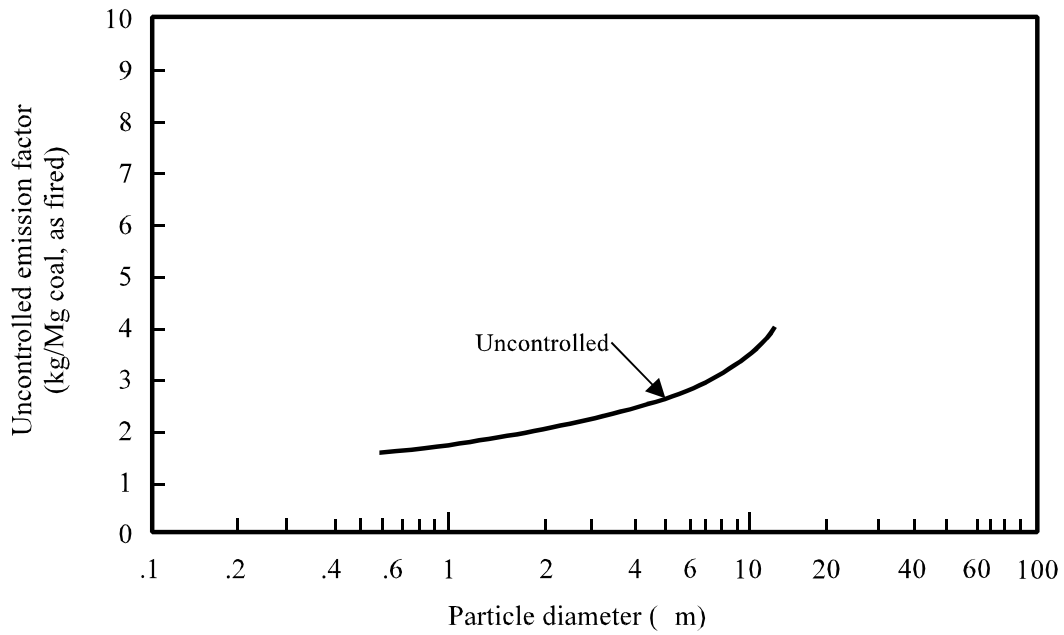


Figure 1.1-6. Cumulative size-specific emission factors for an example underfeed stoker burning bituminous coal.

References For Section 1.1

1. Bartok, B., Sarofina, A. F. (eds), *Fossil Fuel Combustion, A Source Book*, John Wiley & Sons, Inc., 1991, p. 239.
2. *Steam: It Generation And Use*, 38th Edition, Babcock and Wilcox, New York, 1975.
3. *Combustion. Fossil Power Systems. Third Edition.* Published by Combustion Engineering, Inc. Windsor, CT., 1981.
4. *Emission Factor Documentation For AP-42 Section 1.1 Bituminous and Subbituminous Coal Combustion*, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1993.
5. *Control Techniques For Nitrogen Oxides Emissions From Stationary Sources*, 2nd Edition, EPA-450/1-78-001, U. S. Environmental Protection Agency, Research Triangle Park, NC, January 1978.
6. *Review Of NO_x Emission Factors For Stationary Fossil Fuel Combustion Sources*, EPA-450/4-79-021, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1979.
7. K. J. Lim, *et al.*, *Technology Assessment Report For Industrial Boiler Applications: NO_x Combustion Modification*, EPA-600/7-79-178f, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1979.
8. Particulate Polycyclic Organic Matter, National Academy of Sciences, Washington, DC, 1972.
9. Vapor Phase Organic Pollutants- Volatile Hydrocarbons and Oxidation Products, National Academy of Sciences, Washington, DC, 1976.
10. D. H. Klein, *et al.*, "Pathways of Thirty-Seven Trace Elements Through Coal-Fired Power Plants", *Environmental Science and Technology*, 9:973-979, 1975.
11. D. G. Coles, *et al.*, "Chemical Studies of Stack Fly Ash from a Coal-Fired Power Plant", *Environmental Science and Technology*, 13:455-459, 1979.
12. S. Baig, *et al.*, *Conventional Combustion Environmental Assessment*, EPA Contract No. 68-02-3138, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1981.
13. L. P. Nelson, *et al.*, *Global Combustion Sources of Nitrous Oxide Emissions*, Research Project 2333-4 Interim Report, Sacramento: Radian Corporation, 1991.
14. R. L. Peer, *et al.*, *Characterization of Nitrous Oxide Emission Sources*, U. S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, 1995.
15. S. D. Piccot, *et al.*, *Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of NO_x , N_2O , CH_4 , CO , and CO_2* , U. S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, 1990.

16. G. Marland and R. M. Rotty, *Carbon Dioxide Emissions from Fossil Fuels: A Procedure For Estimation and Results For 1951-1981*, DOE/NBB-0036 TR-003, Carbon Dioxide Research Division, Office of Energy Research, U.S. Department of Energy, Oak Ridge, TN, 1983.
17. G. Marland and R. M. Rotty, *Carbon Dioxide Emissions from Fossil Fuels: A Procedure For Estimation and Results For 1950-1982*, *Tellus*, 36B: 232-261.
18. *Sector-Specific Issues and Reporting Methodologies Supporting the General Guidelines for the Voluntary Reporting of Greenhouse Gases under Section 1605(b) of the Energy Policy Act of 1992* (1994) DOE/PO-0028, Volume 2 of 3, U.S. Department of Energy.
19. *Control Techniques For Sulfur Dioxide Emissions From Stationary Sources, 2nd Edition*, EPA-450/3-81-004, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1981.
20. *Alternative Control Techniques Document--NO_x Emissions From Utility Boilers*, EPA-453/R-94-023, March 1994, pp. 2-15, 2-18, 5-103.
21. *Emission Factor Documentation For AP-42, Section 1.1, Bituminous and Subbituminous Coal Combustion*, Prepared by Acurex Environmental Corp., Edward Aul & Associates, Inc., E. H. Pechan And Associates, Inc., EPA Contract No. 68-D0-11210, April 1993.
22. Carlo Castaldini, and Meredith Angwin, *Boiler Design And Operating Variables Affecting Uncontrolled Sulfur Emissions From Pulverized Coal Fired Steam Generators*, EPA-450/3-77-047, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1977.
23. K. Cushing, *et al.*, "Fabric Filtration Experience Downstream From Atmospheric Fluidized Bed Combustion Boilers", Presented at the Ninth Particulate Control Symposium, October 1991.
24. Susan Stamey-Hall, *Evaluation of Nitrogen Oxide Emissions Data from TVA Coal-Fired Boilers*, EPA-600/R-92-242, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1992.
25. Joel Vatsky and Timothy W. Sweeney, *Development of an Ultra-Low No_x Pulverizer Coal Burner*, Presented at the EPA/EPRI 1991 Joint Symposium on Combustion No_x Control, March 25-28, 1991, Washington, DC.
26. T. L. Lu, R. L. Lungren, and A. Kokkinos, *Performance of a Large Cell-Burner Utility Boiler Retrofitted with Foster Wheeler Low-NO_x Burners*, Presented at the EPA/EPRI 1991 Joint Symposium on Combustion NO_x Control, March 25-28, 1991, Washington, DC.
27. *Alternative Control Techniques Document NO_x Emissions from Utility Boilers*, EPA-453/R-94-023, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1994.
28. *Standards Of Performance For New Stationary Sources*, 36 FR 24876, December 23, 1971.

29. *Field Tests Of Industrial Stoker Coal Fired Boilers For Emission Control And Efficiency Improvement - Sites L1 17*, EPA-600/7-81-020a, U. S. Environmental Protection Agency, Washington, DC, February 1981.
30. *Application Of Combustion Modifications To Control Pollutant Emissions From Industrial Boilers Phase I*, EPA-650/2-74-078a, U. S. Environmental Protection Agency, Washington, DC, October 1974.
31. *Source Sampling Residential Fireplaces For Emission Factor Development*, EPA-50/3-6-010, U. S. Environmental Protection Agency, Research Triangle Park, NC, November 1875.
32. *Atmospheric Emissions From Coal Combustion: An Inventory Guide*, 999-AP-24, U. S. Environmental Protection Agency, Washington, DC, April 1966.
33. *Inhalable Particulate Source Category Report For External Combustion Sources*, EPA Contract No. 68-02-3156, Acurex Corporation, Mountain View, CA, January 1985.
34. Results of the March 28, 1990 Dioxin Emission Performance Test on Unit 3 at the NSP Sherco Plant in Becker, Minnesota. Interpoll Laboratories, Inc., Circle Pines, Minnesota. July 11, 1990.
35. Field Chemical Emissions Monitoring Project: Site 22 Emissions Report. Radian Corporation, Austin, Texas. February, 1994.
36. Toxics Assessment Report. Illinois Power Company. Baldwin Power Station- Unit 2. Baldwin, Illinois. Volumes I- Main Report. Roy F. Weston, Inc. West Chester, Pennsylvania. December, 1993.
37. Toxics Assessment Report. Minnesota Power Company Boswell Energy Center- Unit 2. Cohasset, Minnesota. Volume 1-Main Report. Roy F. Weston, Inc. West Chester, Pennsylvania. December, 1993. (EPRI Report)
38. Field Chemical Emissions Monitoring Project: Site 11 Emissions Monitoring. Radian Corporation, Austin, Texas. October, 1992. (EPRI Report)
39. Field Chemical Emissions Monitoring Project: Site 21 Emissions Monitoring. Radian Corporation, Austin, Texas. August, 1993. (EPRI Report)
40. Field Chemical Emissions Monitoring Project: Site 111 Emissions Report. Radian Corporation, Austin, Texas. May, 1993. (EPRI Report)
41. Field Chemical Emissions Monitoring Project: Site 115 Emissions Report. Radian Corporation, Austin, Texas. November, 1994. (EPRI Report)
42. Draft Final Report. A Study of Toxic Emissions from a Coal-Fired Power Plant-Niles Station No. 2. Volumes One, Two, and Three. Battelle, Columbus, Ohio. December 29, 1993.
43. Draft Final Report. A Study of Toxic Emissions from a Coal-Fired Power Plant Utilizing an ESP/Wet FGD System. Volumes One, Two, and Three. Battelle, Columbus, Ohio. December 1993.

44. Assessment of Toxic Emissions From a Coal Fired Power Plant Utilizing an ESP. Final Report-Revision 1. Energy and Environmental Research Corporation, Irvine, California. December 23, 1993.
45. 500-MW Demonstration of Advanced Wall-Fired Combustion Techniques for the Reduction of Nitrogen Oxide (NOx) Emissions from Coal-Fired Boilers. Radian Corporation, Austin, Texas.
46. Results of the November 7, 1991 Air Toxic Emission Study on the Nos. 3, 4, 5 & 6 Boilers at the NSP High Bridge Plant. Interpoll Laboratories, Inc., Circle Pines, Minnesota. January 3, 1992.
47. Results of the December 1991 Air Toxic Emission Study on Units 6 & 7 at the NSP Riverside Plant. Interpoll Laboratories, Inc., Circle Pines, Minnesota. February 28, 1992.
48. Field Chemical Emissions Monitoring Project: Site 10 Emissions Monitoring. Radian Corporation, Austin, Texas. October, 1992. (EPRI Report)
49. Field Chemical Emissions Monitoring Project: Site 12 Emissions Monitoring. Radian Corporation, Austin, Texas. November, 1992. (EPRI Report)
50. Field Chemical Emissions Monitoring Project: Site 15 Emissions Monitoring. Radian Corporation, Austin, Texas. October, 1992. (EPRI Report)
51. Field Chemical Emissions Monitoring Project: Site 101 Emissions Report. Radian Corporation, Austin, Texas. October, 1994. (EPRI Report)
52. Field Chemical Emissions Monitoring Project: Site 114 Report. Radian Corporation, Austin, Texas. May, 1994. (EPRI Report)
53. Field Chemical Emissions Monitoring Report: Site 122. Final Report, Task 1 Third Draft. EPRI RP9028-10. Southern Research Institute, Birmingham, Alabama. May, 1995. (EPRI Report)
54. *Hydrogen Chloride And Hydrogen Fluoride Emission Factors For The NAPAP Inventory*, EPA-600/7-85-041, U. S. Environmental Protection Agency, October 1985.
55. *Electric Utility Trace Substances Synthesis Report, Volume 1*, Report TR-104614, Electric Power Research Institute, Palo Alto, CA, November 1994.
56. *Locating And Estimating Air Emissions From Sources Of Chromium*, EPA-450/4-84-007g, U. S. Environmental Protection Agency, July 1984.
57. *Locating And Estimating Air Emissions From Sources Of Formaldehyde*, (Revised), EPA-450/4-91-012, U. S. Environmental Protection Agency, March 1991.
58. *Estimating Air Toxics Emissions From Coal And Oil Combustion Sources*, EPA-450/2-89-001, Radian Corporation, Project Officer: Dallas W. Safriet, Research Triangle Park, NC, April 1989.
59. *Canadian Coal-Fired Plants, Phase I: Final Report And Appendices*, Report for the Canadian Electrical Association, R&D, Montreal, Quebec, Contract Number 001G194, Report by Battelle, Pacific Northwest Laboratories, Richland, WA.

60. R. Meij, Auferu dr., *The Fate Of Trace Elements At Coal-Fired Plants*, Report No. 2561-MOC 92-3641, Rapport te bestellen bij; bibliotheek N.V. KEMA, February 13, 1992.
61. *Locating And Estimating Air Emissions From Sources Of Manganese*, EPA-450/4-84-007h, September 1985.
62. Results of the September 10 and 11, 1991 Mercury Removal Tests on the Units 1 & 2, and Unit 3 Scrubber Systems at the NSP Sherco Plant in Becker, Minnesota. Interpoll Laboratories, Inc., Circle Pines, Minnesota. October 30, 1991.
63. Results of the November 5, 1991 Air Toxic Emission Study on the No. 1, 3 & 4 Boilers at the NSP Black Dog Plant. Interpoll Laboratories, Inc., Circle Pines, Minnesota. January 3, 1992.
64. Results of the January 1992 Air Toxic Emission Study on the No. 2 Boiler at the NSP Black Dog Plant. Interpoll Laboratories, Inc., Circle Pines, Minnesota. May 4, 1992.
65. Results of the May 29, 1990 Trace Metal Characterization Study on Units 1 and 2 at the Sherburne County Generating Station in Becker, Minnesota. Interpoll Laboratories, Inc., Circle Pines, Minnesota. July, 1990.
66. Results of the May 1, 1990 Trace Metal Characterization Study on Units 1 and 2 at the Sherburne County Generating Station. Interpoll Laboratories, Inc., Circle Pines, Minnesota. July 18, 1990.
67. Results of the March 1990 Trace Metal Characterization Study on Unit 3 at the Sherburne County Generating Station. Interpoll Laboratories, Circle Pines, Minnesota. June 7, 1990.
68. Field Chemical Emissions Monitoring Project: Site 19 Emissions Monitoring. Radian Corporation, Austin, Texas. April, 1993. (EPRI Report)
69. Field Chemical Emissions Monitoring Project: Site 20 Emissions Monitoring. Radian Corporation, Austin, Texas. March, 1994. (EPRI Report)
70. Characterizing Toxic Emissions from a Coal-Fired Power Plant Demonstrating the AFGD ICCT Project and a Plant Utilizing a Dry Scrubber /Baghouse System. Final Draft Report. Springerville Generating Station Unit No. 2. Southern Research Insititute, Birmingham, Alabama. December, 1993.
71. *Emissions Of Reactive Volatile Organic Compounds From Utility Boilers*, EPA-600/7-80-111, U. S. Environmental Protection Agency, Washington, DC, May 1980.
72. *EPA/IFP European Workshop On The Emission Of Nitrous Oxide For Fuel Combustion*, EPA Contract No. 68-02-4701, Rueil-Malmaison, France, June 1-2, 1988.
73. R. Clayton, *et al.*, *NO_x Field Study*, EPA-600/2-89-006, U. S. Environmental Protection Agency, Research Triangle Park, NC, February 1989.
74. L. E. Amand, and S. Anderson, "Emissions of Nitrous Oxide from Fluidized Bed Boilers", Presented at the Tenth International Conference on Fluidized Bed Combustor, San Francisco, CA, 1989.

75. *Alternative Control Techniques Document--NO_x Emissions From Utility Boilers*, EPA-453/R-94-023, Office of Air Quality Standards, Research Triangle Park, NC, 1994.
76. Alliance Technologies Corporation, *Evaluation of Significant Anthropogenic Sources of Radiatively Important Trace Gases*, U. S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, 1990.
77. R. A. Winschel, Richard, "The Relationship of Carbon Dioxide Emissions with Coal Rank and Sulfur Content," *Journal of the Air and Waste Management Association*, Vol. 40, no. 6, pp. 861-865, June 1990.
78. Public Service Electric and Gas Company Mercer Generating Station Unit No. 2 Emission Compliance Test Program. November 1994.
79. Particulate Emission Study Performed for Madison Gas and Electric Company at the Blount Street Station Units 7, 8, 9 Inlets/Outlets. Mostardi-Platt Associates, Inc. December 6, 1994.
80. Particulate Emission Study Performed for Marshfield Electric and Water Department at the Wildwood Station Marshfield Wisconsin Boiler 5 Stack. Mostardi-Platt Associates, Inc. January 23-25, 1990.
81. Report on Particulate, SO₂, and NO_x Compliance Testing. Dairyland Power Cooperative J.P. Madgett Stack. Alma, Wisconsin. CAE. January 6, 1995.
82. Particulate Emissions Test Results. Portland General Electric Coal-fired Power Plant. Boardman, Oregon. SAIC, Inc. January 25, 1994.
83. Report on Compliance Testing Performed at Marshfield Electric and Water Department Wildwood Station Unit 5, Marshfield, Wisconsin. Clean Air Engineering, December 11, 1989.
84. Portland General Electric Company Boardman Coal Plant. Unit #1 Coal-fired Boiler. Boardman, Oregon. August 24-27, 1995.
85. Particulate Emission Compliance Study Performed for Portland General Electric at the Boardman Plant Unit 1 Stack. Boardman, Oregon. September 19, 1996.
86. Emissions Source Test Report. Portland General Electric Coal-Fired Power Plant. Boardman, Oregon. OMNI Environmental Services, Inc. October 17, 1990.
87. Source Emissions Test Report Compliance. Portland General Electric Coal-Fired Power Plant. Boardman, Oregon. OMNI Environmental Services. January 29, 1991.
88. Source Test Report. Particulate Emissions. Portland General Electric Coal-Fired Power Plant. Boardman, Oregon. OMNI Environmental Services, Inc. January 14, 1991.
89. Emissions Source Test Report. Portland General Electric Coal-Fired Power Plant. Boardman, Oregon. OMNI Environmental Services, Inc. April 3, 1991.
90. Source Emissions Test Report. Portland General Electric Coal-Fired Power Plant. Boardman, Oregon. OMNI Environmental Services, Inc. January 21, 1992.

91. Particulate Emissions Test Results. Portland General Electric Coal-fired Power Plant. Boardman, Oregon. OMNI Environmental Services, Inc. April 4, 1992.
92. Particulate Emissions Test Results. Portland General Electric Coal-Fired Power Plant. Boardman, Oregon. OMNI Environmental Services, Inc. September 9, 1992.
93. Particulate Emissions Test Results. Portland General Electric Coal-Fired Power Plant. Boardman, Oregon. OMNI Environmental Services, Inc. November 6, 1992.
94. Particulate Emissions Test Results. Portland General Electric Coal-Fired Power Plant. Boardman, Oregon. OMNI Environmental Services, Inc. January 26, 1993.
95. Stationary Source Sampling Report. Keystone Cogeneration Facility. Keystone Cogeneration Facility. Logan Township, NJ. November 1994.
96. Source Emissions Survey of City Public Service Board J.K. Spruce Unit Number 1 Stack. METCO Environmental. December 1992.
97. Report of Particulate Emission Testing on the Number 1 Boiler at Associated Milk Products Incorporated Located in Jim Falls, Wisconsin. Environmental Services of American, Inc. November 1994.
98. Appleton Papers, Inc. Boiler Emission Test at Appleton, WI. May 11 and 12, 1993. Badger Laboratories and Engineering.
99. Appleton Papers, Inc. Boiler Emission Test Report at Appleton, WI. Badger Laboratories and Engineering. October 11, 1993.
100. Results of a Source Emission Compliance Test on Boiler #2 at the Hills Farm Heating Plant, Madison, Wisconsin. MMT Environmental Services, Inc. January 22, 1993.
101. Results of a Source Emission Compliance Test on Boiler #2 at the Hills Farm Heating Plant, Madison, Wisconsin. MMT Environmental Services, Inc. March 2, 1995.
102. Report to Mosinee Paper Company for Particulate Matter Emission Testing. No. 6 Boiler at Mosinee, Wisconsin. May 18, 19, and 20, 1993.
103. Report to Milwaukee County for Particulate Matter Emission Test Boiler No. 21. Environmental Technology and Engineering Corporation. November 5, 1991.
104. Report on Compliance Testing Conducted at Oscar Mayer Foods Corporation, Madison, Wisconsin. Clean Air Engineering. July 21, 1989.