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AIR POLLUTION CONTROL SYSTEMS  
FOR  
BOILERS AND INCINERATORS

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No. 5-815-1  
AIR FORCE REGULATION  
No. 19-6

HEADQUARTERS  
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## AIR POLLUTION CONTROL SYSTEMS FOR BOILERS AND INCINERATORS

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# CHAPTER 1

## GENERAL

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### 1-1. Purpose

*a.* This manual is designed to facilitate the identification of air pollutant emission rates, and the selection of control equipment required to meet local, state, and federal compliance levels. Presented herein are fuel classifications, burning equipment types, emission rate factors, emission measuring techniques, control equipment types, and control methods. Also included are discussions of stack dispersion techniques, and control equipment selection.

*b.* Each control equipment chapter provides performance data and equipment limitations which aid in the comparative selection of control equipment types. Each chapter includes a discussion of the basic control theory, various equipment types, collection efficiency, pressure drop, operating requirements and limitations, application, materials of construction, and advantages and disadvantages in relation to other type control equipment.

### 1-2. Scope

*a.* This manual has been limited to the application of control equipment to fuel burning boilers and incinerators for the purpose of reducing point-source emission rates. A procedural schematic for its use is illustrated in figure 1-1. Although the selection of a site, a fuel, and burning equipment are outside the scope of this manual, there are alternatives available to the engineer in arriving at the least-cost solution to air pollutant problems. Once these factors have been decided, boiler or incineration emission rates and reduction requirements can be estimated using chapters 2 and 3.

*b.* If emission rates are in compliance with local, state, and federal regulations for point-sources, their effect on local air quality must yet be ascertained. Such factors as stack height and prevailing meteorological conditions, while affecting ambient pollution levels, do not have an effect on point-source emission rates. They are considered in this manual only to make the reader aware of their importance. These factors are unique for each particular site, and usually warrant expert consultation. If emission rates for a boiler or incinerator are above local, state or federal requirements, or if air-quality regulations might be violated, selection of a pollution control device will be required. The technical and cost selection of control equipment are embodied in this manual.

*c.* Appendix A contains a list of references used in this manual. A bibliography listing publications of sub-

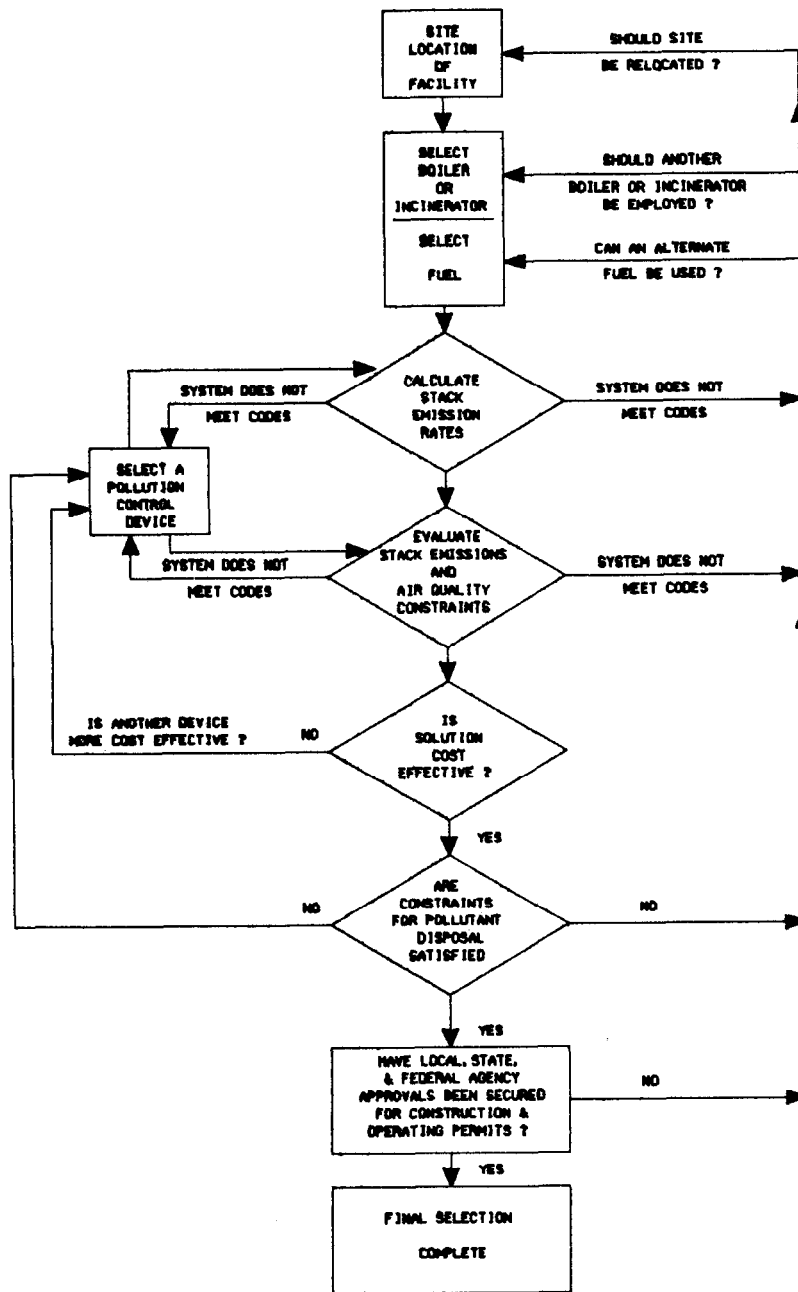
ject material relating to the topic of this manual can be found at the end of this manual. Also included is a glossary listing abbreviations and a brief definition of terminology used in the text.

### 1-3. Unique control problems

Military facilities have air pollution control problems which are unique to their mission. Among the problems are those associated with classified waste disposal, ammunition, plant wastes, chemical warfare wastes, hazardous toxic waste, and radioactive wastes. Each will require a consultant or a specialist to help solve the unique problem. Therefore, each unique problem will require special handling on a case-to-case basis. The manual does not include any information on treatment of emissions, or the incineration of these unique materials.

### 1-4. Economic considerations

The selection of one particular type of design for a mechanical system for a given application when two or more types of design are known to be feasible must be based on the results of a life cycle cost analyses, prepared in accordance with the requirements of the Department of Defense Construction Criteria Manual (DOD 4270.1-M). Standards for the conduct of all economic studies by and for the Department of the Army and the Department of the Air Force are contained in AR 11-28 and AFR 178-1, respectively. Subject to guidance resulting from implementation of Executive Order 12003 and related guidance from DOD, the cited economic analysis techniques are to remain valid. The basic underlying principles and the most commonly used techniques of economic analysis are described in some detail in a variety of publications and standard textbooks on engineering economy such as *Principles of Engineering Economy* by Grant, Ireson, and Leavenworth; guides published by professional organizations such as the American Institute of Architects' *Life Cycle Cost Analysis-a Guide for Architects*; and handbooks prepared by government agencies such as the Naval Facilities Engineering Command's "Economic Analysis Handbook", NAVFAC P-442. Clarification of the basic standards and guidelines for a particular application and/or supplementary standards for guidelines which may be required for special cases may be obtained by request through normal channels to Headquarters of the particular service branch involved.



U.S. Army Corps of Engineers

Figure 1-1. Emission control procedure.



## CHAPTER 2

# INCINERATOR EMISSIONS

### 2-1. Incineration

This chapter describes and quantifies whenever possible the air pollution particulate emissions which are the direct result of the incineration process.

*a. Incineration process.* The incineration process consists of burning solid, semisolid, liquid, or gaseous waste to produce carbon dioxide, water, and ash. It is an efficient means of reducing waste volume. The solid, incombustible residue of incineration is inert, sanitary, and sensibly odorless.

*b. Emissions.* Incineration contributes to air pollution. The polluting emissions are ash, hydrocarbons, sulfur oxides (SO<sub>x</sub>), nitrous oxides (NO<sub>x</sub>), chlorides, and carbon monoxide. Estimating absolute quantities of these pollutants is not an exact science, but historical testing data from typical incinerators allow estimates of emissions to be made. Also, measurement methods for incinerator emissions are sufficiently advanced to permit actual data to be obtained for any existing incinerator. These measurements are preferred in all cases over analytical estimates.

*c. Pollution codes.* Air pollution particulate emissions must be considered in regard to federal, state and local pollution codes. In general, incinerators cannot meet current pollution code requirements without particulate control devices.

### 2-2. Types of incinerator waste materials

Waste materials are classified as shown in table 2-1. An ultimate analysis of a typical general solid waste is shown in table 2-2. Because of the wide variation in composition of waste materials, an analysis of the actual material to be incinerated should be made before sizing incineration equipment.

Table 2-2

*Ultimate analysis of a typical general solid waste*

Moisture	35.00%
Carbon	20.00%
Oxygen	18.00%
Hydrogen	2.50%
Nitrogen	0.60%
sulfur	0.06%
Noncombustibles	23.84%
	100.00%

From: Environmental Protection Agency, "Control Techniques for Particulate Emissions for Stationary Sources"

### 2-3. Function of incinerators

Incinerators are engineered apparatus capable of withstanding heat and are designed to effectively reduce

solid, semi-solid, liquid, or gaseous waste at specified rates, so that the residues contain little or no combustible material. In order for an incinerator to meet these specifications, the following principles of solid fuel combustion generally apply:

- Air and fuel must be in the proper proportion,
- Air and fuel, especially combustible gases, must be properly mixed,
- Temperatures must be high enough to ignite both the solid fuel and the gaseous components,
- Furnace volumes must permit proper retention time needed for complete combustion,
- Furnace configurations must maintain ignition temperatures and minimize fly-ash entrainment.

### 2-4. Effect of waste properties

The variability of chemical and physical properties of waste materials, such as ash content, moisture content, volatility, burning rate, density, and heating value, makes control of incineration difficult. All of these factors affect to some degree the operating variables of flame-propagation rate, flame travel, combustion temperature, combustion air requirements, and the need for auxiliary heat. Maximum combustion efficiency is maintained primarily through optimum incinerator design.

### 2-5. Types of incinerators

*a. Municipal incinerators.* Incinerators are classified either as large or small units, with the dividing point at a processing rate of 50 tons of waste per day. The trend is toward the use of the smaller units because of their lower cost, their simplicity, and lower air emission control requirements. There are three major types of municipal incinerators.

- (1) *Rectangular incinerators.* The most common municipal incinerator is the rectangular type. The multiple chamber units are either refractory lined or water cooled and consist of a combustion chamber followed by a mixing chamber. The multicell units consist of two or more side-by-side furnace cells connected to a common mixing chamber. Primary air is fed under the grate. Secondary air is added in the mixing chamber to complete combustion. A settling chamber often follows the mixing chamber. Ash is removed from pits in the bottom of all of the chambers.

TABLE 2-1

WASTE CLASSIFICATIONS

TYPE	DESCRIPTION	PRINCIPAL COMPONENTS	APPROXIMATE COMPOSITION % BY WEIGHT	MOISTURE CONTENT	INCOMBUSTIBLE SOLIDS %	BTU VALUE/ LB OF REFUSE AS FIRED
0	Trash	Highly combustible waste; paper, wood, cardboard cartons, including up to 10% treated papers, plastic or rubber scraps; commercial and industrial sources.	Trash 100	10	5	8500
1	Rubbish	Combustible waste, paper, cartons, rags, wood scraps, combustible floor sweepings, domestic, commercial, and industrial sources.	Rubbish 80 Garbage 20	25	10	6500
2	Refuse	Rubbish and garbage; residential sources.	Rubbish 50 Garbage 50	50	7	4300
3	Garbage	Animal and vegetable wastes; restaurants, hotels, markets; institutional commercial, and club sources	Garbage 65 Rubbish 35	70	5	2500
4	Animal solids and organic waste	Carcasses, organs, solid organic wastes from hospital, laboratory, abattoirs, animal pounds and similar sources.	Animal and Human Tissue 100	85	5	1000
5	Gaseous, liquid or semi-liquid wastes	Industrial process wastes such as, tar, paint, solvent, sludge and fumes.	Variable	Dependent on pre-dominant components	Varies according to wastes	Varies according to wastes
6	Semi-solid and solid wastes	Industrial process wastes, such as, rubber, plastic and wood.	Variable	Dependent on pre-dominant components	Varies according to wastes	Varies according to wastes

U. S. Army Corps of Engineers.

- (2) Vertical circular incinerators. Waste is usually fed into the top of the refractory lined chamber. The grate consists of a rotating cone in the center surrounded by a stationary section with a dumping section around it. Arms attached to the rotating cone agitate the waste and move the ash to the outside. Primary air is fed underneath the grate. Overtire air is fed into the upper section of the chamber.
- (3) Rotary kiln incinerators. Rotary kiln incinerators are used to further the combustion of waste that has been dried and partially burned in a rectangular chamber. The waste is mixed

with combustion air by the tumbling action of the kiln. Combustion is completed in the mixing chamber following the kiln where secondary air is added. The ash is discharged at the end of the kiln.

*b. Industrial and commercial incinerators.* Industrial and commercial incinerators generally fall into six categories. The capacities of these incinerators generally range from a half to less than 50 tons per day. They are usually operated intermittently.

- (1) Single chamber incinerators. Single chamber incinerators consist of a refractory lined combustion chamber and an ash pit separated by a

grate. There is no separate mixing chamber. An auxiliary fuel burner is normally provided underneath the grate. The units are normally natural draft (no fans). Emissions from single chamber units are high because of incomplete combustion.

- (2) **Multiple chamber incinerators.** Multiple chamber refractory lined incinerators normally consist of a primary chamber, a mixing chamber and a secondary combustion chamber. The primary chamber is similar to a single chamber unit. Air is fed under the grate and through overfire air ports. Secondary air is added in the mixing chamber. Combustion is completed in the secondary combustion chamber where some settling occurs. These units are also normally natural draft.
- (3) **Conical incinerators.** Conical incinerators known commonly as "tee-pee" burners have been used primarily in the wood products industry to dispose of wood waste. Since they cannot meet most local particulate emission requirements, and since wood waste is becoming more valuable as a fuel, conical incinerators are being phased out.
- (4) **Trench incinerators.** Trench incinerators are used for disposal of waste with a high heat content and a low ash content. The incinerator consists of a U-shaped chamber with air nozzles along the rim. The nozzles are directed to provide a curtain of air over the pit and to provide air in the pit.
- (5) **Controlled-air incinerators.** Controlled-air incinerators consist of a refractory lined primary chamber where a reducing atmosphere is maintained and a refractory lined secondary chamber where an oxidizing atmosphere is maintained. The carbon in the waste burns and supplies the heat to release the volatiles in the waste in the form of a dense combustible smoke. Overfire air is added between chambers. The smoke is ignited in the secondary chamber with the addition of air. Auxiliary fuel burners are sometimes provided in the secondary chamber if the mixture does not support combustion. Air for this type of incinerator is provided by a forced draft fan and is controlled by dampers in order to provide the proper distribution. Controlled-air incinerators are efficient units with low particulate emission rates.
- (6) **Fluidized bed incinerators.** Fluidized bed incinerators consist of a refractory lined vertical cylinder with a grid in the lower part that supports a bed of granular material, such as sand or fine gravel. Air is blown into the chamber below the grid causing the bed to fluidize.

Waste is fed above the bed and then mixes with the media where it burns. Fluidized bed incinerators are normally self sustaining and require an auxiliary fuel burner only for start-up. Fluidizing air is supplied by a centrifugal blower. Ash leaves the fluidized bed incinerator when it becomes fine enough to be carried out by the flue gas. Fluidized bed incinerators are capable of burning most types of liquid or solid waste.

c. **Sludge incinerators.** Sludge incinerators handle materials high in water content and low in heat content. Two types of incinerators are normally used for sludge incineration.

- (1) **Multiple hearth incinerators.** Multiple hearth incinerators consist of vertically stacked grates. The sludge enters the top where the exiting flue gas is used to drive off the moisture. The burning sludge moves through the furnace to the lower hearths. Ash is removed from under the last hearth.
- (2) **Fluidized bed incinerator.** Fluidized bed incinerators are particularly well suited for sludge disposal because of the high heat content of the bed media. Heat from the combustion of the sludge is transferred to the bed media. This heat is then transferred back to the incoming sludge, driving off the moisture.

## 2-6. Particulate emission standards

The Clean Air Act requires all states to issue regulations regarding the amount of particulate emission from incinerators. Each state must meet or exceed the primary standards set forth by the federal act, limiting particulate emissions for incinerators with a charging rate of more than 50 tons per day of solid to .08 grains per standard cubic foot (gr/std ft<sup>3</sup>) of dry gas at 12 percent carbon dioxide (CO<sub>2</sub>). Federal guidelines for sewage sludge incinerators limit emissions to 1.3 pounds (lbs) per ton of dry sludge input and opacity to 20 percent maximum. No federal guidelines currently exist for gaseous emissions. State and local regulations may meet or exceed the federal guidelines. These regulations are subject to change and must be reviewed prior to selecting any air pollution control device.

## 2-7. Particulate emission estimating

In order to select a proper pollution control device, the quantities of particulate emissions from an incinerator must be measured or estimated. Measurement is the preferred method. For new incinerator installations where particulate emissions must be estimated, tables 2-3 and 2-4 should be used unless concurrent data guaranteed by a qualified Vendor is provided.

a. **Factors affecting emission variability.** The quantity and size of particulate emissions leaving the furnace of an incinerator vary widely, depending upon

TABLE 2-3

EMISSION FACTORS FOR REFUSE INCINERATORS WITHOUT CONTROLS<sup>a</sup>

	Particu- lates	Sulfur oxides <sup>b</sup>	Carbon monoxide	Hydro- carbons <sup>c</sup>	Nitrogen oxides <sup>d</sup>
Incinerator Type	lb/ton	lb/ton	lb/ton	lb/ton	lb/ton
Municipal					
Multiple chamber, uncontrolled	30	2.5	35	1.5	3
With settling chamber and water spray system <sup>e</sup>	14	2.5	35	1.5	3
Industrial/Commercial					
Multiple chamber	7	2.5 <sup>f</sup>	10	3	3
Single chamber	15	2.5 <sup>f</sup>	20	15	2
Wood	13	0.1 <sup>g</sup>	NA <sup>h</sup>	NA	4
Rubber tires	138	NA	NA	NA	NA
Municipal refuse	37	2.5 <sup>f</sup>	NA	NA	NA
Controlled air	1.4	1.5	Neg	Neg	10
Flue-fed single chamber	30	0.5	20	15	3
Flue-fed (modified) <sup>i</sup>	6	0.5	10	3	10
Domestic single chamber					
Without primary burner	35	0.5	300	100	1
With primary burner	7	0.5	Neg	2	2
Pathological	8	Neg	Neg	Neg	3

- a Average factors given based on EPA pro-  
cedures of incinerator stack testing.
- b Expressed as sulfur dioxide.
- c Expressed as methane.
- d Expressed as nitrogen dioxide.
- e Most municipal incinerators are  
equipped with at least this much control.

- f Based on municipal incinerator data
- g Based on data for wood combustion in  
conical burners.
- h Not available.
- i With afterburners and draft controls

From: Environmental Protection Agency, "Compilation  
of Air Emission Factors".

TABLE 2-4

EMISSION FACTORS FOR SEWAGE SLUDGE INCINERATORS

<u>Pollutant</u>	<u>Emissions* Uncontrolled lb/ton</u>
Particulate	100
Sulfur dioxide	1
Carbon monoxide	Neg
Nitrogen oxides (as NO <sub>2</sub> )	6
Hydrocarbons	1.5
Hydrogen chloride gas	1.5

\* Unit weights in terms of dried sludge.

From: Environmental Protection Agency, "Compilation of Air Emission Factors".

such factors as incinerator design, refuse type, incinerator capacity, method of feeding, and method of operation. Improved incinerator performance reduces both dust loading and mean particle size.

- (1) *Incinerator capacity.* Large incinerators burn refuse at higher rates creating more turbulent gas flow conditions at the grate surface. Rapid, turbulent, combustion aided by the use of more underfire air causes particle suspension and carry over from the incinerator grate surface resulting in higher emission rates for large incinerators.
- (2) *Underfire air flow.* The effect of increasing underfire grate air flow is to increase particulate emission rate.
- (3) *Excess air.* Excess air is used to control combustion efficiency and furnace temperatures. Incinerators are operated at levels of excess air from 50 percent to 400 percent. However, particulate emission levels increase with the amount of excess air employed. Increases in excess air create high combustion gas velocities and particle carry over. Excess air is important as a furnace temperature control because incomplete combustion will occur at furnace temperatures below 1400 degrees Fahrenheit, and ash slagging at the grate surface and increased NO<sub>x</sub> emissions will occur above furnace temperatures of 1900 degrees Fahrenheit.

(4) *Opacity.* For information on the use of visible opacity measurement as an aid to achieving efficient combustion, see paragraph 3-8.

b. *Data reduction.* The state regulations for particulate emissions are expressed in a variety of units. The following techniques permit the user to reduce particulate test data to grains per dry standard cubic foot at 12 percent CO<sub>2</sub>, as well as to convert other particulate concentration units, as used by some states, to this basis.

- (1) Test data conversion to grains per dry standard cubic foot at 12 percent CO<sub>2</sub>. Equation 2-1 applies.

$$C_s \text{ at 12 percent CO}_2 = \frac{0.68}{p} \times \frac{(t_m + 460)}{C} \times C \quad (\text{eq. 2-1})$$

where: C<sub>s</sub> at 12 percent CO<sub>2</sub> = particulate concentration in grains per dry standard cubic foot at gas conditions corrected to 12 percent CO<sub>2</sub> and standard temperature of 68 degrees Fahrenheit.

- C = particulate concentration at test conditions in grains per dry cubic foot of gas
- t<sub>m</sub> = gas temperature at the test equipment conditions
- C O<sub>2</sub> = percent by volume of the CO<sub>2</sub> in the dry gas

P = barometric pressure in inches of mercury at the test equipment conditions.

- (2) To convert particulate loadings given as pounds per 1000 pounds of dry gas at 50 percent excess air, equation 2-2 applies.

$$C_s \text{ at 12 percent CO}_2 = \frac{C \text{ at 50 percent EA}}{\text{CO}_2} \quad (\text{eq. 2-2})$$

$$\times .325 \times \frac{A_T \times M}{A_A}$$

where: C at 50 percent EA = pounds of particulate per 1000 pounds of gas at 50 percent excess air

$\frac{A_T}{A_A}$  = theoretical air required per actual air used

M = Molecular weight of the gas sample

$$\frac{A_T}{A_A} = \frac{N_2 - 3.788 (O_2 - .5 \text{ CO})}{N_2} \quad (\text{eq. 2-3})$$

$$M = .16 \text{ CO}_2 + .04 \text{ O}_2 + 28 \quad (\text{eq. 2-4})$$

where: N<sub>2</sub> = percent N<sub>2</sub> from Orsat analysis

O<sub>2</sub> = percent O<sub>2</sub> from Orsat analysis

CO = percent CO from Orsat analysis

C O<sub>2</sub> = percent CO, from Orsat analysis

- (3) To convert grains per dry standard cubic foot at 50 percent excess air to grains per dry standard cubic foot at 12 percent CO<sub>2</sub>, equation 2-5 applies.

$$C_s \text{ at 12 percent CO}_2 = \frac{18 \times C_s \text{ at 50 percent EA}}{\text{CO}_2} \quad (\text{eq. 2-5})$$

$$\times \frac{A_T}{A_A}$$

- (4) To convert pounds of particulate per ton of refuse charged to grains per dry standard cubic foot at 12 percent CO<sub>2</sub>, equation 2-6 applies.

$$C_s \text{ at 12 percent CO}_2 = \frac{\text{lbs of particulate}}{\text{tons-of refuse}} \quad (\text{eq. 2-6})$$

$$\times \frac{.42 \times 10^6 \times 1}{\text{GCV} \times F_c}$$

where: GCV = gross calorific value of waste, British thermal units (Btu)/lb

F<sub>c</sub> = carbon F factor, std ft<sup>3</sup>/million (MM)Btu

$$F_c = \frac{0.321 \times 10^6 \times \text{percent carbon}}{\text{GCV}} \quad (\text{eq. 2-7})$$

Percent carbon is by weight from the ultimate analysis of the refuse. The GCV and tons of refuse must be consistent with the ultimate analysis. If the ultimate analysis is on a dry basis, the GCV and tons of refuse must be on a dry basis.

- (5) To convert grains per dry standard cubic foot at 7 percent O<sub>2</sub> to grains per dry standard cubic foot at 12 percent CO<sub>2</sub>, equation 2-8 applies.

$$C_s \text{ at 12 percent CO}_2 = 1.714 \quad (\text{eq. 2-8})$$

$$\times C_s \text{ at 7 Percent O}_2 \times \frac{\text{O}_2}{\text{CO}_2}$$

- (6) To convert pounds of particulate per million British thermal units fired to grains per dry standard cubic foot at 12 percent CO<sub>2</sub>, equation 2-9 applies.

$$C_s \text{ at 12 percent CO}_2 = \frac{\text{lbs of particulate}}{\text{MMBtu}} \quad (\text{eq. 2-9})$$

$$\times \frac{840}{F_c}$$

## 2-8 Sample calculations

a. An industrial multichamber incinerator burns a type I waste at 10 percent moisture of the analysis shown below. What is the estimated particulate emission rate in grains per dry standard cubic foot at 12 percent CO<sub>2</sub>?

*Waste Analysis (Percent by Weight on Wet Basis)*

Carbon	50 percent
Heating value	8500 Btu/lb

- (1) Table 2-3 lists industrial multichamber incinerators as having a particulate emission factor of 7 lb/ton of refuse.

- (2) Using equation 2-7,

$$F_c = \frac{0.321 \times 10^6 \times 50}{8500} = 1888$$

- (3) Using equation 2-6,

$$C_s \text{ at 12 percent CO}_2 = \frac{.42 \times 10^6}{7 \times 8500} \times \frac{1}{1888}$$

$$= 0.183 \text{ gr/std ft}^3$$

b. Test data from an incinerator indicates a particulate concentration of 0.5 gr/ft<sup>3</sup> at 9 percent CO<sub>2</sub>. Correct the particulate concentration to grains per dry standard cubic foot at 12 percent CO<sub>2</sub>. Test conditions were at 72 degrees Fahrenheit and a barometric pressure of 24 inches of mercury.

(1) Using equation 2-1,

$$\frac{C_s \text{ at } 12 \text{ percent CO}_2}{\text{percent CO}_2} = 0.5 \times \frac{0.68}{9} \times \frac{(72 + 460)}{24}$$

$$= 0.84 \text{ gr/std ft}^3$$

c. The emission rate of an incinerator is 10 lb/1000 lb of dry flue gas at 50 percent excess air. The Orsat analysis is 8.0 percent O<sub>2</sub>, 82.5 percent N<sub>2</sub>, 9.5 percent CO<sub>2</sub> and 0 percent CO. Convert the emission rate to grains per dry standard cubic foot at 12 percent CO<sub>2</sub>.

(1) Using equation 2-3,

$$\frac{A_r}{A_a} = \frac{82.5 - 3.788(8.0 - .5(0))}{82.5} = 0.633$$

(2) Using equation 2-4,

$$M = .16(9.5) + .04(8.0) + 28 = 29.84$$

(3) Using equation 2-2,

$$\frac{C_s \text{ at } 12 \text{ percent CO}_2}{\text{percent CO}_2} = \frac{10}{9.5} \times .325 \times .633 \times 29.84$$

$$= 6.46 \text{ gr/std ft}^3$$

d. An incinerator burning waste of the analysis shown below has a measured emission rate of 5 pounds/MMBtu. What is the expected particulate emission rate in grains per dry standard cubic foot at 12 percent CO<sub>2</sub>?

Waste Analysis

Carbon	35 percent by weight on dry basis
Heating Value	6500 Btu/pound as fired
Moisture	21 percent

(1) In order to use equation 2-7, the percent carbon and the heating value must be on the same basis.

$$\text{Percent C on wet basis} = \frac{35 \times (100 - 21)}{100} = 28$$

(2) Using equation 2-7,

$$F_c = \frac{0.321 \times 10^6 \times 28}{6500} = 1382$$

(3) Using equation 2-9,

$$\frac{C_s \text{ at } 12 \text{ percent CO}_2}{\text{percent CO}_2} = 5 \times \frac{840}{1383}$$

$$= 3.04 \text{ gr/std ft}^3$$

## CHAPTER 3

# BOILER EMISSIONS

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### 3-1. Generation processes

The combustion of a fuel for the generation of steam or hot water results in the emission of various gases and particulate matter. The respective amounts and chemical composition of these emissions formed are dependent upon variables occurring within the combustion process. The interrelationships of these variables do not permit direct interpretation by current analytical methods. Therefore, most emission estimates are based upon factors compiled through extensive field testing and are related to the fuel type, the boiler type and size, and the method of firing. Although the use of emission factors based on the above parameters can yield an accurate first approximation of on-site boiler emissions, these factors do not reflect individual boiler operating practices or equipment conditions, both of which have a major influence on emission rates. A properly operated and maintained boiler requires less fuel to generate steam efficiently thereby reducing the amount of ash, nitrogen and sulfur entering the boiler and the amount of ash, hydrocarbons, nitrogen oxides (NO<sub>x</sub>) and sulfur oxides (SO<sub>x</sub>) exiting in the flue gas stream. Emissions from conventional boilers are discussed in this chapter. Chapter 13 deals with emissions from fluidized bed boilers.

### 3-2. Types of fuels

*a. Coal.* Coal is potentially a high emission producing fuel because it is a solid and can contain large percentages of sulfur, nitrogen, and noncombustibles. Coal is generally classified, or “ranked”, according to heating value, carbon content, and volatile matter. Coal ranking is important to the boiler operator because it describes the burning characteristics of a particular coal type and its equipment requirements. The main coal fuel types are bituminous, subbituminous, anthracite, and lignite. Bituminous is most common. Classifications and analyses of coal may be found in “Perry’s Chemical Engineering Handbook”,

*b. Fuel oil.* Analyses of fuel oil may be found in “Perry’s Chemical Engineering Handbook”.

- (1) *Distillates.* The lighter grades of fuel oil (No.1, No.2) are called distillates. Distillates are clean burning relative to the heavier grades because they contain smaller amounts of sediment, sulfur, ash, and nitrogen and can be fired in a variety of burner types without a need for pre-heating.

- (2) *Residuals.* Residual fuel oils (No.4, No.5, No.6) contain a greater amount of ash, sediment, sulfur, and nitrogen than is contained in distillates. They are not as clean burning as the distillate grades.

*c. Gaseous fuel.* Natural gas, and to a limited extent liquid petroleum (butane and propane) are ideally suited for steam generation because they lend themselves to easy load control and require low amounts of excess air for complete combustion. (Excess air is defined as that quantity of air present in a combustion chamber in excess of the air required for stoichiometric combustion). Emission levels for gas firing are low because gas contains little or no solid residues, noncombustibles, and sulfur. Analyses of gaseous fuels may be found in “Perry’s Chemical Engineering Handbook”.

*d. Bark and wood waste.* Wood bark and wood waste, such as sawdust, chips and shavings, have long been used as a boiler fuel in the pulp and paper and wood products industries. Because of the fuel’s relatively low cost and low sulfur content, their use outside these industries is becoming commonplace. Analyses of bark and wood waste may be found in Environmental Protection Agency, “Control Techniques for Particulate Emissions from Stationary Sources”. The fuel’s low heating value, 4000-4500 British thermal units per pound (Btu/lb), results from its high moisture content (50-55 percent).

*e. Municipal solid waste (MSW) and refuse derived fuel (RDF).* Municipal solid waste has historically been incinerated. Only recently has it been used as a boiler fuel to recover its heat content. Refuse derived fuel is basically municipal solid waste that has been prepared to burn more effectively in a boiler. Cans and other noncombustibles are removed and the waste is reduced to a more uniform size. Environmental Protection Agency, “Control Techniques for Particulate Emissions from Stationary Sources” gives characteristics of refuse derived fuels.

### 3-3. Fuel burning systems

*a. Primary function.* A fuel burning system provides controlled and efficient combustion with a minimum emission of air pollutants. In order to achieve this goal, a fuel burning system must prepare, distribute, and mix the air and fuel reactants at the optimum concentration and temperature.



*b. Types of equipment.*

- (1) **Traveling grate stokers.** Traveling grate stokers are used to burn all solid fuels except heavily caking coal types. Ash carryout from the furnace is held to a minimum through use of overfire air or use of the rear arch furnace design. At high firing rates, however, as much as 30 percent of the fuel ash content may be entrained in the exhaust gases from grate type stokers. Even with efficient operation of a grate stoker, 10 to 30 percent of the particulate emission weight generally consists of unburned combustibles.
- (2) **Spreader stokers.** Spreader stokers operate on the combined principles of suspension burning and nonagitated type of grate burning. Particulate emissions from spreader stoker fired boilers are much higher than those from fuel bed burning stokers such as the traveling grate design, because much of the burning is done in suspension. The fly ash emission measured at the furnace outlet will depend upon the firing rate, fuel sizing, percent of ash contained in the fuel, and whether or not a fly ash reinjection system is employed.
- (3) **Pulverized coal burners.** A pulverized coal fired installation represents one of the most modern and efficient methods for burning most coal types. Combustion is more complete because the fuel is pulverized into smaller particles which require less time to burn and the fuel is burned in suspension where a better mixing of the fuel and air can be obtained. Consequently, a very small percentage of unburned carbon remains in the boiler fly ash. Although combustion efficiency is high, suspension burning increases ash carry over from the furnace in the stack gases, creating high particulate emissions. Fly ash carry over can be minimized by the use of tangentially fired furnaces and furnaces designed to operate at temperatures high enough to melt and fuse the ash into slag which is drained from the furnace bottom. Tangentially fired furnaces and slag-tap furnaces decrease the amount of fuel ash emitted as particulates with an increase in NO<sub>x</sub> emissions.
- (4) **Fuel oil burners.** Fuel oil may be prepared for combustion by use of mechanical atomizing burners or twin oil burners. In order for fuel oil to be properly atomized for combustion, it must meet the burner manufacturers requirements for viscosity. A fuel oil not heated to the proper viscosity cannot be finely atomized and will not burn completely. Therefore, unburned carbon or oil droplets will exit in the furnace flue gases. A fuel oil heated above the proper

viscosity may ignite too rapidly forming pulsations and zones of incomplete combustion at the burner tip. Most burners require an atomizing viscosity between 100 and 200 Saybolt Universal Seconds (SUS); 150 SUS is generally specified.

- (5) **Municipal solid waste and refuse derived fuel burning equipment.** Large quantities of MSW are fired in water tube boilers with overfeed stokers on traveling or vibrating grates. Smaller quantities are fired in shop assembled hopper or ram fed boilers. These units consist of primary and secondary combustion chambers followed by a waste heat boiler. The combustion system is essentially the same as the "controlled-air" incinerator described in paragraph 2-5(b)(5). The type of boiler used for RDF depends on the characteristics of the fuel. Fine RDF is fired in suspension. Pelletized or shredded RDF is fired on a spreader stoker. RDF is commonly fired in combination with coal, with RDF constituting 10 to 50 percent of the heat input.

**3-4. Emission standards**

The Clean Air Act requires all states to issue regulations regarding the limits of particulate, SO<sub>x</sub> and NO<sub>x</sub> emissions from fuel burning sources. State and local regulations are subject to change and must be reviewed prior to selecting any air pollution control device. Table 3-1 shows current applicable Federal Regulations for coal, fuel oil, and natural gas. The above allowable emission rates shown are for boilers with a heat input of 250 million British thermal units (MMBtu) and above.

**Table 3-1**  
**Allowable federal emission rates**

Fuel	Particulate	SO <sub>x</sub>	NO <sub>x</sub>	Opacity
Coal	0.1 lb/MMBtu	1.2 lb/MMBtu	.7 lb/MMBtu	20 Percent
Fuel Oil	0.1 lb/MMBtu	0.8 lb/MMBtu	.3 lb/MMBtu	20 Percent
Natural Gas	0.1 lb/MMBtu	-	.2 lb/MMBtu	20 Percent

From: 40CFR86-"National Primary and Secondary Ambient Air Quality Standards".

**3-5. Formation of emissions**

a. **Combustion parameters.** In all fossil fuel burning boilers, it is desirable to achieve a high degree of combustion efficiency, thereby reducing fuel consumption and the formation of air pollutants. For each particular type fuel there must be sufficient time, proper temperature, and adequate fuel/air mixing to insure complete combustion of the fuel. A deficiency in any of these three requirements will lead to incomplete combustion and higher levels of particulate emission in the form of unburned hydrocarbon. An excess in time, temperature, and fuel/air mixing will increase the boiler formation of gaseous emissions (NO<sub>x</sub>). Therefore, there is some optimum value for these three requirements

within the boiler's operating range which must be met and maintained in order to minimize emission rates. The optimum values for time, temperature, and fuel-air mixing are dependent upon the nature of the fuel (gaseous, liquid or solid) and the design of the fuel burning equipment and boiler.

*b. Fuel type.*

- (1) *Gaseous fuels.* Gaseous fuels burn more readily and completely than other fuels. Because they are in molecular form, they are easily mixed with the air required for combustion, and are oxidized in less time than is required to burn other fuel types. Consequently, the amount of fuel/air mixing and the level of excess air needed to burn other fuels are minimized in gas combustion, resulting in reduced levels of emissions.
- (2) *Solid and liquid fuels.* Solid and liquid fuels require more time for complete burning because they are fired in droplet or particle form. The solid particles or fuel droplets must be burned off in stages while constantly being mixed or swept by the combustion air. The size of the droplet or fired particle determines how much time is required for complete combustion, and whether the fuel must be burned on a grate or can be burned in suspension. Systems designed to fire solid or liquid fuels employ a high degree of turbulence (mixing of fuel and air) to complete combustion in the required time, without a need for high levels of excess air or extremely long combustion gas paths. As a result of the limits imposed by practical boiler design and necessity of high temperature and turbulence to complete particle burnout, solid and liquid fuels develop higher emission levels than those produced in gas firing.

### 3-6. Fuel selection

Several factors must be considered when selecting a fuel to be used in a boiler facility. All fuels are not available in some areas. The cost of the fuel must be factored into any economic study. Since fuel costs vary geographically, actual delivered costs for the particular area should be used. The capital and operating costs of boiler and emission control equipment vary greatly depending on the type of fuel to be used. The method and cost of ash disposal depend upon the fuel and the site to be used. Federal, state and local regulations may also have a bearing on fuel selection. The Power Plant and Fuel Use Act of 1978 requires that a new boiler installation with heat input greater than 100 MMBtu have the capability to use a fuel other than oil or natural gas. The Act also limits the amount of oil and natural gas firing in existing facilities. There are also regulations within various branches of the military service

regarding fuel selection, such as AR 420-49 for the Army's use.

### 3-7. Emission factors

Emission factors for particulates,  $\text{SO}_x$ , and  $\text{NO}_x$ , are presented in the following paragraphs. Emission factors were selected as the most representative values from a large sampling of boiler emission data and have been related to boiler unit size and type, method of firing and fuel type. The accuracy of these emission factors will depend primarily on boiler equipment age, condition, and operation. New units operating at lower levels of excess air will have lower emissions than estimated. Older units may have appreciably more. Therefore, good judgement should accompany the use of these factors. These factors are from, Environmental Protection Agency, "Compilation of Air Pollutant Emission Factors". It should be noted that currently MSW and RDF emission factors have not been established.

*a. Particulate emissions.* The particulate loadings in stack gases depend primarily on combustion efficiency and on the amount of ash contained in the fuel which is not normally collected or deposited within the boiler. A boiler firing coal with a high percentage of ash will have particulate emissions dependent more on the fuel ash content and the furnace ash collection or retention time than on combustion efficiency. In contrast, a boiler burning a low ash content fuel will have particulate emissions dependent more on the combustion efficiency the unit can maintain. Therefore, particulate emission estimates for boilers burning low ash content fuels will depend more on unit condition and operation. Boiler operating conditions which affect particulate emissions are shown in table 3-2. Particulate emission factors are presented in tables 3-3, 3-4, 3-5 and 3-6.

*b. Gaseous emissions.*

- (1) *Sulfur oxide emissions.* During combustion, sulfur is oxidized in much the same way carbon is oxidized to carbon dioxide ( $\text{CO}_2$ ). Therefore, almost all of the sulfur contained in the fuel will be oxidized to sulfur dioxide ( $\text{SO}_2$ ) or sulfur trioxide ( $\text{SO}_3$ ) in efficiently operated boilers. Field test data show that in efficiently operated boilers, approximately 98 percent of the fuel-bound sulfur will be oxidized to  $\text{SO}_2$ , one percent to  $\text{SO}_3$ , and the remaining one percent sulfur will be contained in the fuel ash. Boilers with low flue gas stack temperatures may produce lower levels of  $\text{SO}_2$  emissions due to the formation of sulfuric acid. Emission factors for  $\text{SO}_x$  are contained in tables 3-3, 3-4, 3-5, and 3-6.

- (2) *Nitrogen oxide emissions.* The level of nitrogen oxides ( $\text{NO}_x$ ) present in stack gases depends upon many variables. Furnace heat release rate, temperature, and excess air are

Table 3-2

FACTORS RELATING TO PARTICULATE EMISSIONS

	<u>Level of Particulate Emissions</u>	
	<u>High</u>	<u>Low</u>
Fuel characteristics:		
High ash content	X	-
High moisture content	X	-
Sizing		
High degree of atomization or pulverization	-	X
Boiler characteristics:		
High combustion rate	X	-
Dry bottom ash collection	X	-
Wet bottom ash collection	-	X
Flue-gas recirculation	X	-
Method of firing		
Tangential	-	X
Horizontal	X	-
Spreader stoker	X	-
Boiler operation:		
Improper oil pressure	X	-
Improper oil viscosity	X	-
High combustion air temperature	-	X
Nonuniform air flow (between register or air compartments)	X	-
High excess air	X	-
Low furnace temperature	X	-
Equipment condition:		
Worn burner (nozzles, sprayer, plates, etc.)	X	-
Unclean or slagging boiler tube surfaces	X	-

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major variables affecting NO<sub>x</sub> emission levels, but they are not the only ones. Therefore, while the emission factors presented in tables 3-3, 3-4, 3-5, and 3-6 may not totally reflect on site conditions, they are useful in determining if a NO<sub>x</sub> emission problem may be present. Factors which influence NO<sub>x</sub> formation are shown in table 3-7.

**3-8. Opacity**

Visual measurements of plume opacity (para 5-3j) can aid in the optimization of combustion conditions. Particulate matter (smoke), the primary cause of plume opacity, is dependent on composition of fuel and effi-

ciency of the combustion process. Smoke varies in color but is generally observed as gray, black, white, brown, blue, and sometimes yellow, depending on the conditions under which certain types of fuels or materials are burned. The color and density of smoke is often an indication of the type or combustion problems which exist in a process.

a. Gray or black smoke is often due to the presence of unburned combustibles. It can be an indicator that fuel is being burned without sufficient air or that there is inadequate mixing of fuel and air.

b. White smoke may appear when a furnace is operating under conditions of too much excess air. It may also be generated when the fuel being burned contains

TABLE 3-3

## EMISSION FACTORS FOR BITUMINOUS COAL COMBUSTION WITHOUT CONTROL EQUIPMENT

Furnace Size, 10 <sup>6</sup> Btu/hr heat input	Particu- lates <sup>a</sup>	Sulfur oxides <sup>b</sup>	Carbon monoxide	Hydro- carbons <sup>c</sup>	Nitrogen oxides	Alde- hydes
	lb/ton coal burned	lb/ton coal burned	lb/ton coal burned	lb/ton coal burned	lb/ton coal burned	lb/ton coal burned
Greater than 100 (Utility and large industrial boilers)						
Pulverized - General	16A	38S	1	0.3	18	0.005
- Wet bottom	13A <sup>d</sup>	38S	1	0.3	30	0.005
- Dry bottom	17A	38S	1	0.3	18	0.005
Cyclone	2A	38S	1	0.3	55	0.005
10 to 100 (large commercial and general industrial boilers) Spreader stoker <sup>e</sup>	13A <sup>f</sup>	38S	2	1	15	0.005
Less than 10 (commercial and domestic furnaces) Underfed stoker	2A	38S	10	3	6	0.005

- The letter A on all units other than hand-fired equipment indicates that the weight percentage of ash in the coal should be multiplied by the value given. Example: If the factor is 16 and the ash content is 10 percent, the particulate emissions before the control equipment would be 10 times 16, or 160 pounds of particulate per ton of coal.
- S equals the sulfur content (see footnote a above)
- Expressed as methane.
- Without fly-ash reinjection.
- For all other stokers use 5A for particulate emission factor.
- Without fly-ash reinjection. With fly-ash reinjection use 20A. This value is not an emission factor but represents loading reaching the control equipment.

From: Environmental Protection Agency, "Compilation of Air Emission Factors".

TABLE 3-4

EMISSION FACTORS FOR FUEL OIL COMBUSTION

Pollutant	Type of Boiler*			
	Power Plant	Industrial and Commercial		Domestic
	Residual	Residual Oil	Distillate Oil	Distillate Oil
	lb/10 <sup>3</sup> gal	lb/10 <sup>3</sup> gal	lb/10 <sup>3</sup> gal	lb/10 <sup>3</sup> gal
Particulate <sup>c</sup>	c	c	2	2.5
Sulfur dioxide <sup>d</sup>	157S	157S	142S	142S
Sulfur trioxide <sup>d</sup>	2S	2S	2S	2S
Carbon monoxide <sup>e</sup>	5	5		5
Hydrocarbons (total, as CH <sub>4</sub> ) <sup>f</sup>	1	1	1	1
(Nitrogen oxides (total, as NO <sub>x</sub> ))	105(50)8 <sup>g</sup>	60 <sup>h</sup>	22	18

- a. Boilers can be classified, roughly, according to their gross (higher) heat input rate as shown below.  
 Power plant (utility) boilers: greater than 250 x 10<sup>6</sup> Btu/hr  
 Industrial boilers: greater than 15 x 10<sup>6</sup> but less than 250 x 10<sup>6</sup> Btu/hr  
 Commercial boilers: greater than 0.5 x 10<sup>6</sup>, but less than 15 x 10<sup>6</sup> Btu/hr  
 Domestic (residential) boilers: less than 0.5 x 10<sup>6</sup> Btu/hr
- b. Particulate is defined in this table as that material collected by EPA Method 5 (front half catch).
- c. Particulate emission factors for residual oil combustion are best described, on the average, as a function of fuel oil grade and sulfur content, as shown below.  
 Grade 6 oil: lb/10<sup>3</sup> gal = 10 (S) + 3  
 Where: S is the percentage, by weight, of sulfur in the oil  
 Grade 5 oil: 10 lb/10<sup>3</sup> gal  
 Grade 4 oil: 7 lb/10<sup>3</sup> gal
- d. S is the percentage, by weight, of sulfur in the oil.
- e. Carbon monoxide emissions may increase by a factor of 10 to 100 if a unit is improperly operated or not well maintained.
- f. Hydrocarbon emissions are generally negligible unless unit is improperly or not well maintained. In which case emissions may increase by several orders of magnitude.
- g. Use 50 lb/10<sup>3</sup> gal for tangentially fired boilers and 105 lb/10<sup>3</sup> gal for all others, at full load, and normal (greater than 15 percent) excess air. At reduced loads, NO<sub>x</sub> emissions are reduced by 0.5 to 1 percent, on the average, for every percentage reduction in boiler load.
- h. Several combustion modifications can be employed for NO<sub>x</sub> reductions: (1) limited excess air firing can reduce NO<sub>x</sub> emissions by 5 to 30 percent. (2) staged combustion can reduce NO<sub>x</sub> emissions by 20 to 45 percent, and (3) flue gas recirculation can reduce NO<sub>x</sub> emissions by 10 to 45 percent. Combinations of the modifications have been employed to reduce NO<sub>x</sub> emissions by as much as 60 percent in certain boilers.
- i. Nitrogen oxides emissions from residual oil combustion in industrial and commercial boilers are strongly dependent on the fuel nitrogen content and can be estimated more accurately by the following empirical relationship:  
 lb NO<sub>x</sub>/10<sup>3</sup> gal = 22 + 400 (N)<sup>2</sup>  
 Where: N is the percentage, by weight, of nitrogen in the oil.  
 Note: For residual oils having high (greater than 0.5 percent by weight) nitrogen contents, one should use 120 lb NO<sub>x</sub>/10<sup>3</sup> gal as an emission factor.  
 From: Environmental Protection Agency, "Compilation of Air Emission Factors".  
 U.S. Corps of Engineers

excessive amounts of moisture or when steam atomization or a water quenching system is employed.

c. A blue or light blue plume may be produced by the burning of high sulfur fuels. However, the color is only observed when little or no other visible emission is present. A blue plume may also be associated with the burning of domestic trash consisting of mostly paper or wood products.

d. Brown to yellow smoke may be produced by processes generating excessive amounts of nitrogen dioxide. It may also result from the burning of semi-solid tarry substances such as asphalt or tar paper encountered in the incineration of building material waste.

### 3-9. Sample problems of emission estimating

- a. Data Conversion. Pounds per million Btu (lb/

MMBtu) to grains per standard cubic foot (gr/std ft<sup>3</sup>) dry basis is accomplished by equation 3-1.

$$E = C \times F_d \times \frac{20.9}{20.9 - \%O_2} \times 7000 \quad (\text{eq. 3-1})$$

- where: E = pound/MMBtu
- C = concentration, gr/std ft<sup>3</sup> dry
- %O<sub>2</sub> = percent by volume of oxygen in the flue gas
- F<sub>d</sub> = dry F factor, std ft<sup>3</sup>/MMBtu

Fuel Type	F <sub>d</sub>
Anthracite coal	10100
Bituminous coal	9780
Fuel oil	9190
Gaseous fuels	8710
Wood	9240
Wood bark	9600

TABLE 3-5

EMISSION FACTORS FOR NATURAL GAS COMBUSTION

Pollutant	Type of Unit		
	Power Plant	Industrial Process Boiler	Domestic and Commercial Heating
	lb/MCF gas	lb/MCF gas	lb/MCF gas
Particulates	5-15	5-15	5-15
Sulfur oxides (SO <sub>2</sub> ) <sup>a</sup>	0.6	0.6	0.6
Carbon monoxide	17	17	20
Hydrocarbons (as CH <sub>4</sub> )	1	3	8
Nitrogen oxides (NO <sub>x</sub> )	700 <sup>b</sup>	(120-230) <sup>c</sup>	(80-120) <sup>d</sup>

- a. Based on an average sulfur content of natural gas of 2000 gr/million cubic feet (MMCF).
- b. Use 300 lb/MCF for tangentially fired units.
- c. This represents a typical range for many industrial boilers. For large industrial units (greater than 100 MMBtu/hr) use the NO<sub>x</sub> factors presented for power plants.
- d. Use 80 for domestic heating units and 120 for commercial units.

From: Environmental Protection Agency, "Compilation of Air Emission Factors".

**b. Sample Problem Number 1.** An underfed stoker fired boiler burns bituminous coal of the analysis shown below. If this unit is rated at 10 MMBtu per hour (hr) of fuel input, what are the estimated emission rates?

Bituminous Coal Analysis (percent by weight)

Ash	13.0
Sulfur	0.7
Heating value	12,360 Btu/pound

- (1) Using table 3-3 (footnote e), particulate emissions are given as 5A pound/ton of coal where A is the percent ash in the coal.
  - (a) 5 x 13% ash = 65 pounds of particulate/ton of coal.

(b) 65 pounds/ton x ton/2000 pounds = .0325 pound of particulate/pound of coal

(c)  $(.0325 \text{ lb/lb}) \times \frac{\text{lb of coal} \times 10^6 \text{ Btu}}{12,360 \text{ Btu MMBtu}}$   
 = 2.63 lbs/MMBtu

- (2) Using table 3-3, SO<sub>2</sub> emissions are given as 38S pound/ton of coal, where S is the percent sulfur in the coal.
  - (a) 38 x .7% sulfur = 26.6 pounds of SO<sub>2</sub>/ton of coal
  - (b) 26.6 pounds/ton = ton/2000 pounds = .0133 pound of SO<sub>2</sub>/pound of coal

TABLE 3-6

EMISSION FACTORS FOR BARR AND  
WOOD WASTE COMBUSTION IN BOILERS

Pollutant	Emissions
	lb/ton
Particulates <sup>a</sup>	
Bark <sup>b</sup>	
With fly-ash reinjection <sup>c</sup>	75
Without fly-ash reinjection	50
Wood/bark mixture <sup>b</sup>	
With fly-ash reinjection <sup>c</sup>	45
Without fly-ash reinjection	30
Wood <sup>d</sup>	5-15
Sulfur oxides (SO <sub>2</sub> ) <sup>e</sup>	1.5
Carbon monoxide <sup>f</sup>	2-60
Hydrocarbons <sup>f</sup>	2-70
Nitrogen oxides (NO <sub>2</sub> )	10

- a. These emission factors were determined for boilers burning gas or oil as an auxiliary fuel, and it was assumed all particulates resulted from the waste fuel alone. When coal is burned as an auxiliary fuel, the appropriate emission factor from Table 3-3 should be used in addition to the above factor.
- b. These factors based on an as-fired moisture content of 50 percent.
- c. This factor represents a typical dust loading reaching the control equipment for boilers employing fly-ash reinjection.
- d. This waste includes clean, dry (5 to 50 percent moisture) sawdust, shavings, ends, etc. and no bark. For well designed and operated boilers, use lower value and higher values for others. This factor is expressed on an as-fired moisture content basis assuming no fly-ash reinjection.
- e. This factor is calculated by material balance assuming a maximum sulfur content of 0.1 percent in the waste. When auxiliary fuels are burned, the appropriate factors from Tables 3-3, 3-4, and 3-5 should be used in addition to determine sulfur oxide emissions.
- f. Use lower values for well designed and operated boilers.

**From:** Environmental Protection Agency, "Compilation of Air Emission Factors"

TABLE 3-7

FACTORS AFFECTING NO<sub>x</sub> EMISSIONS

<u>Variable</u>	<u>Effect on NO<sub>x</sub> Emission</u>	
	<u>Increase</u>	<u>Decrease</u>
Heat release rate	X	-
Heat quenching rate (water cooled furnaces)	-	X
Boiler capacity	X	-
Boiler load	X	-
Excess air	X	-
Furnace temperature	X	-
Combustion air temperature	X	-
Fuel nitrogen content	X	-
Fuel oxygen content	X	-
Fuel moisture content	-	X
Distance between burners	-	X
Number of burners per unit	-	X
Fuel/air mixing (turbulence)	X	-
Time available for particle burnout (tangentially fired boilers)	-	X

U. S. Army Corps of Engineers.

$$(c) (.0133 \text{ lb/lb}) \times \frac{\text{lb of coal}}{12,360 \text{ Btu}} \times \frac{10^6 \text{ Btu}}{\text{MMBtu}} = 1.08 \text{ lbs/MMBtu}$$

(3) Using table 3-3, NO<sub>x</sub> emissions are given as 15 pounds/ton of coal.

$$(a) 15 \text{ pounds/ton} \times \text{ton}/2000 \text{ pounds} = .0075 \text{ pound of NO}_x/\text{pound of coal}$$

$$(b) (.0075 \text{ lb/lb}) \times \frac{\text{lb of coal}}{12,360 \text{ Btu}} \times \frac{10^6 \text{ Btu}}{\text{MMBtu}} = .61 \text{ lbs/MMBtu}$$

(4) If particulate emission must be reduced to .2

pounds/MMBtu, the required removal efficiency is determined as,

$$1 - \frac{.2}{2.63} = .924 \text{ (92.4\%)}$$

(5) If the oxygen in the flue gas is estimated at 5 percent by volume, what is the dust concentration leaving the boiler in grains/standard cubic foot (dry)?

$$\begin{aligned} \text{Using equation 3-1,} \\ C &= \frac{7000 \times 2.63}{9780} \frac{20.9 - 5}{20.9} \\ &= 1.43 \text{ gr/std ft}^3 \text{ dry} \end{aligned}$$



c. *Sample Problem Number 2.* A boiler rated at 50 MMBtu/hr burns fuel oil of the analysis shown below. What are the estimated emission rates?

#6 Fuel Oil Analysis (percent by weight)

Sulfur	2
Nitrogen	.2
Heating Value	150,000 Btu per gallon (gal)

(1) Using table 3-4, particulate emissions are given as  $[10(S) + 3]$  pound/1000 gal, where S is the percent sulfur in the fuel oil.

(a)  $(10 \times 2\% \text{ sulfur}) + 3 = 23$  pounds of particulate/1000 gal

$$(b) \ 23 \text{ lbs/1000 gal} \times \frac{\text{gal of oil}}{150,000 \text{ Btu}} \times \frac{10^6 \text{ Btu}}{\text{MMBtu}} = .15 \text{ lb/MMBtu}$$

(2) Using table 3-4, SO<sub>x</sub> emissions are given as 157S pound/1000 gal, where S is the percent sulfur in the fuel oil.

(a)  $157 \times 2\% \text{ sulfur} = 314$  pounds/1000 gal

$$(b) \ 314 \text{ lbs/1000 gal} \times \frac{\text{gal of oil}}{150,000 \text{ Btu}} \times \frac{10^6 \text{ Btu}}{\text{MMBtu}} = 2.09 \text{ lb/MMBtu}$$

(3) Using table 3-4, NO<sub>x</sub> emissions are given as  $[22 + 400(N)^2]$  pound/1000 gal, where N is the percent nitrogen in the fuel oil.

(a)  $22 + 400 \times (.2)^2 = 38$  pounds of NO<sub>x</sub>/1000 gal

$$(b) \ 38 \text{ lbs/1000 gal} \times \frac{\text{gal of oil}}{150,000 \text{ Btu}} \times \frac{10^6 \text{ Btu}}{\text{MMBtu}} = .25 \text{ lb/MMBtu}$$

d. *Sample Problem Number 3.* A commercial boiler rated at 10 MMBtu/hr fires natural gas with a heating value of 1000 Btu/ft<sup>3</sup>. What are the estimated particulate and NO<sub>x</sub> emission rates?

(1) Using table 3-5, particulate emissions are given as a maximum of 15 pound per million cubic feet (MCF) of natural gas.

$$(a) \ 15 \text{ lb/MCF} \times \frac{\text{MCF}}{10^6 \text{ ft}^3} \times \frac{10 \times 10^6 \text{ Btu}}{\text{hr}} \times \frac{\text{ft}^3}{1000 \text{ Btu}} = .15 \text{ lb/hr}$$

$$(b) \ .15 \text{ lb/hr} \times \frac{\text{hr}}{10 \text{ MMBtu}} = .015 \text{ lb/MMBtu}$$

(2) Using table 3-5 (footnote d), NO<sub>x</sub> emissions are given as 120 pound/MCF of natural gas.

$$(a) \ 120 \text{ lb/MCF} \times \frac{\text{MCF}}{10^6 \text{ ft}^3} \times \frac{10 \times 10^6 \text{ Btu}}{\text{hr}} \times \frac{\text{ft}^3}{1000 \text{ Btu}} = 1.2 \text{ lb/hr}$$

$$(b) \ 1.2 \text{ lb/hr} \times \frac{\text{hr}}{10 \text{ MMBtu}} = .12 \text{ lb/MMBtu}$$

e. *Sample Problem Number 4.* A spreader stoker fired boiler without reinjection burns bark and coal in combination. The bark firing rate is 2000 pound/hr. The coal firing rate is 1000 pound/hr of bituminous coal with an ash content of 10 percent and a heating value of 12,500 Btu/pound. What is the estimated particulate emission rate from this boiler?

(1) Using table 3-6, the bark firing particulate emission rate is given as 50 pounds/ton of fuel.  
50 pounds/ton  $\times$  ton/2000 pounds  $\times$  2000 pound/hr = 50 pounds/hr of particulate from bark.

(2) Using table 3-3, the coal firing particulate emission rate for a heat input of 12.5 MMBtu/hr is 13A pounds/ton of fuel.  
(13  $\times$  10) pound/ton  $\times$  1000 pound/hr  $\times$  ton/2000 pound = 65 pounds/hr of particulate from coal.

(3) The total particulate emission rate from the boiler is,  
50 pounds/hr from bark + 65 pounds/hr from coal = 115 pounds/hr

## CHAPTER 4

# STACK EMISSION REGULATIONS AND THE PERMITTING PROCESS

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### 4-1. Stack emissions

The discharge of pollutants from the smokestacks of stationary boilers and incinerators is regulated by both Federal and State Agencies. A permit to construct or modify an emission source will almost certainly be required.

*a.* The emissions must comply with point source regulations, dependent upon characteristics of the point source, and also with ambient air quality limitations which are affected by physical characteristics of the location and the meteorology of the area of the new source.

*b.* The permitting procedure requires that estimates be made of the effect of the stack emissions on the ambient air quality. Predictive mathematical models are used for arriving at these estimates.

*c.* Due to the time requirements and the complexity of the process and the highly specialized nature of many of the tasks involved, it is advisable to engage consultants who are practiced in the permitting procedures and requirements. This should be done at a very early stage of planning for the project.

### 4-2. Air quality standards

*a. Federal standards.* Environmental Protection Agency Regulations on National Primary and Secondary Ambient Air Quality Standards (40 CFR 50).

*b. State standards.* Federal installations are also subject to State standards.

### 4-3. Permit acquisition process

*a. New Source Review.* The state agency with jurisdiction over pollution source construction permits should be contacted at the very beginning of the project planning process because a New Source Review (NSR) application will probably have to be filed in addition to any other State requirements. A New Source Review is the process of evaluating an application for a "Permit to Construct" from the Air Quality Regulatory Agency having jurisdiction.

*b. Planning.* Consideration of air quality issues very early in the planning process is important because engineering, siting, and financial decisions will be affected by New Source Review. Engineering and construction schedules should include the New Source Review process which can take from 6 to 42 months to complete and which may require the equivalent of one year of monitoring ambient air quality before the review process can proceed.

*c. Emission levels.* One must file for a New Source Review application if, after use of air pollution control equipment, the new boiler or incinerator will result in increased emissions of any pollutant greater than a specified limit. Proposed modifications of existing boilers and incinerators that will cause increases in pollutant emissions greater than certain threshold levels ("de minimis" emission rate) require New Source Review.

*d. General determinants for steps required for permitting.* Steps required for a New Source Review depend upon the location of the new source, characteristics of the other sources in the area, and on discussions with the State Air Pollution Control Agencies, possibly the EPA, and how well one is current with the changes in regulations and administrative practices. Because of the constantly changing picture, it is usually very beneficial to engage an air quality consultant to aid in planning permitting activities.

*e. Technical tasks.* The principal technical tasks that are required for the permitting effort in most cases may be summarized as follows:

- (1) Engineering studies of expected emission rates and the control technology that must be used.
- (2) Mathematical modeling to determine the expected impact of the changed emission source.
- (3) Collection of air quality monitoring data required to establish actual air quality concentrations and to aid in analysis of air quality related values. All technical tasks are open to public questioning and critique before the permitting process is completed.

*f. New Source Review program steps.* The steps required in a New Source Review vary. However, it is always required that a separate analysis be conducted for each pollutant regulated under the Act. Different pollutants could involve different paths for obtaining a permit, and may even involve different State and Federal Agencies.

- (1) *Attainment or nonattainment areas.* A concern which must be addressed at the beginning of a New Source Review is whether the location is in a "nonattainment" or "attainment" area. An area where the National Ambient Air Quality Standards (NAAQS) are not met is a "nonattainment" area for any particular pollu-

tant exceeding the standards. Areas where the National Ambient Air Quality Standards (NAAQS) that are being met are designated as an “attainment” area. Designation of the area as “attaining”, or “nonattaining”, for each pollutant encountered determines which of the two routes is followed to procure a permit. Note that the area can be attaining for one pollutant and nonattaining for another pollutant. If this occurs one must use different routes for each of the pollutants and would have to undertake both “prevention of significant deterioration” (PSD) and “nonattainment” (NA) analyses simultaneously.

- (2) *Attainment urea.* If the proposed source is in an “attainment” area, there is a specified allowed maximum increase, or “increment”, of higher air pollutant concentrations. The upper limit of this increment may be well below the prevailing National Ambient Air Quality Standard (NAAQS). The “increment” concept is intended to “prevent significant deterioration” of ambient air quality. The new source might be allowed to consume some part of the “increment” as determined by regulatory agency negotiations.
- (3) *Nonattainment urea.* If the proposed new source is in a “nonattainment” area, it may have to be more than off-set by decreases of emissions from existing sources, resulting in air cleaner after addition of the new source than before it was added. In the absence of pollutant reductions at an existing source which is within administrative control, it may be necessary to negotiate for, and probably pay for, emission reductions at other sources.
- (4) *Summary of permitting path.* The steps listed below present a summary of the permitting steps:
  - (a) Formulate a plan for obtaining a construction permit. It is usually advisable to engage a consultant familiar with the permitting procedures to aid in obtaining the permit.
  - (b) Contact state regulatory agencies.
  - (c) Determine if the modification could qualify for exemption from the New Source Review process.
  - (d) Determine if the proposed facility will be considered a “major source” or “major modification” as defined by the regulations.
  - (e) Determine if, and how, with appropriate controls, emissions can be held to less than “de minimis” emission rates for the pollutant so New Source Review procedures might be avoided.

- (f) Consider the questions related to prevention of significant deterioration and nonattainment. If it is found the facility will be a major source, determine for which areas and pollutants you will have to follow PSD rules. Determine possible “off-sets” if any will be required.
- (g) List the tasks and steps required for a permit and estimate the costs and time increments involved in the review process. Coordinate the New Source Review schedule with the facility planning schedule and determine how the New Source Review will affect construction plans, siting, budgetary impact, schedules and the engineering for controls technology.

#### 4-4. Mathematical modeling

*a. Modeling requirement.* Air quality modeling is necessary to comply with rules for proposed sources in both attaining and nonattaining areas. Modeling is a mathematical technique for predicting pollutant concentrations in ambient air at ground level for the specific site under varying conditions.

*b. Modeling in attainment ureas.* Modeling is used, under PSD rules, to show that emissions from the source will not cause ambient concentrations to exceed either the allowable increments or the NAAQS for the pollutant under study. It may be necessary to model the proposed new source along with others nearby to demonstrate compliance for the one being considered.

*c. Modeling in nonattainment ureas.* Modeling is used to determine the changes in ambient air concentrations due to the proposed new source emissions and any off-setting decreases which can be arranged through emissions reduction of existing sources. The modeling then verifies the net improvement in air quality which results from subtracting the proposed off-sets from the new source emissions.

*d. Monitoring.* Modeling is also used to determine the need for monitoring and, when necessary, to select monitoring sites.

*e. Guideline models.* EPA’s guideline on air quality recommends several standard models for use in regulatory applications. Selection requires evaluation of the physical characteristics of the source and surrounding area and choice of a model that will best simulate these characteristics mathematically. Selection of the proper model is essential because one that greatly over-predicts may lead to unnecessary control measures. Conversely, one that under-predicts ambient pollution concentration requires expensive retrofit control measures. Because of the subtleties involved, it is usually advisable to consult an expert to help select and apply the model.

#### 4-5. Monitoring

For a New Source Review, monitoring may be required to obtain data which shows actual baseline air quality concentrations. If monitoring is required, prepare a monitoring plan that includes monitor siting, measurement system specifications, and quality assurance program design. Once the plan is ready, it should be reviewed with the relevant agencies.

#### 4-6. Presentation and hearings

After a New Source Review application is prepared, it must be reviewed with the appropriate agency. Often a public hearing will be necessary and the application will have to be supported with testimony. At the hearing, all phases of work will be subject to public scrutiny and critique.

#### 4-7. Factors affecting stack design

*a.* Design of the stack has a significant effect on the resulting pollutant concentrations in nearby ambient air. Stack emission dispersion analysis is used to determine increases in local air pollution concentrations for specific emission sources. Factors which bear upon the design of stacks include the following:

- Existing ambient pollutant concentrations in the area where the stack will be located
- Meteorological characteristics for the area
- Topography of the surrounding area

*b.* Specific regulations having to do with stack design have been promulgated by the EPA to assure that the control of air pollutant shall not be impacted by stack height that exceeds "good engineering practice" or by any other dispersion technique. These regulations have a direct bearing on the specific location and height of a stack designed for a new pollution source.

# CHAPTER 5

## MEASURING TECHNIQUES

### 5-1. Criteria

In order to evaluate the nature and magnitude of air pollution, establish remedial measures, and determine control programs, it is necessary to test for the existence of pollutants. In the upgrading of existing installations, compliance is determined through "point source emission rate tests." Revisions to the regulations regarding air pollution test requirements for federal installations appear in the Federal Register.

### 5-2. Stack and source measurement techniques

The point source emission rate test methods and requirements are covered under Environmental Protection Agency Regulations on Standards of Performance for New Stationary Sources, 40 CFR 60 and subsequent revisions. The techniques are listed in table 5-1.

Table 5-1

*EPA emissions sampling techniques*

EPA Method Number	To Determine:
1	Sampling site and the maximum number of sampling points required for the extraction of a representative sample of flue gas from a stationary source.
2	Velocity and volumetric flow rate of flue gas.
3	Concentration by volume of carbon dioxide (CO <sub>2</sub> ), carbon monoxide (CO) and Oxygen (O <sub>2</sub> ) in flue gas, also excess air and dry molecular weight.
4	Moisture content of flue gas.
5	Particulate emissions from stationary sources.
6	Sulphur dioxide (SO <sub>2</sub> ) concentration in flue gas.
6A	SO <sub>2</sub> , CO <sub>2</sub> , moisture.
6B	SO <sub>2</sub> and CO <sub>2</sub> daily average emission.
7	All nitrogen oxides (NO <sub>x</sub> ) in flue gas except nitrous oxide (NO).
7A	All NO <sub>x</sub> emissions except nitrous oxides (NO).
8	Sulphur dioxide and sulphuric acid (H <sub>2</sub> SO <sub>4</sub> ) mist concentrations in flue gas.
9	Opacity of visible emissions.
10	Carbon monoxide (CO) emissions from stationary sources when specified for determining compliance with new Source Performance Standards.
17	Particulate emissions from stationary sources (in-stack filtration method).
18	Gaseous organic compound emissions determination by gas chromatography.

### 5-3. Meteorological and ambient air measurement

*a. Measurements.* Air quality measurements are used to trace emission sources and determine if these

sources comply with federal, state, and local air quality standards. For the determination of possible violations of air quality, the continuous monitoring of pollutant concentrations is normally required for a one-year period. Air quality measurements are a function of the sampling site, the local meteorology, the methods used, and the existing pollutant concentration in the atmosphere. Personnel knowledgeable and experienced in meteorology and air quality testing are needed to conduct and evaluate air-quality measurements.

*b. Sampling technique.* The criteria for instrumentation, calibration, and use of EPA-approved sampling techniques are covered under 40 CFR 53 Environmental Protection Agency Regulations on Ambient Air Monitoring Reference and Equivalent Methods. See table 5-2.

Table 5-2

*Air quality sampling method summary*

Pollutant	Method	EPA	
		Approved	Unapproved
CO	* Nondispersive infrared	X	-
	*Flame ionization	-	X
SO <sub>2</sub>	West-Gaeke sulfuric acid	X	-
	* West-Gaeke calorimetric	-	X
	* Conductimetric	-	X
	* Coulometric	-	X
	*G. C. flame photometric	-	X
Oxidants (O <sub>3</sub> )	*Pulsed fluorescence	-	X
	* Chemiluminescence	X	-
NO <sub>2</sub>	Calorimetric	-	X
	* Coulometric	-	X
	Gas Phase Chemiluminescence	X	-
Hydrocarbon (corrected for methane)	* Calorimetric	-	X
	* Coulometric	-	X
	Sodium arsenite bubbler	-	X
	Gas Chromatography	X	-

\*Continuous sampling method

(1) Continuous sampling is the recommended technique for obtaining the most reliable information concerning the variation of pollutant concentration in the real atmosphere. Discrete sampling can be used for plume tracking and random checking. Discrete sampling should be used with caution, however, when measuring any of several pollutants that have daily variations. (For example, ozone has very low concentrations at night.) In addition, use of

discrete sampling methods will often result in economically unacceptable manpower requirements. In these cases, sampling with continuous instruments and recording on data charts provides a lower cost solution.

- (2) Air quality regulations require the measurement of extremely small pollutant concentrations (1/100 of a part per million by volume). Sensitive instruments capable of detecting small concentrations are needed.

*c. Sampling method for carbon monoxide.* The federal reference method for measuring carbon monoxide is the instrumental nondispersive infrared technique. A typical instrument consists of a reference cell filled with CO free air, and a sample, or detector, cell. The difference in transmittance of infrared radiation passing through the sample cell and the reference cell is sensed by a photon detector. The difference is a measure of the optical absorption of the CO in the sample cell and is proportional to the CO concentration in the sample. The signal from the detector is amplified and used to drive an output meter as a direct measure of CO concentration. This method is precise and accurate.

*d. Sampling method for sulfur dioxide.* The West-Gaeke sulfuric acid method is the Federal reference method for measuring sulfur oxides. The West-Gaeke method is a discrete bubbler technique which involves bubbling ambient air through an impinger for 24 hours. Sulfuric acid is added to the absorber to eliminate interferences from oxides of nitrogen. SO<sub>2</sub> is collected in a tetrachloromercurate solution. When acid bleach pararosaniline is added to the collected SO<sub>2</sub> together with formaldehyde, a red-violet compound is formed which is then measured spectrophotometrically. This method is a discrete instrumental sampling method, but may be modified for continuous use.

*e. Sampling method for oxidants and ozone.* The instrumental-chemiluminescence method is the federal reference method for measuring ozone. Upon mixing ambient air and ethylene in the testing instrument, ozone reacts with the ethylene to emit light. This light is measured by a photomultiplier. If the air and ethylene flow rates are constant, and the proportion of air and ethylene therefore known, the resulting signal can be related to ozone concentration. Analyzers are calibrated with a known ozone concentration.

*f. Sampling method for nitrogen dioxide.* The federal reference method for NO<sub>2</sub> is the indirect measurement of the concentration of nitrogen dioxide by photometrically measuring the light intensity of wavelengths greater than 600 nanometers resulting from the gas phase chemiluminescent reaction of nitric oxide (NO) with ozone (O<sub>3</sub>).

*g. Sampling method for total hydrocarbons.* Gas chromatography flame ionization is the federal reference method of measuring total hydrocarbons.

*h. Sampling method for particulates.*

- (1) *Total suspended particulates.* The high volume air sample is the federal reference method for measuring total suspended particulates. Air is drawn (at 40 to 60 ft<sup>3</sup>/min) through a glass fiber filter by means of a blower, and suspended particles having an aerodynamic diameter between 100 and 1.0 micron are collected. The suspended particulate is calculated by dividing the net weight of the particulate by the total air volume samples and is reported in ug/m<sup>3</sup>.

- (2) *Coefficient of haze (COH).* A few states have standards for a particulate measurement called the coefficient of haze. This measurement is reported in units of COH/1000 linear feet of sampled air. In this method, air is drawn through a small spot on a circle of filter paper until the equivalent of a 1000 feet long column of air of the diameter of the spot has passed through the filter paper. Transmittance through this spot then serves as a measurement of particulate material collected on the filter. There are considerable doubts as to the usefulness and true meaning of COH data, since the transmittance recorded is a function of the nature of the particulate as well as the total weight sampled.

- (3) *Dustfall (settleable particulates).* Several states have standards for the amount of particulate that settles out of the air over a given length of time (one common unit is grams/square meter/30 days). The method of collection is generally the dust bucket. A dust bucket is a 15-inch deep metal or plate container with a 6-inch opening that is exposed to the air generally for a period of one month. Dust buckets should be partially filled with distilled water (or antifreeze) which prevents the transporting of dust out of the buckets by strong winds. This water also acts as a wash at analysis time. After evaporating the water, the remaining material is weighed and the residues are converted to the required units.

*i. Traceable compounds.* Test methods for compounds other than those for which standards exist are often useful in evaluating stack dispersion. If unusual fuel additives are used, or if incinerators are used to dispose of specialized materials, laboratory chemists can often devise sampling methods to measure these compounds in the atmosphere.

*j. Ringelmann standards.* Particulate matter such as soot, fly ash, and droplets of unburned combustibles present in exhaust gases tend to impart blackness or opacity to a plume. It is assumed that the darker the shade of gray or black, the greater the concentration of particulate matter present in a plume. The Ringelmann Chart offers a set of standards with which to measure the opacity of an effluent plume. By the comparison of

the blackness of a plume to the blackness of a series of graduated light diffusers, a Ringelmann number corresponding to a percent opacity can be assigned to the plume (see table 5-3). It should be noted that while Ringelmann numbers give a relative indication of plume opacity, they bear no direct relationship to plume particulate loading. They should supplement but not replace point-source emission tests.

*Table 5-3*  
*Ringelmann standards*

<u>Ringelmann</u>	<u>Opacity (percent)</u>
No. 1	20
No. 2	40
No. 2-½	50
No. 3	60
No. 3-½	70
No. 4	80
No. 4-½	90
No. 5	100

#### **5-4. Flue gas sampling ports**

Sampling ports are approximately 4 inches in diameter, extend out approximately 4 inches from the stack, and

have a removable cover. On double wall stacks sampling ports may consist of a 4-inch diameter pipe extending from 4 inches outside the stack to the inner edge of the inner stack wall. Accessible sampling ports shall be provided and located so that the cross sectional area of the stack or flue can be traversed to sample the flue gas in accordance with the applicable current federal or state regulations for fuel burning equipment.

#### **5-5. Air pollution project contacts**

U.S. Army Environmental Hygiene Agency (AEHA), Aberdeen Proving Grounds, MD, may be contacted for the respective service air pollution projects on the following:

- a. Source testing to characterize pollutants for design controls.
- b. Consultation on test performance standards and witnessing tests.
- c. Testing of installed air pollution abatement equipment for compliance with regulatory standards.

## CHAPTER 6

# CYCLONES AND MULTICYCLONES

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### 6-1. Cyclone

The cyclone is a widely used type of particulate collection device in which dust-laden gas enters tangentially into a cylindrical or conical chamber and leaves through a central opening. The resulting vortex motion or spiraling gas flow pattern creates a strong centrifugal force field in which dust particles, by virtue of their inertia, separate from the carrier gas stream. They then migrate along the cyclone walls by gas flow and gravity and fall into a storage receiver. In a boiler or incinerator installation this particulate is composed of fly-ash and unburned combustibles such as wood char. Two widely used cyclones are illustrated in figure 6-1.

### 6-2. Cyclone types

a. Cyclones are generally classified according to their gas inlet design and dust discharge design, their gas handling capacity and collection efficiency, and their arrangement. Figure 6-2 illustrates the various types of gas flow and dust discharge configurations employed in cyclone units. Cyclone classification is illustrated in table 6-1.

b. *Conventional cyclone.* The most commonly used cyclone is the medium efficiency, high gas throughput (conventional) cyclone. Typical dimensions are illustrated in figure 6-3. Cyclones of this type are used primarily to collect coarse particles when collection efficiency and space requirements are not a major consideration. Collection efficiency for conventional cyclones on 10 micron particles is generally 50 to 80 percent.

c. *High efficiency cyclone.* When high collection efficiency (80-95 percent) is a primary consideration in cyclone selection, the high efficiency single cyclone is commonly used (See figure 6-4). A unit of this type is usually smaller in diameter than the conventional cyclone, providing a greater separating force for the same inlet velocity and a shorter distance for the particle to migrate before reaching the cyclone walls. These units may be used singly or arranged in parallel or series as shown in figure 6-5. When arranged in parallel they have the advantage of handling larger gas volumes at increased efficiency for the same power consumption of a conventional unit. In parallel they also have the ability to reduce headroom space requirements below that of a single cyclone handling the same gas volumes by varying the number of units in operation.

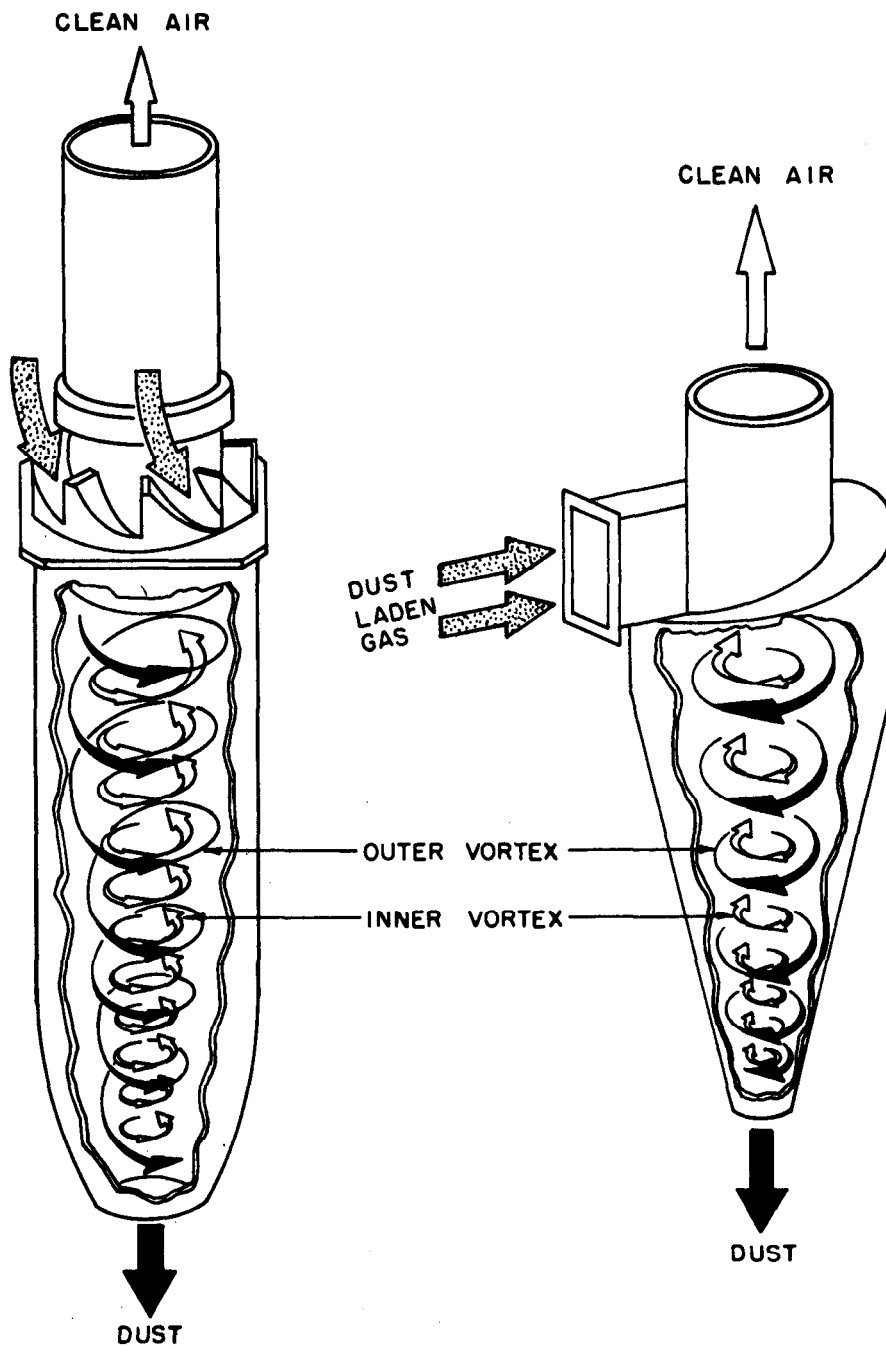
d. *Multicyclones.* When very large gas volumes must be handled and high collection efficiencies are needed a multiple of small diameter cyclones are usually nested together to form a multicyclone. A unit of this type consists of a large number of elements joined together with a common inlet plenum, a common outlet plenum, and a common dust hopper. The multicyclone elements are usually characterized by having a small diameter and having axial type inlet vanes. Their performance may be hampered by poor gas distribution to each element, fouling of the small diameter dust outlet, and air leakage or back flow from the dust bin into the cyclones. These problems are offset by the advantage of the multicyclone's increased collection efficiency over the single high efficiency cyclone unit. Problems can be reduced with proper plenum and dust discharge design. A typical fractional efficiency curve for multicyclones is illustrated in figure 6-6.

e. *Wet or irrigated cyclone.* Cyclones may be operated wet in order to improve efficiency and prevent wall buildup or fouling (See fig. 6-7). Efficiency is higher for this type of operation because dust particles, once separated, are trapped in a liquid film on the cyclone walls and are not easily re-entrained. Water is usually sprayed at the rate of 5 to 15 gallons per 1,000 cubic feet (ft<sup>3</sup>) of gas. Wet operation has the additional advantages of reducing cyclone erosion and allowing the hopper to be placed remote from the cyclones. If acids or corrosive gases are handled, wet operation may result in increased corrosion. In this case, a corrosion resistant lining may be needed. Re-entrainment caused by high values of tangential wall velocity or accumulation of liquid at the dust outlet can occur in wet operation. However, this problem can be eliminated by proper cyclone operation. Wet operation is not currently a common procedure for boilers and incinerators.

### 6-3. Cyclone collection efficiency

a. *Separation ability.* The ability of a cyclone to separate and collect particles is dependent upon the particular cyclone design, the properties of the gas and the dust particles, the amount of dust contained in the gas, and the size distribution of the particles. Most efficiency determinations are made in tests on a geometrically similar prototype of a specific cyclone design in which all of the above variables are accurately known. When a particular design is chosen it is usually accurate to estimate cyclone collection efficiency based





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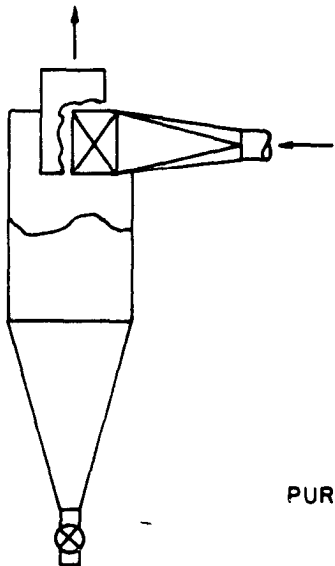
**Figure 6-1. Cyclone configuration**

upon the cyclone manufacturer's efficiency curves for handling a similar dust and gas. All other methods of determining cyclone efficiency are estimates and should be treated as such.

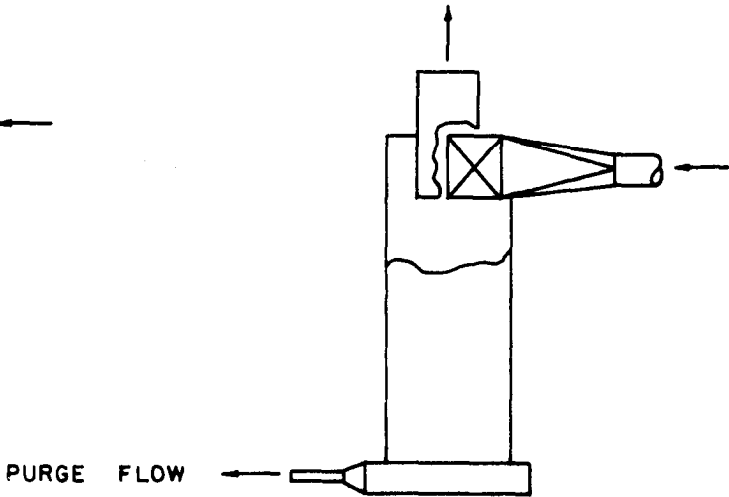
*b. Predicting cyclone collection efficiency.* A particle size distribution curve for the gas entering a cyclone is used in conjunction with a cyclone fractional effi-

ciency curve in order to determine overall cyclone collection efficiency.

- (1) A particle size distribution curve shows the weight of the particles for a given size range in a dust sample as a percent of the total weight of the sample. Particle size distributions are determined by gas sampling and generally con-



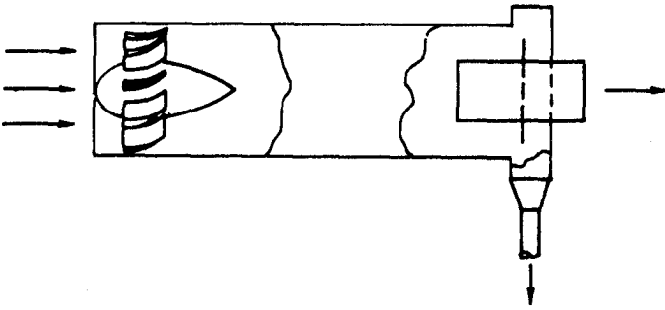
(A) TANGENTIAL INLET  
AXIAL DISCHARGE



(B) TANGENTIAL INLET  
PERIPHERAL DISCHARGE



(C) AXIAL INLET  
AXIAL DISCHARGE



(D) AXIAL INLET  
PERIPHERAL DISCHARGE

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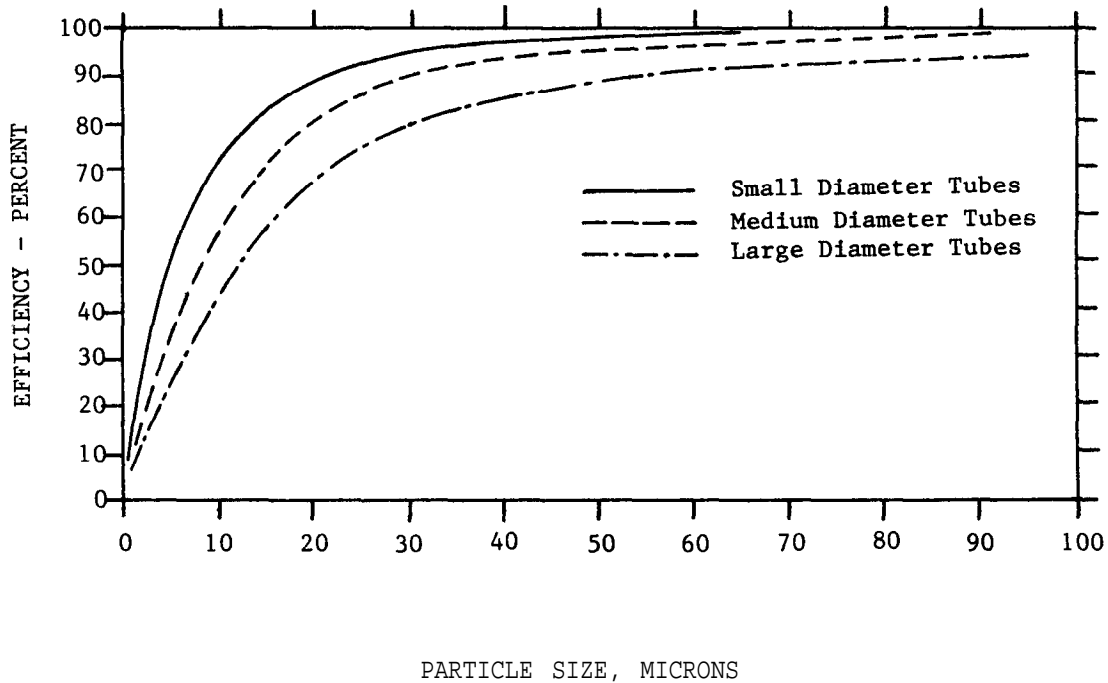
Figure 6-2. Types of cyclones in common use.

**TABLE 6-1**  
**CYCLONE CLASSIFICATION**

Type	Body Diameter (ft.)	Gas Flow (ft <sup>3</sup> /min)	Pressure Drop (in H <sub>2</sub> O)	Inlet Velocity (ft/s)	Collection Efficiency (%)	Application	Other
Conventional	4-12	1,000-20,000	.5-2	20-70	50-80	Material handling Exhaust gas precleaner	Large headroom requirements. Limited to large coarse particulates, large grain loadings.
High efficiency single cyclone	less than 3	100-2,000	2-6	50-70	80-95	Industrial boiler particulate control	Smaller space requirement. Parallel arrangement, inlet vane flow controls needed continuous dust removal system purge operation.
Multi-cyclones	.5-1	30,000 and up	3-6	50-70	90-95	Industrial and utility boiler. Particulate control	Plenums required. Problems: gas recirculation fouling. Continuous dust removal system, flow control.
Irrigated cyclone (wet) high efficiency single unit	less than 3	100-2,000	2-6	50	90-95	Boiler application (low sulfur fuel) (low gas temperature).	Water rate 5-15 gal/1,000 ft <sup>3</sup> /min. Corrosion resistant materials.

NOTE: Cyclone collection efficiency must be evaluated for each specific application due to the sensitivity of cyclone performance on gas and dust properties and loadings. Refer to Table 6-8 for expected collection efficiency estimates.

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ADAPTED FROM EPA-450/3-81-005a,  
CONTROL TECHNIQUES FOR  
PARTICULATE EMISSIONS FROM  
STATIONARY SOURCES

Figure 6-3. Relative effect of cyclone dimensions on efficiency.

form to statistical distributions. See figure 6-8.

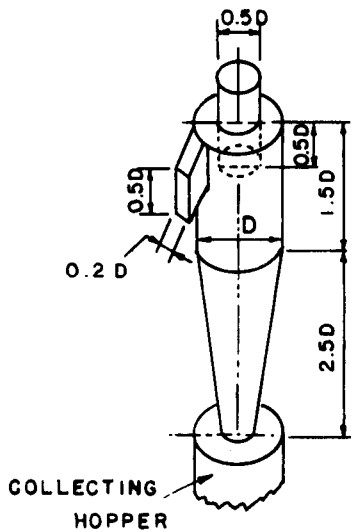
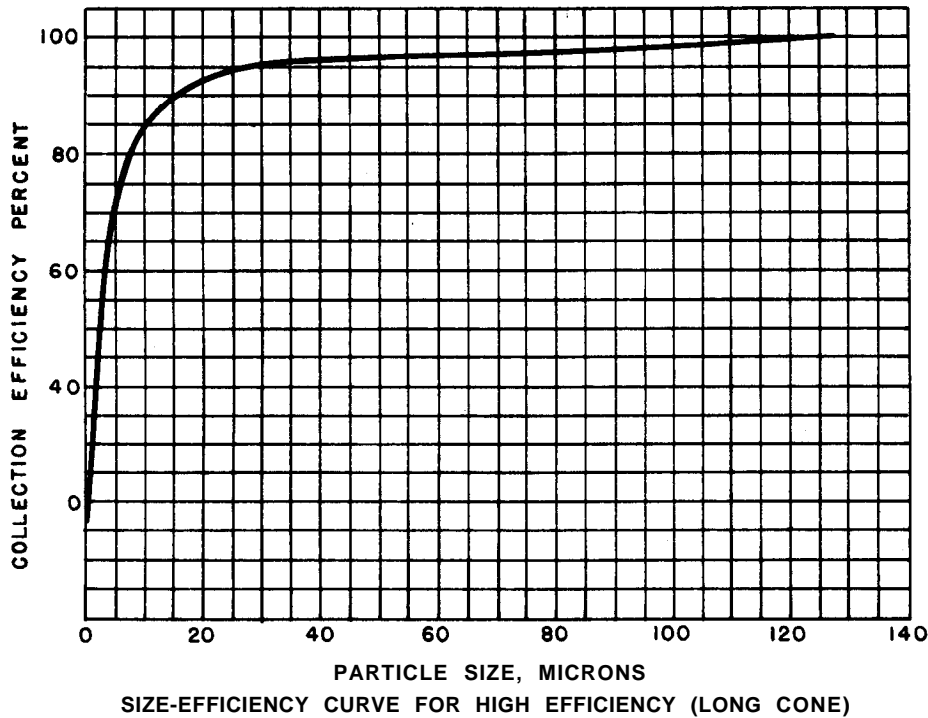
- (2) A fractional cyclone efficiency curve is used to estimate what weight percentage of the particles in a certain size range will be collected at a specific inlet gas flow rate and cyclone pressure drop. A fractional efficiency curve is best determined by actual cyclone testing and may be obtained from the cyclone manufacturer. A typical manufacturer's fraction efficiency curve is shown on figure 6-9.
- (3) Cyclone collection efficiency is determined by multiplying the percentage weight of particles in each size range (size distribution curve) by the collection efficiency corresponding to that size range (fractional efficiency curve), and adding all weight collected as a percentage of the total weight of dust entering the cyclone.

#### 6-4. Cyclone pressure drop and energy requirements

*a. Pressure drop.* Through any given cyclone there will be a loss in static pressure of the gas between the

inlet ductwork and the outlet ductwork. This pressure drop is a result of entrance and exit losses, frictional losses and loss of rotational kinetic energy in the exiting gas stream. Cyclone pressure drop will increase as the square of the inlet velocity.

*b. Cyclone energy requirements.* Energy requirements in the form of fan horsepower are directly proportional to the volume of gas handled and the cyclone resistance to gas flow. Fan energy requirements are estimated at one quarter horsepower per 1000 cubic feet per minute (cfm) of actual gas volume per one inch, water gauge, pressure drop. Since cyclone pressure drop is a function of gas inlet and outlet areas, cyclone energy requirements (for the same gas volume and design collection efficiency) can be minimized by reducing the size of the cyclone while maintaining the same dimension ratios. This means adding more units in parallel to handle the required gas volume. The effect on theoretical cyclone efficiency of using more units in parallel for a given gas volume and system pressure drop is shown in figure 6-10. The increased collection efficiency gained by compounding cyclones in parallel can be lost if gas recirculation among individual units is allowed to occur.



HIGH EFFICIENCY  
SINGLE CYCLONE UNIT (LONG CONE)

DESIGN CRITERIA

- 100 - 2,000 ft<sup>3</sup>/min
- 50 - 70 ft/s
- D - LESS THAN 3 FEET
- P - 2 TO 6 in H<sub>2</sub>O

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Figure 6-4. Efficiency curve and dimensions for a high efficiency single cyclone

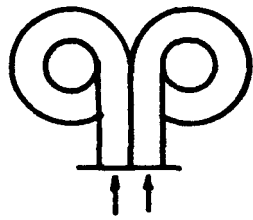
**6-5. Application**

*a. Particulate collection.* Cyclones are used as particulate collection devices when the particulate dust is coarse, when dust concentrations are greater than 3 grains per cubic foot (gr/ft<sup>3</sup>), and when collection efficiency is not a critical requirement. Because collection efficiencies are low compared to other collection equipment, cyclones are often used as pre-cleaners for other

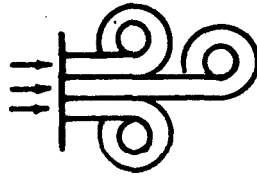
equipment or as a final cleaner to improve overall efficiency.

*b. Pre-cleaner.* Cyclones are primarily used as pre-cleaners in solid fuel combustion systems such as stoker fired coal burning boilers where large coarse particles may be generated. The most common application is to install a cyclone ahead of an electrostatic precipitator. An installation of this type is particularly

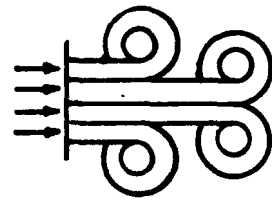
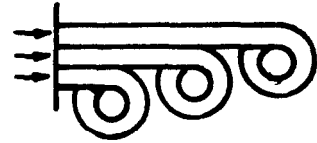
a. Parallel



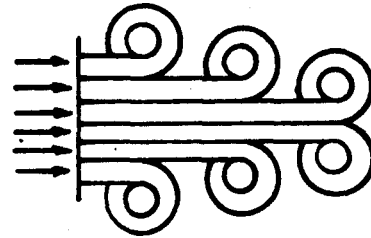
TWIN CYCLONES



GROUP OF THREE CYCLONES

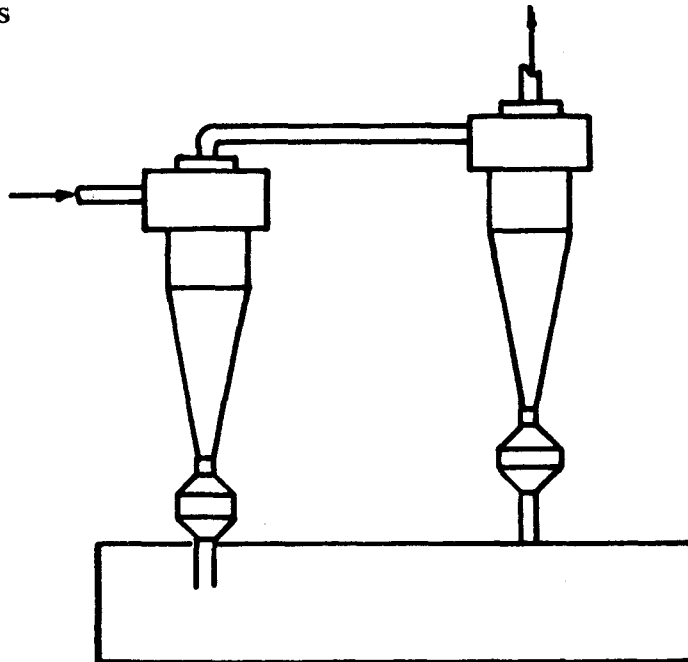


GROUP OF FOUR CYCLONES



GROUP OF SIX CYCLONES

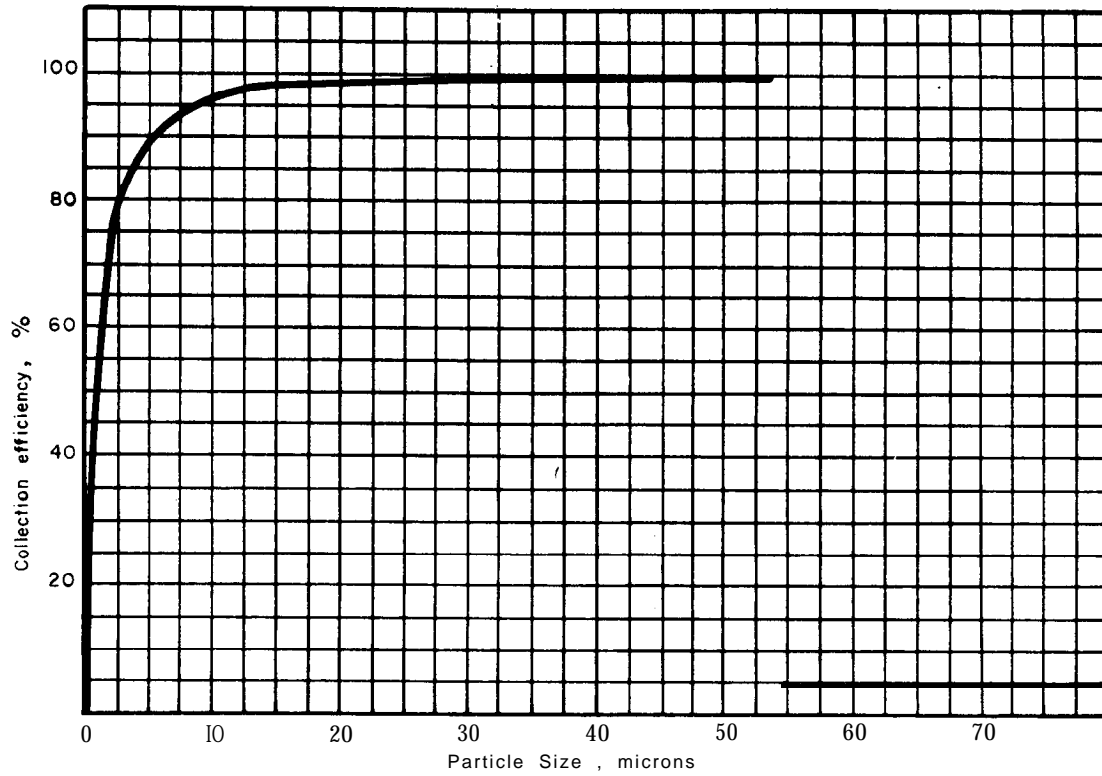
b. Series



SERIES CYCLONE ARRANGEMENT

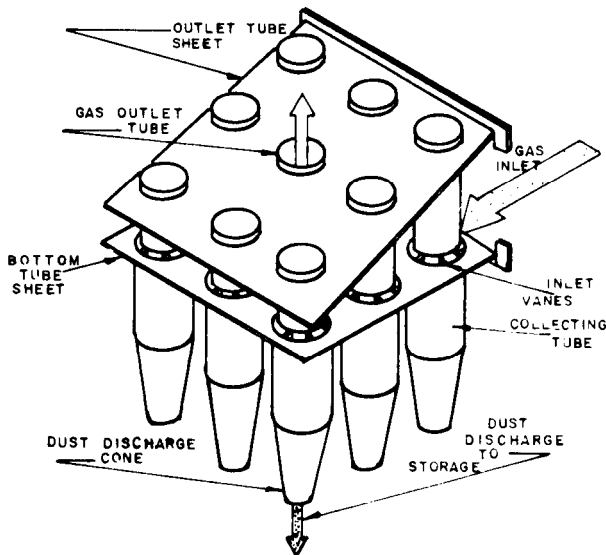
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Figure 6-5. Parallel and series arrangements for cyclones.



SIZE-EFFICIENCY CURVE FOR SMALL-DIAMETER MULTIPLE CYCLONE

**HIGH EFFICIENCY MULTIPLE  
CYCLONE UNITS (MULTICLONES)**

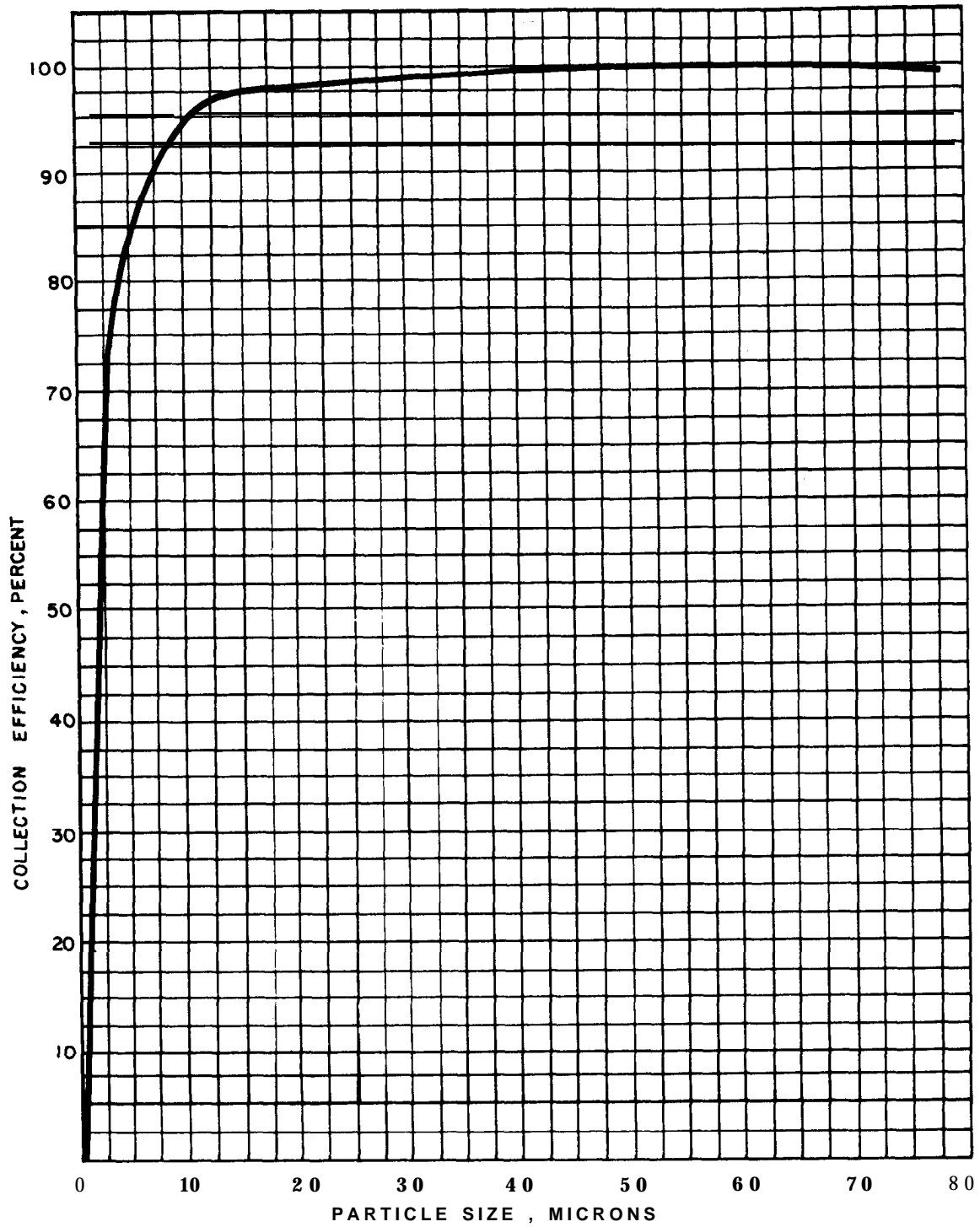


**DESIGN CRITERIA**

- 30,000 - 100,000 ft<sup>3</sup>/min
- 50 - 70 ft/s
- D - 6 - 12 inches
- $\Delta p$  - 3 to 6 in H<sub>2</sub>O

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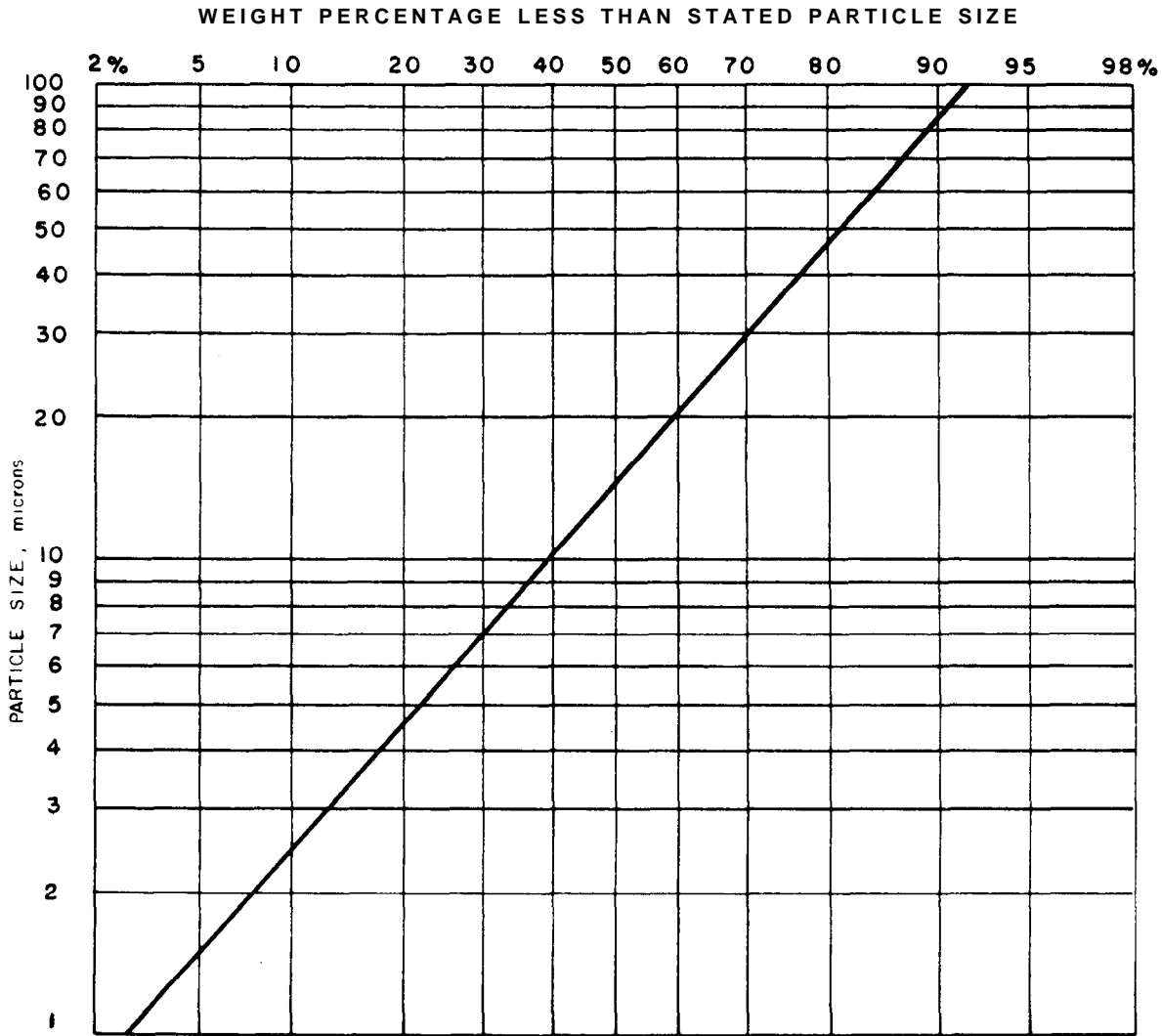
Figure 6-6. Efficiency curve and illustration of a multicyclone unit.



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Figure 6-7. Size-efficiency curve for high-efficiency (long cone) irrigated cyclone.





**PARTICLE SIZE DISTRIBUTIONS OF PARTICULATE EMITTED FROM UNCONTROLLED POWER PLANTS (PULVERIZED COAL FIRED BOILER) (7)**

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Figure 6-8. Particle size distribution curve (by weight) of particulate emitted from uncontrolled power

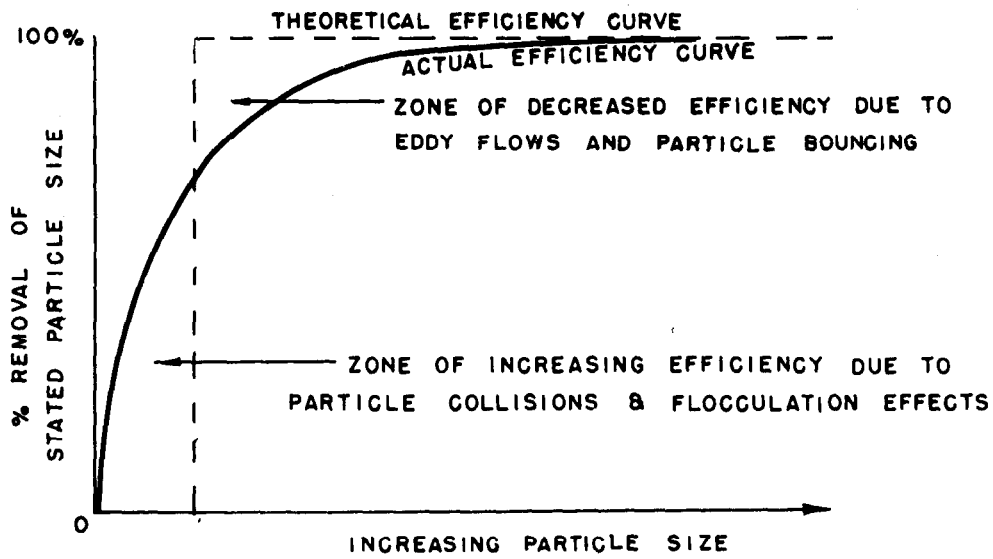
efficient because the cyclone exhibits an increased collection efficiency during high gas flow and dust loading conditions, while the precipitator shows and increase in collection efficiency during decreased gas flow and dust loading. The characteristics of each type of equipment compensate for the other, maintaining good efficiency over a wide range of operating flows and dust loads. Cyclones are also used as pre-cleaners when large dust loads and coarse abrasive particles may affect the performance of a secondary collector. They can also be used

for collection of unburned particulate for re-injection into the furnace.

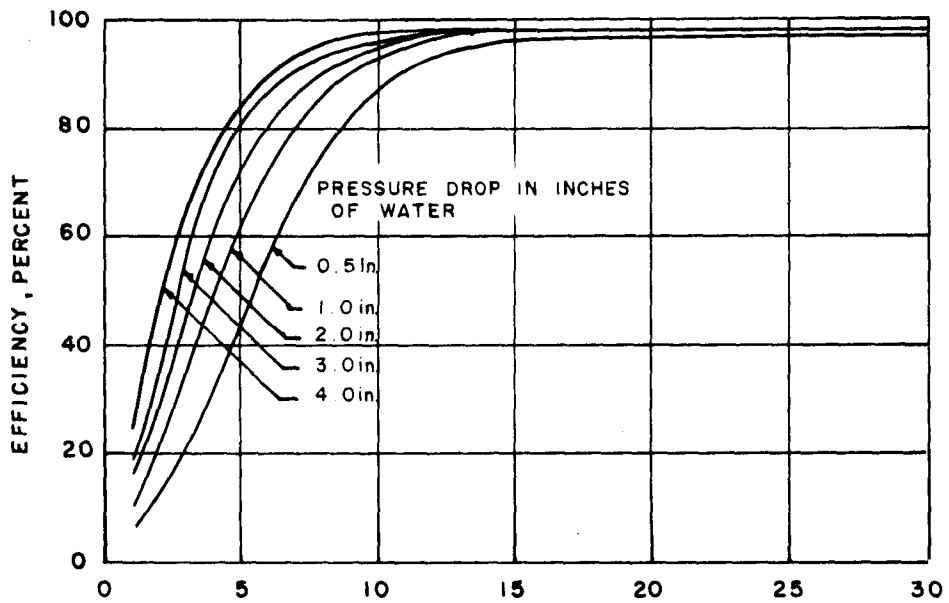
*c. Fine particles.* Where particularly fine sticky dust must be collected, cyclones more than 4 to 5 feet in diameter do not perform well. The use of small diameter multicyclones produces better results but may be subject to fouling. In this type of application, it is usually better to employ two large diameter cyclones in series.

*d. Coarse particles.* When cyclones handle coarse

a. THEORETICAL FRACTIONAL EFFICIENCY CURVE

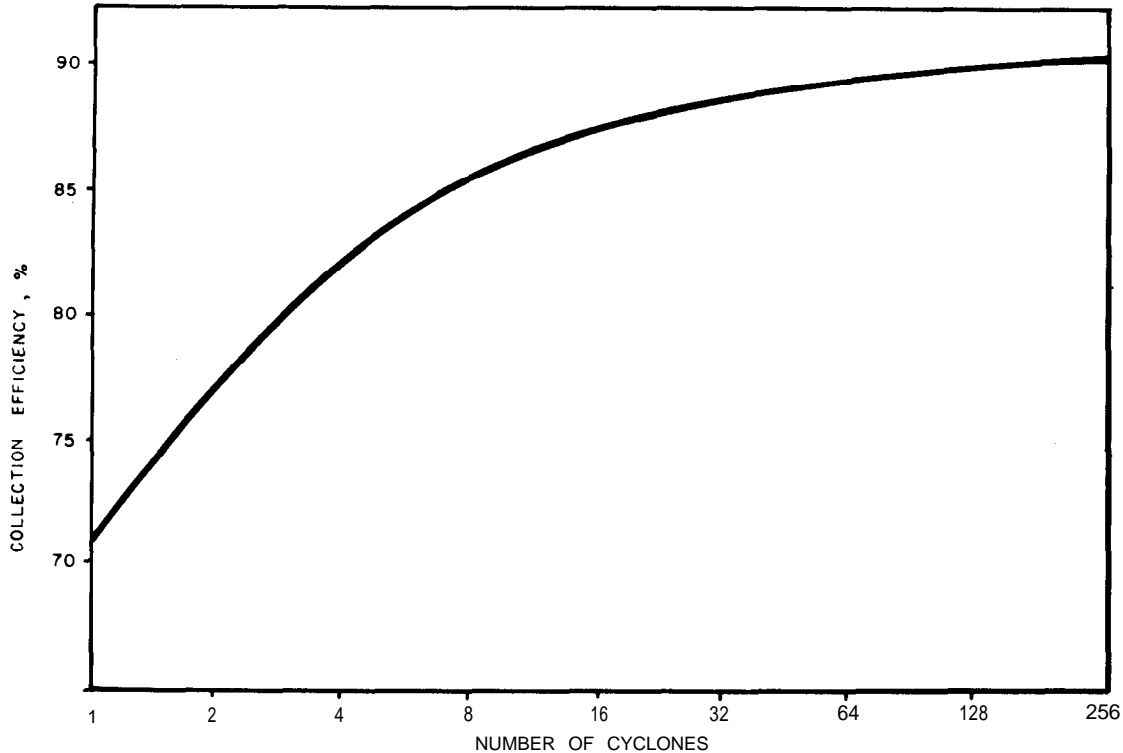


b. TYPICAL MANUFACTURER'S FRACTIONAL EFFICIENCY CURVE



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Figure 6-9. Fractional efficiency curves



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Figure 6-10. Effect of smaller cyclones in parallel on theoretical cyclone collection efficiency

particles, they are usually designed for low inlet velocities 5-10 feet per second (ft/sec). This is done to minimize erosion on the cyclone walls and to minimize breakdown of coarser particles that would normally be separated, into particles too fine for collection.

*e. Limited space.* In cases where cyclones must be erected in limited space, smaller diameter multi-cyclones have an obvious space advantage over larger diameter units. Small cyclones also have the advantage of increased efficiency over a single unit handling the same gas capacity, although this advantage is sometimes lost by uneven gas distribution to each unit with resultant fouling of some elements.

### 6-6. Cyclone performance

*a. Collection efficiency and pressure drop.* For any given cyclone it is desirable to have as high a collection efficiency and as low a pressure drop as possible. Unfortunately, changes in design or operating variables which tend to increase collection efficiency also tend to increase pressure drop at a greater rate than the collection efficiency. Efficiency will increase with an increase in particle size, particle density, gas inlet velocity, cyclone body or cone length, and the ratio of body diameter to gas outlet diameter. Decreased efficiency is caused by an increase in gas viscosity, gas density, cyclone diameter, gas outlet diameter, and inlet widths or area. The effect on theoretical collection efficiency of

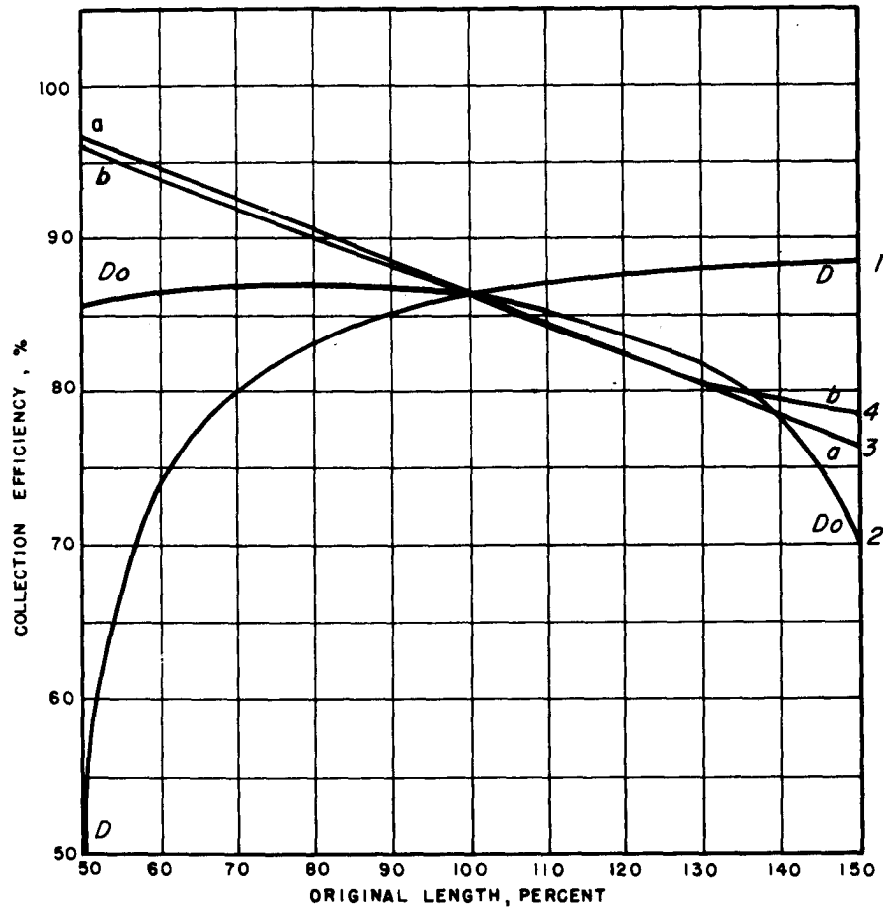
changing the dimensions of an 8 inch diameter cyclones is shown in figure 6-11. The effects of changing gas inlet velocity, grain loading, particle specific gravity, gas viscosity, and particle size distribution on a 50 inch diameter cyclone are shown in figures 6-12 and 6-13. These figures illustrate the dependence of cyclone collection efficiency on those variables and the importance of maintaining proper gas inlet conditions.

*b. Field performance.* The actual in-field performance of cyclone units will vary because of changes in operating conditions such as dust load and gas flow. Table 6-2 illustrates the optimum expected performance of cyclone units for particulate removal application in combustion processes.

Table 6-2  
Removal of uncontrolled particulate emissions from combustion processes

Source	Cyclones	
	Conventional	High Efficiency
	percent removed	
Coal tied:		
1. Spreader, chain grate, and vibrating stokers	70-80	80-90
2. Other stokers	75-80	90-95
3. Cyclone furnances	20-30	30-40
4. Other pulverized coal units	40-60	65-75

From EPA-42, "Compilation of Air Pollution Emission Factors," 3rd edition.



Curve 1 = cyclone body diameter  
 Curve 2 = cyclone gas outlet diameter  
 Curve 3 = cyclone inlet width  
 Curve 4 = cyclone inlet height

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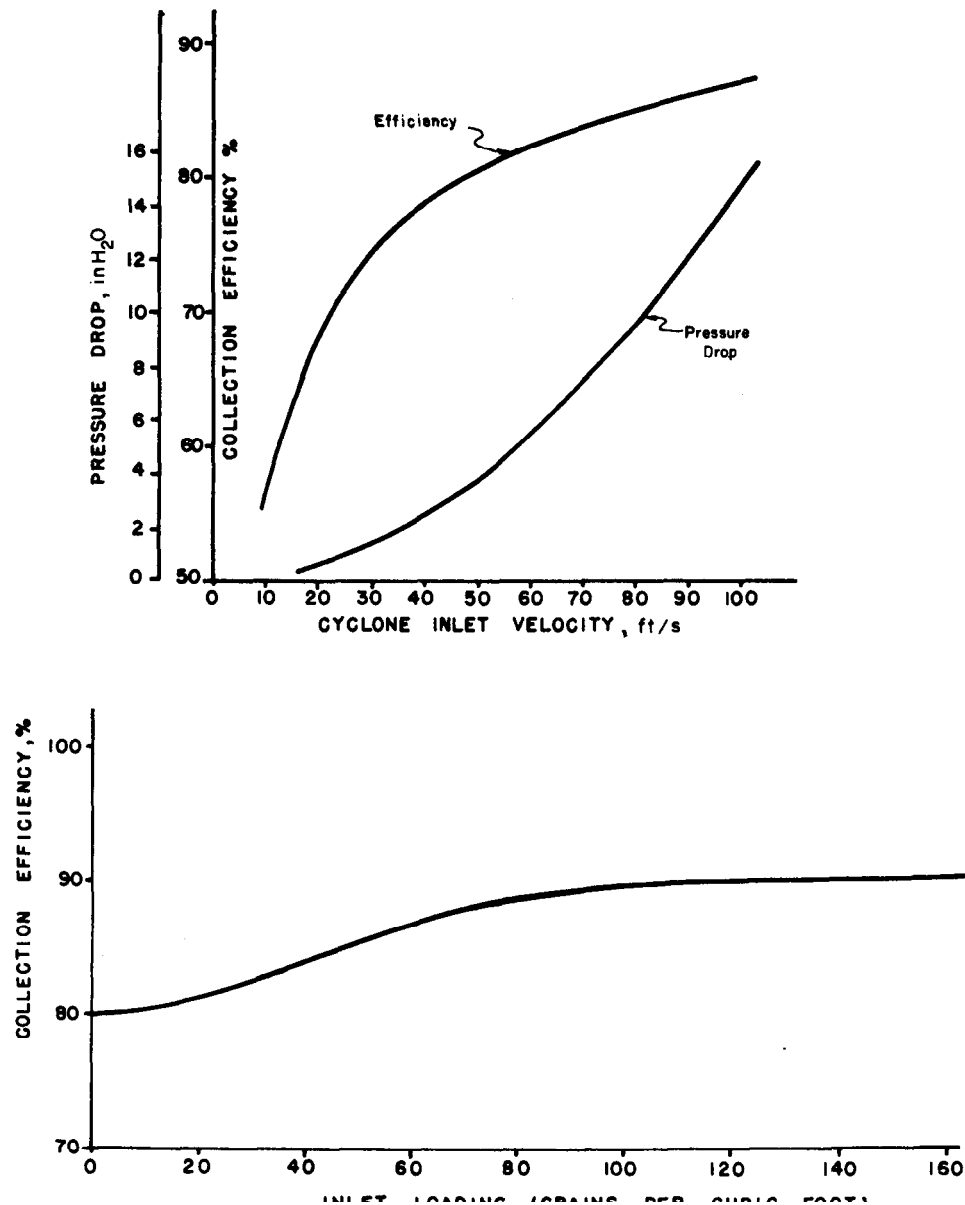
**Figure 6-11.** Effect of altering individual cyclone dimensions on theoretical collection efficiency for an 8-inch diameter cyclone

## 6-7. Cyclone operation

*a. Erosion.* Erosion in cyclones is caused by impingement and rubbing of dust on the cyclone walls. Erosion becomes increasingly worse with high dust loading, high inlet velocities, larger particle size, and more abrasive dust particles. Any defect in cyclone design or operation which tends to concentrate dust moving at high velocity will accelerate erosion. The areas most subject to erosive wear are opposite the inlet, along lateral or longitudinal weld seams on the cyclone walls, near the cone bottom where gases reverse their axial flow, and at mis-matched flange seams on the inlet or dust outlet ducting. Surface irregularities at welded joints and the annealed softening of the adjacent metal at the weld will induce rapid wear. The use of welded seams should be kept to a minimum and heat treated to maintain metal hardness. Continuous and effective removal of dust in the dust outlet

region must be maintained in order to eliminate a high circulating dust load and resultant erosion. The cyclone area most subject to erosion is opposite the gas inlet where large incoming dust particles are thrown against the wall, and in the lower areas of the cone. Erosion in this area may be minimized by use of abrasion resistant metal. Often provisions are made from removable linings which are mounted flush with the inside surface of the shell. Erosion resistant linings of troweled or cast refractory are also used. Dust particles below the 5 to 10 micron range do not cause appreciable erosion because they possess little mass and momentum. Erosion is accelerated at inlet velocities above approximately 75 ft/sec.

*b. Fouling.* Decreased collection efficiency, increased erosion, and increased pressure drop result from fouling in cyclones. Fouling generally occurs either by plugging of the dust outlet or by buildup of



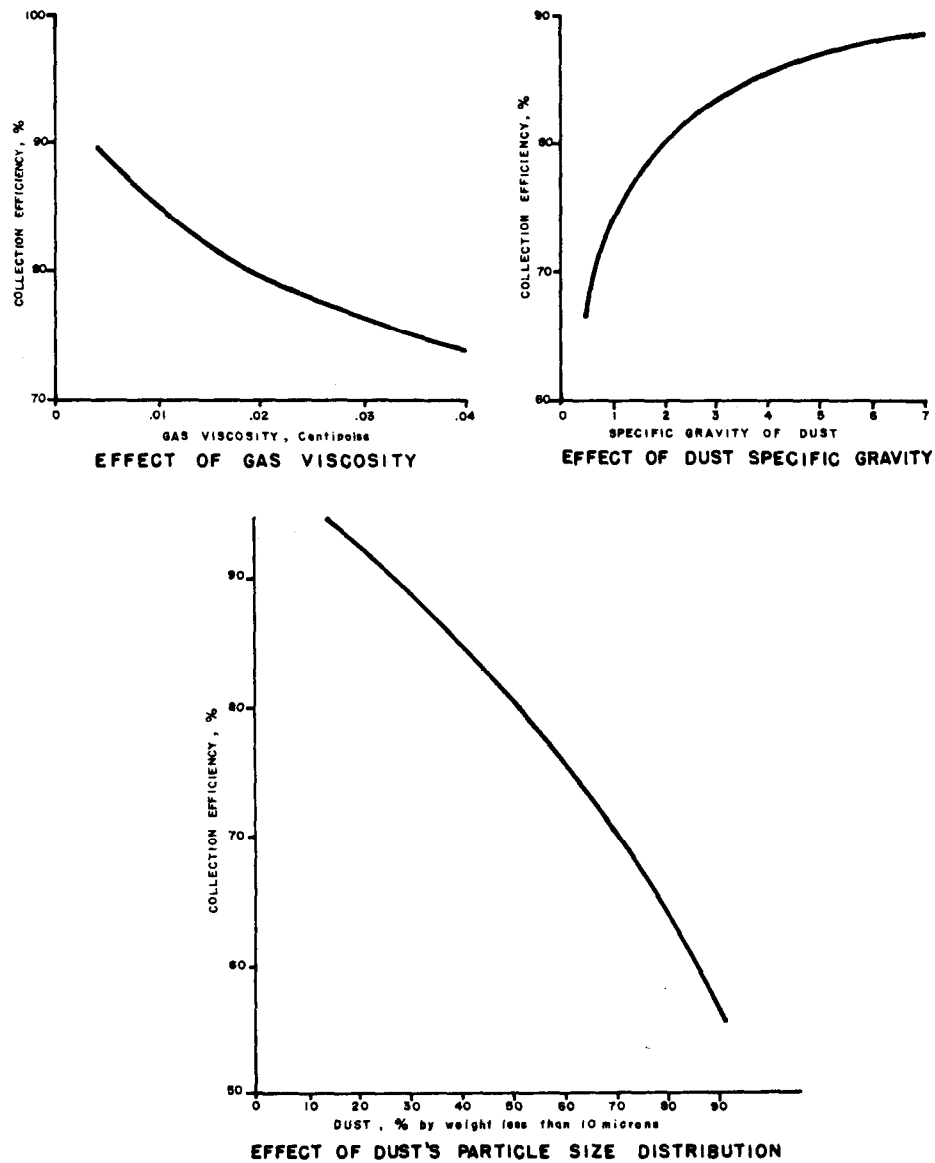
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Figure 6-12. Effects of cyclone inlet velocity and grain loading

materials on the cyclone wall. Dust outlets become plugged by large pieces of extraneous material in the system, by overfilling of the dust bin, or by the break-off of materials caked on the cyclone walls. The buildup of sticky materials on the cyclone walls is primarily a function of the dust properties. The finer or softer the dust, the greater is the tendency to cake on the walls. Condensation of moisture on the walls will contribute to dust accumulations. The collector should therefore be insulated to keep the surface temperature above the flue gas dew point. Wall buildup can generally be minimized by keeping the gas inlet velocity above 50 ft/sec.

c. *Corrosion.* Cyclones handling gases containing

sulfur oxides or hydrogen chloride are subject to acid corrosion. Acids will form when operating at low gas temperatures, or when the dust hopper may be cool enough to allow condensation of moisture. Corrosion is usually first observed in the hopper or between bolted sections of the cyclone inlet or outlet plenum spaces where gasketing material is used and cool ambient air can infiltrate. Corrosion at joints can be minimized by using welded sections instead of bolted sections. Ductwork and hoppers should be insulated and in cold climates the hoppers should be in a weather protected enclosure. Heat tracing of the hoppers may be necessary.



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Figure 6-13. Effects of gas viscosity, dust specific gravity, and dust particle size distribution.

*d. Dust hopper design.* A properly designed dust hopper should be air tight and large enough to prevent the dust level from reaching the cyclone dust outlets. Dust hoppers are usually conical or pyramidal in shape and are designed to prevent dust buildup against the walls. All designs should include a means of continuous removal of dust from the hopper to a storage bin, with an adequate alarm system to indicate a malfunction. Bin level alarms are frequently used for this purpose. On negative pressure systems, hoppers and removal system must be air tight. If hot unburned combustibles or char are present in the collected particulate, introduction of fresh air can cause a hopper fire. Pneumatic ash transport systems are not recommended for ash

containing unburned combustibles or char for the same reason.

## 6-8. Selection of materials

*a. Conditions.* Cyclones can be constructed of a variety of types of metals. The type of materials specified is dependent upon the erosion characteristics of the dust, the corrosion characteristics of the gases, and the operating temperature of the cyclone. Generally, cyclones are constructed of mild steel or cast iron. (See para 7-5 for additional information on materials selection for pollution control systems).

*b. Erosion.* Erosion is the single most important criterion in specifying the materials for cyclone con-

struction. Erosion life of a cyclone may be extended by using harder and thicker grades of steel. A stainless steel of 400 Brinell rating or better is normally chosen for cyclones subject to erosive conditions. When erosion is extreme, it is necessary to provide for replaceable liners in cyclone construction. Liners are made of hard stainless steels or erosion resistant refractory. In low temperature fly ash applications, cyclones of mild steel or iron can be used because dust loadings are generally too small to cause appreciable erosion. Cast iron is most often used in multicyclones in boiler service.

*c. Temperature.* Cyclones operated above 800 degrees Fahrenheit cannot be constructed of mild steels because the metal will creep and form ridges or buckled sections. Above 800 degrees Fahrenheit, nickel-copper bearing steel such as Monel is used to provide added strength. When temperatures are in excess of 1000 degrees Fahrenheit, nickel-chromium steel of the 400 series is used in conjunction with refractory linings. Silica carbide refractories provide excellent protection against erosion and high temperature deformation of the cyclone metal parts.

## 6-9. Advantages and disadvantages

*a. Advantages.* The advantages of selecting cyclones over other particulate collection devices are:

- No moving parts,
- Easy to install and replace defective parts,
- Constructed of a wide variety of materials,
- Minimum space requirements,
- Designed to handle severe service conditions of temperature, pressure, dust loading, erosion, corrosion, and plugging,
- Can be designed to remove liquids from gas,
- Low capital costs,
- Low maintenance costs.

*b. Disadvantages.* The disadvantages of selecting cyclones over other particulate collection devices are:

- Lower collection efficiency,
- Higher collection efficiencies (90-95 percent) only at high pressure drops (6 inches, water gauge),
- Collection efficiency sensitive to changes in gas flow, dust load, and particle size distribution,
- Medium to high operating costs.

## CHAPTER 7

# HIGH AND LOW ENERGY SCRUBBER SYSTEMS

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### 7-1. Scrubbers

A scrubber utilizes a liquid to separate particulate or gaseous contaminants from gas. Separation is achieved through mass contact of the liquid and gas. Boiler emissions to be controlled include fly ash and sulfur oxides. Incinerator emissions to be controlled include fly ash, sulfur oxides and hydrogen chloride.

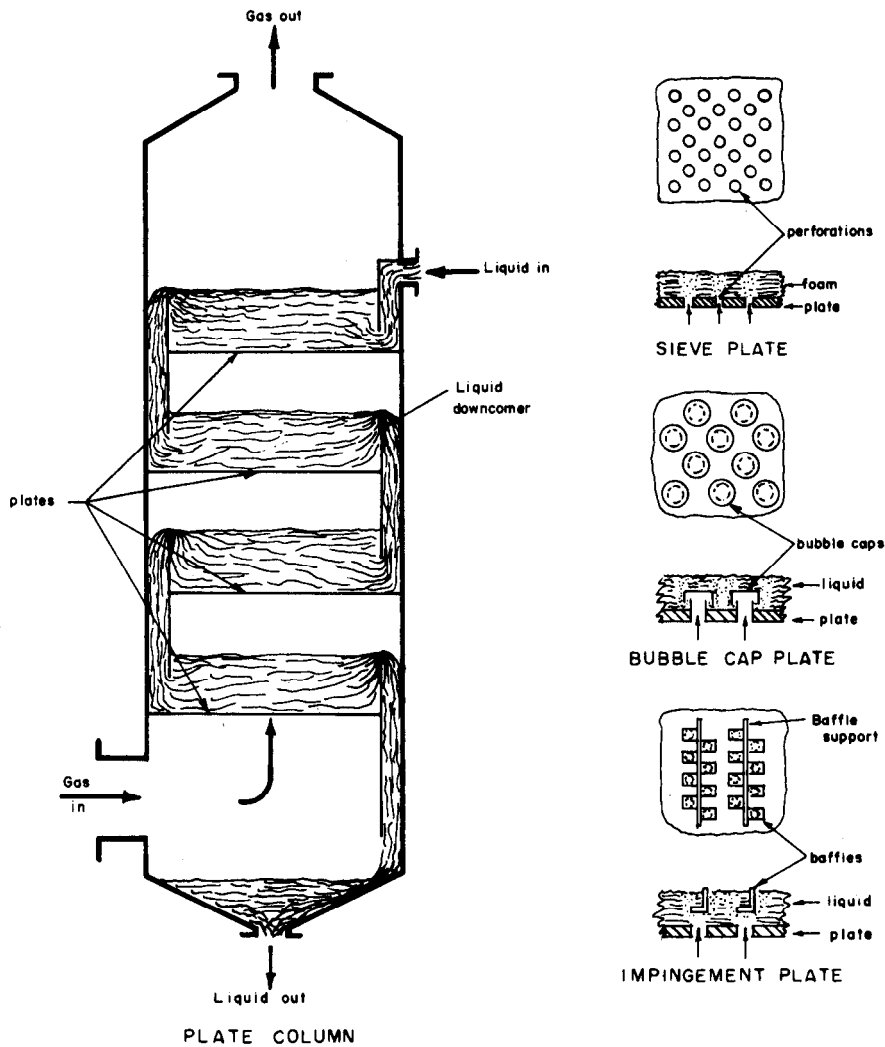
### 7-2. Types of scrubbers

*a. Low energy scrubbers.* Low energy scrubbers are more efficient at gaseous removal than at particulate removal. A low energy scrubber utilizes a long liquid-gas contact time to promote mass transfer of gas. Low energy scrubbers depend on extended contact surface or interface between the gas and liquid streams to allow collection of particulate or gaseous emissions.

- (1) **Plate-type scrubbers.** A plate-type scrubber consists of a hollow vertical tower with one or more plates (trays) mounted transversely in the tower (figure 7-1). Gas comes in at the bottom of the tower, and must pass through perforations, valves, slots, or other openings in each plate before exiting from the top. Liquid is usually introduced at the top plate, and flows successively across each plate as it moves downward to the liquid exit at the bottom. Gas passing through the openings in each plate mixes with the liquid flowing over the plate. The gas and liquid contact allows the mass transfer or particle removal for which the plate scrubber was designed. Plate-type scrubbers have the ability to remove gaseous pollutants to any desired concentration provided a sufficient number of plates are used. They can also be used for particle collection with several sieve (perforated) plates combining to form a sieve-plate tower. In some designs, impingement baffles are placed a short distance above each perforation on a sieve plate, forming an impingement plate upon which particles are collected. The impingement baffles are below the level of liquid on the perforated plates and for this reason are continuously washed clean of collected particles. Particle collection efficiency is good for particles larger than one micron in diameter. Design pressure drop is about 1.5 inches of water for each plate.

- (2) **Preformed spray scrubbers.** A preformed spray scrubber (spray tower) is a device which collects particles or gases on liquid droplets and utilizes spray nozzles for liquid droplet atomization (figure 7-2). The sprays are directed into a chamber suitably shaped to conduct the gas through the atomized liquid droplets. Spray towers are designed for low pressure drop and high liquid consumption. They are the least expensive method for achieving gas absorption because of their simplicity of construction with few internals. The operating power cost is low because of the low gas pressure drop. Spray towers are most applicable to the removal of gases which have high liquid solubilities. Particle collection efficiency is good for particles larger than several microns in diameter. Pressure drops range from 1 to 6 inches, water gauge.
- (3) **Centrifugal scrubbers.** Centrifugal scrubbers are cylindrical in shape, and impart a spinning motion to the gas passing through them. The spin may come from introducing gases to the scrubber tangentially or by directing the gas stream against stationary swirl vanes (figure 7-2). More often, sprays are directed through the rotating gas stream to catch particles by impaction upon the spray drops. Sprays can be directed outward from a central spray manifold or inward from the collector walls. Spray nozzles mounted on the wall are more easily serviced when made accessible from the outside of the scrubber. Centrifugal scrubbers are used for both gas absorption and particle collection and operate with a pressure drop ranging from 3 to 8 inches, water gauge. They are inefficient for the collection of particles less than one or two microns in diameter.
- (4) **Impingement and entrainment scrubbers.** Impingement and entrainment scrubbers employ a shell which holds liquid (figure 7-3). Gas introduced into a scrubber is directed over the surface of the liquid and atomizes some of the liquid into droplets. These droplets act as the particle collection and gas absorption surfaces. Impingement and entrainment scrubbers are most frequently used for particle





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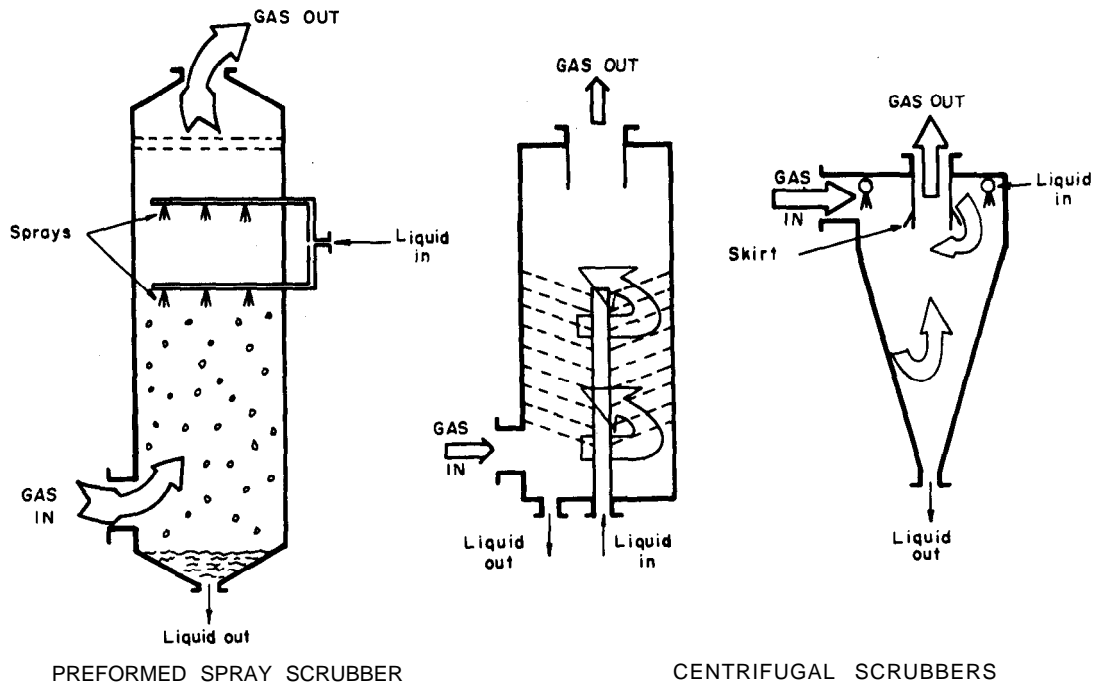
Figure 7-1. Plate type scrubber

collection of particles larger than several microns in diameter. Pressure drops range from 4 to 20 inches, water gauge.

(5) *Moving bed scrubbers.* Moving bed scrubbers provide a zone of mobile packing consisting of plastic, glass, or marble spheres where gas and liquid can mix intimately (figure 7-3). A cylindrical shell holds a perforated plate on which the movable packing is placed. Gas passes upward through the perforated plate and/or down over the top of the moving bed. Gas velocities are sufficient to move the packing material when the scrubber is operating which aids in making the bed turbulent and keeps the packing elements clean. Moving bed scrubbers

are used for particle collection and gas absorption when both processes must be carried out simultaneously. Particle collection efficiency can be good down to particle sizes of one micron. Gas absorption and particulate collection are both enhanced when several moving bed stages are used in series. Pressure drops range from 2.5 to 6 inches water gauge per stage.

b. *High energy scrubbers.* High energy scrubbers utilize high gas velocities to promote removal of particles down to sub-micron size. Gas absorption efficiencies are not very good because of the co-current movements of gas and liquid and resulting limited gas/liquid contact time.



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Figure 7-2. Types of spray and centrifugal scrubbers

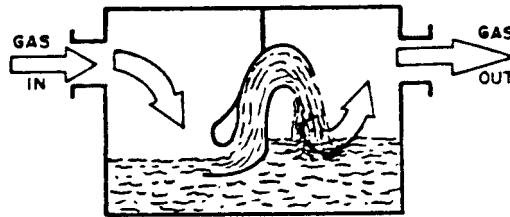
- (1) *Venturi scrubbers.* The venturi scrubber utilizes a moving gas stream to atomize and accelerate the liquid droplets (figure 7-4). A convergent-divergent nozzle is used to achieve a gas velocity of 200 to 600 feet per second (ft/sec) which enhances liquid atomization and particulate capture. Collection efficiency in a gas atomized venturi scrubber increases with pressure drop. Pressure drops of 25 inches water gauge or higher are utilized to collect sub-micron particles. Scrubbers of the gas atomized type have the advantage of adjustment of pressure drop and collection efficiency by varying gas velocity. The gas velocity is controlled by adjusting the area of the venturi throat. Several possible methods for doing this are illustrated in figure 7-5. This can be used to control performance under varying gas flow rates by maintaining a constant pressure drop across the venturi throat. Due to the absence of moving parts, scrubbers of this type may be especially suitable for the collection of sticky particles. Disadvantages include high pressure drop for the collection of sub-micron particles and limited applicability for gas absorption.
- (2) *Ejector venturi.* The ejector venturi scrubber utilizes a high pressure spray to collect particles and move the gas. High relative velocity between drops and gas aids in particle collection. Particle collection efficiency is good for

particles larger than a micron in diameter. Gas absorption efficiency is low because of the co-current nature of the gas and liquid flow. Liquid pumping power requirements are high and capacity is low making this type impractical for boiler or incinerator emissions control.

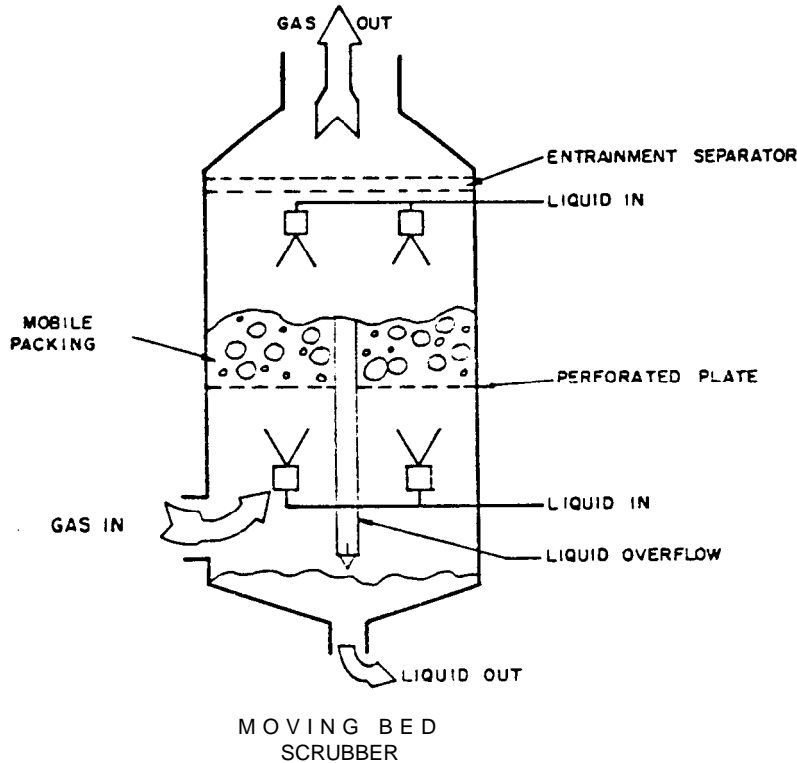
- (3) *Dynamic (wetted fan) scrubber.* This scrubber combines a preformed spray, packed bed or centrifugal scrubber with an integral fan to move the gas stream through the scrubber. Liquid is also sprayed into the fan inlet where the rotor shears the liquid into dispersed droplets. The turbulence in the fan increases liquid/gas contact. This type of scrubber is effective in collection of fine particulate. Construction of this scrubber is more complex due to the necessity of the fan operating in a wet and possibly corrosive gas stream. The design must prevent build-up of particulates on the fan rotor.

c. *Dry scrubbers.* Dry scrubbers are so named because the collected gas contaminants are in a dry form.

- (1) *Spray dryer* The spray dryer is used to remove gaseous contaminants, particularly sulfur oxides from the gas stream. An alkaline reagent slurry is mechanically atomized in the gas stream. The sulfur oxides react with the slurry droplets and are absorbed into the droplets. At the same time, the heat in the gas



IMPINGEMENT AND ENTRAINMENT SCRUBBER



MOVING BED SCRUBBER

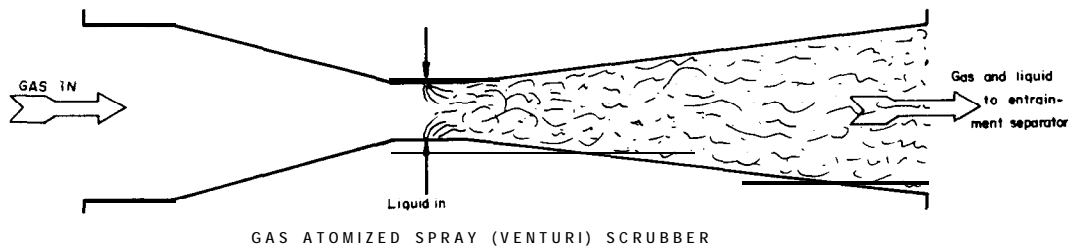
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Figure 7-3. Types of entrainment and moving bed scrubbers

stream evaporates the water from the droplets leaving a dry powder. The gas stream is then passed through a fabric filter or electrostatic precipitator where the dry product and any fly ash particulate is removed. The scrubber chamber is an open vessel with no internals other than the mechanical slurry atomizer nozzles. The vessel is large enough to allow complete drying of the spray before impinging on the walls and to allow enough residence time for the chemical reaction to go to completion. A schematic of the system is shown in figure 7-6. Refer to chapters 8 and 9 for discussion of the fabric filter or electrostatic precipitator.

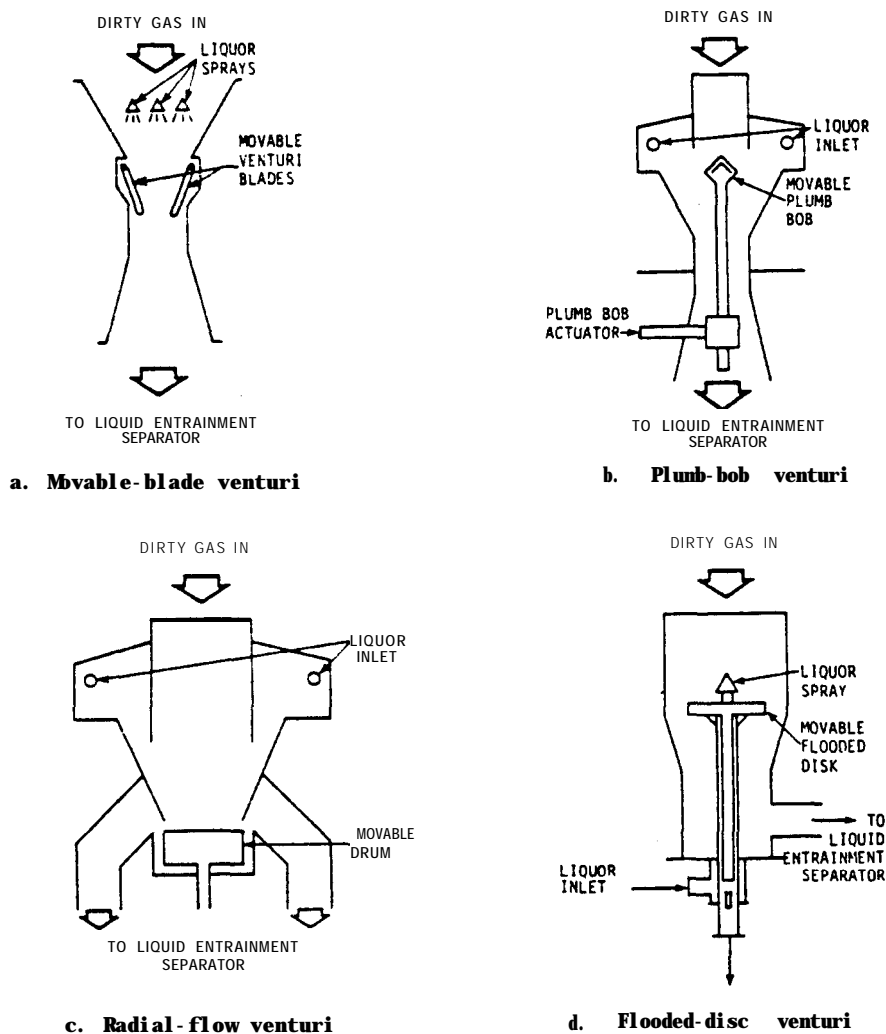
(2) Gravel bed. The gravel bed, while referred to

as a dry scrubber, is more a filter using sized gravel as the filter media. A bed of gravel is contained in a vertical cylinder between two slotted screens. As the gas passes through the interstices of the gravel, particulates impact on, and are collected on the gravel surface. Sub-micron size particles are also collected on the surface because of their Brownian movement. Dust-laden gravel is drawn off the bottom and the dust is separated from the gravel by a mechanical vibrator or pneumatic separator. The cleaned gravel is then conveyed up and dumped on top of the gravel bed. The cylindrical bed slowly moves down and is constantly recycled.



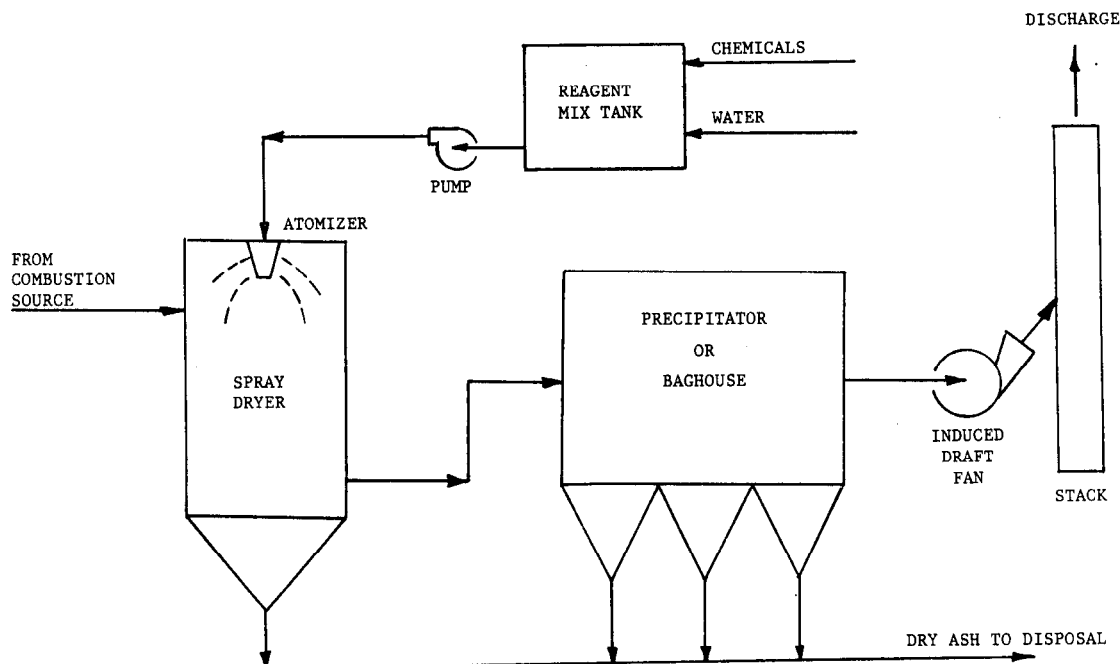
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Figure 7-4. Gas atomized spray (venturi) scrubber



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Figure 7-5. Throat sections of variable venturi scrubbers



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Figure 7-6. Spray dryer system

### 7-3. Application

a. *Particulate removal.* Scrubbers may be used as control devices on incinerators and boilers for fly ash collection. The plate, spray, venturi, and moving bed types have been successfully applied; however, their application has been limited because they require:

- more energy than dry particulate collection devices of the same collection efficiency,
- water supply and recovery system,
- more extensive solid waste disposal system,
- system to control the scrubbing process in response to gas flow rate changes.

b. In making decisions on applicability to a particular process, figure 7-7 is useful in determining all components which must be taken into consideration.

c. *Gaseous removal.* Scrubbers have been used primarily for the removal of sulfur oxides in stack gases. (See chapter 10 for a more detailed description of sulfur oxides (SO<sub>2</sub>) control techniques.) However, as new control systems are devised, simultaneous removal of gases and particulate material will become the accepted procedure for designing scrubbers for combustion processes.

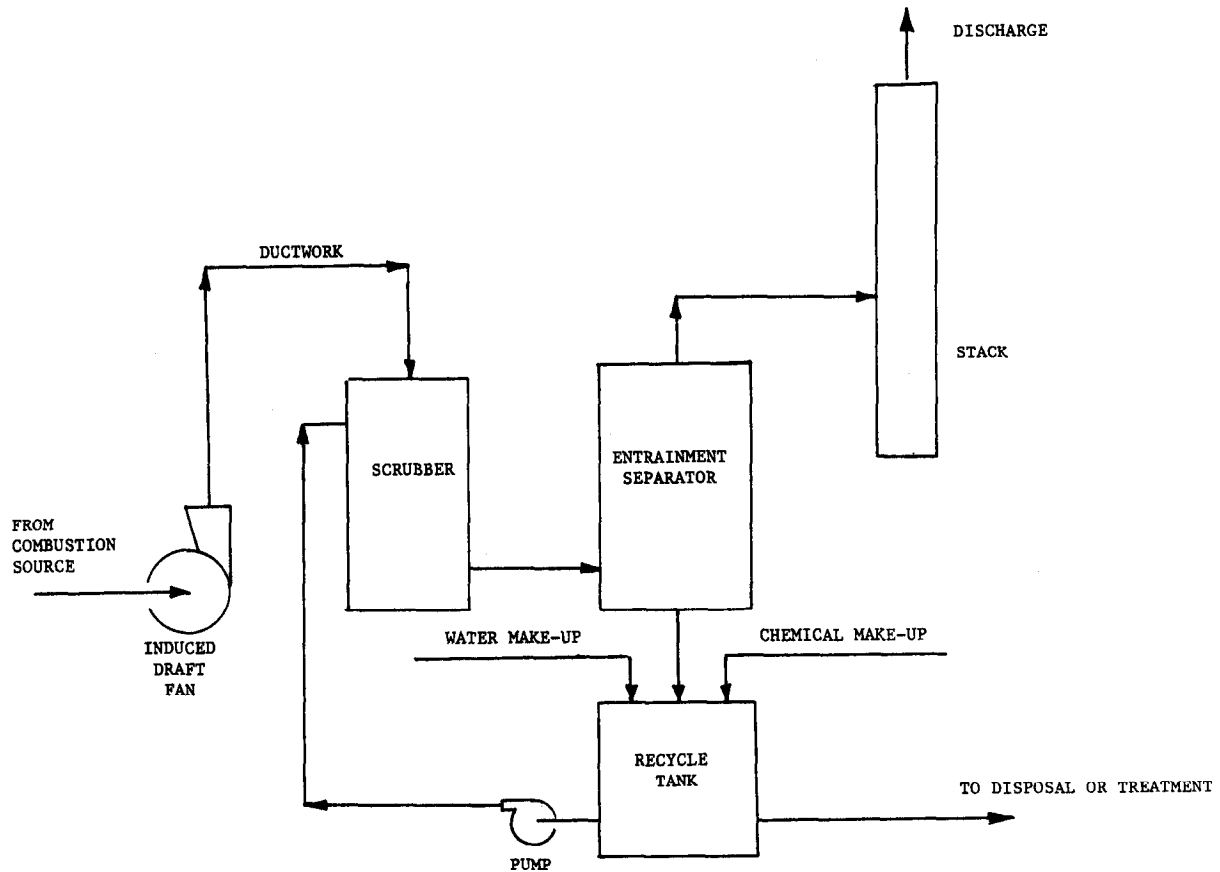
### 7-4. Treatment and disposal of waste materials

Wet scrubber systems are designed to process exhaust streams by transfer of pollutants to some liquid medium, usually water seeded with the appropriate

reactants. Liquid effluent treatment and disposal are therefore an essential part of every wet scrubber system. Installation and maintenance of the associated components can add appreciably to the system capital and operating costs. The degree of treatment required will depend upon the methods of disposal or recycle and on existing regulations. Required effluent quality, environmental constraints, and availability of disposal sites must be established before design of a treatment facility or the determination of a disposal technique can proceed. In many industrial applications the scrubber liquid wastes are combined with other plant wastes for treatment in a central facility. Design of this waste treatment should be by an engineer experienced in industrial waste treatment and disposal.

### 7-5. Selection of materials

a. *General conditions.* When choosing construction materials for scrubber systems, certain pertinent operating parameters should be considered. The metal surface of an exhaust gas or pollution control system will behave very differently in the same acid mist environment, depending on conditions of carrier gas velocity, temperature, whether the conditions are reducing or oxidizing, and upon the presence of impurities. For example, the presence of ferric or cupric iron traces in acids can dramatically reduce corrosion rates of stainless steels and titanium alloys. On the other hand, traces of chloride or fluoride in sulfuric acid can cause



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Figure 7-7. Schematic diagram of scrubber flow

severe pitting in stainless steels. This condition is frequently encountered in an incinerator which burns large quantities of disposable polyvinyl chloride (PVC) materials.

*b. Temperature.* Corrosion rates generally increase with increases in exhaust temperatures. This is due to the increased mobility of ions and increased reaction rates. However, in cases where the corrosion process is accelerated by the presence of oxygen, increasing the acid temperature eventually boils out dissolved oxygen, rapidly diminishing corrosion rate. This is the case with Monel, a nickel-copper alloy.

*c. Velocity.* Often the corrosion resistance of an alloy depends on the existence of an adhering oxide layer on its surface. A high exhaust gas velocity can remove or erode the surface layer. Once removed, this layer cannot be renewed because the oxide film is washed away as it forms.

*d. State of oxidation.* Under reducing condition, Monel is very resistant to moderate sulfuric-acid concentrations. Under oxidizing conditions, or in the presence of oxidizing ions, however, very rapid corrosion

occurs. The reverse is true of stainless steels which are resistant to oxidizing acid environments, but are attacked by acids under reducing conditions. The equipment designer should select materials based on individual case conditions including temperature, abrasion, pH, etc.

## 7-6. Auxiliary equipment

### *a. Gas transport.*

- (1) *Ducts and stacks.* Large boiler plant stacks have a wind shield of reinforced concrete or of steel, with a separate inner flue or numerous flues of steel, acid-resistant brick, and occasionally, stainless steel. The space between the inner flue and the outer wind shield may be insulated with a mineral wool wrapping. This is to prevent the condensation of acid dew on the inside of the metal chimney, which occurs below dew point temperature, and also to prevent acid "smut" from being blown out of the chimney. Acid smut is a term for ash particles contaminated with acid. It is heavy and tends

to fall out of the gas plume soon after exiting from the stack. In smaller plants, stacks may be a single wall steel construction with insulation and lagging on the outer surface. For wet scrubbing practice, chimneys for vapor-saturated gases containing corrosive substances may be made of rubber-lined steel, fiberglass-reinforced resin or other corrosion-resistant material. With materials that have a limited maximum temperature, provisions must be made to protect the stack from high temperatures because of loss of scrubbing liquid. Chimney or stack velocities are generally 30 ft/sec to prevent re-entrainment of moisture from the stack wall which would rain down around the plant. Sometimes cones are fitted at the top to give exit velocities as high as 75 ft/sec. The chief reason for high velocities is to eject the gases well away from the top of the stack to increase the effective height and to avoid downwash. Downwash can damage the metal structure supporting the stack, the stack itself, or the outside steel of a lined metal stack. (For a more detailed analysis of the meteorological considerations involved in stack design, see chapter 4.)

- (2) *Fans.* In a wet scrubber system the preferred location for the boiler or incinerator induced-draft fan is upstream of the scrubber. This eliminates the need for special corrosion-resistant construction required to handle the wet downstream gas. The fan should be selected to resist build-up of dry ash or erosion of the rotor surfaces. For high dust load applications a radial blade or radial tip blade fan is more durable. In a dry scrubber application the fan should be downstream of the scrubber in the clean gas stream. Here a more efficient air-foil or squirrel-cage rotor can be used.

*b. Liquid transport.*

- (1) *Pipework.* For most scrubbing duties, the liquid to be conveyed will be corrosive. There exists a wide variety of acid resistant pipework to choose from, but generally speaking, rubber-lined steel pipe has high versatility. It is easy to support, has the strength of steel, will withstand increases in temperature for a short time and will not disintegrate from vibration or liquid hammer. Fiberglass filament wound plastic pipe is also suitable for a very wide range of conditions of temperature, pressure, and chemicals. The chief disadvantage of rubber-lined pipe is that it cannot be cut to size and has to be precisely manufactured with correct lengths and flange drilling. Site fabrication is not possible. Most piping is manufactured to

ANSI specifications for pressure piping. Considerations must also be made for weather-proofing against freezing conditions.

- (2) *Pumps.* Centrifugal pumps are used to supply the scrubbing liquid or recycled slurry to the scrubber nozzles at the required volume flow rate and pressure. Where no solids are present in the liquid, bare metal pumps, either iron or stainless steel construction, are used. In recycle systems with solids in the liquid, special rubber-lined or hard-iron alloy pumps are used to control erosion of the pump internals. These are generally belt driven to allow selection of the proper speed necessary for the design capacity and head. Solids content must still be controlled to limit the maximum slurry consistency to meet the scrubber and pump requirements.

*c. Entrainment separation.* After the wetted gas stream leaves the scrubbing section, entrained liquid droplets must be removed. Otherwise they would rain out of the stack and fall on the surrounding area. Removal can be by gravity separation in an expanded vessel with lowered velocity or a cyclonic separator can swirl out the droplets against the vessel wall. Knitted wire or plastic mesh demisters or chevron or "zig-zag" vanes can be located at the scrubber outlet to catch any droplets.

*d. Process measurement and control.* The scrubber control system should be designed to follow variations in the boiler or incinerator gas flow and contaminant load to maintain outlet emissions in compliance with selected criteria.

- (1) *Measurements.* Measurement of data from the process to provide proper control should include inlet gas flow rate, temperature and pressure, scrubber gas pressure drop, liquid pressure, flow rate, solids consistency, pH, and outlet gas temperature. Selection of instrumentation hardware should be on an individual application basis.
- (2) *Control.* Pressure drop across a scrubber can be referenced as an indication of performance following initial or periodic, outlet gas testing. In a variable throat venturi, for instance, this pressure drop can be used to control the throat opening, maintaining constant performance under varying gas volume flow rates. Measurement of scrubber slurry solids consistency can be used to control bleed-off of high solids slurry and make-up with fresh water. If sulfur dioxide (SO<sub>2</sub>) is being controlled then measurement of scrubber liquid pH can control make-up of caustic to maintain efficiency of SO<sub>2</sub> removal. Complete specification or design of a control system must be on a case-by-case basis.

## 7-7. Advantages and disadvantages

*a. Advantages.* The advantages of selecting scrubbers over other collection devices are:

- Capability of gas absorption for removal of harmful and dangerous gases,
- High efficiency of particulate removal,
- Capability of quenching high temperature exhaust gases,
- Capability of controlling heavy particulate loadings,

*b. Disadvantages.* The disadvantages of selecting scrubbers over other collection devices are:

- Large energy usage for high collection efficiency,
- High maintenance costs,
- Continuous expenses for chemicals to remove gaseous materials,
- Water supply and disposal requirements,
- Exhaust gas reheat may be necessary to maintain plume dispersion,
- Weather proofing is necessary to prevent freeze-up of equipment.



## CHAPTER 8

### ELECTROSTATIC PRECIPITATORS

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#### 8-1. Electrostatic precipitator (ESP)

An electrostatic precipitator is a device which removes particles from a gas stream. It accomplishes particle separation by the use of an electric field which:

- imparts a positive or negative charge to the particle,
- attracts the particle to an oppositely charged plate or tube,
- removes the particle from the collection surface to a hopper by vibrating or rapping the collection surface.

#### 8-2. Types of electrostatic precipitators

*a. Two stage ESPs.* Two stage ESPs are designed so that the charging field and the collecting field are independent of each other. The charging electrode is located upstream of the collecting plates. Two stage ESPs are used in the collection of fine mists.

*b. Single stage ESPs.* Single stage ESPs are designed so that the same electric field is used for charging and collecting particulates. Single stage ESPs are the most common type used for the control of particulate emissions and are either of tube or parallel plate type construction. A schematic view of the tube and parallel plate arrangement is given in figure 8-1.

- (1) The tube type precipitator is a pipe with a discharge wire running axially through it. Gas flows up through the pipe and collected particulate is discharged from the bottom. This type of precipitator is mainly used to handle small gas volumes. It possesses a collection efficiency comparable to the parallel plate types, usually greater than 90 percent. Water washing is frequently used instead of rapping to clean the collecting surface.
- (2) Parallel plate precipitators are the most commonly used precipitator type. The plates are usually less than twelve inches apart with the charging electrode suspended vertically between each plate. Gas flow is horizontal through the plates.

#### 8-3. Modes of operation.

All types of ESPs can be operated at high or low temperatures, with or without water washing (table 8-1).

*a. Hot precipitation.* A hot precipitator is designed to operate at gas temperatures above 600 degrees Fahr-

enheit and is usually of the single stage, parallel plate design. It has the advantage of collecting more particulate from the hot gas stream because particle resistance to collection decreases at higher temperatures. The ability to remove particles from the collection plates and hoppers is also increased at these temperatures. However, hot precipitators must be large in construction in order to accommodate the higher specific volume of the gas stream.

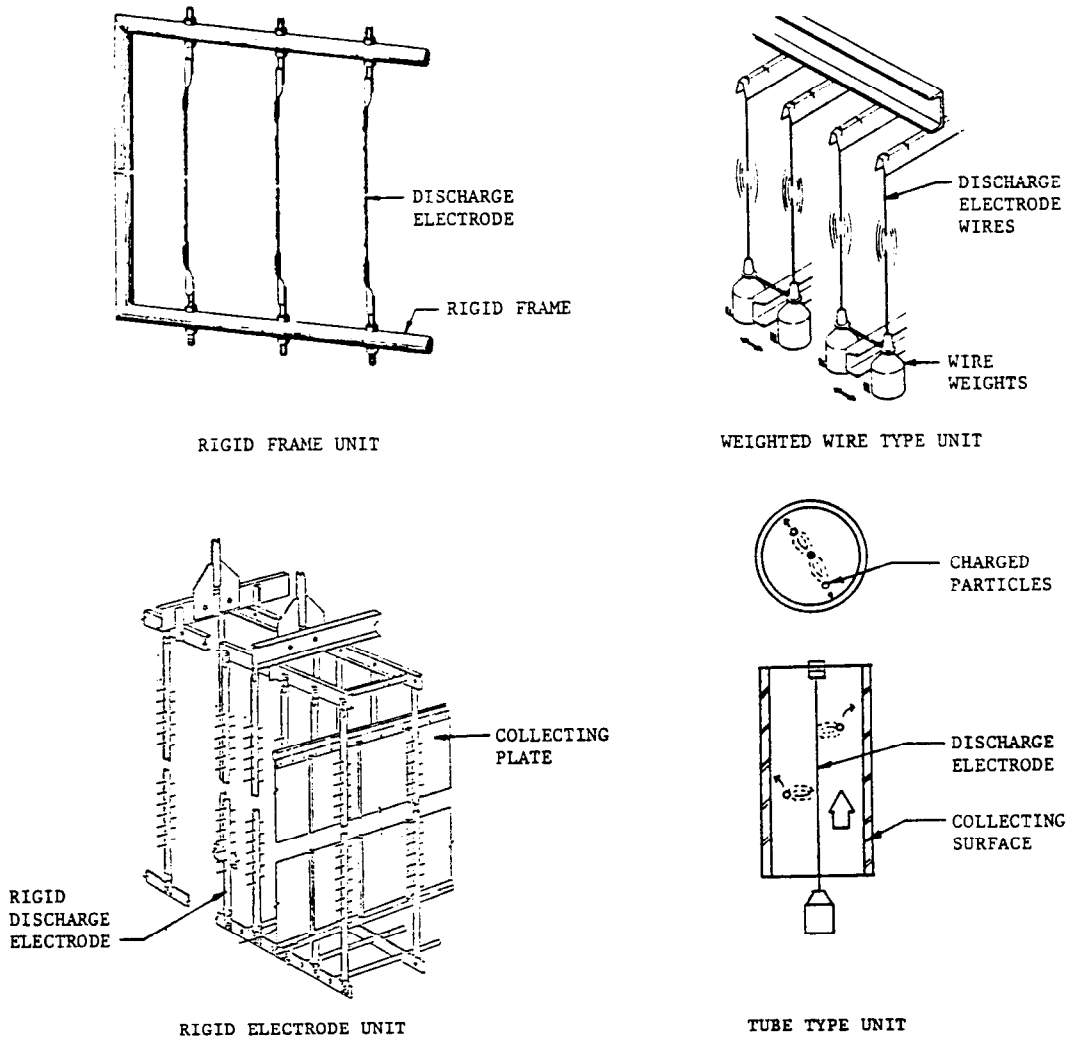
*b. Cold precipitation.* Cold precipitators are designed to operate at temperatures around 300 degrees Fahrenheit. The term "cold" is applied to any device on the low temperature side of the exhaust gas heat exchanger. Cold ESPs are also generally of the single stage, parallel plate design. They are smaller in construction than hot precipitator types because they handle smaller gas volumes due to the reduced temperature. Cold precipitators are most effective at collecting particles of low resistivity since particle resistance to collection is greater at lower temperatures. These precipitators are subject to corrosion due to the condensation of acid mist at the lower temperatures.

*c. Wet precipitation.* A wet precipitator uses water to aid in cleaning the particulate collection plates. It may employ water spray nozzles directed at the collection plates, or inject a fine water mist into the gas stream entering the precipitator. Wet precipitators enhance the collection efficiency of particulates by reducing reentrainment from the collection plates. Care should be taken so that water addition does not lower gas temperature below the dewpoint temperature, thus allowing the formation of acids. A wet precipitator can be of either plate or tube type construction.

#### 8-4. Applications

Electrostatic precipitators are among the most widely used particulate control devices. They are used to control particulate emissions from the electric utility industry, industrial boiler plants, municipal incinerators, the non-ferrous, iron and steel, chemical, cement, and paper industries. It is outside the scope of this manual to include all of these application areas. Only applications to boilers and incinerators will be reviewed.

*a. Boiler application.* Parallel plate electrostatic precipitators are commonly employed in the utility



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Figure 8-1. Schematic views of flat end tubular surface type electrostatic precipitators

industry to control emissions from coal-fired boilers. Cold type precipitators are the prevalent type because they are most easily retrofitted. In the design of new installations, the use of hot precipitators has become more common, because of the greater use of lower sulfur fuels. Low sulfur fuels have higher particle resistivity and therefore particulate emissions are more difficult to control with cold precipitation. Figure 8-2 may be used for estimating whether hot precipitators or cold precipitators should be selected for a particular sulfur content of coal.

*b. Wood refuse boiler applications.* An ESP can be used for particulate collection on a wood fired boiler installation if precautions are taken for fire prevention. The ESP should be preceded by some type of mechanical collection device to prevent hot glowing char from entering the precipitator and possibly starting a fire.

*c. Incinerator application.* Until relatively recently, ESPs were used for pollution control on incineration units only in Europe. In the United States, however, the ESP is now being viewed as one of the more effective methods for the control of emissions from incinerators. The major problem associated with the use of precipitators on incinerators is high gas temperatures. Temperatures up to 1800 degrees Fahrenheit can be encountered at the incinerator outlet. These temperatures must be reduced before entering a precipitator. Several methods can be used to accomplish this temperature reduction:

- mixing of the gas with cooler air,
- indirect cooling such as waste heat boilers,
- evaporative cooling in which droplets of water are sprayed into the gas.

TABLE 8-1  
OPERATING CHARACTERISTICS OF PRECIPITATORS

Type	Operating Temperature °F	Dust Resistivity at 300°F ohm-cm	Gas Flow ft <sup>3</sup> /min.	Pressure Drop in. of water	Design Collection Efficiency % by weight	Application	Other
Hot ESP	600+	greater than 10 <sup>12</sup>	100,000+	less than 1"	Usually 90+ can go to 99+	Before pre-heater in boilers, incinerator, industrial	Can collect high resistivity dust. Has higher gas flow and is large in size. Corrosion usually not a problem.
Cold ESP	300	less than 10 <sup>10</sup>	100,000+	less than 1"	Usually 90+ Can go to 99+	After pre-heater in boilers, incinerator, industrial	Limited to dust resistivities lower than 10 <sup>10</sup> ohm-cm. Corrosion can be a problem.
Wet ESP	300-	greater than 10 <sup>12</sup> below 10 <sup>4</sup>	100,000	less than 1"	Usually 90+ Can go to 99+	Industrial, boilers, incinerator	Useful for high or low resistivity dust collection. Corrosion usually not a problem.

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### 8-5. Performance

The performance of an electrostatic precipitator is predominantly affected by particle resistivity, particle size, gas velocity, flow turbulence, and the number of energized bus sections (electrically independent sections) in operation.

a. *Particle resistivity.* Particle resistivity is an electrical property of a particle and is a measure of its resistance of being collected. Particle resistivity is affected by gas temperature, humidity, sodium content, and sulfur trioxide (SO<sub>3</sub>) content. See figure 8-3.

b. *Collection plate area.* Collection plate area, and gas volume, affect electrostatic precipitator performance. The basic function relating these factors is shown in equation 8-1.

$$CE = 1 - e^{-\left(\frac{A_c}{V_g} \times w\right)^c} \quad (\text{eq. 8-1})$$

Where: CE = collection efficiency

A<sub>c</sub> = collection plate area in square feet (ft<sup>2</sup>)

V<sub>g</sub> = gas flow rate in cubic feet/minute (ft<sup>3</sup>/min)

w = migration velocity or precipitation rate parameter, feet/minute (ft/min).

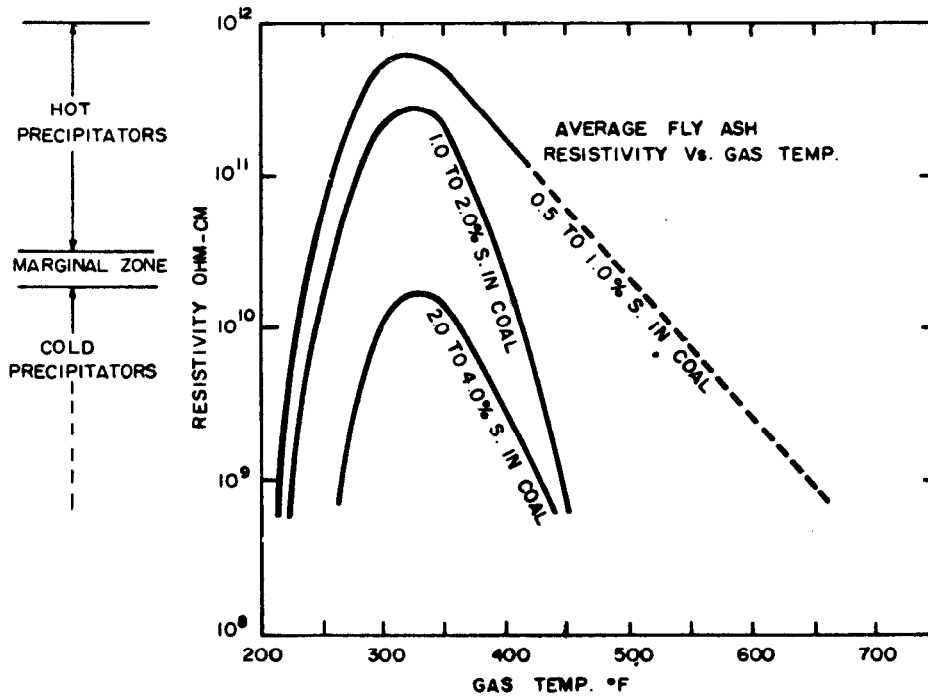
c. *Bus sections.* The number of energized bus sections in a precipitator has an effect upon collection efficiency. A power loss in one energized bus section will reduce the effectiveness of the precipitator. See figure 8-4.

d. *Turbulence.* Turbulence in the gas flow through an electrostatic precipitator will decrease its collection efficiency. For proper operation all segments of the flow should be within 25 percent of the mean flow velocity.

### 8-6. Description of components

a. *Shell.* The shell of an ESP has three main functions: structural support, gas flow containment, and insulation. Shell material is most commonly steel; if necessary, insulation can be applied to the exterior to prevent heat loss, Brick or concrete linings can be installed on shell interiors if gas stream corrosion of the metal may occur. Corrosion resistant steel can also be used as a lining, but the cost may be uneconomical and at times prohibitive. Since the shell is also used for structural support, normal civil engineering precautions should be taken in the design.

b. *Weighted wire discharge electrodes.* Wires vary in type, size, and style. Provision is made to keep the



COAL FLY ASH  
RESISTIVITY-SULPHUR-TEMPERATURE

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Figure 8-2. Operating ranges for hot/cold electrostatic precipitators

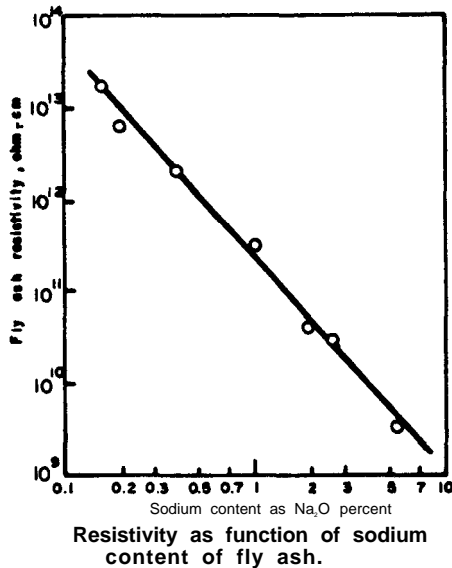
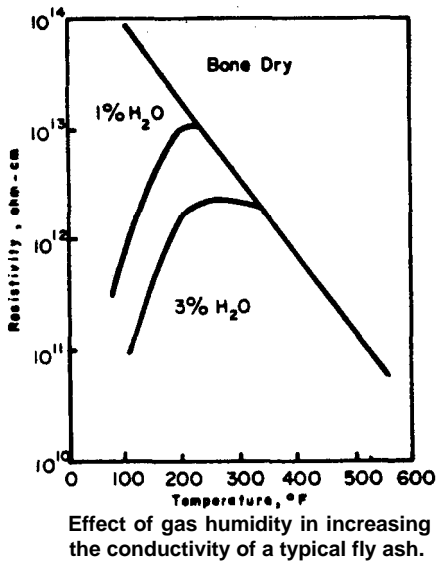
discharge wire from displacement by attachment to a suspended weight. The wires can be made stiff, consisting of a formed sheet, or they can be simple variations of the normal straight round wire such as being barbed or pronged. Steel alloys are commonly used for wire construction, but actually any conducting material with a proper configuration and sufficient tensile strength can be used.

- (1) *Rigid frame discharge electrodes.* Rigid frame designs incorporate a framework which supports the discharge electrodes. By using the rigid frame design the need for wire weights is eliminated since the frame keeps the wires properly supported and aligned.
- (2) *Rigid electrodes.* The rigid electrode design uses electrodes that have sufficient strength to stay in alignment their entire length. The elec-

trodes are supported from the top and kept in alignment by guides at the bottom. Rigid electrodes are the least susceptible to breakage.

*c. Collection electrodes.* There are numerous types of collection electrodes designed to minimize reentrainment and prevent sparking. The material used in construction, however, must be strong enough to withstand frequent rapping. In order to insure correct electrode application, it is wise to see if the electrode chosen has exhibited good performance at similar installations.

*d. Hoppers.* A hopper is used to collect ash as it falls from the precipitator. The hopper should be designed using precautions against corrosion in the precipitator, as any leakage due to corrosion will enhance entrainment. If the precipitator is dry, a hopper angle should be chosen that will prevent bridging of collected dust.



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Figure 8-3. Factors affecting particle resistivity

Hoppers must be sized so that the amount of dust collected over a period of time is not great enough to overflow and be reentrained. Seals also must be provided around the outlet to prevent any air leakage. If the precipitator is wet, the hopper should allow removal of sludge in a manner compatible with the overall removal system. In general the collected dust in the hoppers is more free flowing when kept hot. The hoppers should be insulated and should have heaters to maintain the desired temperatures. Hoppers heaters will also prevent the formation of acids that may occur

at low temperatures. Provisions should be made for safe rodding out the hoppers should they become plugged.

*e. Rappers.* Rappers are used to remove dust from the discharge and collection electrodes. Rappers are usually one of two types, impulse or vibrator. The vibrator type removes dust from the discharge electrode by imparting to it a continuous vibration energy. They are used to remove dust from the collection electrodes. Impulse rappers consist of electromagnetic solenoids, motor driven cams, and motor driven hammers. Important features to note in choosing rappers are long service life without excessive wear and flexible enough operation to allow for changing precipitator operating conditions. Low intensity rapping of plates (on the order of one impact per minute) should be used whenever possible to avoid damage to the plates. Visual inspection of the effect of rapping on reentrainment is usually sufficient to determine a good rapping cycle.

*f. High tension insulators.* High tension insulators serve both to support the discharge electrode frame and also to provide high voltage insulation. The materials used are ceramic, porcelain, fused silica and alumina. Alumina is the most common. The insulators must be kept clean to prevent high voltage shorting and resultant equipment damage. Compressed air or steam can be used for this purpose.

*g. Four point suspension.* Rigid electrode and rigid frame units may utilize a four point suspension system to support the discharge electrode framework in each chamber. This type of suspension system assures a better alignment of the discharge and collection electrodes. This in turn provides a more consistent operation.

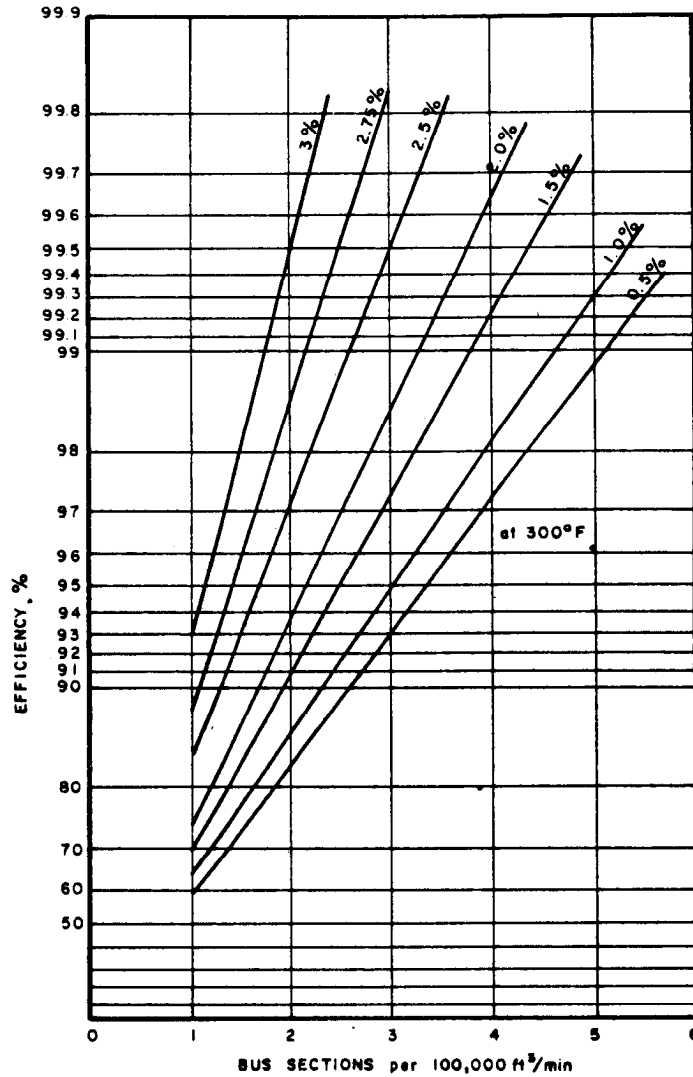
*h. Distribution devices.* Perforated plates, baffles or turning vanes are usually employed on the inlet and outlet of an ESP to improve gas distribution. Improper distribution can cause both performance and corrosion problems. These distribution devices may require rappers for cleaning.

*i. Model testing.* Gas flow models are used to determine the location and type of distribution devices. The models may include both the inlet and outlet ductwork in order to correctly model the gas flow characteristics. Gas flow studies may not be required if a proven precipitator design is installed with a proven ductwork arrangement.

### 8-7 Control systems

The electric power control system is the most important component system of any ESP. The basic components of this system are: step-up transformer; high voltage rectifier; voltage and amperage controls; and sensors.

*a. Automatic power control.* By utilizing a signal from a stack transmissionmeter the power level in the precipitator can be varied to obtain the desired performance over a wide range of operating conditions.



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Figure 8-4. Bus sections vs. efficiency for different sulfur percentages in coal.

*b. High voltage transformer.* The standard iron core transformer is the only instrument generally used to step-up the input voltage. The only care that need be taken is that the transformer is of superior quality and able to put out the quantity of voltage required by the precipitator. Transformers are designed to withstand high ambient temperatures and electrical variations induced by sparking. For high temperature operation, the most common transformer cooling method is liquid immersion.

*c. High voltage rectifier.* Silicon rectifiers are the latest advance in rectifying circuitry. They are solid state devices which have a few of the disadvantages of the other types of rectifiers. An assembly of silicon

rectifiers is used for lower rated current sets, typically 500 milli-amperes (mA).

*d. Voltage and amperage controls.* Controls are needed to insure that the precipitator is supplied with the maximum amount of voltage or power input, and to control the effects of sparking. The most modern method of accomplishing these aims is through the use of silicon controlled rectifiers (SCR). Other modern control devices are saturable reactors and thyristors (four element, solid state devices). Voltage control can also be accomplished by tapped series dropping resistors, series rheostats, tapped transformer primaries, and variable inductances.

*e. Auxiliary control equipment.* As with any control

device, gas flow should be monitored either by read-out of amperage from the fans or by measuring static pressure. It is also useful to have sensors which measure the sulfur dioxide (SO<sub>2</sub>) concentration and temperature of the inlet gas stream in order to determine the dew-point temperature.

### 8-8. Advantages and disadvantages

#### a. Advantages.

- (1) The pressure drop through a precipitator is a function of inlet and outlet design and precipitator length. Pressure drop rarely exceeds 0.5 inches, water gauge.
- (2) The ESP can be designed to have 99.9 + percent collection efficiency.
- (3) Silicon control rectifiers and other modern control devices allow an electrostatic precipitator to operate automatically.

(4) Low maintenance costs.

#### b. Disadvantages.

- (1) Due to the size of a typical ESP and the erratic nature of most processes (especially if frequent start-up and shutdowns occur) the temperature in different parts of the structure could at times drop below the acid dew point. Corrosion can cause structural damage and allow air leakage.
- (2) An ESP is sensitive to its design parameters. A change in the type of coal used, for example, could drastically affect performance.
- (3) High capital costs.
- (4) If particulate emission concentrations are high, a mechanical precleaner may be necessary.
- (5) High voltages are required.
- (6) No SO<sub>2</sub> control is possible with an ESP.

## CHAPTER 9

### FABRIC FILTERS

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#### 9-1. Fabric filtration

Fabric filters are used to remove particles from a gas stream. Fabric filters are made of a woven or felted material in the shape of a cylindrical bag or a flat supported envelope. These elements are contained in a housing which has gas inlet and outlet connections, a dust collection hopper, and a cleaning mechanism for periodic removal of the collected dust from the fabric. In operation, dust laden gas flows through the filters, which remove the particles from the gas stream. A typical fabric filter system (baghouse) is illustrated in figure 9-1.

#### 9-2. Types of filtering systems

The mechanisms of fabric filtration are identical regardless of variations in equipment structure and design. In all cases, particulates are filtered from the gas stream as the gas passes through a deposited dust matrix, supported on a fabric media. The dust is removed from the fabric periodically by one of the available cleaning methods. This basic process may be carried out by many different types of fabric filters with a variety of equipment designs. Filtering systems are differentiated by housing design, filter arrangement, and filter cleaning method.

*a. Housing design.* There are two basic housing configurations which apply to boiler and incinerator flue gas cleaning. These are closed pressure, and closed suction.

- (1) The closed pressure baghouse is a completely closed unit having the fan located on the dirty side of the system. Toxic gases and gases with high dew points are handled in this type of baghouse. Fan maintenance problems arise due to the fact that the fan is in the dirty gas stream before the baghouse. The floor of the unit is closed and the hoppers are insulated. A closed pressure baghouse is illustrated in figure 9-2.
- (2) The closed suction is the most expensive type of baghouse, with the fan being located on the clean gas side. The closed suction baghouse is an all-welded, air-tight structure. The floor is closed, and the walls and hopper are insulated. Fan maintenance is less than with the pressure type, but inspection of bags is more difficult. A

closed suction system is illustrated in figure 9-2.

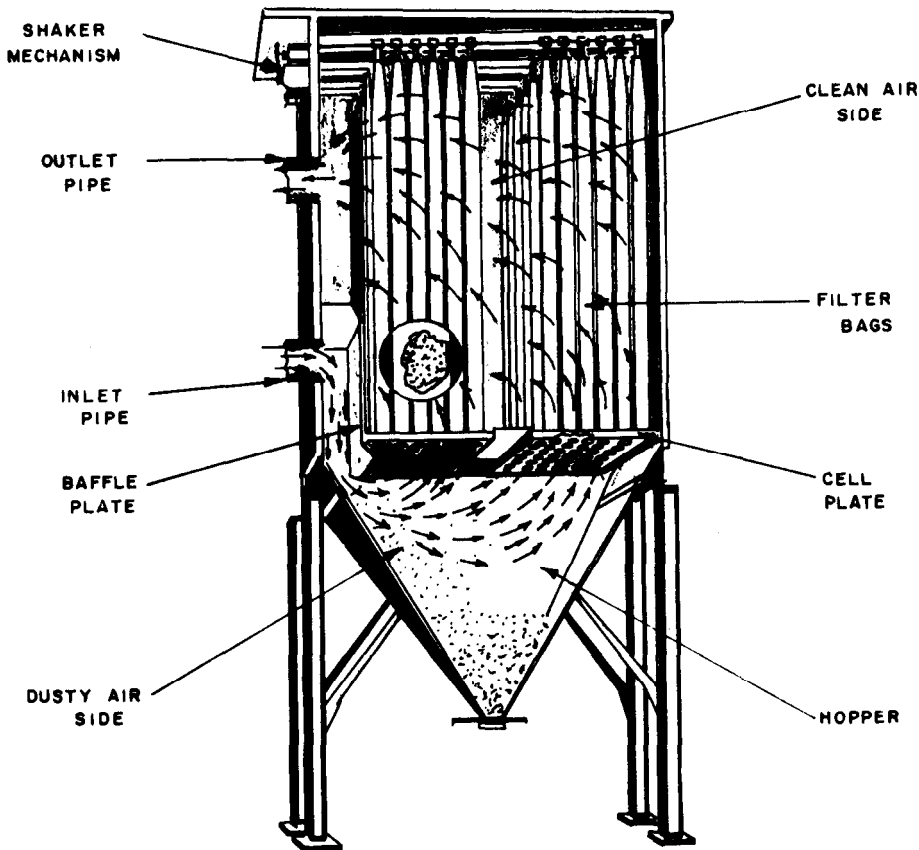
*b. Filter shape and arrangements.*

- (1) The cylindrical filter is the most common filter shape used in fabric filtration. The principal advantage of a cylindrical filter is that it can be made very long. This maximizes total cloth area per square foot of floor space. Cylindrical filters are arranged to accommodate each of the basic flow configurations shown in figure 9-3.
- (2) A panel type filter consists of flat areas of cloth stretched over an adjustable frame. (See figure 9-3.) Flow directions are usually horizontal. Panel filters allow 20 to 40 percent more cloth per cubic foot of collector volume and panels may be brushed down if dust build-up occurs. However, panel-type filters are not widely used in boiler and incinerator applications.

*c. Cleaning methods.* A fabric cleaning mechanism must impart enough energy to the cloth to overcome particle adhering forces without damaging the cloth, disturbing particle deposits in the hopper, or removing too much of the residual dust deposit on the filter. The cleaning period should be much shorter than the filtering period. The correct choice of cleaning method for a particular application will greatly enhance the performance of the fabric filter system. An incorrectly matched cleaning method can result in high pressure drops, low collection efficiency, or decreased bag life. A performance comparison of the various cleaning methods is given in table 9-1.

- (1) *Mechanical shake.* Some baghouses employ a type of mechanical shaking mechanism for cleaning. Bags are usually shaken from the upper fastenings, producing vertical, horizontal, or a combination of motions, on the bag. All bags in a compartment may be fastened to a common framework, or rows of bags are attached to a common rocking shaft. After the bags have been shaken, loosened dust is allowed to settle before filtration is resumed. The entire cleaning cycle may take from 30 seconds to a few minutes. Some designs incorporate a slight reversal of gas flow to aid in dust cake removal and settling, as any slight flow in





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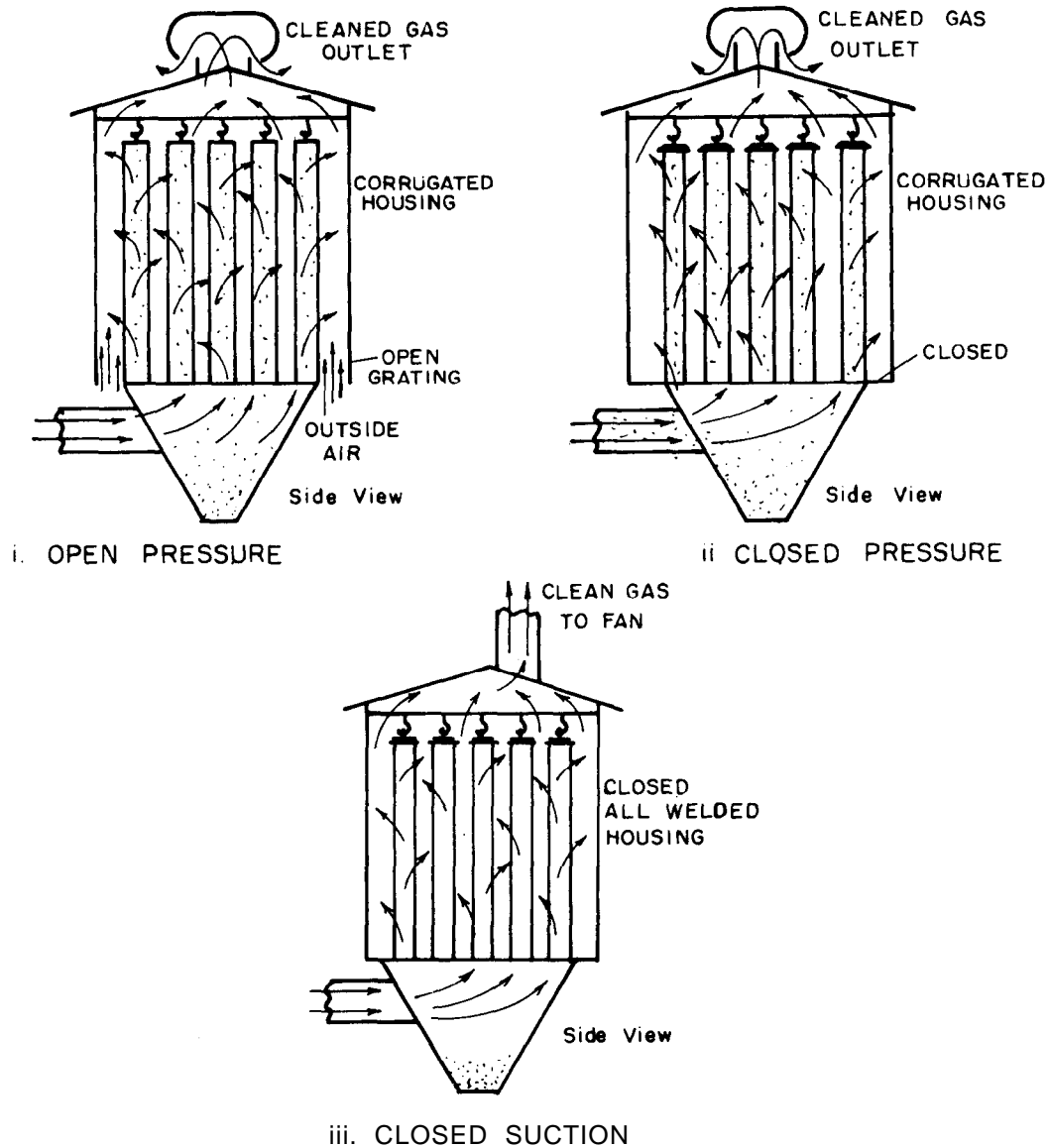
Figure 9-1. Typical baghouse (shake clean)

the direction of normal filtration will greatly reduce the effectiveness of cleaning. For this reason a positive sealing type valve is recommended for baghouse inlet and outlet. Shaker baghouses are normally used in small capacity systems or systems with a large number of filtering compartments.

(2) *Reverse flow without bag collapse.* This cleaning method is used with a dust that releases fairly easily from the fabric. (See figure 9-4). A low pressure reversal of flow is all that is necessary to remove deposited dust from fabric. To minimize flexure and wear, the fabric is supported by a metal grid, mesh, or rings, sewn into the bag. Any flow that is reversed through the filter must be refiltered. This results in increased total flow, requiring a greater cloth area, and producing a higher filtering velocity. This net increase in flow is normally less than 10 percent. Reverse pressures range from 125 pounds/square inch ( $\text{lb/in}^2$ ) down to a few inches, water gauge. The gentle cleaning action of reverse flow allows the use of glass

fabric bags in high-temperature applications.

- (3) *Reverse flow with bag collapse.* Even though flexure can be detrimental to the bag, it is frequently utilized in order to increase the effectiveness of cleaning in a reverse baghouse. Filter bags collecting dust on the inside of the fabric are collapsed by a burst of reverse air which snaps the dust cake from the cloth surface. The bags do not collapse completely but form a cloverleaf type pattern. Collapse cleaning uses the same equipment arrangement as reverse flow without bag collapse. One design sends a short pulse of air down the inside of the bag, along with the reverse flow, to produce increased flexure and cleaning as is illustrated in figure 9-5. The principal disadvantage of flexural cleaning is the increased fabric wear. If the dust cake fails to be removed completely, the bag will stiffen in that area and cause wear in adjacent areas during cleaning.
- (4) *Reverse-flow heating.* With a reverse flow cleaning system it may be necessary to have a reverse flow heating system. This system



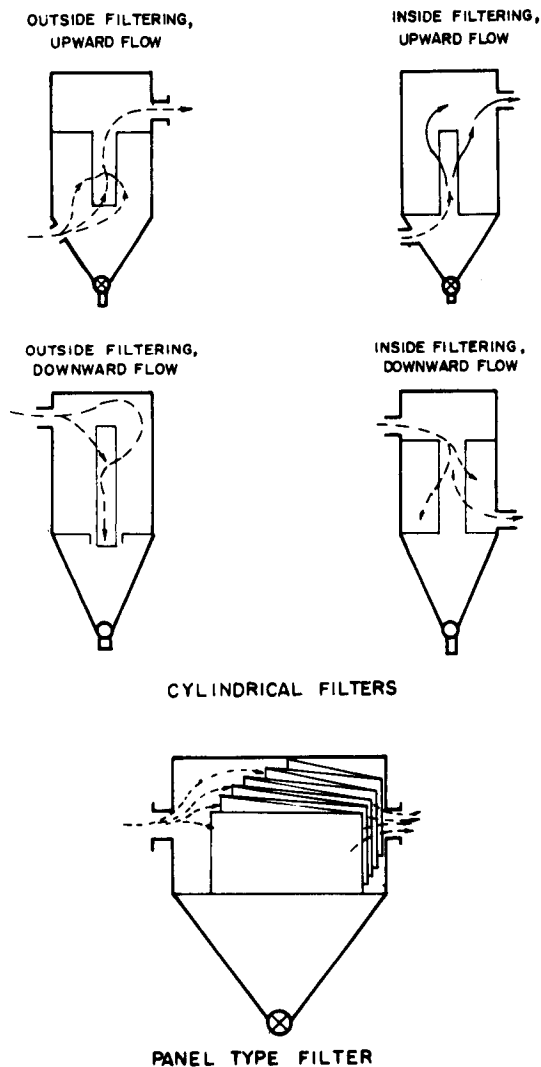
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Figure 9-2. Fabric filter housing design

would be used to keep the gas temperatures in the baghouse above the acid dew point during the cleaning cycle.

(5) *Pulse-jet.* A pulse jet system is illustrated in figure 9-6. A short blast of air at 29 to 100 lb/in, is directed into the top of the filter. This blast is usually sent through a venturi which increases the shock effect. As the pulse starts down the filter tube, more air is drawn in through the top. This combination causes the flow within the bag to temporarily reverse, bulges the fabric, and releases the dust cake from the outside of the filter tube. The whole process occurs in a fraction of a second which

enables a virtually continuous filtering flow. Filter elements can be pulsed individually, or in rows. With a multicompart ment baghouse, a whole section may be pulsed at one time through a single venturi. The pulse produces less fabric motion than in shaking and also allows tighter bag spacing. A pulse-jet cleaning system requires no moving parts for cleaning and is designed to handle high gas flows per square foot of cloth area (air to cloth ratio). However, this system requires a compressed air system with a timer mechanism and control air solenoid valve for automatic cyclic cleaning. Pulse-jet baghouses are used when dust con-



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Figure 9-3. Filter shape and arrangement

centrations are high and continuous filtering is needed.

### 9-3. Fabric characteristics and selection

Fabric filter performance depends greatly upon the correct selection of a fabric. A fabric must be able to efficiently collect a specific dust, be compatible with the gas medium flowing through it, and be able to release the dust easily when cleaned. Fiber, yarn structure, and other fabric parameters will affect fabric performance. At the present time, the prediction of fabric pressure drop, collection efficiency, and fabric life is determined from past performance. It is generally accepted practice to rely on the experience of the manufacturer in selecting a fabric for a specific condition. However, the important fabric parameters are defined below to aid the user in understanding the significance of the fabric media in filtration.

*a. Fabric type.* The two basic types of fabric used in filtration are woven and felted. The woven fabric acts as a support on which a layer of dust is collected which forms a microporous layer and removes particles from the gas stream efficiently. A felted material consists of a matrix of closely spaced fibers which collect particles within its structure, and also utilizes the filter cake for further sieving. Filtering velocities for woven fabrics are generally lower than felts because of the necessity of rebuilding the cake media after each cleaning cycle. It is necessary that woven fabrics not be overcleaned, as this will eliminate the residual dust accumulation that insures rapid formation of the filter cake and high collection efficiencies. Felts operate with less filter cake. This necessitates more frequent cleaning with a higher cleaning energy applied. Woven products, usually more flexible than felts, may be shaken or flexed for cleaning. Felts are usually back-washed with higher pressure differential air and are mainly used in pulse-jet baghouses. However, felted bags do not function well in the collection of fines because the very fine particles become embedded in the felt and are difficult to remove in the cleaning cycle.

*b. Fiber.* The basic structural unit of cloth is the single fiber. Fiber must be selected to operate satisfactorily in the temperature and chemical environment of the gas being cleaned. Fiber strength and abrasion resistance are also necessary for extended filter life. The first materials used in fabric collectors were natural fibers such as cotton and wool. Those fibers have limited maximum operating temperatures (approximately 200 degrees Fahrenheit) and are susceptible to degradation from abrasion and acid condensation. Although natural fibers are still used for many applications, synthetic fibers such as acrylics, nylons, and teflon have been increasingly applied because of their superior resistance to high temperatures and chemical attack (table 9-2).

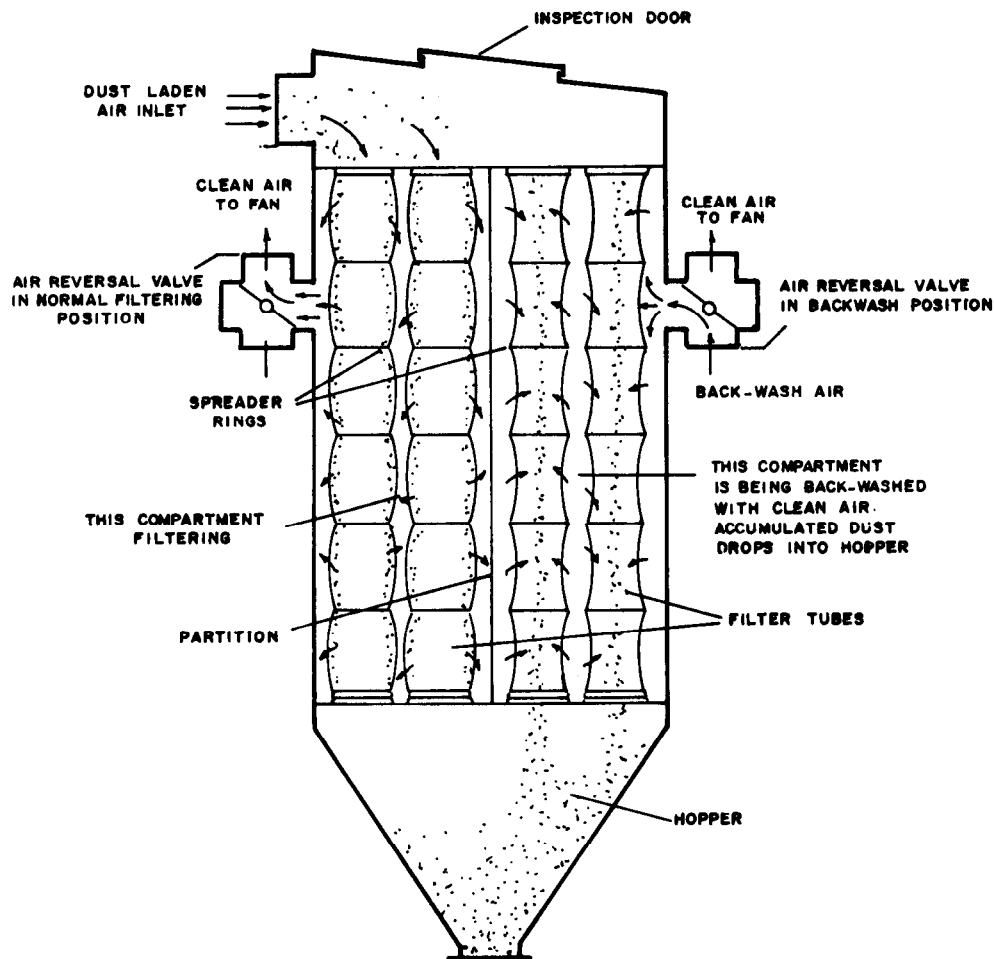
- (1) Acrylics offer a good combination of abrasion resistance and resistance to heat degradation under both wet and dry conditions. An outstanding characteristic of acrylics is the ability to withstand a hot acid environment, making them a good choice in the filtration of high sulfur-content exhaust gases.
- (2) An outstanding nylon fiber available for fabric filters is Nomex, a proprietary fiber developed by DuPont for applications requiring good dimensional stability and heat resistance. Nomex nylon does not melt, but degrades rapidly in temperatures above 700 degrees Fahrenheit. Its effective operating limit is 450 degrees Fahrenheit. When in contact with steam or with small amounts of water vapor at elevated temperatures, Nomex exhibits a progressive loss of strength. However, it withstands these conditions better than other

TABLE 9-1

PERFORMANCE COMPARISON OF FABRIC FILTER CLEANING METHODS

System Type	Pressure Loss (in. of water)	Efficiency	Typical Cloth Type	Filter (cfm/ft <sup>2</sup> Cloth area)	Recommended Application	Advantages	Disadvantages
Shaker	3-6	99+%	Woven	1-5	Dust with good filter cleaning properties, intermittent collection	Relatively low initial investment	Bag failure increases with intensity and frequency of cleaning. Not suitable for fragile fabric and sticky dusts.
Reverse Flow	3-6	99+%	Woven	1-5	Dust with good filter cleaning properties, high temperature collection (incinerator fly ash) with glass bags	Low cloth attrition	Requires extra cloth capacity, additional fan and dampers.
Pulse Jet	3-6	99+%	Felted	5-20	Efficient for coal and oil fly ash collection.	Continuous flow pattern, low cloth attrition, unlimited dust concentration capability, no moving parts, no need for ducting dampers.	Compressed air required, high equipment cost.

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Figure 9-4. Reverse flow baghouse (without bag collapse)

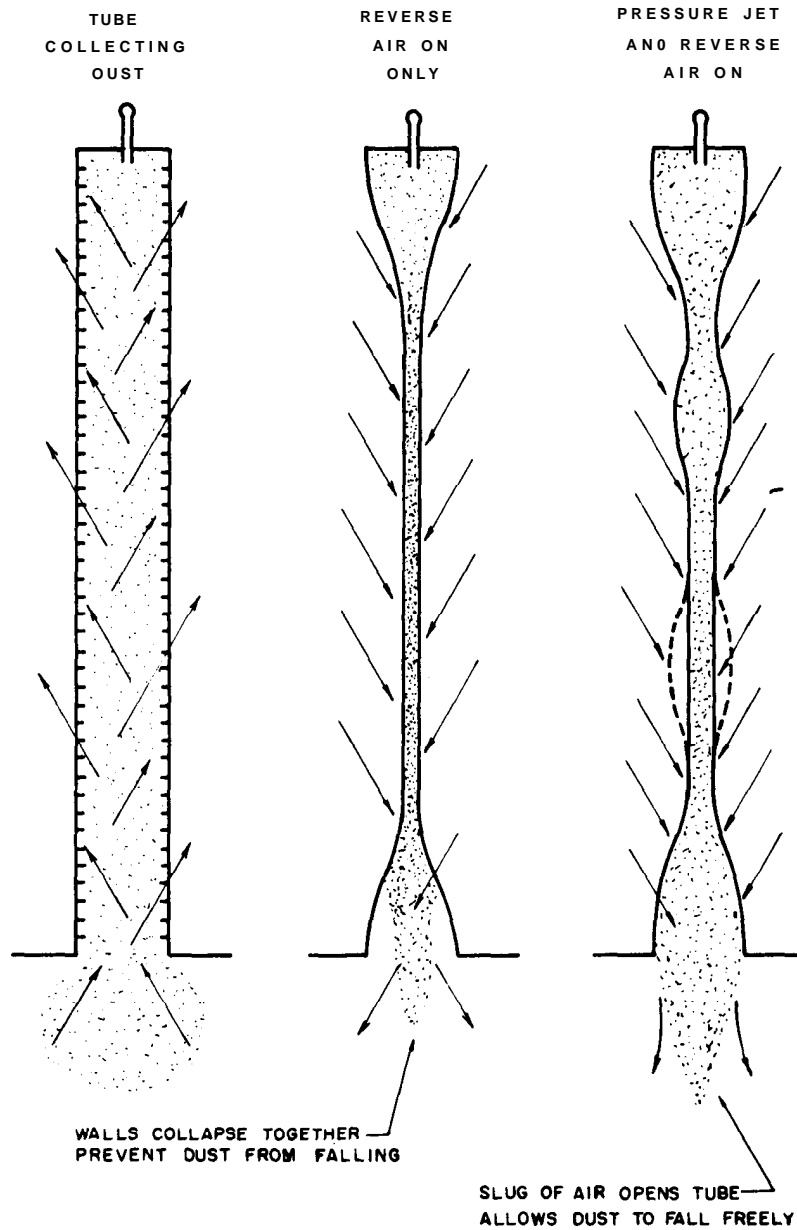
nylons and many other fibers. Because of Nomex's high abrasion resistance, it is used in filtration of abrasive dusts or wet abrasive solids and its good elasticity makes it ideal for applications where continuous flexing takes place. All nylon fabrics provide good cake discharge for work with sticky dusts.

- (3) Teflon is the most chemically resistant fiber produced. The only substances known to react with this fiber are molten alkali metals, fluorine gas at high temperature and pressure, and carbon trifluoride. Teflon fibers have a very low coefficient of friction which produces excellent cake discharge properties. This fact, coupled with its chemical inertness and resistance to dry and moist heat degradation, make Teflon suitable for filtration and dust collection under severe conditions. Its major disadvantages are its poor abrasion resistance and high price. For

these reasons, Teflon would be an economical choice only in an application where extreme conditions will shorten the service life of other filter fibers. It should be noted that the toxic gases produced by the decomposition of Teflon at high temperatures can pose a health hazard to personnel and they must be removed from the work area through ventilation.

c. Yarn *type*. Performance characteristics of filter cloth depend not only on fiber material, but also on the way the fibers are put together in forming the yarn. Yarns are generally classified as staple (spun) or filament.

- (1) Filament yarns show better release characteristics for certain dusts and fumes, especially with less vigorous cleaning methods.
- (2) Staple yarn generally produces a fabric of greater thickness and weight with high permeability to air flow. Certain fumes or dusts



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Figure 9-5. Reverse flow cleaning (with bag collapse)

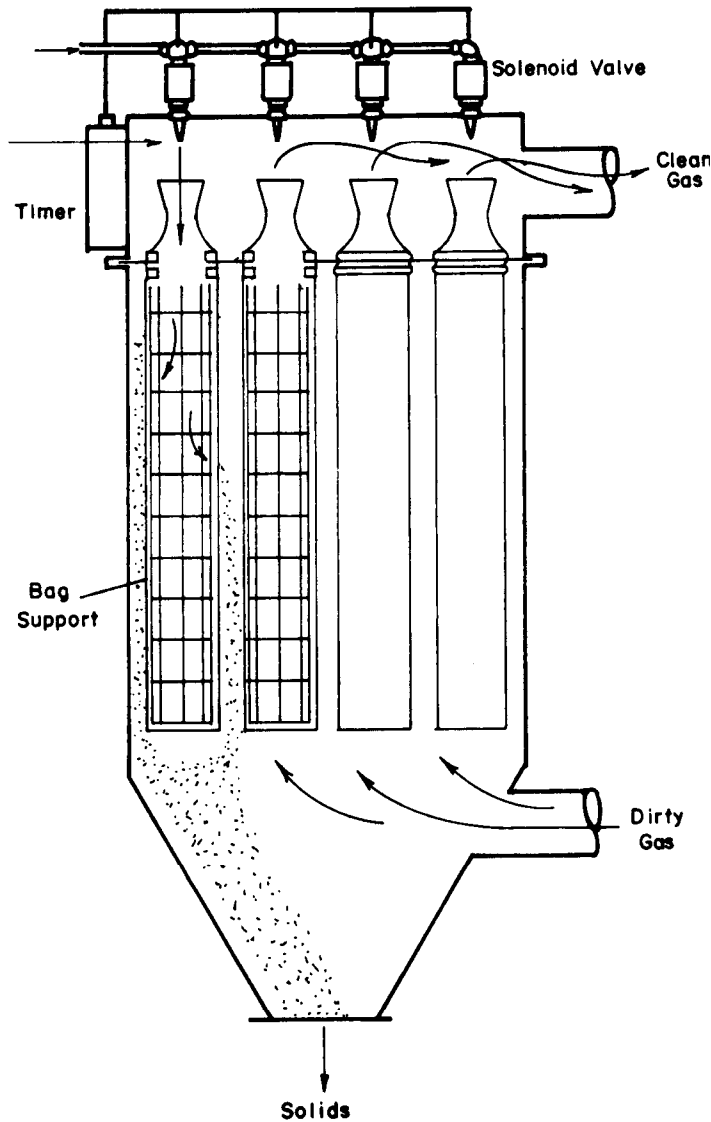
undergoing a change of state may condense on fiber ends and become harder to remove from the fabric.

*d. Weave.* The weave of a fabric is an important characteristic which affects filtration performance. The three basic weaves are plain, twill, and satin.

- (1) Plain weave is the simplest and least expensive method of fabric construction. It has a high thread count, is firm, and wears well.
- (2) Twill weave gives the fabric greater porosity, greater pliability, and resilience. For this reason, twill weaves are commonly used where strong construction is essential.

- (3) Satin fabrics drape very well because the fabric weight is heavier than in other weaves. The yarns are compacted which produces fabric body and lower porosity, and they are often used in baghouses operating at ambient temperatures.

*e. Finish.* Finishes are often applied to fabrics to lengthen fabric life. Cotton and wool can be treated to provide waterproofing, mothproofing, mildewproofing, and fireproofing. Synthetic fabrics can be heat-set to minimize internal stresses and enhance dimensional stability. Water repellents and antistatic agents may also be applied. Glass fabrics are lubricated with silicon



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Figure 9-6. Pulse-jet baghouse

or graphite to reduce the internal abrasion from brittle yarns. This has been found to greatly increase bag life in high temperature operations.

*f. Weight.* Fabric weight is dependent upon the density of construction, and fiber or yarn weight. Heavier fabric construction yields lower permeability and increased strength.

#### 9-4. Materials and construction

*a. Collector housing.* Small unit collectors can be assembled at the factory or on location. Multicompartment assemblies can be shipped by compartment or module (group of compartments), and assembled on-site. Field assembly is disadvantageous because of the need for insuring a good seal between panels, modules and flanges. Baghouse collector wall and ceiling panels

are constructed of aluminum, corrugated steel, or concrete, the limitations being pressure, temperature, and corrosiveness of the effluent. The metal thickness must be adequate to withstand the pressure or vacuum within the baghouse and sufficient bracing should be provided. If insulation is needed, it can be placed between wall panels of adjacent compartments and applied to the outside of the structure. Pressure-relieving doors or panels should be included in the housing or ductwork to protect equipment if any explosive dust is being handled. An easy access to the baghouse interior must be provided for maintenance. Compartmented units have the advantage of being able to remain on-line while one section is out for maintenance. Walkways should be provided for access to all portions of the cleaning mechanism. Units with bags longer than 10 to

TABLE 9-2

PROPERTIES OF FIBERS FOR HIGH TEMPERATURE DRY FILTRATION

Generic Name	Aramid	Glass	PTFE	polyphenylene Sulfide	polybenzimidazole	Metal	Ceramic
Fiber Trade Name	Nomex	Fiberglas	Teflon	Ryton	PBI	Bekinox	Nextel 312
Recommended continuous operation temperature (dry heat)	400°F	500°F	500°F	385°F	500°F	850°F	2,100°F
Water vapor saturated condition (moist heat)	350°F	500°F	500°F	375°F	500°F	750°F	2,199°F
Maximum (short time) operation temperature (dry heat)	450°F	550°F	550°F	450°F	650°F	950°F	2,600°F
Specific density	1.38	2.54	2.3	1.38	1.43	7.9	2.7
Relative moisture regain in % (at 68°F and 65% relative moisture)	4.5	0	0	0.6	14	0	0
Supports combustion	No	No	No	No	No	No	No
Biological resistance (bacteria, mildew)	No Effect	No Effect	No Effect	No Effect	No Effect	No Effect	No Effect
Resistance to alkalis	Good	Fair	lent	Excellent	Good	Good	Good
Resistance to mineral acids	Fair	Very Good	Excel- lent	Excellent	Excellent	Very Good	Very Good
Resistance to organic acids	Fair +	Very Good	Excel- lent	Excellent	Excellent	Very Good	Very Good
Resistance to oxidizing agents	Poor	Excel- lent	Excel- lent	attacked by strong oxidiz- ing agents.	Fair	Very Good	Excellent
Resistance to organic solvents	Very Good	Very Good	Excel- lent	Excellent	Excellent	Very Good	Excellent

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12 feet should be provided with walkways at the upper and lower bag attachment levels.

*b. Hopper and disposal equipment.* The dust-collection hopper of a baghouse can be constructed of the same material as the external housing. In small light duty, hoppers 16 gage metal is typical. However, metal wall thicknesses should be increased for larger baghouses and hopper dust weight. The walls of the hopper must be insulated and should have heaters if condensation might occur. The hopper sides should be sloped a minimum of 57 degrees to allow dust to flow freely. To prevent bridging of certain dusts, a greater hopper angle is needed, but continuous removal of the dust will also alleviate bridging. If dust bridging is a significant problem, vibrators or rappers may be installed on the outside of the hopper. The rapping mechanism can be electrically or pneumatically operated and the size of the hopper must be sufficient to hold the collected dust until it is removed. Overfilled hoppers may cause an increased dust load on the filter cloths and result in increased pressure drop across the collector assembly. Storage hoppers in baghouses which are under positive or negative pressure warrant the use of an air-lock valve for discharging dust. Since this will prevent re-entrainment of dust or dust blow-out. A rotary air valve is best suited for this purpose.

*c.* For low solids flow, a manual device such as a slide gate, trip gate, or trickle valve may be used, however, sliding gates can only be operated when the compartment is shut down. For multicompartimented units, screw conveyors, air slides, belt conveyors or bucket conveying systems are practical. When a screw conveyor or rotary valve is used, a rapper can be operated by a cam from the same motor.

## 9-5. Auxiliary equipment and control systems

*a. Instrumentation.* Optimum performance of a fabric filter system depends upon continuous control of gas temperature, system pressure drop, fabric pressure, gas volume, humidity, condensation, and dust levels in hoppers. Continuous measurements of fabric pressure drop, regardless of the collector size, should be provided. Pressure gages are usually provided by the filter manufacturer. With high and with variable dust loadings, correct fabric pressure drop is critical for proper operation and maintenance. Simple draft gages may be used for measuring fabric pressure drop, and they will also give the static pressures at various points within the system. Observation of key pressures within small systems, permits manual adjustment of gas flows and actuation of the cleaning mechanisms.

*b.* The number and degree of sophistication of pressure-sensing devices is relative to the size and cost of the fabric filter system. High temperature filtration will require that the gas temperature not exceed the tolerance limits of the fabric and temperature displays

are required to indicate whether necessary dilution air-dampers or pre-cooling sprays are operating correctly. A well-instrumented fabric filter system protects the investment and decreases chances of malfunctions. It also enables the operating user to diagnose and correct minor problems without outside aid.

*c.* Gas preconditioning. Cooling the inlet gas to a fabric filter reduce the gas volume which then reduces required cloth area; extends fabric life by lowering the filtering temperature; and permits less expensive and durable materials to be used. Gas cooling is mandatory when the effluent temperature is greater than the maximum operating temperature of available fabrics. Three practical methods of gas cooling are radiation convection cooling, evaporation, and dilution.

- (1) Radiation convection cooling enables fluctuations in temperature, pressure, or flow to be dampened. Cooling is achieved by passing the gas through a duct or heat-transfer device and there is no increase in gas filtering volume. However, ducting costs, space requirements, and dust sedimentation are problems with this method.
- (2) Evaporative cooling is achieved by injecting water into the gas stream ahead of the filtering system. This effectively reduces gas temperatures and allows close control of filtering temperatures. However, evaporation may account for partial dust removal and incomplete evaporation may cause wetting and chemical attack of the filter media. A visible stack plume may occur if gas temperatures are reduced near to or below the dew point.
- (3) Dilution cooling is achieved by mixing the gas steam with outside air. This method is inexpensive but increases filtered gas volume requiring an increase in baghouse size. It is possible the outside air which is added may also require conditioning to control dust and moisture content from ambient conditions.

## 9-6. Energy requirements.

The primary energy requirement of baghouses is the power necessary to move gas through the filter. Resistance to gas flow arises from the pressure drop across the filter media and flow losses resulting from friction and turbulent effects. In small or moderately sized baghouses, energy required to drive the cleaning mechanism and dust disposal equipment is small, and may be considered negligible when compared with primary fan energy. If heating of reverse air is needed this will require additional energy.

## 9-7. Application

*a. Incinerators.* Baghouses have not been widely used with incinerators for the following reasons:

- (1) Maximum operating temperatures for fabric filters have typically been in the range of 450 to

550 degrees Fahrenheit, which is below the flue gas temperature of most incinerator installations

- (2) Collection of condensed tar materials (typically emitted from incinerators) could lead to fabric plugging, high pressure drops, and loss of cleaning efficiency
- (3) Presence of chlorine and moisture in solid waste leads to the formation of hydrochloric acid in exhaust gases, which attacks fiberglass and most other filter media

- (4) Metal supporting frames show distortion above 500 degrees Fahrenheit and chemical attack of the bags by iron and sulphur at temperatures greater than 400 degrees Fahrenheit contribute to early bag failure. Any fabric filtering systems designed for particulate control of incinerators should include:

- fiberglass bags with silica, graphite, or teflon lubrication; or nylon and, teflon fabric bags for high temperature operation, or stainless steel fabric bags,
- carefully controlled gas cooling to reduce high temperature fluctuations and keep the temperature above the acid dew point,
- proper baghouse insulation and positive sealing against outside air infiltration. Reverse air should be heated to prevent condensation.

*b. Boilers.* Electric utilities and industrial boilers primarily use electrostatic precipitators for air pollution control, but some installations have been shown to be successful with reverse air and pulse-jet baghouses. The primary problem encountered with baghouse applications is the presence of sulphur in the fuel which leads to the formation of acids from sulphur dioxide ( $\text{SO}_2$ ) and sulphur trioxide ( $\text{SO}_3$ ) in the exhaust gases. Injection of alkaline additives (such as dolomite and limestone) upstream of baghouse inlets can reduce  $\text{SO}_2$  present in the exhaust. Fabric filtering systems designed for particulate collection from boilers should:

- operate at temperatures above the acid dew point,
- employ a heated reverse air cleaning method,
- be constructed of corrosion resistant material,
- be insulated and employ internal heaters to prevent acid condensation when the installation is off-line.

*c.  $\text{SO}_2$  removal.* The baghouse makes a good control device downstream of a spray dryer used for  $\text{SO}_2$  removal and can remove additional  $\text{SO}_2$  due to the passage of the flue-gas through unreacted lime collected on the bags.

*d. Wood refuse boiler applications.* It is not recommended that a baghouse be installed as a particulate collection device after a wood fired boiler. The possibility of a fire caused by the carry over of hot glowing particles is to great.

## 9-8. Performance

Significant testing has shown that emissions from a fabric filter consist of particles less than 1 micron in diameter. Overall fabric filter collection efficiency is 99 percent or greater (on a weight basis). The optimum operating characteristics attainable with proper design of fabric filter systems are shown in table 9-3.

## 9-9. Advantages and disadvantages

### *a. Advantages.*

- (1) Very high collection efficiencies possible (99.9+ percent) with a wide range of inlet grain loadings and particle size variations. Within certain limits fabric collectors have a constancy of static pressure and efficiency, for a wider range of particle sizes and concentrations than any other type of single dust collector.
- (2) Collection efficiency not affected by sulfur content of the combustion fuel as in ESPs.
- (3) Reduced sensitivity to particle size distribution.
- (4) No high voltage requirements.
- (5) Flammable dust may be collected.
- (6) Use of special fibers or filter aids enables sub-micron removal of smoke and fumes.
- (7) Collectors available in a wide range of configurations, sizes, and inlet and outlet locations.

### *b. Disadvantages.*

- (1) Fabric life may be substantially shortened in the presence of high acid or alkaline atmospheres, especially at elevated temperatures.
- (2) Maximum operating temperature is limited to 550 degrees Fahrenheit, unless special fabrics are used.
- (3) Collection of hygroscopic materials or condensation of moisture can lead to fabric plugging, loss of cleaning efficiency, large pressure losses.
- (4) Certain dusts may require special fabric treatments to aid in reducing leakage or to assist in cake removal.
- (5) High concentrations of dust present an explosion hazard.
- (6) Fabric bags tend to burn or melt readily at temperature extremes.

TABLE 9-3OPERATING CHARACTERISTICS OF FABRIC FILTERS

Collection efficiency	99 percent+
Particle size collected	Greater than .5 microns
Pressure drop	.5-6 inches, water gauge
Maximum operating temperatures	550 degrees Fahrenheit peak and 500 degrees Fahrenheit continuous with common fabrics
Dust concentration handled in particulate collection	0-10 gr/ft <sup>3</sup>
Gas volume	Unlimited
Cloth area	Several square feet to several thousand square feet
Filtering velocities	1-15 ft/min
Average bag life	18 months to 2 years

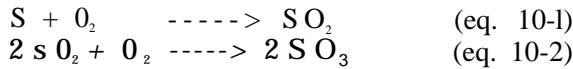
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# CHAPTER 10

## SULFUR OXIDE (SO<sub>x</sub>) CONTROL SYSTEMS

### 10-1. Formation of sulfur oxides (SO<sub>x</sub>)

a. *Definition of sulfur oxide.* All fossil fuels contain sulfur compounds, usually less than 8 percent of the fuel content by weight. During combustion, fuel-bound sulfur is converted to sulfur oxides in much the same way as carbon is oxidized to CO<sub>2</sub>. Sulfur dioxide (SO<sub>2</sub>) and sulfur trioxide (SO<sub>3</sub>) are the predominant sulfur oxides formed. See equations 10-1 and 10-2.



b. *Stack-gas concentrations.* In efficient fuel combustion processes, approximately 95 percent of the fuel-bound sulfur is oxidized to sulfur dioxide with 1 to 2% being converted to sulfur trioxide.

c. *Factors affecting the formation of SO<sub>x</sub>.*

- (1) SO<sub>3</sub> formation increases as flame temperature increases. Above 3,150 degrees Fahrenheit, SO<sub>3</sub> formation no longer increases.
- (2) SO<sub>3</sub> formation increases as the excess air rate is increased.
- (3) SO<sub>3</sub> formation decreases with coarser atomization.

### 10-2. Available methods for reducing SO<sub>x</sub> emissions

a. *Fuel substitution.* Burning low sulfur fuel is the most direct means of preventing a SO<sub>x</sub> emissions problem. However, low sulfur fuel reserves are decreasing and are not available in many areas. Because of this, fuel cleaning technology has received much attention. There are presently more than 500 coal cleaning plants in this country. At present, more than 20% of the coal consumed yearly by the utility industry is cleaned. Forty to ninety percent of the sulfur in coal can be removed by physical cleaning, depending upon the type of sulfur deposits in the coal. As fuel cleaning technology progresses and the costs of cleaning decrease, fuel cleaning will become a long term solution available for reducing sulfur oxide emissions.

b. *Considerations of fuel substitution.* Fuel substitution may involve choosing a higher quality fuel grade; or it may mean changing to an alternate fuel type. Fuel substitution may require any of the following considerations:

- (1) Alternations in fuel storage, handling, preparation, and combustion equipment.
- (2) When changing fuel type, such as oil to coal, a new system must be installed.

- (3) When choosing a higher quality fuel, as in changing from residual to distillate fuel oil, modest modifications, such as changing burner tips, and oil feed pumps, are required.

c. *Changes in fuel properties.* Consideration of possible differences in fuel properties is important. Some examples are:

- (1) Higher ash content increases particulate emissions.
- (2) Lower coal sulfur content decreases ash fusion temperature and enhances boiler tube slagging.
- (3) Lower coal sulfur content increases fly-ash resistivity and adversely affects electrostatic precipitator performance.
- (4) Low sulfur coal types may have higher sodium content which enhances fouling of boiler convection tube surfaces.
- (5) The combination of physical coal cleaning and partial flue gas desulfurization enables many generating stations to meet SO<sub>2</sub> standards at less expense than using flue gas desulfurization alone.

d. *Modification of fuel.* Some possibilities are:

- (1) Fuels of varying sulfur content may be mixed to adjust the level of sulfur in the fuel to a low enough level to reduce SO<sub>2</sub> emissions to an acceptable level.
- (2) Fuels resulting from these processes will become available in the not too distant future. Gasification of coal removes essentially all of the sulfur and liquification of coal results in a reduction of more than 85% of the sulfur.

e. *Applicability of boiler conversion from one fuel type to another.* Table 10-1 indicates that most boilers can be converted to other type of firing but that policies of the agencies must also be a consideration.

Table 10-1

*Convertibility of steam boilers*

As designed			Convertible to:		
Coal	Oil	Gas	Coal	Oil	Gas
**X	x	-	-	-	yes
**X	-	X	-	yes	-
**X	-	-	-	yes	yes
-	X	-	*possible	-	yes
-	-	X	*possible	yes	-

Note: \*Large DOD boilers must be convertible to coal firing.  
 \*\* Changing from coal to oil or gas firing is not in accordance with present AR 420-49.

*f. Approach to fuel substitution.* An approach to fuel substitution should proceed in the following manner:

- (1) Determine the availability of low sulfur fuels.
- (2) For each, determine which would have sulfur emissions allowable under appropriate regulations.
- (3) Determine the effect of each on particulate emissions, boiler capacity and gas temperatures, boiler fouling and slagging, and existing particulate control devices.
- (4) Identify the required equipment modifications, including transport, storage, handling, preparation, combustion, and control equipment.
- (5) For the required heat output calculate the appropriate fuel feed rate.
- (6) Determine fuel costs.
- (7) Determine the cost of boiler and equipment modification in terms of capital investment and operation.
- (8) Annualize fuel costs, capital charges, and operating and maintenance costs.
- (9) With the original fuel as a baseline, compare emissions and costs for alternate fuels.

*g. Modification to boiler operations and maintenance.*

- (1) A method of reducing sulfur oxides emissions is to improve the boiler use of the available heat. If the useful energy release from the boiler per unit of energy input to the boiler can be increased, the total fuel consumption and emissions will also be reduced.
- (2) An improvement in the boiler release of useful energy per unit of energy input can be achieved by increasing boiler steam pressure and temperature. Doubling the steam drum pressure can increase the useful heat release per unit of energy input by seven percent. Increasing the steam temperature from 900 to 1000 degrees Fahrenheit can result in an improvement in the heat release per unit of energy input of about 3.5 percent.
- (3) Another way to maximize the boiler's output per unit of energy input is to increase the attention given to maintenance of the correct fuel to air ratio. Proper automatic controls can perform this function with a high degree of accuracy.
- (4) If additional emphasis can be put on maintenance tasks which directly effect the boilers ability to release more energy per unit of energy input they should be considered a modification of boiler operations. Items which fall into this category are:
  - Washing turbine blades
  - adjusting for maximum throttle pressure

- adjusting turbine control valves to insure proper lift
- adjusting preheater seals and feedwater heaters
- insuring cleanliness of heat transfer surfaces, such as condensers, superheaters, reheaters, and air heaters.

*h. Limestone injection.* One of the earliest techniques used to reduce sulfur oxide emission was the use of limestone as a fuel additive. This technique involves limestone injection into the boiler with the coal or into the high temperature zone of the furnace. The limestone is calcined by the heat and reacts with the SO<sub>2</sub> in the boiler to form calcium sulfate. The unreacted limestone, and the fly ash are then collected in an electrostatic precipitator, fabric bag filter, or other particulate control device. There are a number of problems associated with this approach:

- (1) The sulfur oxide removal efficiency of the additive approach is in the range of 50 to 70% in field applications. However, it is considered feasible that when combined with coal cleaning, it is possible to achieve an overall SO<sub>2</sub> reduction of 80 percent.
- (2) The limestone used in the process cannot be recovered.
- (3) The addition of limestone increases particulate loadings. In the precipitator this adversely affects collection efficiency.
- (4) The effects of an increased ash load on slagging and fouling as well as on particulate collection equipment present a group of problems which must be carefully considered.
- (5) The high particulate loadings and potential boiler tube fouling in high heat release boilers tend to cause additional expense and technical problems associated with handling large particulate loadings in the collection equipment.
- (6) There have been many claims over the years regarding the applicability of fuel additives to the reduction of sulfur oxide emissions. The United States Environmental Protection Agency has tested the effect of additives on residual and distillate oil-fired furnaces. They conclude that the additives have little or no effect.

*i. Flue gas desulfurization (FGD).* There are a variety of processes which have demonstrated the ability to remove sulfur oxides from exhaust gases. Although this technology has been demonstrated for some time, its reduction to sound engineering practice and widespread acceptance has been slow. This is particularly true from the standpoint of high system reliability. The most promising systems and their performance characteristics are shown in table 10-2.

*j. Boiler injection of limestone with wet scrubber.* In this system limestone is injected into the boiler and is

System Type	SO <sub>x</sub> Removal Efficiency (%)	Pressure Drop (inches of water)	Recovery and Regeneration	Operational Reliability	Retrofit to Existing Installation	Advantages	Disadvantages
1) Limestone, boiler injection type	30-40%	less than 6"	no recovery of limestone	High	Yes	high reliability	low efficiency, scalling in boiler and scrubber, small units only, solids disposal to landfill
2) Limestone, Scrubber injection type	30-40%	greater than 6"	no recovery of lime	High	Yes	high reliability no boiler scalling	low efficiency, scalling and plugging of nozzles and surfaces in scrubber solids disposal.
3) Lime, Scrubber injection type	90%	greater than 6"	no recovery of lime	Low	Yes	high efficiency, no boiler scalling, less scalling to scrubber than limestone in some cases	low reliability; solids disposal to landfill
4) Magnesium Oxide	90%	greater than 6"	recovery of Mg and sulfuric acid	Low	Yes	high efficiency; no solids disposal	low reliability; corrosion and erosion of scrubber and piping. Need pre-cleaning of flue gas.
5) Wellman-Lord	90%	greater than 6"	recovery of NaSO <sub>3</sub> and sulfur	Unknown	Yes	high efficiency, little scalling	unknown reliability; need natural gas for SO <sub>2</sub> Reduction.
6) Catalytic Oxidation	45%	may be as high as 24"	recovery of H <sub>2</sub> SO <sub>4</sub>	Unknown	No	high efficiency; no solids disposal problem; catalyst regeneration not necessary	Vanadium pentoxide needed as catalyst; high pressure drop system; unknown reliability; need pre-cleaning of flue gas by high efficiency device.
7) Single Alkali Systems	90%	Tray tower pressure drop 1.6-2.0 in. H <sub>2</sub> O/tray with Venturi added 10-14 in. H <sub>2</sub> O	little recovery of sodium	Unknown	Yes	high efficiency; reduces scalling and plugging of scrubber	throwaway process; chemical costs high when burning high sulfur fuels; disposal of sodium salts; high water makeup rate.
8) Dual alkali Systems	90-95%		Regeneration of sodium hydroxide and sodium sulfites	Unknown	Yes	absorption efficiency potentially higher than other systems; scalling problems reduced; produces solid rather than liquid waste.	solids buildup in reactor system; problems with de-watering system.
9) Dry, post furnace limestone injection	70-80%	Greater than 6"	No recovery of limestone	High	Yes	reduced water consumption lower capital cost simplicity	most suitable for low and medium sulfur coals.
10) Dry furnace injection of LIMESTONE	40-70%	Less than 6"	No recovery of limestone	High	Yes	reduced water consumption lower capital costs simplicity	increased ash load on particulate collection equipment.

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calcined to lime. The lime reacts with the  $\text{SO}_2$  present in the combustion gases to form calcium sulfate and calcium sulfite. As the gas passes through a wet scrubber, the limestone, lime, and reacted lime are washed with water to form sulfite. As the gas passes through a wet scrubber, the limestone, lime, and reacted lime are washed with water to form a slurry. The resulting effluent is sent to a settling pond and the sediment is disposed by landfilling. Removal efficiencies are below 50% but can be reliably maintained. Scaling of boiler tube surfaces is a major problem.

*k. Scrubber injection of limestone.* In this FGD system limestone is injected into a scrubber with water to form a slurry (5 to 15% solids by weight). The limestone is ground into fines so that 85% passes through a 200-mesh screen.  $\text{CaCO}_3$  absorbs  $\text{SO}_2$  in the scrubber and in a reaction tank where additional time is allowed to complete the reaction. Makeup is added to the reusable slurry as necessary and the mixture is recirculated to the scrubber. The dischargeable slurry is taken to a thickener where the solids are precipitated and the water is recirculated to the scrubber. Limestone scrubbing is a throwaway process and sludge disposal may be a problem. At  $\text{SO}_2$  removal efficiencies of about 30%, performance data indicate that limestone scrubbers have a 90% operational reliability. Plugging of the demister, and corrosion and erosion of stack gas reheat tubes have been major problems in limestone scrubbers. Figure 10-1 shows a simplified process flow-sheet for a typical limestone scrubbing installation.

*l. Scrubber injection of lime.* This FGD process is similar to the limestone scrubber process, except that lime ( $\text{Ca(OH)}_2$ ) is used as the absorbent. Lime is a more effective reactant than limestone so that less of it is required for the same  $\text{SO}_2$  removal efficiency. The decision to use one system over the other is not clear-cut and usually is decided by availability.

*m. Post furnace limestone injection with spray drying.* In this system, a limestone slurry is injected into a spray dryer which receives flue gas directly from the boiler. The limestone in the slurry reacts with the  $\text{SO}_2$  present in the combustion gases to form calcium sulfate and calcium sulfite. The heat content of the combustion gases drives off the moisture resulting in dry particulates exiting the spray dryer and their subsequent capture in a particulate collector following the spray dryer. The particulates captured in the collector are discharged as a dry material and the cleaned flue gases pass through the filter to the stack (fig 10-la).

*n. Dry, post furnace limestone injection.* Ground dry limestone is injected directly into the flue gas duct prior to a fabric filter. The limestone reacts in the hot medium with the  $\text{SO}_2$  contained in the combustion gases and is deposited on the filter bags as sodium sulfate and sodium sulfite. The dry particulate matter is then discharged to disposal and the cleaned flue gases pass through the filter medium to the stack (fig 10-lb).

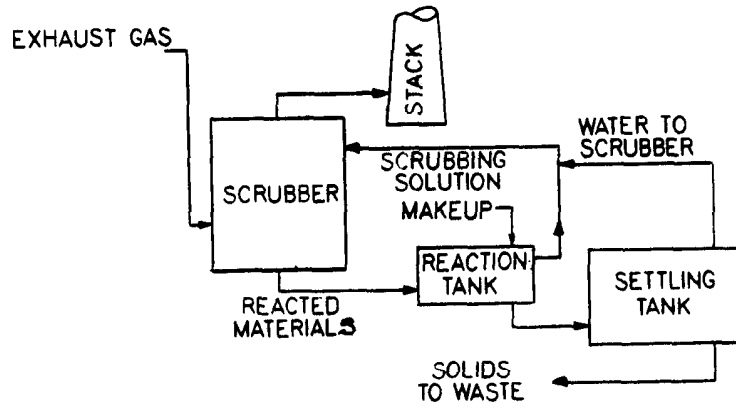
*o. Dry furnace injection of limestone.* In this system, dry ground limestone is injected into the boiler where it is calcined and reacts with the  $\text{SO}_2$  formed during combustion of the fuel. The flue gases containing the sodium sulfate, sodium sulfite, unreacted limestone, and fly ash all exit the boiler together and are captured on a particulate collector. The cleaned flue gases pass through the filter medium and out through the stack (fig 10-1c).

*p. Magnesium oxide (MgO) scrubber.* This is a regenerative system with recovery of the reactant and sulfuric acid. As can be seen in figure 10-2 the flue gas must be precleaned of particulate before it is sent to the scrubber. An ESP or venturi scrubber can be used to remove the particulate. The flue gas then goes to the MgO scrubber where the principal reaction takes place between the MgO and  $\text{SO}_2$  to form hydrated magnesium sulfite. Unreacted slurry is recirculated to the scrubber where it combines with makeup MgO and water and liquor from the slurry dewatering system. The reacted slurry is sent through the dewatering system where it is dried and then passed through a recovery process, the main step of which is calcination. High reliability of this system has not yet been obtained.  $\text{SO}_2$  removal efficiencies can be high, but scaling and corrosion are major problems.

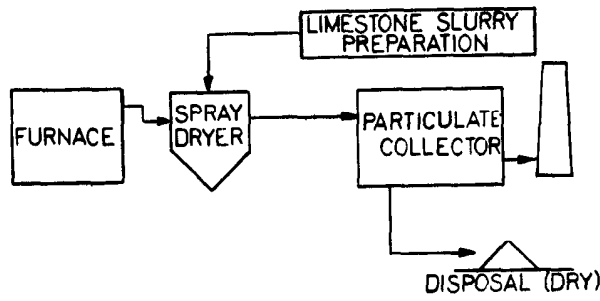
*q. Wellman Lord process.* Sodium sulfite is the scrubbing solution. It captures the  $\text{SO}_2$  to produce sodium bisulfite, which is later heated to evolve  $\text{SO}_2$  and regenerate the sulfite scrubbing material. The  $\text{SO}_2$  rich product stream can be compressed or liquified and oxidized to sulfuric acid, or reduced to sulfur. Scaling and plugging are minimal problems because the sodium compounds are highly soluble in water. A Wellman-Lord unit has demonstrated an  $\text{SO}_2$  removal efficiency of greater than 90 percent and an availability of over 85 percent. The harsh acid environment of the system has caused some mechanical problems (See figure 10-3).

*r. Catalytic oxidation.* The catalytic oxidation process uses a high temperature (850 degrees Fahrenheit) and a catalyst (vanadium pentoxide) to convert  $\text{SO}_2$  to  $\text{SO}_3$ . The heated flue gas then passes through a gas heat exchanger for heat recovery and vapor condensation. Water vapor condenses in the heat exchanger and combines with  $\text{SO}_3$  to form sulfuric acid. The acid mist is then separated from the gas in an absorbing tower. The flue gas must be precleaned by a highly efficient particulate removal device such as an electrostatic precipitator preceding the cat-ox system to avoid poisoning the catalyst. The major drawback of this system is that it cannot be economically retro-fitted to existing installations (fig 10-4).

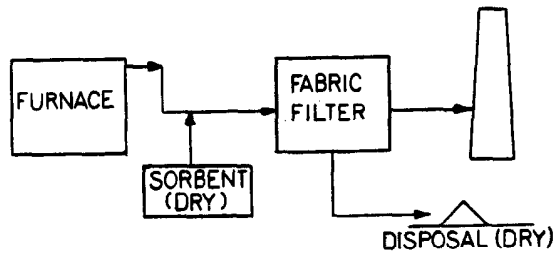
*s. Single alkali sodium carbonate scrubbing.* In order to eliminate the plugging and scaling problems associated with direct calcium scrubbing, this FGD system was developed. As shown in figure 10-5, the process is a once through process involving scrubbing



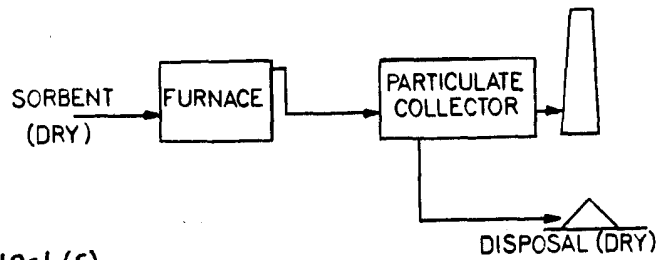
10-1



10-1 (a)



10-1 (b)

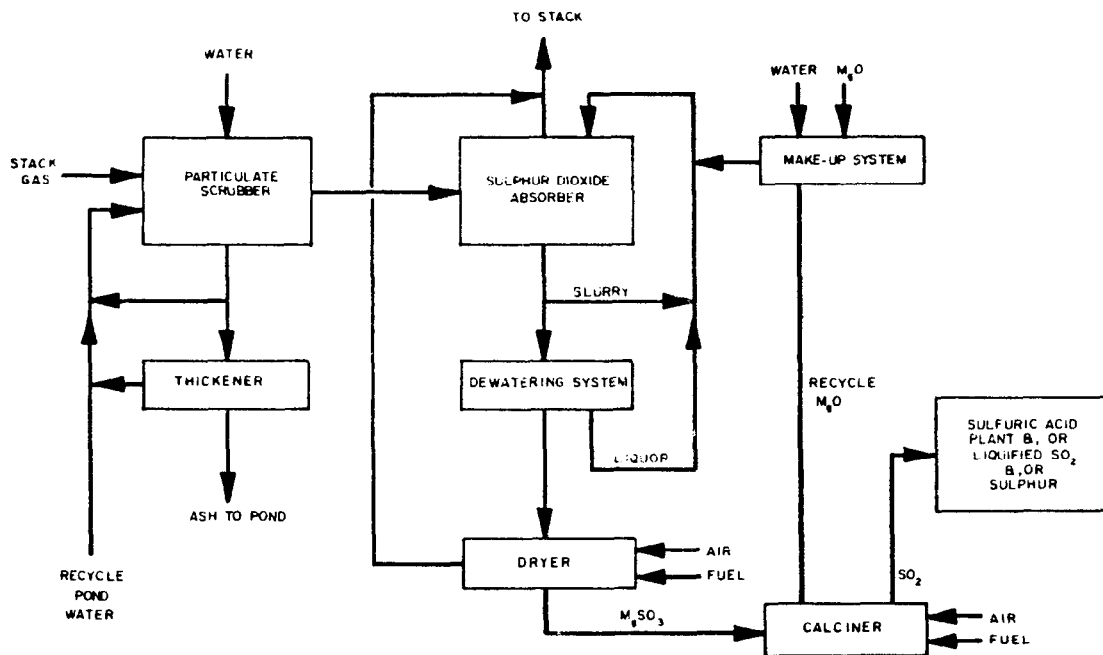


10-1 (c)

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Figure 10-1. Lime (limestone) injection system schematic





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Figure 10-2. Magnesia slurry  $SO_2$  recovery process

with a solution of sodium carbonate or sodium hydroxide to produce a solution of dissolved sodium sulfur salts. The solution is then oxidized to produce a neutral solution of sodium sulfate. Because it is a throwaway process, the cost of chemicals make it an unattractive  $SO_x$  removal process when burning high sulfur fuels (greater than 1 percent).

*t. Dual alkali sodium scrubbing.*

(1) The dual alkali  $SO_x$  removal system is a regenerative process designed for disposal of wastes in a solid/slurry form. As shown in figure 10-6, the process consists of three basic steps; gas scrubbing, a reactor system, and solids dewatering. The scrubbing system utilizes a sodium hydroxide and sodium sulfite solution. Upon absorption of  $SO_2$  in the scrubber, a solution of sodium bisulfite and sodium sulfite is produced. The scrubber effluent containing the dissolved sodium salts is reacted outside the scrubber with lime or limestone to produce a precipitate of calcium salts containing calcium sulfate. The precipitate slurry from the reactor system is dewatered and the solids are disposed of in a landfill. The liquid fraction containing soluble salts is recirculated to the absorber. Double alkali systems can achieve efficiencies of 90 - 95% and close to 100% reagent utilization.

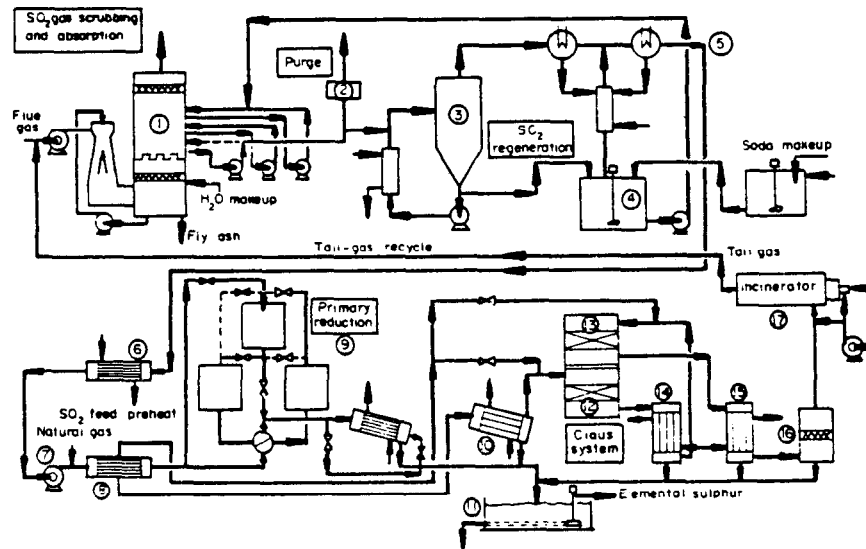
(2) This system is designed to overcome the inherent difficulties of direct calcium slurry scrub-

bing. All precipitation occurs outside the scrubber under controlled reactor conditions. The principal advantages of the dual alkali system are:

- (a) Scaling problems associated with direct calcium-based scrubbing processes are significantly reduced.
- (b) A less expensive calcium base can be used.
- (c) Due to high solubility and concentration of active chemicals, lower liquid volumes can be used thereby lowering equipment costs.
- (d) Slurries are eliminated from the absorption loop, thereby reducing plugging and erosion problems.
- (e) A sludge waste, rather than a liquid waste, is produced for disposal.
- (f) High  $SO_2$  removal efficiency (90% or more).

*u. Absorption of  $SO_2$ .*

(1) Activated carbon has been used as an absorbent for flue-gas desulfurization. Activated carbon affects a catalytic oxidation of  $SO_2$  to  $SO_3$ , the latter having a critical temperature of 425 degrees Fahrenheit. This allows absorption to take place at operating temperatures. The carbon is subsequently regenerated in a separate reactor to yield a waste which is used in the production of high grade sulfuric acid, and the regenerated absorbent. There are serious problems involved in the regeneration of the absorbent, including carbon losses due



- |                              |                                |
|------------------------------|--------------------------------|
| 1) ABSORBER                  | 9) CATALYTIC REDUCTION SECTION |
| 2) SURGE TANK                | 10) COOLER                     |
| 3) REGENERATION SECTION      | 11) SULPHUR HOLDING PIT        |
| 4) DISSOLVING TANK           | 12,13) CLAUS CONVERTER         |
| 5) CONCENTRATED SO DISCHARGE | 14, 15) CONDENSORS             |
| 6) PREHEATER                 | 16) COALESCER                  |
| 7) NATURAL GAS ADDITION      | 17) INCINERATOR                |
| 8) HEATER                    |                                |

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Figure 10-3. Wellman-Lord SO<sub>2</sub> reduction system

to attrition, chemical decomposition, serious corrosion problems, and danger of combustion of the reactivated carbon.

(2) Zeolites are a class of highly structured aluminum silicate compounds. Because of the regular pore size of zeolites, molecules of less than a certain critical size may be incorporated into the structure, while those greater are excluded. It is often possible to specify a certain zeolite for the separation of a particular material. Zeolites possess properties of attrition resistance, temperature stability, inertness to regeneration techniques, and uniform pore size which make them ideal absorbents. However, they lack the ability to catalyze the oxidation of SO<sub>2</sub> to SO<sub>3</sub> and thus cannot desulfurize flue-gases at normal operating temperatures. Promising research is under way on the development of a zeolite material that will absorb SO<sub>2</sub> at flue-gas temperatures

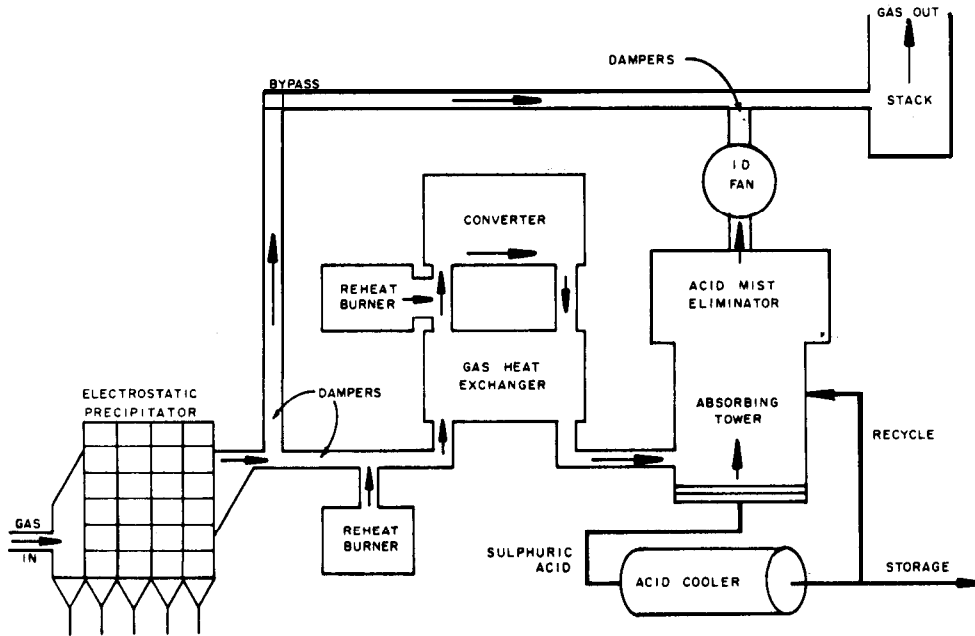
by oxidation of SO<sub>2</sub> and subsequently store it as a sulphate in the pores of the zeolite.

v. *Cost of flue-gas desulfurization.* The actual capital and operating costs for any specific installation are a function of a number of factors quite specific to the plant and include:

- Plant size, age, configuration, and locations,
- Sulfur content of the fuel and emission control requirements,
- Local construction costs, plant labor costs, and cost for chemicals, water, waste disposal, etc.,
- Type of FGD system and required equipment,
- Whether simultaneous particulate emission reduction is required.

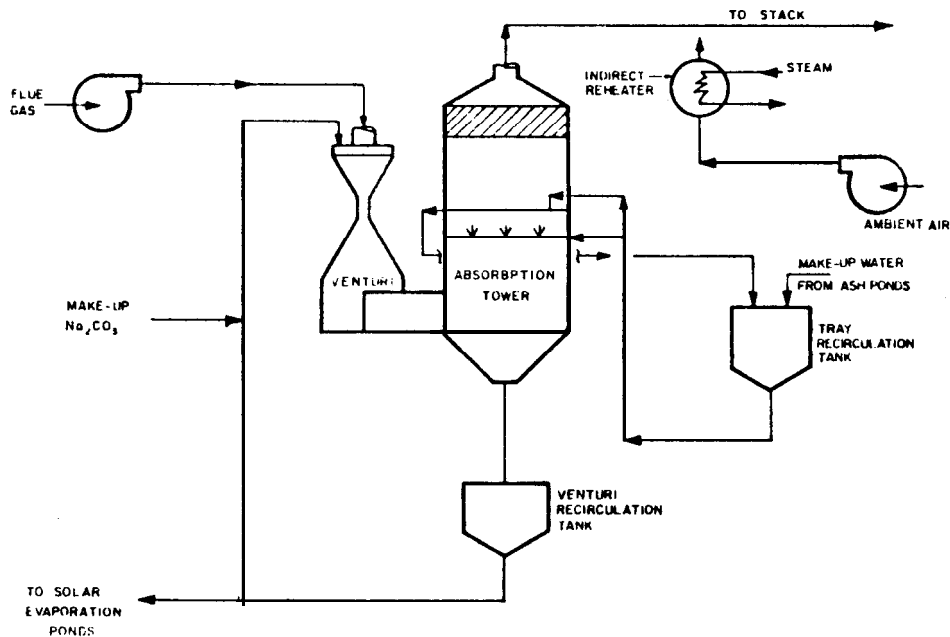
### 10-3. Procedure to minimize SO<sub>x</sub> emission

a. *Efficiency requirement.* The SO<sub>x</sub> removal efficiency necessary for any given installation is dependent upon the strictest regulation governing that installation. Given a certain required efficiency, a choice can be



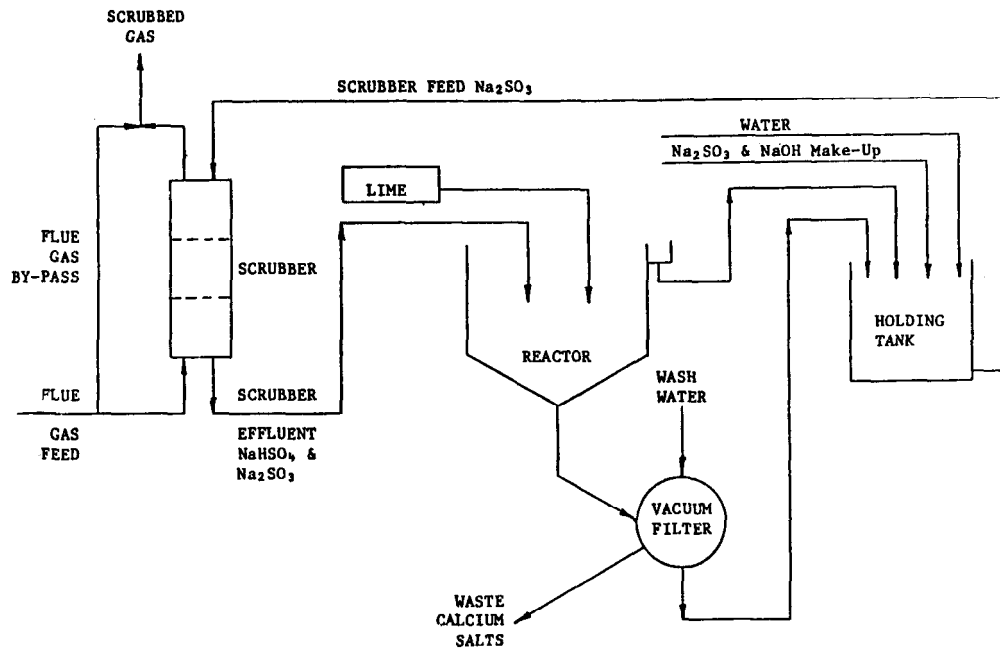
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Figure 10-4. Catalytic oxidation system



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Figure 10-5. Single alkali sodium carbonate scrubber



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Figure 10-6. Dual alkali system

made among the different reduction techniques. This section shows how a rational basis can be utilized to determine the best method.

**b. Boiler modification.** This technique is useful in reducing SO<sub>x</sub> emissions by 0 to 6% depending upon the boiler. For industrial boilers operating above 20% excess-air the use of proper control equipment or low excess-air combustion will usually reduce emissions by 4 to 5%. If the operating engineer is not familiar with boiler optimization methods, consultants should be utilized.

**c. Fuel substitution.** This method can be used for almost any percent reduction necessary. Availability and cost of the fuel are the major factors to be considered. Fuels can be blended to produce the desired sulfur input. Care must be taken, however, so that the ash produced by the blending does not adversely affect the boiler by lowering the ash fusion temperature or causing increased fouling in the convection banks.

**d. Flue-gas desulfurization.** Various systems are available for flue-gas desulfurization. Some of these systems have demonstrated long term reliability of operation with high SO<sub>x</sub> removal efficiency. Lime/limestone injection and scrubbing systems have been most frequently used. It must be recognized that each boiler control situation must be accommodated in the overall system design if the most appropriate system is to be installed. The selection and design of such a control system should include the following considerations:

- (1) Local SO<sub>2</sub> and particulate emission requirements, both present and future,

- (2) Local liquid and solid waste disposal regulations,
- (3) Local market demand for recovered sulfur,
- (4) Plant design limitations and site characteristics,
- (5) Local cost and availability of chemicals, utilities, fuels, etc.,
- (6) Added energy costs due to process pumps, reheaters, booster fans, etc.

#### 10-4. Sample problems.

The following problems have been provided to illustrate how to determine the maximum fuel sulfur content allowable to limit SO<sub>x</sub> emission to any particular level.

a. Approximately 90 to 97 percent of fuel sulfur is oxidized to sulfur dioxide (SO<sub>2</sub>) during combustion. This means that for every lb of sulfur in the fuel, approximately 2 lbs of sulfur oxides will appear in the stack gases. (The atomic weight of oxygen is 1/2 that of sulfur.) Since most of the sulfur oxides are in the form of SO<sub>2</sub>, emissions regulations are defined in these units. To estimate maximum probable SO<sub>2</sub> emissions, the following equation applies:

$$\frac{\text{lbs SO}_2}{\text{MMBtu}} = \frac{2 \times \% \text{ Sulfur by Weight in Fuel}}{\text{Fuel Heating Value (Btu/lb)}} \times 10^4 \quad (\text{eq. 10-1})$$

b. Assume a fuel-oil burning boiler must limit emissions to .35 lbs/MMBtu. What is the maximum allowable sulfur content if No. 6 Residual fuel-oil is to be used?

- (1) From table 10-3, Typical Analysis of Fuel-Oil

Types, an average heating value of 18,300 Btu/lb for No. 6 residual fuel has been assumed. Maximum allowable sulfur content is determined as:

$$\frac{.35 \text{ lbs SO}_2}{\text{MMBtu}} \times \frac{2 \times \% \text{ Sulfur by Weight in Fuel}}{18,300 \text{ Btu}} \times 10^4$$

$$\% \text{ Sulfur} = \frac{(.35)(18,300)}{2 \times 10^4} = .32\%$$

(2) Table 10-3 shows that No. 5 and No. 6 fuel oils have fuel sulfur contents in excess of .32%. If No. 4 fuel oil is chosen, a fuel with less than .32% sulfur may be available.

c. Assume a fuel-oil burning boiler must limit SO<sub>x</sub> emission to .65 lbs/MMBtu. If No. 6 residual fuel oil is to be used, can SO<sub>x</sub> emission limits be met?

(1) From table 10-3, the minimum sulfur content in No. 6 fuel oil is .7%. If .7% sulfur fuel can be purchased, the heating value of the fuel must be:

a) 
$$.65 \frac{\text{lb SO}_2}{\text{MMBtu}} = \frac{2 \times .7\% \text{ Sulfur}}{\text{H. Value}} \times 10^4$$

b) Heating Value = 21,538 Btu/lb

(2) Since the heating value of No. 6 fuel oil is generally between 17,410 and 18,990 Btu/lb, SO<sub>x</sub> emission limits cannot be met using this fuel. If we assume a No. 6 fuel-oil with one percent sulfur and a heating value of 18,600 Btu/lb is used the percent SO<sub>x</sub> removal efficiency that will be required is determined as:

a) 
$$\frac{\text{lbs SO}_2 \text{ emissions.}}{\text{MMBtu}} \times \frac{2 \times 1\% \text{ Sulfur}}{18,600 \text{ Btu/lb}} \times 10^4 = 1.08$$

b) 
$$\frac{1.08 - .65}{1.08} = 40\% \text{ removal of SO}_2 \text{ required}$$

d. Assume a boiler installation burns No. 4 fuel-oil with a heating value of 19,000 Btu/lb. What is the maximum fuel sulfur content allowable to limit SO<sub>x</sub> emissions to .8 lbs/MMBtu?

(1) 
$$.80 \frac{(\text{lbs SO}_2)}{\text{Mil Btu}} = \frac{2 \times \% \text{ Fuel Sulfur}}{19,000 \text{ Btu/lb}} \times 10^4$$

(2) 
$$\% \text{ Fuel Sulfur} = \frac{.80 (19,000)}{2 \times 10^4} = .76\%$$

e. Assume a coal burning boiler must limit SO<sub>x</sub> emissions to 1 lb/MMBtu. If sub-bituminous coal with a heating value of 12,000 to 12,500 Btu/lb (see table 10-4) is to be used what is the maximum allowable fuel sulfur content?

(1) 
$$\frac{(1.0 \text{ lbs SO}_2)}{\text{MMBtu}} = \frac{2 \times \% \text{ Fuel Sulfur}}{12,000 \text{ Btu/lb}} \times 10,000$$

(2) 
$$\% \text{ Fuel Sulfur} = \frac{1.0 (12,000)}{2 \times 10,000} = .60\%$$

f. Since coal of this low sulfur content is not available, what SO<sub>x</sub> removal efficiency would be required burning 1% sulfur coal?

(1) 
$$\text{Estimated SO}_2 \text{ emissions} = \frac{\text{lbs}}{\text{MMBtu}} \frac{2 \times 1\%}{12,000} \times 10^4 = \frac{1.67 \text{ lbs SO}_2}{\text{Mil Btu}}$$

(2) 
$$\% \text{ Removal Efficiency} = \frac{1.66 - 1.0}{1.66} = 40\%$$

TABLE 10-3

## TYPICAL ANALYSIS OF FUEL OIL TYPES

Grade of Fuel Oil	No. 1	No. 2	No. 4	No. 5	No. 6
Weight, percent					
Sulfur	0.01-0.5	0.05-1.0	0.2-2.0	0.5-3.0	0.7-3.5
Hydrogen	12.3-14.5	11.8-13.9	(10.6-13.0)	(10.5-12.0)	(86.5-90.2)
Carbon	85.9-86.7	86.1-88.2	(86.5-89.2)	(86.5-89.2)	(86.5-90.2)
Nitrogen	Nil-0.1	Nil-0.1	-	-	-
Oxygen	-	-	-	-	-
Ash	-	-	0-0.1	0-0.1	0.01-0.5
Gravity					
Deg API	40-44	28-40	15-30	14-22	7-22
Specific	0.825-0.806	0.887-0.825	0.996-0.876	0.972-0.922	1.022-0.922
Lb per gal	6.87-6.71	7.39-6.87	8.04-7.30	8.10-7.68)	8.51-7.68
Pour point, F	0 to -50	0 to -40	-10 to +50	-10 to +80	+15 to +85
Viscosity					
Centistokes at 100°F	1.4-2.2	1.9-3.0	10.5-65	65-200	260-750
SUS at 100°F	-	32-38	60-300	-	-
SSF at 122°F	-	-	-	20-40	45-300
Water and Sediment, Vol%	-	0-0.1	tr-1.0	0.05-1.0	0.05-2.0
Heating Value					
Btu, per lb, gross	19,670-19,860	19,170-19,750	18,280-19,400	18,100-19,020	17,410-18,990

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TABLE 10-4  
TYPICAL ANALYSIS OF COAL TYPES

Source	Anthracite	Bituminous	Subbituminous	Lignite
	Pennsylvania Arkansas	Pennsylvania West Virginia	Wyoming	Texas North Dakota
Moisture (as received)	4-6%	4-12%	12-20%	20-40%
Proximate Analysis (Dry Basis)				
Volatile Matter	3-12%	16-40%	40-45%	45-50%
Fixed Carbon	75-84%	50-80%	45-55%	35-45%
Ash (average)	14-15%	4- 9%	5-14%	10-12%
Sulfur	1- 2%	1- 2%	1- 4%	1- 2%
Ultimate Analysis (Dry Basis)				
Hydrogen	.5-3.5%	5%	4- 5%	4-4.5%
Carbon	75-84%	73-85%	60-73%	65%
Nitrogen	.1-.5%	1.5%	.9-1.3%	1.2-1.9%
Oxygen	1- 3%	3-13%	14-16%	15-18%
Heating Value	11,500-13,000	13,000-15,000	10,500-13,000	11,000-12,000
Agglomerating Character	non- agglomerating	Commonly agglomerating	non- agglomerating	non- agglomerating
Weathering Character	-	-	-	weathering
Relative Hardness	Hard	Granular	Sandlike	Soft and Fibrous
Method of Firing				
Traveling Grate Stoker	X	-	X	X
Spreader Stokers	-	X	X	X
Pulverized Coal Burners	X	X	X	X

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## CHAPTER 11

# NITROGEN OXIDES (NO<sub>x</sub>) CONTROL AND REDUCTION, TECHNIQUES

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### 11-1. Formation of nitrogen oxides.

*a. Nitrogen oxides (NO<sub>x</sub>).* All fossil fuel burning processes produce NO<sub>x</sub>. The principle oxides formed are nitric oxide (NO) which represents 90-95 percent (%) of the NO<sub>x</sub> formed and nitrogen dioxide (NO<sub>2</sub>) which represents most of the remaining nitrogen oxides.

*b. NO<sub>x</sub> formation.* Nitrogen oxides are formed primarily in the high temperature zone of a furnace where sufficient concentrations of nitrogen and oxygen are present. Fuel nitrogen and nitrogen contained in the combustion air both play a role in the formation of NO<sub>x</sub>. The largest percentage of NO<sub>x</sub> formed is a result of the high temperature fixation reaction of atmospheric nitrogen and oxygen in the primary combustion zone.

*c. NO<sub>x</sub> concentration.* The concentration of NO<sub>x</sub> found in stack gas is dependent upon the time, temperature, and concentration history of the combustion gas as it moves through the furnace. NO<sub>x</sub> concentration will increase with temperature, the availability of oxygen, and the time the oxygen and nitrogen simultaneously are exposed to peak flame temperatures.

### 11-Z. Factors affecting NO<sub>x</sub> emissions

*a. Furnace design and firing type.* The size and design of boiler furnaces have a major effect on NO<sub>x</sub> emissions. As furnace size and heat release rates increase, NO<sub>x</sub> emissions increase. This results from a lower furnace surface-to-volume ratio which leads to a higher furnace temperature and less rapid terminal quenching of the combustion process. Boilers generate different amounts of NO<sub>x</sub> according to the type of firing. Units employing less rapid and intense burning from incomplete mixing of fuel and combustion gases generate lower levels of NO<sub>x</sub> emissions. Tangentially fired units generate the least NO<sub>x</sub> because they operate on low levels of excess air, and because bulk misting and burning of the fuel takes place in a large portion of the furnace. Since the entire furnace acts as a burner, precise proportioning of fuel/air at each of the individual fuel admission points is not required. A large amount of internal recirculation of bulk gas, coupled with slower mixing of fuel and air, provides a combustion system which is inherently low in NO<sub>x</sub> production for all fuel types.

*b. Burner design and configuration.* Burners oper-

ating under highly turbulent and intense flame conditions produce more NO<sub>x</sub>. The more bulk mixing of fuel and air in the primary combustion zone, the more turbulence is created. Flame color is an index of flame turbulence. Yellow hazy flames have low turbulence, whereas, blue flames with good definition are considered highly turbulent.

*c. Burner number.* The number of burners and their spacing are important in NO<sub>x</sub> emission. Interaction between closely spaced burners, especially in the center of a multiple burner installation, increases flame temperature at these locations. The tighter spacing lowers the ability to radiate to cooling surfaces, and greater is the tendency toward increased NO<sub>x</sub> emissions.

*d. Excess air.* A level of excess air greatly exceeding the theoretical excess air requirement is the major cause of high NO<sub>x</sub> emissions in conventional boilers. Negotiable quantities of thermally formed NO<sub>x</sub> are generated in fluidized bed boilers.

*e. Combustion temperature.* NO<sub>x</sub> formation is dependent upon peak combustion temperature, with higher temperatures producing higher NO<sub>x</sub> emissions.

*f. Firing and quenching rates.* A high heat release rate (firing rate) is associated with higher peak temperatures and increased NO<sub>x</sub> emissions. A high rate of thermal quenching, (the efficient removal of the heat released in combustion) tends to lower peak temperatures and contribute to reduced NO<sub>x</sub> emissions.

*g. Mass transportation and mixing.* The concentration of nitrogen and oxygen in the combustion zone affects NO<sub>x</sub> formation. Any means of decreasing the concentration such as dilution by exhaust gases, slow diffusion of fuel and air, or alternate fuel-rich/fuel-lean burner operation will reduce NO<sub>x</sub> formation. These methods are also effective in reducing peak flame temperatures.

*h. Fuel type.* Fuel type affects NO<sub>x</sub> formation both through the theoretical flame temperature reached, and through the rate of radiative heat transfer. For most combustion installations, coal-fired furnaces have the highest level of NO<sub>x</sub> emissions and gas-fired installations have the lowest levels of NO<sub>x</sub> emissions.

*i. Fuel nitrogen.* The importance of chemically bound fuel nitrogen in NO<sub>x</sub> formation varies with the temperature level of the combustion processes. Fuel



nitrogen is important at low temperature combustion, but its contribution is nearly negligible as higher flame temperatures are reached, because atmospheric nitrogen contributes more to NO<sub>x</sub> formation at higher temperatures.

**11-3. NO<sub>x</sub> reduction techniques**

*a. Fuel selection.* Reduction of NO<sub>x</sub> emissions may be accomplished by changing to a fuel which decreases the combustion excess air requirements, peak flame temperatures, and nitrogen content of the fuel. These changes decrease the concentration of oxygen and nitrogen in the flame envelope and the rate of the NO<sub>x</sub> formation reaction.

- (1) The specific boiler manufacturer should be consulted to determine if a fuel conversion can be performed without adverse effects. The general NO<sub>x</sub> reduction capability of initiating a change in fuel can be seen comparatively in table 11-1.
- (2) A consideration when contemplating a change in fuel type is that NO<sub>x</sub> emission regulations are usually based on fuel type. Switching to a cleaner fuel may result in the necessity of conforming to a more strict emission standard.

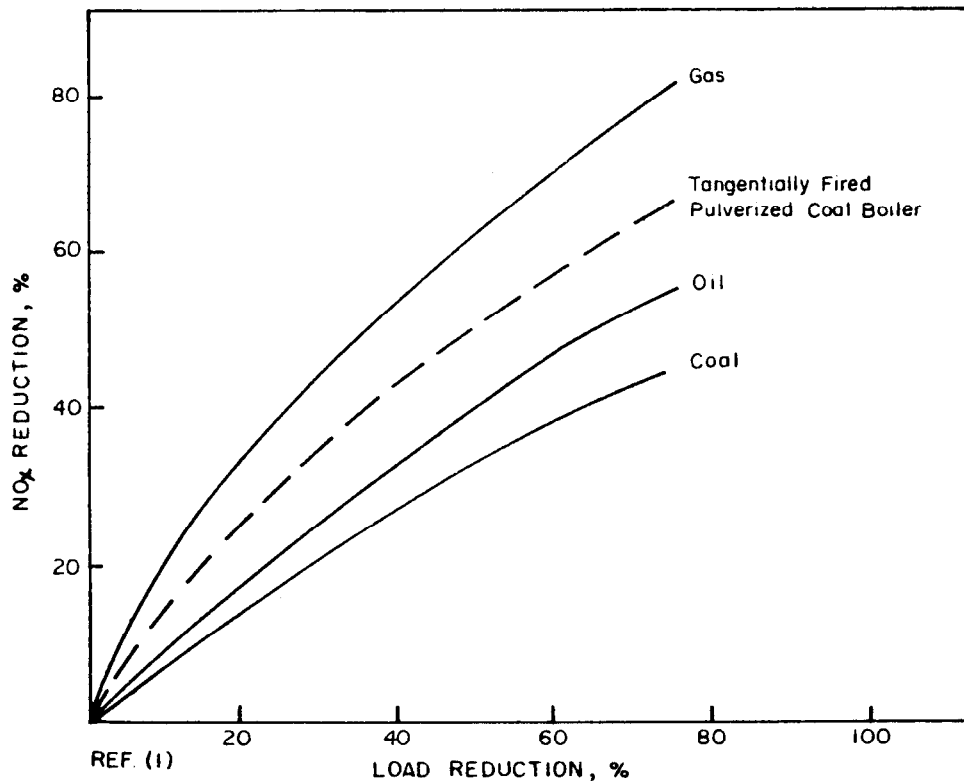
**Table 11-1**  
**General NO<sub>x</sub> emission and excess air requirements for fuel types**

Fuel Type	Range of Excess Air Level, percent above stoichiometric	NO <sub>x</sub> Emissions lbs/Mil Btu
coal	18-25	.5-1.1
(Lignite)	-	(.9-1.1)
Fuel Oil	3-15	.1- .4
Gaseous fuels	7-10	.3

- (3) Changing from a higher to a lower NO<sub>x</sub> producing fuel is not usually an economical method of reducing NO<sub>x</sub> emissions because additional fuel costs and equipment capital costs will result. For additional information on fuel substitution, see paragraph 10-3. In doing so, it should be noted that changing from coal to oil or gas firing is not in accordance with present AR 420-49.

*b. Load reduction.* Load reduction is an effective technique for reducing NO<sub>x</sub> emissions. Load reduction has the effect of decreasing the heat release rate and reducing furnace temperature. A lowering of furnace temperature decreases the rate of NO<sub>x</sub> formation.

- (1) NO<sub>x</sub> reduction by load reduction is illustrated in figure 11-1. As shown, a greater reduction



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**Figure 11-1. Possible NO<sub>x</sub> reductions vs load reductions**

in NO<sub>2</sub> is attainable burning gas fuels because they contain only a small amount of fuel-bound nitrogen. Fuel-bound nitrogen conversion does not appear to be affected by furnace temperatures, which accounts for the lower NO<sub>x</sub> reductions obtained with coal and oil firing. Some units such as tangentially fired boilers show as much as 25 percent decrease in NO<sub>x</sub> emissions with a 25 percent load reduction while burning pulverized coal.

- (2) Although no capital costs are involved in load reduction, it is sometimes undesirable to reduce load because it may reduce steam cycle efficiency.

*c. Low excess air firing (LEA).* In order to complete the combustion of a fuel, a certain amount of excess air is necessary beyond the stoichiometric requirements. The more efficient the burners are in misting, the smaller will be the excess air requirement. A minimum amount of excess air is needed in any system to limit the production of smoke or unburned combustibles; but larger amounts may be needed to maintain steam temperature to prevent refractory damage; to complete combustion when air supply between burners is unbalanced; and to compensate for instrument lag between operational changes. Practical minimums of excess air are 7 percent for natural gas, 3 to 15 percent for oil firing, and 18 to 25 percent for coal firing.

- (1) Since an increase in the amount of oxygen and nitrogen in a combustion process will increase the formation and concentration of NO<sub>x</sub>, low excess air operation is the first and most important technique that should be utilized to reduce NO<sub>x</sub> emissions. A 50 percent reduction in excess air can usually reduce NO<sub>x</sub> emissions from 15 to 40 percent, depending upon the level of excess air normally applied. Average NO<sub>x</sub> reductions corresponding to a 50 percent reduction in excess air for each of the three fuels in different boiler types are shown in table 11-2. Reductions in NO<sub>x</sub> emissions up to 62 percent have been reported on a pulverized coal fired boiler when excess air is decreased from a level of 22 percent to a level of 5 percent.

Table 11-2

Possible NO<sub>x</sub> emission reductions attainable with a 50% reduction in excess air from normal levels (greater than 10% excess air)

Furnace Type	Fuel Type		
	Gas	Oil	Coal
Horizontal front wall	15-20	20-25	25-35
Horizontal opposed firing	15-25	25-30	30-40
Tangentially fired	15	20-25	25-30

NOTE: Overall NO<sub>x</sub> reduction potential for industrial and commercial size boilers for LEA operation is limited to about 40% reduction dependent upon the level of excess air normally applied.

- (2) The successful application of LEA firing to any unit requires a combustion control system to regulate and monitor the exact proportioning of fuel and air. For pulverized coal fired boilers, this may mean the additional expense of installing uniform distribution systems for the coal and air mixture.
- (3) Low excess air firing is a desirable method of reducing NO<sub>x</sub> emission because it can also improve boiler efficiency by reducing the amount of heat lost up the stack. Consequently, a reduction in fuel combustion will sometimes accompany LEA firing.

*d. Low excess air firing with load reduction.* NO<sub>x</sub> emissions may be reduced by implementing a load reduction while operating under low excess air conditions (table 11-2). This combined technique may be desirable in an installation where NO<sub>x</sub> emissions are extremely high because of poor air distribution and the resultant inefficient operation of combustible equipment. A load reduction may permit more accurate control of the combustion equipment and allow reduction of excess air requirements to a minimum value. NO<sub>x</sub> reduction achieved by simultaneous implementation of load reduction and LEA firing is slightly less than the combined estimated NO<sub>x</sub> reduction achieved by separate implementation.

*e. Two-stage combustion.* The application of delayed fuel and air mixing in combustion boilers is referred to as two stage combustion. Two-stage combustion can be of two forms. Normally it entails operating burners fuel-rich (supplying only 90 to 95 percent of stoichiometric combustion air) at the burner throat, and admitting the additional air needed to complete combustion through ports (referred to as NO ports) located above and below the burner. There are no ports to direct streams of combustion air into the burner flame further out from the burner wall thus allowing a gradual burning of all fuel. Another form of two-stage combustion is off-stoichiometric firing. This technique involves firing some burners fuel-rich and others air-rich (high percentage of excess air), or air only, and is usually applied to boilers having three or more burner levels. Off-stoichiometric firing is accomplished by staggering the air-rich and fuel-rich burners in each of the burner levels. Various burner configuration tests have shown that it is generally more effective to operate most of the elevated burners air-rich or air only. Off-stoichiometric firing in pulverized coal fired boilers usually consists of using the upper burners on air only while operating the lower levels of burners fuel-rich. This technique is called over-fire air operation.

- (1) Two-stage combustion is effective in reducing NO<sub>x</sub> emissions because: it lowers the concentration of oxygen and nitrogen in the primary combustion zone by fuel-rich firing; it lowers the attainable peak flame temperature

by allowing for gradual combustion of all the fuel; and it reduces the amount of time the fuel and air mixture is exposed to higher temperatures.

- (2) The application of some form of two stage combustion implemented with overall low excess air operation is presently the most effective method of reducing NO<sub>x</sub> emissions in utility boilers. Average NO<sub>x</sub> reductions for this combustion modification technique in utility boilers are listed in table 11-3. However, it should be noted that this technique is not usually adaptable to small industrial boilers where only one level of burners is provided.

Table 11-3

Possible NO<sub>x</sub> reductions, percent of normal emissions

Furnace Type	Fuel Type		
	Gas	Oil	Coal
	Percent Reduction		
Two-stage combustion			
Range	40-70	20-50	20-40
Average	50	40	35
Off-stoichiometric	-	-	39-60
Two-stage combustion or off-stoichiometric with LEA or load reduction			
Range	50-90	40-70	40-60
Average	70	60	50

**f. Reduced preheat temperature.** NO<sub>x</sub> emissions are influenced by the effective peak temperature of the combustion process. Any modifications that lower peak temperature will lower NO<sub>x</sub> emissions. Lower air preheat temperature has been demonstrated to be a factor in controlling NO<sub>x</sub> emissions. However, reduced preheat temperature is not a practical approach to NO<sub>x</sub> reduction because air preheat can only be varied in a narrow range without upsetting the thermal balance of the boiler. Elimination of air preheat might be expected to increase particulate emissions when burning coal or oil. Preheated air is also a necessary part of the coal pulverizer operation on coal fired units. In view of the penalties of reduced boiler efficiency and other disadvantages, reduced preheat is not a preferred means of lowering NO<sub>x</sub> emissions.

**g. Flue-gas recirculation.** This technique is used to lower primary combustion temperature by recirculating part of the exhaust gases back into the boiler combustion air manifold. This dilution not only decreases peak combustion flame temperatures but also decreases the concentration of oxygen available for NO<sub>x</sub> formation. NO<sub>x</sub> reductions of 20 to 50 percent have been obtained on oil-fired utility boilers but as yet have not been demonstrated on coal-fired units. It is estimated that flue gas recirculation has a potential of decreasing NO<sub>x</sub> emissions by 40 percent in coal-fired units.

- (1) Flue gas recirculation has also produced a

reduction on CO concentrations from normal operation because of increased fuel-air mixing accompanying the increased combustion air/gas volume. Gas recirculation does not significantly reduce plant thermal efficiency but it can influence boiler operation. Radiation heat transfer is reduced in the furnace because of lower gas temperatures, and convective heat transfer is increased because of greater gas flow.

- (2) The extent of the applicability of this modification remains to be investigated. The quantity of gas necessary to achieve the desired effect in different installations is important and can influence the feasibility of the application. Implementing flue-gas recirculation means providing duct work and recycle fans for diverting a portion of the exhaust flue-gas back to the combustion air windbox. It also requires enlarging the windbox and adding control dampers and instrumentation to automatically vary flue-gas recirculation as required for operating conditions and loads.

**h. Steam or water injection.** Steam and water injection has been used to decrease flame temperatures and reduce NO<sub>x</sub> emissions. Water injection is preferred over steam because of its greater ability to reduce temperature. In gas and coal fired units equipped with standby oil firing with steam atomization, the atomizer offers a simple means for injection. Other installations require special equipment and a study to determine the proper point and degree of atomization. The use of water or steam injection may entail some undesirable operating conditions, such as decreased efficiency and increased corrosion: A NO<sub>x</sub> reduction rate of up to 10 percent is possible before boiler efficiency is reduced to uneconomic levels. If the use of water injection requires installation of an injection pump and attendant piping, it is usually not a cost-effective means of reducing NO<sub>x</sub> emissions.

#### 11-4. Post combustion systems for NO<sub>x</sub> reduction.

**a. Selective catalytic reduction (SCR) of NO<sub>x</sub>** is based on the preference of ammonia to react with NO, rather than with other flue-gas constituents. Ammonia is injected so that it will mix with flue-gas between the economizer and the air heater. Reaction then occurs as this mix passes through a catalyst bed. Problems requiring resolution include impact of ammonia on downstream equipment, catalyst life, flue-gas monitoring, ammonia availability, and spent-catalyst disposal.

**b. Selective noncatalytic reduction (SNR)** Ammonia is injected into the flue-gas duct where the temperature favors the reaction of ammonia with NO<sub>x</sub> in the flue-gas. The narrow temperature band which favors the

reaction and the difficulty of controlling the temperature are the main drawbacks of this method.

c. Copper oxide is used as the acceptor for SO<sub>2</sub> removal, forming copper sulfate. Subsequently both the copper sulfate which was formed and the copper oxide catalyze the reduction of NO to nitrogen and water by reaction with ammonia. A regeneration step produces an SO<sub>2</sub>-rich steam which can be used to manufacture by-products such as sulfuric acid.

### 11-5. Step-by-step NO<sub>x</sub> reduction method

a. *Applicability.* The application of NO<sub>x</sub> reduction techniques in stationary combustion boilers is not extensive. (However, NO<sub>x</sub> reduction techniques have been extensively applied on automobiles.) These techniques have been confined to large industrial and utility boilers where they can be more easily implemented where NO<sub>x</sub> emissions standards apply, and where equipment modifications are more economically justified. However, some form of NO<sub>x</sub> control is available for all fuel-burning boilers without sacrificing unit output or operating efficiency. Such controls may become more widespread as emission regulations are broadened to include all fuel-burning boilers.

b. *Implementation.* The ability to implement a particular combustion modification technique is dependent upon furnace design, size, and the degree of equipment operational control. In many cases, the cost of conversion to implement a modification such as flue-gas recirculation may not be economically justified. Therefore, the practical and economic aspects of boiler design and operational modifications must be ascertained before implementing a specific reduction technique.

- (1) Temperature reduction through the use of two-stage combustion and flue-gas recirculation is most applicable to high heat release boilers with a multiplicity of burners such as utility and large industrial boilers.
- (2) Low excess air operation (LEA) coupled with flue-gas recirculation offers the most viable solution in smaller industrial and commercial size boilers. These units are normally designed for lower heat rates (furnace temperature) and generally operate on high levels of excess air (30 to 60%).

c. *Compliance.* When it has been ascertained that NO<sub>x</sub> emissions must be reduced in order to comply with state and federal codes, a specific program should be designed to achieve the results desired. The program direction should include:

- an estimate of the NO<sub>x</sub> reduction desired,
- selection of the technique or combination thereof, which will achieve this reduction;
- an economic evaluation of implementing each technique, including equipment costs, and changes in operational costs;
- required design changes to equipment

-the effects of each technique upon boiler performance and operational safety.

d. *Procedure.* A technical program for implementing a NO<sub>x</sub> reduction program should proceed with the aid of equipment manufacturers and personnel who have had experience in implementing each of the NO<sub>x</sub> reduction techniques that may be required in the following manner:

- (1) *NO<sub>x</sub> emission test.* A NO<sub>x</sub> emission test should be performed during normal boiler load times to ascertain actual on-site NO<sub>x</sub> generation. This test should include recording of normal boiler parameters such as: flame temperature; excess air; boiler loads; flue-gas temperatures; and firing rate. These parameters can be referred to as normal operating parameters during subsequent changes in operation.
- (2) *Reduction capabilities.* The desired reduction in NO<sub>x</sub> emissions, in order to comply with standards, should be estimated based on measured NO<sub>x</sub> emission data. Specific NO<sub>x</sub> reduction techniques can then be selected based on desired reductions and reduction capabilities outlined in preceding paragraph 11-3.
- (3) *Equipment optimization.* Any realistic program for NO<sub>x</sub> reduction should begin with an evaluation and overhaul of all combustion related equipment. A general improvement of boiler thermal efficiency and combustion efficiency will reduce the normal level of NO<sub>x</sub> emissions. Of major importance are:
  - (a) the cleanliness of all heat transfer surfaces (especially those exposed to radiative heat absorption),
  - (b) maintaining proper fuel preparation (sizing, temperature, viscosity),
  - (c) insuring control and proper operation of combustion equipment (burners nozzles, air registers, fans, preheaters, etc.),
  - (d) maintaining equal distribution of fuel and air to all burners.
- (4) *Low excess air operation.* Low excess air operation is the most recommended modification for reducing NO<sub>x</sub> emission. Possible reductions are given in preceding table 11-2. However, a control system is needed to accurately monitor and correct air and fuel flow in response to steam demands. Of the control systems available, a system incorporating fuel and air metering with stack gas O<sub>2</sub> correction will provide the most accurate control. A system of this nature will generally pay for itself in fuel savings over a 2 to 3-year period, and is economically justified on industrial boilers rated as low as 40,000 lb of steam/hr.
- (5) *Flue-gas recirculation.* Flue-gas recirculation is the second most effective NO<sub>x</sub> reduction

technique for boilers where two stage combustion cannot be applied. Low excess air operation and flue-gas recirculation must be implemented simultaneously from a design point of view. LEA operation may require installation or retrofitting of air registers to maintain proper combustion air speed and mixing at reduced levels or air flow. Flue gas recirculation will require larger air registers to accommodate the increased volume of flow. Therefore, simultaneous application of LEA operation and flue-gas recirculation may mini-

mize the need for redesign of burner air registers. Knowledge of furnace thermal design must accompany any application of flue-gas recirculation which effectively lowers furnace temperature and thus, radiative heat transfer. Convective heat transfer is also increased by increased gas flow due to the dilution of combustion air. It is advisable to consult boiler manufacturers as to the applicability of flue-gas recirculation to their furnaces.

e. *Summary.* The potential and applicability of each  $\text{NO}_x$  reduction technique is summarized in table 11-4.

**TABLE 11-4**

**COMPARISON OF NO<sub>x</sub> REDUCTION TECHNIQUES**

<b>Technique</b>	<b>Potential NO<sub>x</sub> Reduction (%)</b>	<b>Advantages</b>	<b>Disadvantages</b>
<b>Load Reduction</b>	See Figure 11-1	Easily implemented; no additional equipment required; reduced particulate and SO <sub>x</sub> emissions.	Reduction in generating capacity; possible reduction in boiler thermal efficiency.
<b>Low Excess Air Firing (LEA)</b>	15 to 40 see Table 11-2	Increased boiler thermal efficiency; possible reduction in particulate emissions may be combined with a load reduction to obtain additional NO <sub>x</sub> emission decrease; reduction in high temperature corrosion and ash deposition.	A combustion control system which closely monitors and controls fuel/air ratios is required.
<b>Two Stage Combustion</b>			
Coal	30	-	Boiler windboxes must be designed for this application.  Furnace corrosion and particulate emissions may increase.
Oil	40	-	
Gas	50	-	
<b>Off-Stoichiometric Combustion</b>			
Coal	45	-	Control of alternate fuel rich/and fuel lean burners may be a problem during transient load conditions.
<b>Reduced Combustion Air Preheat</b>	10-50	-	Not applicable to coal or oil fired units; reduction in boiler thermal efficiency; increase in exit gas volume and temperature; reduction in boiler load.
<b>Flue Gas Recirculation</b>	20-50	Possible improvement in combustion efficiency and reduction in particulate emissions.	Boiler windbox must be modified to handle the additional gas volume; ductwork, fans and controls required.

## CHAPTER 12

## EMISSION CONTROL EQUIPMENT SELECTION FOR INCINERATORS AND BOILERS

**12-1. Principles of selection**

a. Selection of emission control equipment is made in three basic steps.

- (1) *Performance.* The control equipment must be capable of continuously controlling the emission of the pollutant below the permitted quantities. The equipment type and design should have a proven record of meeting the required removal or collection efficiency and the manufacturer should guarantee the equipment for continuous performance.
- (2) *Construction.* The materials of construction should be compatible with the characteristics and constituents in the flue gases. Materials should be resistant to erosion and corrosion and should be suitable for the operating temperatures. The unit should have adequate access manholes and service platforms and stairs to inspect and maintain the equipment. Units should be adequately insulated and weather protected.
- (3) *Operation.* Where more than one design or type of device can provide the necessary pollution control it then becomes necessary to evaluate the various designs based on a life-cycle cost-analysis, and the ease of operation.

b. Preliminary information which is needed to properly select pollution control equipment are as follows:

- (1) Site-specific emissions limitations for the stack serving the particular boiler or incinerator must be determined for the applicable source and ambient condition. This information is to be derived from existing federal, state and local regulations.
- (2) Obtain detailed descriptions of the boiler or incinerator including the combustion control system(s) and all support auxiliaries including outline drawings available from the manufacturers; and the predicted uncontrolled, gaseous emissions established for the units.
- (3) For the particular fuel to be burned, determine the method of firing and maximum continuous rated heat input per British Thermal Units per hour (BTU's/Hr) along with applicable combustion calculations for normal and upset operating conditions. This may require a fuel

analysis. In the case of coal firing the analysis should include ultimate and proximate properties and an analysis of the residual ash.

- (4) Obtain required construction and operations permit forms from applicable regulatory agencies, complete, and submit where required.
- (5) Obtain the requirements and restraints for disposing of the collected pollutant. Under some circumstances such as preliminary studies it becomes necessary to calculate the process data and then use empirical data to estimate the emission quantities.

c. The U.S. Environmental Protection Agency (EPA) has published a Technical Manual "AP-42" and excerpts from the EPA publication have been reproduced and included in Chapters 2 and 3 of this manual to be used as a guide for predicting the emissions that will be generated by various fuels and combustions apparatus.

d. Present emissions control requirements and laws are complicated and stringent, and emission control equipment represents a significant portion of the combustion equipment costs. Inadequately specified or applied control devices could be a very costly error. It is advisable wherever possible to utilize qualified engineers experienced in boiler or incinerator plant designs and operation of such tasks. It is beneficial for the engineer to also have experience in securing necessary permits.

**12-2. Flue gas properties**

a. Gas properties influence the design and performance of the pollution control equipment. When working with a particular emission standard or code the gas properties must be converted to the units used in the codes, such as lbs per million BTU; gr/ACFM; DSCFM at 32; DSCFM at 68; DSCFM corrected to 8 percent O<sub>2</sub>.

b. *Flow rate.* The flow-rate of exhaust gases generated in the combustion process must be measured or calculated to determine the required volumetric size of the collection equipment. Flow-rate variations result in velocity changes and thus influence collector efficiency and pressure drop. It is necessary therefore to obtain maximum, average, and minimum values for a cyclical or modulating operation.

c. *Temperature.* Gas temperature affects gas volume

(and simultaneously collector volume) and materials of construction for the collector. Temperature may also limit use of certain collectors. For instance, temperatures above 550 degree Fahrenheit rule out the use of fabric filters.

*d. Pressure.* Carrier gas pressure must be known or calculated to determine the structural requirements for the collector under operating and upset conditions.

*e. Viscosity.* Gas viscosity is a measure of molecular activity in a gas stream. The greater the gas viscosity, the greater the resistance to particle migration across the stream normal to gas flow. Since gas viscosity increases with gas temperature, it is an important factor in the performance of dry particulate collection devices. Viscosity effects can be minimized if equipment is properly specified.

*f. Moisture content.* Moisture content affects the performance of collection equipment and the choice of construction materials. It is important to know the dew point of the exhaust gas, as temperatures below dew point allows acid vapors to condense and attack structural surfaces. This is a particular concern with boiler flue-gas which often contains a significant amount of sulfuric acid vapor.

*g. Chemical composition.* Chemical composition primarily affects the choice of construction materials for a collector. Collectors must be suitably protected to handle corrosive gases.

*h. Toxicity.* Handling of toxic gases requires special treatment and equipment and must be reviewed on an individual basis. This manual does not address incineration of toxic or hazardous wastes.

### 12-3. Particulate properties

*a.* Particulate properties that must be determined for control equipment selection and design are described below. Appropriate test methods are listed in table 5-1.

*b. Concentration (loading).* Particulate loading is a measurement of particulate concentration in flue gases (see this manual, chapters 2 and 3) expressed in grains per cubic foot. Particulate loading is used as a criteria to design and select applicable collection equipment. Fluctuations in loading (for example: soot blowing in boilers) must be noted and maximum, minimum, and average values should be recorded. High grain loadings may require a series system of control devices to meet particulate emissions and air quality standards. For instance, a cyclone followed by an electrostatic precipitator or baghouse.

*c. Particle size.* The particle size analysis affects the collection efficiency for each control device. Fine particulate collection requires high-efficiency equipment such as venturi scrubbers, electrostatic precipitators, or fabric filters.

*d. Resistivity.* Particulate resistivity is a limiting factor in the design of electrostatic precipitators.

Resistivity must be determined if an electrostatic precipitator is to be selected to control particulate emissions. As a general guideline, resistivity above  $10^{10}$  ohm-cm normally rules out the use of electrostatic precipitation unless provisions are made for particulate electrical conditioning.

*e. Handling characteristics.* Particle-handling characteristics influence dust-handling systems (ductwork, collector structure, hoppers, conveyors) and materials of construction. Dust-handling characteristics include flow properties, abrasiveness, hygroscopicity, moisture content, agglomerating tendencies. These properties, including specific gravity and bulk density should be evaluated in the design of a dust-collecting system.

*f. Chemical composition.* Chemical composition of particulate affects materials of construction and design of the collector and ash disposal equipment as does carrier gas composition.

### 12-4. Application of emission control systems for boilers.

As a result of current, stringent, stack emission regulations, applications of certain conventional emissions control systems have evolved that provide satisfactory performance when properly sized and specified. Referenced are CFR40 part 60 for new source performance standards (NSPS) only, as ambient regulations have wide variation from site-to-site requiring investigation for each location. Following is a brief description of the most common combustion sources, fuels, and control devices employed:

*a. Natural gas fired power boiler.* NSPS cover particulates; sulfur dioxide  $SO_2$ ; nitrogen dioxide  $NO_2$ ; and opacity.

- (1) External devices are not usually required. Properly adjusted combustion controls, burner(s), furnace designs, and gas monitoring are sufficient to meet the performance standards.
- (2) Even though natural gas is a relatively clean fuel, some emissions can occur from the combustion reaction. For example, improper operating conditions, including items such as poor mixing and insufficient air, may cause large amounts of smoke, carbon monoxide, and hydrocarbons to be produced. Moreover, because a sulfur-containing mercaptan is added to natural gas for detection purposes, small amounts of sulfur oxides will also be produced in the combustion process.
- (3) Nitrogen oxides are the major pollutants of concern when burning natural gas. Nitrogen dioxide emissions are a function of the temperature in the combustion chamber and the rate of cooling of the combustion products. Emission levels generally vary considerably



with the type and size of unit and are also a function of loading.

- (4) In some large boilers, several operating modifications have been employed for  $\text{NO}_x$  control. In staged combustion, for example, including off-stoichiometric firing, also called "biased firing," some burners are operated fuel-rich, some fuel-lean, while others may supply air only. In two-staged combustion, the burners are operated fuel-rich (by introducing only 80 to 95 percent stoichiometric air) with combustion being completed by air injected above the flame zone through second-stage " $\text{NO}_x$ -ports". In staged combustion,  $\text{NO}_x$  emissions are reduced because the bulk of combustion occurs under fuel-rich, reducing conditions.

*b. Distillate oil fired power boilers.* NSPS cover particulates;  $\text{SO}_2$ ;  $\text{NO}_x$ ; and opacity. Methods of modifying or controlling emissions are discussed in the following.

- (1) *Particulate.* The user should note that in most cases external pollution control devices are not required for boilers firing No. 1 or No. 2 fuel oils.
- (2)  *$\text{SO}_2$ .* Most distillates will contain sulfur quantities low enough so that no treatment will be necessary. However, a fuel analysis must be reviewed as some distillates can have as much as one percent sulfur. When the sulfur content produces  $\text{SO}_2$  emissions in excess of the allowable a wet scrubbing system will be required.
- (3)  *$\text{NO}_x$ .* Control requires the proper combustion controls, and burners and furnaces designed to limit  $\text{NO}_x$  generation from high combustion temperatures. Usually  $\text{NO}_x$  reductions are accomplished by limiting excess air firing and staged combustion. Large utility system units sometimes also employ flue-gas recirculation in addition to the other methods.
- (4) *Opacity.* This may be controlled by proper air-fuel ratios; good combustion controls; limiting particulate emissions; and proper engineering design of the burners and furnace chamber.

*c. Residual oil fired power boilers.* NSPS cover particulates;  $\text{SO}_2$ ;  $\text{NO}_x$ ; and opacity. Methods of modifying or controlling emissions are discussed in the following.

- (1) *Particulate control.*
  - (a) When using low-sulfur oils, cyclonic mechanical collectors are usually adequate. On larger utility size units electrostatic precipitators are employed to limit particulate emissions.
  - (b) For emissions from combustion of high-sulfur oils a wet scrubbing system can be used for both  $\text{SO}_2$  removal and particulate control.
- (2)  *$\text{SO}_2$ .* Use wet scrubbing system with a low pressure drop.

- (3)  *$\text{NO}_x$ .* May be controlled by utilizing limited excess-air firing; flue gas recirculation; staged combustion; or combinations of these.
- (4) *Opacity.* May be controlled by limiting or collecting the particulates and by properly adjusted and designed combustion controls with good burner and furnace designs.

*d. Pulverized coal-fired power boiler.* NSPS cover limitations for particulates;  $\text{SO}_2$ ;  $\text{NO}_x$ ; and opacity. Methods of modifying or controlling emissions are discussed in the following.

- (1) *Particulates.*
  - (a) Control by use of electrostatic precipitator
  - (b) Control by use of fabric filters
  - (c) Control by use of venturi scrubber
  - (d) Control by combination of a mechanical collector followed by either (a), (b), or (c), above
- (2)  *$\text{SO}_2$ .*
  - (a) Use suitable wet scrubber (can double for both  $\text{SO}_2$  and particulates)
  - (b) Use suitable dry scrubber followed by fabric filters or electrostatic precipitator
  - (c) Selection of a wet or dry scrubbing system is determined by evaluating the economics (installation and operating costs) and the disposal of the collected pollutant.
- (3)  *$\text{NO}_x$ .* Ensure that the burner and furnace are designed for limited excess-air firing and staged combustion. In some cases it may be necessary to have a second stage air fan designated as an  $\text{NO}_x$  control fan in order to gain compliance.
- (4) *Opacity.* This may be controlled by particulate removal and properly adjusted combustion controls. In some cases this could be the more stringent requirement for particulate removal.

*e. Spreader and muss feed stoker coal fired boilers with a traveling grate.* NSPS cover limitations for particulates;  $\text{SO}_2$ ;  $\text{NO}_x$ ; and opacity. Methods of modifying or controlling emissions are discussed in the following.

- (1) *Particulates.*
  - (a) Control by use of electrostatic precipitator
  - (b) Control by use of suitable fabric filter
  - (c) Control by use of suitable wet scrubber
  - (d) Control by a combination of a mechanical collector followed by either (a), (b), or (c) above
- (2)  *$\text{SO}_2$ .*
  - (a) Use suitable wet scrubber (can double for both  $\text{SO}_2$  and particulate).
  - (b) Use suitable dry scrubber followed by either a fabric filter or an electrostatic precipitator
- (3)  *$\text{NO}_x$ .* Control by specifying furnace and combustion air controls designed to maintain lim-

ited flame temperatures under operating conditions.

- (4) *Opacity*. Control by particulate removal and properly adjusted combustion controls. This can be the more stringent requirement for particulate removal.

*f. Wood waste and bark fired boilers.* NSPS cover limitation for particulates and opacity. Methods of modifying or controlling emissions are discussed in the following.

- (1) *Particulates*.
  - (a) Control by use of a mechanical collector followed by either a scrubber or an electrostatic precipitator.
  - (b) Control by use of wet scrubber.
  - (c) Control by use of electrostatic precipitator.
  - (d) Control by use of gravel bed filter.
- (2) *Opacity*. Opacity is controlled by particulate collection and properly adjusted combustion controls. The "as-fired" condition of wood waste fuel will impact the choice of particulate control equipment.
  - (a) Hogged bark and wood chips with 45% to 55% moisture usually require a mechanical collector followed by a scrubber or an ESP. Material collected in the mechanical collector is a combination of char, ash, and sand. The material is classified to separate the char from the ash/sand mixture so the char can be reinjected into the furnace combustion zone. The ash/sand mixture is discharged by gravity or conveyor to a holding tank which can be either wet or dry. All ash-hopper discharge openings must be protected from air infiltration by rotary-seal discharge valves or an air-lock damper arrangement, to prevent ignition of hot combustibles.
  - (b) Dry wood wastes that are chipped to less than 1" x 1/2" size may not require the mechanical collector and reinjection equipment. Gas clean-up equipment of choice may then be either the scrubber or electrostatic precipitator. Ash discharge hoppers need to be protected by seal valves or air locks in all cases.
  - (c) Fabric filters are avoided because of the potential for burning the fabric with hot char carry over.
  - (d) Ash-handling is usually accomplished using a hydraulic conveying system discharging to an ash settling pond.
  - (e) Screw conveyors or drag-chain conveyors are acceptable alternatives for dry handling of ash from wood-fired boilers when ponding is not viable. The dry ash should be

cooled and conditioned with water before being transported for land fill disposal.

*g. Coal fired fluidized bed boilers.* NSPS cover limitation for particulates; SO<sub>2</sub>; NO<sub>x</sub>; and opacity. Methods of modifying or controlling emissions are discussed in the following.

- (1) *Particulates*. Control by use of fabric filter or an electrostatic precipitator. Most units will not require a mechanical collector in series with the baghouse or electrostatic precipitator. However, if high dust loadings are anticipated an in-line mechanical collector in series with the baghouse or electrostatic precipitator may be justified.
- (2) *SO<sub>2</sub>*. Controlled by the metering (feeding) of lime stone into the fluidized fuel bed.
- (3) *NO<sub>x</sub>*. The comparatively low furnace temperatures experienced in fluidized bed boilers limits the heat generated NO<sub>x</sub> formation. No special devices or controls are required for NO<sub>x</sub> control on fluidized bed units.
- (4) *Opacity*. Controlled by particulate removal and properly adjusted and designed combustion controls.
- (5) *Ash handling and removal systems*. Can be dry or wet and may be automated cycles or continuous ash removal utilizing equipment and methods previously discussed.

#### 12-5. Municipal solid waste-fired boilers (MSW) and boilers using refuse derived fuels (RDF)

*a.* Municipal solid waste fired boilers fall in the same emission regulation category as an incinerator. Compliance is only required for particulate emission regulations.

*b.* Boilers using refuse derived fuels must meet the incinerator regulations and are also required to meet emission standards for any other fuels fired in the boiler. In most states the allowable emissions are calculated on the ratio of fuels fired and which cover control of particulate, SO<sub>2</sub>, NO<sub>x</sub>, and opacity.

- (1) *Particulates* Use mechanical collectors as a primary device followed by either a fabric filter or an electrostatic precipitator. The ESP is favored when there is co-firing with coal in the MSW boiler. Without coal co-firing, resistivity of the particulate can be extremely high. Wet scrubbers should be avoided because of possible odor pick up.
- (2) *SO<sub>2</sub>*. SO<sub>2</sub> formation is a function of the sulfur content in the refuse and fuel. In most cases no SO<sub>2</sub> removal devices are necessary. However, when required a dry scrubber system followed by either a baghouse or an electrostatic precipitator is preferred.

- (3)  $NO_x$ . Furnace design and firing methods are used to limit  $NO_x$ . Two-step combustion is employed. The primary zone is fired with limited air to maintain a reducing atmosphere and the secondary zone uses an oxidizing atmosphere to provide a controlled low-temperature flame with minimum excess air.
- (4) *Opacity*. Opacity is controlled by limiting particulate emissions and by properly designed combustion controls.

## 12-6. Applications of emission control systems for incinerators

Refuse incinerators are type categorized as: municipal; industrial; commercial; and sludge. NSPS cover particulate emissions only. However, incineration of many solid, liquid, and gaseous wastes will produce noxious gases that require special treatment.

*a. Municipal incinerators.* Optimum control of incinerator particulate emissions begins with proper furnace design and careful operation. A proper design includes: a furnace/grate system appropriate to the waste; an adequate combustion gas retention time and velocity in the secondary combustion chamber; a suitable underfire and overfire air system; and establishing the optimum underfire/overfire air ratios.

- (1) for compliance with NSPS it is necessary to utilize gas cleaning equipment and to optimize operating conditions for the furnace.
- (2) Particulates. May be controlled with mechanical collectors; settling chambers; after burners; and low efficiency scrubbers used as precleaners. These must be followed by an electrostatic precipitator or a high efficiency venturi/orifice scrubber for final cleaning. Fabric filters may be used if emissions gas temperature is maintained below the maximum temperature rating of fabric media being used. This will usually require water spray injection for evaporative cooling of the gas stream.
- (3) Odor control is frequently required and can be accomplished with after-burners strategically located in the furnace to oxidize the odorous gases.

*b. Industrial and commercial incinerators.* Design of the incinerators and emissions control requirements are greatly influenced by the composition of the solid waste that is incinerated.

- (1) Single chamber and conical (Teepee) type incinerators will not meet current NSPS emission requirements.
- (2) Multiple chamber incinerators with controlled-combustion features, and fluidized-bed incinerators including sludge incinerators may be equipped with one or more of the previously discussed or following gas-cleaning systems to meet NSPS.

- (3) When particulates are the controlled pollutant, primary collection devices commonly used are: after-burners; mechanical collectors; wetted baffles; and spray chambers.
- (4) The final collection of small particulate material is usually accomplished with one of the following devices:
  - venturi or orifice-type scrubber
  - electrostatic precipitator
  - fabric filter.

*c. Incinerator vapor and odor control.* Objectionable vapors and odors in incinerator exhaust streams sometimes necessitate specialized control systems. Odorous components present downstream of conventional cleaning systems are usually organic in gaseous or *fine* particulate form. Several methods available for their control are discussed below.

- (1) *Afterburners.* Direct thermal incineration can be utilized to oxidize odorous fumes. A fume incineration system, or afterburner, basically consists of a gas or oil-fired burner mounted to a refractor-lined steel shell. Odorous vapors and particulate matter are exposed to a high temperature flame (1200 to 1400 degrees Fahrenheit) and are oxidized into water vapor and carbon dioxide. The principal advantages of direct thermal incineration of odorous pollutants are simplicity, consistent performance, easy modification to accommodate changes in standards, and ease of retrofit. The major disadvantage is the uncertainty and expense of fuel supply usually natural gas.
- (2) *Vapor condenser.* Vapor condensers are utilized to control obnoxious odors, particularly in processes where the exhaust gases contain large quantities of moisture. Condensers can be either the direct contact type, or shell and tube surface condensers. The resulting condensate is rich in odorous material and can be sewerred or treated and disposed of by other conventional methods. (See paragraph 7-4 for further information on treatment and disposal of waste materials.) Condensers are often used in conjunction with an afterburner. In such a system, exhaust gases are condensed to ambient temperature before incineration, reducing gas stream volume by as much as 95 percent and reducing moisture content. Lowering gas volume and moisture content can substantially reduce the cost and fuel requirements of the afterburner assembly.
- (3) *Catalytic oxidation.* Incineration of odorous pollutants in the presence of a suitable catalyst can lower the temperature required for complete combustion and reduce the overall reaction time. Advantages of catalytic oxidation are:

- Smaller units required because lower gas temperatures reduce gas volume,
- Less oxygen required in the effluent stream since catalyst promotes efficient use of oxygen,
- Lower NO<sub>x</sub> emissions due to lower flame temperatures and reduced oxygen loads.

(4) *The principle disadvantages are:*

- High initial capital equipment costs
  - Periodic replacement of expensive catalysts
- (5) *Absorbers.* Absorption systems for odor control involve the use of selected liquid absorbents to remove odorous molecules from effluent gases. The gas to be absorbed should have a high solubility in the chosen absorbent or should react with the absorbing liquid. Various methods are used to affect intimate contact of liquid absorbent and gaseous pollutant.

## 12-7. Technical evaluation of control equipment

a. Given the site-specific ambient air quality requirements, and the NSPS emissions limitations, and then comparing them with the uncontrolled emissions data for the combustor, it becomes possible to make a selection of various emissions controls systems to meet the emission restraints. Required is a knowledge of the various emissions control devices and their application to specific problems including their sizing and operation.

b. Other factors which must be evaluated in selecting control equipment include: site compatibility; disposition of the collected pollutant; installation and operation costs; maintainability; and the ability to provide continuous protection during operation of the combustion units. Tables 12-1 and 12-2 offer a comparison of these characteristics to serve as an aid in the final determination of the best control system for a particular application.

c. Specific operating characteristics that should be compared in evaluating suitable collection equipment are listed below. Each control device section of this manual should be consulted for specific descriptions of various control equipment.

- (1) *Temperature and nature of gas and particles.* Collection equipment must be compatible with operating temperatures and chemical composition of gas and particles.
- (2) *Collector pressure loss.* The power requirement for gas-moving fans can be a major cost in air pollution control.
- (3) *Power requirement.* Electrostatic precipitators, scrubbers, and fabric filters have additional electrical requirements beside fan power.
- (4) *Space requirement.* Some control equipment requires more space than others. This factor

may, in certain cases, preclude the use of otherwise satisfactory equipment.

- (5) *Refuse disposal needs.* Methods of removal and disposal of collected materials will vary with the material, plant process, quantity involved, and collector design (chap 6, 7, and 9). Collectors can be unloaded continuously, or in batches. Wet collectors can require additional water treatment equipment and if the pollution control device uses water directly or indirectly, the supply and disposal of used water must be provided for.

## 12-8. Tradeoffs and special considerations

a. *Design considerations.* In order to design equipment to meet air pollution control requirements, the top output or maximum ratings should be used in the selection of control equipment. The additional cost for extra capacity is negligible on the first cost basis, but a later date addition could cost a substantial sum. It should also be noted whether the dust-generating process is continuous or cyclic, since an average dust concentration design may not satisfy high emissions at start-up or shut-down. Cyclic operation could also lead to problems in terms of equipment performance relative to high or low temperatures and volumes. Ductwork providing good gas distribution arrangements for a specific volume could cause significant problems if the gas volume were to increase or decrease.

b. *Reliability of equipment.* Since particulate control equipment is relatively expensive, and due to the fact that it is usually an integral part of the power generation process, it is of utmost importance that the equipment provide reliable service. Wrong choices of fabric for fabric filters; wrong materials of construction for wet scrubbers; the wrong choice of a multicyclone to achieve high efficiency on fine particles; can all lead to collector outages, or complete failure. Collector failures may be accompanied by a loss of production or by expensive replacement with new devices. Evaluation trade-offs should be made between costs for an auxiliary control unit and the cost of shutting down the entire process due to collector failure.

c. *Space allowance.* Special consideration by the design engineer must be given to provide space in the planned plant layout for adding more pollution control equipment in the future. Future plant modifications will in most cases have to meet more stringent standards than the existing NSPS.

d. *Gas cooling.* When high temperature (greater than 450 degrees Fahrenheit) exhaust gasses are being handled, a study should be made on the cost of installing equipment to operate at the elevated temperature versus the cost and effects of gas cooling.

e. *Series operation of collectors.* Dust collectors may be used in series operation for the following reasons:

- (1) A primary dust collector acts as a precleaner to

TABLE 12-1

RANGE OF COLLECTION EFFICIENCIES FOR COMMON TYPES  
OF PARTICULATE CONTROL EQUIPMENT

TYPE OF FURNACE	RANGE OF COLLECTION EFFICIENCIES - PERCENT							
	FABRIC FILTER	ELECTRO-STATIC PRECIPITATOR	WET SCRUBBER (VENTURI)	MECHANICAL COLLECTOR (MULTI-CLONE)	LARGE DIA-METER CYCLONE	SETTLING CHAMBER	SETTLING CHAMBER WITH WATER SPRAY	GRAVEL BED FOLLOWING A MECH. COLLECTOR
<b>COAL</b>								
Cyclone	95 - 99.7	65 - 99.5	65 - 99	30 - 40	20 - 30	10	NA	97-99
Pulverizers	- 99.7	80 - 99.5	80 - 99	65 - 75	40 - 60	20	NA	97-99
Spreader Stoker	- 99.7	- 99.7	- 99	80 - 85	70 - 80	20-30	NA	97-99
Other Stoker	- 99.7	- 99.5	- 99	80 - 85	75 - 85	25-50	NA	97-99
Fluidized Bed Bubbling	- 99.7	- 99.5	- 99	80 - 85	75 - 85	25-50	NA	97-99
Fluidized Bed Circulating	- 99.7	- 99.5	- 99	80 - 85	75 - 85	25-50	NA	97-99
<b>WOOD WASTE</b>								
Spreader Stoker		- 99.5	- 99	70 - 85	65 - 75	20-30	NA	97-99
Suspension Firing		- 99.5	- 99	60 - 80	40 - 60	20-30	NA	97-99
Municipal Incinerator	97 - 99.7	93 - 99.0	80 - 99	30 - 80	NA	30	30 - 60	97-99
Municipal Solid Waste Fired Boilers	- 99.7	- 99.5	80 - 99	30 - 80	NA	NA	NA	97-99

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TABLE 12-2  
COMPARISON OF SOME DUST COLLECTOR CHARACTERISTICS

TYPE	COLLECTOR EFFICIENCY	POWER USED kW 1,000 cfm	RE-LATIVE COSTS	ADVANTAGES	DISADVANTAGES	RECOMMENDED APPLICATIONS	GENERAL CONDITIONS
Electrostatic Precipitator	99 + % including sub-micron size	2-3	2-6	High collecting efficiency for fine particles. Very versatile, collects wide variety of matter; wet or dry collection; low pressure loss and power requirement; can be used with a dry scrubber for SO <sub>2</sub> reduction. Can be used in high temperature (1500°F) application with favorable conditions. Medium to low operating costs.	High initial cost; sensitivity to variable dust loading and gas flow rates. Performance depends on the resensitvity of the particulate. Emission electrodes emit sparks thus precipitator not suitable for use combustible material	Coal and wood waste fired boilers; cement and lime kilns; large utility oil fired boilers; municipal solid waste fired boilers.	Low sulfur coals (including western coal) will require "hot" position precipitators or larger capacity units.
Fabric Filter	99 + %	.5-3	3-5	High collecting efficiency for fine particles. Fly-ash collection not affected by sulfur content of coal. Can be used with a dry scrubber for SO <sub>2</sub> reduction. Low to medium operating costs.	Fabric bags susceptible to chemical attack. Fabric materials limit the temperature and limit useful life of the fabric bags.	Coal fired boilers; municipal solid waste fired boilers; incinerators that have controlled C <sub>2</sub> A <sub>3</sub> temperature.	Care must be taken to protect the filter cloth from overheating, moisture, acid vapors, and mechanical stress.
Wet Scrubbers 1) Venturi 2) Dynamic	99%	4-12	1-3	Low initial cost; simultaneous gas absorption and particle removal possible; eliminates fire hazards from char and hot ash carry over.	Corrosion, erosion, scale build up problems. Disposal costs of waste water. Vapor plume. High operating costs.	Wood waste and combination wood and other fuel boilers. Coal and oil fired boilers SO <sub>2</sub> reductions and particulate control.	Scaling sensitive to water quality. Poor down stream separation can cause stack raining.
Mechanical Collectors 1) Multiclone 2) Cyclone	85% 30-40	3-6 1-2	.3-.5 .1-.3	Low initial cost; simple operation; low to moderate pressure losses.	Low collection efficiency of fine particles; erosion problems.	Precleaner to more efficient device. Used on boiler where char reinjection is employed.	High Brinell hardness collecting tubes recommended on abrasive ash. Leave space for additional cyclones in the future

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prevent plugging, reduce abrasions, or reduce the dust loading to the secondary collector. The addition of a precleaner adds pressure drop and costs, and should only be applied where the performance of the secondary is inadequate without a primary collector of the type proposed.

- (2) Mechanical collectors of the multicyclone type are usually the first choice for primary collector service. They are low cost; provide reliable collection of large diameter suspended solids in the 85 percent collection efficiency range; and can be specified in a wide variety of wear resistant metals. There are very few NSPS applications where the single or (in series) double mechanical collector can meet the particulate emission standards. Consequently, a final cleaning device of high efficiency on small size particulate should follow the mechanical collector.

- (3) Utilizing a primary and secondary collector in series provides some flexibility to the system in the event there is a failure of one of the collectors.

*f. Wet vs. dry collection.* Factors to be taken into consideration in a comparison of wet and dry collection include:

- Solubility of aerosol
- Ultimate pH of scrubbing liquor
- Liquor corrosion and erosion potential
- Special metals or protective coatings
- Availability of make-up water
- Disposal and treatment of waste water
- Space required for liquid-handling equipment
- Vapor plume visibility
- Operating and installed costs
- Maintenance and operation

*g. Summary.* A summary of the general guidelines in the selection of emission control equipment for boiler flue gases is provided in table 12-3.

TABLE 12-3

GENERAL GUIDELINES IN THE  
SELECTION OF EMISSION CONTROL EQUIPMENT FOR BOILER FLUE CASES

	Boilers with less than 100 million Btu input	Boilers with 100 to 209 million Btu input	Boilers with 250 million Btu furnace input and larger
Statement on emission regulations	<ol style="list-style-type: none"> <li>1. Are not regulated by the EPA's present new source performance standards.</li> <li>2. Local and state air emission regulations prevail. Most states enforce laws which limit the rate of emissions based on a process weight formula designed to allow higher emission rates for the smaller boilers and decreasing the rate as the furnace input increases.</li> <li>3. Controls are usually for particulate, sulfur dioxide and NO<sub>x</sub>. Limits are usually expressed in pounds per hour or tons per year.</li> </ol>	<ol style="list-style-type: none"> <li>1. Presently the laws are the same as the smaller units. However, the EPA has proposed changes in the laws which would include boilers in this size range in their regulations.</li> <li>2. Timing for the adoption or if in fact this becomes law is conjecture at this time.</li> </ol>	<ol style="list-style-type: none"> <li>1. All boilers this size must meet EPA's new source performance standards (NSPS)                     <ul style="list-style-type: none"> <li>CO.1 0.1 lb/mm Btu of particulate</li> <li>1.2 lb/mm Btu of SO<sub>2</sub></li> <li>0.7 lb/mm Btu of NO<sub>x</sub></li> <li>20% opacity</li> <li><u>Fuel Oil</u> 0.1 lb/mm Btu of particulate</li> <li>0.8 lb/mm Btu of SO<sub>2</sub></li> <li>0.3 lb/mm Btu of NO<sub>x</sub></li> <li>20% opacity</li> <li><u>Nat. Gas.</u> 0.1 lb/mm Btu of particulate</li> <li>0.2 lb/mm Btu of NO<sub>x</sub></li> </ul> </li> <li>2. All boilers must also meet (l) above state and local ambient air quality standards. The NSPS represent the maximum stack emissions allowed and in a great many cases will not meet the ambient air quality standards; in these cases emission rates are met by the best available control technology (BACT).</li> </ol>
Natural gas	<ol style="list-style-type: none"> <li>1. No control device. needed.</li> <li>2. Laws usually cover particulate and NO<sub>x</sub>.</li> </ol>	<ol style="list-style-type: none"> <li>1. Presently same as smaller boilers.</li> </ol>	<ol style="list-style-type: none"> <li>1. No particulate control required.</li> <li>2. NO<sub>x</sub> requires proper burners, furnace and combustion control design.</li> </ol>
No. 2 fuel (distillate)	<ol style="list-style-type: none"> <li>1. No control device. needed.</li> <li>2. Laws usually cover particulate and NO<sub>x</sub>.</li> </ol>	<ol style="list-style-type: none"> <li>1. Presently same as smaller boilers.</li> </ol>	<ol style="list-style-type: none"> <li>1. No particulate control required.</li> <li>2. No SO<sub>2</sub> control device. usually needed.</li> <li>3. NO<sub>x</sub> requires proper burner and furnace design and properly adjusted combustion control..</li> </ol>
Wood and wood wastes	<ol style="list-style-type: none"> <li>1. Particulate control by multiclone mechanical collector.</li> <li>2. SO<sub>2</sub> and NO<sub>x</sub> are not controlled.</li> </ol>	<ol style="list-style-type: none"> <li>1. Particulate usually controlled by two multiclone collectors in series.</li> <li>2. SO<sub>2</sub> and NO<sub>x</sub> are not usually controlled.</li> </ol>	<ol style="list-style-type: none"> <li>1. Particulate is controlled by:                     <ul style="list-style-type: none"> <li>a. a mechanical collector followed by a wet scrubber;</li> <li>b. a mechanical collector followed by ESP</li> </ul> </li> <li>2. SO<sub>2</sub> is not controlled.</li> <li>3. NO<sub>x</sub> is controlled by properly adjusted combustion control. and special methods of distributing combustion air.</li> </ol>
Pulverized co.1 (compliance) - low sulfur -	<ol style="list-style-type: none"> <li>1. Particulate control by multiclone mechanical collector.</li> <li>2. SO<sub>2</sub> controlled by use of low sulfur coal.</li> </ol>	<ol style="list-style-type: none"> <li>1. Particulate controlled by two mechanical collectors in series up to + 150 mm BTU.</li> <li>2. Above the 150 mm BTU size it usually requires an electrostatic precipitator or baghouse to meet codes.</li> <li>3. SO<sub>2</sub> controlled by low sulfur coal.</li> <li>4. NO<sub>x</sub> controlled by properly adjusted combustion controls and special method. of distributing combustion air.</li> </ol>	<ol style="list-style-type: none"> <li>1. Particulate controlled by:                     <ul style="list-style-type: none"> <li>a. an electrostatic precipitator;</li> <li>b. a baghouse;</li> <li>c. a mechanical collector followed by either a or b.</li> </ul> </li> <li>2. SO<sub>2</sub> controlled by low sulfur quantity in coal.</li> <li>3. NO<sub>x</sub> is controlled by properly adjusted combustion controls and special method. of distributing combustion air.</li> </ol>
Pulverized co.1 (high sulfur)	<ol style="list-style-type: none"> <li>1. Particulate and NO<sub>x</sub> are same as compliance coal.</li> <li>2. Where state limits will be exceeded by SO<sub>2</sub>, the hour. of operation will have to be limited or an SO<sub>2</sub> scrubber will be required.</li> </ol>	<ol style="list-style-type: none"> <li>1. Particulate and NO<sub>x</sub> are controlled the same as on low sulfur coal.</li> <li>2. SO<sub>2</sub> emissions are usually controlled by a wet scrubber in series with an electrostatic precipitator and located down stream of the I.D. fan. Dry scrubbers are employed in series with either a baghouse or electrostatic precipitator. The dry scrubber is located directly up stream of the particulate collector.</li> </ol>	<ol style="list-style-type: none"> <li>1. Particulate and NO<sub>x</sub> are controlled the same as shown for low sulfur coal.</li> <li>2. SO<sub>2</sub> is controlled by either a wet or a dry scrubber.                     <ul style="list-style-type: none"> <li>- Wet scrubbers are usually located just up stream of the stack.</li> <li>- Dry scrubbers are located directly upstream of either the baghouse or the electrostatic precipitator.</li> </ul> </li> </ol>



## CHAPTER 13

### FLUIDIZED BED BOILERS

#### 13-1. Fluidized bed boilers.

a. Fluidized bed combustion has now progressed through the first and into the second and third generation of development. Fluidized bed technology is not new but has been revived in this country because of fuel costs and the availability of poor quality fuels. Commercial and industrial power plants now have a third type of solid fuel boiler to consider for steam requirements. Economics, fuel pricing, availability of low grade fuels and environmental considerations have made the fluidized bed boiler a viable option to evaluate along with the stoker or pulverized coal fired units. The units can with care be designed to burn a number of fuels including low grade coals, lignite, coal mine wastes (culm), refinery gas, woodwastes, waste solvents, sludge, etc.

b. Fluidized bed combustion offers the ability to burn high sulfur coal and meet environmental requirements without the use of scrubbers. The mixture of fuel and limestone is injected in such a way that the fuel and limestone are distributed across the bed. The fuel and limestone are kept in turbulent motion by upward air flow from the bottom of the furnace. The furnace combustion takes place at about 1550 degrees Fahrenheit to 1750 degrees Fahrenheit. Control of sulfur dioxide and nitrogen oxide emissions in the combustion chamber without the need for additional control equipment is one of the major advantages over conventional boilers.

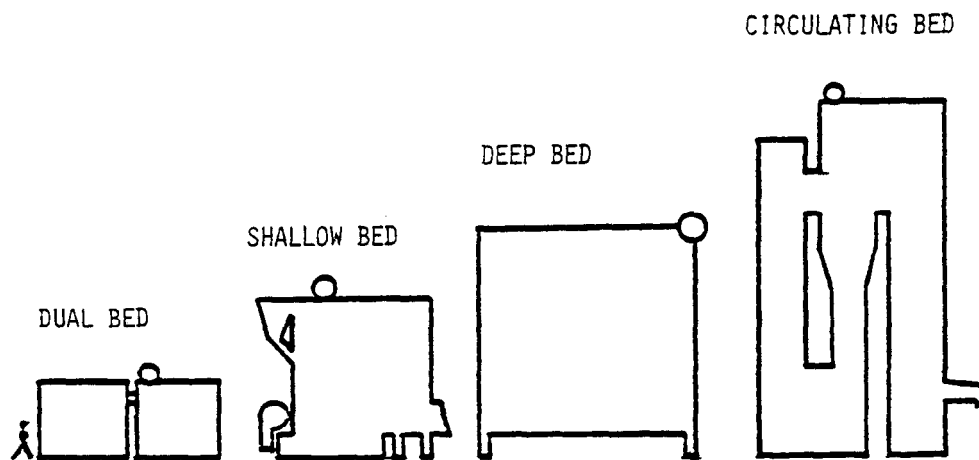
#### 13-2. Types of fluidized bed boilers.

a. Fluidized bed boilers cover a variety of systems. There is no unique design. An industrial fluidized bed boiler could assume several possible configurations depending on such factors as bed pressure, the choice between natural or assisted circulation, the gas velocity in the bed, fuel and air distribution systems, bed design and method of achieving high carbon utilization and control of sulfur dioxide.

b. There are four types which will be given consideration for control of sulfur dioxide and nitrogen oxide emissions. These are shown in figure 13-1 and size is also compared for a 50 million Btu/hour heat input unit.

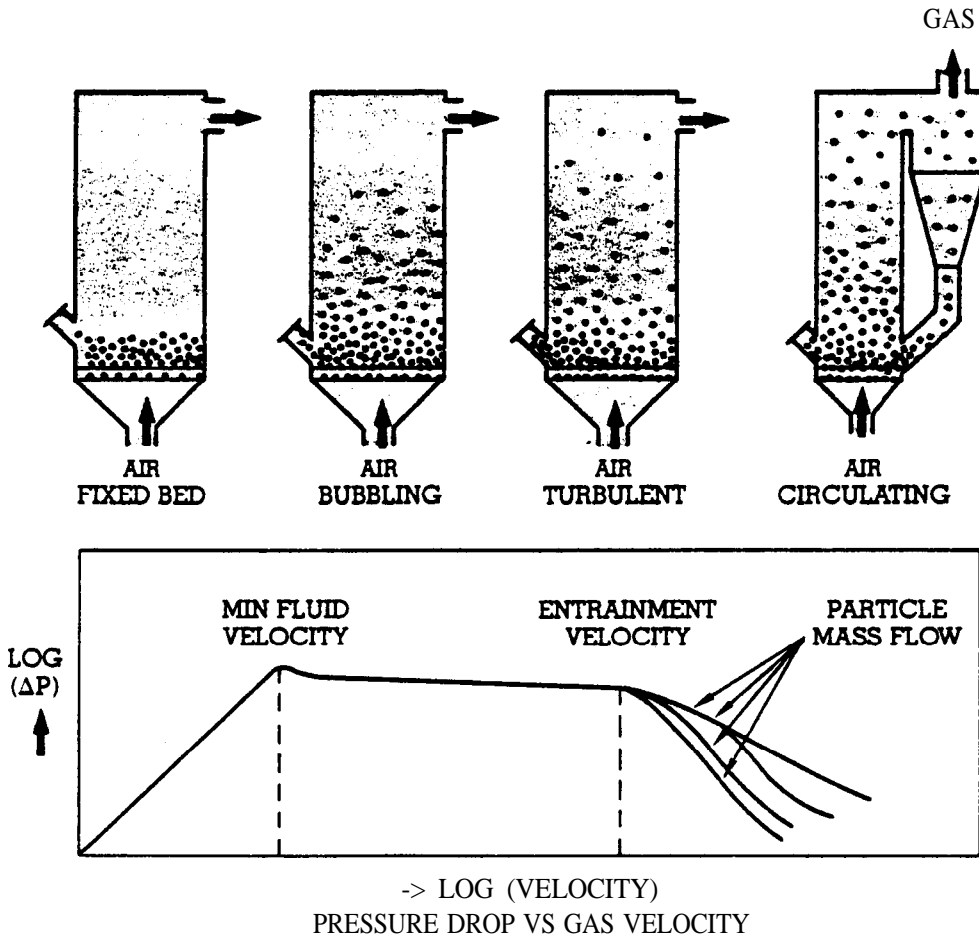
c. The types can further be demonstrated by comparing them as stationary fluid bed (bubbling bed) or circulating bed designs. To determine this type, the relationship between the gas velocity and the differential pressure in the fluidized bed must be established. Figure 13-2 shows this relationship for various bed designs.

d. The fluidized bed is a system in which the air distributed by a grid or distribution plate, is blown through the bed 'solids developing a "fluidized condition." Fluidization depends largely on the particle size and the air velocity. At low air velocities, a dense defined bed surface forms and is usually called a bubbling fluidized bed. With higher air velocities, the bed



**U.S. Army Corps of Engineers**

*Figure 13-1. Types of fluid bed combustors size comparison*



Courtesy of Pyropower Corporation

Figure 13-2. Pressure drop vs. gas velocity

particles leave the combustion chamber with the flue gases so that solids recirculation is necessary to maintain the bed solids. This type of fluidization is called circulating fluidized bed.

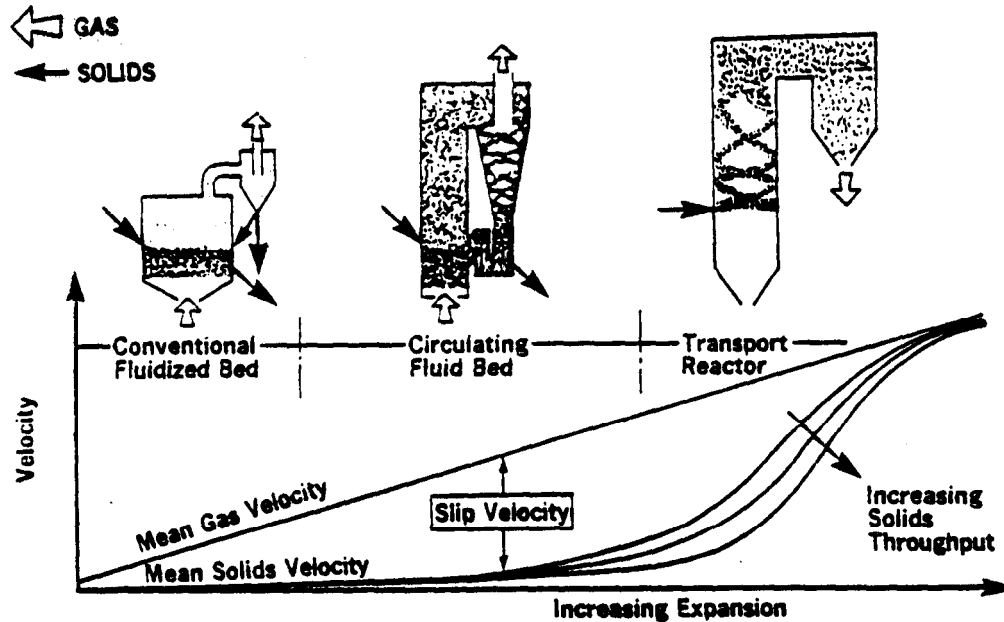
e. The mean solids velocity increases at a slower rate than does the gas velocity, as illustrated in figure 13-3. Therefore, a maximum slip velocity between the solids and the gas can be achieved resulting in good heat transfer and contact time with the limestone, for sulfur dioxide removal. When gas velocity is further increased, the mean slip velocity decreases again. These are the operating conditions for transport reactor or pulverized coal boiler. The design of the fluidized bed falls between the stoker fired boiler and the pulverized coal boiler using the bed expansion.

f. The shallow fluidized bed boiler operates with a single bed at a low gas velocity. A shallow bed minimizes fan horsepower and limits the free-board space. The bed depth is usually about 6 inches to 9 inches and

the free-board heights are only four to five feet. Desulfurization efficiency of a shallow bed is poor, with only about 60 to 80 percent removal, because  $SO_2$  does not have adequate time to react with the limestone before moving out of the shallow bed. The shallow bed fluidized boiler is of the bubbling bed design. The shallow bed will be of very limited use because of its poor sulfur dioxide removal.

g. A deep fluidized bed boiler is a bubbling bed design.

- (1) The bed depth is usually 3 feet to 5 feet deep and the pressure drop averages about one inch of water per inch of bed depth. The bulk of the bed consists of limestone, sand, ash, or other material and a small amount of fuel. The rate at which air is blown through the bed determines the amount of fuel that can be reacted. There are limits to the amount of air that can be blown through before the bed material and fuel are



Courtesy of Combustion Engineering, Inc.

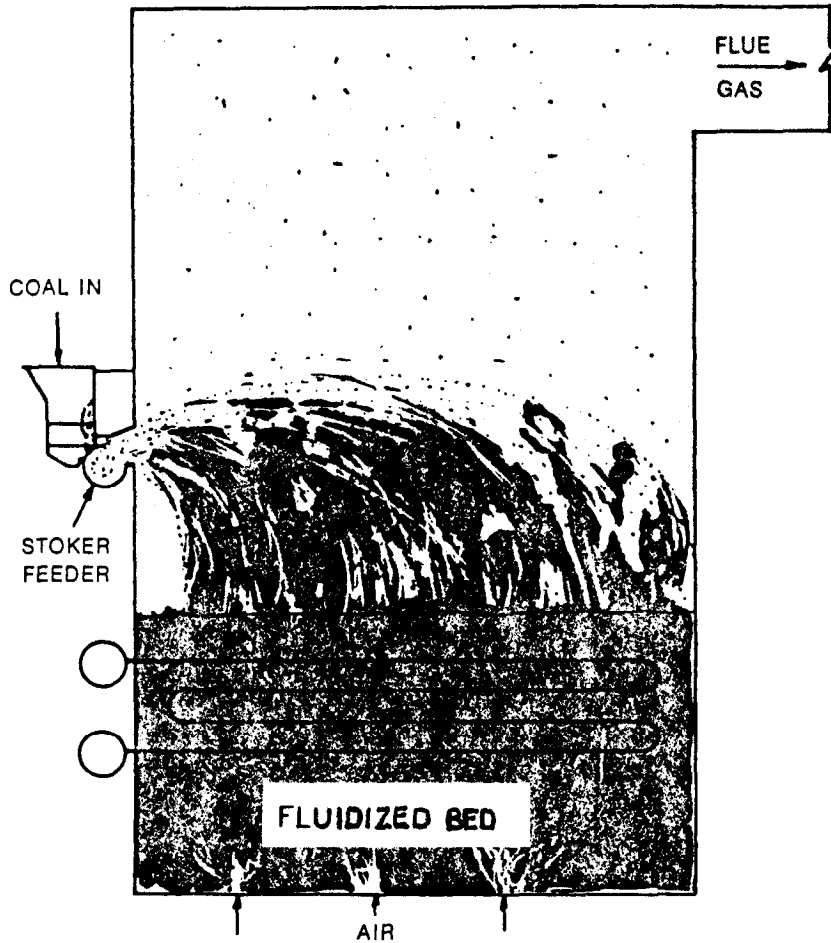
Figure 13-3. Velocity vs. bed expansion

entrained and blown out of the furnace. Conversely, when air flow is reduced below the minimum fluidizing velocity, the bed slumps and fluidization stops.

- (2) The fuel feed systems available are either under-bed feed system or over-the-bed feed system. The under-bed feed system is quite complex. It requires coal at less than 8 percent surface moisture and crushed to about 6 MM top size to minimize plugging the coal pipes. Operating and maintenance costs are usually high for the under-bed feed system. The major advantage of the under-bed feed system is that with use of recycle combustion efficiency approaches 99 percent. The over-the-bed feed system is an adaptation of the spreader stoker system for conventional boilers. This system has a potential problem of effective carbon utilization. Carbon elutriation can be as high as 10 percent.
- (3) Some bubbling bed units have sectionalized or modular design for turndown or load response. This allows a section to be cut in or out as required. Some are actually divided with water cooled or refractory walls. This type unit should be matched to the facility demand profile to avoid continual bed slumping and operator attention. When continuous stopping of

sections is required to control load for extended periods, the fluidized bed boiler may become a big user of auxiliary fuel to maintain bed temperature.

- (4) Major limitations of the bubbling bed design are high calcium/sulfur ratios, low combustion efficiency, limited turndown without sectionalization of the furnace bottom and complexity of the under bed feed system required to minimize elutriation of unburned fines. Typical fluidized bed combustors of this type are shown in figures 13-4 and 13-5.
  - h. In the circulating fluidized bed boiler, the fuel is fed into the lower combustion chamber and primary air is introduced under the bed.
    - (1) Because of the turbulence and velocity in the circulating bed, the fuel mixes with the bed material quickly and uniformly. Since there is not a definite bed depth when operating, the density of the bed varies throughout the system, with the highest density at the level where the fuel is introduced. Secondary air is introduced at various levels to ensure solids circulation, provide stage combustion for NO<sub>x</sub> reduction, and supply air for continuous fines combustion in the upper part of the combustion chamber.
    - (2) Combustion takes place at about 1600 degrees



Courtesy of Foster Wheeler Energy Corporation

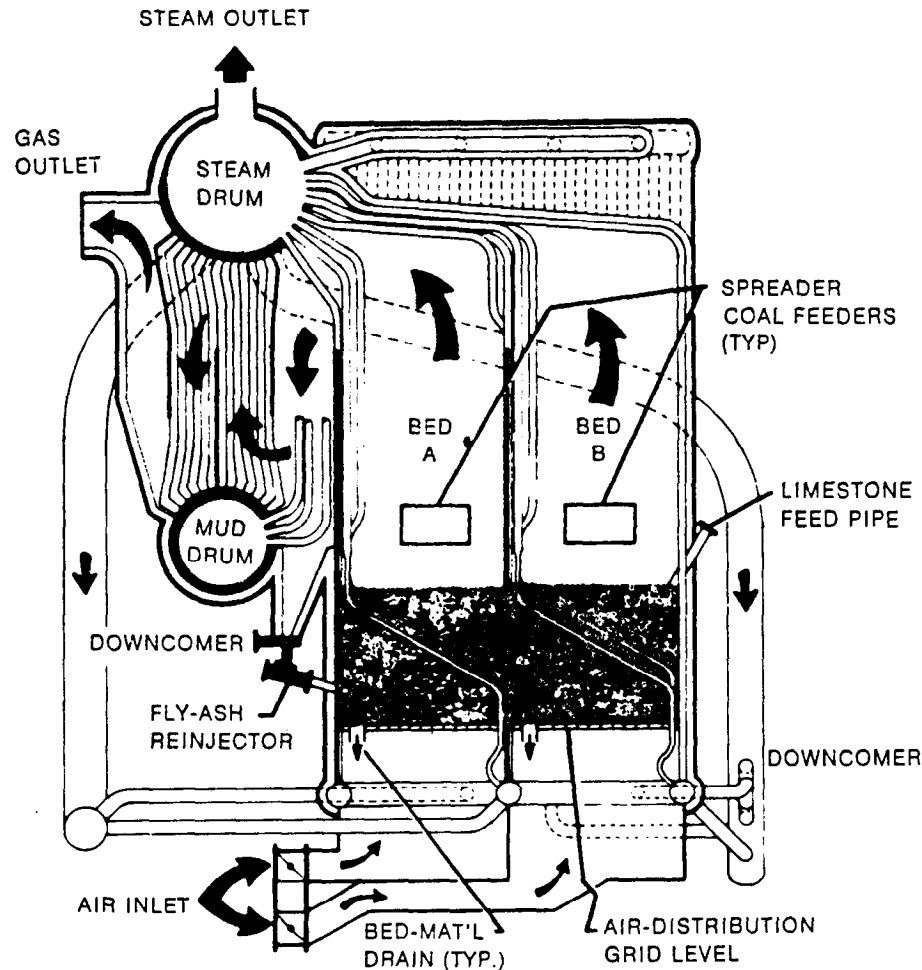
Figure 13-4. Bubbling bed boiler I

Fahrenheit for maximum sulfur retention. The hot gases are separated from the dust particles in a cyclone collector. The materials collected are returned to the combustion chamber through a nonmechanical seal, and ashes are removed at the bottom. The hot gases from the cyclone are discharged into the convection section of a boiler where most of the heat is absorbed to generate steam. Typical fluidized bed boilers of this type are as shown in figure 13-6.

- (3) Major performance features of the circulating bed system are as follows:
- (a) It has a high processing capacity because of the high gas velocity through the system.
  - (b) The temperature of about 1600 degrees Fahrenheit is reasonably constant throughout the process because of the high

turbulence and circulation of solids. The low combustion temperature also results in minimal  $\text{NO}_x$  formation.

- (c) Sulfur present in the fuel is retained in the circulating solids in the form of calcium sulphate so it is removed in solid form. The use of limestone or dolomite sorbents allows a higher sulfur retention rate, and limestone requirements have been demonstrated to be substantially less than with bubbling bed combustor.
- (d) The combustion air is supplied at 1.5 to 2 psig rather than 3-5 psig as required by bubbling bed combustors.
- (e) It has a high combustion efficiency.
- (f) It has a better turndown ratio than bubbling bed systems.



Courtesy of Foster Wheeler  
Energy Corporation

Figure 13-5. Bubbling bed boiler II

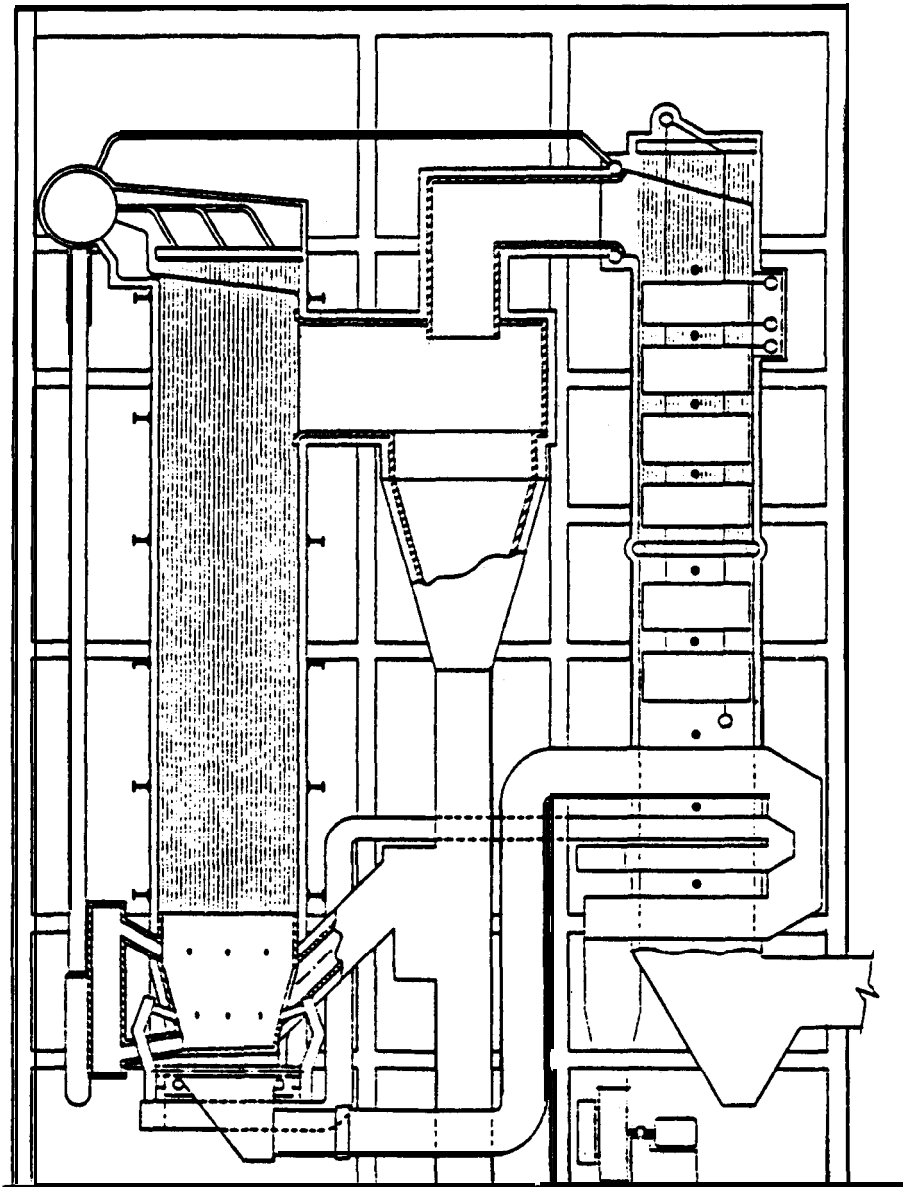
(g) Erosion of the heat transfer surface in the combustion chamber is reduced, since the surface is parallel to the flow. In a bubbling bed system, the surface generally is perpendicular to the flow.

i. In the dual bed fluidized combustor, combustion and desulfurization take place in two separate beds, allowing each different reaction to occur under optimal conditions.

- (1) The lower bed burns coal in a bed of sand, fluidized from below by the combustion air and gases, and maintained at a steady equilibrium temperature by the extraction of energy through in-bed steam generator tubes. The bed depth is more shallow than the conventional bubbling bed design.
- (2) The flue gas then travels through an upper bed

of finely ground limestone where desulfurization takes place. The dual bed design allows coals to be burned at about 1750 degrees Fahrenheit while desulfurization takes place at about 1550 degrees Fahrenheit. The upper bed also serves to catch unburned coal particles that may have escaped to complete combustion of any unburned carbon.

- (3) A dual bed can be utilized on capacities up to 200,000 pounds per hour of steam. The major advantages are: shop fabrication; can be retrofitted to some existing oil and gas fired boilers; enhanced combustion efficiency by allowing the lower bed to operate at 1750 degrees Fahrenheit; lower free-board heights required; and better load following. A typical dual bed fluidized combustor is shown in figure 13-7.



Courtesy of Pyropower Corporation

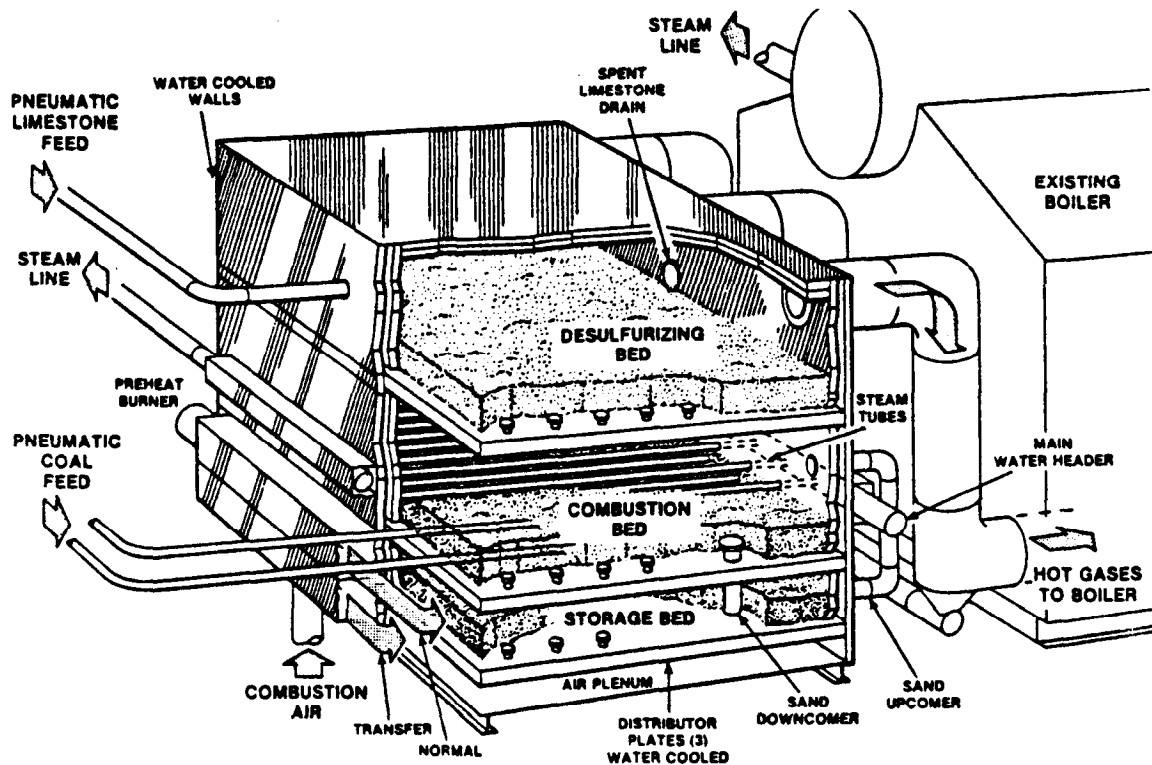
Figure 13-6. Circulating fluid bed boiler system

### 13-3. Applications

#### a. Fuel Application.

(1) A wide range of high grade and low grade fuels of solid, liquid or gaseous type can be fired. The primary applications are fuels with low heating value, high sulfur, waste materials, usually the least expensive. Fuel can be lignite, coal washing waste (culm), high sulfur coal, delayed petroleum coke, or waste material that would not burn satisfactorily in a conventional boiler. The fluidized bed boiler has the ability to burn most any residual fuel and reduce emissions by removal of sulfur compounds in the limestone bed.

- (2) A complete evaluation of fuels to be burned should be given consideration in selection of the equipment. Many factors including heating value, moisture, ash fusion temperature, sulfur content, and ash content will affect the system configuration.
- (3) Fuel sizing is important. For coal it is recommended that it not be run-of-mine. It should be crushed to avoid large rocks and pieces of coal causing problems in the bed. Coal sizing is important and will vary with each fluidized bed manufacturer. Typically, sizing will vary from



WORMSER GRATE FLUIDIZED BED COAL COMBUSTION SYSTEM

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Figure 13-7. Dual bed fluidized bed boiler

0-¼ inch x 0 for overfeed systems to ¼ inch x 0 for underfeed systems.

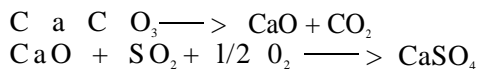
**b. Process application.**

- (1) The fluidized bed can be utilized to control SO<sub>2</sub> emissions when high sulfur fuels are used. Also reduction of SO<sub>2</sub> emissions can be achieved when nonattainment areas are looking for additional steam for process. The capability of fluidized bed combustion to control emissions makes this technology particularly suited for applications where stringent emissions control regulations are in effect.
- (2) Steam generation in a fluidized bed boiler versus a conventional boiler will not be economical when using compliance coal for control of sulfur dioxide emissions. However, several studies indicate that fluidized bed boilers are competitive with conventional coal fired boilers that include flue-gas desulfurization systems. Facility location may dictate Best Available Control Technology (BACT) be used to control SO<sub>2</sub> and NO<sub>2</sub> emissions.
- (3) Nitrogen oxide emissions can be controlled with a fluidized bed boiler. The fluidized bed boiler generates very little thermal nitrogen oxide because of the low temperature of operation.
- (4) Pressurized fluidized bed boilers continue in research and development. Higher efficiency designs for utility applications involve considerably higher initial costs and design complexity. Also, a cost effective way to clean up the hot flue gases before they reach the turbine has not been found.
- (5) The fluidized bed boiler can be used to incinerate low grade fuels that would be normally considered waste residues.

### 13-4. Fluidized bed performance

a. With the exception of a baghouse or precipitator, which is required for particulate removal, additional gas cleaning devices are not required for environmental control with fluidized bed systems.

b. Fluidized bed boilers are able to remove sulfur dioxide directly in the combustor. This is accomplished by using limestone in the fluid bed. The limestone calcines to form calcium oxide (CaO) and then reacts with SO<sub>2</sub> to form calcium sulfate as follows:



The ideal temperature range for desulfurization in a fluidized bed is about 1600 degrees Fahrenheit.

c. A bubbling fluidized bed boiler will require a higher calcium to sulfur ratio for control of SO<sub>2</sub>, while the circulating fluidized bed boiler can achieve similar SO<sub>2</sub> removal with the Ca/S ratio of 1.5 to 2. See figure 13-8.

d. Nitrogen oxide is controlled by distribution of primary air under the bed and secondary air part way up the combustor. The staging of combustion limits the nitrogen oxide to that which is formed only by fuel-bound nitrogen. Thermally formed nitrogen oxide is negligible in the fluidized bed. See figure 13-9 for predicted nitrogen oxide emissions.

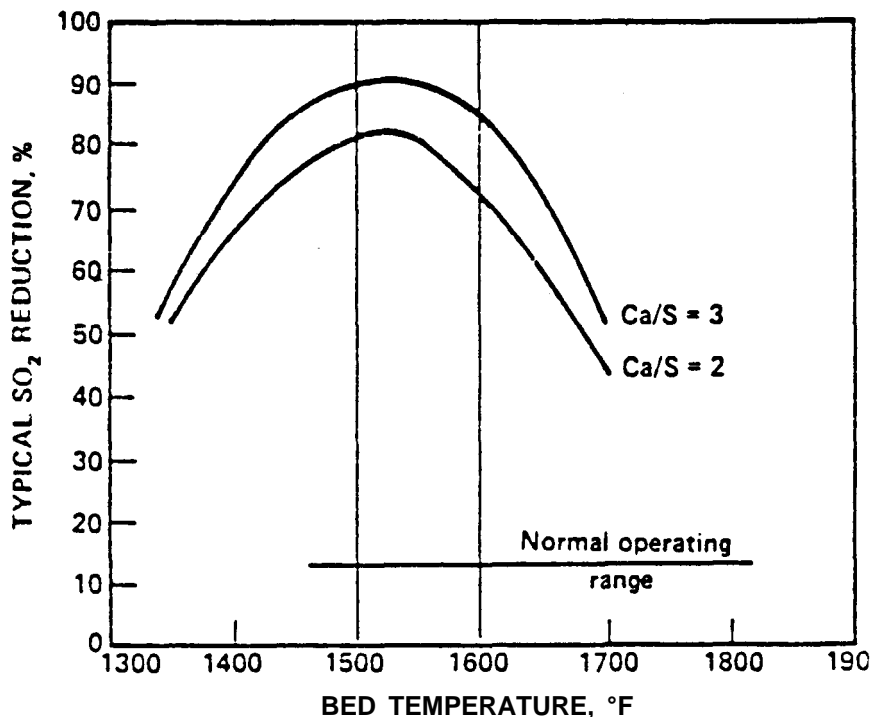
e. Several fluidized bed boiler manufacturers are now offering performance guarantees based upon experience in the bubbling, circulating, and dual bed designs.

### 13-5. Materials and construction

The materials used for construction of fluidized bed units are similar to those used in conventional boilers depending on the design pressure and temperature of the system.

a. *In-bed tubes.* The fluidized bed boilers that have in-bed tubes have experienced high erosion rates in some cases. Vertically oriented tubes are less prone to erosion than the horizontal ones. Where in-bed tubes are used, consideration should be given to use of thicker walls on the tubes and their metallurgy. Wear fins can be installed to reduce erosion. Also, some corrosion may be experienced due to the reducing atmosphere in the lower regions.

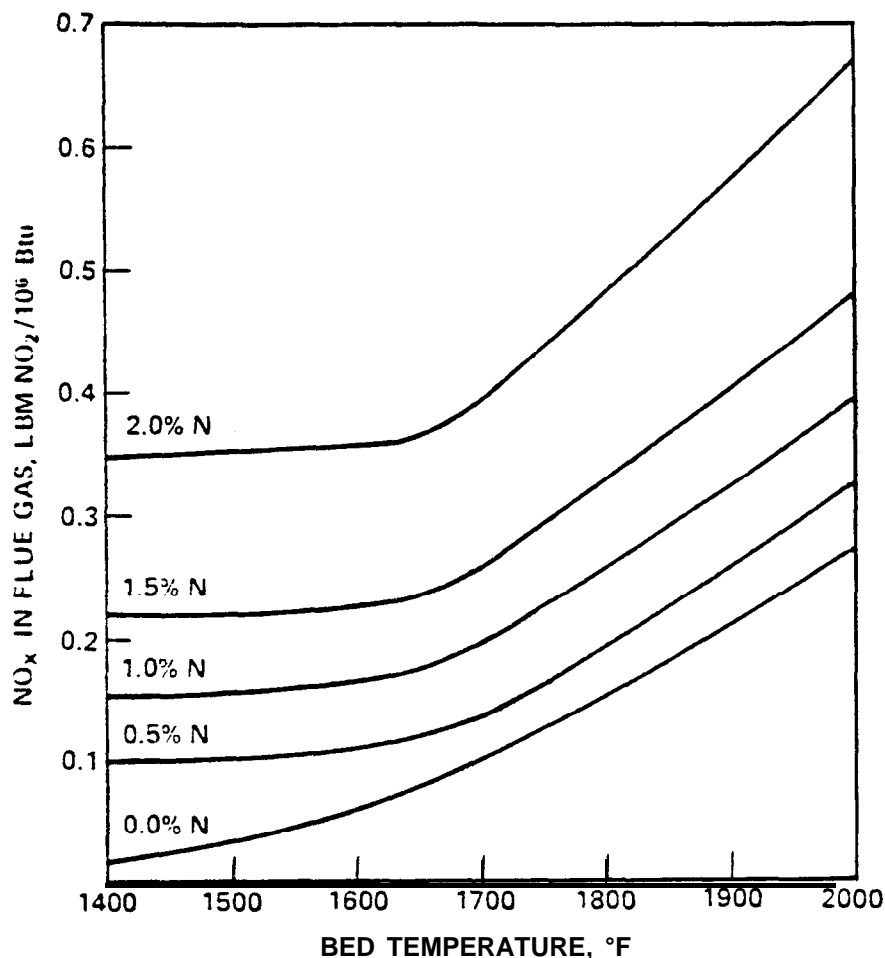
b. *Fluidized bed.* The fluidized bed or bottom of the combustor section varies considerably with each type of design. The method used for air distribution is important in maintaining uniform fluidization across the bed. Some units have had problems with plugging of the air openings. The bottom is castable refractory-lined on some units. Others have heat transfer tubes protected



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Figure 13-8. SO<sub>2</sub> reduction vs. combustion temperature





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Figure 13-9.  $NO_x$  emissions vs. combustion temperature

with abrasion resistant refractory in regions where the gas flow changes directions.

c. Cyclone. In the circulating fluidized bed unit, the cyclone separator is lined with refractory to minimize abrasion and prevent heat losses.

d. Ash cooler. The ash cooler is also refractory lined to increase life of the unit due to abrasion of the solids being handled.

### 13-6. Auxiliary equipment

a. The following briefly describes the major components of auxiliary equipment for the fluidized bed boilers.

- (1) Materials handling for fuel and limestone. The handling of fuel and limestone will vary depending on the source of supply and the type of delivery. Delivery is usually by truck or rail
- (2) The conveying systems for the fuel and limestone can be either a pneumatic or a mechan-

ical system. The mechanical system may be belt, chain, bucket, or screw conveyor, or a combination of these.

- (3) Coal can be stored in open piles or storage silos. From storage, coal is fed to a crusher or dryer as required for efficient burning. Crushing of the coal is required when it is run-of-mine, for efficient burning, elimination of rocks in the bed, high moisture content, high ash content and when pneumatic conveying is necessary.
- (4) Drying of the coal is recommended when the fuel moisture content exceeds fifteen percent for all fluidized bed boilers except the circulating fluidized bed boiler. The flue gas from the fluidized bed can be used for drying the fuel.

b. Coal feed stream splitter. The dual bed unit has a proprietary stream splitter which permits accurate feed of coal to multipoints under the bed for maximum combustion efficiency.

*c. Startup burners.* Startup burners are supplied in the bed or air ducts to heat the bed up to coal ignition temperature. The startup burner can be used for low loads. Usually it is capable of carrying about 20 percent or more of boiler capacity.

*d. Fluidized bed heat exchanger.* The fluid bed heat exchanger is used to cool the ash to about 750 degrees Fahrenheit. The coolant can be feedwater or any process fluid which requires heating. The metallurgy of the heat exchanger must be compatible with the fluids it is handling.

*e. Flue gas clean-up for particulate.* Either an electrostatic precipitator or a baghouse may be used for particulate control. Basic guidelines established for determining which type unit to use on a conventional coal fired unit may be used to select the particulate control device for a fluidized bed boiler. Electrostatic precipitators can encounter resistivity problems because of the low sulfur content in the particulate to be collected.

*f. Ash-handling systems.*

- (1) The ash-handling systems are similar to ash-handling systems for conventional boilers. The bottom ash does have to be cooled prior to disposal. Most of the ash-handling systems are dry, and the ash can be sold for use in other products.
- (2) Some potential uses of the ash are: aggregate in concrete; road base ingredients; stabilization of soil embankments; pozzolan in masonry units and mortar; agriculture and livestock feeds extender; and neutralization of spent acid wastes.

- (2) Low NO<sub>x</sub> emission due to staged combustion and changing of the primary to secondary air ratio
- (3) Only fuel bound nitrogen converted to NO<sub>x</sub> (thermally formed NO<sub>x</sub> is negligible)
- (4) High combustion efficiency, (as high as 99 plus percent)
- (5) High turn-down and load following ability
- (6) Uses a variety of fuels including:
  - high sulfur
  - low BTU
  - high ash
  - low cost
  - waste materials
- (7) High boiler efficiency (85 to 90 plus percent)
- (8) Load changes greater than 5% per minute
- (9) No retractable sootblowers. Rotary sootblower may be used
- (10) No slagging of coal ash
- (11) Low maintenance
- (12) Dry ash
- (13) Broad tolerance to changes in coal quality
- (14) Sulfur removal w/o need for scrubbers

*b. Disadvantages:*

- (1) Bed turn-down capability not clear
- (2) Startup procedures more complex
- (3) Control response almost instantaneous
- (4) Use of partial bed slumping as load control mechanism for bubbling bed
- (5) Requirement of a free-board for combustion efficiency for bubbling bed
- (6) Corrosion susceptibility in bubbling bed
- (7) Calcium-to-sulfur ratio greater than 2.5 causes degradation of boiler efficiency
- (8) Fluidized bed is a newer technology than conventional boilers
- (9) Complex under-bed fuel-feed system required for some bubbling beds

### 13-7. Advantages and disadvantages

*a. Advantage:*

- (1) Low SO<sub>2</sub> emissions

## APPENDIX A

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## GLOSSARY

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Acid Dew Point	Temperature at which acid vapor condenses to form acid droplets.
Actual Combustion Air	The total amount of air supplied for complete combustion and equal to the theoretical plus the excess air.
Air Register	A type of burner mounting which admits secondary air to the combustion area.
Air-to-Cloth Ratio	The rate of volumetric capacity of a fabric filter (volume of air or gas in ft <sup>3</sup> /min per ft <sup>2</sup> of filter fabric) commonly expressed as ft/min. Also called filtering velocity, superficial face velocity, and filtration rate.
°API	Scale adopted by the American Petroleum Institute to indicate the specific gravity of a fluid. (API gravity for a liquid rises as its temperature rises.)
Ash	Non-combustible mineral matter which remains after a fuel is burned.
Atmospheric Stability	Degree of non-turbulence in the lower atmosphere.
Atomization	The breaking of a liquid into a multitude of tiny droplets.
Blinding (blinded)	Loading or accumulation of filter cake to the point where the capacity rate is diminished. Also termed “plugging” (Plugged).
Boiler (thermal) Efficiency	Ratio of useful heat in delivered steam to the theoretical gross heat in the fuel supplied.
Burner	A device which positions a flame in a desired location by delivering fuel (and sometimes air) to that location. Some burners may also atomize the fuel, and some mix the fuel and air.
Calcine	To render a substance friable by the expulsion of its volatile content through heat.
Cloth Area	The total amount of cloth area in the form of bags or envelopes in a fabric filter system.
Cloth Weight	A measure of filter fabric density. It is usually expressed in ounces per square yard or ounces per square foot.
Co-Current	Scrubbing spray liquid and exhaust gas flowing in the same direction.
Combustion Air Windbox	Inlet plenum for preheated combustion air.
Combustion Efficiency	The actual combustion heat released divided by the maximum possible heat that can be released by combustion of a fuel.
Continuous Automatic Filtering System	A fabric filter unit that operates continuously, without interruption for cleaning. The flow pattern through the system is relatively constant.
Critical Temperature	Temperature above which the substance has no liquid-vapor transition.
Dilution Air	The air added downstream of the combustion chambers in order to lower the exhaust gas temperature (In incinerators).
Entrainment Spray	Atomized liquid downstream of scrubber spray nozzles.
ESP	Electrostatic precipitator.
Excess Air	The air remaining after a fuel has been completely burned (also, that air which is supplied in addition to the theoretical quantity required).
Felted Fabrics	Structures built up by the interlocking action of the fibers themselves, without spinning, weaving, or knitting.
Filament	A continuous fiber element.
Flue Gas	All gases which leave the furnace by way of the flue, including gaseous products of combustion and water vapor, excess oxygen and nitrogen.

Fly Ash	Suspended particles, charred paper, dust, soot, or other partially burned matter, carried in the gaseous by-products of combustion. (Sometimes referred to as particulate matter, or pollutants).
Gas Absorption	A process for removing a gas constituent from an exhaust gas stream by chemical reaction between the constituent to be removed and a scrubbing liquor.
Grain	Unit of weight, equal to $\frac{1 \text{ lb.}}{7000}$
Heat Content	The sum total of latent and sensible heat stored in a substance minus that contained at an arbitrary set of conditions chosen as the base or zero point. Usually expressed as Btu/lb, Btu/gal, Btu/ft <sup>3</sup> for solid, liquid and gaseous fuels, respectively.
Heat Release Rate (firing rate)	The amount of heat liberated during the process of complete combustion and expressed in Btu/hr/ft <sup>3</sup> of internal furnace volume.
High Temperature Fixation Reaction	Reaction between nitrogen and oxygen at a high temperature in air forming nitrogen oxides.
Horizontal Front Wall Firing	Horizontal furnace firing with all burners located in the front wall.
Horizontal Opposed Firing	Horizontal furnace firing with burners located on directly opposing walls.
Impaction	Particle to liquid adherence from collision.
Intermittent Filtering System	A flow pattern in a fabric filter system which is saw-tooth-like. The flow continually decreases until it is stopped. Then cleaning takes place and flow is then again resumed at an increased value which again decreases, etc.
In. Water	Inches of water column used in measuring pressure. One inch of water column equals a pressure of .036 lb/in <sup>2</sup> .
Mass Transport	Any process or force that causes a mass to flow through an open system.
Micron	Unit of length, equal to 1 millionth of a meter.
Multiple Chamber In-Line	An incinerator design that allows combustion gases to flow straight through the incinerator with 90-degree turns in only the vertical direction.
Multiple Chamber Retort	An incinerator design that causes combustion gases to flow through 90-degree turns in both horizontal and vertical directions.
Mulicompartment Baghouse	A compartmented filter baghouse that permits a uniform gas flow pattern as compartments are taken offline for cleaning.
NO <sub>x</sub>	Nitrogen oxides.
Overtire Air (Secondary Air)	Any air controlled with respect to quantity and direction, which is supplied beyond the fuel bed (as through ports in the walls of the primary combustion chamber) for the purpose of completing combustion of materials in gases from the fuel bed. (Also used to reduce operating temperatures within the furnace and referred to as secondary air).
Orsat Analysis	An apparatus used to determine the percentages (by volume) of CO <sub>2</sub> , O <sub>2</sub> , and CO in flue gases.
Permeability (of fabric)	The ability of air (gas) to pass through filter fabric, expressed in ft <sup>3</sup> of air per min. per ft <sup>2</sup> of fabric with .5" H <sub>2</sub> O pressure differential.
Peak Flame Temperature	The highest temperature achieved in the primary combustion zone.
Plant Thermal Efficiency	The actual power output of a plant divided by the theoretical heat input rate.
Plenum (or Plenum Chamber)	Part of a piping or duct flow system having a cross-sectional area considerably larger than that of any connecting ducts pipes or openings.
Porosity (Fabric)	A term often used interchangeably with permeability. (Actually a percentage of voids per unit volume).
Preheated Air	Air heated prior to its use for combustion, frequently by hot flue gases.
Primary Combustion Temperature	Temperature measured at the flame.

Reentrainment (re-entrainment)	Particles reentering the gas stream after having been captured in a particulate collection device.
Residual Dust Accumulation	The fairly stable matrix of dust that remains in a woven fabric after it is cleaned. It accounts for the relatively high collection efficiency of a woven fabric immediately after cleaning.
Tangential Firing	Four-cornered fuel firing to create a swirling flame pattern in a furnace.
Theoretical Air	The exact amount of air required to supply oxygen for complete combustion of a given quantity of a specific fuel.
Theoretical Flame Temperature	The maximum possible flame temperature from burning a fuel.
Thread Count	The number of warp and filling yarns per inch in woven cloth.
Underfire Air	Any air controlled with respect to quantity and direction, forced or induced and supplied beneath the grate, that passes through the fuel bed.
Volume Flow Rate	The quantity (measured in units of volume) of a fluid flowing per unit of time, as ft <sup>3</sup> /min or gal/hr.
Woven Fabric	Fabric produced by interlacing strands at approximate right angles. Lengthwise strands are called warp yarns and cross-wise strands are called filling yarns.

### LIST OF ABBREVIATIONS USED IN THIS MANUAL

Actual Cubic Feet per Minute	(ACFM)
Best. Available Control Technology	(BACT)
British Thermal Units per Hour	(Btu/hr)
Carbon Dioxide	(CO <sub>2</sub> )
Carbon Monoxide	(CO)
Cubic Feet per Minute	(CFM)
Degrees Fahrenheit	(Deg F)
Department of Defense	(DOD)
Dry Standard Cubic Feet, per Minute	(DSCFM)
Electrostatic Precipitators	(ESP's)
Feet per Minute	(Ft/Min)
Feet per Second	(Ft/Sec)
Flue Gas Desulfurization	(FGD)
Grains per Cubic Foot	(Gr/Ft <sup>3</sup> )
Grains per Square Meter	(Gr/M <sup>2</sup> )
Grains per Standard Cubic Foot	(Gr/ Std. Ft <sup>3</sup> )
Micro-grams per Cubic Meter	(Ug/M <sup>3</sup> )
Mili-amperes	(mA)
Million British Thermal Units	1) (Mil Btu) 2) (MM Btu)
Municipal Solid Waste	(MSW)
Month	(Mo)
National Ambient Air Quality Standards	(NAAQs)
Navy Energy and Environmental Support Activity	(NEESA)
New Source Review	(NSR)
New Source Performance Standards	(NSPS)
Nitrogen Dioxide	(NO <sub>2</sub> )
Nitric Oxide	(NO)
Nitrogen Oxides	(NO <sub>x</sub> )
Non-attainment (in conjunction w/PSD)	(NA)
Ozone	(O <sub>3</sub> )
Percent	(%)

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Pound	(lb)
Pounds per Square Inch	(Lb/in <sup>2</sup> )
Prevention of Significant Deterioration	(PSD)
Refuse Derived Fuels	(RDF)
Square Feet	(Ft <sup>2</sup> )
Square Meter	(m <sup>2</sup> )
Sulfur Dioxide	(SO <sub>2</sub> )
Sulfur Oxides	(SO <sub>x</sub> )
Sulfur Trioxide	(SO <sub>3</sub> )
U.S. Environmental Protection Agency	1) (U S E P A)
	2) (EPA)
U.S. Army Environmental Hygiene Agency	(USAEHA)
Year	(Yr)



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