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## Air Pollution

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## 12.1 Introduction

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The quality of the ambient air is an issue that is a common denominator among all people throughout the world. This statement is based on the simple fact that to live everyone must breathe. Despite this fact, air quality is an issue that has been historically ignored until it deteriorates to a point where breathing is uncomfortable or even to where life itself is threatened. However, this approach to air quality is changing rapidly as no aspect of the environment has recently received greater attention than that of air pollution and its effects on our health and well-being.

In the U.S., this attention is illustrated by the Clean Air Act Amendments of 1990. This legislation is one of the most comprehensive pieces of environmental legislation ever enacted. The scope of this legislation's effects can be illustrated by the cost of compliance with its provisions. The estimated cost of compliance in the year 2000 was \$25.6 billion (year 2000 dollars). The expected cost of compliance in the year 2010 will be \$35.6 billion (year 2000 dollars). The estimated monetary benefit from enhanced health and welfare was \$93.5 and \$144.9 billion, respectively. This was based on a review of both the costs and benefits of the Clean Air Act Amendments required under section 812 of the CAAA. The level of attention the issue of air quality management is receiving is indeed significant, but the field is often misunderstood.

The focus of this chapter is to provide a synopsis of the various aspects involved in air quality engineering and management. The chapter will begin by presenting an overview of the major air quality regulations and pollutants of concern. This discussion will be followed by descriptions of methods used in estimating and quantifying emissions, methods of controlling typical emission sources, a discussion of the meteorology affecting dispersion of emitted pollutants, and conclude with a discussion of the models used to estimate the effects of emission of pollutants on the ambient atmosphere.

## 12.2 Regulations

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### Historical Perspective

The regulation of air pollution has evolved from a level of local ordinances in the late 1800s to the federally driven regulatory efforts of today. In 1881, Cincinnati and Chicago became the first American cities to pass smoke control ordinances. This type of local ordinance was the primary means of air quality regulation until the federal government began addressing the issue with the passage of the Air Pollution Control–Research and Technical Assistance Act in 1955. However, this act was not a means of federal regulation, but only a means of providing funds for federal research and technical assistance for an issue that, at the time, was felt to be a state and local problem.

In 1963, the president of the U.S. pushed for the passage of the first Clean Air Act. At that time Congress recognized that air pollution “resulted in mounting dangers to the public health and welfare, including injury to agricultural crops and livestock, damage to and deterioration of property, and hazards to air and ground transportation” [Cooper and Alley, 1990]. This act was the first to address interstate air pollution problems. Further regulations on air pollution were introduced in 1965 with the first set of amendments to the Clean Air Act. These amendments were divided into two provisions addressing air pollution prevention and air pollution resulting from motor vehicles. This act set a national standard for emissions from automobiles to prevent automobile manufacturers from having to comply with 50 different sets of emission standards.

Regulation of ambient air quality was first addressed with the Air Quality Act of 1967. This act was also significant in that for the first time the federal government was granted enforcement authority and was required to develop and promulgate air quality criteria based on scientific studies.

The foundations of the air quality regulations that are in effect today were laid in 1970 with the second set of amendments to the Clean Air Act. These amendments grouped areas of the country into two classes based on the quality of their ambient air in relation to established standards. Separate regulations were developed to apply to the areas based on the air quality in that particular area. This set of amendments also set a time frame in which the areas of the country not in compliance with established ambient air standards would come into compliance with these standards. The authority of the federal government over air quality issues took a giant step forward with this act, and a giant leap forward when this act was coupled with the National Environmental Policy Act that established the Environmental Protection Agency (U.S. EPA) in 1970. This provided for air quality regulation that could be developed and managed at the federal level but implemented by the individual states.

Despite the new level of federal enforcement over the Clean Air Act, the deadlines for compliance with the ambient air standards were not met and in 1977, the Clean Air Act was amended for the third time. The Amendments of 1977 took a proactive stance toward ambient air quality with provisions to prevent areas currently meeting ambient air standards from deteriorating, while at the same time requiring those areas not in compliance with ambient air standards to come into compliance. The amendments of 1977 further required review of air quality and regulations every five years by the U.S. EPA.

Again, despite the new regulations, air quality did not improve. However, federal regulatory efforts plateaued until 15 November 1990 when the Clean Air Act was revised for the fourth time and created the air quality regulations in effect today.

The Clean Air Act Amendments of 1990 are a comprehensive set of regulations that address air pollution from many sources and include systems to measure progress and assure compliance of affected entities. The seven titles of the Clean Air Act are:

- Title I: Air Pollution Prevention and Control (Includes Section 112 Hazardous Air Pollutants)
- Title II: Emissions Standards for Moving Sources
- Title III: General (includes citizen suits, emergency powers, and administrative details)
- Title IV: Acid Deposition Control

- Title V: Permits
- Title VI: Stratospheric Ozone Protection
- Title VII: Enforcement

## Regulatory Overview

### Air Pollution Sources

Air pollution is defined as the intentional or unintentional release of various compounds into the atmosphere. These compounds consist of both gases (vapors and fumes) and solids (particulates and aerosols) which can be emitted from natural and/or human sources. Typically, pollution arising from human sources, such as manufacturing and automobiles, far outweighs the contribution of compounds arising from natural sources, such as volcanoes, forest fires, and decay of natural compounds [Environmental Resources Management, 1992].

When evaluating the regulatory effects of the emission of various pollutants, the source of the pollutant is always considered. However, the term *source* takes on several meanings when used in different situations. In this chapter, it will be used to relate to human sources that are stationary in nature.

There are two types of stationary sources that must be considered when addressing emissions: point and nonpoint sources. Point sources include such things as stacks, vents, and other specific points where gas streams are designed to be emitted. Nonpoint sources, or fugitive or secondary sources, include releases of compounds from leaking valves, flanges, and pumps, or release of compounds from wastewater treatment plants [Environmental Resources Management, 1992].

### Regulation of Ambient Air Quality

#### *National Ambient Air Quality Standards*

National Ambient Air Quality Standards (NAAQS) have been established for criteria pollutants. These consist of six primary pollutants and one secondary pollutant. The six primary criteria pollutants, or pollutants that are emitted directly to the atmosphere, are carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), particulates PM<sub>10</sub> and PM<sub>2.5</sub>, sulfur oxides (SO<sub>x</sub>), volatile organic compounds (VOCs), and lead. The secondary criteria pollutant is ground-level ozone, and is called a secondary pollutant because it is formed through photochemical reactions between VOCs, NO<sub>x</sub>, and sunlight. Therefore, ground-level ozone is not emitted directly to the atmosphere, but formed only after its precursors have been emitted and photochemically react.

NAAQS were set by the U.S. EPA based on two criteria: primary standards for the protection of human health and secondary standards for the protection of the public well-being (such as vegetation, livestock, and other items that can be related to nonhealth effects). These standards differ in that the primary standards are designed to directly protect human health, while the secondary standards are designed to protect the quality of life. [Table 12.1](#) lists the NAAQS for each of the criteria pollutants and the time frame over which the standard is applied. For further definitions of a regulated air pollutant the reader is advised to contact a state environmental regulatory office for the most current definitions from the U.S. EPA.

#### *Attainment and Nonattainment*

The U.S. EPA monitors concentrations of the criteria pollutants through a national monitoring network. If the monitoring data show that the NAAQS levels have been exceeded then that area of the country is in nonattainment. If the monitoring shows that NAAQS levels have not been exceeded then the area is in attainment.

The attainment/nonattainment designation applies to each criteria pollutant. As a result an area may have exceeded the NAAQS for SO<sub>2</sub> and is therefore still an attainment area for SO<sub>2</sub>.

With the implementation of the Clean Air Act Amendments of 1990, the nonattainment provisions were amended to expand nonattainment designations based on the air quality in the area. While the previous regulations only considered areas to be attainment or nonattainment, the new regulations have

**TABLE 12.1** National Ambient Air Quality Standards

Criteria Pollutant	Averaging Period	Primary NAAQS ( $\mu\text{g}/\text{m}^3$ )	Secondary NAAQS ( $\mu\text{g}/\text{m}^3$ )
PM <sub>10</sub>	Annual	50	150
	24 hours	150	150
PM <sub>2.5</sub>	Annual <sup>a</sup>	15	15
	24 hours <sup>a</sup>	65	65
Sulfur dioxide (SO <sub>2</sub> )	Annual	80	
	24 hours	365	
	3 hours		1300
Nitrogen dioxide (NO <sub>2</sub> )	Annual	100	100
Ozone	1 hour	235	235
	8 hours <sup>a</sup>	157	157
Carbon monoxide (CO)	8 hours	10,000	10,000
	1 hour	40,000	40,000
Lead	Quarterly	1.5	1.5

<sup>a</sup> The 1997 Revised PM<sub>2.5</sub> and 8-hour ozone were challenged in court and were the subject of a significant question regarding the constitutionality of EPA's power to make policy without legislative review and EPA's responsibility to consider economic implications of policymaking. A February 27, 2001 ruling by the Supreme Court found the EPA could move forward with the PM<sub>2.5</sub> standard but must review the proposed ozone standard. The revised standards were cleared of remaining legal hurdles in March 2002.

**TABLE 12.2** Ozone Nonattainment Area Classifications

Ozone Concentration (ppm)	Nonattainment Classification
0.120–0.138	Marginal
0.139–0.160	Moderate
0.161–0.180	Serious
0.181–0.280	Severe
Above 0.280	Extreme

established classes of nonattainment that range from marginal to extreme. [Table 12.2](#) lists the new definitions of nonattainment for ground-level ozone. The new regulations also include differing requirements for areas in various classes of nonattainment in an effort to bring these areas into compliance with the NAAQS.

### Regulation of Emission Rates

The NAAQS set acceptable concentrations for pollutants in the ambient atmosphere but do not enforce emission rates for sources such that these levels are met. Regulation of emission rates from stationary sources to control ambient concentrations arise from four programs: Prevention of Significant Deterioration (PSD), New Source Review (NSR), New Source Performance Standards (NSPS), and Hazardous Air Pollutants (HAPs). Each is described below.

#### *Prevention of Significant Deterioration*

When the Clean Air Act was amended in 1977, provisions were included to prevent areas in attainment with the NAAQS from being polluted up to the level of the NAAQS. These provisions are the major regulatory program for attainment areas and are known as the PSD provisions. PSD regulates new major sources and major modifications to existing sources.

Under PSD, a major source is defined as a source that has the potential to emit more than 100 tons per year (tpy) if the source is one of the 28 listed sources in the program, or has the potential to emit 250 tpy if the source is not among the listed sources. A major modification is the expansion of an existing source that increases emissions beyond a specific de-minimis amount.

Any new source that is regulated by PSD must apply for a PSD permit prior to beginning construction. A PSD permit application requires the preparation of an extensive amount of information on not only the process but also the impacts of the project [Environmental Resources Management, 1992]. To comply with the PSD provisions, an applicant must demonstrate the use of Best Available Control Technology (BACT) and demonstrate that the project will have no adverse effects on ambient air quality through ambient monitoring and/or dispersion modeling.

BACT specifies a level of emissions control a process must have. BACT can be a piece of add-on control equipment such as a catalytic incinerator or baghouse, or can involve process modifications or work-practice standards such as the use of water-based paints as opposed to solvent-based paints, or ensuring solvent storage tanks are covered when not in use. A control technology review is done in the preparation of a PSD permit to determine what other, similar sources have used as a BACT level of control. This ensures that suggested BACT is at least as effective as what has been previously used.

### ***New Source Review***

The NSR provisions were established at the same time as the PSD provisions and regulate new major sources and major modifications in nonattainment areas. The NSR provisions are more stringent than the PSD provisions. The goal of the NSR program is to improve the ambient air quality in areas that do not meet the NAAQS.

NSR requires that each new major source or major modification install a Lowest Achievable Emission Rate (LAER) level of emissions control, obtain emissions offsets equal to the source's emission rate plus a penalty for cleaner air, and investigate alternate sites for the proposed expansion. Unlike the PSD provisions, a major source under NSR depends on the classification of the nonattainment area the source is to be constructed in. For example, a major source in an extreme ozone nonattainment area is any source emitting more than 10 tpy of VOCs. However, in a moderate nonattainment area a major source is any source emitting more than 100 tpy of VOCs.

Under NSR, a LAER level of control is required to be installed. This level of control is similar to BACT in that it is at least as stringent, but often is more stringent and is related to process modification. The LAER level of control is determined on a case-by-case basis as is BACT emissions control.

Emissions offsets are also required under the NSR provisions. Emissions offsets are a method of lowering total emissions in a nonattainment area by requiring new sources to first reduce emissions from an existing operating source. This is done by a ratio such that for the total new emissions a greater amount of existing emissions will be offset or eliminated. This reduction in existing emissions can result from adding new controls on existing sources, shutting existing sources down, or purchasing "banked" offsets from another company that has previously shut a source down and has documented these emissions.

### ***New Source Performance Standards***

NSPS are based on the premise that new sources should be able to operate with lesser amounts of emissions than older sources. As a result, the NSPS establish emission rates for specific pollutants for specific sources that have been constructed since 1971. NSPS standards have been established for more than 60 different types of sources.

### ***Hazardous Air Pollutants***

The emission of HAPs was originally regulated in 1970 when Congress authorized the U.S. EPA to establish standards for HAPs not regulated under the NAAQS. The National Emission Standards for Hazardous Air Pollutants (HESHAP) program was developed for this purpose. However, this program was ineffective and managed to regulate only seven hazardous compounds by 1990: asbestos, benzene, mercury, beryllium, vinyl chloride, arsenic, and radionuclides.

In 1990, a new HAPs program was established to regulate a new list of 189 hazardous compounds. The U.S. EPA has the authority to modify the list and issue a clarification regarding listed chemicals such as has been done with the “certain glycol-ether” category. Industry may also petition to have substances deleted from the list as a group successfully did in 1996 to have caprolactam removed from the list. [Table 12.3](#) lists the 188 regulated HAPs. This program regulates major sources of HAPs by requiring the installation of Maximum Achievable Control Technology (MACT) and assessment of residual risk after the application of MACT.

A major HAPs emission is any source with the potential to emit 10 tpy of any single HAP or 25 tpy of any combination of three or more HAPs. Federal EPA has developed MACT standards for many but not all industrial categories. Many industries are still awaiting final rulings. This has resulted in states implementing case-by-case MACT to prevent significant increases in HAP emissions prior to the federal promulgation of MACT standards for an industry category. This requires the state departments of environmental quality to demand the installation or incorporation of control technologies at least as stringent as any other control device being used in or on a similar process on newly constructed and reconstructed facilities.

### ***Title V Permits***

Title V of the Clean Air Act established a national air permit program. States and Regions must develop permitting programs as stringent as or more so than those set forth by the U.S. EPA. Title V requires major sources of criteria pollutants, sources subject to NSPS, municipal waste incinerators, PSD & NSR sources, and major air toxics sources to obtain a Title V operating permit. Facilities may avoid the Title V permit process by formally agreeing to restrict emissions below thresholds via the use of a synthetic minor permit or Federally Enforceable State Operating Permit (FESOP). These are filed and negotiated with the state permitting agency or local air board.

Preparation of the Title V permit application is not a trivial task. The paperwork associated with applications for a moderate size facility is often measured in feet. Consistency, attention to detail, and clear communication with the permit granting authority will speed the application process. In general a Title V permit requires the following:

- Identification: Including each process with its feed stocks and emission points.
- Emissions: Must be estimated from each process.
- Applicable Regulations: Must be identified for each process and the facility as a whole.
- Compliance Demonstration: Show how the facility is in compliance with applicable regulations for each process.
- Compliance Dedication: Show how the facility and each process will remain in compliance with applicable regulations for each process.
- Certification: A responsible company representative must verify the information provided is truthful and accurate.

*Source:* Air Quality Permitting, R. Leon Leonard

The permit preparer should refer to the specific state application forms and presiding authority where the facility is located for further guidance in permit preparation.

### ***Compliance Assurance Monitoring***

Title VI of the Clean Air Act Amendments includes Compliance Assurance Monitoring (CAM) provisions. The CAM rule, issued in 1997, requires operators of emissions control equipment to monitor the operation and maintenance of their control equipment. Performance tests and design parameters are used to determine a normal range or “indicator range” of operation. If the control device is later found to be out of this “indicator range” steps must be taken to investigate the aberration and correct it if the control device is found to be faulty. State and local authorities must be informed of any non-compliance status that occurred or is occurring due to problems associated with the control device. Extended operation of a control device outside of its prescribed normal condition can result in state mandated intensive evaluation and improvement of control practices.

**TABLE 12.3** Hazardous Air Pollutants

Chemical Abstract Service #	Chemical Name
75-07-0	Acetaldehyde
60-35-5	Acetamide
75-05-8	Acetonitrile
98-86-2	Acetophenone
53-96-3	2-Acetylaminofluorene
107-02-8	Acrolein
79-06-1	Acrylamide
79-10-7	Acrylic acid
107-13-1	Acrylonitrile
107-05-1	Allyl chloride
62-53-3	Aniline
90-04-0	o-Anisidine
1332-21-4	Benzene (including benzene from gasoline)
92-87-5	Benzidine
98-07-7	Benzotrichloride
117-81-7	Bis(2-ethylhexyl)phthalate (DEHP)
542-88-1	Bis(chloromethyl) ether
72-25-2	Bromoform
106-99-0	1,3-Butadiene
156-62-7	Calcium cyanamide
105-60-2	Caprolactam (Removed 6/18/96, 61FR30816)
133-06-2	Captan
63-25-2	Carbaryl
75-15-0	Carbon disulfide
56-23-5	Carbon tetrachloride
463-58-1	Carbonyl sulfide
120-80-9	Catechol
133-90-4	Chloramben
57-74-9	Chlordane
7782-50-5	Chlorine
79-11-8	Chloroacetic acid
532-27-4	2-Chloroacetophenone
108-90-7	Chlorobenzene
510-15-6	Chlorobenzilate
67-66-3	Chloroform
107-30-2	Chloromethyl methyl ether
126-99-8	Chloroprene
1319-77-3	Cresol/Cresylic acid (mixed isomers)
95-48-7	o-Cresol
108-39-4	m-Cresol
106-44-5	p-Cresol
98-82-8	Cumene
N/A	2,4-D (2,4-Dichlorophenoxyacetic Acid) (including salts and esters)
72-55-9	DDE (1,1-dichloro-2,2-bis(p-chlorophenyl) ethylene)
334-88-3	Diazomethane
132-64-9	Dibenzofuran
96-12-8	1,2-Dibromo-3-chloropropane
84-74-2	Dibutyl phthalate
106-46-7	1,4-Dichlorobenzene
91-94-1	3,3'-Dichlorobenzidine
111-44-4	Dichloroethyl ether (Bis[2-chloroethyl]ether)
542-75-6	1,3-Dichloropropene
62-73-7	Dichlorvos
111-42-2	Diethanolamine
64-67-5	Diethyl sulfate
119-90-4	3,3'-Dimethoxybenzidine

**TABLE 12.3 (continued)** Hazardous Air Pollutants

Chemical Abstract Service #	Chemical Name
60-11-7	4-Dimethylaminoazobenzene
121-69-7	N,N-Dimethylaniline
119-93-7	3,3'-Dimethylbenzidine
79-44-7	Dimethylcarbamoyl chloride
68-12-2	N,N-Dimethylformamide
57-14-7	1,1-Dimethylhydrazine
131-11-3	Dimethyl phthalate
77-78-1	Dimethyl sulfate
N/A	4,6-Dinitro-o-cresol (including salts)
51-28-5	2,4-Dinitrophenol
121-14-2	2,4-Dinitrotoluene
123-91-1	1,4-Dioxane (1,4-Diethyleneoxide)
122-66-7	1,2-Diphenylhydrazine
106-89-8	Epichlorohydrin (1-Chloro-2,3-epoxypropane)
106-88-7	1,2-Epoxybutane
140-88-5	Ethyl acrylate
100-41-4	Ethylbenzene
51-79-6	Ethyl carbamate (Urethane)
75-00-3	Ethyl chloride (Chloroethane)
106-93-4	Ethylene dibromide (Dibromoethane)
107-06-2	Ethylene dichloride (1,2-Dichloroethane)
107-21-1	Ethylene glycol
151-56-4	Ethyleneimine (Aziridine)
75-21-8	Ethylene oxide
96-45-7	Ethylene thiourea
75-34-3	Ethylidene dichloride (1,1-Dichloroethane)
50-00-0	Formaldehyde
76-44-8	Heptachlor
118-74-1	Hexachlorobenzene
87-68-3	Hexachlorobutadiene
N/A	1,2,3,4,5,6-Hexachlorocyclohexane (all stereo isomers, including lindane)
77-47-4	Hexachlorocyclopentadiene
67-72-1	Hexachloroethane
822-06-0	Hexamethylene diisocyanate
680-31-9	Hexamethylphosphoramide
110-54-3	Hexane
302-01-2	Hydrazine
7647-01-0	Hydrochloric acid (Hydrogen Chloride)
7664-39-3	Hydrogen fluoride (Hydrofluoric acid)
123-31-9	Hydroquinone
78-59-1	Isophorone
108-31-6	Maleic anhydride
67-56-1	Methanol
72-43-5	Methoxychlor
74-83-9	Methyl bromide (Bromomethane)
74-87-3	Methyl chloride (Chloromethane)
71-55-6	Methyl chloroform (1,1,1-Trichloroethane)
78-93-3	Methyl ethyl ketone (2-Butanone)
60-34-4	Methylhydrazine
74-88-4	Methyl iodide (Iodomethane)
108-10-1	Methyl isobutyl ketone (Hexone)
624-83-9	Methyl isocyanate
80-62-6	Methyl methacrylate
1634-04-4	Methyl tert-butyl ether
101-14-4	4-4'-Methylenebis(2-chloroaniline)
75-09-2	Methylene chloride (Dichloromethane)

**TABLE 12.3 (continued)** Hazardous Air Pollutants

Chemical Abstract Service #	Chemical Name
101-68-8	4,4'-Methylenediphenyl diisocyanate (MDI)
101-77-9	4,4'-Methylenedianiline
91-20-3	Naphthalene
98-95-3	Nitrobenzene
92-93-3	4-Nitrobiphenyl
100-02-7	4-Nitrophenol
79-46-9	2-Nitropropane
684-93-5	N-Nitroso-N-methylurea
62-75-9	N-Nitrosodimethylamine
59-89-2	N-Nitrosomorpholine
56-38-2	Parathion
82-68-8	Pentachloronitrobenzene (Quintobenzene)
87-86-5	Pentachlorophenol
108-95-2	Phenol
106-50-3	p-Phenylenediamine
75-44-5	Phosgene
7803-51-2	Phosphine
7723-14-0	Phosphorus
85-44-9	Phthalic anhydride
1336-36-3	Polychlorinated biphenyls (Aroclors)
1120-71-4	1,3-Propane sultone
57-57-8	beta-Propiolactone
123-38-6	Propionaldehyde
114-26-1	Propoxur (Baygon)
78-87-5	Propylene dichloride (1,2-Dichloropropane)
75-56-9	Propylene oxide
75-55-8	1,2-Propylenimine (2-Methylaziridine)
91-22-5	Quinoline
106-51-4	Quinone (p-Benzoquinone)
100-42-5	Styrene
96-09-3	Styrene oxide
1746-01-6	2,3,7,8-Tetrachlorodibenzo-p-dioxin
79-34-5	1,1,2,2-Tetrachloroethane
127-18-4	Tetrachloroethylene (Perchloroethylene)
7550-45-0	Titanium tetrachloride
108-88-3	Toluene
95-80-7	Toluene-2,4-diamine
584-84-9	2,4-Toluene diisocyanate
95-53-4	o-Toluidine
8001-35-2	Toxaphene
120-82-1	1,2,4-Trichlorobenzene
79-00-5	1,1,2-Trichloroethane
79-01-6	Trichloroethylene
95-95-4	2,4,5-Trichlorophenol
88-06-2	2,4,6-Trichlorophenol
121-44-8	Triethylamine
1582-09-8	Trifluralin
540-84-1	2,2,4-Trimethylpentane
108-05-4	Vinyl acetate
593-60-2	Vinyl bromide
75-01-4	Vinyl chloride
75-35-4	Vinylidene chloride (1,1-Dichloroethylene)
1330-20-7	Xylenes (mixed isomers)
95-47-6	o-Xylene
108-38-3	m-Xylene
106-42-3	p-Xylene

**TABLE 12.3 (continued)** Hazardous Air Pollutants

Chemical Abstract Service #	Chemical Name
	Antimony Compounds
	Arsenic Compounds (inorganic including arsine)
	Beryllium Compounds
	Cadmium Compounds
	Chromium Compounds
	Cobalt Compounds
	Coke Oven Emissions
	Cyanide Compounds <sup>1</sup>
	Glycol ethers <sup>2</sup>
	Lead Compounds
	Manganese Compounds
	Mercury Compounds
	Fine mineral fibers <sup>3</sup>
	Nickel Compounds
	Polycyclic Organic Matter <sup>4</sup>
	Radionuclides (including radon) <sup>5</sup>
	Selenium Compounds

*Note:* For all listings above which contain the word “compounds” and for glycol ethers, the following applies: Unless otherwise specified, these listings are defined as including any unique chemical substance that contains the named chemical (i.e., antimony, arsenic, etc.) as part of that chemical’s infrastructure.

<sup>1</sup> X’CN where X = H’ or any other group where a formal dissociation may occur. For example, KCN or Ca(CN)<sub>2</sub>.

<sup>2</sup> On January 12, 1999 (64FR1780), the EPA proposed to modify the definition of glycol ethers to exclude surfactant alcohol ethoxylates and their derivatives (SAED). On August 2, 2000 (65FR47342), the EPA published the final action. This action deletes individual compounds in a group called the surfactant alcohol ethoxylates and their derivatives (SAED) from the glycol ethers category in the list of hazardous air pollutants (HAP) established by section 112(b)(1) of the Clean Air Act (CAA). EPA also made conforming changes in the definition of glycol ethers with respect to the designation of hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

The following definition of the glycol ethers category of hazardous air pollutants applies instead of the definition set forth in 42 U.S.C. 7412(b)(1), footnote 2: Glycol ethers include mono- and di-ethers of ethylene glycol, diethylene glycol, and triethylene glycol R-(OCH<sub>2</sub>CH<sub>2</sub>)<sub>n</sub>-OR’

Where:

n = 1, 2, or 3

R = alkyl C7 or less, or phenyl or alkyl substituted phenyl

R’ = H, or alkyl C7 or less, or carboxylic acid ester, sulfate, phosphate, nitrate, or sulfonate

The U.S. EPA maintains a summary of modifications to the list of air toxics at (<http://www.epa.gov/ttn/atw/atwsmod.html>). On this page is an extensive (200+ pages) list of many of the chemicals within the glycol ethers category.

<sup>3</sup> (Under Review) Includes mineral fiber emissions from facilities manufacturing or processing glass, rock, or slag fibers (or other mineral derived fibers) of average diameter 1 micrometer or less.

<sup>4</sup> (Under Review) Includes organic compounds with more than one benzene ring, and which have a boiling point greater than or equal to 100°C. Limited to, or refers to, products from incomplete combustion or organic compounds (or material) and pyrolysis processes having more than one benzene ring, and which have a boiling point greater than or equal to 100°C.

<sup>5</sup> A type of atom which spontaneously undergoes radioactive decay.

### ***State and Local Air Quality Programs***

In addition to the federal air quality programs described above, many state and local governments have their own air quality regulations. These regulations are required to be at least as stringent as the federal programs; many are far more stringent.

One of the most common requirements at the state and local levels of regulation is the requirement for all new sources, regardless of size, to obtain an air pollution construction permit prior to beginning construction of the source. In many cases, small sources are determined to be exempt from the permitting requirements, or are merely given registration status as opposed to a full construction and operating permit. Nonetheless, even small sources are required to give notification prior to beginning construction or face serious penalties for not doing so.

## 12.3 Emissions Estimation

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Estimation of emissions from a source is a process which involves the qualification and quantification of pollutants that are generated by the source. This process is of paramount importance as the emission estimates will be used to describe the applicability of various regulations, and thus influence how the source is constructed and operated.

To begin the process of estimation, the source must be reviewed to determine its size and nature. This includes the quantification of all raw material inputs (existing or planned), production steps, and release points to qualify what types of emissions might possibly exist. In this step, review of similar sources is imperative as this information can provide a vast array of information that is easily overlooked. The reader is referred to the Air and Waste Management Association's *Air Pollution Engineering Manual* or the U.S. EPA's AP-40 as references for the review of similar sources. These texts provide an overview of a variety of industrial processes and the types and quantities of emissions they generate and emissions controls they employ.

After the source has been reviewed and the potential emissions qualified, the process of assessing the quantities of pollutants that are or can be emitted can begin.

Typically, emissions estimates are generated in two ways: by mass balance or by the use of emission factors. A mass balance is a process based on the fact that because mass is neither created nor destroyed, the mass of raw material into an operation can be quantified and proportioned as to their amounts in either the finished product or in a waste stream. As a result, the portion of the raw materials released into the air can be quantified. However, an appropriate mass balance is a difficult task as there are typically many different raw material inputs into a facility, making the process very complex. Further, many types of raw material inputs result in emissions that are not readily apparent. Because of these factors, the mass balance approach to estimating emissions is not recommended.

The second method of quantifying emissions is the use of an emission factor. An emission factor is a relation between a common operation and the average emissions it generates. For example, the combustion of 1,000,000 standard cubic feet of natural gas in a small industrial boiler results in the emission of 35 pounds of CO. Therefore, the emission factor would be 35 lb CO/10<sup>6</sup> scf of natural gas combusted. Emission factors are generated simply by relating emissions to a representative operating variable, and are often a single number that is the weight of pollutant divided by a unit weight of the activity that generates the pollutant [U.S. EPA, 1993]. Further, when operating variables become complex or contain a number of variables, the emission factor might consist of a series of equations encompassing the variables to determine emissions.

The use of emission factors is common, and the U.S. EPA compiles emission factors for almost every conceivable process. These factors are published in a manual entitled the *Compilation of Air Pollutant Emission Factors*, or AP-42, available from the National Technical Information Service (NTIS) Wide Web at ([www.epa.gov/ttn/chief](http://www.epa.gov/ttn/chief)). Recent revisions have reduced the number of subcategories within general process emission groups, for example: particulate emission factors for natural gas combustion were previously divided into utility/large boilers, small industrial boilers, commercial boilers, and residential furnaces. Recent revisions of the natural gas emission factors present only a single PM emission factor without regard to the size of the source. This reflects recent analysis that demonstrated boiler emission factors were generally dependant on operating practices and not so dependant on the physical characteristics and capacity of the boiler. Examples of typical emission factors are given in Tables 12.4, 12.5, and 12.6.

**TABLE 12.4** Emission Factors for Criteria Pollutants and Greenhouse Gases from Natural Gas Combustion<sup>a</sup>

Pollutant	Emission Factor (lb/10 <sup>6</sup> scf)	Emission Factor Rating
CO <sub>2</sub> <sup>b</sup>	120,000	A
Lead	0.0005	D
N <sub>2</sub> O (Uncontrolled)	2.2	E
N <sub>2</sub> O (Controlled-low-NO <sub>x</sub> burner)	0.64	E
PM (Total) <sup>c</sup>	7.6	D
PM (Condensable) <sup>c</sup>	5.7	D
PM (Filterable) <sup>c</sup>	1.9	B
SO <sub>2</sub> <sup>d</sup>	0.6	A
TOC	11	B
Methane	2.3	B
VOC	5.5	C

<sup>a</sup> Units are in pounds of pollutant per million standard cubic feet of natural gas fired. Data are for all natural gas combustion sources. To convert from lb/10<sup>6</sup> scf to kg/10<sup>6</sup> m<sup>3</sup>, multiply by 16. To convert from lb/10<sup>6</sup> scf to lb/MMBtu, divide by 1020. The emission factors in this table may be converted to other natural gas heating values by multiplying the given emission factor by the ratio of the specified heating value to the average natural gas heating value of 1020 BTU/scf. TOC = Total Organic Compounds. VOC = Volatile Organic Compounds.

<sup>b</sup> Based on approximately 100% conversion of fuel carbon to CO<sub>2</sub>. CO<sub>2</sub>[lb/10<sup>6</sup> scf] = (3.67) (CON)(C)(D), where CON = fractional conversion of fuel carbon to CO<sub>2</sub>, C = carbon content of fuel by weight (0.76), and D = density of fuel, 4.2 × 10<sup>4</sup> lb/10<sup>6</sup> scf.

<sup>c</sup> All PM (total, condensable, and filterable) is assumed to be less than 1.0 μm in diameter. Therefore, the PM emission factors presented here may be used to estimate PM<sub>10</sub>, PM<sub>2.5</sub>, or PM<sub>1</sub> emissions. Total PM is the sum of the filterable PM and condensable PM. Condensable PM is the particulate matter collected using EPA Method 202 (or equivalent). Filterable PM is the particulate matter collected on, or prior to, the filter of an EPA Method 5 (or equivalent) sampling train.

<sup>d</sup> Based on 100% conversion of fuel sulfur to SO<sub>2</sub>. Assumes sulfur content in natural gas of 2000 grains/10<sup>6</sup> scf. The SO<sub>2</sub> emission factor in this table can be converted to other natural gas sulfur contents by multiplying the SO<sub>2</sub> emission factor by the ratio of the site-specific sulfur content (grains/10<sup>6</sup> scf) to 2000 grains/10<sup>6</sup> scf.

Source: U.S. EPA. 1998. AP-42 Section 1.4 Natural Gas Combustion

The use of emissions factors is relatively simple and typically consists of the process of unit cancellation once the quantity of operational variable has been determined. For example, the determination of annual emissions from a 20 MMBtu/hr (MMBtu denotes a million British thermal units) natural-gas-fired boiler consists of the following process.

### Example 12.1

Natural gas higher heating value (HHV) = 1,020 Btu/scf. Therefore, the boiler uses

$$\left( \frac{20,000,000 \text{ Btu/hr}}{1020 \text{ Btu/ft}^3} \right) = 19,608 \text{ ft}^3/\text{hr} \quad (12.1)$$

or for operation over 8760 hours/year, annual use is

$$19,608 \frac{\text{ft}^3}{\text{hr}} \times 8760 \frac{\text{hr}}{\text{year}} = 1.718 \times 10^8 \frac{\text{ft}^3}{\text{year}} \quad (12.2)$$

**TABLE 12.5** Emission Factors for Nitrogen Oxide (NO<sub>x</sub>) and Carbon Monoxide (CO) from Natural Gas Combustion<sup>a</sup>

Combustor Type (MMBtu/hr Heat Input) [SCC]	NO <sub>x</sub> <sup>b</sup>		CO	
	Emission Factor (lb/10 <sup>6</sup> scf)	Emission Factor Rating	Emission Factor (lb/10 <sup>6</sup> scf)	Emission Factor Rating
Large Wall Fired Boilers (>100) [1-01-006-1, 1-02-006-01, 1-03-006-01]				
Uncontrolled (Pre-NSPS) <sup>c</sup>	280	A	84	B
Uncontrolled (Post-NSPS) <sup>c</sup>	190	A	84	B
Controlled-Low NO <sub>x</sub> burners	140	A	84	B
Controlled-Flue gas recirculation	100	D	84	B
Small Boilers (<100) [1-01-006-02, 1-02-006-02, 1-03-006-02, 1-03-006-03]				
Uncontrolled	100	B	84	B
Controlled-Low NO <sub>x</sub> burners	50	D	84	B
Controlled-Flue gas recirculation	32	C	84	B
Tangential-Fired Boilers (All Sizes) [1-01-006-04]				
Uncontrolled	170	A	24	C
Controlled-Flue gas recirculation	76	D	98	D
Residential Furnaces (<0.3) [No SCC]				
Uncontrolled	94	B	40	B

<sup>a</sup> Units are in pounds of pollutant per million standard cubic feet of natural gas fired. To convert from lb/10<sup>6</sup> m<sup>3</sup>, multiply by 16. Emission factors are based on an average natural gas higher heating value of 1020 Btu/scf. To convert from lb/10<sup>6</sup> scf to lb/MMBtu, divide by 1020. The emission factors in this table may be converted to other natural gas heating values by multiplying the given emission factor by the ratio of the specified heating value to this average heating value. SCC - Source Classification Code.

<sup>b</sup> Expressed as NO<sub>2</sub>. For large and small wall fired boilers with SNCR control, apply a 24 percent reduction to the appropriate NO<sub>x</sub> emission factor. For tangential-fired boilers with SNCR control, apply a 13% reduction to the appropriate NO<sub>x</sub> emission factor.

<sup>c</sup> NSPS = New Source Performance Standard as defined in 40 CFR 60 Subparts D and Db. Post-NSPS units are boilers with greater than 250 MMBtu/hr of heat input that commenced construction modification, or reconstruction after August 17, 1971, and units with heat input capacities between 100 and 250 MMBtu/hr that commenced construction modification, or reconstruction after June 19, 1984.

thus, the operational variable for the emission factor has been quantified for annual use. Now, turning to Tables 12.4 through 12.6, the emissions factors are used for a small, uncontrolled industrial boiler. Emissions are determined in the following manner. For filterable particulate matter, the emission factor = 1.9 lb/10<sup>6</sup> ft<sup>3</sup> (Table 12.4):

$$\frac{1.9 \text{ lb}}{10^6 \text{ ft}^3} \times 1.718 \times 10^8 \frac{\text{ft}^3}{\text{year}} = 326 \text{ lb part/year} \quad (12.3)$$

For condensible particulate matter, the emission factor = 5.7 lb/10<sup>6</sup> ft<sup>3</sup> (Table 12.4):

$$\frac{5.7 \text{ lb}}{10^6 \text{ ft}^3} \times 1.718 \times 10^8 \frac{\text{ft}^3}{\text{year}} = 979 \text{ lb part/year} \quad (12.4)$$

For sulfur dioxide, the emission factor = 0.6 lb/10<sup>6</sup> ft<sup>3</sup> (Table 12.5):

$$\frac{0.6 \text{ lb}}{10^6 \text{ ft}^3} \times 1.718 \times 10^8 \frac{\text{ft}^3}{\text{year}} = 103 \text{ lb SO}_2/\text{year} \quad (12.5)$$

**TABLE 12.6** Selected Hazardous Air Pollutant Emission Factors from Natural Gas Combustion<sup>a,b,c</sup>

CAS No.	Pollutant	Emission Factor (lb/10 <sup>6</sup> scf)	Emission Factor Rating
71-43-2	Benzene	2.1 E-03	B
25321-22-6	Dichlorobenzene	1.2 E-03	E
206-44-0	Fluoranthene	3.0 E-06	E
86-73-7	Fluorene	2.8 E-06	E
50-00-0	Formaldehyde	7.5 E-02	B
110-54-3	Hexane	1.8 E+00	E
91-20-3	Napthalene	6.1 E-4	E
108-88-3	Toluene	3.4 E-3	C
7440-50-8	Copper	8.5 E-04	C
7440-02-0	Nickel	2.1 E-03	C

<sup>a</sup> Units are in pounds of pollutant per million standard cubic feet of natural gas fired. To convert from lb/10<sup>6</sup> scf to kg/10<sup>6</sup> m<sup>3</sup>, multiply by 16. Data are for all natural gas combustion sources. Emission factors are based on an average natural gas higher heating value of 1020 Btu/scf. To convert from lb/10<sup>6</sup> scf to lb/MMBtu, divide by 1020. The emission factors in this table may be converted to other natural gas heating values by multiplying the given emission factor by the ratio of the specified heating value to this average heating value.

<sup>b</sup> Hazardous Air Pollutant as defined by Section 112(b) of the Clean Air Act.

<sup>c</sup> This table does not contain all metal or speciated organic compound emission factors for natural gas combustion. Selected emission factors were chosen. Refer to AP-42 for the complete compilation of emission factors.

For nitrogen oxides (NO<sub>x</sub>), the emission factor = 100 lb/10<sup>6</sup> ft<sup>3</sup> (Table 12.5):

$$\frac{100 \text{ lb}}{10^6 \text{ ft}^3} \times 1.718 \times 10^8 \frac{\text{ft}^3}{\text{year}} = 17,200 \text{ lb NO}_x/\text{year} \quad (12.6)$$

For carbon monoxide, the emission factor = 84 lb/10<sup>6</sup> ft<sup>3</sup> (Table 12.5):

$$\frac{84 \text{ lb}}{10^6 \text{ ft}^3} \times 1.718 \times 10^8 \frac{\text{ft}^3}{\text{year}} = 14,400 \text{ lb CO/year} \quad (12.7)$$

For VOC, the emission factor = 5.5 lb/10<sup>6</sup> ft<sup>3</sup> (Table 12.4):

$$\frac{5.5 \text{ lb}}{10^6 \text{ ft}^3} \times 1.718 \times 10^8 \frac{\text{ft}^3}{\text{year}} = 945 \text{ lb VOC/year} \quad (12.8)$$

For Toluene, a hazardous air pollutant, the emission factor = 3.4E-03/10<sup>6</sup> ft<sup>3</sup> (Table 12.6):

$$\frac{3.4 \text{ E-03 lb}}{10^6 \text{ ft}^3} \times 1.718 \times 10^8 \frac{\text{ft}^3}{\text{year}} = 0.584 \text{ lb Toluene/year} \quad (12.9)$$

## 12.4 Stack Sampling

In the field of air pollution, the process of quantifying emissions is often referred to as air or stack sampling. This process consists of examining a sample of gas from the emission stream to determine both the physical characteristics of the stream and the concentrations of pollutants contained therein. While this seems relatively easy, the process is somewhat more complicated because of the nature of the medium being sampled.

As opposed to a liquid sample that can be contained, transported, and examined in a remote location with relative ease, a gas sample obtained on-site must either be quantified directly or be altered such that the constituents contained within the sample are immobilized. Immobilization is necessary because it is impractical to transport an actual quantity of the gas sample for later analysis. However, even though the sample has been transformed for evaluation at a separate location, the sample must still provide an accurate depiction of the pollutants in the gas stream being emitted. As the pollutants of concern consist of both the solid and gaseous states, sampling methods consist of a wide variety of procedures that are specific to the pollutant of concern. These methods vary from sampling for entrained particulate to the detection of multitudes of different organics and inorganics.

As a wide variety of procedures exist, the U.S. EPA has standardized these procedures and codified them such that the data resulting from their application are precise and accurate if appropriate methods are used in specific sampling scenarios. These procedures or methods refer directly to the analysis of one or more pollutants. Table 12.7 is a listing of the currently approved U.S. EPA methods with their title and appropriate *Code of Federal Regulations* reference. It should be noted that the references for the technical corrections should be reviewed in addition to the original citation for a complete description of the relevant sampling methodology.

All of the methods listed in Table 12.7 employ similar initial methods to measure the basic characteristics of the gas stream. For instance, sampling methods 1 through 3 consist of the measurement of the physical dimensions of the duct or stack, velocity, and CO<sub>2</sub> and O<sub>2</sub> concentrations, respectively. These methods are used to reflect on the appropriate locations and sample volumes that must be withdrawn to provide a representative sample of the gas stream. As a result, many other sampling methods employ these basic methods during their trials.

Of all the sampling methods, the first five are typically employed in most sampling scenarios. As a result of the great number and variation between all of the individual methods, this discussion will focus on the basic procedures and hardware of method 5, as this is the most common sampling method. The reader is referred to 40 CFR Part 60 for the specific sampling procedures for method 5 and other methods. Additionally, the reader is referred to *Methods of Air Sampling and Analysis* for further information on the analysis of specific compounds.

The U.S. EPA method 5 sampling train is used in the determination of particulate in gas streams. The method 5 sampling train is composed of a heated sampling probe, a sample case, and a control case. A schematic of the assembly is illustrated in Fig. 12.1.

In Fig. 12.1, the heated sampling probe is attached to the sample case. The probe consists of a nozzle of known inner diameter, a thermistor to determine stack temperature, another thermistor to determine probe temperature, and a pitot tube. Ending in a stainless steel or glass ball joint depending on the probe liner material, the probe is joined to the filter housing in the sample case by a ground glass joint. The pitot tube and thermistors are connected to the control case through the “umbilical cord” running from the sample case to the control case. The umbilical cord houses both a section of tubing the gas stream is drawn through and a wire harness connecting the control case and the sample case. This configuration results in the sample being drawn from the gas stream through the probe, the sample case, and finally the control case.

Inside the sample case, the gas stream is passed through a heated filter housing to remove particulate. The housing is heated to prevent the gas stream from falling below the dew point, and fouling the filter with moisture and most importantly to control the particulate formation temperature at 250°F. After the filter housing, the gas stream is passed through a set of four impingers immersed in an ice bath. The first two impingers are filled with a liquid-absorbing reagent (dependent on the pollutant being sampled) to remove a pollutant from the gas stream. These are followed by an empty third impinger serving as a moisture trap, and a fourth impinger filled with silica gel to adsorb any remaining moisture. As a result of passing through the sample case, the gas stream being sampled has had the particulate filtered from it, and the moisture and pollutant removed. To sample other pollutants, the contents of the first two impingers are altered to remove the specific pollutant of concern.

**TABLE 12.7** Summary of U.S. EPA Emission Test Methods

Method	Status <sup>a</sup>	Reference	Date	Description
Part 60, Appendix A				
1-29	P	62 FR 45639 42 FR	8/27/1997	Reformat, revise, amend methods.
1-8		41754 43 FR 11984	8/18/1977 3/23/1978	Velocity, Orsat, PM, SO <sub>2</sub> , NO <sub>x</sub> , etc. Corr. and amend. to M-1 thru 8.
1/24		52 Fr 34639 52 FR 42061	9/14/1987 11/2/1987	Technical corrections. Corrections.
2-25		55 FR 47471 48 FR	11/14/1990	Technical amendments.
1		45034 51 FR	9/30/1983	Reduction of number of traverse points.
1		20286 54 FR	6/4/1986	Alternative procedure for site selection.
1A		12621 48 FR	3/28/1989	Traverse points in small ducts.
2A		37592 48 FR	8/18/1983	Flow rate in small ducts — vol. meters.
2B		37594 54 FR	8/18/1983	Flow rate — stoichiometry.
2C		12621 54 FR	3/28/1989	Flow rate in small ducts — std. pitot.
2D		12621 61 FR	3/28/1989	Flow rate in small ducts — rate meters.
2E		9929 64 FR	3/12/1996	Flow rate from landfill wells.
2F		26484 64 FR	5/14/1999	3D pitot for velocity.
2G		26484 64 FR	5/14/1999	2D pitot for velocity.
2H		26484 55 FR	5/14/1999	Velocity decay near the stack wall.
3		05211 55 FR 18876	2/14/1990 5/7/1990	Molecular weight. Method 3B applicability.
3A		51 FR 21164 55 FR	6/11/1986	Instrumental method for O <sub>2</sub> and CO <sub>2</sub> .
3B		05211 61 FR	2/14/1990	Orsat for correction factors and excess air.
3C		9929 48 FR	3/12/1996	Gas composition from landfill gases.
3		49458 48 FR	10/25/1983	Addition of QA/QC.
4		55670 48 FR	12/14/1983	Addition of QA/QC.
5		55670 45 FR	12/14/1983	Addition of QA/QC.
5		66752 48 FR	10/7/1980	Filter specification change.
5		39010 50 FR	8/26/1983	DGM revision.
5		01164	1/9/1985	Incorp. DGM and probe cal. procedures.

**TABLE 12.7 (continued)** Summary of U.S. EPA Emission Test Methods

Method	Status <sup>a</sup>	Reference	Date	Description
5		52 F 09657	3/26/1987	Use of critical orifices as cal stds.
5		52 FR 22888	6/16/1987	Corrections.
5A		47 FR 34137	8/6/1982	PM from asphalt roofing (Prop. as M-26).
5A		51 FR 32454	9/12/1986	Addition of QA/QC.
5B		51 FR 42839	11/26/1986	Nonsulfuric acid PM.
5C		Tentative 49 FR		PM from small ducts.
5D		43847 51 FR	10/31/1984	PM from fabric filters.
5D		32454 50 FR	9/12/1986	Addition of QA/QC.
5E		07701 51 FR	2/25/1985	PM from fiberglass plants.
5F		42839 53 FR	11/26/1986	PM from FCCU.
5F		29681 53 FR	8/8/1988	Barium titration procedure.
5G		05860 53 FR	2/26/1988	PM from wood stove — dilution tunnel.
5H		05860 64 FR	2/26/1988	PM from wood stove — stack.
5I		53027 49 FR	9/30/1999	PM for RATA of PM CEMS.
6		26522 48 FR	6/27/1984	Addition of QA/QC.
6		39010 52 FR	8/26/1983	DGM revision.
6		41423 47 FR	10/28/1987	Use of critical orifices for FR/vol meas.
6A		54073 47 FR	12/1/1982	SO <sub>2</sub> /CO <sub>2</sub> — manual method.
6B		54073 49 FR	12/1/1982	Auto SO <sub>2</sub> /CO <sub>2</sub> .
6A/B		90684 51 FR	3/14/1984	Incorp. coll. test changes.
6A/B		32454 51 FR	9/12/1986	Addition of QA/QC.
6C		21164	6/11/1986	Instrumental method for SO <sub>2</sub> .
6C		52FR 18797	5/27/1987	Corrections.
7		49 FR 26522	6/27/1984	Addition of QA/QC.
7A		48 FR 55072	12/8/1983	Ion chromatograph NO <sub>x</sub> analysis.
7A		53 FR 20139	6/2/1988	ANPRM.
7A		55 FR 21752	5/29/1990	Revisions.
7B		50 FR 15893	4/23/1985	UV NO <sub>x</sub> analysis for nitric acid plants.
7A/B		Tentative 49 FR		High SO <sub>2</sub> interference.

**TABLE 12.7 (continued)** Summary of U.S. EPA Emission Test Methods

Method	Status <sup>a</sup>	Reference	Date	Description
7C		38232 49 FR	9/27/1984	Alkaline permanganate/colorimetric for NO <sub>x</sub> .
7D		38232 51 FR	9/27/1984	Alkaline permanganate/IC for NO <sub>x</sub> .
7E		21164 36 FR	6/11/1986	Instrumental method for NO <sub>x</sub> .
8		24876 42 FR	12/23/1971	Sulfuric Acid mist and SO <sub>2</sub> .
8		41754 43 FR	8/18/1977	Addition of particulate and moisture.
8		11984 39 FR	3/23/1978	Miscellaneous corrections.
9		39872 46 FR	11/12/1974	Opacity.
9A		53144 39 FR	10/28/1981	Lidar opacity; called Alternative 1.
10		09319 53 FR	3/8/1978	CO.
10		41333 52 FR	10/21/1988	Alternative trap.
10A		30674 52 FR	8/17/1987	Colorimetric method for PS-4.
10A		33316 53 FR	9/2/1987	Correction notice.
10B		41333 43 FR	10/21/1988	GC method for PS-4.
11		01494 47 FR	1/10/1978	H <sub>2</sub> S.
12		16564 49 FR	4/16/1982	Pb.
12		33842	8/24/1984	Incorp. method of additions.
13A		45 FR 41852 45 FR	6/20/1980	F — colorimetric method.
13B		41852 45 FR	6/20/1980	F — SIE method.
13A/B		85016 45 FR	12/24/1980	Corr. to M-13A and 13B.
14		44202	6/30/1980	F from roof monitors.
14A		Tentative 43 FR		Cassette Sampling for Total Florides.
15		10866 54 FR	3/15/1978	TRS from petroleum refineries.
15		46236 54 FR	11/2/1989	Revisions.
15		51550 52 FR	12/15/1989	Correction notice.
15A		20391 43 FR	6/1/1987	TRS alternative/oxidation.
16		07568 43 FR	2/23/1978	TRS from kraft pulp mills.
16		34784 44 FR	8/7/1978	Amend to M-16, H <sub>2</sub> S loss after filters
16		02578 54 FR	1/12/1979	Amend to M-16, SO <sub>2</sub> scrubber added.
16		46236 55 FR	11/2/1989	Revisions.

**TABLE 12.7 (continued)** Summary of U.S. EPA Emission Test Methods

Method	Status <sup>a</sup>	Reference	Date	Description
16		21752 50 FR	5/29/1990	Correction of figure ( $\pm 10\%$ ).
16A		09578 52 FR	3/8/1985	TRS alternative.
16A		36408 52 FR	9/29/1987	Cylinder gas analysis alternative method.
16B		36408 53 FR	9/29/1987	TRS alternative/GC analysis of SO <sub>2</sub> .
16A/B		02914 43 FR	2/2/1988	Correction 16A/B.
17		07568 48 FR	2/23/1978	PM, in-stack.
18		48344 49 FR	10/18/1983	VOC, general GC method.
18		22608 52 FR	5/30/1984	Corrections to M-18.
18		51105 52 FR	2/19/1987	Revisions to improve method.
18		10852	4/3/1987	Corrections.
18		59 FR 19308 44 FR	4/22/1994	Revisions to improve QA/QC.
19		33580 52 FR	6/11/1979	F-factor, coal sampling.
19		47826 48 FR	12/16/1987	M-19A incorp. into M-19.
19		49460 44 FR	10/25/1983	Corr. to F factor equations and F <sub>c</sub> value.
20		52792 47 FR	9/10/1979	NO <sub>x</sub> from gas turbines.
20		30480 51 FR	7/14/1982	Corr. and amend.
20		32454 48 FR	9/12/1986	Clarifications.
21		37598 49 FR	8/18/1983	VOC leaks.
21		56580 55 FR	12/22/1983	Corrections to Method 21.
21		25602 47 FR	6/22/1990	Clarifying revisions.
22		34137 48 FR	8/6/1982	Fugitive VE.
22		48360 56 FR	10/18/1983	Add smoke emission from flares.
23		5758 60 FR	2/13/1991	Dioxin/dibenzo furan.
23R		28378 45 FR	5/31/1995	Revisions and corrections.
24		65956 47 FR	10/3/1980	Solvent in surface coatings.
24A		50644	11/8/1982	Solvent in ink (Prop. as M-29).
24		Tentative 57 FR		Solvent in water-borne coatings.
24		30654 60 FR	7/10/1992	Multicomponent coatings.
24		47095 45 FR	9/11/1995	Radiation-cured coatings.

**TABLE 12.7 (continued)** Summary of U.S. EPA Emission Test Methods

Method	Status <sup>a</sup>	Reference	Date	Description
25		65956 53 FR	10/3/1980	TGNMO.
25		04140 53 FR	2/12/1988	Revisions to improve method.
25		11590 48 FR	4/7/1988	Correction notice.
25A		37595	8/18/1983	TOC/FID.
25B		48 FR 37597 61 FR	8/18/1983	TOC/NDIR.
25C		9929 59 FR	3/12/1996	VOC from landfills.
25D		19311 59 FR	4/22/1994	VOC from TSDF — purge procedure.
25E		62896 56 FR	12/6/1994	VOC from TSDF — vapor pressure procedure.
26		5758 57 FR	2/13/1991	HCl.
26		24550 59 FR	6/10/1992	Corrections to Method 26.
26		19309 59 FR	4/22/1994	Add 26 HCl, halogens, other hydrogen halides.
26A		19309 48 FR	4/22/1994	Isokinetic HCl, halogens, hydrogen halides.
27		37597 53 FR	8/18/1983	Tank truck leaks.
28		05860 53 FR	2/26/1988	Wood stove certification.
28A		05860 61 FR	2/26/1988	Air to fuel ratio.
29		18262	4/25/1996	Multiple metals.
Part 60, Appendix B				
PS-2-9	P	62 FR 45639 48 FR	8/27/1997	Reformat, revise, amend performance specs.
PS-1		13322 59 FR	3/30/1983	Opacity.
PS-1	P	60585 65 FR	11/25/1994	Revisions.
PS-1		48914 48 FR	8/10/2000	Revisions, final rule.
PS-2		23608 55 FR	5/25/1983	SO <sub>2</sub> and NO <sub>x</sub> .
PS 1-5		47471 48 FR	11/14/1991	Technical amendments.
PS-3		23608 50 FR	5/25/1983	CO <sub>2</sub> and O <sub>2</sub> .
PS-4		31700 56 FR	8/5/1985	CO.
PS-4A		5526 61 FR	2/11/1991	CO for MWC.
PS-4B	P	17495	4/19/1996	CO and O <sub>2</sub> for HWI (BIF rules).
PS-4B		64 FR 53032 48 FR	9/30/1999	Final rule.

**TABLE 12.7 (continued)** Summary of U.S. EPA Emission Test Methods

Method	Status <sup>a</sup>	Reference	Date	Description
PS-5		32984 53 FR	7/20/1983	TRS.
PS-6		07514 55 FR	3/9/1988	Velocity and mass emission rate.
PS-7		40171 59 FR	10/2/1990	H <sub>2</sub> S.
PS-8		64580 61 FR	12/15/1994	VOC CEMS performance specifications.
PS-8A	P	17495 64 FR	4/19/1996	VOC CEMS for HWI (BIF rules).
PS-8A		53033 59 FR	9/30/1999	Final rule.
PS-9		64580 61 FR	12/15/1994	GC CEMS performance specifications.
PS-10A	P	17495	4/19/1996	Metals CEMS.
PS-11		Tentative 61 FR		PM CEMS.
PS-11A	P	17495	4/19/1996	PM CEMS (BIF MACT).
PS-12		Tentative 61 FR		Hg CEMS.
PS-12A	P	17495	4/19/1996	Hg CEMS (BIF MACT).
PS-13		Tentative 61 FR		HCl CEMS.
PS-13A	P	17495	4/19/1996	HCl CEMS (BIF MACT).
PS-14		Tentative 61 FR		Cl CEMS.
PS-14A		17495 62 FR	4/19/1996	Cl CEMS (BIF MACT).
PS-15	P	45372	8/27/1997	FTIR CEMS.
			Part 60, Appendix F	
		52 FR		
Prc 1		21003 56 FR	6/4/1987	Quality assurance for CEMS.
Prc1		5527	2/11/1991	Revisions.
			Part 60, Appendix J	
		55 FR		
App-J		33925	8/20/1990	Wood stove thermal efficiency.
			Alternative Procedures and Miscellaneous	
		48 FR		
		44700	9/29/1983	S-Factor method for sulfuric acid plants.
		48 FR		
		48669	10/20/1983	Corrections to S-Factor publication.
		49 FR		
		30672	7/31/1984	Add fuel analysis procedures for gas turbines.
		51 FR		
		21762	6/16/1986	Alternative PST for low level concentrations.
		54 FR		
		46234	11/2/1989	Misc. revisions to Appendix A, 40 CFR Part 60.
		55 FR		
		40171	10/2/1990	Monitoring revisions to Subpart J (Petr. Ref.).
		54 FR		
		06660	2/14/1989	Test methods & procedures rev. (40 CFR 60).

**TABLE 12.7 (continued)** Summary of U.S. EPA Emission Test Methods

Method	Status <sup>a</sup>	Reference	Date	Description
		54 FR 21344	5/17/1989	Correction notice.
		54 FR 27015	6/27/1989	Correction notice.
			Part 61, Appendix B	
101-111	P	62 FR 45639	8/27/1997	Reformat, revise, amend methods.
101		47 FR 24703	6/8/1982	Hg in air streams.
101A		47 FR 24703	6/8/1982	Hg in sewage sludge incinerators.
101A		61 FR 18262	4/25/1996	Revisions — Consistency with Method 29.
101		49 FR 35768	9/12/1984	Corrections to M-101 and 101A.
102		47 FR 24703	6/8/1982	Hg in H <sub>2</sub> streams.
103		48 FR 55266	12/9/1983	Revised Be screening method.
104		48 FR 55268	12/9/1983	Revised beryllium method.
105		48 FR 48299	10/14/1975	Hg in sewage sludge.
105		49 FR 35768	9/12/1984	Revised Hg in sewage sludge.
106		47 FR 39168	9/7/1982	Vinyl chloride.
107		47 FR 39168	9/7/1982	VC in process streams.
107		52 FR 20397	6/1/1987	Alternative calibration procedure.
107A		47 FR 39485	9/8/1982	VC in process streams.
108		51 FR 28035	8/4/1986	Inorganic arsenic.
108A		51 FR 28035	8/4/1986	Arsenic in ore samples.
108B		51 FR 22026	5/31/1990	Arsenic in ore alternative.
108C		55 FR 22026	5/31/1990	Arsenic in ore alternative.
108B/C		55 FR 32913	8/13/1990	Correction notice.
111		50 FR 05197	2/6/1985	Polonium-210.
114		54 FR 51695	12/15/1989	Monitoring of radio nuclides.
115		54 FR 51702	12/15/1989	Radon-22.
Part 61				
		53 FR 36972	9/23/1988	Corrections.
			Part 51, Appendix M	
201		55 FR 14246	4/17/1990	PM-10 (EGR procedure).

**TABLE 12.7 (continued)** Summary of U.S. EPA Emission Test Methods

Method	Status <sup>a</sup>	Reference	Date	Description
201A		55 FR 14246	4/17/1990	PM-10 (CSR procedure).
201A		55 FR 24687	6/18/1990	Correction of equations.
201		55 FR 37606	9/12/1990	Correction of equations.
202		56 FR 65433	12/17/1991	Condensable PM.
203	P	57 FR 46114	10/7/1992	Transmissometer for compliance.
203A	P	58 FR 61640	11/22/1993	Visible Emissions — 2-6 min avg.
203B	P	58 FR 61640	11/22/1993	Visible Emissions — time exceptions.
203C	P	58 FR 61640	11/22/1993	Visible Emissions — instantaneous.
204		62 FR 32500	6/16/1997	VOC Capture Efficiency.
204A		62 FR 32500	6.16.1997	VOC Capture Efficiency.
204B		62 FR 32500	6/16/1997	VOC Capture Efficiency.
204C		62 FR 32500	6/16/1997	VOC Capture Efficiency.
204D		62 FR 32500	6/16/1997	VOC Capture Efficiency.
204E		62 FR 32500	6/16/1997	VOC Capture Efficiency.
204F		62 FR 32500	6/16/1997	VOC Capture Efficiency.
205		59 FR 19590	5/30/1994	Dilution calibration verification.
206		Tentative 62 FR		Ammonia (NH <sub>3</sub> ).
207	P	64532	12/8/1997	Isocyanates.
Part 63, Appendix A				
303-306	P	62 FR 45639	8/27/1997	Reformat, revise, amend methods.
301		57 FR 61970	12/29/1992	Field data validation protocol.
302				(Reserved)
303		58 FR 57898	10/27/1993	Coke Oven Door Emissions.
304A		62 FR 2793	1/17/1997	Biodegradation rate (vented).
304B		62 FR 2793	1/17/1997	Biodegradation rate (enclosed).
305		59 FR 19590	4/22/1994	Compound specific liquid waste.
306		60 FR 4948	1/25/1995	Chromium from electroplaters/anodizers.
306A		60 FR 4948	1/25/1995	Simplified Chromium sampling.
306B		60 FR 4948	1/25/1995	Surface tension of chromium suppressors.
		59 FR		

**TABLE 12.7 (continued)** Summary of U.S. EPA Emission Test Methods

Method	Status <sup>a</sup>	Reference	Date	Description
307		61801 58 FR	12/2/1994	Solvent Degreaser VOC.
308	P	66079	12/17/1993	Methanol.
309	P	62 FR	6/6/1994	Aerospace solvent recovery material balance.
310A		12546 62 FR	3/17/1997	Residual hexane in EPDM rubber.
310B		12546 62 FR	3/17/1997	Residual hexane in EPDM rubber.
310C		12546 60 FR	3/17/1997	Residual hexane in EPDM rubber.
311		62930	12/7/1995	VOC HAPS in furniture coatings.
312A		62 FR 12546 62 FR	3/17/1997	Residual styrene in SBR rubber.
312B		12546 62 FR	3/17/1997	Residual styrene in SBR rubber.
312C		12546 62 FR	3/17/1997	Residual styrene in SBR rubber.
313A		12546 62 FR	3/17/1997	Residual styrene in PBR rubber.
313B		12546	3/17/1997	Residual styrene in PBR rubber.
314		Tentative 62 FR		Halogenated compounds in solvents.
315		52418 62 FR	10/7/1997	MeCl extractable organic matter.
316	P	15257	3/31/1997	Formaldehyde — manual method.
317		Tentative 62 FR		Phenol — manual method.
318	P	52266 61 FR	3/31/1997	Formaldehyde, phenol, methanol with FTIR.
319	P	55862 64 FR	10/29/1996	Filter efficiency, paint over-spray.
320		31898 64 FR	6/14/1999	Extractive FTIR.
321		31898	6/14/1999	FTIR for HCl from Portland cement kilns.
322		Tentative		GFC/IR for HCl from Portland cement kilns.

<sup>a</sup> Unless designated by “P”, method has been promulgated. “P” implies the method is a proposal. Tentative implies the method is under evaluation.

Source: U.S. EPA, Office of Air Quality Planning and Standards.

After being drawn through the sample case, the gas stream passes through the umbilical cord to the control case. In Fig. 12.1, the control case flow path is shown, while Fig. 12.2 is a photograph of a typical control case. A vacuum gauge indicates negative pressure in the line downstream of the filter. To control flow to the pump, two valves are used. The first valve is the coarse control valve, and is plumbed immediately upstream in line with the pump. A second valve, or the fine control valve, controls a recycle stream around the pump. These valves serve to control the amount of gas sample being drawn by the system. After the pump, the gas stream passes through a dry gas meter and then through an orifice plate.

The system described above allows a known volume of gas to be drawn with known velocities in the nozzle. This is important because the velocity of the gas in the ductwork and the velocity of the sample being drawn by the system can be matched. As a result, particulate in the gas stream can be sampled in the gas stream or isokinetically. If the sample is collected such that the velocity in the nozzle is greater than in the duct, the sample is said to be superisokinetic and provides a particulate sample biased on the low side with regard to mass. A nozzle velocity below the duct velocity is said to be subisokinetic and

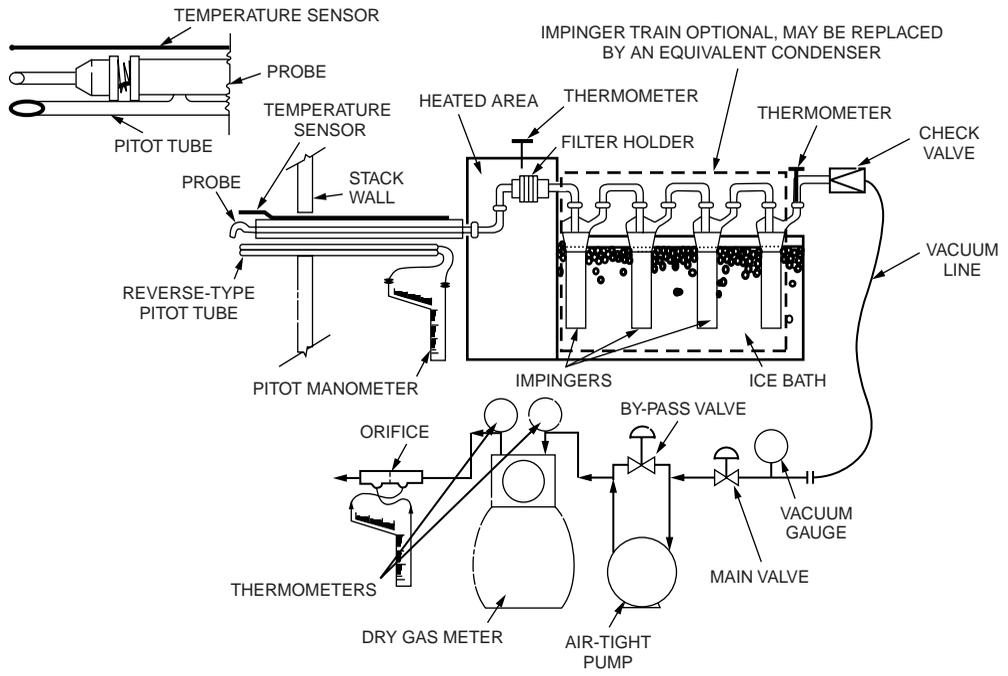


FIGURE 12.1 Method 5 sampling hardware schematic.

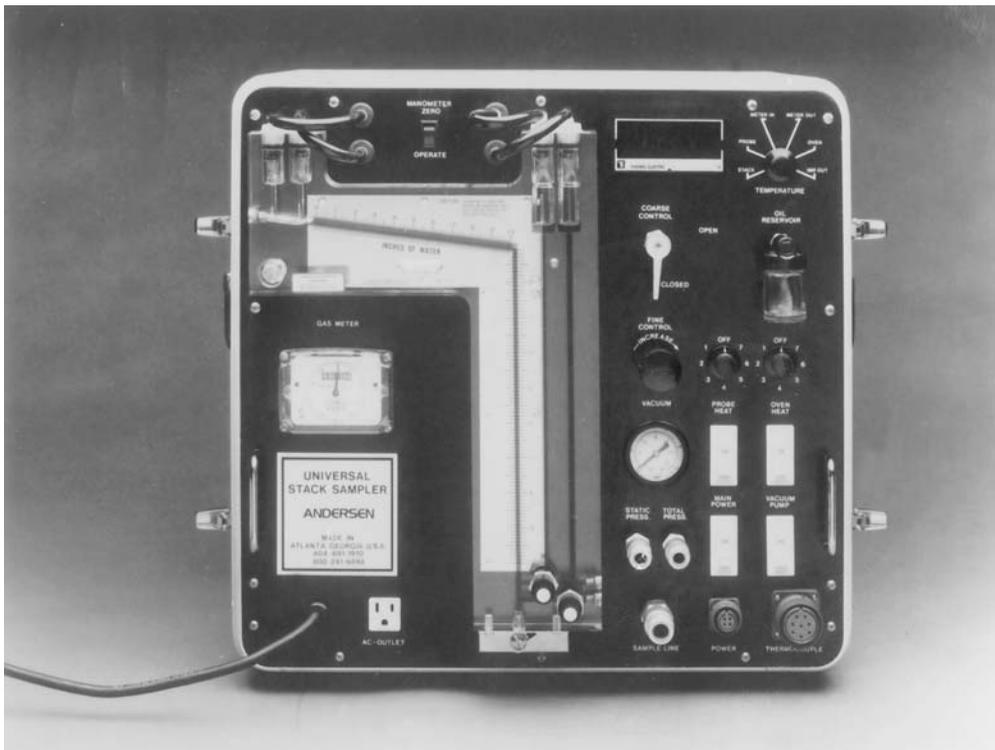


FIGURE 12.2. Typical control case.

provides a particulate sample biased on the high side with regard to mass. Thus, to provide an accurate depiction of the particulate emissions the sample needs to be isokinetic. To this end, the EPA specifies that the sample be between 90 and 110% isokinetic.

With known stack gas parameters of temperature, pressure, composition, and moisture content, values for the pressure drop across the orifice in the control case under a different temperature and pressure can be determined. Thus, with changing duct velocities, different standard flows in the system necessary to maintain appropriate nozzle velocities can be determined from the calibration graphs for the control case. As mentioned previously, standard flows are then used to determine the appropriate  $\Delta H$  (pressure drop across the orifice meter) value for a specific velocity pressure. The method 5 sampling train is unique in that both a rate meter (orifice plate) and totalizing meter (dry gas meter) allow for a post-test check of the isokinetic percentage.

## 12.5 Emissions Control

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### Particulates

#### Aerodynamic Diameter

Engineers who are concerned with the removal of solid particles from gas streams are less concerned with the physical shape of the particle and more interested in the particles' aerodynamic behavior in the gas stream. As such, the term *aerodynamic diameter* is widely used in the design and selection of air pollution control hardware for particulate control. Aerodynamic diameter can be defined as an equivalent diameter of a nonspherical particle whose actual shape can be spherical but is usually nonspherical and whose aerodynamic behavior is identical to a unit density sphere in stokes flow.

The measurement of aerodynamic diameter is best performed using isokinetic sampling procedures directly in the gas stream with a multistage impactor which has been calibrated with unit density spheres. One such impactor is the Anderson® Impactor seen in Fig. 12.3. As the particles proceed through the multistage impactor, their velocities are stepwise increased at each impaction stage. Immediately following this acceleration, the conveying gas stream is routed through 90 degree turns at each stage of the impactor. Since the particles have much greater inertia than the gas molecules, the particles cannot negotiate the 90 degree turns; that is, they deviate from the streamlines of gas flow and impact a collection surface or stage.

Each collection stage is gravimetrically analyzed and the data is presented graphically on a log-probability plot seen in Fig. 12.4. Most particulates generated by abrasion, fracturing, or condensation phenomena have aerodynamic diameters that are log-normally distributed as is reflected by the straight line shown in Fig. 12.4. This plot is very useful to the engineer either designing or selecting the appropriate control hardware. For example, particles with an extremely wide aerodynamic diameter distribution would be represented by an almost vertical line or an infinite slope in Fig. 12.4. On the other hand, particles which did not vary widely in their aerodynamic diameters would be represented by an almost horizontal line or a line with near-zero slope. Therefore, a quick glance at the slope immediately tells the engineer whether he or she is dealing with an almost infinite variability in particle sizes or a near mono-dispersion of particles.

Additionally, the intersection of the line in Fig. 12.4 with the 50% probability value on the abscissa is the mass median diameter of the particle distribution. This mass median diameter immediately tells the engineer what type of particulate control hardware probably will be needed. For example, particle diameter distributions having submicron mass median diameters require relatively high-energy devices for removal while super-micron-diameter particles require lesser amounts of energy.

Typically, for particles larger than 40 microns in aerodynamic diameter, gravity force is utilized for removal. Obviously this force is very cost-effective and if properly combined with low transport velocities and subsequently high residence times respectable removal efficiencies can result.

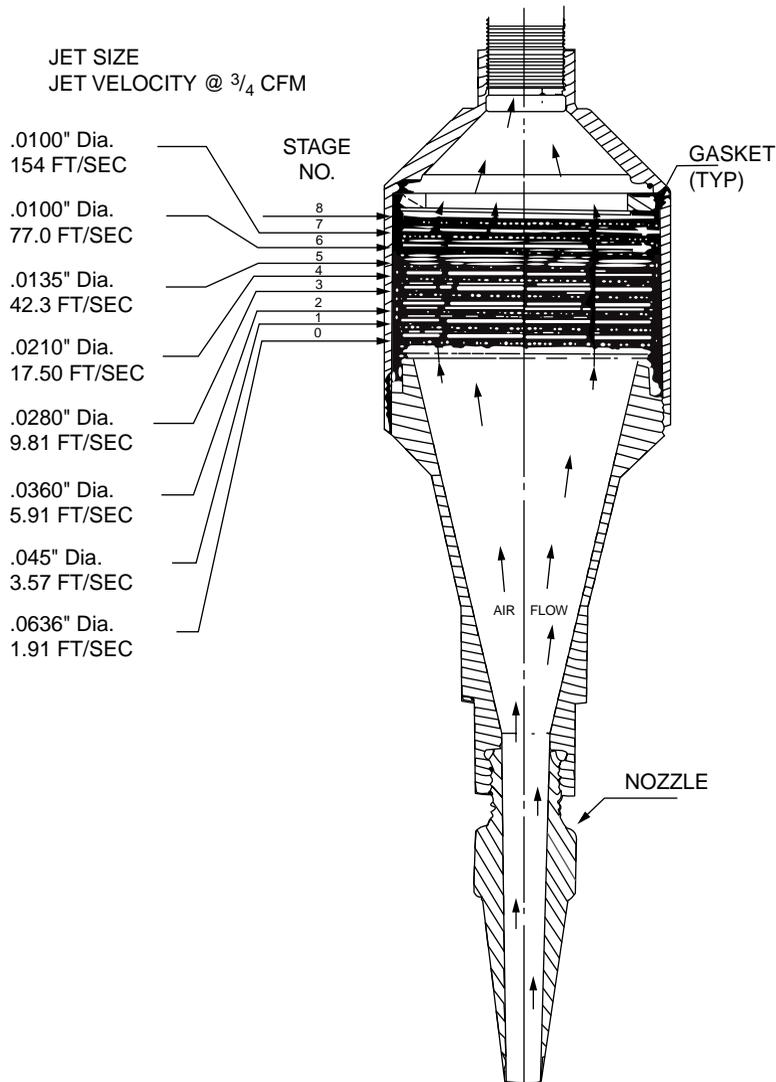


FIGURE 12.3 Anderson® impactor.

As the particles become smaller, greater forces must be brought into play for their removal. For particles between 10 to 40 microns in aerodynamic diameter, centrifugal forces are brought into play through the use of cyclones. For the removal of particles smaller than 10 microns in aerodynamic diameter, fabric filtration, electrostatic precipitators, and high-energy wet scrubbing are employed.

### Settling Chambers

Particles larger than 40 microns in aerodynamic diameter settle readily under the influence of gravity. If the particulate matter is being carried in an exhaust gas stream as opposed to fugitive dust in the atmosphere, a settling chamber is a very cost-effective device for their removal. A settling chamber is essentially a wide spot in a duct which significantly reduces the gas velocity and, therefore, the particulate transport velocity, allowing enough residence time for gravity to act on the particle and separate it from the gas stream.

A side view of a settling chamber is seen in Fig. 12.5. As the entering particle decelerates due to the increased cross-sectional area for flow, gravity force accelerates the particle to its terminal settling velocity.

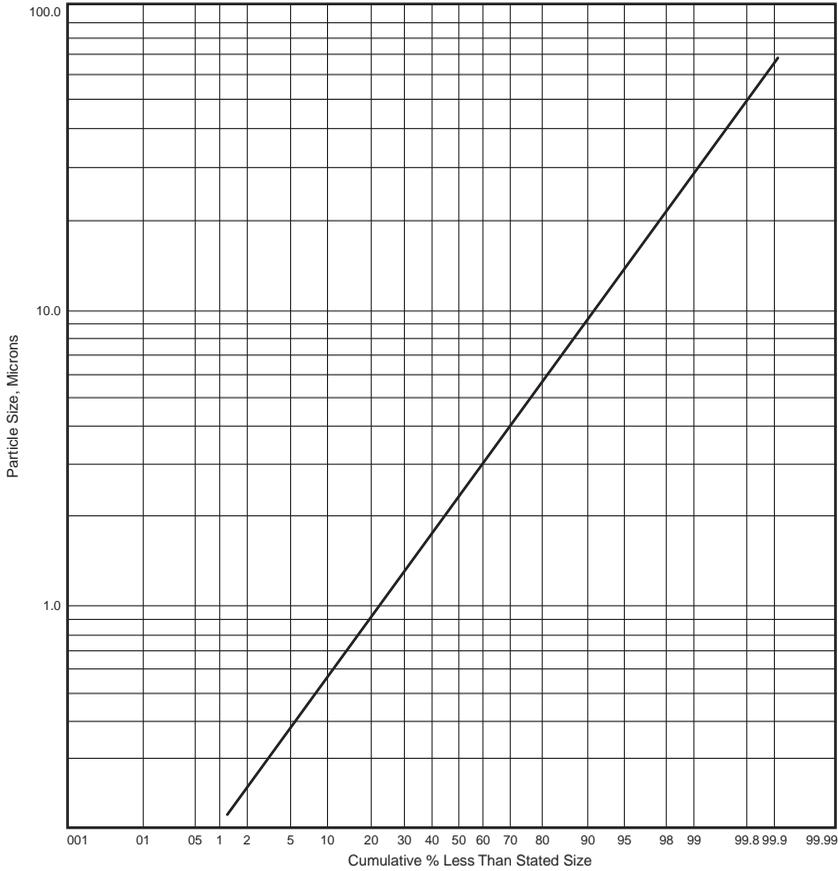


FIGURE 12.4 Log probability plot.

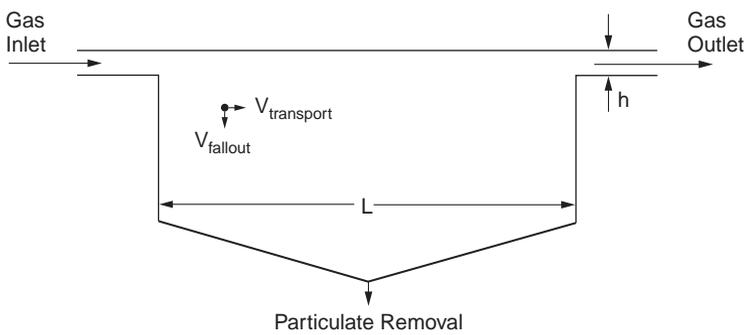


FIGURE 12.5 Settling chamber.

If the residence time in the chamber is sufficient such that the particle falls at least a distance  $h$ , the particle will be captured in the chamber. In other words, for 100% capture, a particle's fallout time must be at least be equal to or less than its transport time (residence time):

$$T_f = T_t \quad (12.10)$$

If particle fallout time is expressed as

$$T_f = \frac{h}{V_t} \quad (12.11)$$

and the particle transport time is expressed as

$$T_t = \frac{L}{V} \quad (12.12)$$

the relationship for 100% particle capture efficiency is

$$\frac{h}{V_t} = \frac{L}{V} \quad (12.13)$$

where  $T_f$  is particle fallout time,  $T_t$  is particle transport time,  $h$  is vertical distance the particle must fall in order to be captured or the distance from the chamber ceiling to the lower lip of the outlet duct,  $L$  is chamber length, and  $V$  is the particle's horizontal transport velocity, which can be assumed to be the same as the gas velocity.

Therefore, geometric combinations which satisfy the relationship  $h/V_t = L/V$  will successfully capture particles greater than 40 microns in diameter provided chamber turbulence is small. A reasonable rule of thumb assumes the terminal settling velocity is one-half of the calculated value and thereby a conservative design is achieved.

### **Particle Settling Velocity**

The terminal settling velocity can be approximated from the following equations according to the particle diameter and expected flow regime. For particles with aerodynamic diameters less than 100 microns whose Reynolds numbers are less than about 2.0, the terminal settling velocity,  $V_t$ , is given by the following:

$$V_t = \frac{d_p^2 g (\rho_p - \rho_f)}{18 \mu_f} \quad (12.14)$$

Equation (12.14) is the terminal settling velocity of a spherical particle in stokes or laminar flow.

For larger particles between 100 and 1000 microns which are in the transition region between laminar and turbulent flow and whose Reynolds numbers are between about 2.0 and 500,  $V_t$  is given by the following relationship:

$$V_t = \frac{0.2 \rho_p^{2/3} g^{2/3} d_p}{\rho_f^{1/3} \mu_f^{1/3}} \quad (12.15)$$

For particles larger than 1000 microns which are in turbulent flow regime and whose Reynolds numbers are between 500 and  $10^5$ ,  $V_t$  is given by the following:

$$V_t = 1.74 \left( \frac{\rho_p g d_p}{\rho_f} \right)^{1/2} \quad (12.16)$$

where  $V_t$  is particle settling velocity, cm/s;  $\rho_p$  is particle density, g/m<sup>3</sup>;  $g$  is acceleration due to gravity, cm/s<sup>2</sup>;  $d_p$  is particle diameter, cm; and  $\mu_f$  is fluid viscosity, g/cm-s.

**TABLE 12.8** Flow Regime  $K$  Values

Flow Regime	$K$ Range
Stokes	$K \leq 3.3$
Intermediate	$3.3 \leq K \leq 43.6$
Turbulent	$43.6 \leq K \leq 2360$

Selecting which particle terminal settling velocity equation to use is more easily and accurately done by forming the following  $K$  criterion:

$$K = d_p \left( \frac{\rho_p g \rho_f}{\mu_f^2} \right)^{1/3} \quad (12.17)$$

and selecting the flow regime according to the value of  $K$  in [Table 12.8](#).

### Cyclones

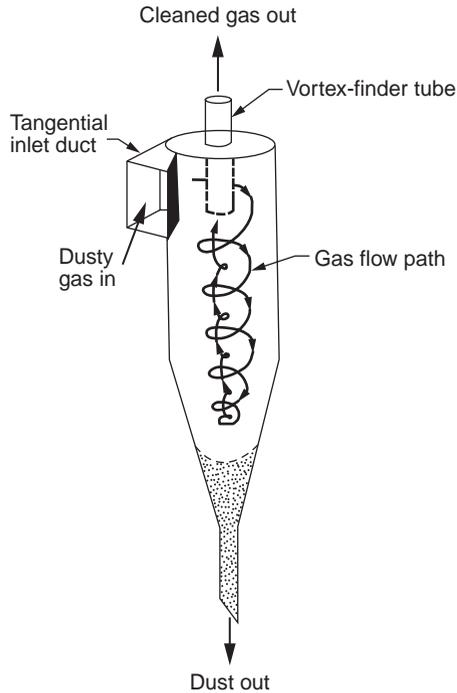
Particle aerodynamic diameters from 40 down to 10 microns are usually removed from a gas stream by cyclonic separation. In this smaller particle diameter range, an additional force, namely centrifugal force, must be applied to effect their removal. In the case of the settling chamber for larger particles, one  $g$  force was utilized. With the cyclone, many equivalent  $g$  forces are utilized via centrifugal force. A ratio of the centrifugal to gravitational force is called the separation factor of the cyclone:

$$\begin{aligned} \text{Separation force} &= \frac{\text{Centrifugal force}}{\text{Gravity force}} \\ &= \frac{mV^2/r}{mg} \\ &= \frac{v^2}{rg} \end{aligned} \quad (12.18)$$

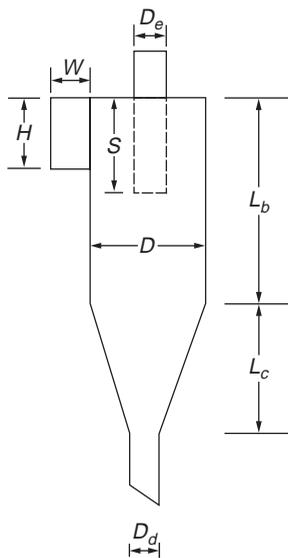
For cyclones this separation factor can be as high as 2500, which means 2500  $g$ s of force are applied to the particles as compared to 1  $g$  in a settling chamber. A cyclonic separator can be thought of as a settling chamber of revolution. In other words, the cyclone is also a wide spot in the exhaust gas duct which provides sufficient residence time for the centrifugal forces to act and remove the particles from the gas stream.

A conventional cyclone consists of a tangential entry, a main cylinder section, a conical lower section with provision for particle removal, and a gas outlet tube, as shown in [Fig. 12.6](#). The gas enters the main cylinder tangentially and spirals downward (forming the primary vortex) into the conical section, thus imposing a centrifugal force on the entrained particles which move radially outward, impacting the side walls and falling to the bottom of the cyclone. Since there is no gas exit at the bottom of the cyclone, the primary vortex downward movement stops, the spiral tightens (now called the secondary vortex) and moves vertically up and out of the top of the cyclone through the outlet tube. The size of these cyclones can vary from 2 feet in diameter up to 12 to 15 feet in diameter. [Figure 12.7](#) shows the dimensional labeling for a typical tangential entry cyclone. The conventional cyclone design geometry dimensional relationships as given by Lapple are shown in [Table 12.9](#). Note that each of the lengths are proportional to the main body diameter of the cyclone. Once the main body diameter is chosen, the remaining lengths are set.

Since Lapple's original work on the conventional cyclone, other researchers have suggested geometry ratios slightly different from that of Lapple. These geometries are shown in [Table 12.9](#), and have been identified as "high efficiency" and "high throughput."



**FIGURE 12.6** Cyclone. (Source: Cooper, C. D. and Alley, F. C. 1990. *Air Pollution Control: A Design Approach*. Waveland Press, Prospect Heights, IL. Reprinted by permission of Waveland Press, Inc. All rights reserved.)



**FIGURE 12.7** Dimensionally labeled cyclone. (Source: Cooper, C. D. and Alley, F. C. 1990. *Air Pollution Control: A Design Approach*. Waveland Press, Prospect Heights, IL. Reprinted by permission of Waveland Press, Inc. All right reserved.)

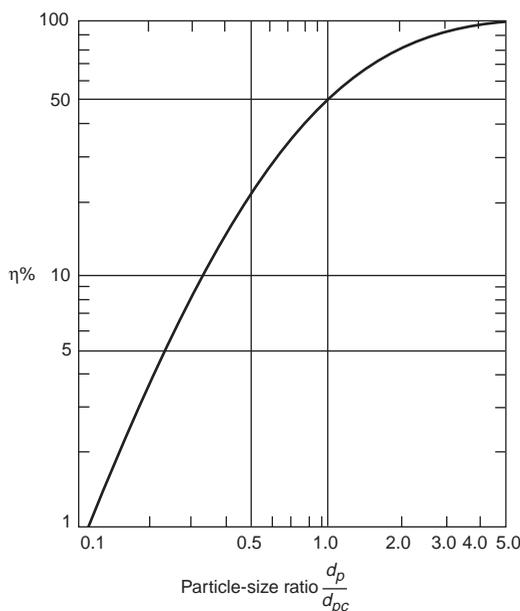
**Conventional Cyclone Design Approach**

In the 1950s, Lapple correlated the collection efficiency data from many sizes of conventional cyclones using a “cut-diameter” variable. This correlation, seen in Fig. 12.8, is the classic approach to designing

**TABLE 12.9** Lapple Design Values for Cyclones

	Cyclone Type		
	High Efficiency	Conventional	High Throughput
Body diameter, $D/D$	1.0	1.0	1.0
Height of inlet, $H/D$	0.5	0.5	0.75
Width of inlet, $W/D$	0.2	0.25	0.375
Diameter of gas exit, $D_e/D$	0.5	0.5	0.75
Length of vortex finder, $S/D$	0.5	0.625	0.875
Length of body, $L_b/D$	1.5	2.0	1.5
Length of cone, $L_c/D$	2.5	2.0	2.5
Diameter of dust outlet, $D_d/D$	0.375	0.25	0.375

Source: Cooper, C. D. and Alley, F. C. 1990. *Air Pollution Control: A Design Approach*. Waveland Press, Prospect Heights, IL. Reprinted by permission of Waveland Press, Inc. All rights reserved.



**FIGURE 12.8** Cut diameter (Source: Cooper, C. D. and Alley, F. C. 1990. *Air Pollution Control: A Design Approach*. Waveland Press, Prospect Heights, IL. Reprinted by permission of Waveland Press, Inc. All rights reserved.)

and sizing a conventional cyclone. The cut-diameter is that diameter of particle captured at a 50% efficiency in the cyclone. It is calculated from the following equation:

$$d_p = \left( \frac{9\mu W_i}{2\pi N v_i (\rho_p - \rho_g)} \right)^{1/2} \quad (12.19)$$

where  $d_{pc}$  is the cyclone cut-diameter,  $\mu$  is the gas viscosity,  $W_i$  is the inlet width of the cyclone,  $v_i$  is the inlet gas velocity,  $\rho_p$  and  $\rho_g$  are the particle and gas densities, respectively, and  $N$  is the number of primary vortex revolutions.  $N$  can be estimated by the ratio of  $L_b/H$  (refer to Fig. 12.6).

Once the cut-diameter  $d_{pc}$  is calculated, the Lapple nondimensional ratio,  $D_p/D_{pc}$  can be formed and Fig. 12.8 used to determine the specific collection efficiency of the particles of interest. The overall

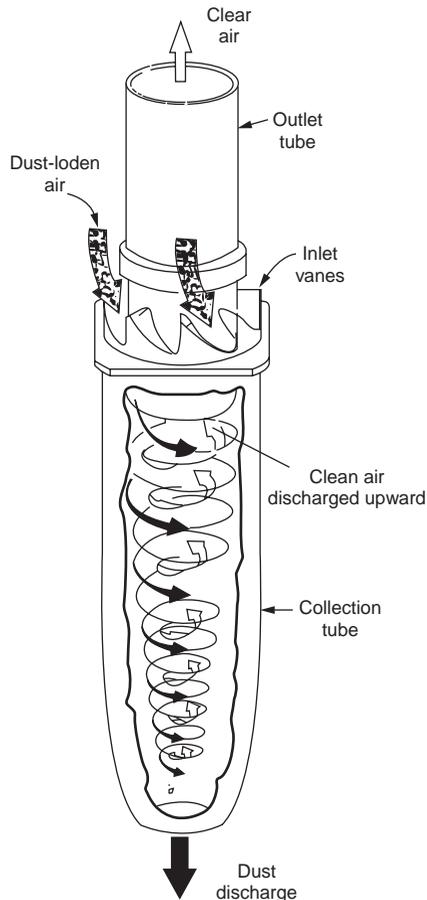


FIGURE 12.9 Axial flow cyclone.

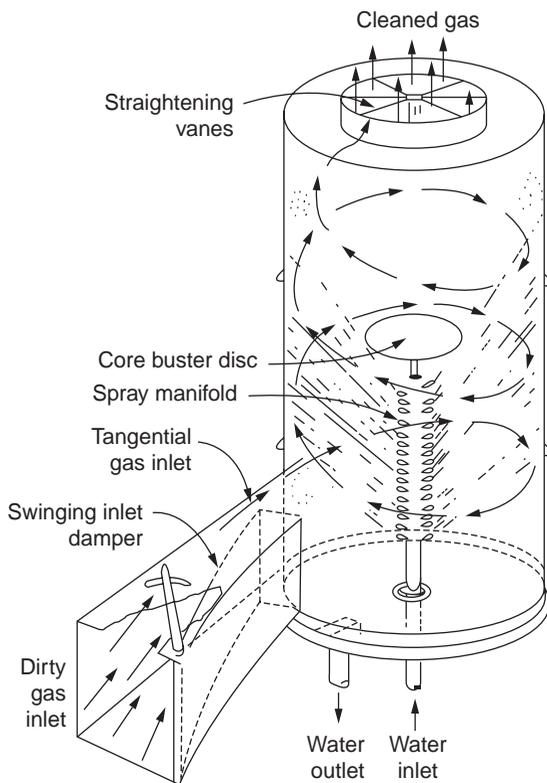
collection efficiency of the cyclone is the summation of the specific efficiency from each size range chosen weighted according to the mass of particles in each size range.

Another version of a cyclonic separator is the axial flow cyclone shown in Fig. 12.9. These units are usually much smaller than the conventional unit and are usually ganged together in parallel to increase the amount of gas they process. These units vary in size from a few inches to 18 inches in diameter.

### Wet Scrubbers

Where gravity or centrifugal forces fail to remove smaller particles, wet scrubbers can be employed. However, keep in mind that the wet scrubber merely converts an air pollution problem into a water pollution problem. The wet scrubber presents a liquid, usually water, into a particulate-laden gas stream where the liquid droplets and particles are brought together. Upon contact, the particle is surrounded by liquid and the apparent mass of the original particle is increased. The particles, now with a greater apparent mass, can be removed from the gas stream using straightforward impaction or cyclonic mechanisms.

Generally, the smaller the particle to be removed, the greater the energy input into the scrubber for effective particulate removal. The water- and particulate-laden gas stream can be brought together in a number of different ways. One common way is to inject the water through spray nozzles into the relatively low-velocity gas stream. These low-energy wet scrubbers are referred to as *spray chamber scrubbers* and are usually effective only for relatively large particles greater than 5 microns. The spray nozzles relative to the gas stream are usually arranged cocurrent, countercurrent, or crosscurrent using a cone-type spray



**FIGURE 12.10** Wet scrubber. (Source: Cooper, C. D. and Alley, F. C. 1990. *Air Pollution Control: A Design Approach*. Waveland Press, Prospect Heights, IL. Reprinted by permission of Waveland Press, Inc. All rights reserved.)

pattern with liquid requirements from 15 to 25 gallons/1000 ft<sup>3</sup> at a liquid delivery pressure of about 40 psi. There are literally hundreds of spray chamber scrubber configurations on the market. Figure 12.10 shows a typical configuration.

Other methods of bringing the water and particulate matter together involve impaction of a liquid droplet–gas mixture on a solid surface. In orifice scrubbers, the gas impinges on a liquid surface and then the droplet–gas mixture must negotiate a series of tortuous turns through a baffle arrangement. In impingement scrubbers the liquid droplet–gas mixture flows upward through perforated trays containing liquid and froth and then impacts on plates above the trays.

High-efficiency scrubbers for submicron particulate matter accelerate the gas stream in a venturi and present the liquid to the gas near the throat of the venturi. These venturi scrubbers are very effective for submicron particulate removal and operate with relatively high gas–side pressure drops from approximately 20 to 120 inches–water column. As a result they are energy intensive and have high operational costs. However, they can achieve collection efficiencies of 93% or greater on particles larger than 0.3 microns [Cooper and Alley, 1990].

The general equation for overall wet scrubber particulate removal efficiency is given by

$$N = 1 - e^{-f_{(\text{system})}} \quad (12.20)$$

where  $f_{(\text{system})}$  is a term representing some function of the particular scrubber system variables. The form of this equation predicts an exponentially increasing collection efficiency with particle diameter and asymptotically approaches 100%.

**Wet Scrubber Design Approach**

Calvert suggests a design approach based on a single droplet target efficiency, impaction parameter and the concept of particle penetration [Calvert, 1972]. Penetration is defined as the converse of collection efficiency:

$$P = 1 - N \tag{12.21}$$

where  $N$  is the particle collection efficiency fraction and  $P$  is the fraction of particles that escape (or penetrate) the collection device.

Combining the general efficiency and penetration equations yields

$$P = 1 - \left( 1 - e^{-f_{(system)}} \right) \tag{12.22}$$

or  $P = e^{-f_{(system)}}$ . Calvert defines  $f_{(system)}$  as an empirical function dependent on the particle aerodynamic diameter,  $d_p$ . Now:

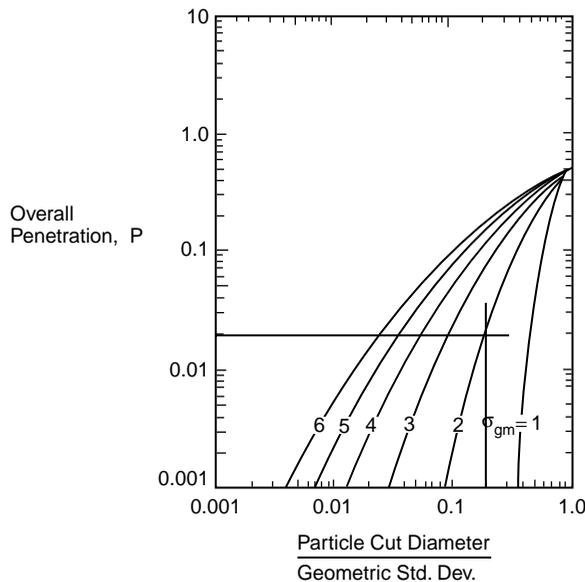
$$f_{(system)} = A_{cut} d_p^{B_{cut}} \tag{12.23}$$

where  $A_{cut}$  is a parameter which characterizes the particulate aerodynamic size distribution and  $B_{cut}$  is an empirical constant of 2.0 for plate towers and venturi scrubbers and 0.7 for centrifugal scrubbers. The penetration is now:

$$P = e^{-A_{cut} d_p^{B_{cut}}} \tag{12.24}$$

which yields the penetration for one particle size distribution. The overall penetration is the summation of the penetration from each chosen size range weighted according to the mass of particles in each size range.

By integrating the penetration,  $P$ , over a lognormal size distribution of particles and various geometric standard deviations, Calvert developed the curves in Fig. 12.11. Knowing



**FIGURE 12.11** Calvert design curves ( $B_{cut} = 2$ ).

the required overall collection efficiency of the scrubber and the mass median diameter of the particle size distribution challenging the scrubber, the cut size of the scrubber can be determined.

Consider this example: an *in situ* aerodynamic particle size sample and subsequent gravimetric analysis indicated that the mass median diameter of the distribution was 10 microns and the geometric standard deviation of the distribution was 2.0. If a collection efficiency of 98% is required to meet the emission standards what must the cut diameter of a venturi ( $B_{\text{cut}} = 2$ ) scrubber be?

$$\begin{aligned} P &= 1 - N \\ &= 1 - 0.98 \\ &= 0.02 \end{aligned} \tag{12.25}$$

Now from Fig. 12.11, for  $P = 0.02$  and  $SD = 2.0$  microns,  $dp_{50}/dp_{\text{gm}} = 0.185$  and, therefore,  $dp_{50} = dp_{\text{gm}} \times 0.185 = 10 \times 0.185 = 1.85$  microns. In this example, the scrubber must collect the 1.85-micron particles with an efficiency of at least 50% to meet the overall scrubber efficiency of 98%.

### Fabric Filters

Where it is not desired to create a water pollution problem from an air pollution problem, dry collection of fine particulate matter in gas streams can be very effectively accomplished using baghouse filtration. Baghouses have been around for quite some time and their usefulness is continually being extended due to advances in the media or substrate material onto which the particles are being collected. The “heart” of a baghouse filtration system is the media which acts as a substrate for collection of a filter “cake” which ultimately does the “filtering.”

Baghouses are typically grouped into three classes based on the method employed to clean the filtration media: reverse air, shaker, and pulse jet. The reverse air baghouse is cleaned by taking the baghouse compartment to be cleaned out of operation and reversing the air flow through the filter, thus removing the cake from the filtration bags. A shaker baghouse also has a compartment taken out of service and mechanically shakes the bags to dislodge the filter cake physically. The most recent innovation in baghouse cleaning consists of the pulse-jet baghouse. This type of baghouse is cleaned by pulsing high pressure blasts of air through the interior of the bag while the bag is in service.

### Filtration Media

Many different types of fabrics are used in baghouse filters. Fiberglass and even ceramic fibers are used in high-temperature applications. More commonly used are cotton, polyesters, and teflon coatings. Matching the proper bag material with the gas stream characteristics is extremely important for long bag life. Table 12.10 is an example of some of the more popular fabric materials with their temperature limitations and acid, alkali, and flexure/abrasion resistance.

As can be seen from Table 12.10, most conventional fibers are limited to operating temperatures less than 260°C (500°F). Nextel® is a relatively new high-temperature fiber developed by 3M which has an upper temperature limit of 760°C (1400°F). The fiber is made of continuous individual ceramic filaments. The technology is based on a “sol-gel” process whereby a chemical sol is extruded through a spinneret and then fired. The resulting metal oxide fibers are polycrystalline woven fiberglass [Hansen, 1994].

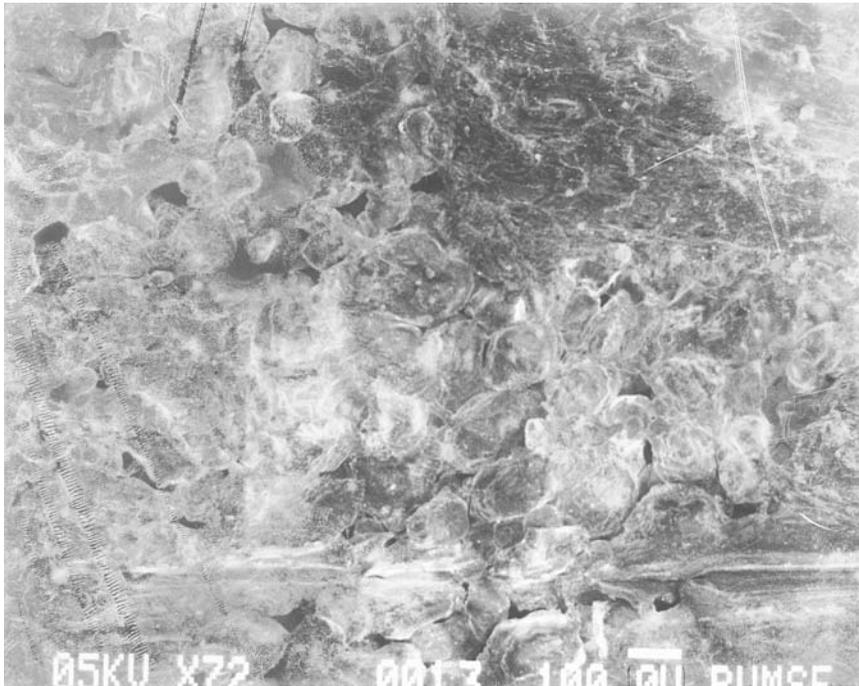
Sintamatic™, a filter matrix consisting of Teflon (PTFE)-coated polyethylene beads sintered into a rigid matrix, is a newer technology in baghouse filter media. As opposed to flexible fabric material, this media is configured in rectangular, hollow, fan-fold rigid panels affixed to an air manifold. The vertically oriented, fan-fold, rigid panels are ganged together in parallel units. Filtration takes place across the outside of the fan-fold panel with the cleaned gas proceeding into the hollow interior space in each panel and up into the clean air manifold.

Since the media is composed of polyethylene and PTFE it is very resistant to acids and bases. However, the major hindrance is temperature; it has an upper limit of about 140°F. A scanning electron microscope was used to examine a cross section of the media [Pedersen, 1993]. Figure 12.12 shows the media magnified 72 times with the horizontal white bar in the lower right of the photo representing 100 microns.

**TABLE 12.10** Properties of Filter Fabrics

Material	Maximum Temperature		Acid Resistance	Alkaline Resistance	Flex Abrasion	Relative Cost
	Continuous (°C)	Surge (°C)				
Cotton	82	107	P	VG	VG	2
Polypropylene	88	93	P-EX	VG	EX	1.5
Wool	93-102	121	VG	P	F-G	3
Nylon	93-107	121	P-F	G-EX	EX	2.5
Orlon	116	127	EX	F-G	G	2.75
Acrylic	127	137	G	F	G	3
Dacron	135	163	G	G	VG	2.8
Nomex	204	218	P-G	G-EX	EX	8
Teflon	204-232	260	EX	EX	F	25
Fiberglass	260	288	F-G	F-G	F	6
Nextel®	760	1200	G-EX	EX-G	EX	High

P — poor, F — fair, G — good, VG — very good, EX — excellent.

**FIGURE 12.12** Sintamatic filter media.

Most of the polyethylene beads are between approximately 50 and 200 microns, with the average being 100 microns. Most of the visible pores appear to be smaller than 100 microns. An analysis of the pore structure indicated the media porosity to be about 0.054 [Pedersen, 1993]. This author has sampled a Sintamatic baghouse handling toxic metal dusts in an ambient air stream and found the unit to perform extremely well.

#### ***Air-to-Cloth Ratio***

The primary design variable for a baghouse filter is the air-to-cloth ratio (A/C) which is the actual air flow rate through the baghouse divided by the filtration or cloth area. The A/C has units of meters/min

and ranges from 1.0 to 7.7 cm/s (2.0 to 15.0 ft/min). A very conservative design has A/C ratios around 1.0 cm/s (2.0 ft/min) while most industrial applications are in the 2.5 to 3.0 cm/s (5 to 6 ft/min) A/C range. Applications in aggregate crushing, sand reclaiming operations, and other applications where the particulate matter is relatively large in diameter and easily cleaned off the surface of the filter media can use A/C ratios between 3.0 to 7.7 cm/s (6 to 15 ft/min).

The selection of an optimum A/C ratio depends on the cleaning method, type of filter media, temperature, and the characteristics of the particles. Also involved are the trade-offs between initial cost and future operation and maintenance costs. A lower A/C means lower power cost, less maintenance, and higher dust collection efficiency. However, a low A/C also means more filter area and higher initial cost. Assuming no short-circuiting of inlet gas is occurring around the bags within the baghouse, poor collection efficiencies usually result from too high an air-to-cloth ratio for the application. Returning to conservative A/C ratios in the range of 2.0 or even 1.0 solves most former baghouse failure problems.

Baghouses typically have overall collection efficiencies greater than 98% for particles less than 10 microns in aerodynamic diameter. Therefore, they are widely used when high collection efficiencies for relatively small particulate matter are required. Their high collection efficiency is due to three mechanisms of impaction, interception, and diffusion acting simultaneously to remove particles down into the submicron size range.

For the environmental engineer, the challenge is to properly match one of the various types of baghouses available with the gas stream and the particulate matter to be collected.

### **Gas Conditioning**

Since most baghouses are not very tolerant of high temperatures and moisture condensation, conditioning of the challenge gas streams is an extremely important consideration. High temperatures can cause bag media failure and even fires. Gas-entrained sparks or static electricity buildup can also cause fires and explosions. If water vapor within the gas stream is allowed to condense on the filter cake, the cake turns to mud, the pressure drop rises rapidly and the filter media becomes impervious to airflow or “blinds.” High gas temperatures and moisture condensation must be avoided in baghouse systems. Three methods of reducing baghouse inlet gas temperatures are ambient air dilution, radiation and free convection, and water injection. A starting point common to the selection or design of any cooling method is the calculation of the heat energy that must be removed from the gas stream prior to baghouse entry.

### **Gas Stream Cooling Requirements**

The following heat transfer rate equation is used to calculate the heat energy that must be removed from the gas stream:

$$q = mc_p(T_p - T_{bi}) \quad (12.26)$$

where  $q$  is the heat removed in Btu/hr;  $m$  is the mass flow rate of gas in lb/hr;  $c_p$  is the specific heat of the gas at constant pressure in Btu/lb, °F;  $T_p$  is the process gas temperature; and  $T_{bi}$  is the baghouse gas inlet temperature in degrees Fahrenheit. Regardless of the method of gas cooling that is employed prior to baghouse entry, the amount of heat to be removed from the gas stream is the same for the three methods.

### **Ambient Air Dilution**

Mixing ambient air with the hot process gas prior to baghouse entry is an effective method of cooling. Even in some systems employing other methods of cooling, emergency cooling is usually affected by dilution with ambient air. Usually, a simple tee employing a butterfly valve in the ambient air leg is inserted in the duct just upstream of the baghouse. A temperature-controlled modulating valve driver can be used to position the butterfly valve and maintain the desired inlet baghouse gas temperature.

The following heat transfer rate equation can be solved for the desired mass flow rate of dilution air to maintain the inlet baghouse gas temperature below desired limits:

$$m_{\text{air}} = \frac{q}{c_{p_{\text{air}}}(T_{bi} - T_{\text{amb}})} \quad (12.27)$$

where  $q$  is the heat energy to be removed from the process gas stream, Btu/hr;  $c_p$  is the specific heat of the ambient air, 0.24 Btu/lb, °F;  $T_{bi}$  is the baghouse inlet gas temperature; and  $T_{\text{amb}}$  is the ambient dilution air temperature, °F.

Now the dilution air volume flow rate,  $Q$ , is calculated from

$$Q = \frac{m_{\text{air}}}{\rho_{bi_{\text{air}}}} \quad (12.28)$$

where  $\rho_{bi_{\text{air}}}$  is the density of the gas entering the baghouse, lb/ft<sup>3</sup>.

While this method is effective for cooling, it must be pointed out that the dilution air volume flow rate is a significant portion of the total gas the baghouse must now handle. In some situations, depending on the original process gas temperature, the dilution air flow rate will exceed the process gas flow rate. Therefore, the main disadvantage with this method of cooling is the added gas that the baghouse must now process.

### ***Radiation and Free Convection***

This cooling method employs a long duct for radiation and free convection gas cooling between the process and the baghouse. With this method, the heat energy needed to be removed from the gas stream can be calculated from the following equation:

$$q = q_{\text{free convection}} + q_{\text{radiation}} \quad (12.29)$$

or

$$q = U_{\text{combined}} A (\text{LMTD}) \quad (12.30)$$

where  $U_{\text{combined}}$  is the overall heat transfer coefficient of the cooling duct, Btu/(hr ft<sup>2</sup> °F);  $A$  is the exterior duct area for heat transfer; and LMTD is the log mean temperature difference between the cooling duct and the ambient air. Since we are interested in the diameter and length required for the cooling duct, the above equation is solved for the heat transfer area,  $A$ , as

$$A = \pi DL = \frac{q}{U_{\text{combined}} \text{LMTD}} \quad (12.31)$$

and for a chosen diameter,

$$L = \frac{q}{U_{\text{combined}} \text{LMTD} \pi D} \quad (12.32)$$

Radiation and free convection cooling has the distinct advantage over the dilution cooling scheme in that the gas handled by the baghouse contains no added dilution air and, therefore, is significantly less in volume flow. There is the added expense of the ductwork, but this is usually more than offset by the reduction in the amount of gas passing through the baghouse. Since the controlling thermal resistance in this cooling method is the internal duct wall convective heat transfer coefficient, schemes to spray water on the external surface of the pipe to significantly reduce the required pipe length are usually not successful.

This cooling method can require up to a few hundred feet of cooling duct, so there must be ample room available at the site for successful implementation. Where space is available, long horizontal duct runs have worked successfully; where space is at a premium, serpentine configurations can be used effectively.

### Evaporative Cooling

Utilization of the latent heat of vaporization of water of about 1000 Btu/(lb water) is an extremely effective method of cooling process gas prior to baghouse entry. This method requires a contact chamber, spray nozzles, and a dew point sensing and feedback control system to modulate the water flow to the spray nozzles. This method has the advantages of small space requirement and lower capital cost, but it does require a reasonably sophisticated water flow control system to prevent dew point problems (liquid drops forming in the baghouse).

The total heat energy to be removed by the injected water is the sum of the sensible and latent heat absorbed by the water. This includes the sensible heat raising the liquid water from its injection temperature up to its vaporization point, the latent heat during vaporization, and the sensible heating of the water vapor up to the desired baghouse inlet gas temperature. In equation form:

$$q_{\text{total}} = q_{\text{sensible}} + q_{\text{latent}} \quad (12.33)$$

where

$$\begin{aligned} q_{\text{sensible}} &= mc_p \Delta T_{\text{liquid}} + mc_p \Delta T_{\text{vapor}} \\ q_{\text{latent}} &= mh_{fg} \end{aligned} \quad (12.34)$$

$c_p$  is the specific heat at constant pressure of liquid water or vapor and  $h_{fg}$  is the latent heat of vaporization of water changing phase from a liquid to a vapor, 1000 Btu/lb.

### Example 12.2

It is desired to cool 50,000 acfm of process gas at 1500°F down to 500°F prior to baghouse entry using water injection. Compute the amount of heat needed to be removed from the gas stream and the needed water injection rate as well as the rise in dew point temperature after injection. Heat to be removed from gas stream:

$$\begin{aligned} q &= mc_p (T_{\text{process gas}} - T_{\text{baghouse inlet}}) \\ q &= (50,000)(0.02)(0.25)(1500 - 400) \\ q &= 275,000 \frac{\text{Btu}}{\text{min}} \end{aligned} \quad (12.35)$$

Mass flow rate of water assuming initial water temperature is 70°F and the vaporization point of water occurs at 212°F:

$$q = mc_p \Delta T_{\text{liquid}} + mc_p \Delta T_{\text{vapor}} + mh_{fg} \quad (12.36)$$

substituting:

$$275,000 \frac{\text{Btu}}{\text{min}} = m \left[ (1.0)(212 - 70) + (0.46)(400 - 212) + \left( 1000 \frac{\text{Btu}}{\text{lb}} \right) \right] \quad (12.37)$$

solving for  $m$ :

$$m = 224 \frac{\text{lb water}}{\text{min}} \quad \text{or} \quad 27 \frac{\text{gal}}{\text{min}} \quad (12.38)$$

Therefore, 27 gpm of water must be injected directly into the gas stream to cool it from 1500°F down to 400°F. This injection of liquid adds 7800 acfm of vapor to the process gas stream at 400°F which must be considered as part of the baghouse air to cloth ratio.

The vapor equivalent of the 27 gpm liquid water injected is calculated as follows:

$$\text{Vapor volume (ft}^3\text{)} = 10.1 \left( \frac{T}{P} \right) L \quad (12.39)$$

where  $L$  is in gallons,  $T$  is temperature in Rankine (i.e., 400 + 460), and  $P$  is pressure in Hg. Substituting:

$$\begin{aligned} \text{Vapor volume (ft}^3\text{)} &= 10.1 \left( \frac{860}{29.92} \right) 27 \\ &= 7838 \text{ acfm at } 400^\circ\text{F} \end{aligned} \quad (12.40)$$

This is a 36% increase in gas flow that the baghouse will have to handle (over that of the cooled process gas of 21,938 acfm at 400°F).

### Effect on Dew Point

The added water vapor to the process gas stream will increase the specific humidity of the mixture. The specific humidity (SH) of the mixture is

$$\begin{aligned} \text{SH} &= 224 \frac{\text{lb water/min}}{(21,938 \text{ acfm})} \left( 0.046 \frac{\text{lb}}{\text{ft}^3} \right) \\ &= 0.22 \frac{\text{lb water}}{\text{lb dry air}} \end{aligned} \quad (12.41)$$

This specific humidity corresponds to a dew point of 151°F and compares to 42°F prior to water injection. Therefore, water injection of 27 gpm elevates the dew point of the baghouse inlet gas from 42°F to 151°F. Caution must be exercised so that the 151°F dew point temperature of the inlet gas is never approached or liquid droplets will blind the baghouse.

## Sulfur Dioxide

The emission of sulfur dioxide (SO<sub>2</sub>) is a common occurrence from the combustion of fossil fuels for power generation and from other industrial processes that involve the use of sulfur. Combustion process, however, generates up to 75% of all SO<sub>2</sub> emissions with the fuel itself being the source of sulfur. As a result, this discussion will focus on the control of SO<sub>2</sub> from combustion sources.

SO<sub>2</sub> is formed when fuel-bound sulfur is combusted, and in the process converted to SO<sub>2</sub> by combining with the combustion air at a molecular weight ratio of 2:1. As a result, one gram of fuel-bound sulfur results in 2 grams of SO<sub>2</sub> and necessitates substantial control measures for flue gas treatment.

The nature of formation of SO<sub>2</sub> leaves two options in its emissions control: one, control emissions by eliminating the formation of SO<sub>2</sub>, or two, remove SO<sub>2</sub> from the combustion flue gas after its formation. The first process is referred to as fuel conversion and the second as flue gas desulfurization (FGD).

### Fuel Conversion

The process of fuel conversion seems relatively simple as it consists of the removal of sulfur from the fuel to be combusted or the use of a different, lower-sulfur fuel. This can involve the use of natural gas, distillate oils with low sulfur contents, or low-sulfur coals in place of higher-sulfur counterparts.

These alternatives pose simple answers to a more complex issue, in that many combustion units are designed to burn a specific fuel type, making switching to a different fuel cost-prohibitive. Additionally,

the use of low-sulfur coal is often cost-prohibitive as the transportation costs are often extreme. Further, fuel conversion involving the removal of sulfur from crude oils that can be distilled is far simpler than the removal of sulfur from coals.

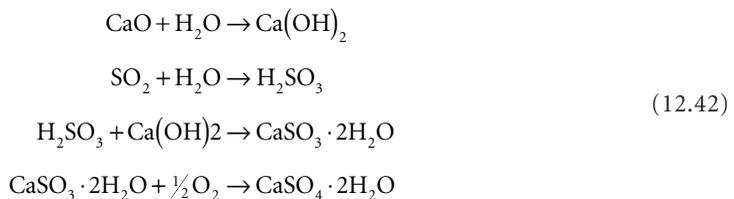
As a result of the cost issues and the complexity of the removal of sulfur from fuel sources, controlling emissions by fuel conversion is typically a good method of reducing SO<sub>2</sub> emissions from sources burning distillate oils or sources that have exposure to a supply of low-sulfur coal. Often fuel conversion is used to lower total control costs or to reduce SO<sub>2</sub> emissions below regulated levels.

## Flue Gas Desulfurization

Flue gas desulfurization (FGD), in this discussion, is a process that focuses on the removal of SO<sub>2</sub> from a combustion gas stream. On a broader scale, flue gas desulfurization can be applied to control sulfurous compounds in many different types of industrial emissions. FGD systems consist of two different types — throwaway and regenerative — that operate on either a wet or dry basis. Throwaway and regenerative systems differ in that throwaway systems convert the sulfur compounds into a form that is disposed of as a solid waste, while regenerative systems convert the sulfur into either an elemental sulfur or sulfuric acid form that can be reused or sold.

### Throwaway Systems

Throwaway systems operate by the scrubbing of the gas stream where the scrubber water contains a reactant, typically lime or limestone, such that the SO<sub>2</sub> present reacts and is removed in a solid form in the scrubber blowdown. Often a simple scrubber configuration is used and is followed by some sort of gravity thickener to remove the solids from the effluent scrubber water. The overall stoichiometry for the reaction can be represented by the following [Cooper and Alley, 1990]:



Limestone and lime systems operated in this manner are capable of 90 and 95% removal efficiencies, respectively.

A variation of the scrubbing method is the spray injection of a lime slurry into the hot gas stream. As the slurry is injected into the hot gas stream the SO<sub>2</sub> reacts with the lime in the aqueous phase, dries, and is removed in the solid phase by filtration in a baghouse. This type of operation results in lower maintenance, energy use, and operating costs [Cooper and Alley, 1990].

Dry lime or limestone injection systems operate by injecting the lime or limestone into the flue gas, causing the SO<sub>2</sub> present to adsorb and react. Final reaction products are then removed by filtration. These systems are limited by the fact that the site of reaction is only on the surface of the reactant, and is thus hindered in a manner that spray injection is not.

### Regenerative Systems

Regenerative FGD systems operate in a manner that is similar to throwaway systems with the exception of an additional step that either transforms or reclaims the reaction products. An example of this is magnesium oxide scrubbing. This process employs the use of MgO as the scrubbing agent, wherein SO<sub>2</sub> is absorbed and forms magnesium sulfite (or sulfate). This reaction by-product is then recalcined, forming MgO and SO<sub>2</sub>, with the MgO being returned to the scrubber and the SO<sub>2</sub> being captured in a concentrated form that can be utilized as a feedstock in sulfuric acid production. Disadvantages to the system lie in the heat required to recalcine the magnesium sulfite [Wark and Warner, 1981]. Other examples of regenerative FGD systems are single alkali scrubbing, double alkali scrubbing, citric acid scrubbing, the Sulf-X process, and the Wellman-Lord process.

## Nitrogen Oxides

The formation of nitrogen oxides ( $\text{NO}_x$ ) is similar to  $\text{SO}_2$  in that  $\text{NO}_x$  is formed as the result of combustion processes.  $\text{NO}_x$  is composed of several different forms of nitrogenous compounds. Included among these are nitrous oxide ( $\text{N}_2\text{O}$ ), nitric oxide ( $\text{NO}$ ), nitrogen dioxide ( $\text{NO}_2$ ), nitrogen trioxide ( $\text{N}_2\text{O}_3$ ), nitrogen tetroxide ( $\text{N}_2\text{O}_4$ ), and nitrogen pentoxide ( $\text{N}_2\text{O}_5$ ). While all of these components can exist in a combustion gas stream at some point,  $\text{NO}_x$  typically refers to  $\text{NO}$  and  $\text{NO}_2$ .

The formation of  $\text{NO}_x$  begins with the formation of  $\text{NO}$  in the flame zone of a combustion process where fuel-bound nitrogen combines with the oxygen present in combustion air to form  $\text{NO}$  and is termed fuel  $\text{NO}_x$ . Additionally, atmospheric nitrogen in the combustion air also combines with oxygen to form  $\text{NO}$  and is known as thermally generated  $\text{NO}_x$ . After formation, the  $\text{NO}$  generated rapidly cools with the gas stream where a majority (approximately 95%) converts to  $\text{NO}_2$ . As a result,  $\text{NO}_2$  is the principal component of  $\text{NO}_x$  that is emitted to the atmosphere. For a more complete discussion of combustion by-product formation, the reader is referred to the chapter on incineration.

$\text{NO}_x$  can be controlled by a variety of methods. These control methods can be grouped in three forms: fuel conversion, combustion modifications, and flue gas treatment. Fuel conversion is the process of changing fuels to take advantage of lower-nitrogen fuels. This consists primarily of the use of natural gas over fuel oils or coals, and suffers from the same type of limitations as fuel conversion to control  $\text{SO}_2$ , described above. Therefore, fuel conversion will be omitted from this discussion. The second form is combustion modifications that lower the potential for formation of  $\text{NO}_x$  during combustion processes. The third form is the use of downstream controls to remove  $\text{NO}_x$  from the flue gas.

### Combustion Modifications

Combustion modifications take advantage of the characteristics of  $\text{NO}_x$  formation in an effort to minimize it. These efforts focus on the combination of nitrogen and oxygen in the region of combustion (flame zone) at a high enough temperature to form  $\text{NO}$ . Modifications employed for this include air variations, low  $\text{NO}_x$  burners (LNB), and fuel reburning [Makansi, 1988].

#### *Combustion Air Variations*

One of the most simple combustion modifications is to alter the manner in which the combustion air is supplied to the flame. This is done in an effort to lower both the peak flame temperature and oxygen concentrations in the regions of highest temperature. Typical methods consist of the following [Makansi, 1988]:

1. Placing burners out of service (BOOS) and fuel biasing that provide combustion regions that are fuel rich followed by regions that are fuel lean to stretch the combustion zone, lowering peak temperatures and oxygen concentrations.  $\text{NO}_x$  reductions of up to 20% are possible with these methods.
2. Low excess air firing (LEAF) to reduce the excess combustion air from typical levels of 10–20% to 2–5%. This reduces oxygen concentrations in the flame zone and results in decreased  $\text{NO}_x$  formation, up to 20%, and a more efficient flame.
3. Overfire air is a means of air staging, or elongating the combustion zone by forcing a portion, 10–20%, of the combustion air to a set of ports above the burners. This in essence creates fuel-rich and fuel-lean zones and results in  $\text{NO}_x$  emission reductions of 15–30%.
4. Flue gas recirculation (FGR) is a process that recycles a portion of the combustion gases back into the virgin combustion air to reduce combustion temperatures and thereby reduces thermally generated  $\text{NO}_x$  up to 20–30%.

#### *Low $\text{NO}_x$ Burners*

Low  $\text{NO}_x$  burners are a technology that has developed in order to retrofit existing,  $\text{NO}_x$  intensive, combustion units with a burner that will allow the combustion unit to operate at its design level, but with substantially lower  $\text{NO}_x$  emissions. This is done within the burner itself by combining the combustion air and fuel in different manners (this varies from vendor to vendor) such that oxygen levels are

reduced in the critical  $\text{NO}_x$  formation zones. Low  $\text{NO}_x$  burners themselves are capable of  $\text{NO}_x$  reductions of up to 20–30%, and when coupled with overfire air systems  $\text{NO}_x$  reduction of up to 50% are possible [Smith, 1993]. Installation of these types of burners is limited by the design of the combustion unit, and in some cases will require modification of existing fuel- and air-handling equipment.

### ***Fuel Reburning***

Fuel reburning is a method of fuel staging wherein a portion of the fuel for the combustion unit is fed into the unit downstream of the initial combustion zone. This action creates a second combustion zone which is operated substoichiometrically. In the second zone, the  $\text{NO}$  created in the first zone is kept at temperature for longer periods of time and thereby allowed to convert back to elemental  $\text{N}_2$ . The fuel added for reburning must be of high enough volatility to allow continued combustion and therefore this method favors oil- and gas-fired units.  $\text{NO}_x$  reductions of 75–90% are possible with this type of configuration [Makansi, 1988].

### **Downstream Processes**

Downstream controls for the removal of  $\text{NO}_x$  from combustion gas streams consists of two types. The first type is the addition of urea or ammonia to the hot combustion stream, causing the  $\text{NO}_x$  in the gas stream to be converted into water and nitrogen. This first type includes both selective catalytic and noncatalytic reduction. The second type of downstream control is the removal of  $\text{NO}_x$  from a gas stream by scrubbing.

#### ***Selective Catalytic Reduction***

Selective catalytic reduction (SCR) of  $\text{NO}_x$  utilizes a catalytic transition metal grid in combination with ammonia at temperatures of 600–700°F to convert the  $\text{NO}_x$  present in the gas stream back to elemental  $\text{N}_2$  and water. This process is governed by the  $\text{NO}_x$  concentration in the flue gas with the injection of ammonia being a function of this concentration. Removal efficiencies for this type of operation range from 80–90% [Makansi, 1988].

However, drawbacks to this type of removal system include a poor catalyst life of only one to five years and emission of unreacted ammonia. The portion of ammonia passing through the system is referred to as ammonia slip.

#### ***Selective Noncatalytic Reduction***

Selective noncatalytic reduction (SNCR) is similar to SCR in that the injection of ammonia or urea is utilized to convert  $\text{NO}_x$  emissions into elemental  $\text{N}_2$  and water. However, this system does not utilize a catalyst for this reaction; instead, the ammonia is injected in a higher-temperature region of the gas stream taking advantage of the heat as a catalyst. The temperature required, typically 1600–2000°F, necessitates that the injection location be either physically in the combustion unit or immediately downstream in the ductwork. Removal efficiencies of up to 80% are possible with SNCR.

#### ***Flue Gas Denitrification***

Flue gas denitrification (FGDN) is the process of scrubbing  $\text{NO}_x$  from a gas stream. However, while the principles of operation for the scrubbing system are the same for its particulate removal and FGD counterparts, the scrubbing liquid is substantially different. This is due to the fact that many of the  $\text{NO}_x$  constituents vary in their degree of water solubility. As a result, scrubbing systems for the removal of  $\text{NO}_x$  typically employ a series of individual scrubbers whose makeup liquid varies with intended removal. Operation of the scrubbers is relatively maintenance free with the requirement of continued chemical addition for the makeup water. Removal efficiencies can approach 90% with FGDN.

## **Volatile Organic Compounds**

The control of VOCs is a complex issue as there are a great number of organic compounds being emitted, either directly or indirectly, with all compounds having various structures and properties. The issue is further complicated by the fact that a majority of the air toxics list, provided earlier in the chapter, is

composed of VOCs and requires a MACT level of control as opposed to the nontoxic VOCs RACT level of control requirement for most cases of VOC emission. As a result, there are a great number of VOC emissions controls that are in place or are being recommended for various situations.

However, the description of all methods of VOC control is beyond the scope of this chapter. The reader is referred to the Air and Waste Management Association's *Air Pollution Engineering Manual* and the chapter in this handbook on incineration for further information on the subject of VOC emissions control for those points not covered in this discussion. Emissions control focused on in this discussion will consist of the standard methods of adsorption and incineration that are capable of high removal efficiencies and are most likely to be considered in control technology reviews.

### **Carbon Absorption**

Carbon absorption is the use of the physicochemical process of adsorption to remove dilute organics from a gas stream. Adsorption itself is the interphase accumulation or concentration of substances at a surface or interface of the adsorbent, in this case activated carbon [Weber, 1972]. Accumulation or concentration of molecules at the surface of the adsorbent is the result of the molecule being attached to the surface by van der Waals forces, physical adsorption, chemical interaction with the adsorbent, or chemical adsorption. Both types of adsorption are reversible, although chemical adsorption requires a greater driving force to desorb the molecules.

The adsorption process itself consists of the use of an adsorbent medium, typically activated carbon, that is placed in the gas stream such that the gas has to pass through the medium. As the gas passes through the carbon, the constituents of the gas stream make contact with it and adsorb. After a period of time, the carbon can no longer adsorb organics and is removed from service. This carbon can then be reactivated by steam stripping or incineration to remove the organics, or disposed of as a solid or hazardous waste. Steam stripping of the carbon provides the option of reclaiming the organics previously lost to the atmosphere. Activated carbon is composed of nutshell or coal that has been charred in the absence of oxygen and activated by steam stripping or various other methods.

In operation, a carbon adsorber consists of a bed of carbon whose dimensions are a function of the VOCs being removed. The bed usually operates in a passive mode, as described earlier, with the carbon that is first exposed being the first expended. As the carbon is expended or spent, a front develops that demarks spent carbon from carbon that is still active. Through the life of the carbon bed, the front progresses from one end of the bed to the other. The end of the operational life of the bed is realized when the front "breaks through" the opposite end of the bed and the bed has lost its ability to remove organics. In operation, the bed is removed from service and replaced prior to breakthrough such that continued emissions control is ensured.

Carbon absorption is employed for a wide variety of uses due to its versatility and the potential to reclaim organics. Operation of carbon beds is a relatively simple process that is maintenance nonintensive. Typically, maintenance of the beds involves only the servicing of the air-handling equipment and exchange or recharge of the bed once the carbon is spent. In many cases, exchange of the carbon is handled by the vendor. Lifetimes of the carbon bed and the removal efficiency it will provide are functions of the design of the bed. However, in most cases carbon adsorbers are designed for removal efficiencies of 99% or greater.

A significant drawback to adsorption is the fact that it is not a means of ultimate disposal. Adsorption provides only the ability to concentrate and transfer a pollutant from a gas stream to a medium where ultimate disposal or reuse is possible. Some facilities employ carbon adsorption in series with incineration. The concentrated gas from the carbon desorption process is ducted to an incinerator for final treatment. This arrangement is attractive to facilities with high volume, low concentration gas streams. Without the concentration provided by the carbon absorption system, a much larger incinerator would have to be selected.

### **Incineration**

The second type of control commonly employed for the emission of VOCs is incineration. This control oxidizes the organics to CO<sub>2</sub> and water by combustion or through the use of a catalyst. Incineration for

the control of VOCs is a means of ultimate disposal and is typically employed for more concentrated gas streams where the composition of organics in the gas stream is known and reasonably constant. Destruction efficiencies in excess of 99% are possible with incineration. However, large variations in the organic feed stream result in inefficiencies during combustion and can produce products of incomplete combustion (PICs) and result in poor destruction efficiencies. The degree to which this is possible is dependent on the type of incinerator employed. Again, the reader is referred to the chapter on incineration for a more complete discussion of combustion and operation of incinerators in general.

There are three types of incinerators: direct, thermal, and catalytic. These vary by the manner in which the oxidation of the organics takes place, or by the manner in which the organics are combusted.

#### ***Direct Incineration***

Direct incineration is the combustion of the gas stream of organics itself. This is done by igniting the gas stream and allowing the organics to combust instantaneously on their own and requires concentrations of organics in the gas stream that will support this type of combustion. As a result, this type of incineration is used on gas streams with concentrated organics. Flaring is a form of direct incineration.

#### ***Thermal Oxidation***

Thermal oxidation is a process that oxidizes organics by introducing the organics around a flame such that oxidation of the organics is the result of the elevated temperature in the chamber. Unlike direct incineration, the organics themselves are never the primary fuel for combustion; they are a secondary combustion process. In fact the concentrations of organics must be below that required for combustion on their own. Oxidation in this case is a function of the temperature, 1200–2000°F, and residence time, 0.2–2.0 seconds, of the organics in the combustion chamber.

#### ***Catalytic Oxidation***

Catalytic oxidation is the third type of oxidation process commonly used in the control of VOCs. This process utilizes the ability of a transition metal catalyst to oxidize organic compounds to CO<sub>2</sub> and water at relatively low temperatures. For this type of oxidation, organic concentrations below those that require thermal or direct incineration are used. Operation of this type of incinerator consists of the introduction of the organic-laden gas stream into a bed of catalyst at temperatures of 650–800°F. As the gas stream passes through the bed, the organics react in the presence of the catalyst and are oxidized.

#### **Condensation**

While not as frequently employed as adsorption or incineration, condensation of waste gases can be an attractive and even profitable alternative in certain cases. A refrigerated condensation system reduces gas emissions by lowering the gas stream temperature to below its dew point and providing extensive condensing surface area in the gas flow path thus accelerating the conversion of the waste back to liquid form. The condensed liquid can be returned to the process and reused or salvaged. Equipment costs can vary widely for similar flow capacity units depending on the character of the gas stream. The units are best suited for gas streams with relatively high solvent loads, low water content, and low solvent volatility. Dilute, highly volatile gas streams saturated with water generally require multistage refrigeration systems, even cryogenic systems, with provisions to avoid icing and in most cases will not be economically viable as an emission control alternative. While the capital cost is generally the highest for condensation, over time the salvaged solvent can reduce the annualized costs significantly even, in some cases, to the point of generating a net financial gain.

## **12.6 Odor**

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Odor is defined as the characteristic of a substance that makes it perceptible to the sense of smell. This definition includes all odors regardless of their hedonic tone. In the field of air pollution, concern over odors is limited to those compounds or mixtures thereof that result in the annoyance of an individual.

In human terms, compounds producing displeasure due to their odor are typically not threatening to human health but do produce a great deal of physiological stress. In fact, in Metcalf and Eddy's text on wastewater engineering, one of the principal characteristics of wastewater considered is the odor. This is due to the fact that offensive odors can cause decreased appetites, lowered water consumption, impaired respiration, nausea, and mental perturbation. The Metcalf and Eddy text further reports that in extreme situations offensive odors from wastewater treatment facilities can have substantial health impacts on a communitywide basis [Tchobanoglous, 1979].

## Sense of Smell

The sense of smell is a sensation that is produced when a stimulant comes into contact with the olfactory membranes located high in the nasal passages. As the stimulants contact the olfactory membranes they are absorbed and excite the membranes. There are thought to be seven primary classes of stimulants that affect the olfactory membranes. These seven stimulants are as follows:

1. Camphoraceous
2. Musky
3. Floral
4. Peppermint
5. Ethereal
6. Pungent
7. Putrid

The seven stimulants are felt to be the primary sensations; however, this is a topic of debate as others feel that there are perhaps 50 or more classes or primary stimulants. The primary stimulants illustrate the complexity of the sense of smell in relation to the other senses in that there are only three primary color sensations of the eye and four primary sensations associated with taste.

While there are seven stimulants of the olfactory membranes, reaction to a stimulant varies from person to person: a rose may not smell as sweet to one person as it does to another. This results in great difficulty in assessing the magnitude of an odor.

## Characteristics of Odor

Human response to odor depends on the characteristics of the property being assessed. The odor intensity, detectability, character, and hedonic tone all influence the response to a particular compound [Prokop, 1992].

The odor intensity is the strength of the perceived sensation. Intensity of the odor is a function of the concentration of the odiferous compound coupled with a human response. Intensities of odors can be the same for different compounds at different concentrations.

Detectability is the minimum concentration of an odiferous compound that produces an olfactory response. The detectable limit for odors is referred to as the odor threshold. Measurement of this characteristic of odor is difficult as the threshold varies from person to person and is further complicated as the detectable concentration varies with previous exposure. Odor threshold limits are often reported as the concentration that produces an olfactory response in 50% of the test population.

The character of an odor refers to the associations of the person sensing the odor. This is the characteristic that separates the odors of different compounds that are presented in similar intensities. [Table 12.11](#) presents a list of several different compounds with their odor thresholds and associated characteristics.

Similar to the character of an odor is the hedonic tone of the odor. The hedonic tone is a reflection on the degree of pleasantness or unpleasantness associated with an odor. Hedonic tone is assessed by the response of different individuals.

**TABLE 12.11** Odor Descriptions of Various Compounds

Compound	Formula	Molecular Weight	50 Percent Detection Thresholds ( $\mu\text{g}/\text{m}^3$ )	Odor Description
Acetaldehyde	$\text{CH}_3\text{CHO}$	44	90	Pungent, fruity
Ammonia	$\text{NH}_3$	17	3700	Pungent, irritating
Dimethyl sulfide	$(\text{CH}_3)_2\text{S}$	62	51	Decayed cabbage
Hydrogen sulfide	$\text{H}_2\text{S}$	34	5.5	Rotten eggs
Methyl mercaptan	$\text{CH}_3\text{SH}$	48	2.4	Rotten cabbage
Pyridine	$\text{C}_5\text{H}_5\text{N}$	79	1500	Pungent, irritating
Trimethylamine	$(\text{CH}_3)_3\text{N}$	59	5.9	Pungent, fishy

Sources: Adapted from Prokop, W. H. 1992. *Air Pollution Engineering Manual — Odors*. Air and Waste Management Association. Van Nostrand Reinhold, New York; and Nagy, G. Z. 1991. The odor impact model. *J. Air Waste Manage. Assoc.* 41(10):1360–1362.

## Odorous Compounds

Odorous compounds are emitted from a variety of sources and consist of both organic and inorganic compounds that exist primarily in the gas phase, but can also exist as solids. Table 12.11 lists examples of both organic (such as acetaldehyde) and inorganic (such as ammonia) compounds. Typically odorous compounds are emitted from processes which involve anaerobic decomposition of organic matter [Prokop, 1992].

Most odorous compounds are significantly volatile compounds with molecular weights from 30 to 150. Typically the lower molecular weight compounds have higher vapor pressures and thus are more volatile [Prokop, 1992]. A positive example of the use of an odiferous compound is the addition of mercaptans to nonodiferous natural gas supplies. This process is done in order to provide a method of detection for leaks of natural gas, and thus, hopefully, prevent catastrophes.

## Measurement

The measurement of odor is subjective as the process necessitates the assessment of odor characteristics by noninstrumental means. Intensity, detectability, character, and hedonic tone are typically assessed by sensory methods involving the use of an odor panel. An odor panel is a group of people that are presented a series of gas streams and asked to qualify and quantify what is presented.

The particulars of the measurement of odor are beyond the scope of this chapter. For further information, the reader is referred to the chapter on odors in the Air and Waste Management Association's *Air Pollution Engineering Manual* for a synopsis of odor measurement involving odor panels.

## Odor Control Techniques

Odor control techniques involve essentially the same elements as the methods employed in the control of VOCs. Controls that are typically used consist of the following:

1. Process modification
2. Masking agents or odor modification
3. Carbon adsorption
4. Absorption/chemical oxidation
5. Incineration

The first control to be considered is prevention of odor formation. This is an attempt to reduce the generation of odors through changes in process equipment design and/or operating procedures. This process would typically involve the identification and elimination of the area in the process that creates the compound of concern. In some instances, this can simply involve ensuring that a waste stream receives proper aeration. However, another situation would be one in which the compound in question is an

**TABLE 12.12** Process Modification

Advantages	Disadvantages
Process changes alone may reduce odors enough to minimize odor complaints	The effect of modifications is difficult to predict without extensive testing
Changes can be made relatively quickly	Process modifications may not be able to provide a suitable reduction
Costs should be lower than the installation of downstream controls	Modifications could result in decreased production capacity

**TABLE 12.13** Carbon Adsorption

Advantages	Disadvantages
Control efficiencies can range from 95 to 98%	Extensive preconditioning of the gas stream may be required
A relatively small amount of auxiliary fuel is required since carbon beds are typically regenerated every 8 to 24 hours	Adsorption beds typically require large amounts of space
	Specialized maintenance may be required
	Even with regenerating systems, periodic replacement of carbon is needed every three to five years
	Regeneration of gas may be another source of odor

**TABLE 12.14** Absorption

Advantages	Disadvantages
Respectable odor control efficiencies are possible	Control efficiencies may not meet required levels for odor control
No auxiliary fuel is needed	Particulate control is needed upstream of the scrubber
	Corrosion of the scrubber is a problem
	Creates a wastewater disposal problem

integral part of the process and as a result necessitates the use of a downstream control. Advantages and disadvantages of process modification are listed in [Table 12.12](#).

A second consideration in the reduction of an emissions odor is odor masking or modification. This type of control method attempts to modify the hedonic tone of the odor or the emissions stream such that the offending odor is less unpleasant. Odor masking does not result in a reduction of the offending compound; it merely attempts to alter the intensity or character of the offending compound. Usually these types of controls are not very effective and are expensive in relation to other methods of control.

Carbon adsorption involves the removal of the odiferous compounds by passing the emission stream through a carbon bed. The carbon is stationary in the bed, and as the gas stream passes through, the organics adsorb onto the carbon through a physicochemical process. As the carbon reaches a maximum capacity it is either exchanged with new carbon or regenerated. Regeneration of the carbon is typically done by passing a steam through the bed to desorb the organics. A few of the advantages and disadvantages are listed in [Table 12.13](#).

Absorption is the removal of organics by wet scrubbing with various oxidizing agents to remove odors from emission streams. A typical scrubbing system would consist of a venturi scrubber followed by a packed-tower scrubber. The venturi scrubber serves to remove particulate and presaturate the gas stream. After the venturi, the gas stream is passed through a packed-tower scrubber where the odiferous organics are removed. Sodium hypochlorite and potassium permanganate are two of the more commonly used oxidants in packed-tower scrubbers. [Table 12.14](#) lists a few of the advantages and disadvantages of absorption for odor control.

The final control option generally used for odors is incineration. Thermal and catalytic incinerators are employed in controlling odors; however, thermal incineration is more common. Temperatures and residence times for thermal incineration vary depending on the nature of the gas stream. Catalytic

incineration is a method to lower operating temperatures and thus lower operating costs; however, catalyst poisoning is a significant problem. Both types of incineration offer the most effective means of odor control, but do so at the highest capital and operating costs.

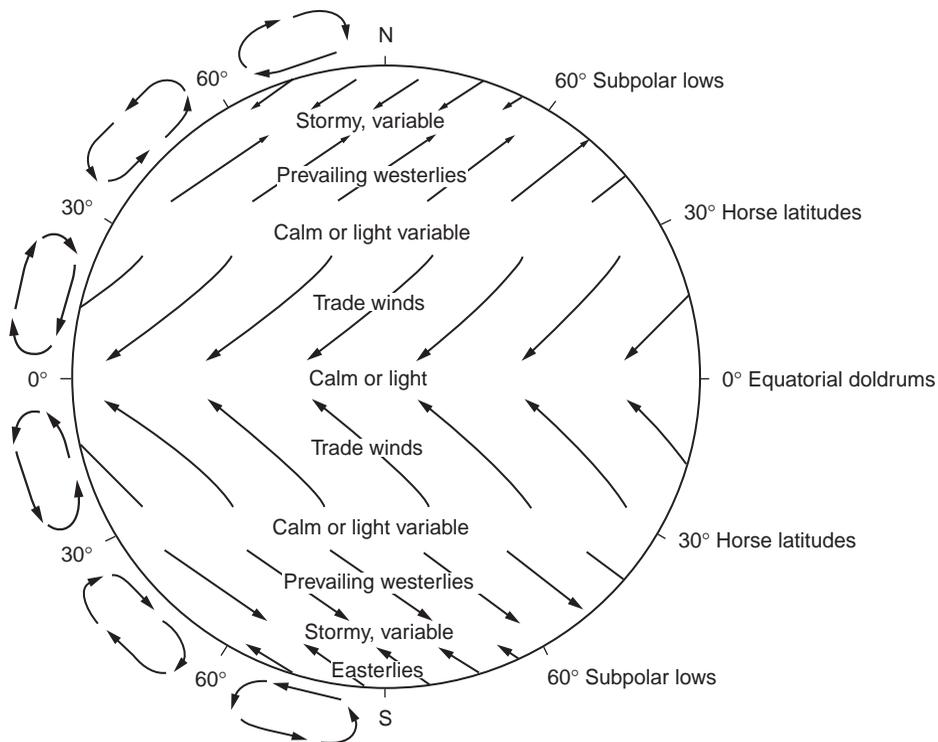
## 12.7 Air Pollution Meteorology

After an emission source has been characterized as to type and size, the question arises as to how the source and the resulting emissions will affect the quality of the downwind ambient air. This determination requires that the source further be described by modeling, or the estimation of the atmospheric dispersion of the various components of the gas stream. The modeling step is often what determines an appropriate emission rate.

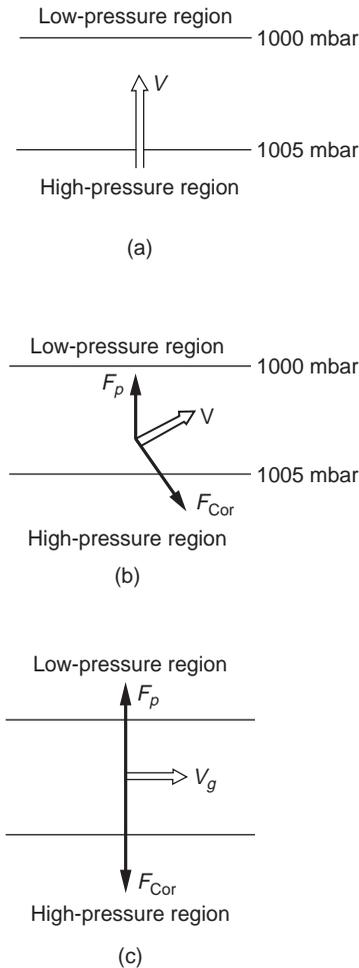
Once the gas stream is emitted into the atmosphere, a complex series of events begins to unfold. The components (or pollutants) in the gas stream join the environment and are transported, dispersed, and eventually removed from the atmosphere according to the physical nature of the component. However, before examining the dispersion of the gas stream, a basic understanding of the environment which governs the dispersion is required.

### Wind (Advection)

The atmosphere is an ocean of air that is in continual motion primarily as a result of solar heating and the rotation of the earth. As the sun heats different parcels of air in different areas, the heated air responds by expanding and increasing in pressure. Subsequently, differential pressure areas arise and result in large-scale air motions, or winds. This is illustrated on a global basis by the large-scale winds created as a result of differential heating between the equator and the poles. [Figure 12.13](#) illustrates the various winds that



**FIGURE 12.13** General global air circulation. (Source: Cooper, C. D. and Alley, F. C. 1990. *Air Pollution Control: A Design Approach*. Waveland Press, Prospect Heights, IL. Reprinted by permission of Waveland Press, Inc. All rights reserved.)



**FIGURE 12.14** Effects of various forces on wind direction relative to pressure isobars. (a) Pressure gradient force only. (b) Pressure gradient force with Coriolis force. (c) Balanced pressure gradient and Coriolis forces. (Source: Wark, K. and Warner, C. F. 1981. *Air Pollution, Its Origin and Control*. Harper & Row, New York. Used by permission.)

would be created by differential heating on a global scale if the earth were smooth and of homogenous composition [Cooper and Alley, 1990].

### Wind Variations

As described previously, movement of air (or wind) is a result of the pressure gradient created by high- and low-pressure regions interacting. This pressure gradient results in a force,  $F_p$ , that creates a velocity vector from the high-pressure region to the low-pressure region and, ideally, is perpendicular to both pressure regions or isobars. This is shown in Fig. 12.14(a), where  $V$  is the velocity vector or wind created by the pressure gradient force.

However, as the earth is rotating the effects of the Coriolis force,  $F_{Cor}$ , are realized on the movement of air as well. These forces result in the deflection of the wind from the ideal perpendicular gradient. In the northern hemisphere, these forces deflect the wind to the right, relative to the surface, while in the southern hemisphere the force deflects the wind to the left. The magnitude of the Coriolis force is a function of the velocity of the air, latitude, and the earth's rotational speed. These forces are at a maximum at the poles and zero at the equator [Wark and Warner, 1981]. When the pressure gradient and Coriolis forces are combined, the result, depicted in Fig. 12.14(b), is a velocity vector whose angle is a function

of the relative magnitude of the two forces to each other. In the ideal case, the pressure gradient and Coriolis forces are balanced such that the resultant velocity vector is parallel to the isobars. This is depicted in Fig. 12.14(c). The resulting wind always moves such that the pressure gradient force is in the direction of the low-pressure region and is balanced by the Coriolis force in the direction of the high-pressure region. The corresponding velocity vector is at a right angle to both. Movement of the wind is to the right of the Coriolis force and is therefore moving such that the low-pressure region is to the left of the vector. This idealized wind is referred to as the geostrophic wind and approximates conditions a few hundred meters above the earth's surface [Wark and Warner, 1981].

While the geostrophic wind is associated with parallel isobars, the gradient wind is associated with curved isobars. The gradient wind differs from the geostrophic wind by the centripetal acceleration,  $a_c$ , associated with the movement of a parcel of air in a curvilinear motion. The gradient wind is evident around centers of high and low pressure [Wark and Warner, 1981].

Winds at the earth's surface are further complicated by the fact that the earth is not smooth and homogenous. As a result several other factors need to be considered when discussing the magnitude and direction of the wind. Among these are [Cooper and Alley, 1990]:

1. Topography
2. Diurnal and seasonal variation in surface heating.
3. Variation in surface heating from the presence of ground cover and large bodies of water

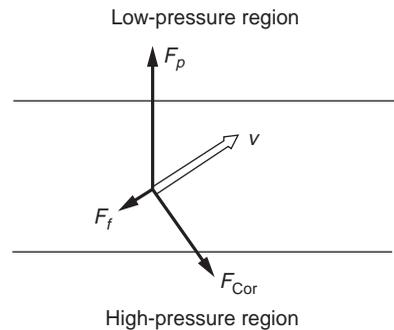
Principal among these factors is the frictional force,  $F_f$ , arising from surface roughness or the effect of the earth's topography. Additionally, variation in heating arises from daily and seasonal changes that affect the movement of air on a local basis. Both of the factors are combined as surface heating is a function of incoming solar radiation and the local surface characteristics.

The region of the atmosphere between the earth's surface and the upper reaches of the atmosphere is referred to as the planetary boundary layer [Wark and Warner, 1981]. In this layer, all of the factors mentioned above result in this frictional force that combines with the pressure and Coriolis force to alter the direction and magnitude of the wind at a slight angle toward the low-pressure region. This is illustrated in Fig. 12.15. The frictional force acts opposite to the direction of the velocity vector, which in turn acts at a right angle to the Coriolis force. The resulting magnitude of the wind velocity is the sum of the components of the individual force vectors, with the direction being at a slight angle toward the low-pressure region. This surface wind is of a magnitude less than the geostrophic wind.

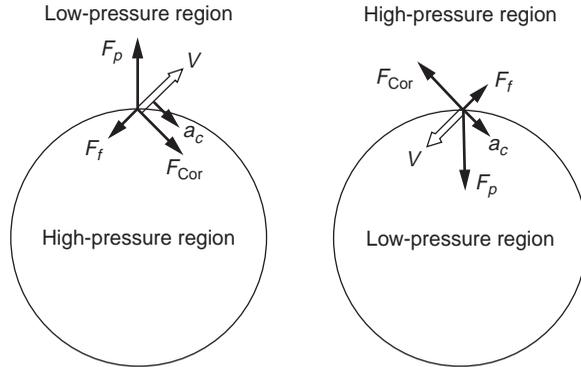
The combination of the pressure gradient, Coriolis, centripetal acceleration, and frictional forces is determined in the clockwise and counterclockwise flow around high- and low-pressure systems, respectively. This pattern of flow is shown in Fig. 12.16.

## Wind Rose

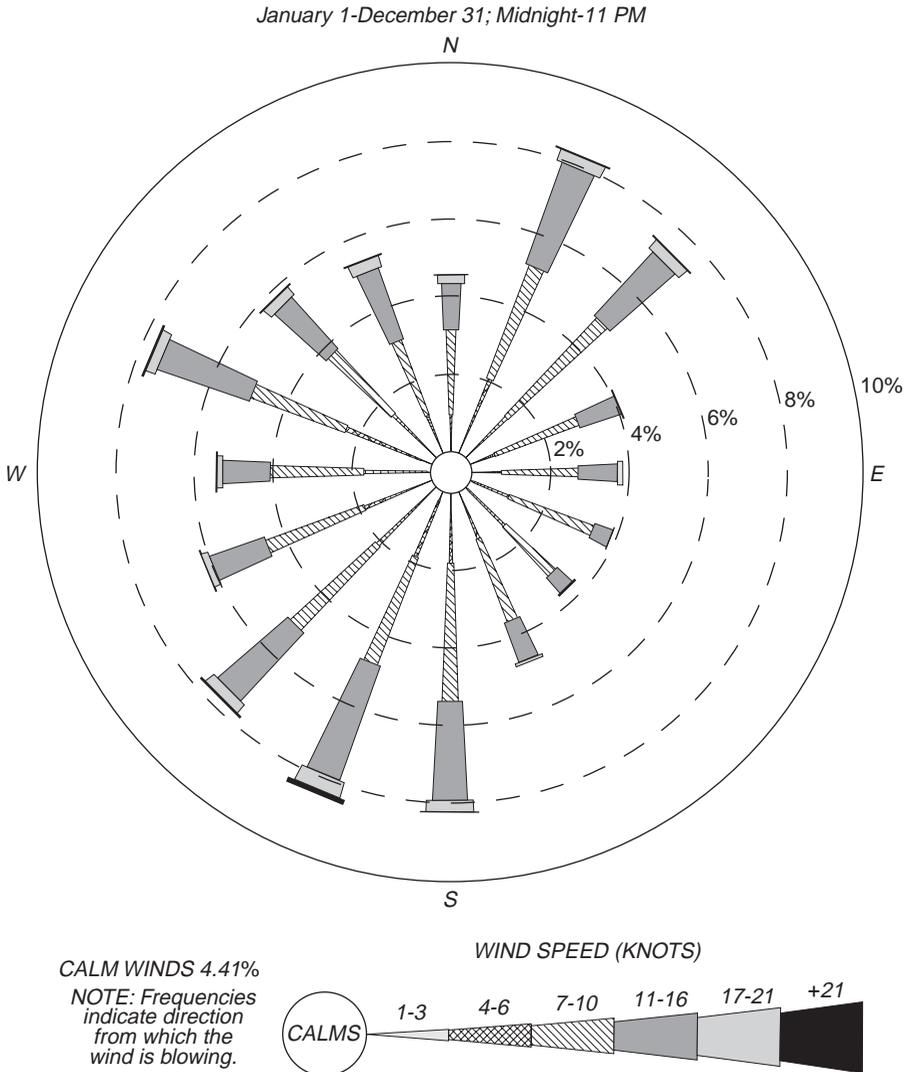
The wind in a specific location varies with the movement of pressure systems and heating patterns and produces characteristic patterns that can be represented by a statistical diagram called a *wind rose* [Turner, 1979]. A wind rose is a polar diagram that plots the frequency of the observed direction of a wind as a spoke. Additionally, the magnitude of the wind from a particular direction is included in the diagram as the length of the individual segments of the spoke. The observed direction of the wind is the direction from which the wind is blowing. Figure 12.17 is a wind rose generated from AIRS data for 1992 in Chicago, Illinois.



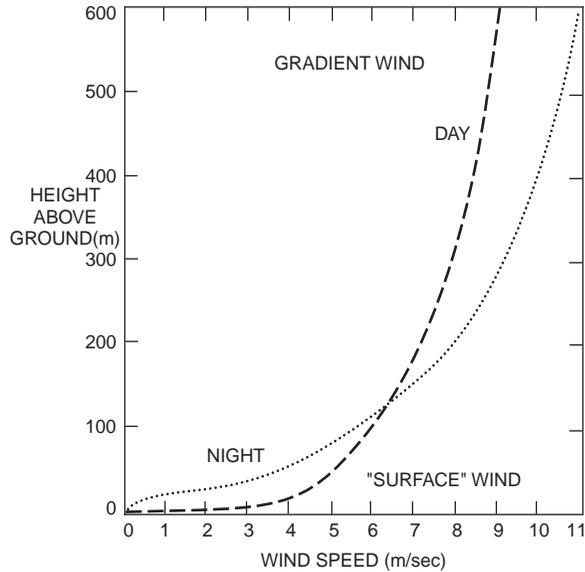
**FIGURE 12.15** Frictional force effect on the magnitude and direction of the wind. (Source: Wark, K. and Warner, C. F. 1981. *Air Pollution, Its Origin and Control*. Harper & Row, New York. Used by permission.)



**FIGURE 12.16** Force balances around (a) a high-pressure region, and (b) a low-pressure region. (Source: Wark, K. and Warner, C. F. 1981. *Air Pollution, Its Origin and Control*. Harper & Row, New York. Used by permission.)



**FIGURE 12.17** 1992 wind rose, Chicago, Illinois.



**FIGURE 12.18** Diurnal variations in the vertical velocity profile. (Source: Turner, D. B. 1979. Meteorological fundamentals. In *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, ed. J. R. Martin. The American Society of Mechanical Engineers, New York. Used by permission.)

### Vertical Velocity Profile

When all of the factors influencing the magnitude and direction combine, the resulting wind is found to vary in magnitude with elevation above the earth's surface. In the lower reaches of the atmosphere the magnitude of the wind is retarded by the frictional forces, but as elevation increases the frictional forces diminish and the magnitude of the wind increases. This relationship is described as the vertical velocity profile of the wind, and can be approximated numerically by

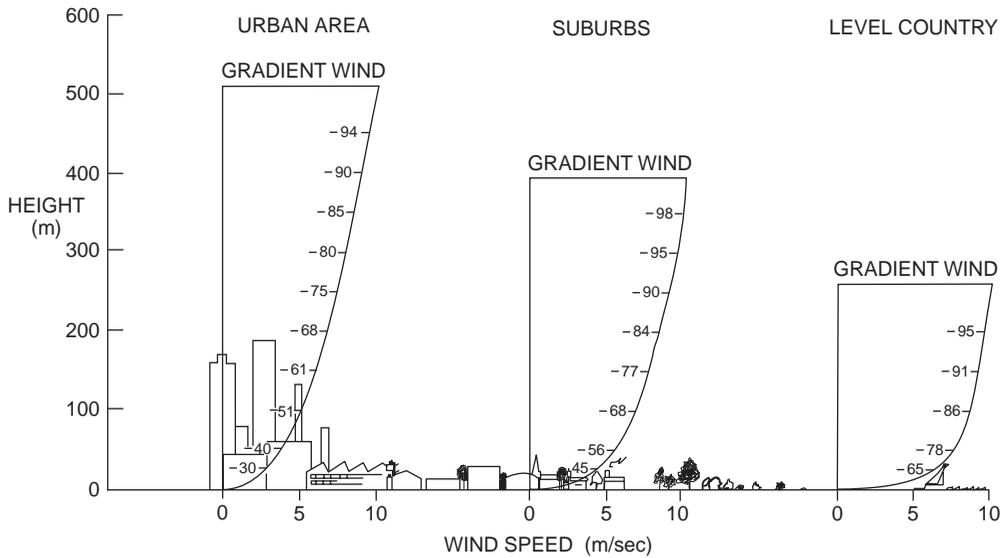
$$\frac{u}{u_1} = \left( \frac{z}{z_1} \right)^p \tag{12.43}$$

where  $u$  is the wind velocity at an elevation of  $z$ ,  $u_1$  is the wind velocity at an altitude of  $z_1$ , and  $p$  is a constant based on the stability of the atmosphere. The constant  $p$  ranges from 0 to 1. Figures 12.18 and 12.19 demonstrate the effects of the local surface characteristics and atmospheric stability on the vertical velocity profile of the wind.

### Stability

As the wind varies with differential heating, elevation, and surface characteristics, the stability of the atmosphere, or its ability to enhance or impede vertical motion, also varies [Turner, 1979]. The turbulence of the lower atmosphere is a function of the vertical temperature gradient, wind speed and direction, and surface characteristics. Stability can be classified into six categories based on general atmospheric conditions. These categories, included in Table 12.15, decrease in dispersional ability as the letter designation increases. Further, actual atmospheric conditions are assigned a stability class by several different methods, with each method varying in degree of complexity. A general description of the atmospheric stability, letter designation, and associated vertical velocity profile constant are given in Table 12.16.

Perhaps the method most often used is based on reference to a given vertical temperature gradient a parcel of air should encounter. The reference gradient is the dry adiabatic lapse rate.



**FIGURE 12.19** Vertical velocity profile variations as a function of surface characteristics. (Source: Turner, D. B. 1979. *Meteorological fundamentals. In Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, ed. J. R. Martin. The American Society of Mechanical Engineers, New York. Used by permission.)

**TABLE 12.15** Key to Stability Categories

Surface Wind at 10 meters (m/s)	Day		Night		
	Incoming Solar Radiation <sup>c</sup>			Thinly Overcast or Low Cloud Cover (≥ 1/2)	Cloud (≤ 3.8)
	Strong <sup>a</sup>	Moderate	Slight <sup>b</sup>		
<2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D <sup>d</sup>	D	D	D
>6	C	D	D	D	D

<sup>a</sup> Strong incoming solar radiation corresponds to a solar altitude greater than 60° with clear skies.

<sup>b</sup> Slight insolation corresponds to a solar altitude from 15° to 35° with clear skies.

<sup>c</sup> Incoming radiation that would be strong with clear skies can be expected to be reduced to moderate with broken (5/8 to 7/8 cloud cover) middle clouds and to slight with broken low clouds.

<sup>d</sup> The neutral class, D, should be assumed for overcast conditions during both the night and day.

Source: Turner, D. B. 1969. *Workbook Atmospheric Dispersion Estimates*. U.S. Public Health Service, Cincinnati, OH.

## Lapse Rates

The dry adiabatic lapse rate is the theoretical rate of cooling that should predict the temperature of a parcel of air as it rises in the atmosphere. This rate is derived by the situation that when a parcel of air rises in the atmosphere it expands and cools as the surrounding pressure decreases. If the parcel is assumed to expand and cool under adiabatic conditions (that is, assuming there is no heat exchange with its surroundings) the parcel of air should cool at a rate of  $-5.4^{\circ}\text{F}$  per 1000 feet ( $-1^{\circ}\text{C}/100$  meters) increase in elevation.

**TABLE 12.16** Stability Category Descriptions

Stability Descriptions <sup>a</sup>	Letter Designations <sup>a</sup>	Velocity Profile Constants ( <i>P</i> Values)
Very unstable	A	0.12
Moderately unstable	B	0.16
Slightly unstable	C	0.20
Neutral	D	0.25
Moderately stable	E	0.30
Very stable	F	0.40

<sup>a</sup>Source: Turner, D. B. 1979. Meteorological fundamentals. In *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, ed. J. R. Martin, pp. 1–15. The American Society of Mechanical Engineers, New York. Used by permission.

## Stability Classes

Actual lapse rates in the atmosphere can be determined readily and correspond to atmospheric conditions at that particular time. There are five general lapse rates found in the atmosphere.

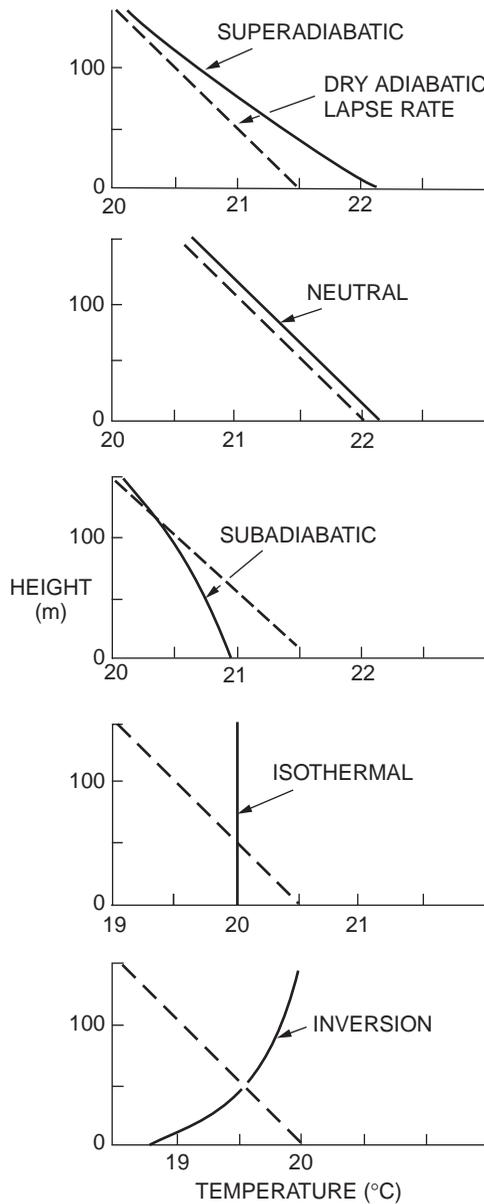
1. *Superadiabatic*. Shown in Fig. 12.20(a), this condition occurs on days when strong solar heating is present, and results in a lapse rate greater than  $-1^{\circ}\text{C}/100$  meters. Superadiabatic conditions are typically found only in the lower 200 meters of the atmosphere and are associated with a stability class of A, or very unstable conditions.
2. *Neutral*. This condition is associated with overcast days and strong to moderate wind speeds. The lapse rate approximates the dry adiabatic lapse rate very closely, as shown in Fig. 12.20(b). Stability classes associated with neutral conditions are B, C, or D indicating moderately unstable to neutral conditions.
3. *Subadiabatic*. This condition is associated with relatively calm days without strong solar heating. The lapse rate is below the  $-1^{\circ}\text{C}/100$  meters rate, as shown in Fig. 12.20(c). Subadiabatic conditions correspond to stability classes of D or E for neutral to moderately stable.
4. *Isothermal*. Shown in Fig. 12.20(d), the temperature in the atmosphere is constant with height, and as a result, there is no lapse rate. Isothermal conditions coincide with a stability class of D.
5. *Inversion*. When the temperature gradient increases with height, often found in the evenings on days with strong solar heating, the condition is referred to as a thermal inversion. This condition demonstrates extremely stable conditions, with a stability class of F, and results in a positive lapse rate. This is shown in Fig. 12.20(e).

## Plume Characteristics

For each of the atmospheric stability classes listed above, there is a plume type that is characteristic in both plume shape and downwind concentration. That is, as the gas stream is emitted from the source, the gas stream (or plume) initially rises and then begins to dissipate in the atmosphere.

Atmospheric stability governs the general characteristics of any plume because the maximum height the plume rises to, the degree of dissipation, and the downwind distances where the plume constituents first come into contact with the surface and the distance that the constituents interact with the surface are all functions of the atmospheric conditions when the plume is emitted. Five general types of plumes can be visually identified, each generally corresponding to an atmospheric stability class.

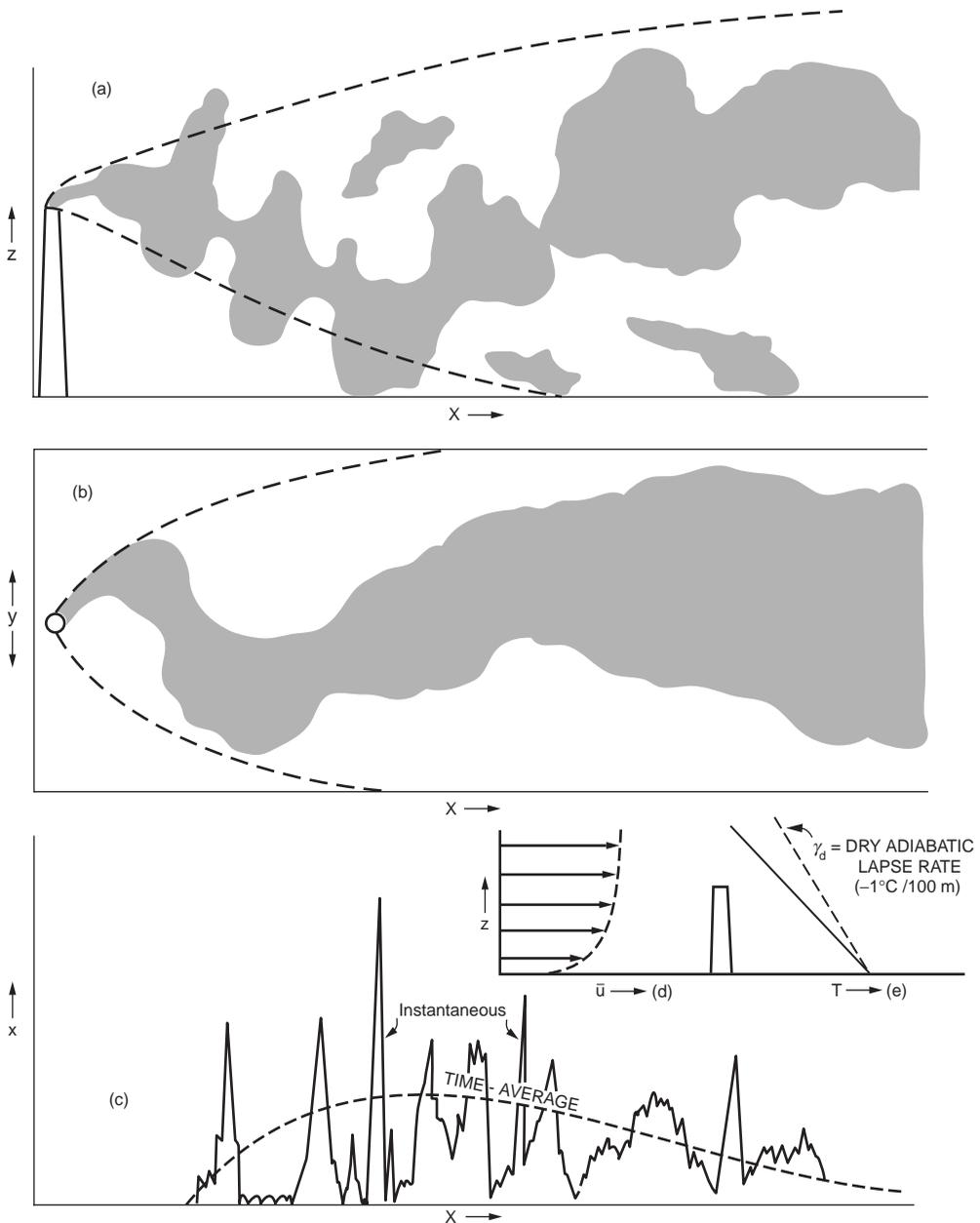
The first type of plume is the *looping plume* associated with great instability in the atmosphere, or a stability class of A. The name of the plume arises from its shape when viewed from a horizontal perspective. A looping plume, shown in Fig. 12.21, is characterized by a tortuous shape that finds the plume rising and falling. This type of plume has a very short downwind initial contact distance with plume constituents resulting in a gradual concentration profile over a long downwind distance. Strong



**FIGURE 12.20** Atmospheric lapse rates in comparison to the dry, adiabatic lapse rate for (a) superadiabatic, (b) neutral, (c) subadiabatic, (d) isothermal, and (e) inversion conditions. (Source: Turner, D. B. 1979. Meteorological fundamentals. In *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, ed. J. R. Martin. The American Society of Mechanical Engineers, New York. Used by permission.)

instability in the atmosphere creates this situation as the plume is influenced only by great mixing and no forces preventing surface contact. Additionally, when viewed vertically, the plume meanders a great distance from its original centerline, and thus has the potential for the plume constituents to affect a large surface area.

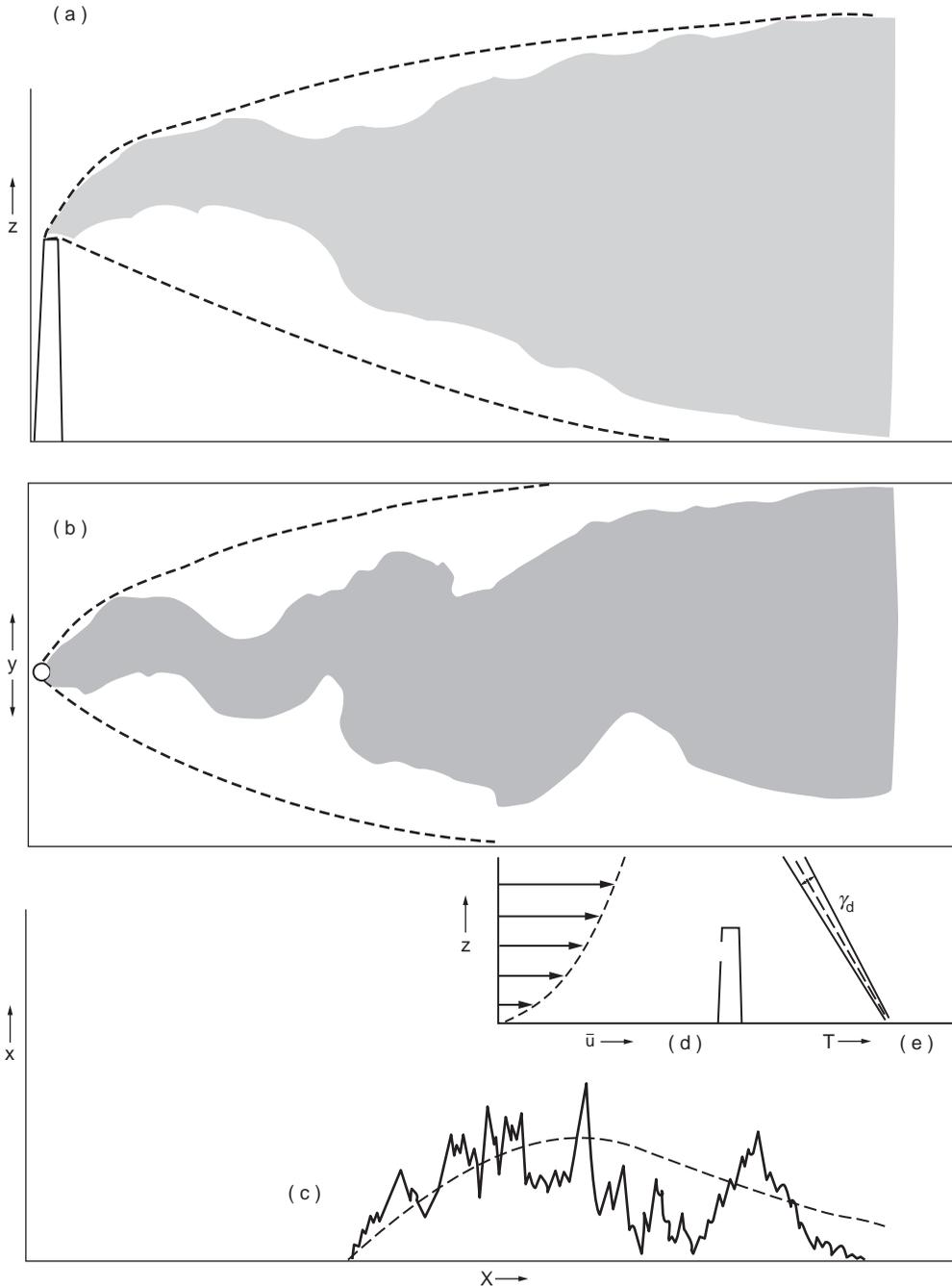
The second type of plume is the *coning plume*, shown in Fig. 12.22, and corresponds to the near-neutral conditions or atmospheric conditions in classes B, C, or D. Initially, the plume follows the same pattern as the looping plume when viewed vertically. However, when viewed horizontally the plume has



**FIGURE 12.21** Looping plume. (Source: Pack, D. H. and Halitsky, J. 1979. Behaviour of airborne effluents. In *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, ed. J. R. Martin. The American Society of Mechanical Engineers, New York. Used by permission.)

a much more gradual pattern of dissipation. This is due to the decreased mixing ability of the atmosphere. As a result of the decreased mixing, the plume is carried over a much greater distance before its initial surface contact. Downwind distances these constituents are deposited over are less than the looping plume, and result in higher surface concentrations of the constituents.

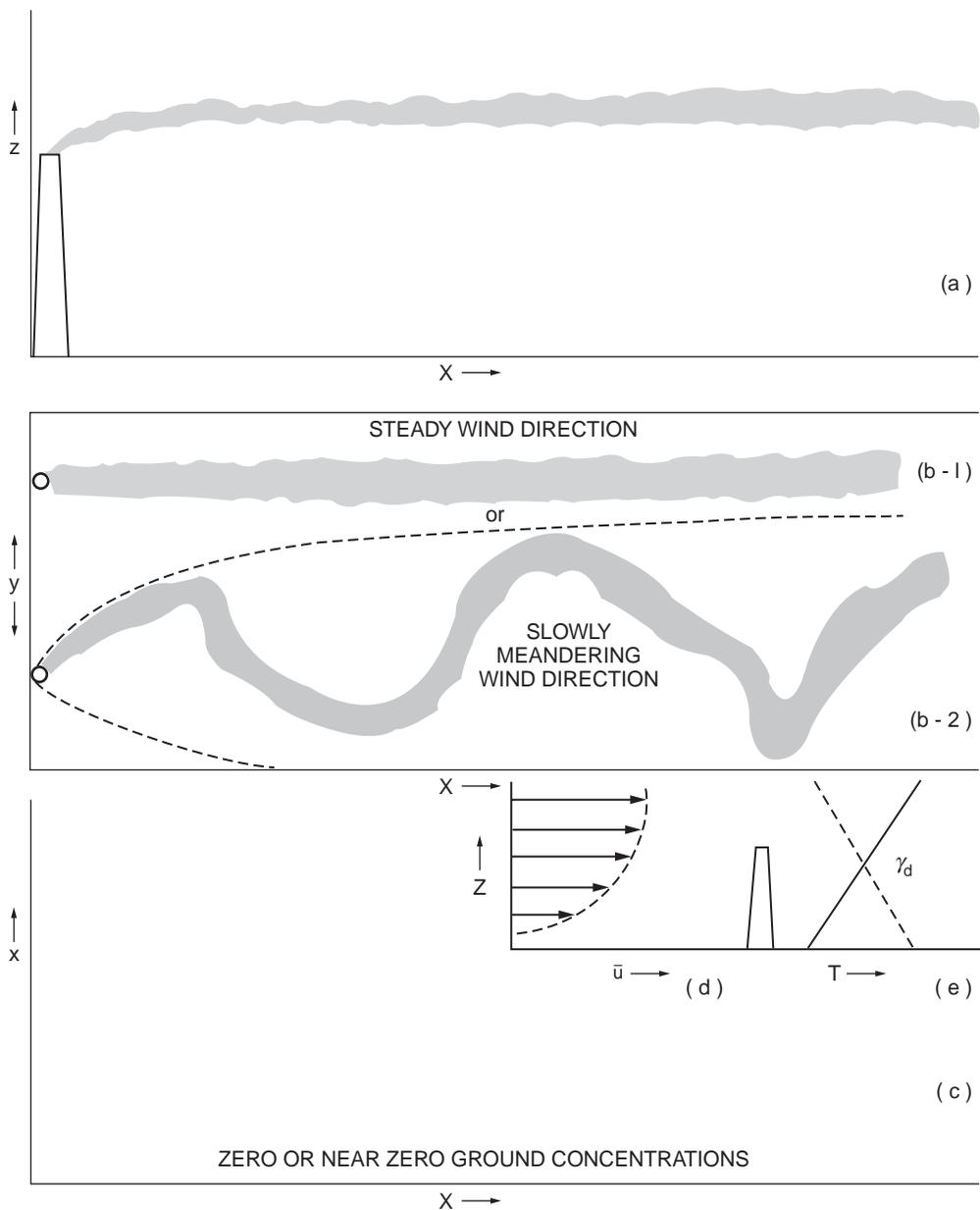
The third type of plume is the *fanning plume*, the plume type associated with inversion conditions. These conditions, with a stability class of F, result in the plume being held in a vertical plane by the cooler air below the stack and the warmer air above it, as is illustrated in Fig. 12.23. As a result, the downwind



**FIGURE 12.22** Coning plume. (Source: Pack, D. H. and Halitsky, J. 1979. Behaviour of airborne effluents. In *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, ed. J. R. Martin. The American Society of Mechanical Engineers, New York. Used by permission.)

concentrations are virtually nonexistent as the plume constituents have a much greater time to dissipate before contacting the earth's surface.

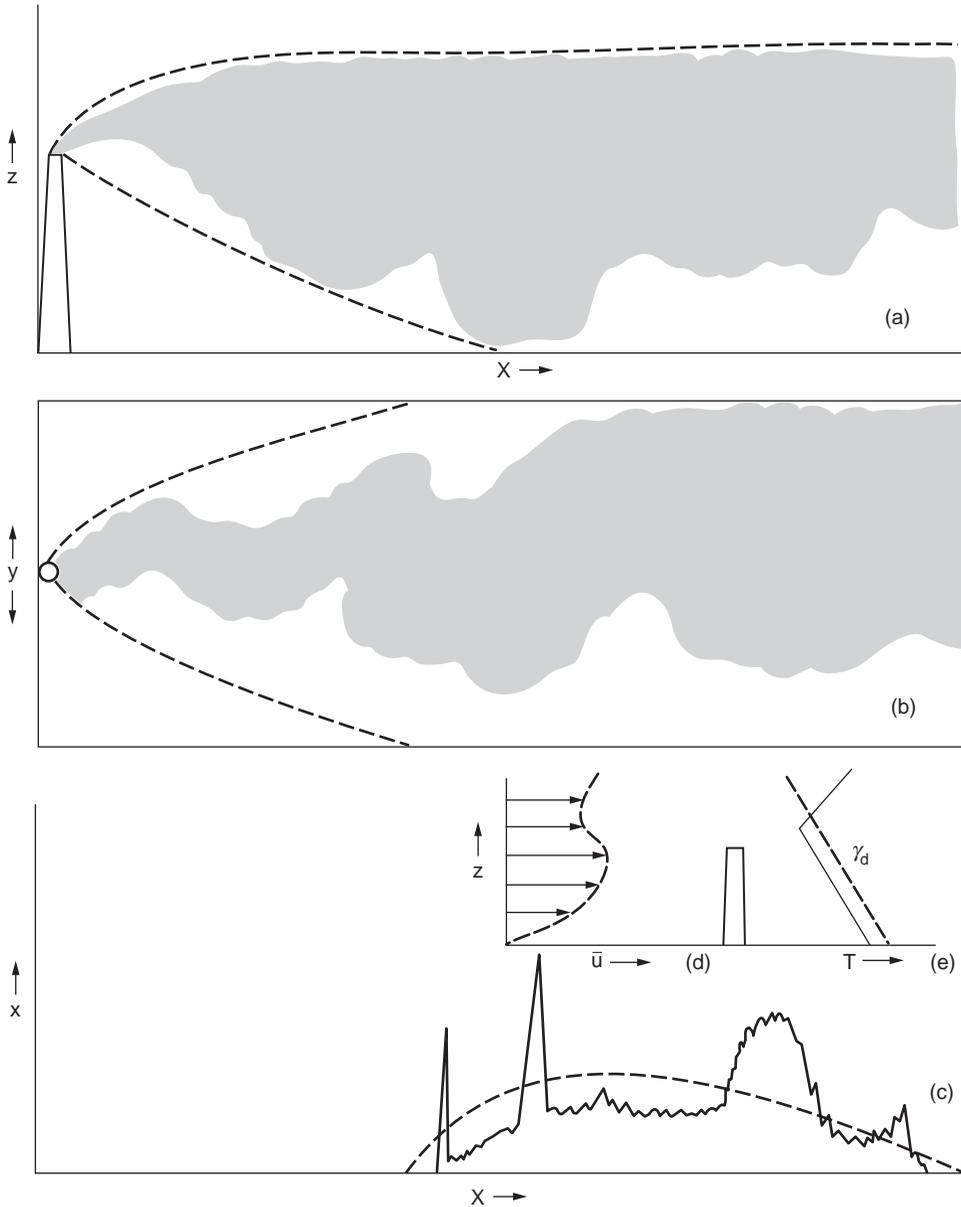
The *fumigation plume* is the fourth type of plume and is the result of an elevated inversion. The warmer air above the stack holds the plume rise to a maximum elevation at the lower limit of the inversion. This



**FIGURE 12.23** Fanning plume. (Source: Pack, D. H. and Halitsky, J. 1979. Behaviour of airborne effluents. In *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, ed. J. R. Martin. The American Society of Mechanical Engineers, New York. Used by permission.)

type of plume, shown in Fig. 12.24, is similar to a coning with the exception that surface concentrations tend to be higher as a result of the limited upper mixing boundary.

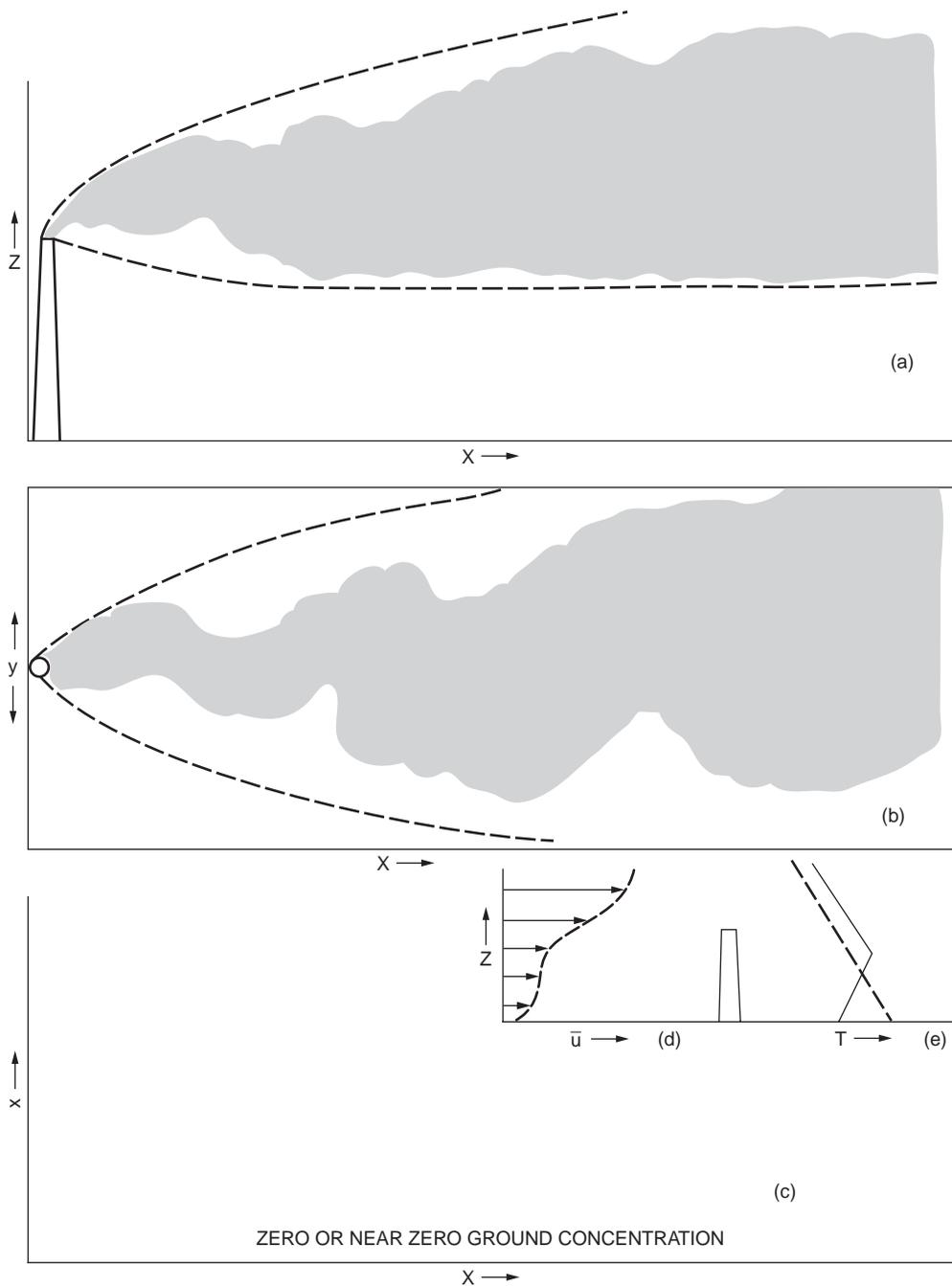
The final type of plume is the *lofting plume*, shown in Fig. 12.25. This plume is the result of a surface inversion that restricts the plume's ability to reach the surface. Concentration profiles for this plume are identical to the fanning plume; none of the plume's constituents are detectable until the plume has traveled through the surface inversion.



**FIGURE 12.24** Fumigation plume. (Source: Pack, D. H. and Halitsky, J. 1979. Behaviour of airborne effluents. In *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, ed. J. R. Martin. The American Society of Mechanical Engineers, New York. Used by permission.)

## 12.8 Dispersion Modeling

The estimation of downwind concentrations of pollutants emitted from a source involves approximating the cumulative effect of many atmospheric and emission variables. This modeling effort is done mainly to determine the effects the source presently has, or will have in the future, on its surrounding environ-



**FIGURE 12.25** Lofting plume. (Source: Pack, D. H. and Halitsky, J. 1979. Behaviour of airborne effluents. In *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, ed. J. R. Martin. The American Society of Mechanical Engineers, New York. Used by permission.)

ment. Types of air pollution models vary from very basic models describing a single source to regional airshed models that describe multitudes of sources over large metropolitan areas.

All of the models employed for air quality analysis are derived from four basic types of models. These are the Gaussian, numerical, statistical or empirical, and physical. Gaussian models are the most widely

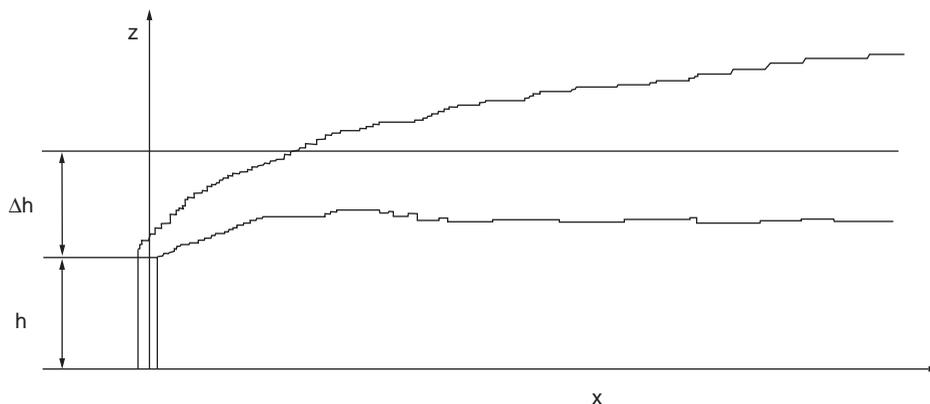


FIGURE 12.26 Plume rise.

used models for the estimation of nonreactive pollutants. Numerical models are favored in the analysis of urban areas with reactive pollutants, but are a great deal more complex. Statistical or empirical models are typically used in situations where data is lacking, and physical models are actual simulations in wind tunnels or other fluid-modeling facilities [U.S. EPA, 1993].

Because of the wide range of models, the description of the fundamentals of each individual model is beyond the scope of this chapter. As a result, this discussion will focus on the basics of the most common, the double Gaussian or normal dispersion model. This model will be described in an effort to cover the basic approaches to modeling a single source in noncomplex terrain for both gaseous and particulate pollutants.

## Plume Rise

### Coordinate System

The first step in describing the plume rise, or effective stack height, is the development of a system of coordinates to describe the dispersion of the plume in three dimensions. The system employed assumes the origin to be at the base of the source. From the origin the  $x$  axis extends in the direction of the mean wind, the  $y$  axis extends perpendicular to the  $x$  axis, and the  $z$  axis extends vertically (along the stack) from the origin, perpendicular to both the  $x$  and  $y$  axes.

### Effective Stack Height

Plume height ( $H$ ), or effective stack height, is the elevation in the  $z$  axis the plume rises to. This is defined by the following equation:

$$H = h + \Delta h \quad (12.44)$$

where the plume height  $H$  is the sum of the height of the actual stack  $h$  and the additional height  $\Delta h$  the plume rises under the effects of the momentum and buoyancy forces of the gas stream being emitted. Figure 12.26 illustrates the plume rise.

The determination of  $\Delta h$  is done by attributing this variable to the major force affecting it. From this plumes are grouped into two categories: momentum sources and buoyant sources. Momentum sources are small-volume sources having appreciable exit speeds with little temperature excess. These are conditions described by exit speeds of greater than or equal to 10 m/s with temperatures less than 50°C above the ambient temperature. Buoyant sources are larger-volume source with higher temperatures. Typically these sources will have volumetric flow rates greater than 50 m<sup>3</sup>/s and temperatures greater than 50°C above ambient temperature [Frizzola et al., 1979]. In describing these situations, only one force is considered in determining the plume rise.

### **Momentum Sources**

Plume rise from a momentum source is described mathematically as a function of the exit conditions and the wind speed at the stack height by the following relationship.

$$\Delta h = D \left( \frac{V_s}{u_s} \right)^{1.4} \quad (12.45)$$

where  $\Delta h$  is the height of the plume above the stack (m)

$D$  is the diameter of the stack (m)

$V_s$  is the emission velocity (m/s)

$u_s$  is the mean wind speed at the stack height (m/s)

### **Buoyant Plume Sources**

Buoyant plume sources, as described previously, can be described mathematically only by inclusion of atmospheric conditions at the time of emission. As plume rise varies accordingly to the atmosphere, three different equations are used to describe this situation. The three equations apply to stable conditions, unstable conditions, and both stable and unstable conditions in the absence of appreciable wind.

Under stable conditions, or stability classes of E or F, the following equations describe the plume rise if there is appreciable wind present.

$$\Delta h = 2.6 \left( \frac{F}{u_s S} \right)^{1/3} \quad \text{and} \quad F = g V_s \left( \frac{D}{2} \right)^2 \left( \frac{\rho_a - \rho_s}{\rho_a} \right) \quad (12.46)$$

where  $g$  is the acceleration due to gravity (9.807 m/s<sup>2</sup>)

$V_s$  is the emission velocity (m/s)

$D$  is the diameter of the stack (m)

$\rho_a$  is the density of the ambient air (g/m<sup>3</sup>)

$\rho_s$  is the stack gas density (g/m<sup>3</sup>)

$S$  is the stability parameter (1/s<sup>2</sup>)

The stability parameter is further defined as

$$S = \left( \frac{g}{T} \right) \left( \frac{\partial \Theta}{\partial z} \right) \quad (12.47)$$

where  $T$  is the ambient temperature (K) and  $\partial \Theta / \partial z$  is the vertical potential temperature gradient. For stability categories E and F,  $\partial \Theta / \partial z$  is 0.02 and 0.04 K/m, respectively.

$$\Delta h = \frac{1.6 F^{1/3} (3.5x)^{2/3}}{u_s} \quad (12.48)$$

where the downwind distance the plume rises to an elevation of  $\Delta h$  is  $3.5x$ .  $x$  is determined by the following equations.

$$\begin{aligned} x &= 14 F^{5/8} \quad \text{when} \quad F \leq 55 \left( \frac{\text{m}^4}{\text{s}^3} \right) \\ x &= 34 F^{2/5} \quad \text{when} \quad f > 55 \left( \frac{\text{m}^4}{\text{s}^3} \right) \end{aligned} \quad (12.49)$$

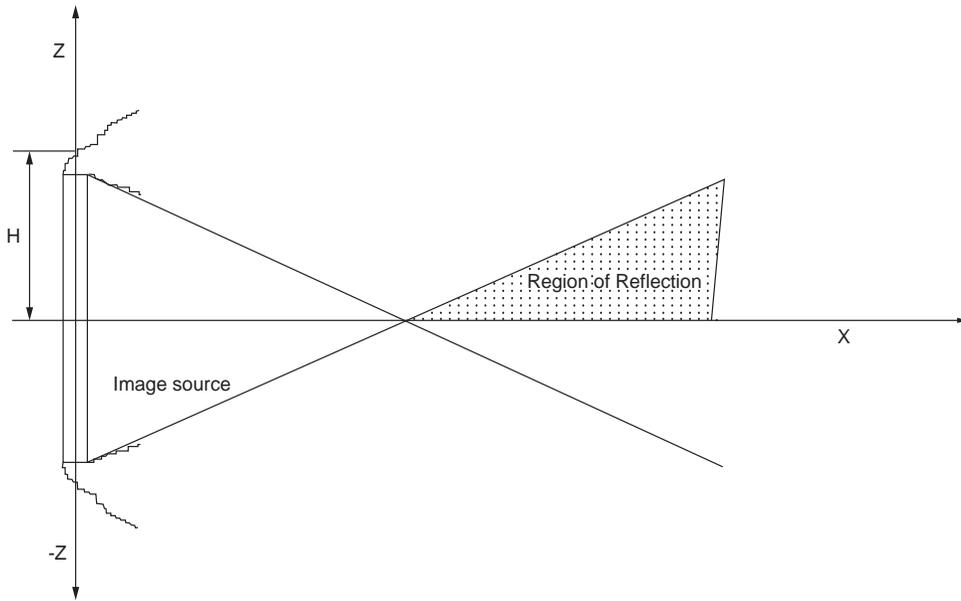


FIGURE 12.27 Region of reflection.

During both stable and unstable conditions, if there is an absence of wind there is an almost vertical rise in the plume. This rise can be described by the following equation.

$$\Delta h = 5.0 \frac{F^{1/4}}{S^{3/8}} \quad (12.50)$$

After the plume type and rise have been determined, the effective stack height should be determined by adding the plume rise to the physical stack height. It should be noted that synonymous units are required in the calculation of effective stack height and that the plume rise equations listed above are all in S.I. units.

## Gaseous Dispersion

Currently, worldwide use is being made of the double normal Gaussian mathematical dispersion model for estimating downwind concentrations of pollutants from point, area, and fugitive sources. The Gaussian model is used throughout the U.S. by the Environmental Protection Agency and the respective state and local air pollution control agencies. Its development over the past 25 years has resulted in a rather powerful and cost-effective tool for regulatory planning and implementation purposes.

The model is a combination of empirical and theoretical considerations. It is certainly not a perfect tool but through validations and sometimes calibrations, it is widely accepted. The model uses an exponential decay term ( $e^{-t}$ ) to account for downwind dilution effects and borrows the Gaussian distribution from statistics to simulate the vertical and crosswind distribution of a pollutant at any point downwind. Furthermore, the model recognizes plume reflection at the earth's surface and provides for a superposition solution or mirror-image stack below the ground plane to account for pollutant reflection at the surface. Figure 12.27 illustrates the plume reflection effect. Elevated sources such as tall stacks are handled by shifting the plume centerline above the surface.

For a surface which absorbs and does not reflect pollutants Eq. (12.51) can be used.

$$C(x, y, z) = \frac{Q}{2\pi u_s \sigma_y \sigma_z} \exp \left[ -\frac{1}{2} \left( \frac{y^2}{\sigma_y^2} + \frac{(z-H)^2}{\sigma_z^2} \right) \right] \quad (12.51)$$

**TABLE 12.17**  $\sigma_y$  and  $\sigma_z$  Determinations for Open-country Conditions with Downwind Distances between 100 and 10,000 Meters

Stability Class	$\sigma_y$ (m)	$\sigma_z$ (m)
A	$0.22x(1 + 0.0001x)^{-1/2}$	$0.20x$
B	$0.16x(1 + 0.0001x)^{-1/2}$	$0.12x$
C	$0.11x(1 + 0.0001x)^{-1/2}$	$0.08x(1 + 0.0001x)^{-1/2}$
D	$0.08x(1 + 0.0001x)^{-1/2}$	$0.06x(1 + 0.0001x)^{-1/2}$
E	$0.06x(1 + 0.0001x)^{-1/2}$	$0.03x(1 + 0.0001x)^{-1}$
F	$0.04x(1 + 0.0001x)^{-1/2}$	$0.016x(1 + 0.0001x)^{-1}$

Source: Smith, M. E., et al. 1979. Calculations of dispersion and deposition. In *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, ed. J.R. Martin. The American Society of Mechanical Engineers, New York. Used by permission.

- where  $Q$  is the mass emission rate of pollutant (g/s)
- $u_s$  is the wind speed at stack height at the time of emission (m/s)
- $\sigma_y$  is a stability constant described in Table 12.1 (m)
- $H$  is the effective stack height (m)
- $\sigma_z$  is a stability constant described in Table 12.1 (m)

For situations which require the consideration of surface reflection, which occurs for most cases, the double normal Gaussian model of Eq. (12.52) must be used.

$$C(x, y, z) = \frac{Q}{2\pi u_s \sigma_y \sigma_z} \left[ \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \right] \left[ \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) \right] \quad (12.52)$$

The  $\sigma_y$  and  $\sigma_z$  values are borrowed from the Gaussian distribution statistics and are analogized here as pollutant dispersion variables instead of standard deviations as we usually think of them in a statistical sense.  $\sigma_y$  is the pollutant dispersion coefficient in the crosswind direction and  $\sigma_z$  is the dispersion coefficient in the vertical. These dispersion coefficients were originally derived from diffusion experiments on the O'Neill, Nebraska grass flats following World War II. Since then they have been modified significantly with experiments in St. Louis, Missouri and elsewhere giving rise to both an urban and a rural version of the model. The dispersion coefficients can be determined from Table 12.17 for various downwind distances and atmospheric stability classes [Smith et al., 1979].

It is interesting to note that Eq. (12.52) does not contain a  $\sigma_x$  or downwind dispersion coefficient. The reason for this is that this model simulates a continuous point source release as opposed to a "puff" or instantaneous release. The resulting downwind pollutant concentration gradient along a limited segment of the plume centerline is insignificant compared to the crosswind and vertical gradients. Hence, no  $\sigma_x$  or downwind dispersion coefficient is used in the continuous release model.

Note that the exponential term in Eq. (12.52) can never be greater than unity and that all parameters with units must cancel out. The engineering units of concentration are formed from the first term in the equation. The numerator has the units of mass per time and the denominator volume per time, yielding mass per volume or pollutant concentration units. A worst-case scenario for the model would be the situation in which the stack height is zero, as in the case of a burning pile of leaves, and the concentration is desired directly downwind on the ground along the plume centerline. In this situation, note that  $y = 0$ ,  $z = 0$ , and  $H = 0$ , resulting in the exponential term going to a unity value (1.0) leaving the final term to be  $Q/(\pi u_s \sigma_y \sigma_z)$ .

## Particulate Dispersion

The double normal Gaussian model just discussed is valid for gases and suspended particulate matter. In addition, the model can be modified to handle settleable particulate matter. This is usually defined as those particles greater than 40 microns in diameter. (A typeset period on this page is about 1000 microns in diameter.) We are interested in having a model consider particulate settling because in some instances surface deposition of a toxic particle from an elevated plume is very important to know. Instead of the model calculating pollutant concentration, we may be more interested in mass of deposition per unit area per unit time.

Examining the dynamics of particles settling out of an elevated plume, we can differentiate the centerline of the gaseous portion of the plume from the centerline of the settleable particulate portion of the plume. Considering only the settleable particulate plume centerline, we note that for each size class of particle there is a distance downwind beyond which no more particles of that size will be found because they have all settled to the ground. In other words, the plume centerline for that particle size has disappeared. We can represent the disappearance of that particle size class with a plume centerline that tilts downward from near the top of the stack and eventually disappears downwind into the surface. This type Gaussian model is referred to as a *tilted plume* model.

The amount of plume tilt is determined from the terminal settling velocities of the various sizes of particles in the plume, the distance downwind where they have settled out, and the mean wind speed. If the terminal settling velocity of the particle is defined as  $V_p$ , the downwind distance as  $x$ , and the wind speed as  $u$ , the ratio  $V_p x/u$  can be used to shift the plume centerline downward. Equation (12.53) is the familiar Gaussian model with the plume-shift term incorporated.

$$C(x, y, z) = \frac{Q_p}{2\pi u_s \sigma_y \sigma_z} \exp \left[ -\frac{1}{2} \left\{ \left( \frac{y}{\sigma_y} \right)^2 + \left( \frac{z - [H - (V_t x/u_s)]}{\sigma_z} \right)^2 \right\} \right] \quad (12.53)$$

Additionally, the mass deposition rate of particulate in a given area can be determined by multiplying the concentration deposited by the terminal settling velocity. This is given by the following equation.

$$\omega(x, y, z) = \frac{Q_p V_t}{2\pi u_s \sigma_y \sigma_z} \exp \left[ -\frac{1}{2} \left\{ \left( \frac{y}{\sigma_y} \right)^2 + \left( \frac{z - [H - (V_t x/u_s)]}{\sigma_z} \right)^2 \right\} \right] \quad (12.54)$$

## Regulatory Air Models

From the first basic Gaussian air models, an entire library of models has developed with each new model being employed for new uses or being a refinement of an existing model. As a result of continuous updating and advancement of air models, the use of specific models in regulatory applications changes as new models become available.

In regulatory efforts the use of a specific model is based on the desired result of the modeling. For example, the use of a simple Gaussian model to describe the impact of a major source in complex terrain is beyond the capabilities of the model and is therefore not recommended. However, if only rough estimates are required for a single source on open terrain, the simple Gaussian model would probably suffice. Because of the existence of these types of situations, individual models are recommended for specific applications. [Tables 12.18](#) and [12.19](#) are a listing of the regulatory air models and their applications currently preferred or recommended as alternatives by the U.S. EPA.

**TABLE 12.18** Preferred Air Quality Models

	Preferred Models
Buoyant line and point source dispersion model (BLP)	BLP is a Gaussian plume dispersion model for plume rise and downwash effects from stationary line sources.
CALINE3	CALINE3 is used to estimate the concentrations of nonreactive pollutants emanating from highway traffic.
Climatological dispersion model (CDM 2.0)	CDM is a climatological steady-state Gaussian plume model for seasonal or annual arithmetic average pollutant concentrations in an urban area.
Gaussian-plume multiple source air quality algorithm (RAM)	RAM is a Gaussian plume model for estimating relatively stable pollutants from point and area sources in level terrain.
Industrial source complex model (ISC3)	ISC3 is a Gaussian plume model to describe an industrial source complex in either short- or long-term models with limited terrain adjustment.
Urban airshed model (UAM)	UAM is a three-dimensional urban simulation model for estimating ozone concentrations from short-term conditions.
Offshore and coastal dispersion model (OCD)	OCD is a Gaussian model developed to estimate the effect of offshore sources on coastal regions.
Emissions and dispersion modeling system (EDMS)	EDMS is a combined emissions/dispersion model for assessing pollution at civilian airports and military air bases.
Complex terrain dispersion model plus algorithms for unstable conditions (CTDMPLUS)	CTDMPLUS is a refined point source Gaussian air quality model for use in all stability conditions for complex terrain situations.

Source: 40 CFR 51 Appendix A to Appendix W.

**TABLE 12.19** Alternative Air Quality Models

	Alternative Models
AVACTA II Model	AVACTA II is a Gaussian model that describes atmospheric dispersion in terms of segment or puff elements. It is particularly suited to simulations of sulfur species but can simulate virtually any pair of primary-secondary pollutants.
Dense Gas Dispersion Model DEGADIS	DEGADIS is used to model the transport of toxic chemical releases in to the atmosphere.
ERT Visibility Model	The ERT visibility model is designed to address visibility impairment for arbitrary lines of sight.
HGSYSTEM	HGSYSTEM is a system of linked models that estimate near and fair-field dispersion from spills of either two-phase, nonreactive multi-compound mixtures or hydrogen fluoride with reactions.
Higher Order Turbulence Model for Atmospheric Circulation/Random Puff Transport and Diffusion HOTMAC/RAPTAD	HOTMAC/RAPTAD combines an Eulerian mesoscale weather prediction model with a Lagrangian random puff model to forecast transport and diffusion over complex terrain. It is significantly different in its physics and modeling system than most regulatory models presented here.
LONGZ	LONGZ is a steady-state Gaussian plume model for urban and rural areas that estimates annual average concentrations of pollutants from up to 14,000 sources.
Maryland Power Plant Siting Program (PPSP) Model	PPSP is a Gaussian plume model applicable to tall stacks in either rural or urban areas with simple terrain.
Mesoscale Puff Model (MESOPUFF II)	MESOPUFF II is a short-term, regional scale puff model used to estimate concentrations of up to five pollutant species.
Mesoscale Transport Diffusion and Deposition Model for Industrial Sources (MTDDIS)	MTDDIS is a variable trajectory Gaussian puff model for long-range transport of point source emissions over level or rolling terrain.
Multi-Source (SCSTER) Model	SCSTER is a steady state, Gaussian dispersion model for multiple sources in urban or rural terrain. SCSTER is a modified version of the EPA CRSTER model.

**TABLE 12.19 (continued)** Alternative Air Quality Models

	Alternative Models
PANACHE	PANACHE simulates continuous or short term pollution dispersion via Eulerian or Lagrangian finite volume fluid mechanics code. Complex terrain and source, receptor relationships can be modeled.
Plume Visibility Model (PLUVUE II)	PLUVUE II is used for estimating visual range reduction and atmospheric discoloration from a single emission source.
Point, Area, Line-Source Algorithm (PAL-DS)	PAL-DS is an algorithm for estimating short-term dispersion from line, point, or area sources based on steady state Gaussian plume assumptions.
Reactive Plume Model (RPM-IV)	RPM-IV is used for estimating short-term concentrations of primary and secondary reactive pollutants from point or area sources.
Shoreline Dispersion Model (SDM)	SDM is a multipoint Gaussian model that calculates source impacts from fumigation events.
SHORTZ	SHORTZ uses the steady-state bivariate Gaussian plume model to estimate ground-level concentrations in urban and rural terrain for both simple and complex terrain.
Simple Line-Source Model	The Simple Line-Source Model is used to determine exhaust concentrations within 100 meters of a roadway in relatively flat terrain.
SLAB	SLAB estimates spatial and temporal distributions of short-term ambient concentrations resulting from the release of denser than air gases.
WYNDValley Model	WYNDValley is a multilayer Eulerian grid dispersion model that permits flexibility in modeling.

Source: 40 CFR 51 Appendix A to Appendix W

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