

CHAPTER 29

INDUSTRIAL GAS CLEANING AND AIR POLLUTION CONTROL

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**I**NDUSTRIAL gas cleaning performs one or more of the following functions:

- Maintains compliance of an industrial process with the laws or regulations for air pollution
- Reduces nuisance or physical damage from contaminants to individuals, equipment, products, or adjacent properties
- Prepares cleaned gases for processes
- Reclaims usable materials, heat, or energy
- Reduces fire, explosion, or other hazards

Equipment that removes particulate matter from a gas stream may also remove or create some gaseous contaminants; on the other hand, equipment that is primarily intended for removal of gaseous pollutants might also remove or create objectionable particulate matter to some degree. In all cases, gas-cleaning equipment changes the process stream, and it is therefore essential that the engineer evaluate the consequences of those changes to the plant's overall operation.

**Equipment Selection**

In selecting industrial gas-cleaning equipment, plant operations and the use or disposal of materials captured by the gas-cleaning equipment must be considered. Because the cost of gas-cleaning equipment affects manufacturing costs, alternative processes should be evaluated early to minimize the effect the equipment may have on the total cost of a product. An alternative manufacturing process may reduce the cost of or eliminate the need for gas-cleaning equipment. However, even when gas-cleaning equipment is required, process and system control should minimize the load on the collection device.

An industrial process may be changed from dirty to clean by substituting a process material (e.g., switching to a cleaner-burning fuel or pretreating the existing fuel). Equipment redesign, such as enclosing pneumatic conveyors or recycling noncondensable gases, may also clean the process. Occasionally, additives (e.g., chemical dust suppressants used in quarrying or liquid animal fat applied to dehydrated alfalfa before grinding) reduce the potential for air pollution or concentrate the pollutants so that a smaller, more concentrated process stream may be treated.

Gas streams containing contaminants should not usually be diluted with extraneous air unless the extra air is required for cooling or to condense contaminants to make them collectible. The volume of gas to be cleaned is a major factor in the owning and operating costs of control equipment. Therefore, source

capture ventilation, where contaminants are kept concentrated in relatively small volumes of air, is generally preferable to general ventilation, where pollutants are allowed to mix into and be diluted by much of the air in a plant space. Chapters 29 and 30 of the 2007 *ASHRAE Handbook—HVAC Applications* address local and general ventilation of industrial environments. Regulatory authorities generally require the levels of emissions to be corrected to standard conditions taking into account temperature, pressure, moisture content, and factors related to combustion or production rate. However, the air-cleaning equipment must be designed using the actual conditions of the process stream as it will enter the equipment.

In this chapter, each generic type of equipment is discussed on the basis of its primary method for gas or particulate abatement. The development of systems that incorporate several of the devices discussed here for specific industrial processes is left to the engineer.

**REGULATIONS AND MONITORING**

**Gas-Cleaning Regulations**

In the United States, industrial gas-cleaning installations that exhaust to the outdoor environment are regulated by the U.S. Environmental Protection Agency (EPA); those that exhaust to the workplace are regulated by the Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor.

The EPA has established Standards of Performance for New Stationary Sources [New Source Performance Standards (NSPSs), GPO] and more restrictive State Implementation Plans (SIP 1991) and local codes as a regulatory basis to achieve air quality standards. Information on the current status of the NSPSs can be obtained through the Semi-Annual Regulatory Agenda, as published in the Federal Register, and through the regional offices of the EPA. Buoncore and Davis (1992) and Sink (1991) provide additional design information for gas-cleaning equipment.

Where air is not affected by combustion, solvent vapors, and toxic materials, it may be desirable to recirculate the air to the workplace to reduce energy costs or to balance static pressure in a building. High-efficiency fabric or cartridge filters, precipitators, or special-purpose wet scrubbers are typically used in general ventilation systems to reduce particle concentrations to levels acceptable for recirculated air.

The Industrial Ventilation Committee of the American Conference of Governmental Industrial Hygienists (ACGIH) and the National Institute of Occupational Safety and Health (NIOSH) have established criteria for recirculation of cleaned process air to the work area (ACGIH 2006; NIOSH 1978). Fine-particle control by various dust collectors under recirculating airflows has been investigated by Bergin et al. (1989).

The preparation of this chapter is assigned to TC 5.4, Industrial Process Air Cleaning (Air Pollution Control).

Public complaints may occur even when the effluent concentrations discharged to the atmosphere are below the maximum permissible emission rates and opacity limits. Thus, in addition to codes or regulations, the plant location, the contaminants involved, and the meteorological conditions of the area must be evaluated.

In most cases, emission standards require a higher degree of gas cleaning than necessary for economical recovery of process products (if this recovery is desirable). Gas cleanliness is a priority, especially where toxic materials are involved and cleaned gases might be recirculated to the work area.

### Measuring Gas Streams and Contaminants

**Stack sampling** is often required to fulfill requirements of operating and installation permits for gas-cleaning devices, to establish conformance with regulations, and to commission new equipment. Also, it can be used to establish specifications for gas-cleaning equipment and to certify that the equipment is functioning properly. The tests determine the composition and quantity of gases and particulate matter at selected locations along the process stream. The following general principles apply to a stack sampling program:

- The sampling location(s) must be acceptable to all parties who will use the results.
- The sampling location(s) must meet acceptable criteria with respect to temperature, flow distribution and turbulence, and distance from disturbances to the process stream. Exceptions based on physical constraints must be identified and reported.
- Samples that are withdrawn from a duct or stack must represent typical conditions in the process stream. Proper stack traverses must be made and particulate samples withdrawn isokinetically.
- Stack sampling should be performed in accordance with approved methods and established protocols whenever possible.
- Variations in the volumetric flow, temperature, and particulate or gaseous pollutant emissions, along with upset conditions, should be identified.
- A report from stack sampling should include a summary of the process, which should identify any deviations from normal process operations that occurred during testing. The summary should be prepared during the testing phase and certified by the process owner at completion of the tests.
- Disposal methods for waste generated during testing must be identified before testing begins. This is especially critical where pilot plant equipment is being tested because new forms of waste are often produced.
- The regulatory basis for the tests should be established so that the results can be presented in terms of process mass rate, consumption of raw materials, energy use, and so forth.

Analyses of the samples can provide the following types of information about the emissions:

- Physical characteristics of the contaminant: solid dust, liquid mist or “smoke,” waxy solids, or a sticky mixture of liquid and solid.
- Distribution of particle sizes: optical, physical, aerodynamic, etc.
- Concentration of particulate matter in the gases, including average and extreme values, and a profile of concentrations in the duct or stack.
- Volumetric flow of gases, including average and extreme values, and a profile of this flow in the duct or stack. The volumetric flow is commonly expressed at actual conditions and at various standard conditions of temperature, pressure, moisture, and process state.
- Chemical composition of gases and particulate matter, including recovery value, toxicity, solubility, acid dew point, etc.
- Particle and bulk densities of particulate matter.
- Handling characteristics of particulate matter, including erosive, corrosive, abrasive, flocculative, or adhesive/cohesive qualities.
- Flammable or explosive limits.

- Electrical resistivity of deposits of particulate matter under stack and laboratory conditions. These data are useful for assessments of electrostatic precipitators and other electrostatically augmented technology.

**EPA Reference Methods.** The EPA has developed methods to measure the particulate and gaseous components of emissions from many industrial processes and has incorporated these in the NSPS by reference. Appendix A of the New Source Performance Standards lists the reference methods (GPO, annual). These are updated regularly in the Federal Register. Guidance for using these reference methods can be found in the *Quality Assurance Handbook for Air Pollution Measurement Systems* (EPA 1994).

The EPA (2004) has promulgated fine particle standards for ambient air quality. Known as PM-10 and PM-2.5 Standards, these revised standards focus particulate abatement efforts toward the collection and control of airborne particles smaller than 10  $\mu\text{m}$  and 2.5  $\mu\text{m}$ , respectively. Fine particles (with aerodynamic particle size smaller than 2.5  $\mu\text{m}$ ) are of concern because they penetrate deeply into the lungs. With the development of these standards, concern has arisen over the efficiency of industrial gas cleaners at various particle sizes.

**ASTM Methods.** The EPA has also approved ASTM test methods when cited in the NSPSs or the applicable EPA reference methods.

**Other Methods.** Sometimes, the reference methods must be modified, with the consent of regulatory authorities, to achieve representative sampling under the less-than-ideal conditions of industrial operations. Modifications to test methods should be clearly identified and explained in test reports.

### Gas Flow Distribution

The control of gas flow through industrial gas-cleaning equipment is important for good system performance. Because of the large gas flows commonly encountered and the frequent need to retrofit equipment to existing processes, space allocations often preclude gradual expansion and long-radius turns. Instead, elbow splitters, baffles, etc., are used. These components must be designed to limit dust buildup and corrosion to acceptable levels.

### Monitors and Controls

Current regulatory trends anticipate or demand continuous monitoring and control of equipment to maintain optimum performance against standards. Under regulatory data requirements, operating logs provide the owner with process control information and others with a baseline for the development or service of equipment.

Larger systems include programmable controllers and computers for control, energy management, data logging, and diagnostics. Increasing numbers of systems have modem connections to support monitoring and service needs from remote locations.

## PARTICULATE CONTAMINANT CONTROL

A large range of equipment for the separation of particulate matter from gaseous streams is available. Typical concentration ranges for this equipment are summarized in [Table 1](#).

High-efficiency particulate air (HEPA) and ultralow penetration air (ULPA) filters are often used in cleanrooms to maintain nearly particulate-free environments. In commercial and residential buildings, air cleaners are used to remove nuisance dust. In other instances, air cleaners are selected to control particulate matter that constitutes a health hazard in the workplace (e.g., radioactive particles, beryllium-containing particles, or biological airborne wastes). Recirculation of air in industrial plants could use air cleaners or may require more heavy-duty equipment. Secondary filtration systems

**Table 1 Intended Duty of Gas-Cleaning Equipment**

|   | Maximum Concentration     |
|---|---------------------------|
| <i>Air cleaners</i>                           | <0.002 gr/ft <sup>3</sup> |
| Cleanrooms                                    |                           |
| Commercial/residential buildings              |                           |
| Plant air recirculation                       |                           |
| <i>Industrial gas cleaners</i>                | <35 gr/ft <sup>3</sup>    |
| <i>Product capture in pneumatic conveying</i> | <3500 gr/ft <sup>3</sup>  |

**Table 2 Principal Types of Particulate Control Equipment**

|  |   |
|--|---|
| <i>Gravity and momentum collectors</i> | <ul style="list-style-type: none"> <li>• Settling chambers</li> <li>• Louvers and baffle chambers</li> </ul>  |
| <i>Centrifugal collectors</i>          | <ul style="list-style-type: none"> <li>• Cyclones and multicyclones</li> <li>• Rotating “centrifugal” mist collectors</li> </ul>  |
| <i>Electrostatic precipitators</i>     | <ul style="list-style-type: none"> <li>• Tubular or plate-type, wet or dry, high-voltage (single-stage) precipitators</li> <li>• Plate-type, wet or dry, low-voltage (two-stage) mist and smoke precipitators</li> </ul>  |
| <i>Fabric filters</i>                  | <ul style="list-style-type: none"> <li>• Baghouses; fabric collectors; cartridge filters</li> <li>• Disposable media filters (for dust and/or mist)</li> </ul>  |
| <i>Granular-bed filters</i>            | <ul style="list-style-type: none"> <li>• Fixed bed</li> <li>• Moving bed</li> </ul>   |
| <i>Particulate scrubbers</i>           | <ul style="list-style-type: none"> <li>• Spray scrubbers</li> <li>• Impingement scrubbers</li> <li>• Centrifugal-type scrubbers</li> <li>• Orifice-type scrubbers</li> <li>• Venturi scrubbers</li> <li>• Packed towers</li> <li>• Mobile bed scrubbers</li> <li>• Electrostatically augmented scrubbers</li> </ul> |

[typically HEPA or 95% dioctyl phthalate (DOP) filter systems] are sometimes required with recirculation systems.

Air cleaners are discussed in [Chapter 28](#). This chapter is concerned with heavy-duty equipment for the control of emissions from industrial processes. The particulate emissions from these processes generally have a concentration in the range of 0.01 to 35 gr/ft<sup>3</sup>. The gas-cleaning equipment is usually installed for air pollution control.

Particulate control technology is selected to satisfy the requirements for specific processes. Available technology differs in basic design, removal efficiency, first cost, energy requirements, maintenance, land use, operating costs, and ability of the collectors to handle various types and sizes of contaminant particles without requiring excessive maintenance. Some of the principal types of particulate control equipment are listed in [Table 2](#) and discussed in the following sections.

### Collector Performance

Particulate collectors may be evaluated for their ability to remove particulate matter from a gas stream and for their ability to reduce the emissions of selected particle sizes. The degree to which particulate matter is separated from a gas stream is known as the efficiency of a collector; the fraction of material escaping collection is the penetration. The reduction of particulate matter in a selected particle size range is known as the fractional efficiency of a particulate collector.

The **efficiency**  $\eta$  of a collector is generally expressed as a percent of the mass flow rate of material entering and exiting the collector.

$$\eta = 100(w_i - w_o)/w_i = 100w_c/w_i \quad (1)$$

where

$$\eta = \text{efficiency of collector, \%}$$

$w_i$  = mass flow rate of contaminant in gases entering collector  
 $w_o$  = mass flow rate of contaminant in gases exiting collector  
 $w_c$  = mass flow rate of contaminant captured by collector

Alternatively, the efficiency of a collector can be expressed in terms of the concentrations of particulate matter entering and exiting the equipment. This approach can be unsatisfactory because of changes that occur in the gas stream due to air leakage in the system, condensation, and temperature and pressure changes.

**Penetration  $P$**  is usually measured, and the efficiency for a collector calculated, using the following equations:

$$P = 100w_o/w_i \quad (2)$$

with

$$\eta = 100 - P \quad (3)$$

The **fractional efficiency** of a particulate collector is determined by measuring the mass rate of contaminants entering and exiting the collector in selected particle size ranges. Methods for measuring the fractional efficiency of particulate collectors in industrial applications are only beginning to emerge, largely because of the need to compare the fine-particle performance of collectors used under the PM-10 and PM-2.5 regulations for ambient air quality.

Measures of performance other than efficiency should also be considered in designing industrial gas-cleaning systems. [Table 3](#) compares some of these factors for typical equipment. Note that this table contains only nominal values and is no substitute for experience, trade studies, and an engineering assessment of requirements for specific installations.

[Table 4](#) summarizes the types of collectors that have been used in industrial applications.

## MECHANICAL COLLECTORS

### Settling Chambers

Particulate matter will fall from suspension in a reasonable time if the particles are larger than about 40  $\mu\text{m}$ . Plenums, dropout boxes, or gravitational settling chambers are thus used for the separation of coarse or abrasive particulate matter from gas streams.

Settling chambers are occasionally used in conjunction with fabric filters or electrostatic precipitators to reduce overall system cost. The settling chamber serves as a precollector to remove coarse particles from the gas stream.

Settling chambers sometimes contain baffles to distribute gas flow and to serve as surfaces for the impingement of coarse particles. Other designs use baffles to change the direction of the gas flow, thereby allowing coarse particles to be thrown from the gas stream by inertial forces.

The fractional efficiency for a settling chamber with uniform gas flow may be estimated by

$$\eta = 100u_t L/HV \quad (4)$$

where

$\eta$  = efficiency of collector for particles with settling velocity  $u_t$ , %  
 $u_t$  = settling velocity for selected particles, fps  
 $L$  = length of chamber, ft  
 $H$  = height of chamber, ft  
 $V$  = superficial velocity of gases through chamber, fps

The **superficial velocity** of gases through the chamber is determined from measurements of the volumetric flow of gases entering and exiting the chamber and the cross-sectional area of the chamber. This average velocity must be low enough to prevent reentrainment of the deposited dust; a superficial velocity below 60 fpm is satisfactory for many materials.

Table 3 Measures of Performance for Gas-Cleaning Equipment

| Type of Particle Collector         | Particle Diameter, <sup>a</sup> μm | Max. Loading, gr/ft <sup>3</sup> | Collection Efficiency, % by mass | Pressure Loss     |             | Utilities per 1000 cfm (gas) | Comparative Energy Requirement | Superficial Velocity, <sup>b</sup> fpm | Capacity Limits, 1000 cfm (Relative) | Space Required |
|------------------------------------|------------------------------------|----------------------------------|----------------------------------|-------------------|-------------|------------------------------|--------------------------------|--|--------------------------------------|----------------|
|                                    |                                    |                                  |                                  | Gas, in. of water | Liquid, psi |                              |                                |  |                                      |                |
| <i>Dry inertial collectors</i>     |                                    |                                  |                                  |                   |             |                              |                                |  |                                      |                |
| Settling chamber                   | >40                                | >5                               | 50                               | 0.1 to 0.5        | —           | —                            | 1                              | 300 to 600                             | None                                 | Large          |
| Baffle chamber                     | >20                                | >5                               | 50                               | 0.5 to 1.5        | —           | —                            | 1.5                            | 1000 to 2000                           | None                                 | Medium         |
| Skimming chamber                   | >20                                | >1                               | 70                               | <1.0              | —           | —                            | 3.0                            | 2000 to 4000                           | 50                                   | Small          |
| Louver                             | >10                                | >1                               | 80                               | 0.3 to 2.0        | —           | —                            | 1.5 to 6.0                     | 2000 to 4000                           | 30                                   | Medium         |
| Cyclone                            | >15                                | >1                               | 85                               | 0.5 to 3.0        | —           | —                            | 1.5 to 9.0                     | 2000 to 4000                           | 50                                   | Medium         |
| Multicyclone                       | >5                                 | >1                               | 95                               | 2.0 to 10.0       | —           | —                            | 6.0 to 20                      | 2000 to 4000                           | 200                                  | Small          |
| Impingement                        | >10                                | >1                               | 90                               | 1.0 to 2.0        | —           | —                            | 3.0 to 6.0                     | 2000 to 4000                           | None                                 | Small          |
| Dynamic                            | >10                                | >1                               | 90                               | Provides pressure | —           | 1.0 to 2.0 hp                | 10 to 20                       | —                                      | 50                                   | —              |
| <i>Electrostatic precipitators</i> |                                    |                                  |                                  |                   |             |                              |                                |  |                                      |                |
| High-voltage                       | >0.01                              | >0.1                             | 99                               | 0.2 to 1.0        | —           | 0.1 to 0.6 kW                | 0.8 to 20                      | 60 to 400                              | 10 to 2000                           | Large          |
| Low-voltage                        | >0.001                             | 0.5                              | 90 to 99                         | 0.2 to 0.5        | —           | 0.03 to 0.06 kW              | 0.5 to 1.0                     | 200 to 700                             | 0.1 to 100                           | Medium         |
| <i>Fabric filters</i>              |                                    |                                  |                                  |                   |             |                              |                                |  |                                      |                |
| Baghouses                          | >0.08                              | >0.5                             | 99                               | 2.0 to 6.0        | —           | —                            | 6.0 to 20                      | 1.0 to 20                              | 200                                  | Large          |
| Cartridge filters                  | >0.05                              | >0.1                             | 99+                              | 2.0 to 8.0        | —           | —                            | —                              | 0.5 to 5                               | 40 to 50                             | Medium         |
| <i>Wet scrubbers</i>               |                                    |                                  |                                  |                   |             |                              |                                |  |                                      |                |
| Gravity spray                      | >10                                | >1                               | 70                               | 0.1 to 1.0        | 20 to 100   | 0.5 to 2.0 gpm               | 5.0                            | 100 to 200                             | 100                                  | Medium         |
| Centrifugal                        | >5                                 | >1                               | 90                               | 2.0 to 8.0        | 20 to 100   | 1 to 10 gpm                  | 12 to 26                       | 2000 to 4000                           | 100                                  | Medium         |
| Impingement                        | >5                                 | >1                               | 95                               | 2.0 to 8.0        | 20 to 100   | 1 to 5 gpm                   | 9.0 to 31                      | 3000 to 6000                           | 100                                  | Medium         |
| Packed bed                         | >5                                 | >0.1                             | 90                               | 0.5 to 10         | 5 to 30     | 5 to 15 gpm                  | 4.0 to 34                      | 100 to 300                             | 50                                   | Medium         |
| Dynamic                            | >2                                 | >1                               | 95                               | Provides pressure | 5 to 30     | 1 to 5 gpm<br>3 to 20 hp     | 30 to 200                      | 3000 to 4000                           | 50                                   | Small          |
| Submerged orifice                  | >2                                 | >0.1                             | 90                               | 2.0 to 6.0        | None        | No pumping                   | 9.0 to 21                      | 3000                                   | 50                                   | Medium         |
| Jet                                | >2                                 | >0.1                             | 90                               | Provides pressure | 50 to 100   | 50 to 100 gpm                | 15 to 30                       | 2000 to 20,000                         | 100                                  | Small          |
| Venturi                            | >0.1                               | >0.1                             | 95 to 99                         | 10 to 60          | 10 to 30    | 3 to 10 gpm                  | 30 to 300                      | 12,000 to 42,000                       | 100                                  | Small          |

Source: IGCI (1964). Information updated by ASHRAE Technical Committee 5.4. <sup>b</sup> Average speed of gases flowing through the equipment's collection region.

<sup>a</sup> Minimum particle diameter for which the device is effective.

Typical data on settling can be found in Table 5. Because of air inclusions in the particle, the density of a dust particle can be substantially lower than the true density of the material from which it is made.

**Inertial Collectors**

**Louver and Baffle Collectors.** Louvers are widely used to control particles larger than about 15 μm in diameter. The louvers cause a sudden change in direction of gas flow. By virtue of their inertia, particles move away from high-velocity gases and are either collected in a hopper or trap or withdrawn in a concentrated sidestream. The sidestream is cleaned using a cyclone or high-efficiency collector, or it is simply discharged to the atmosphere. In general, the pressure drop across inertial collectors with louvers or baffles is greater than that for settling chambers, but this loss is balanced by higher collection efficiency and more compact equipment.

Inertial collectors are occasionally used to control mist. In some applications, the interior of the collector may be irrigated to prevent reentrainment of dry dust and to remove soluble deposits.

Typical louver and baffle collectors are shown in Figure 1.

**Cyclones and Multicyclones.** A cyclone collector transforms a gas stream into a confined vortex, from which inertia moves suspended particles to the wall of the cyclone's body. The inertial effect of turning the gas stream, as used in the baffle collector, is used continuously in a cyclone to improve collection efficiency. Cyclone collectors are often used as precleaners to reduce the loading of more efficient pollution control devices. Figure 2 shows some typical cyclone collectors.

A low-efficiency cyclone operates with a static pressure drop from 1 to 1.5 in. of water between its inlet and outlet and can remove 50% of the particles from 5 to 10 μm. High-efficiency cyclones operate with static pressure drops from 3 to 8 in. of water between

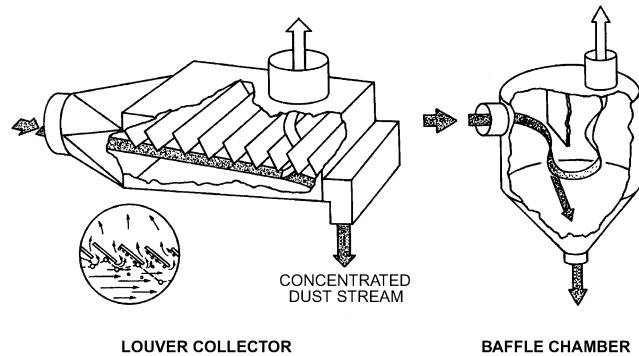


Fig. 1 Typical Louver and Baffle Collectors

their inlet and outlet and can remove 70% of the particulates of approximately 5 μm.

The efficiency of a cyclone depends on particle density, shape, and size (aerodynamic size  $D_p$ , which is the average of the size range). Cyclone efficiency may be estimated from Figure 3.

The parameter  $D_{pc}$ , known as the **cut size**, is defined as the diameter of particles collected with 50% efficiency. The cut size may be estimated using the following equation:

$$D_{pc} = \sqrt{\frac{9\mu b}{2N_e V_i (\rho_p - \rho_g) \pi}} \tag{5}$$

where

- $D_{pc}$  = cut size, ft
- $\mu$  = absolute gas viscosity, centipoise

Table 4 Collectors Used in Industry

| Operation                                   | Concentration     | Particle Size    | Cyclone    | Wet Collectors              |                           |                 | Self-Cleaning |               |                         | Electrostatic Precipitators |             |       |
|---|-------------------|------------------|------------|-----------------------------|---------------------------|-----------------|---------------|---------------|-------------------------|-----------------------------|-------------|-------|
|   |                   |                  |            | High-Efficiency Centrifugal | Rotating Centrifugal Mist | Medium-Pressure | High-Energy   | Fabric Filter | Disposable Media Filter | High-Voltage                | Low-Voltage | Notes |
| <b>Ceramics</b>                             |                   |                  |            |                             |                           |                 |               |               |                         |                             |             |       |
| a. Raw product handling                     | Light             | Fine             | Rare       | Seldom                      | N/A                       | Frequent        | N/U           | Frequent      | N/A                     | N/U                         | N/A         | 1     |
| b. Fertilizing                              | Light             | Fine to medium   | Rare       | Occasional                  | N/A                       | Frequent        | N/U           | Frequent      | N/A                     | N/U                         | N/A         | 2     |
| c. Refractory sizing                        | Heavy             | Coarse           | Seldom     | Occasional                  | N/A                       | Frequent        | Rare          | Frequent      | N/A                     | N/U                         | N/A         | 3     |
| d. Glass and vitreous enamel spray          | Moderate          | Medium           | N/U        | N/U                         | N/A                       | Usual           | N/U           | Occasional    | N/A                     | N/A                         | N/A         | —     |
| e. Glass melting                            | Light             | Fine             | N/A        | N/A                         | N/A                       | Occasional      | N/U           | Occasional    | N/A                     | Usual                       | N/A         | —     |
| f. Frit smelting                            | Light             | Fine             | N/A        | N/A                         | N/A                       | N/U             | Often         | Often         | N/A                     | Often                       | N/A         | —     |
| g. Fiberglass forming and curing            | Light             | Fine             | N/A        | N/A                         | N/A                       | Occasional      | N/U           | N/U           | Rare                    | Usual                       | N/A         | —     |
| <b>Chemicals</b>                            |                   |                  |            |                             |                           |                 |               |               |                         |                             |             |       |
| a. Material handling                        | Light to moderate | Fine to medium   | Occasional | Frequent                    | N/A                       | Frequent        | Frequent      | Frequent      | N/A                     | N/U                         | N/A         | 4     |
| b. Crushing, grinding                       | Moderate to heavy | Fine to coarse   | Often      | Frequent                    | N/A                       | Frequent        | Occasional    | Frequent      | N/A                     | N/U                         | N/A         | 5     |
| c. Pneumatic conveying                      | Very heavy        | Fine to coarse   | Usual      | Occasional                  | N/A                       | Rare            | Rare          | Usual         | N/A                     | N/U                         | N/A         | 6     |
| d. Roasters, kilns, coolers                 | Heavy             | Medium to coarse | Occasional | Usual                       | N/A                       | Usual           | Frequent      | Rare          | N/A                     | Often                       | N/A         | 7     |
| e. Incineration                             | Light to medium   | Fine             | N/U        | N/U                         | N/A                       | N/U             | Frequent      | Rare          | N/A                     | Frequent                    | N/A         | 8     |
| <b>Coal Mining and Handling</b>             |                   |                  |            |                             |                           |                 |               |               |                         |                             |             |       |
| a. Material handling                        | Moderate          | Medium           | Rare       | Occasional                  | N/A                       | Occasional      | N/U           | Usual         | N/A                     | N/A                         | N/A         | 9     |
| b. Bunker ventilation                       | Moderate          | Fine             | Occasional | Frequent                    | N/A                       | Occasional      | N/U           | Usual         | N/A                     | N/A                         | N/A         | 10    |
| c. Dedusting, air cleaning                  | Heavy             | Medium to coarse | Occasional | Frequent                    | N/A                       | Occasional      | N/U           | Usual         | N/A                     | N/A                         | N/A         | 11    |
| d. Drying                                   | Moderate          | Fine             | Rare       | Occasional                  | N/A                       | Frequent        | Occasional    | N/U           | N/A                     | N/A                         | N/A         | 12    |
| <b>Combustion Fly Ash</b>                   |                   |                  |            |                             |                           |                 |               |               |                         |                             |             |       |
| a. Coal burning:                            |                   |                  |            |                             |                           |                 |               |               |                         |                             |             |       |
| Chain grate                                 | Light             | Fine             | N/A        | Rare                        | N/A                       | N/U             | N/U           | Frequent      | N/A                     | N/U                         | N/A         | 13    |
| Spreader stoker                             | Moderate          | Fine to coarse   | Rare       | Rare                        | N/A                       | N/U             | N/U           | Frequent      | N/A                     | Rare                        | N/A         | 14    |
| Pulverized coal                             | Heavy             | Fine             | N/A        | Frequent                    | N/A                       | N/U             | N/U           | Frequent      | N/A                     | Usual                       | N/A         | 14    |
| Fluidized bed                               | Moderate          | Fine             | Usual      | —                           | N/A                       | —               | —             | Frequent      | N/A                     | Frequent                    | N/A         | —     |
| Coal slurry                                 | Light             | —                | —          | —                           | N/A                       | —               | —             | Often         | N/A                     | Often                       | N/A         | —     |
| b. Wood waste                               | Varied            | Coarse           | Usual      | Usual                       | N/A                       | N/U             | N/U           | Occasional    | N/A                     | Often                       | N/A         | 15    |
| c. Municipal refuse                         | Light             | Fine             | N/U        | N/U                         | N/A                       | Occasional      | N/U           | Usual         | N/A                     | Frequent                    | N/A         | —     |
| d. Oil                                      | Light             | Fine             | N/U        | N/U                         | N/A                       | N/U             | N/U           | Usual         | N/A                     | Often                       | N/A         | —     |
| e. Biomass                                  | Moderate          | Fine to coarse   | N/U        | N/U                         | N/A                       | Occasional      | N/U           | Usual         | N/A                     | Frequent                    | N/A         | —     |
| <b>Foundry</b>                              |                   |                  |            |                             |                           |                 |               |               |                         |                             |             |       |
| a. Shakeout                                 | Light to moderate | Fine             | Rare       | Rare                        | N/A                       | Rare            | Seldom        | Usual         | N/A                     | N/U                         | N/A         | 16    |
| b. Sand handling                            | Moderate          | Fine to medium   | Rare       | Rare                        | N/A                       | Usual           | N/U           | Rare          | N/A                     | N/U                         | N/A         | 17    |
| c. Tumbling mills                           | Moderate          | Medium to coarse | N/A        | N/A                         | N/A                       | Frequent        | N/U           | Usual         | N/A                     | N/U                         | N/A         | 18    |
| d. Abrasive cleaning                        | Moderate to heavy | Fine to medium   | N/A        | Occasional                  | N/A                       | Frequent        | N/U           | Usual         | N/A                     | N/U                         | N/A         | 19    |
| <b>Grain Elevator, Flour and Feed Mills</b> |                   |                  |            |                             |                           |                 |               |               |                         |                             |             |       |
| a. Grain handling                           | Light             | Medium           | Usual      | Occasional                  | N/A                       | Rare            | N/U           | Frequent      | N/A                     | N/A                         | N/A         | 20    |
| b. Grain drying                             | Light             | Coarse           | N/A        | N/A                         | N/A                       | N/U             | N/U           | See Note 20   | N/A                     | N/A                         | N/A         | 21    |
| c. Flour dust                               | Moderate          | Medium           | Rare       | Often                       | N/A                       | Occasional      | N/U           | Usual         | N/A                     | N/A                         | N/A         | 22    |
| d. Feed mill                                | Moderate          | Medium           | Often      | Often                       | N/A                       | Occasional      | N/U           | Frequent      | N/A                     | N/A                         | N/A         | 23    |
| <b>Metal Melting</b>                        |                   |                  |            |                             |                           |                 |               |               |                         |                             |             |       |
| a. Steel blast furnace                      | Heavy             | Varied           | Frequent   | Rare                        | N/A                       | Frequent        | Frequent      | N/U           | N/A                     | Frequent                    | N/A         | 24    |
| b. Steel open hearth, basic oxygen furnace  | Moderate          | Fine to coarse   | N/A        | N/A                         | N/A                       | N/A             | Often         | Rare          | N/A                     | Frequent                    | N/A         | 25    |
| c. Steel electric furnace                   | Light             | Fine             | N/A        | N/A                         | N/A                       | N/A             | Occasional    | Usual         | N/A                     | Rare                        | N/A         | 26    |
| d. Ferrous cupola                           | Moderate          | Varied           | N/A        | N/A                         | N/A                       | Frequent        | Often         | Frequent      | N/A                     | Occasional                  | N/A         | 27    |
| e. Nonferrous reverberatory furnace         | Varied            | Fine             | N/A        | N/A                         | N/A                       | Rare            | Occasional    | Usual         | N/A                     | N/U                         | N/A         | 28    |
| f. Nonferrous crucible                      | Light             | Fine             | N/A        | N/A                         | N/A                       | Rare            | Rare          | Occasional    | N/A                     | N/U                         | N/A         | 29    |

Table 4 Collectors Used in Industry (Continued)

| Operation  | Concentration                  | Particle Size                        | Cyclone    | High-Efficiency Centrifugal |             |              | Wet Collectors  |              |                             | Electrostatic Precipitators |              |             |
|--|--------------------------------|--------------------------------------|------------|-----------------------------|-------------|--------------|-----------------|--------------|-----------------------------|-----------------------------|--------------|-------------|
|  |                                |                                      |            | Rotating Mist               | Centrifugal | High-Energy  | Medium-Pressure | High-Energy  | Self-Cleaning Fabric Filter | Disposable Media Filter     | High-Voltage | Low-Voltage |
| <b>Metal Mining and Rock Products</b>                        |                                |                                      |            |                             |             |              |                 |              |                             |                             |              |             |
| a. Material handling   | Moderate                       | Fine to medium                       | Rare       | Occasional                  | N/A         | Usual        | N/U             | Considerable | N/A                         | N/U                         | N/A          | 30          |
| b. Dryers, kilns   | Moderate                       | Medium to coarse                     | Frequent   | Occasional                  | N/A         | Frequent     | Occasional      | N/U          | N/A                         | Occasional                  | N/A          | 31          |
| c. Cement rock dryer   | Moderate                       | Fine to medium                       | N/A        | Frequent                    | N/A         | Occasional   | Rare            | N/U          | N/A                         | Occasional                  | N/A          | 30          |
| d. Cement kiln   | Heavy                          | Fine to medium                       | N/A        | Frequent                    | N/A         | Rare         | N/U             | Usual        | N/A                         | Usual                       | N/A          | 32          |
| e. Cement grinding   | Moderate                       | Fine                                 | N/A        | Rare                        | N/A         | N/U          | N/U             | Usual        | N/A                         | Rare                        | N/A          | 33          |
| f. Cement clinker cooler                                     | Moderate                       | Coarse                               | N/A        | Occasional                  | N/A         | N/U          | N/U             | Occasional   | N/A                         | N/U                         | N/A          | 34          |
| <b>Metal Working</b>   |                                |                                      |            |                             |             |              |                 |              |                             |                             |              |             |
| a. Production grinding, scratch brushing, abrasive cutoff    | Light                          | Coarse                               | Occasional | Frequent                    | N/A         | Considerable | N/U             | Considerable | N/A                         | N/U                         | N/A          | 35          |
| b. Portable and swing frame                                  | Light                          | Medium                               | Rare       | Frequent                    | N/A         | Frequent     | N/U             | Considerable | N/A                         | N/U                         | N/A          | —           |
| c. Buffing   | Light                          | Varied                               | Frequent   | Rare                        | N/A         | Frequent     | N/U             | Rare         | N/A                         | N/U                         | N/A          | 36          |
| d. Tool room   | Light                          | Fine                                 | Frequent   | Frequent                    | N/A         | Frequent     | N/U             | Frequent     | N/A                         | N/U                         | N/A          | 37          |
| e. Cast-iron machining                                       | Moderate                       | Varied                               | Rare       | Frequent                    | N/A         | Considerable | N/U             | Considerable | N/A                         | N/U                         | N/A          | 38          |
| f. Steel, brass, aluminum machining                          | Light to moderate              | Submicron smoke, med. mist to solids | N/A        | N/A                         | Frequent    | Occasional   | N/U             | Occasional   | Frequent                    | N/U                         | Frequent     | 39          |
| g. Welding   | Light to moderate              | Submicron fume to med.               | N/A        | N/A                         | N/A         | Occasional   | N/U             | Frequent     | Frequent                    | Rare                        | Occasional   | 40          |
| h. Plasma and laser cutting                                  | Moderate                       | Submicron fume to med.               | N/A        | N/A                         | N/A         | Occasional   | N/U             | Frequent     | Rare                        | N/A                         | N/U          | 41          |
| i. Laser welding   | Moderate                       | Moderate                             | N/A        | N/A                         | N/A         | Occasional   | N/U             | Frequent     | Rare                        | N/A                         | N/U          | 41          |
| j. Abrasive machining  | Moderate to heavy              | Fine to submicron                    | N/A        | N/U                         | Occasional  | Occasional   | N/U             | Rare         | Frequent                    | N/A                         | Rare         | 39          |
| k. Milling, turning, cutting tools                           | Light to moderate              | Fine to submicron                    | N/A        | N/U                         | Frequent    | Occasional   | N/U             | N/A          | Frequent                    | N/A                         | Frequent     | —           |
| l. Annealing, heat treating, induction heating, quenching    | Moderate to heavy              | Submicron                            | N/A        | N/U                         | N/A         | Rare         | Rare            | N/A          | Rare                        | N/A                         | Frequent     | —           |
| <b>Pharmaceutical and Food Products</b>                      |                                |                                      |            |                             |             |              |                 |              |                             |                             |              |             |
| a. Mixers, grinders, weighting, blending, bagging, packaging | Light                          | Medium                               | Rare       | Frequent                    | N/A         | Frequent     | N/U             | Frequent     | Occasional                  | N/U                         | N/U          | 42          |
| b. Coating pans  | Varied                         | Fine to medium                       | Rare       | Rare                        | N/A         | Frequent     | N/U             | Frequent     | Rare                        | N/U                         | N/U          | 43          |
| <b>Plastics</b>  |                                |                                      |            |                             |             |              |                 |              |                             |                             |              |             |
| a. Raw material processing                                   | (See comments under Chemicals) |                                      |            |                             |             |              |                 |              |                             |                             |              | 44          |
| b. Plastic finishing   | Light to moderate              | Varied                               | Frequent   | Frequent                    | N/A         | Frequent     | N/U             | Frequent     | Rare                        | N/U                         | N/U          | 45          |
| c. Molding, extruding, curing                                | Light to moderate              | Submicron smoke                      | N/A        | N/A                         | N/A         | Rare         | N/U             | N/A          | Occasional                  | N/U                         | Considerable | 46          |
| <b>Pulp and Paper</b>  |                                |                                      |            |                             |             |              |                 |              |                             |                             |              |             |
| a. Recovery boilers:   |                                |                                      |            |                             |             |              |                 |              |                             |                             |              |             |
| Direct contact   | Heavy                          | Medium                               | N/U        | N/U                         | N/A         | N/U          | N/U             | Occasional   | N/A                         | Usual                       | N/A          | —           |
| Low odor   | Heavy                          | Medium                               | N/U        | N/U                         | N/A         | N/U          | N/U             | Occasional   | N/A                         | Usual                       | N/A          | —           |
| b. Lime kilns  | Heavy                          | Coarse                               | N/U        | N/U                         | N/A         | N/U          | N/U             | Often        | N/A                         | Often                       | N/A          | —           |
| c. Wood-chip dryers  | Varied                         | Fine to coarse                       | N/U        | N/U                         | N/A         | N/U          | N/U             | Occasional   | N/A                         | Often                       | N/A          | —           |
| <b>Rubber Products</b>                                       |                                |                                      |            |                             |             |              |                 |              |                             |                             |              |             |
| a. Mixers  | Moderate                       | Fine                                 | N/A        | N/A                         | N/A         | Frequent     | N/U             | Usual        | Rare                        | N/U                         | N/U          | 47          |
| b. Batch-out rolls   | Light                          | Fine                                 | N/A        | N/A                         | N/A         | Usual        | N/U             | Frequent     | N/A                         | N/U                         | Rare         | 48          |
| c. Talc dusting and dedusting                                | Moderate                       | Medium                               | N/A        | N/A                         | N/A         | Frequent     | N/U             | Usual        | Rare                        | N/U                         | N/U          | 49          |
| d. Grinding  | Moderate                       | Coarse                               | Often      | Often                       | N/A         | Frequent     | N/U             | Often        | Rare                        | N/U                         | N/U          | 50          |
| e. Molding, extruding, curing                                | Light to moderate              | Submicron smoke                      | N/A        | N/A                         | N/A         | Rare         | N/U             | N/A          | Occasional                  | N/A                         | Considerable | 46          |
| <b>Wood Particle Board and Hard Board</b>                    |                                |                                      |            |                             |             |              |                 |              |                             |                             |              |             |
| a. Particle dryers   | Moderate                       | Fine to coarse                       | Usual      | Occasional                  | N/A         | Frequent     | Occasional      | Rare         | N/A                         | Occasional                  | Rare         | 51          |
| <b>Woodworking</b>   |                                |                                      |            |                             |             |              |                 |              |                             |                             |              |             |
| a. Woodworking machines                                      | Moderate                       | Varied                               | Usual      | Occasional                  | N/A         | Rare         | N/U             | Frequent     | N/A                         | N/U                         | N/A          | 52          |
| b. Sanding   | Moderate                       | Fine                                 | Frequent   | Occasional                  | N/A         | Occasional   | N/U             | Frequent     | Rare                        | N/U                         | N/A          | 53          |
| c. Waste conveying, hogs                                     | Heavy                          | Varied                               | Usual      | Rare                        | N/A         | Occasional   | N/U             | Occasional   | N/A                         | N/U                         | N/A          | 54          |

Source: Kane and Alden (1982). Information updated by ASHRAE Technical Committee 5.4.

Notes for Table 4

Definitions

N/A: Not applicable because of inefficiency or process incompatibility.  
 N/U: Not widely used.

Particle size

Fine: 50% in 0.5 to 7 μm diameter range  
 Medium: 50% in 7 to 15 μm diameter range  
 Coarse: 50% over 15 μm diameter range

Concentration of particulate matter entering collector (loading)

Light: <2 gr/ft<sup>3</sup>  
 Moderate: 2 to 5 gr/ft<sup>3</sup>  
 Heavy: >5 gr/ft<sup>3</sup>

- <sup>1</sup> Dust released from bin filling, conveying, weighing, mixing, pressing, forming. Refractory products, dry pan, and screening operations more severe.
- <sup>2</sup> Operations found in vitreous enameling, wall and floor tile, pottery.
- <sup>3</sup> Grinding wheel or abrasive cutoff operation. Dust abrasive.
- <sup>4</sup> Operations include conveying, elevating, mixing, screening, weighing, packaging. Category covers so many different materials that recommendation will vary widely.
- <sup>5</sup> Cyclone and high-efficiency centrifugal collectors often act as primary collectors, followed by fabric filters or wet collectors.
- <sup>6</sup> Usual setup uses cyclone as product collector followed by fabric filter for high overall collection efficiency.
- <sup>7</sup> Dust concentration determines need for dry centrifugal collector; plant location, product value determine need for final collectors. High temperatures are usual, and corrosive gases not unusual. Liquid smoke emissions may be controlled by condensing precipitator systems using low-voltage, two-stage electrostatic precipitators.
- <sup>8</sup> Ionizing wet scrubbers are widely used.
- <sup>9</sup> Conveying, screening, crushing, unloading.
- <sup>10</sup> Remote from other dust-producing points. Separate collector generally used.
- <sup>11</sup> Heavy loading suggests final high-efficiency collector for all except very remote locations.
- <sup>12</sup> Loadings and particle sizes vary with different drying methods.
- <sup>13</sup> Boiler blowdown discharge is regulated, generally for temperature and, in some places, for pH limits; check local environmental codes on sanitary discharge.
- <sup>14</sup> Collection for particulate or sulfur control usually requires a scrubber (dry or wet) and a fabric filter or electrostatic precipitator.
- <sup>15</sup> Public loading from settled wood char indicates collectors are needed.
- <sup>16</sup> Hot gases and steam usually involved.
- <sup>17</sup> Steam from hot sand, adhesive clay bond involved.
- <sup>18</sup> Concentration very heavy at start of cycle.
- <sup>19</sup> Heaviest load from airless blasting because of high cleaning speed. Abrasive shattering greater with sand than with grit or shot. Amounts removed greater with sand castings, less with forging scale removal, least when welding scale is removed.
- <sup>20</sup> Operations such as car unloading, conveying, weighing, storing.
- <sup>21</sup> Special filters are successful.
- <sup>22</sup> In addition to grain handling, cleaning rolls, sifters, purifiers, conveyors, as well as storing, packaging operations are involved.
- <sup>23</sup> In addition to grain handling, bins, hammer mills, mixers, feeders, conveyors, bagging operations need control.
- <sup>24</sup> Primary dry trap and wet scrubbing usual. Electrostatic precipitators are added where maximum cleaning is required.
- <sup>25</sup> Air pollution control is expensive for open hearth, accelerating the use of substitute melting equipment, such as basic oxygen process and electric-arc furnace.

- <sup>26</sup> Fabric filters have found extensive application for this air pollution control problem.
- <sup>27</sup> Cupola control varies with plant size, location, melt rate, and air pollution emission regulations.
- <sup>28</sup> Corrosive gases can be a problem, especially in secondary aluminum.
- <sup>29</sup> Zinc oxide plume can be troublesome in certain plant locations.
- <sup>30</sup> Crushing screening, conveying, storing involved. Wet ores often introduce water vapor in exhaust airstream.
- <sup>31</sup> Dry centrifugal collectors are used as primary collectors, followed by a final cleaner.
- <sup>32</sup> Collectors usually permit salvage of material and also reduce nuisance from settled dust in plant area.
- <sup>33</sup> Salvage value of collected material is high. Same equipment used on raw grinding before calcining.
- <sup>34</sup> Coarse abrasive particles readily removed in primary collector types.
- <sup>35</sup> Roof discoloration, deposition on autos can occur with cyclones and, less frequently, with dry centrifugal. Heavy-duty air filter sometimes used as final cleaner.
- <sup>36</sup> Linty particles and sticky buffing compounds can cause trouble in high-efficiency centrifugals and fabric filters. Fire hazard is also often present.
- <sup>37</sup> Unit collectors extensively used, especially for isolated machine tools.
- <sup>38</sup> Dust ranges from chips to fine floats, including graphitic carbon.
- <sup>39</sup> Coolant mist and thermal smoke, often with solid swarf particulate entrained.
- <sup>40</sup> Submicron smoke. Arc welding creates mostly dry metal oxide particulate, sometimes with liquid oil smoke. Resistance welding usually creates only liquid oil smoke, unless done at extremely high currents that vaporize some of the metal being welded.
- <sup>41</sup> Plasma and laser cutting and welding of clean metals usually creates dry submicron smoke, but oily work pieces frequently generate a sticky mix of liquid and solid submicron smoke or fume.
- <sup>42</sup> Materials involved vary widely. Collector selection may depend on salvage value, toxicity, sanitation yardsticks.
- <sup>43</sup> Controlled temperature and humidity of supply air to coating pans makes recirculation from coating pans desirable.
- <sup>44</sup> Manufacture of plastic compounds involves operations allied to many in chemical field and vanes with the basic process used.
- <sup>45</sup> Operations are similar to woodworking, and collector selection involves similar considerations.
- <sup>46</sup> Submicron liquid smoke is frequently emitted when plastic and rubber products are heated.
- <sup>47</sup> Concentration is heavy during feed operation. Carbon black and other fine additions make collection and dust-free disposal difficult.
- <sup>48</sup> Often, no collection equipment is used where dispersion from exhaust stack is good and stack location is favorable.
- <sup>49</sup> Salvage of collected material often dictates type of high-efficiency collector.
- <sup>50</sup> Fire hazard from some operations must be considered.
- <sup>51</sup> Granular-bed filters, at times electrostatically augmented, have occasionally been used in this application.
- <sup>52</sup> Bulky material. Storage for collected material is considerable; bridging from splinters and chips can be a problem.
- <sup>53</sup> Production sanding produces heavy concentrations of particles too fine to be effectively captured by cyclones or dry centrifugal collectors.
- <sup>54</sup> Primary collector invariably indicated with concentration and partial size range involved; when used, wet or fabric collectors are used as final collectors.

Table 5 Terminal Settling Velocities of Particles, fps

| Particle Density Relative to Water | Particle or Aggregate Diameter, μm |         |         |         |         |         |         |      |      |      |
|------------------------------------|------------------------------------|---------|---------|---------|---------|---------|---------|------|------|------|
|                                    | 1                                  | 2       | 5       | 10      | 20      | 50      | 100     | 200  | 500  | 1000 |
| 0.05                               | 5.9 E-6                            | 2.3 E-5 | 1.3 E-4 | 5.2 E-4 | 2.3 E-3 | 1.3 E-3 | 5.2 E-2 | 0.18 | 0.75 | 1.7  |
| 0.1                                | 1.2 E-5                            | 4.6 E-5 | 2.6 E-4 | 1.0 E-3 | 4.6 E-3 | 2.6 E-3 | 9.8 E-2 | 0.36 | 1.3  | 2.7  |
| 0.2                                | 2.4 E-5                            | 9.2 E-5 | 5.2 E-4 | 2.1 E-3 | 9.2 E-3 | 5.2 E-2 | 0.19    | 0.62 | 2.1  | 4.3  |
| 0.5                                | 5.9 E-5                            | 2.3 E-4 | 1.3 E-3 | 5.2 E-3 | 2.3 E-2 | 0.13    | 0.46    | 1.4  | 4.0  | 8.2  |
| 1.0                                | 1.2 E-4                            | 4.6 E-4 | 2.6 E-3 | 1.0 E-2 | 3.9 E-2 | 0.25    | 0.82    | 2.3  | 6.4  | 12.8 |
| 2.0                                | 2.4 E-4                            | 9.2 E-4 | 5.2 E-3 | 2.1 E-2 | 8.2 E-2 | 0.46    | 1.5     | 3.7  | 10.2 | 20.5 |
| 5.0                                | 5.9 E-4                            | 2.3 E-3 | 1.3 E-2 | 4.9 E-2 | 0.21    | 1.1     | 3.2     | 7.3  | 18.9 | 36.1 |
| 10.0                               | 1.2 E-3                            | 4.6 E-3 | 2.6 E-2 | 0.10    | 0.39    | 2.0     | 5.4     | 11.5 | 29.2 | 56.8 |

Source: Billings and Wilder (1970).

Note: E-6 = ×10<sup>-6</sup>, etc.

$b$  = cyclone inlet width, ft

$N_e$  = effective number of turns within cyclone; approximately 5 for a high-efficiency cyclone and may be from 0.5 to 10 for other cyclones

$V_i$  = inlet gas velocity, fpm

$\rho_p$  = density of particle material, lb/ft<sup>3</sup>

$\rho_g$  = density of gas, lb/ft<sup>3</sup>

At inlet gas velocity above 4800 fpm, internal turbulence limits improvements in the efficiency of a given cyclone. The pressure drop through a cyclone is proportional to the inlet velocity pressure and hence the square of the volumetric flow.

ELECTROSTATIC PRECIPITATORS

Electrostatic precipitators use the forces acting on charged particles passing through an electric field to separate those particles from the airstream in which they were suspended. In every precipitator, three distinct functions must be accomplished:

1. **Ionization:** Charging contaminant particles
2. **Collection:** Subjecting particles to a precipitating force that moves them toward collecting electrodes
3. **Collector cleaning:** Removal of collected contaminant from precipitator

Units in which ionization and collection are accomplished simultaneously in a single structure are called **single-stage precipitators** (Figure 4). They have widely spaced electrodes (3.15 to 6 in.) and typically operate with high voltages (20 to 60 kV) but relatively low (rarely as high as 11 kV/in.) field gradients.

In **two-stage precipitators**, ionization and collection are performed independently in discrete charging and precipitating structures (Figure 5). Because their ionizing and collecting electrodes are closely spaced (0.7 to 1.5 in.), two-stage precipitators normally operate with high field gradients (usually more than 10 kV/in.) but low voltages (usually 10 kV or less, and never more than 14 kV) (White 1963).

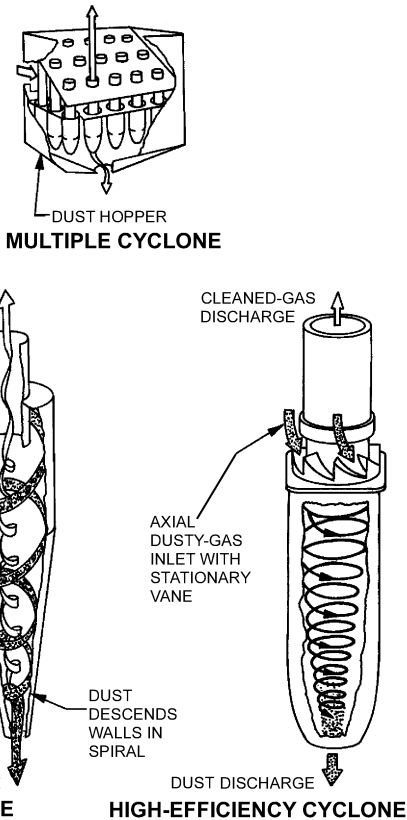


Fig. 2 Typical Cyclone Collectors

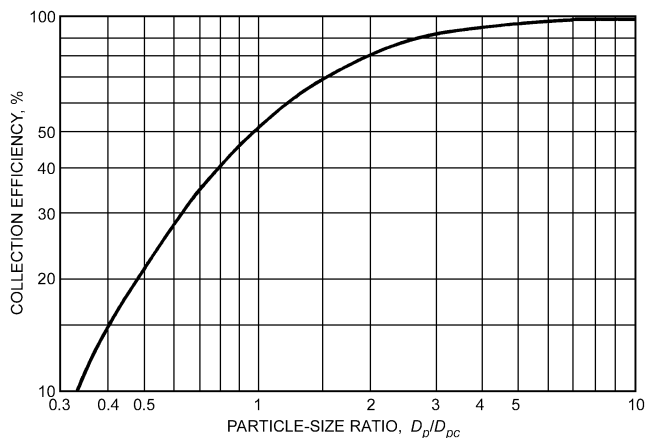


Fig. 3 Cyclone Efficiency (Lapple 1951)

Because of fundamental differences in their ionization processes and practical differences in the way they are usually constructed, high-voltage (single-stage) and low-voltage (two-stage) precipitators are suited for entirely different air-cleaning requirements.

**Single-Stage Designs**

Figure 6 shows several types of single-stage precipitators. The charging electrodes are located between parallel collecting plates. The gas flows horizontally through the precipitators. High-voltage precipitators collect larger particles better than small particles (they are less efficient at collecting contaminants smaller than 1 to 2  $\mu$ m). Their precipitation efficiency depends in part on the relative electrical resistivity of the pollutant being collected; most are less efficient when collecting either conductive or highly dielectric contaminants.

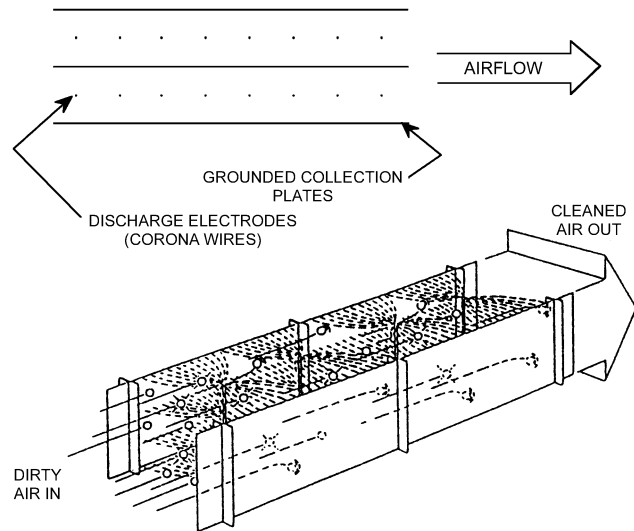


Fig. 4 Typical Single-Stage Electrostatic Precipitator

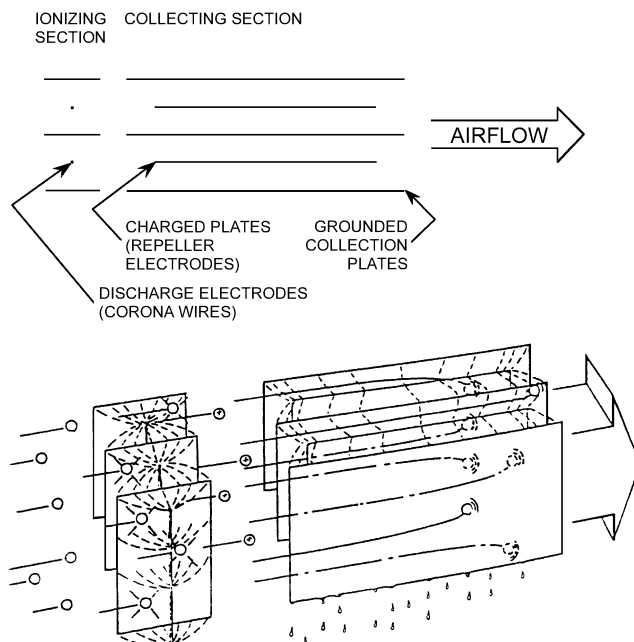


Fig. 5 Typical Two-Stage Electrostatic Precipitators

Single-stage high-voltage precipitators can easily handle heavy loadings of dry dust. Most are configured to operate continuously (using online vibratory or shaker cleaning). They can continuously collect large quantities (hundreds of pounds per hour) of airborne materials such as foundry shakeout, cement, ceramics, chemical dusts, fly ash, blast furnace dust and fumes, and paper mill recovery boiler emissions.

Although they are rarely used to clean exhaust airflows much smaller than 50,000 cfm, single-stage precipitators can be constructed to handle airflows as large as 2,000,000 cfm. Gas velocity through the electrostatic field is ordinarily 60 to 400 fpm, with treatment time in the range of 2 to 10 s. Only special-purpose single-stage “wet” precipitators are configured for collection of liquid contaminants.

Single-stage industrial electrostatic precipitators are distinguished from low-voltage two-stage precipitator designs by several attributes:

1. Separation between the electrodes is larger to secure acceptable collection and electrode cleaning under the high dust loading and hostile conditions of industrial gas streams.
2. Construction is heavy-duty for operation to 850°F and +30 in. of water.
3. They are generally used for exhaust applications where ozone generation is not of concern. Consequently, they may operate with negative ionization, the polarity that gives the maximum electric field strength between the electrodes.
4. They are normally custom-engineered and assembled on location for a particular application.

Single-stage precipitators can be designed to operate at collection efficiencies above 99.9% for closely specified conditions. Properties of the dust, such as particle size distribution and a deposit’s electrical resistivity, can affect performance significantly, as can variations in gas composition and flow rate.

**Two-Stage Designs**

Two-stage precipitators are manufactured in two general forms: (1) electronic air cleaners, which are commonly used for light dust loadings in commercial/residential ventilation and air-conditioning service (see Chapter 28); and (2) heavy-duty industrial electrostatic precipitators designed primarily to handle the heavy loadings of

submicron liquid particulates that are emitted from hot industrial processes and machining operations. Two-stage industrial precipitators often include sumps and drainage provisions that encourage continuous gravity runoff of collected liquids (Beck 1975; Shabsin 1985).

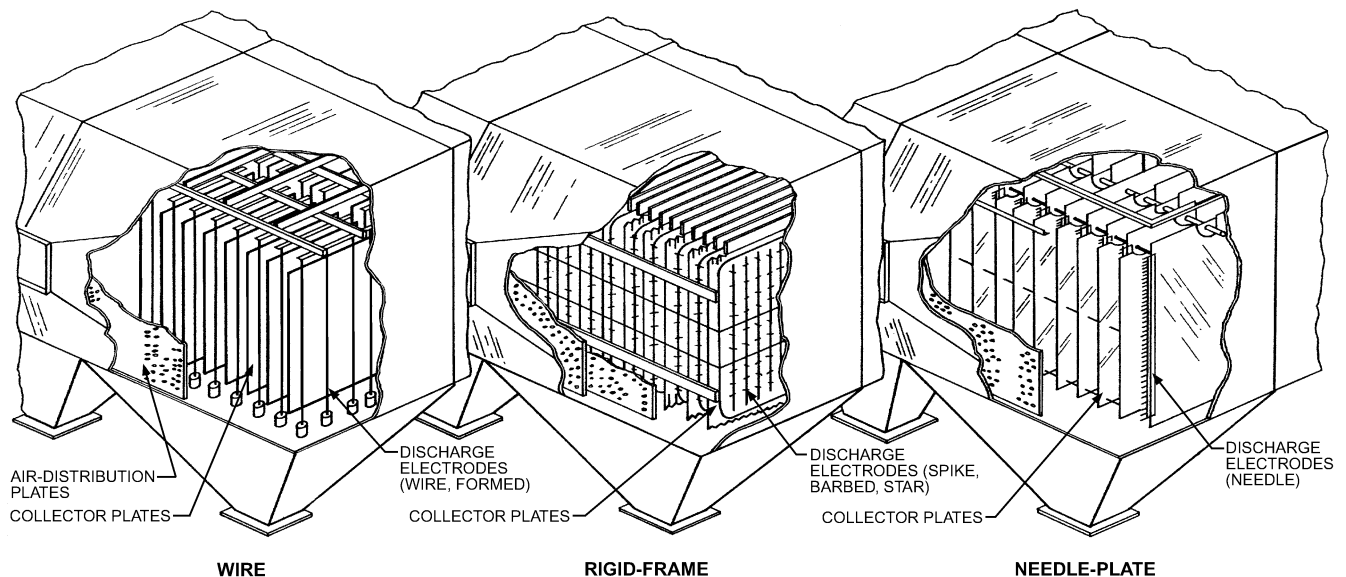
Two-stage precipitators are frequently used in industry to collect submicron pollutants that would be difficult (or impossible) to collect in other types of equipment. Two-stage precipitators are frequently sized to handle less than 1000 cfm of air and rarely built to handle more than 50,000 to 75,000 cfm of contaminated air in one unit. Gas velocity through the collecting fields usually ranges from 200 to 700 fpm, with treatment times per pass of 0.015 to 0.05 s in the ionizing fields and 0.06 to 0.25 s in the collecting fields.

Because gravity drainage of precipitated liquid smoke or fog is a dependable collector-cleaning mechanism, low-voltage two-stage precipitators are most often recommended to collect liquefiable pollutants in which few (or no) solids are entrained.

Since the early 1970s, an important application for low-voltage two-stage electrostatic precipitators has been as the gas-cleaning component of **condensing precipitator systems**. Design of these air pollution control systems (and of similar **condensing filtration systems**) is based on the following principle: although the hot gases or fumes emitted by many processes are not easily filtered or precipitated (because they are in the vapor phase), the condensation aerosol fogs or smokes that form as those vaporized pollutants cool can be efficiently collected by filtration or precipitation (Figure 7). Many condensation aerosol smokes consist of submicron liquid droplets, making them a good match for the collecting capability of low-voltage two-stage precipitators (Rosnagel 1973; Sauerland 1976; Thiel 1977).

Low-voltage precipitators can be very effective at collecting the aerosol particles smaller than 1 μm (down to 0.001 to 0.01 μm) that are responsible for most plume opacity and for virtually all blue smoke (blue-tinted) emissions. Condensing precipitator systems may therefore be a good choice for eliminating the residual opacity of blue smoke formed by condensation aerosol plumes from hot processes, dryers, ovens, furnaces, or other exhaust air cleaning devices (Beltran 1972; Beltran and Surati 1976; Thiel 1977).

When condensation aerosol pollutants are odorous in character, precipitation of the submicron droplets of odorant can prevent the long-distance drift of odorous materials, possibly eliminating neighborhood complaints that are associated with submicron particulate



**Fig. 6 Typical Single-Stage Precipitators**

smokes. Odors that have been successfully controlled by precipitation include asphalt fumes, food frying smokes, meat smokehouse smoke, plasticizer smokes, rubber curing smoke, tar, and textile smokes (Chopyk and Larkin 1982; Thiel 1983).

### FABRIC FILTERS

Fabric filters are dry dust collectors that use a stationary medium to capture the suspended dust and remove it from the gas stream. This medium, called fabric, can be composed of a wide variety of materials, including natural and synthetic cloth, glass fibers, and even paper.

Three types of industrial fabric filters are in common use: pulse jet (and, rarely, reverse air or shaker) cleaned baghouses, pulse jet cleaned cartridge filters, and disposable media filters. Although most commercially available fabric filter systems are currently one of these three types, there are a number of design variations among competing products that can greatly influence the suitability of a particular collector for a specific air-cleaning application.

Most **baghouses** (see Figures 9, 10, 12, and 13) use flexible cloth or other fabric-like filter media in the shape of long cylindrical bags. Bags in pulse jet cleaned systems are rarely more than 6.25 in. in diameter but can be up to 20 ft long. Timed pulses of compressed air flex the bags while blowing collected dust off the media surface. Continuous operation, with no downtime for filter cleaning or dust removal, is common (Figure 12).

**Cartridge filters**, illustrated in Figure 14, use a nearly identical compressed-air media cleaning system. However, their fabric is relatively rigid material, packaged into pleated cylindrical cartridges. Cartridges are self-supported and much easier to handle and replace than are long tubular baghouse bags. Most cartridges are 12.75 in. or less in diameter and rarely longer than 30 in.

With the pleated media construction, a large filter surface area can be packaged in a relatively small housing to reduce both cost and space required. Most cartridge filter units are not nearly as tall as baghouses having comparable capacity. Pleat depth and spacing are critically important variables that determine the suitability and useful lifetime of particular filter cartridges under the conditions of each specific application.

Both baghouse and cartridge filter systems are practical only when airborne contaminants consist almost exclusively of dry dust. The presence of any entrained liquid in the airstream usually creates a severe maintenance problem because the filter self-cleaning systems (i.e., pulse jet, reverse air, or shaker) become less effective, so the filters become plugged or “blinded” by collected material and fail after only brief operation.

Conservatively selected and carefully applied baghouse and cartridge filter systems, on the other hand, can easily provide excellent dust collection performance with a filter service life of more than

1 year. They often require very little maintenance, even when handling heavy dust loads in continuous 24 h, 7 day operation.

**Disposable fabric (or disposable-media)** filter collectors are usually simple and economical units that hold enough fabric or similar media to collect modest quantities of almost any particulate pollutant, including liquid, solid, and sticky or waxy materials, regardless of particle size (at least for particles larger than 0.5 to 1  $\mu\text{m}$ ). When each filter has accumulated as much material as it can practically hold, it is discarded and replaced by a new element. Both envelope bag arrays and pleated rectangular cartridge elements are popular media forms for use in disposable filter collectors.

When considering using disposable media filter collectors, serious attention must be given to safe, legal, and ethical disposal of spent and/or contaminated filter elements.

### Principle of Operation

When contaminated gases pass through a fabric, particles may attach to the fibers and/or other particles and separate from the gas stream. The particles are normally captured near the inlet side of a fabric to form a deposit known as a **dust cake**. In self-cleaning designs, the dust cake is periodically removed from the fabric to prevent excessive resistance to the gas flow. Finer particles may penetrate more deeply into a fabric and, if not removed during cleaning, may blind it.

The primary mechanisms for particle collection are direct interception, inertial impaction, electrostatic attraction, and diffusion (Billings and Wilder 1970).

**Direct interception** occurs when the fluid streamline carrying the particle passes within one-half of a particle diameter of a fiber. Regardless of the particle’s size, mass, or inertia, it will be collected if the streamline passes sufficiently close.

**Inertial impaction** occurs when the particle would miss the fiber if it followed the streamline, but its inertia overcomes the resistance offered by the flowing gas, and the particle continues in a direct enough course to strike the fiber.

**Electrostatic attraction** occurs when the particle, the filter, or both possess sufficient electrical charge to cause the particles to precipitate on the fiber.

**Diffusion** makes particles more likely to pass near fibers and thus be collected. Once a particle resides on a fiber, it effectively increases the size of the fiber.

Self-cleaning fabric filters have several **advantages** over other high-efficiency dust collectors such as electrostatic precipitators and wet scrubbers:

- They provide high efficiency with lower installed cost.
- The particulate matter is collected in the same state in which it was suspended in the gas stream (a significant factor if product recovery is desired).

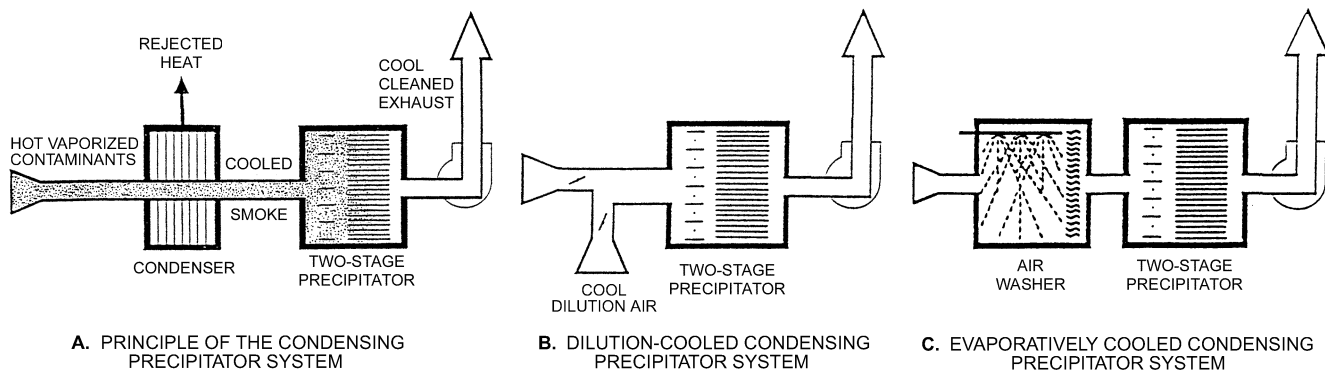


Fig. 7 Condensing Precipitator Systems for Control of Hot Organic Smokes

- Process upsets seldom result in the violation of emission standards. The mass rate of particulate matter escaping collection remains low over the life of the filter media and is insensitive to large changes in the mass-loading of dust entering the collector.

Self-cleaning fabric filter dust collectors also have some **limitations**:

- Liquid aerosols, moist and sticky materials, and condensation blind fabrics and reduce or prevent gas flow. These actions can curtail plant operation.
- Fabric life may be shortened in the presence of acidic or alkaline components in the gas stream.
- Use of fabric filters is generally limited to temperatures below 500°F.
- Should a spark or flame accidentally reach the collector, fabrics can contribute to the fire/explosion hazard.
- When a large volume of gas is to be cleaned, the large number of fabric elements (bags, cartridges, or envelopes) required and the maintenance problem of detecting, locating, and replacing a damaged element should be considered. Monitoring equipment can detect leakage in an individual row of filters or an individual bag.

**Pressure-Volume Relationships**

The size of a fabric filter is based on empirical data on the amount of fabric media required to clean the desired volumetric flow of gas with an acceptable static pressure drop across the media. The appropriate media and conditions for its use are selected by pilot test or from experience with media in similar full-scale installations. These tests provide a recommended range of approach velocities for a specific application.

The **approach velocity** is stated in practical applications as a gas-to-media ratio or filtration velocity (i.e., the velocity at which gas flows through the filter media). The **gas-to-media ratio** is the ratio of the volumetric flow of gases through the fabric filter to the area of fabric that participates in the filtration. It is the average approach velocity of the gas to the surface of the filter media.

It is difficult to estimate the correlation between pressure drop and gas-to-media ratio for a new installation. However, when the flow entering a filter with a dust cake is laminar and uniform, the pressure drop is proportional to the approach velocity:

$$\Delta p = KV_iW = KQW/A \tag{6}$$

where

- $\Delta p$  = pressure drop, in. of water
- $K$  = specific resistance coefficient, pressure drop per unit air velocity and mass of dust per unit area
- $V_i$  = approach velocity or gas-to-media ratio, fpm
- $W$  = area density of dust cake, oz/ft<sup>2</sup>
- $Q$  = volumetric flow of gases, cfm
- $A$  = area of cloth that intercepts gases, ft<sup>2</sup>

Equation (6) suggests that increasing the area of the fabric during initial installation has some advantage. A larger fabric area reduces both the gas-to-media ratio and the thickness of the dust cake, resulting in a decreased pressure drop across the collector and reduced cleaning requirements. A lower gas-to-media ratio generally lowers operational cost for the fabric filter system, extends the useful life of the filter elements, and reduces maintenance frequency and expense. In addition, the lower gas-to-media ratio allows for some expansion of the system and, more importantly, additional surge capacity when upset conditions such as unusually high moisture content occur.

The specific resistance coefficient  $K$  is usually higher for fine dusts. The use of a primary collector to remove the coarse fraction seldom causes a significant change in the pressure drop across the collector. In fact, the coarse dust fraction helps reduce operating

pressure because it results in a more porous dust cake, which provides better dust cake release.

Figure 8 illustrates the dependence of the pressure drop on time for a single-compartment fabric filter, operating through its cleaning cycle. The volumetric flow, particulate concentration, and distribution of particle sizes are assumed to remain constant. In practice, these assumptions are not usually valid. However, the interval between cleaning events is usually long enough that these variations are insignificant for most systems; between cleaning events, the dependence of pressure drop on time is approximately linear.

The volumetric flow of gases from a process often varies in response to changes in pressure drop across the fabric filter. The degree to which this variation is significant depends on the operating point for the fan and the requirements for the process.

**Electrostatic Augmentation**

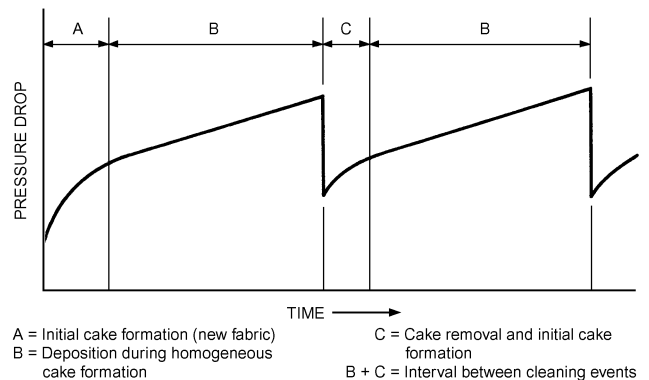
Electrostatic augmentation involves establishing an electric field between the fabric and another electrode, precharging the dust particles, or both. The effect of electrostatic augmentation is that the interstitial openings in the fabric material function as if they were smaller, and hence smaller particles are retained. Its principle advantage has been in the more rapid build-up of the dust layer and somewhat higher efficiency for a given pressure drop. Although tested by many, this technique has not been broadly applied.

**Fabrics**

Commercially available fabrics, when applied appropriately, will separate 1 μm or larger particles from a gas with an efficiency of 99.9% or better. Particle size is not the major factor influencing efficiency attained from an industrial fabric filter. Most manufacturers of fabric filters will guarantee such efficiencies on applications in which they have prior experience. Lower efficiencies are generally attributed to poor maintenance (torn fabric seams, loose connections, etc.) or the inappropriate selection of lighter/higher-permeability fabrics in an effort to reduce the cost of the collector.

Fabric specifications summarize information on such factors as cost, fiber diameter, type of weave, fabric density, tensile strength, dimensional stability, chemical resistance, finish, permeability, and abrasion resistance. Usually, comparisons are difficult, and the supplier must be relied on to select the appropriate material for the service conditions.

Table 6 summarizes experience with the exposure of fabrics to industrial atmospheres. Although higher temperatures are acceptable for short periods, reduced fabric life can be expected with continued use above the maximum temperature. The filter is often protected from high temperatures by thermostatically controlled air bleed-in or collector bypass dampers.



**Fig. 8 Time Dependence of Pressure Drop Across Fabric Filter**

When the gases are moist or the fabric must collect hygroscopic or sticky materials, **synthetic media** are recommended. They are also recommended for high-temperature gases. Polypropylene is a frequent selection. One limitation of synthetic media is greater penetration of the media during the cleaning cycle.

Woven fabrics are generally porous, and effective filtration depends on prior formation of a dust cake. New cloth collects poorly until particles bridge the openings in the cloth. Once the cake is formed, the initial layers become part of the fabric; they are not destroyed when the bulk of the collected material is dislodged during the cleaning cycle.

**Cotton and wool fibers** in woven media as well as most felted fabrics accumulate an initial dust cake in a few minutes. Synthetic woven fabrics may require a few hours in the same application because of the smoothness of the monofilament threads. Spun threads in the fill direction, when used, reduce the time required to build up the initial dust cake. Felted fabrics contain no straight-through openings and have a reasonably good efficiency for most particulates, even when clean. After the dust cake builds internally, as well as on the fabric's surface, shaking does not make it porous.

Cartridges manufactured from **pleated paper** and various **synthetic microfibers** (usually spun-bonded, not resin-glued, to form a stiff, nonwoven, microporous media) are also fabric filters because they operate in the same general manner as high-efficiency fabrics. As with cloth filters, the efficiency of the filter is increased by the formation of a dust cake on the medium.

Media used in cartridge type filters is usually manufactured to have many more pores (through which gas flows while being filtered) than do any of the common baghouse fabrics. Initial filtration efficiency of clean new cartridge filters is usually much greater, particularly for submicron-sized dust particles, than that of bare baghouse media (before a significant cake of filtered dust forms) because the pores in cartridge media are much smaller than those in baghouse fabrics. Despite having pores approximately one-tenth the diameter of those in the best baghouse felts, both cellulose (paper) and synthetic (most often polyester) cartridge media have so many pores that their permeability to gas flow is considerably greater than that of commonly used polyester felt baghouse media.

Because cartridge filters pack much more filter media per unit volume into their cartridges than can conventional bag filters, pulse jet cartridge filter collectors usually have less resistance to gas flow and operate with lower pressure drop from inlet to outlet than any of the three baghouse variations.

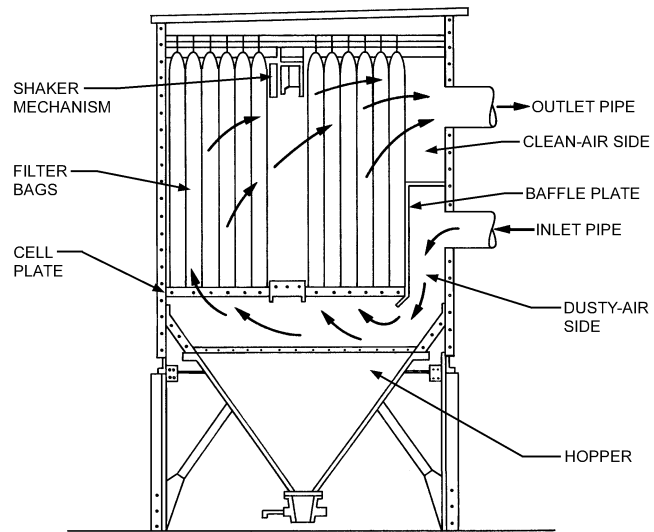
Pulse jet cleaned cartridge filter dust collectors are usually designed to operate at much lower filtration velocity (typically 1 to 3 fpm) than pulse jet cleaned tubular media baghouses. Submicron dust collection efficiency of cartridge filter media is so high that

cartridge-type collectors are often used in applications where cleaned air will be directly recirculated back into the factory to reduce the expense of heating or cooling replacement (makeup) air.

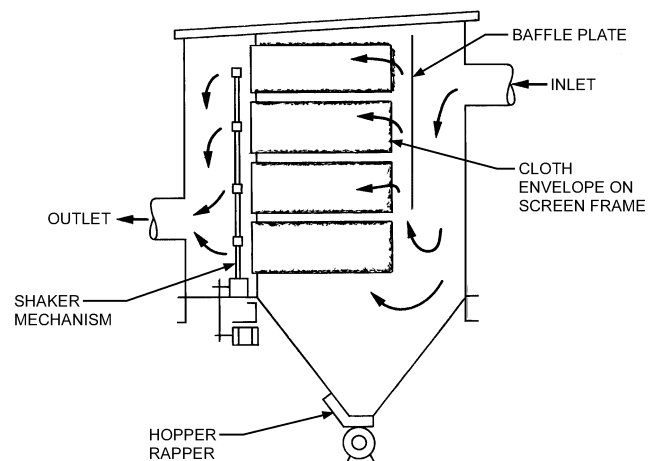
**Types of Self-Cleaning Mechanisms for Fabric Dust Collectors**

The most common filter cleaning methods are (1) shaking the bags, (2) reversing the flow of gas through the bags, and (3) using an air pulse (pulse jet) to shock the dust cake and break it from the bags. Pulse jet fabric filters are usually cleaned on-line, whereas fabric filters using shakers or reverse air cleaners are usually cleaned off-line. Generally, large installations are compartmented and use off-line cleaning. Other cleaning methods include shake-deflate, a combination of shaker and reverse air cleaning, and acoustically augmented cleaning.

**Shaker Collectors.** When a single compartment is needed that can be cleaned off-line during shift change or breaks, shaker-type fabric filters are usually the least expensive choice. The fabric medium in a shaker-type fabric filter, whether formed into cylindrical tubes or rectangular envelopes, is mechanically agitated to remove the dust cake. **Figures 9 and 10** show typical shaker-type fabric filters using bag and envelope media, respectively.



**Fig. 9 Bag-Type Shaker Collector**



**Fig. 10 Envelope-Type Shaker Collector**

**Table 6 Temperature Limits and Characteristics of Fabric Filter Media**

|                        | Maximum Continuous Operating Temp., °F | Acid Resistance | Alkali Resistance | Flex Abrasion | Cost               |
|------------------------|--|-----------------|-------------------|---------------|--------------------|
|                        |  |                 |                   |               | Relative to Cotton |
| Cotton                 | 180                                    | Poor            | Very good         | Very good     | 1.00               |
| Wool                   | 200                                    | Good            | Poor              | Fair to good  | 2.75               |
| Nylon <sup>a,b</sup>   | 200                                    | Poor            | Excellent         | Excellent     | 2.50               |
| Nomex <sup>a,b</sup>   | 400                                    | Fair            | Very good         | Very good     | 8.00               |
| Acrylic                | 260                                    | Good            | Fair              | Good          | 3.00               |
| Polypropylene          | 180                                    | Excellent       | Excellent         | Very good     | 1.75               |
| Polyethylene           | 145                                    | Excellent       | Excellent         | Very good     | 2.00               |
| Teflon <sup>b</sup>    | 425                                    | Excellent       | Excellent         | Good          | 30.00              |
| Glass fiber            | 500                                    | Fair to good    | Fair to good      | Poor          | 5.00               |
| Polyester <sup>a</sup> | 275                                    | Good            | Good              | Very good     | 2.50               |
| Cellulose              | 180                                    | Poor            | Good              | Good          | —                  |

<sup>a</sup>These fibers are subject to hydrolysis when they are exposed to hot, wet atmospheres.  
<sup>b</sup>DuPont trademark.

When the fabric filter cannot be stopped for cleaning, the collector is divided into a number of independent sections that are sequentially taken off-line for cleaning. Because it is usually difficult to maintain a good seal with dampers, relief dampers are often included. The relief dampers introduce a small volume of reverse gas to keep the gas flow at the fabric suitable for cake removal. Use of compartments, with their frequent cleaning cycles, does not permit a substantial increase in flow rates over those of a single-compartment unit cleaned periodically. The best situation for fabric reconditioning is when the system is stopped because even small particles will then fall into the hopper.

Figure 11 shows typical pressure diagrams for four- and six-compartment fabric filters that are continuously cleaned with mechanical shakers. Continuously cleaned units have compartment valves that close for the shaking cycle. This diagram is typical for a multiple-compartment fabric filter where individual compartments are cleaned off-line.

The gas-to-media ratio for a shaker-type dust collector is usually in the range of 2 to 4 fpm; it might be lower where the collector filters particles that are predominantly smaller than 2  $\mu\text{m}$ . The abatement of metallurgical fumes is one example where a shaker collector is used to control particles that are less than 1  $\mu\text{m}$  in size.

The bags are usually 4 to 8 in. in diameter and 10 to 20 ft in length, whereas envelope assemblies may be almost any size or shape. For ambient air applications, a woven cotton or polypropylene fabric is usually selected for shaker-type fabric filters. Synthetics are chosen for their resistance to elevated temperature and to chemicals.

**Reverse-Flow Collectors.** Reverse-flow cleaning is generally chosen when the volumetric flow of gases is very large. This method of cleaning inherently requires a compartmented design because the reverse flow needed to collapse the bags entrains dust that must be returned to on-line compartments of the fabric filter. Each compartment is equipped with one main shut-off valve and one reverse gas valve (whether the system is blown-through or drawn-through). A secondary blower and duct system is required to reverse the gas flow in the compartment to be cleaned. When a compartment is isolated for cleaning, the reverse gas circuit increases the volumetric flow and dust loading through the collector's active compartments.

The fabric medium is reconditioned by reversing the direction of flow through the bags, which partially collapse. The cleaning action is illustrated in Figure 12. After cleaning, the reintroduction of gas is delayed to allow dislodged dust to fall into the hopper.

Reverse-flow cleaning reduces the number of moving parts in the fabric filter system—a maintenance advantage, especially when large volumetric flows are cleaned. However, the cleaning or reconditioning is less vigorous than other methods, and the residual drag of the reconditioned fabric is higher. Reverse-flow cleaning is particularly suited for fabrics, like glass cloth, that require gentle cleaning.

Reverse-flow bags are usually 8 to 12 in. in diameter and 22 to 33 ft long and are generally operated at flow velocities in the 2 to 4 fpm range. As a consequence, reverse-air dust collectors tend to

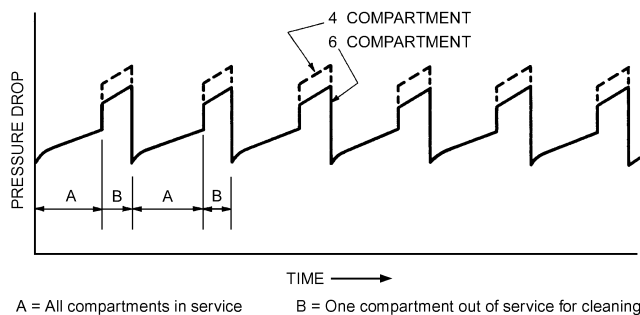


Fig. 11 Pressure Drop Across Shaker Collector Versus Time

be substantially larger than pulse-jet-cleaned designs of similar capacity.

For ambient air applications, a woven cotton or polypropylene fabric is the usual selection for reverse-flow cleaning. For higher temperatures, woven polyester, glass fiber, or trademarked fabrics are often selected.

**Pulse Jet Collectors.** Efforts to decrease fabric filter sizes by increasing the flow rates through the fabric have concentrated on methods of implementing frequent or continuous cleaning cycles without taking major portions of the filter surface out of service. In the pulse jet design shown in Figure 13, a compressed air jet operating for a fraction of a second causes a rapid vibration or ripple in the fabric, which dislodges the accumulated dust cake. Simultaneously, outflow of both compressed cleaning air and entrained air

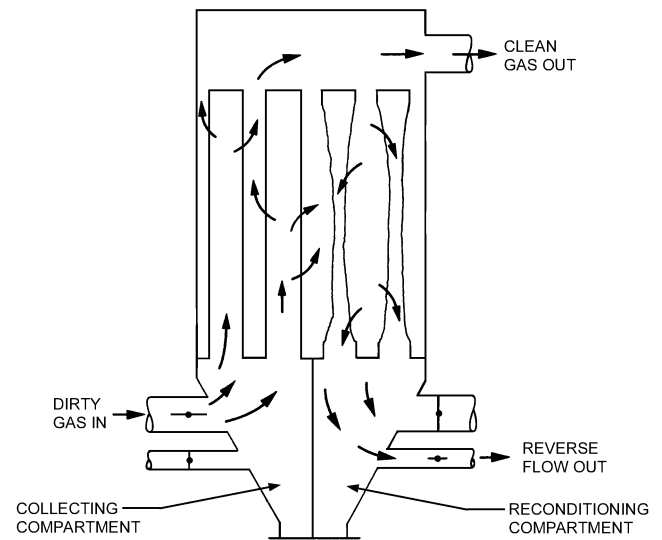


Fig. 12 Draw-Through Reverse-Flow Cleaning of Fabric Filter

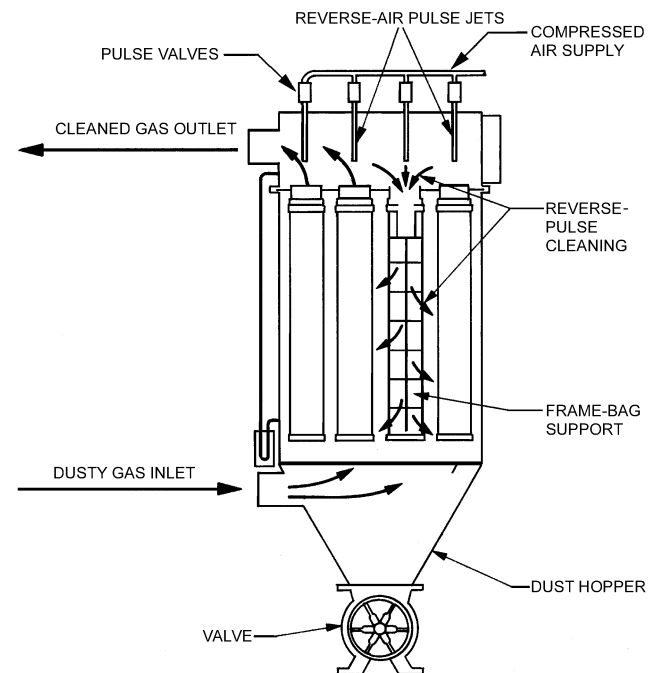


Fig. 13 Typical Pulse Jet Fabric Filter

from the top clean air plenum helps to sweep pulsed-off dust away from the filter surface. The pulse jet design is predominantly used because (1) it is easier to maintain than the reverse-jet mechanism and (2) collectors can be smaller and less costly because the greater useful cleaning energy makes operation with higher filtration velocities practical.

The tubular bags are supported by wire cages during normal operation. The reverse-flow pulse breaks up the dust layer on the outside of the bag, and the dislodged material eventually falls to a hopper. Filtration velocities for reverse jet or pulse jet designs range from 5 to 15 fpm for favorable dusts but require greater fabric area for many materials that produce a low-permeability dust cake. Felted fabrics are generally used for these designs because the jet cleaning opens the pores of woven cloth and produces excessive leakage through the filter.

Most pulse jet designs require high-pressure, dry, compressed (up to 100 psi) air, the cost of which should be considered when air-cleaning systems are designed.

When collecting light or fluffy dust of low bulk density (such as arc welding fumes, plasma or laser cutting fumes, finish sanding of wood, fine plastic dusts, etc.), serious attention must be given to the direction and velocity at which dust-laden air travels as it moves from the collector inlet to approach the filter media surface. Dusty air velocity is called **can velocity** and is defined as the actual velocity of airflow approaching the filter surfaces. Can velocity is computed by subtracting the total area occupied by filter elements (bags or cartridges), measured perpendicularly to the direction of gas flow) from the overall cross-sectional area of the collector's dusty air housing to compute the actual area through which dusty gas flows. The total gas flow being cleaned is then divided by that flow area to yield can velocity:

$$V_c = \frac{Q}{A_h - NA_f} \quad (7)$$

where

- $V_c$  = can velocity, fpm
- $Q$  = gas flow being cleaned, cfm
- $A_h$  = cross-sectional area of collector dusty gas housing, ft<sup>2</sup>
- $N$  = number of filter bags or cartridges in collector
- $A_f$  = cross-sectional area, perpendicular to gas flow, of each filter bag or cartridge, ft<sup>2</sup>

The maximum can velocity in **upflow** collectors (i.e., those in which dusty gas enters through a plenum or hopper beneath the filter elements) exists at the bottom end of the filter elements, where the entire gas flow must pass between and around the filters. Unless the maximum can velocity is low enough that pulsed-off dust can fall through the upwardly flowing gas, dust will simply redeposit on filter surfaces. The result is that on-line pulse cleaning cannot function, and the collector must be operated in the downtime pulse mode, with filter cleaning done only when there is no airflow through the collector.

Can velocity is sometimes overlooked when attempting to increase upflow collector capacity with improved fabrics or cartridges. Regardless of the theoretical gas-to-media ratio at which a filter operates, if released dust cannot fall through the rising airflow into the hopper, the collector will not be able to clean itself.

Collector designs in which dusty gas flows **downward** around the filters are much less susceptible to problems caused by high can velocity because the downward gas flow sweeps pulsed-off dust down toward (and into) the bottom dust discharge hopper, from which it can easily be removed.

Perhaps the most significant design difference among the many commercially available cartridge filter units is orientation of the filter cartridges. In collectors having **vertical filter surfaces** (Figure 14), all the pulsed-off dust can fall (by gravity) toward the bottom discharge flange, where it can be removed from the system (presuming

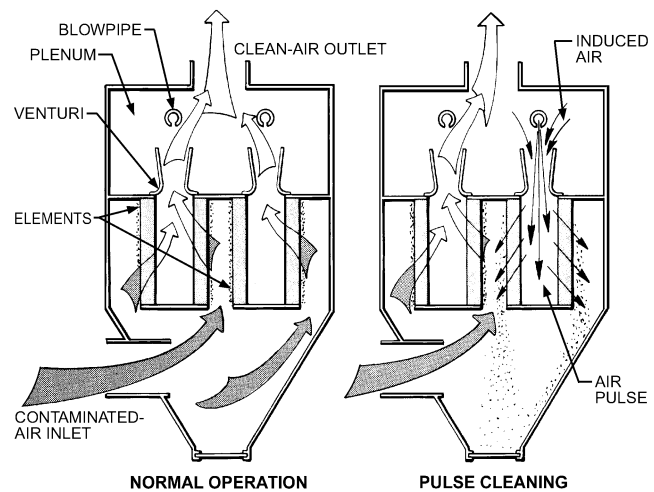


Fig. 14 Pulse Jet Cartridge Filters (Upflow Design with Vertical Filters)

that can velocity is low enough in upflow collectors). However, in designs having **horizontal or sloped filter surfaces**, nearly half of all pulsed-off dust (i.e., that from the top surfaces of the cartridges) must fall back onto that top surface. As a result, up to 50% of the total media area (i.e., nearly all media above the horizontal centerline of each filter cartridge) rapidly becomes blinded by a dust cake that is so thick that little or no gas can pass through to be filtered. This means that collectors having horizontal filter surfaces require twice as much installed filter area to achieve the same level of performance and useful filter life as collectors having vertical filter surfaces.

This chapter can not adequately cover all the collector design variables and experience-related factors that must be considered when deciding which baghouse or cartridge self-cleaning dust collector design is best suited for each particular application. Engineers making dust collector selections are encouraged to discuss all aspects of each application in detail with all vendors being considered. It is necessary to judge

- The relative expertise of each prospective vendor
- Which dust collector design is most desirable
- How much media surface is needed in each design for each specified gas flow rate
- Which filter media is best suited to the particular application
- In the case of pulse-jet-cleaned cartridge collectors, what pleat spacing and pleat depth will give optimum or acceptable dust cake removal performance under the particular application conditions

## GRANULAR-BED FILTERS

Usually, granular-bed filters use a fixed bed of granular material that is periodically cleaned off-line. Continuously moving beds have been developed. Most commercial systems incorporate electrostatic augmentation to enhance fine particle control and to achieve good performance with a moving bed. Reentrainment in moving granular-bed filters still significantly influences overall bed efficiency (Wade et al. 1978).

### Principle of Operation

A typical granular-bed filter is shown in Figure 15. Particulate-laden gas travels horizontally through the louvers and a granular medium, while the bed material flows downward. The gases typically travel with a superficial velocity near 100 to 150 fpm.

The filter medium moves continuously downward by gravity to prevent a filter cake from forming on the face of the filter and to

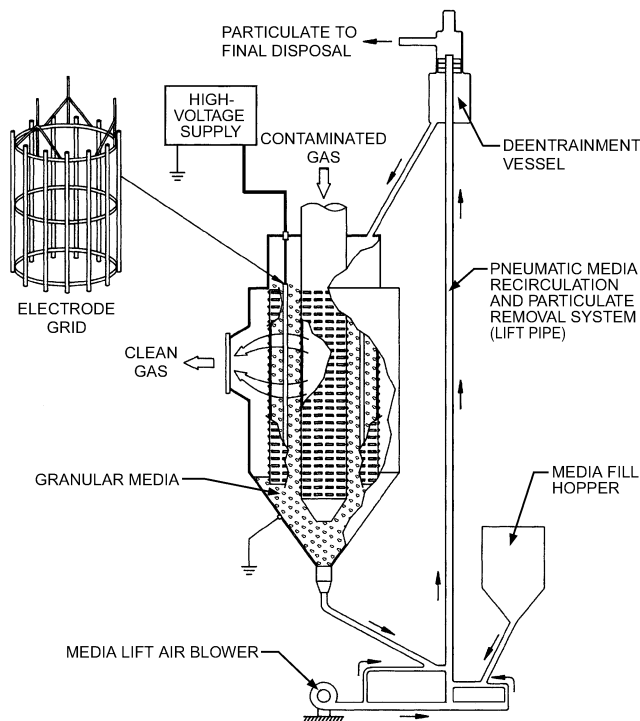


Fig. 15 Typical Granular-Bed Filter

prevent a high pressure drop. To provide complete cleaning of the louver's face, the louvers are designed so that some of the medium falls through each louver opening, thus preventing any bridging or build-up of particulate material.

**Electrostatic augmentation** gives the granular-bed filter many of the characteristics of a two-stage electrostatic precipitator. The obvious disadvantage of a granular-bed filter is in removal of the collected dust, which requires liquid backwash or circulation and cleaning of the filter material.

### PARTICULATE SCRUBBERS (WET COLLECTORS)

Wet-type dust collectors use liquid (usually, but not necessarily, water) to capture and separate particulate matter (dust, mist, and fumes) from a gas stream. Some scrubbers operate by spraying the **scrubbing liquid** into the contaminated air. Others bubble air through the scrubbing liquid. In addition, many hybrid designs exist.

Particle sizes, which can be controlled by a wet scrubber, range from 0.3 to 50  $\mu\text{m}$  or larger. Wet collectors can be classified into three categories: (1) **low-energy** (up to 1 W/cfm, 1 to 6 in. of water); (2) **medium-energy** (1 to 3 W/cfm, 6 to 18 in. of water); and (3) **high-energy** ( $>3$  W/cfm,  $>18$  in. of water). Typical wet-scrubber performance is summarized in [Table 3](#).

Wet collectors may be used for the collection of most particulates from industrial process gas streams where economics allow for collection of the material in a wet state.

**Advantages** of wet collectors include

- Constant operating pressure
- No secondary dust sources
- Small spare parts requirement
- Ability to collect both gases and particulates
- Ability to handle high-temperature and high-humidity gas streams, as well as to reduce the possibility of fire or explosion
- Reasonably small space requirements for scrubbers

- Ability to continuously collect sticky and hygroscopic solids without becoming fouled

**Disadvantages** include

- High susceptibility to corrosion (corrosion-resistant construction is expensive)
- High humidity in the discharge gas stream, which may give rise to visible and sometimes objectionable fog plumes, particularly during winter
- Large pressure drops and high power requirement for most designs that can efficiently collect fine (particularly submicron) particles
- Possible difficulty or high cost of disposal of waste water or clarification waste
- Rapidly decreasing fractional efficiency for most scrubbers for particles less than 1  $\mu\text{m}$  in size
- Freeze protection required in many applications in colder environments

### Principle of Operation

The more important mechanisms involved in the capture and removal of particulate matter in scrubbers are inertial impaction, Brownian diffusion, and condensation.

**Inertial impaction** occurs when a dust particle and a liquid droplet collide, resulting in the capture of the particle. The resulting liquid/dust particle is relatively large and may be easily removed from the carrier gas stream by gravitation or impingement on separators.

**Brownian diffusion** occurs when the dust particles are extremely small and have motion independent of the carrier gas stream. These small particles collide with one another, making larger particles, or collide with a liquid droplet and are captured.

**Condensation** occurs when the gas or air is cooled below its dew point. When moisture is condensed from the gas stream, fogging occurs, and the dust particles serve as condensation nuclei. The dust particles become larger as a result of the condensed liquid, and the probability of their removal by impaction is increased.

Wet collectors perform two individual operations. The first occurs in the **contact zone**, where the dirty gas comes in contact with the liquid; the second is in the **separation zone**, where the liquid that has captured the particulate matter is removed from the gas stream. All well-designed wet collectors use one or more of the following principles:

- High liquid-to-gas ratio
- Intimate contact between the liquid and dust particles, which may be accomplished by formation of large numbers of small liquid droplets or by breaking up the gas flow into many small bubbles that are driven through a bath of scrubbing liquid, to increase the chances that contaminants will be wetted and collected
- Abrupt transition from dry to wet zones to avoid particle build-up where the dry gas enters the collectors

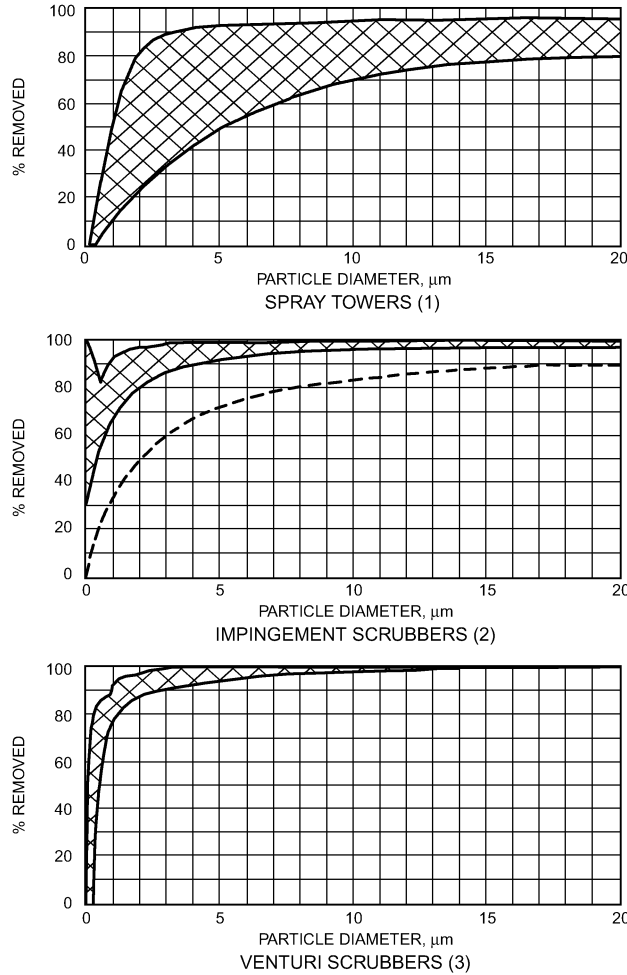
For a given type of wet collector, the greater the power applied to the system, the higher will be the collection efficiency (Lapple and Kamack 1955). This is the contacting power theory. [Figure 16](#) compares the fractional efficiencies of several wet collectors, and [Figure 17](#) shows the relationship between the pressure drop across a venturi scrubber and the abatement of particulate matter.

### Spray Towers and Impingement Scrubbers

Spray towers and impingement scrubbers are available in many different arrangements. The gas stream may be subjected to a single spray or a series of sprays, or the gas may be forced to impinge on a series of irrigated baffles. Except for packed towers, these types of scrubbers are in the low-energy category; thus, they have relatively low particulate removal efficiency. A typical spray tower

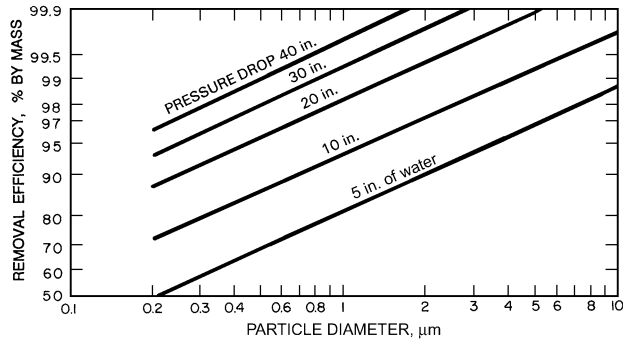
and an impingement scrubber are illustrated in [Figures 18 and 19](#), respectively.

The efficiency of a spray tower can be improved by adding high-pressure sprays. A spray tower efficiency of 50 to 75% can be improved to 95 to 99% (for dust particles with size near 2  $\mu\text{m}$ ) by pressures in the range of 30 to 100 psig.



Notes:  
 1. Efficiency depends on liquid distribution.  
 2. Upper curve is for packed tower; lower curve is for orifice-type wet collector. Dashed lines indicate performance of low-efficiency, irrigated baffles or rods.  
 3. Efficiency is directly related to fluid rate and pressure drop.

**Fig. 16 Fractional Efficiency of Several Wet Collectors**



**Fig. 17 Efficiency of Venturi Scrubber**

**Centrifugal-Type Collectors**

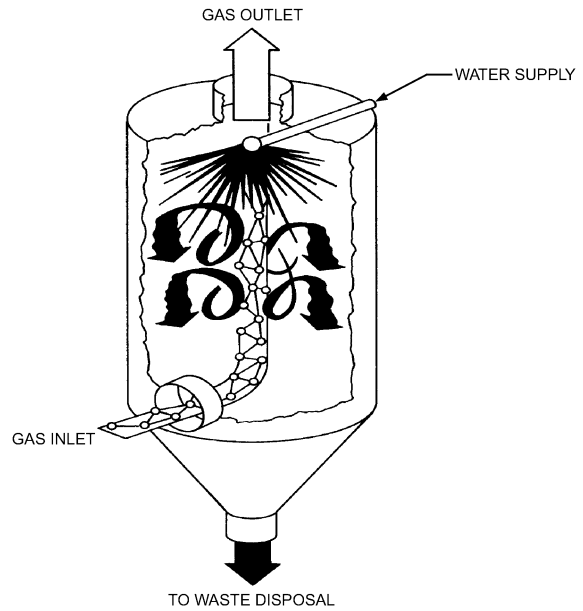
These collectors are characterized by a tangential entry of the gas stream into the collector. They are classed with medium-energy scrubbers. The impingement scrubber shown in [Figure 19](#) is an example of a centrifugal-type wet collector.

**Orifice-Type Collectors**

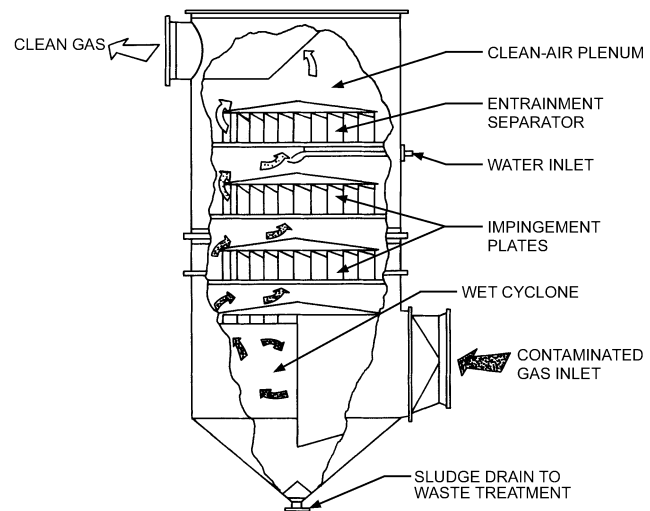
Orifice-type collectors are also classified in the medium-energy category. Usually, the gas stream is made to impinge on the surface of the scrubbing liquid and is forced through constrictions where the gas velocity is increased and where the liquid-gaseous-particulate interaction occurs. Water usage for orifice collectors is limited to evaporation loss and removal of collected pollutants. A typical orifice-type wet collector is illustrated in [Figure 20](#).

**Venturi Scrubber**

A high-energy venturi scrubber passes the gas through a venturi-shaped orifice where the gas is accelerated to 12,000 fpm or more.



**Fig. 18 Typical Spray Tower**



**Fig. 19 Typical Impingement Scrubber**

Depending on the design, the scrubbing liquid is added at, or ahead of, the throat. The rapid acceleration of the gas shears the liquid into a fine mist, increasing the chance of liquid-particle impaction. Yung has developed a mathematical model for the performance and design of venturi scrubbers (Semrau 1977). Subsequent validation experiments (Rudnick et al. 1986) demonstrated that this model yields a more representative prediction of venturi scrubber performance than other performance models do.

In typical applications, the pressure drop for gases across a venturi is higher than for other types of scrubber. Water circulation is also higher; thus, venturi systems use water reclamation systems. One example of a venturi scrubber is illustrated in Figure 21.

**Electrostatically Augmented Scrubbers**

Several gas-cleaning devices combine electrical charging of particulate matter with wet scrubbing. Electrostatic augmentation enhances fine particle control by causing an electrical attraction between the particles and the liquid droplets. Compared to venturi scrubbers, electrostatically augmented scrubbers remove particles smaller than 1 μm at a much lower pressure drop.

There are three generic designs for electrostatic augmentation:

1. Unipolar charged aerosols pass through a contact chamber containing randomly oriented packing elements of dielectric material. A typical electrostatically augmented scrubber of this design is shown in Figure 22.
2. Unipolar charged aerosols pass through a low-energy venturi scrubber.
3. Unipolar charged aerosols pass into a spray chamber where they are attracted to oppositely charged liquid droplets.

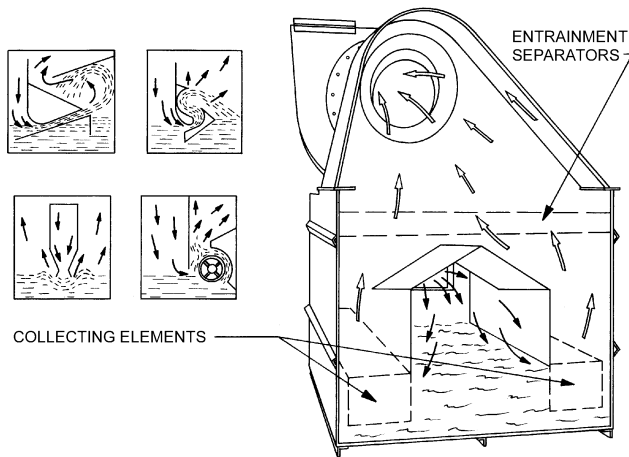


Fig. 20 Typical Orifice-Type Wet Collector

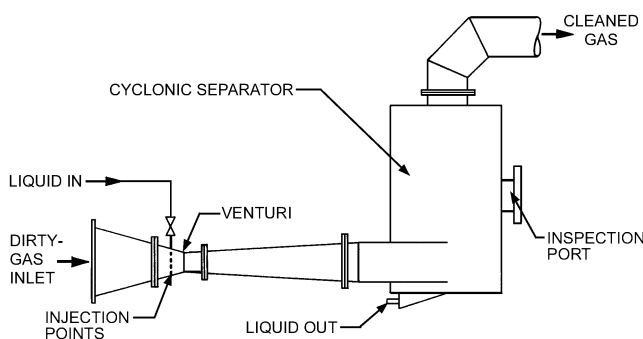


Fig. 21 Typical High-Energy Venturi Scrubber

Collection efficiencies of 50 to 90% can be achieved in a single particle charging and collection stage, depending on the mass loading of fine particles and the superficial velocity of gases in the collector. Higher collection efficiencies can be obtained by using two or more stages. Removal efficiency of gaseous pollutants depends on the mass transfer and absorption design of the scrubber section.

In most applications of electrostatically augmented scrubbers, the dirty gas stream is quenched by adiabatic cooling with liquid sprays; thus, it contains a large amount of water vapor that wets the particulate contaminants. This moisture provides a dominant influence on particle adhesion and the electrical resistivity of deposits within the collector.

Electrical equipment for particle charging is similar to that for electrostatic precipitators. The scrubber section is usually equipped with a liquid recycle pump, recycle piping, and a liquid distribution system.

**GASEOUS CONTAMINANT CONTROL**

Many industrial processes produce large quantities of gaseous or vaporized contaminants that must be separated from gas streams. Removal of these contaminants is usually achieved through absorption into a liquid or adsorption onto a solid medium. Incineration of the exhaust gas (see the section on Incineration of Gases and Vapors) has also been successfully used to remove organic gases and vapors. Low-vapor-pressure odorous materials that condense to form sub-micron condensation aerosols after being emitted from hot industrial processes can sometimes be successfully controlled by well-designed condensing filter or condensing precipitator submicron particulate collection systems (see the section on Two-Stage Designs under Electrostatic Precipitators).

**SPRAY DRY SCRUBBING**

Spray dry scrubbing is used to absorb and neutralize acidic gaseous contaminants in hot industrial gas streams. The system uses an alkali spray to react with the acid gases to form a salt. The process heat evaporates the liquid, resulting in a dry particulate that is removed from the gas stream.

Typical industrial applications of spray dry scrubbing are

- Control of hydrochloric acid (HCl) emissions from biological hazardous-waste incinerators

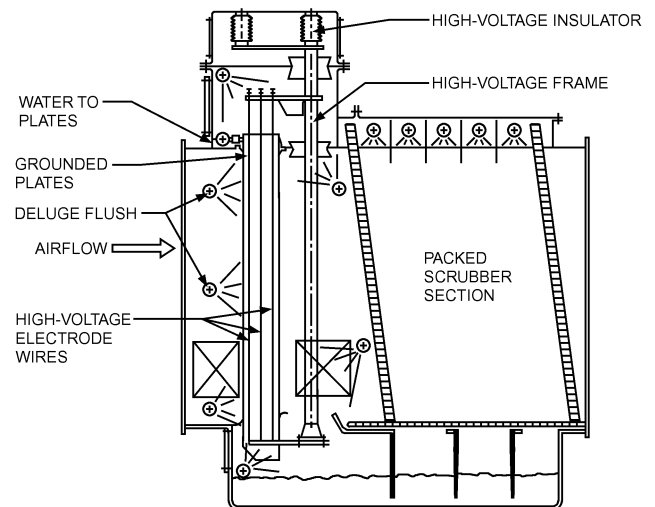


Fig. 22 Typical Electrostatically Augmented Scrubber

- Control of sulfuric acid and sulfur trioxide emissions from burning high-sulfur coal
- Control of sulfur oxides (SO<sub>x</sub>), boric acid, and hydrogen fluoride (HF) gases from glass-melting furnaces.

### Principle of Operation

Spray drying involves four operations: (1) atomization, (2) gas droplet mixing, (3) drying of liquid droplets, and (4) removal and collection of a dry product. These operations are carried out in a tower or a specially designed vessel.

In any spray dryer design, good mixing and efficient gas droplet contact are desirable. Dryer height is largely determined by the time required to dry the largest droplets produced by the atomizer. Towers used for acid gas control typically have gas residence times of about 10 s, compared to about 3 s for towers designed for evaporative cooling. The longer residence time is needed because drying by itself is not the primary goal for the equipment. Many of the acid/alkali reactions are accelerated in the liquid state. It is, therefore, desirable to cool the gases to as close as possible to the adiabatic saturation temperature (dew point) without risking condensation in downstream particulate collectors. At these low temperatures, droplets survive against evaporation much longer, thus obtaining a better chance of contacting all acidic contaminants while the alkali compounds are in their most reactive state.

### Equipment

The **atomizer** must disperse a liquid containing an alkali compound that will react with acidic components of the gas stream. The liquid must be distributed uniformly within the dryer and mixed thoroughly with the hot gases in droplets of a size that will evaporate before striking a dryer surface.

In typical spray dryers used for acid gas control, the droplets have diameters ranging from 50 to 200 μm. The larger droplets are of most concern because these might survive long enough to impinge on equipment surfaces. In general, a tradeoff must be made between the largest amount of liquid that can be sprayed and the largest droplets that can be tolerated by the equipment. The angular distribution or **fan-out** of the spray is also important. In spray drying, the angle is often 60 to 80°, although both lower and higher angles are sometimes required. The fan-out may change with distance from the nozzle, especially at high pressures.

An important aspect of spray dryer design and operation is the production and control of the gas flow patterns within the drying chamber. Because of the importance of the flow patterns, spray dryers are usually classified on the basis of gas flow direction in the chamber relative to the spray. There are three basic designs: (1) **cocurrent**, in which the liquid feed is sprayed with the flow of the hot gas; (2) **countercurrent**, in which the feed is sprayed against the flow of the gas; and (3) **mixed flow**, in which there is a combined cocurrent and countercurrent flow.

There are several types of atomizers. High-speed rotating **disks** achieve atomization through centrifugal motion. Although disks are bulky and relatively expensive, they are also more flexible than nozzles in compensating for changes in particle size caused by variations in feed characteristics. Disks are also used when high-pressure feed systems are not available. They are frequently used when high volumes of liquid must be spray dried. Disks are not well suited to counterflow or horizontal flow dryers.

Nozzles are also commonly used. These may be subdivided into two distinct types: centrifugal pressure nozzles and two-fluid (or pneumatic) nozzles. In the **centrifugal pressure nozzle**, energy for atomization is supplied solely by the pressure of the feed liquid. Most pressure nozzles are of the swirl type, in which tangential inlets or slots spin the liquid in the nozzle. The pressure nozzle satisfactorily atomizes liquids with viscosities of 300 centipoise or higher. It is well suited to counterflow spray dryers and to installations requiring multiple atomizers. Capacities up to 10,000 lb/h

through a single nozzle are possible. Pressure nozzles have some disadvantages. For example, pressure, capacity, and orifice size are independent, resulting in a certain degree of inflexibility. Moreover, pressure nozzles (particularly those with small passages) are susceptible to erosion in applications involving abrasive materials. In such instances, tungsten carbide or a similarly tough material is mandatory.

In **two-fluid nozzles**, air (or steam) supplies most of the energy required to atomize the liquid. Liquid, admitted under low pressure, may be mixed with the air either internally or externally. Although energy requirements for this atomizer are generally greater than for spinning disks or pressure nozzles, the two-fluid nozzle can produce very fine atomization, particularly with viscous materials.

The density and viscosity of the feed materials and how these might change at elevated temperature should be considered. Some alkali compounds do not form a solution at the concentrations needed for acid gas control. It is not uncommon that pumps and nozzles must be chosen to handle and meter slurries.

Spray dryer systems include metering valves, pumps and compressors, and controls to assure optimal chemical feed and temperature within the gas-cleaning system.

## WET-PACKED SCRUBBERS

Packed scrubbers are used to remove gaseous and particulate contaminants from gas streams. Scrubbing is accomplished by impingement of particulate matter and/or by absorption of soluble gas or vapor molecules on the liquid-wetted surface of the packing. There is no limit to the amount of particulate capture, as long as the properties of the liquid film are unchanged.

Gas or vapor removal is more complex than particulate capture. The contaminant becomes a solute and has a vapor pressure above that of the scrubbing liquid. This vapor pressure typically increases with increasing concentration of the solute in the liquid and/or with increasing liquid temperature. Scrubbing of the contaminant continues as long as the partial pressure of contaminant in the gas is above its vapor pressure with respect to the liquid. The rate of contaminant removal is a function of the difference between the partial pressure and vapor pressure, as well as the rate of diffusion of the contaminant.

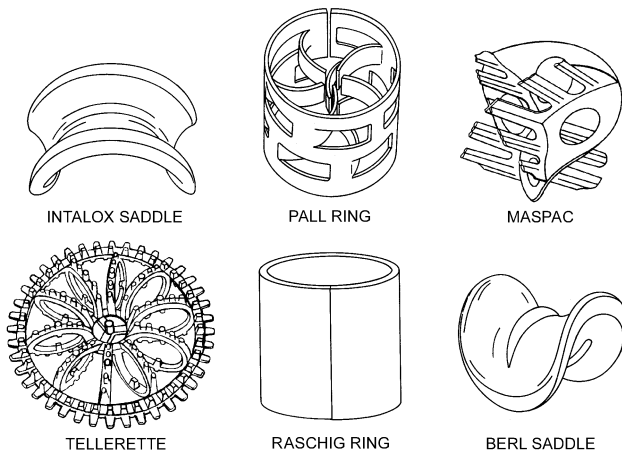
In most common gas-scrubbing operations, small increases in the superficial velocity of gases through the collector decrease the removal efficiency; therefore, these devices are operated at the highest possible superficial velocities consistent with acceptable contaminant control. Usually, increasing the liquid rate has little effect on efficiency; therefore, liquid flow is kept near the minimum required for satisfactory operation and removal of particulate matter. As the superficial velocity of gases in the collector increases above a certain value, there is a tendency to strip liquid from the surface of the packing and entrain the liquid from the scrubber. If the pressure drop is not the limiting factor for operation of the equipment, maximum scrubbing capacity will occur at a gas rate just below the rate that causes excessive liquid reentrainment.

### Scrubber Packings

Packings are designed to present a large surface area that will wet evenly with liquid. They should also have high void ratio so that pressure drop will be low. High-efficiency packings promote turbulent mixing of the gas and liquid. [Figure 23](#) illustrates six types of packings that are randomly dumped into scrubbers. Packings are available in ceramic, metal, and thermoplastic materials. Plastic packings are extensively used in scrubbers because of their low mass and resistance to mechanical damage. They offer a wide range of chemical resistance to acids, alkalies, and many organic compounds; however, plastic packing can be deformed by excessive temperatures or by solvent attack.

**Table 7 Packing Factor  $F$  for Various Scrubber Packing Materials**

| Type of Packing | Material | Nominal Size, in. |     |     |    |          |
|-----------------|----------|-------------------|-----|-----|----|----------|
|                 |          | 3/4               | 1   | 1.5 | 2  | 3 or 3.5 |
| Super Intalox   | Plastic  |                   | 40  |     | 21 | 16       |
| Super Intalox   | Ceramic  |                   | 60  |     | 30 |          |
| Intalox saddles | Ceramic  | 145               | 92  | 52  | 40 | 22       |
| Berl saddles    | Ceramic  | 170               | 110 | 65  | 45 |          |
| Raschig rings   | Ceramic  | 255               | 155 | 95  | 65 | 37       |
| Hy-Pak          | Metal    |                   | 43  | 26  | 18 | 15       |
| Pall rings      | Metal    |                   | 48  | 33  | 20 | 16       |
| Pall rings      | Plastic  |                   | 52  | 40  | 24 | 16       |
| Tellerettes     | Plastic  |                   | 36  |     | 18 | 16       |
| Maspac          | Plastic  |                   |     |     | 32 | 21       |



**Fig. 23 Typical Packings for Scrubbers**

The relative capacity of tower packings at constant pressure drop can be obtained by calculation from the **packing factor  $F$** . The gas-handling capacity  $G$  of a packing is inversely proportional to the square root of  $F$ :

$$G = K/\sqrt{F} \tag{8}$$

where

- $G$  = mass flow rate of gases through scrubber
- $F$  = packing factor (surface area of packing per unit volume of gently poured material)

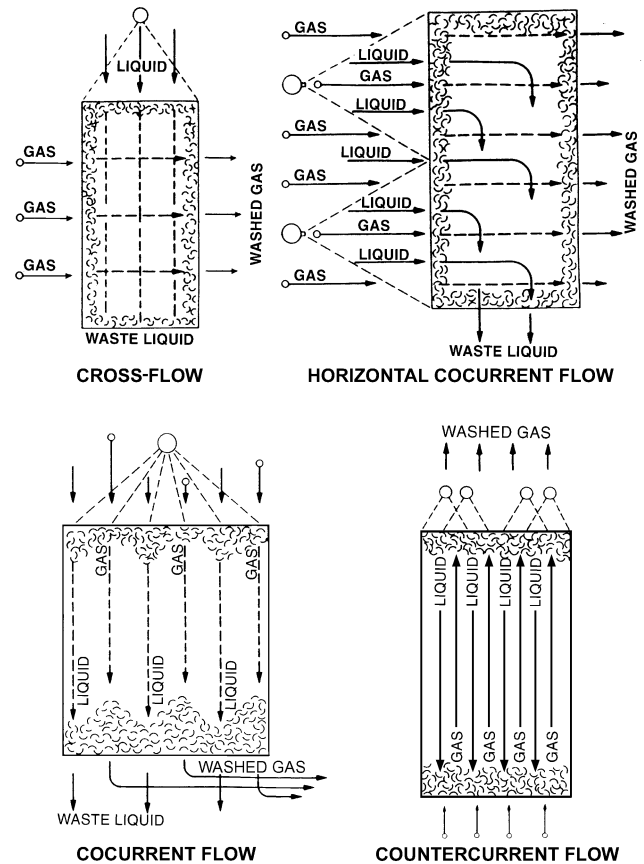
The smaller the packing factor of a given packing, the greater will be its gas-handling capacity. Typical packing factors for scrubber packings are summarized in [Table 7](#).

**Arrangements of Packed Scrubbers**

The four generic arrangements for wet-packed scrubbers are illustrated in [Figure 24](#):

- Horizontal cocurrent scrubber
- Vertical cocurrent scrubber
- Cross-flow scrubber
- Countercurrent scrubber

Cocurrent flow scrubbers can be operated with either horizontal or vertical gas and liquid flows. A **horizontal cocurrent scrubber** depends on the gas velocity to carry the liquid into the packed bed. It operates as a wetted entrainment separator with limited gas and liquid contact time. The superficial velocity of gases in the collector is limited by liquid reentrainment to about 650 fpm. A **vertical**



**Fig. 24 Flow Arrangements Through Packed Beds**

**cocurrent scrubber** can be operated at very high pressure drop (1 to 3 in. of water per foot of packing depth) because there is no flooding limit for the superficial velocity. The contact time in a cocurrent scrubber is a function of bed depth. The effectiveness of absorption processes is lower in cocurrent scrubbers than in the other arrangements because the liquid containing contaminant is in contact with the exit gas stream.

**Cross-flow scrubbers** use downward-flowing liquid and a horizontally moving gas stream. The effectiveness of absorption processes in cross-flow scrubbers lies between those for cocurrent and countercurrent flow scrubbers.

**Countercurrent scrubbers** use a downward-flowing liquid and an upward-flowing gas. The gas-handling capacity of countercurrent scrubbers is limited by pressure drop or by liquid entrainment. The contact time can be controlled by the depth of packing used. The effectiveness of absorption processes is maximized because the exiting gas is in contact with fresh scrubbing liquid.

The most broadly used arrangement is the countercurrent packed scrubber. This type of scrubber, illustrated in [Figure 25](#), gives the best removal of gaseous contaminants while keeping liquid consumption to a minimum. The effluent liquid has the highest contaminant concentration.

**Extended-surface packings** have been used successfully for the absorption of highly soluble gases such as HCl because the required contact time is minimal. This type of packing consists of a woven mat of fine fibers of a plastic material that is not affected by chemical exposure. [Figure 26](#) shows an example of a scrubber consisting of three wetted stages of extended surface packing in series with the gas flow. A final dry mat is used as an entrainment eliminator. If solids are present in the inlet gas stream, a wetted impingement stage precedes the wetted mats to prevent plugging of the woven mats.

Figure 27 shows a scrubber with a vertical arrangement of extended surface packing. This design uses three complete stages in series with the gas flow. The horizontal mat at the bottom of each stage operates as a flooded bed scrubber. The flooded bed is used to minimize water consumption. The two inclined upper mats operate as entrainment eliminators.

**Pressure Drop**

The pressure drop through a particular packing in countercurrent scrubbers can be calculated from the airflow and water flow per unit area. Charts, such as the one shown in Figure 28, are available from manufacturers of each type and size of packing.

The pressure drop for any packing can also be estimated by using the data on packing factors in Table 7 and the modified generalized pressure drop correlation shown in Figure 29. This correlation was developed for a gas stream substantially of air, with water as the scrubbing liquid. It should not be used if the properties of the

gas or liquid vary significantly from air or water, respectively. Countercurrent scrubbers are generally designed to operate at pressure drops between 0.25 and 0.65 in. of water per foot of packing depth. Liquid irrigation rates typically vary between 5 and 20 gpm per square foot of bed area.

**Absorption Efficiency**

The prediction of the absorption efficiency of a packed bed scrubber is much more complex than estimating its capacity because performance estimates involve the mechanics of absorption. Some of the factors affecting efficiency are superficial velocity

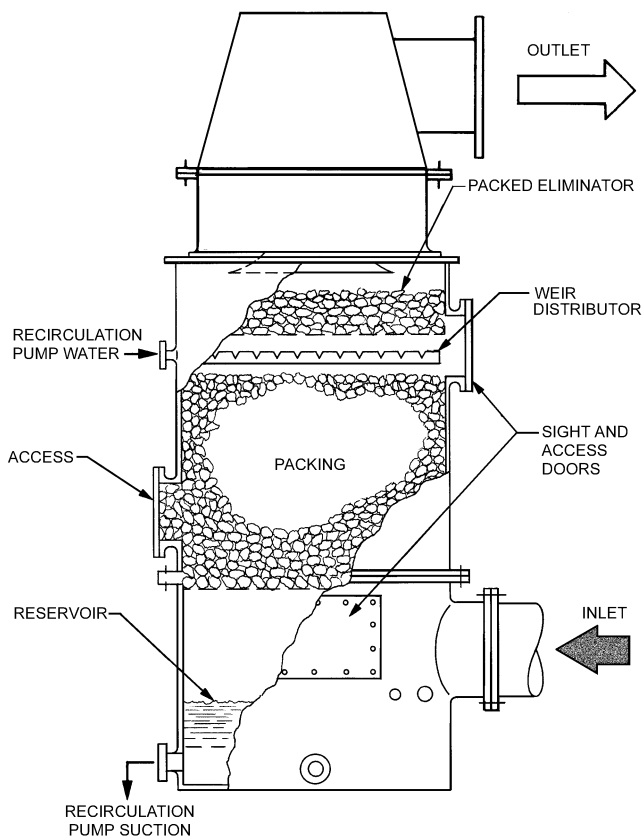


Fig. 25 Typical Countercurrent Packed Scrubber

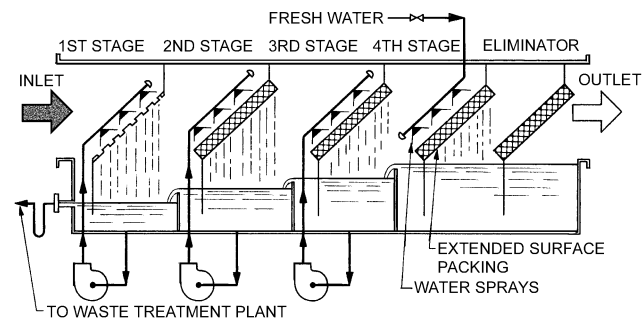


Fig. 26 Horizontal Flow Scrubber with Extended Surface

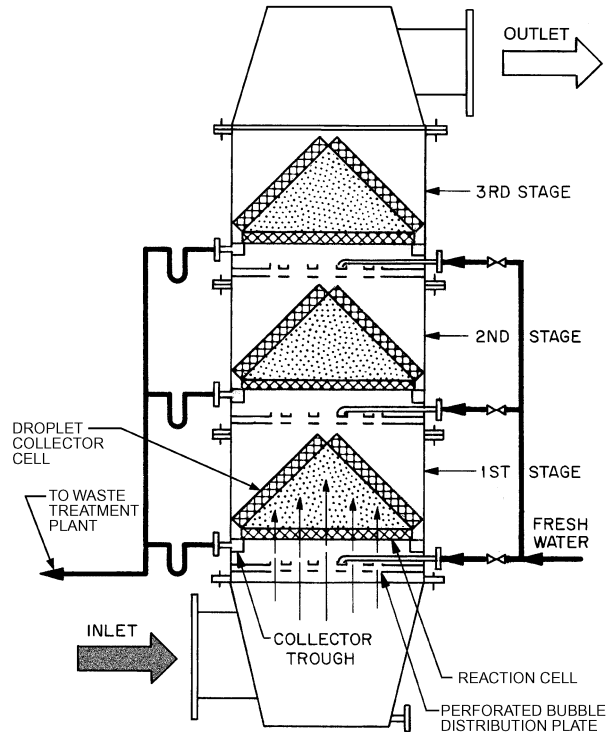


Fig. 27 Vertical Flow Scrubber with Extended Surface

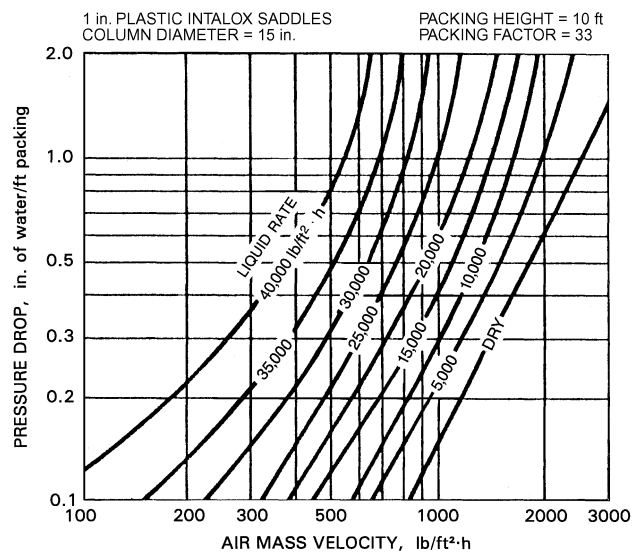


Fig. 28 Pressure Drop Versus Gas Rate for Typical Packing

of gases in the scrubber, liquid injection rate, packing size, type of packing, amount of contaminant to be removed, distribution and amount of absorbent available for reaction, temperature, and reaction rate for absorption.

Practically all commercial packings have been tested for absorption rate (mass transfer coefficient) using standard absorber conditions: carbon dioxide (CO<sub>2</sub>) in air and a solution of caustic soda (NaOH) in water. This system was selected because the interaction of the variables is well understood. Further, the mass transfer coefficients for this system are low; thus, they can be determined accurately by experiment. The values of mass transfer coefficients ( $K_G a$ ) for various packings under these standard test conditions are given in Table 8.

The vast majority of wet absorbers are used to control low concentrations (less than 0.005 mole fraction) of contaminants in air. Dilute aqueous solutions of NaOH are usually chosen as the scrubbing fluid. These conditions simplify the design of scrubbers somewhat. Mass transfer from the gas to the liquid is then explained by the **two-film theory**: the gaseous contaminant travels by diffusion from the main gas stream through the gas film, then through the liquid film, and finally into the main liquid stream. The relative influences of the gas and liquid films on the absorption rate depend on the solubility of the contaminant in the liquid. Sparingly soluble gases like hydrogen sulfide (H<sub>2</sub>S) and CO<sub>2</sub> are said to be liquid-film-controlled; highly soluble gases such as HCl and ammonia (NH<sub>3</sub>) are said to be gas-film-controlled. In liquid-film-controlled systems, the mass transfer coefficient varies with the liquid injection rate but is only slightly affected by the superficial velocity of the gases. In gas-film-controlled systems, the mass transfer coefficient is a function of both the superficial velocity of the gases and the liquid injection rate.

In the absence of leakage, the percentage by volume of the contaminant removed from the air can be found from the inlet and outlet concentrations of contaminant in the airstream:

$$\% \text{ Removed} = 100(1 - Y_o/Y_i) \tag{9}$$

where

$Y_i$  = mole fraction of contaminants entering scrubber (dry gas basis)  
 $Y_o$  = mole fraction of contaminants exiting scrubber (dry gas basis)

The driving pressure for absorption (assuming negligible vapor pressure above the liquid) is controlled by the logarithmic mean of inlet and outlet concentrations of the contaminant:

$$\Delta p_{ln} = p \frac{Y_i - Y_o}{\ln(Y_i/Y_o)} \tag{10}$$

where

$\Delta p_{ln}$  = driving or diffusion pressure acting to absorb contaminants on packing  
 $p$  = inlet pressure

The rate of absorption of contaminant (mass transfer coefficient) is related to the depth of packing as follows:

$$K_G a = N/H A \Delta p_{ln} \tag{11}$$

where

$N$  = solute absorbed, lb·mol/h  
 $H$  = depth of packing, ft  
 $A$  = cross-sectional area of scrubber, ft<sup>2</sup>

The value of  $N$  can be determined from

$$N = G(Y_i - Y_o) \tag{12}$$

where  $G$  = mass flow rate of gases through scrubber, lb·mol/h.

The superficial velocity of gases is a function of the unit gas flow rate and the gas density:

$$V = 60 T G M_v / C_1 A \tag{13}$$

where

$V$  = superficial gas velocity, fpm  
 $M_v$  = molar volume, ft<sup>3</sup>/lb·mol  
 $T$  = exit gas temperature, °R = °F + 460  
 $C_1$  = 460°R

**Table 8 Mass Transfer Coefficients ( $K_G a$ ) for Scrubber Packing Materials**

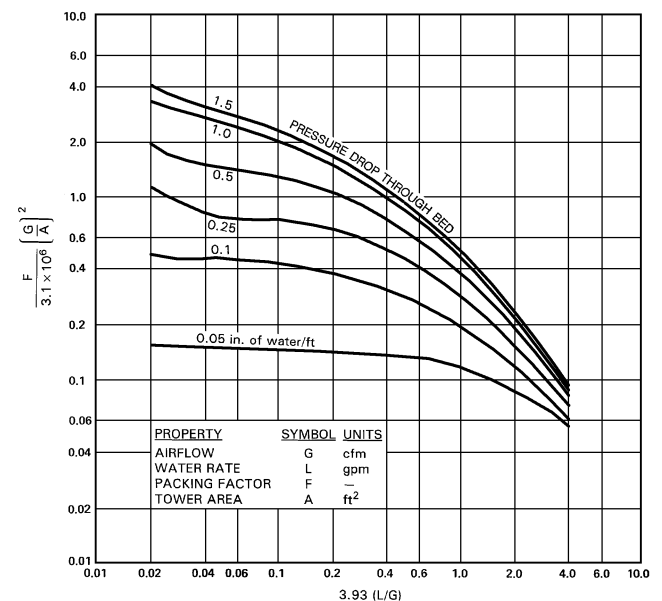
| Type of Packing                         | Material | Nominal Size, in. |      |      |          |
|---|----------|-------------------|------|------|----------|
|   |          | 1                 | 1.5  | 2    | 3 or 3.5 |
| $K_G a$ , lb·mol/h·ft <sup>3</sup> ·atm |          |                   |      |      |          |
| Super Intalox                           | Plastic  | 2.19              |      | 1.44 | 0.887    |
| Intalox saddles                         | Ceramic  | 1.96              | 1.71 | 1.44 | 0.820    |
| Raschig rings                           | Ceramic  | 1.73              | 1.50 | 1.21 |          |
| Hy-Pak                                  | Metal    | 2.20              | 1.87 | 1.69 | 1.09     |
| Pall rings                              | Metal    | 2.32              | 1.87 | 1.62 | 0.91     |
| Pall rings                              | Plastic  | 1.98              | 1.73 | 1.46 | 0.89     |
| Tellerettes                             | Plastic  | 2.19              |      | 1.98 |          |
| Maspac                                  | Plastic  |                   |      | 1.44 | 0.89     |

System: CO<sub>2</sub> and NaOH; gas rate: 110 cfm/ft<sup>2</sup>; liquid rate: 4 gpm/ft<sup>2</sup>.

**Table 9 Relative  $K_G a$  for Various Contaminants in Liquid-Film-Controlled Scrubbers**

| Gas Contaminant  | Scrubbing Liquid  | $K_G a$                       |
|------------------|-------------------|-------------------------------|
|                  |                   | lb·mol/h·ft <sup>3</sup> ·atm |
| CO <sub>2</sub>  | 4% (by mass) NaOH | 2.0                           |
| H <sub>2</sub> S | 4% (by mass) NaOH | 5.92                          |
| SO <sub>2</sub>  | Water             | 2.96                          |
| HCN              | Water             | 5.92                          |
| HCHO             | Water             | 5.92                          |
| Cl <sub>2</sub>  | Water             | 4.55                          |

Note: Data for 2 in. plastic Super Intalox. Temperatures: from 60 to 75°F; liquid rate: 10 gpm/ft<sup>2</sup>; gas rate: 215 cfm/ft<sup>2</sup>.



**Fig. 29 Generalized Pressure Drop Curves for Packed Beds**

By combining these equations and assuming ambient pressure, a graphical solution can be derived for both liquid-film- and gas-film-controlled systems. Figures 30, 31, and 32 show the height of packing required versus percent removal for various mass transfer coefficients at superficial velocities of 120, 240, and 360 fpm, respectively, with liquid-film-controlled systems. Figures 33, 34, and 35 show the height of packing versus percent removal for various mass transfer coefficients at the same three superficial velocities with gas film-controlled systems.

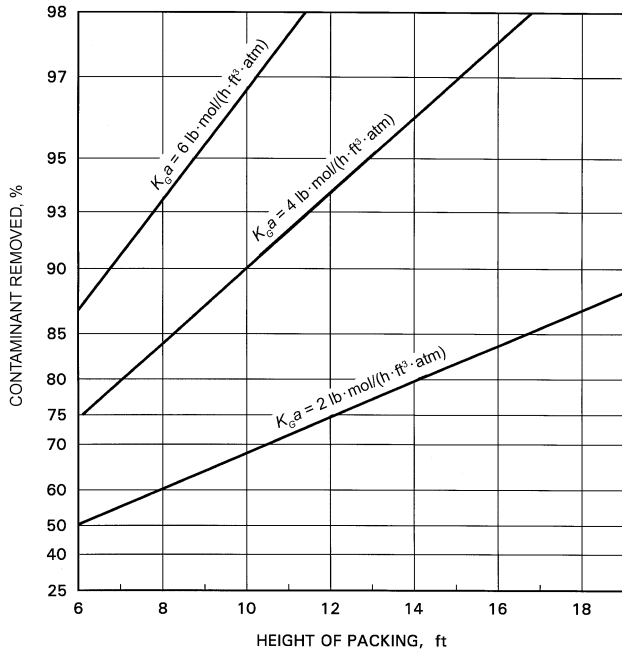


Fig. 30 Contaminant Control at Superficial Velocity = 120 fpm (Liquid-Film-Controlled)

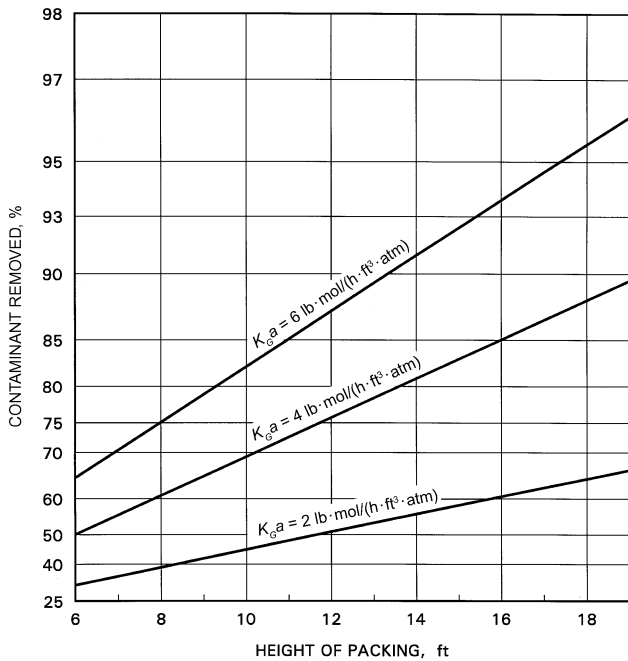


Fig. 31 Contaminant Control at Superficial Velocity = 240 fpm (Liquid-Film-Controlled)

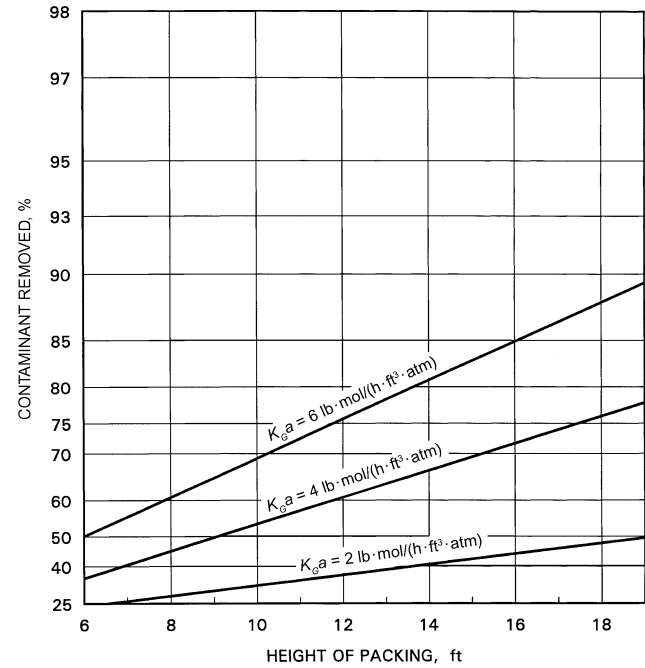


Fig. 32 Contaminant Control at Superficial Velocity = 360 fpm (Liquid-Film-Controlled)

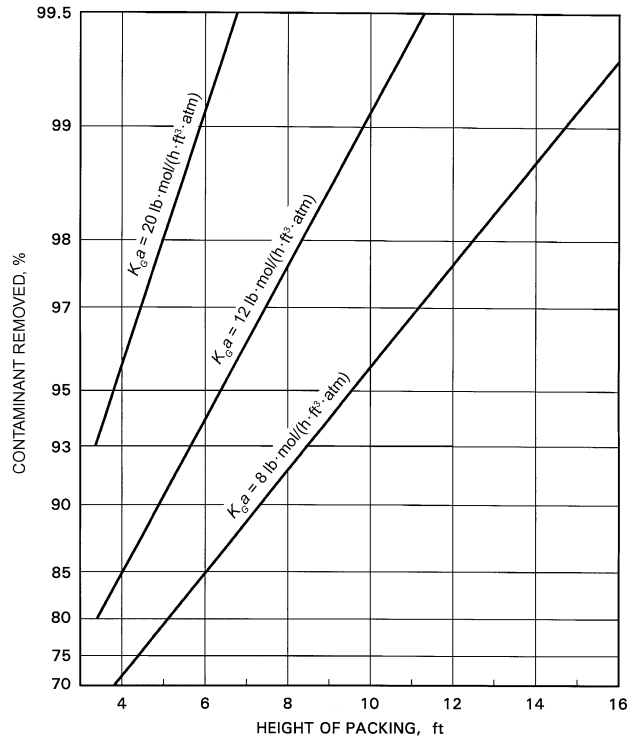


Fig. 33 Contaminant Control at Superficial Velocity = 120 fpm (Gas-Film-Controlled)

These graphs can be used to determine the height of 2 in. plastic Intalox saddles (see Figure 23) required to give the desired percentage of contaminant removal. The height for any other type or size of packing is inversely proportional to the ratio of standard  $K_G a$  taken

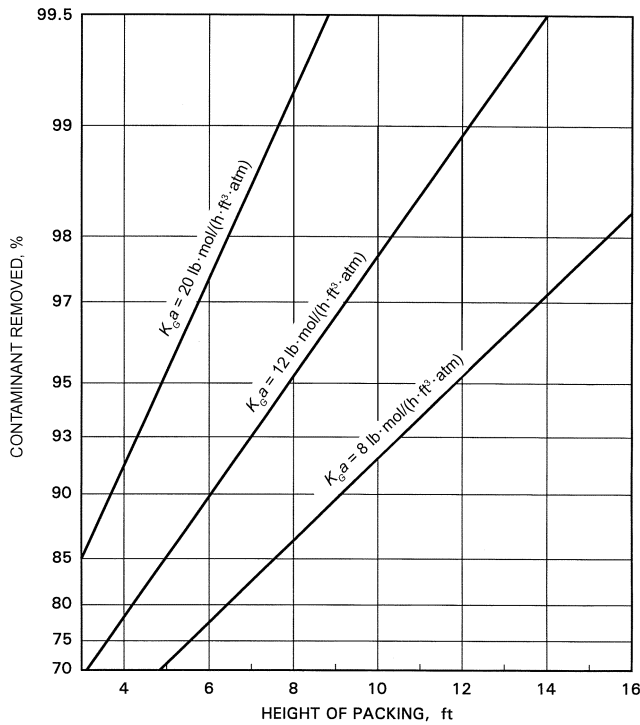


Fig. 34 Contaminant Control at Superficial Velocity = 240 fpm (Gas-Film-Controlled)

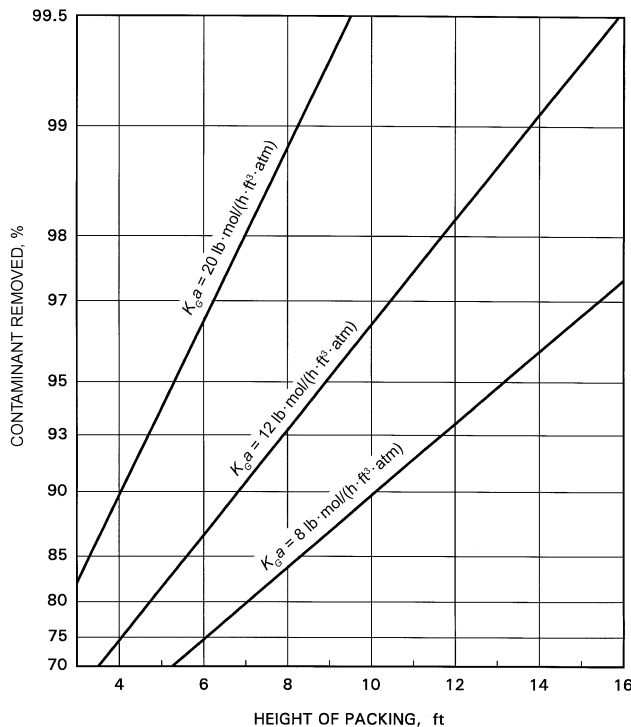


Fig. 35 Contaminant Control at Superficial Velocity = 360 fpm (Gas-Film-Controlled)

from Table 8. Thus, if 13 ft packing depth were required for 95% removal of contaminants, the same efficiency could be obtained with a 9.5 ft depth of 1 in. plastic pall rings (Figure 23), at the same superficial velocity and liquid injection rate. However, the pressure drop would be higher for the smaller-diameter packing.

Table 10 Relative  $K_G a$  for Various Contaminants in Gas-Film-Controlled Scrubbers

| Gas Contaminant | Scrubbing Liquid                              | $K_G a$                          |
|-----------------|---|----------------------------------|
|                 |   | lb·mol<br>h·ft <sup>3</sup> ·atm |
| HCl             | Water   | 18.66                            |
| HBr             | Water   | 5.92                             |
| HF              | Water   | 7.96                             |
| NH <sub>3</sub> | Water   | 17.30                            |
| Cl <sub>2</sub> | 8% (by mass) NaOH                             | 14.33                            |
| SO <sub>2</sub> | 11% (by mass) Na <sub>2</sub> CO <sub>3</sub> | 11.83                            |
| Br <sub>2</sub> | 5% (by mass) NaOH                             | 5.01                             |

Note: Data for 2 in. plastic Super Intalox. Temperatures 60 to 75°F; liquid rate 10 gpm/ft<sup>2</sup>; gas rate 215 cfm/ft<sup>2</sup>.

Figures 30 to 35 are useful when the value of the mass transfer coefficient for the particular contaminant to be removed is known. Table 9 contains mass transfer coefficients for 2 in. plastic Intalox saddles in typical liquid-film-controlled scrubbers. These values can be compared with the mass transfer coefficients in Table 10 for the same packing used in gas-film-controlled scrubbers. When the scrubbing liquid is not water, the mass transfer coefficients in these tables can only be used if the amount of reagent in the solution exceeds by at least 33% the amount needed to completely absorb the gaseous contaminant.

When HCl is dissolved in water, there is little vapor pressure of HCl above solutions of less than 8% (by mass) concentration. On the other hand, when NH<sub>3</sub> is dissolved in water, there is an appreciable vapor pressure of NH<sub>3</sub> above solutions, even at low concentrations. The height of packing needed for NH<sub>3</sub> removal, obtained from Figures 33 through 35, is based on the use of dilute acid to maintain the pH of the solution below 7.

The following is an example of a typical scrubbing problem.

**Example 1.** Remove 95% of the HF from air at 90°F. The concentration of HF is 600 ppm on a dry gas basis. The concentration of HF in the exhaust gas should not exceed 30 ppm.

The following design conditions apply:

- Total volumetric flow of gas  $G = 4600$  cfm
- Liquid injection rate  $= 3.75$  gpm/ft<sup>2</sup>
- Liquid temperature  $= 68^\circ\text{F}$
- Packed tower diameter  $= 4$  ft
- Packing material is 2 in. polypropylene Super Intalox

**Solution:**

Cross-sectional area of absorber

$$A = \pi(4/2)^2 = 12.6 \text{ ft}^2$$

Total liquid flow rate

$$L = 3.75 \times 12.6 = 47.1 \text{ gpm}$$

Packing factor (from Table 7)

$$F = 21$$

Figure 29 may be used to find the pressure drop through the packed tower:

$$\begin{aligned} x\text{-axis} &= 3.93(L/G) = 0.040 \\ y\text{-axis} &= (F/3.1 \times 10^6)(G/A)^2 = 0.90 \end{aligned}$$

From Figure 29, the pressure drop is about 0.28 in. of water per foot of packing depth.

From Table 10,  $K_G a = 0.35$  for HF. From Figure 33, the depth of packing required for 95% removal is 13 ft. Thus, the total pressure drop is  $13 \times 0.28 = 3.6$  in. of water.

### General Efficiency Comparisons

Figure 35 indicates that, with  $K_G a = 0.35$ , 90% removal of HF could be achieved with 10 ft of packing; this is 23% less packing than needed for 96% removal. Furthermore, with the same superficial velocity, both liquid-film- and gas-film-controlled systems require a 43% increase in absorbent depth to raise the removal efficiency from 80 to 90%.

A comparison of Figures 34 and 35 shows that increasing the superficial velocity by 50% in a gas-film-controlled scrubber requires only a 12% increase in bed depth to maintain equal removal efficiencies. In the liquid-film-controlled system (Figures 31 and 32), increasing the superficial velocity by 50% requires an approximately 50% increase in bed depth to maintain equal removal efficiencies.

Thus, in a gas-film-controlled system, the superficial velocity can be increased significantly with only a small increase in bed depth required to maintain the efficiency. In practical terms, gas-film-controlled scrubbers of fixed depth can handle an overload condition with only a minor loss of removal efficiency. The performance of liquid-film-controlled scrubbers degrades significantly under similar overload conditions. This occurs because the mass transfer coefficient is independent of superficial velocity.

### Liquid Effects

Some liquids tend to foam when they are contaminated with particulates or soluble salts. In these cases, the pressure drop should be kept in the lower half of the normal range: 0.25 to 0.40 in. of water per foot of packing depth.

In the control of gaseous pollution, most systems do not destroy the pollutant but merely remove it from the air. When water is used as the scrubbing liquid, effluent from the scrubber will contain suspended particulate or dissolved solute. Water treatment is often required to alter the pH and/or remove toxic substances before the solutions can be discharged.

### ADSORPTION OF GASEOUS CONTAMINANTS

The surface of freshly broken or heated solids often contains van der Waals (London dispersion) forces that are able to physically or chemically adsorb nearby molecules in a gas or liquid. The captured molecules form a thin layer on the surface of the solid that is typically one to three molecules thick. Commercial adsorbents are solids with an enormous internal surface area. This large surface area enables them to capture and hold large numbers of molecules. For example, each gram of a typical activated carbon adsorbent contains over 10,000 ft<sup>2</sup> of internal surface area. Adsorbents are used for removing organic vapors, water vapor, odors, and hazardous pollutants from gas streams.

The most common adsorbents used in industrial processes include activated carbons, activated alumina, silica gel, and molecular sieves. Activated carbons are derived from coal, wood, or coconut shells. They are primarily selected to remove organic compounds in preference to water. The other three common gas-phase adsorbents have a great affinity for water and will adsorb it to the exclusion of any organic molecules also present in a gas stream. They are used primarily as gas-drying agents. Molecular sieves also find use in several specialized pollution control applications, including removal of mercury vapor, sulfur dioxide (SO<sub>2</sub>), or nitrogen oxides (NO<sub>x</sub>) from gas streams. The capacity of a particular activated carbon to adsorb any organic vapor from an exhaust gas stream is related to the concentration and molecular weight of the organic compound and the temperature of the gas stream. Compounds with a higher molecular weight are usually more strongly adsorbed than those with lower molecular weight. The capacity of activated carbon to adsorb any given organic compound increases with the concentration of that compound. Reducing the temperature also favors adsorption. Typical adsorption capacities of an activated carbon for toluene (molecular weight 92) and acetone

(molecular weight 58) are illustrated in Figure 36 for various temperatures and concentrations.

**Regeneration.** Adsorption is reversible. An increase in temperature causes some or all of an adsorbed vapor to desorb. The temperature of low-pressure steam is sufficient to drive off most of a low-boiling-point organic compound previously adsorbed at ambient temperature. Higher-boiling-point organic compounds may require high-pressure steam or hot inert gas to secure good desorption. Compounds with a very high molecular weight can require reactivation of the carbon adsorber in a furnace at 1350°F to drive off all the adsorbed material. Regeneration of the carbon adsorbents can also be accomplished, in some instances, by washing with an aqueous solution of a chemical that will react with the adsorbed organic material, making it water soluble. An example is washing carbon containing adsorbed sulfur compounds with NaOH.

The difference between an adsorbent's capacity under adsorbing and desorbing conditions in any application is its **working capacity**. Activated carbon for air pollution control is found in canisters under the hoods of most automobiles. The adsorber in these canisters captures gasoline vapors escaping from the carburetor (when the engine is stopped) and from the fuel tank's breather vent. Desorption of gasoline vapors is accomplished by pulling fresh air through the carbon canister and into the carburetor when the engine is running. Although there is no temperature difference between adsorbing and desorbing conditions in this case, the outside airflow desorbs enough gasoline vapors to give the carbon a substantial working capacity.

For applications where only traces of a pollutant must be removed from exhaust air, the life of a carbon bed is very long. In these cases, it is often more economical to replace the carbon than to invest in regeneration equipment. Larger quantities can be returned to the carbon manufacturer for high-temperature thermal reactivation. Regeneration in place by steam, hot inert gas, or washing with a solution of alkali is sometimes practiced.

**Impregnated (chemically reactive) adsorbents** are used when physical adsorption alone is too weak to remove a particular gaseous contaminant from an industrial gas stream. Through impregnation, the reactive chemical is spread over the immense internal surface area of an adsorbent.

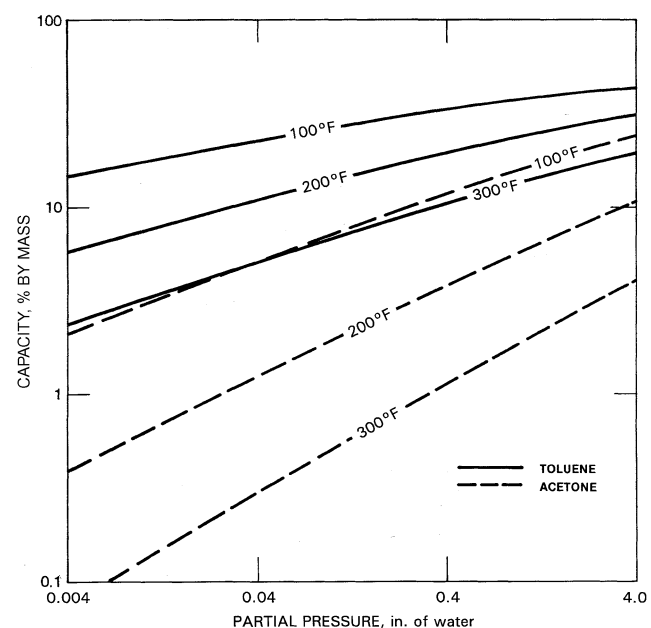


Fig. 36 Adsorption Isotherms on Activated Carbon

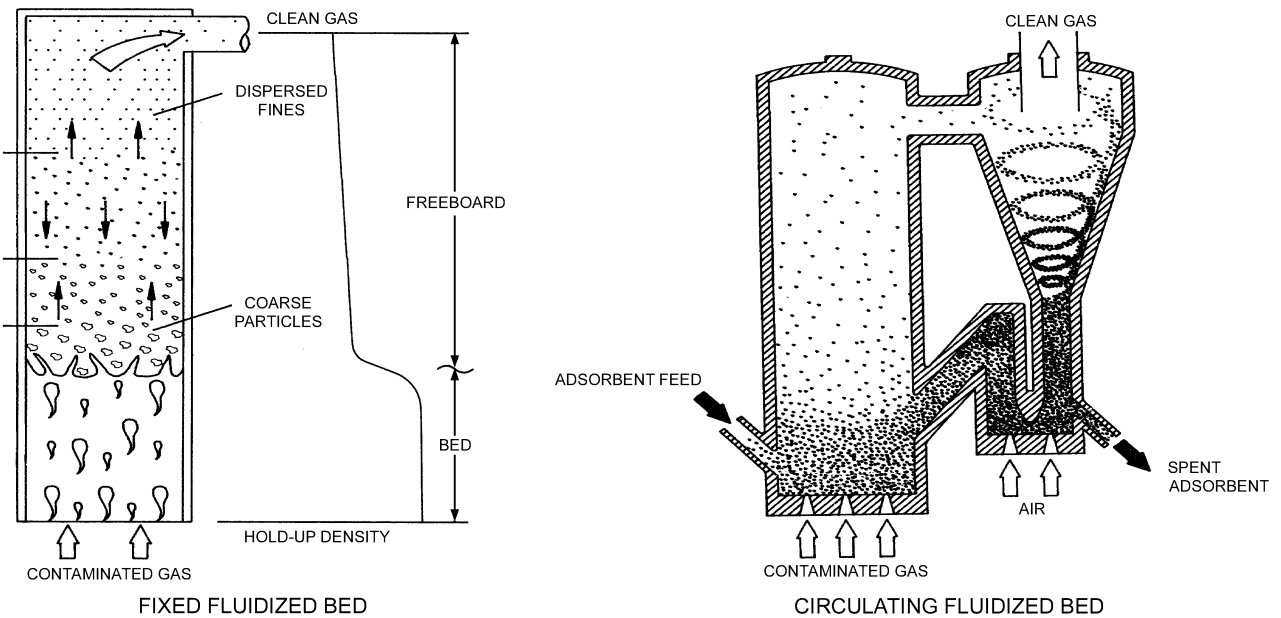


Fig. 37 Fluidized-Bed Adsorption Equipment

Typical applications of impregnated adsorbent include the following:

- Sulfur- or iodine-impregnated carbon removes mercury vapor from air, hydrogen, or other gases by forming mercuric sulfide or iodide.
- Metal oxide-impregnated carbons remove hydrogen sulfide.
- Amine- or iodine-impregnated carbons and silver exchanged zeolites remove radioactive methyl iodide from nuclear power plant work areas and exhaust gases.
- Alkali-impregnated carbons remove acid gases.
- Activated alumina impregnated with potassium permanganate removes acrolein and formaldehyde.

**Equipment for Adsorption**

Three types of adsorbers are usually found in industrial applications: (1) fixed beds, (2) moving beds, and (3) fluidized beds (Figure 37).

**Fixed beds** of regenerable or disposable media are most common. Carbon filter elements are a typical example.

**Moving beds** use granular adsorbers placed on inclined trays or on vertical frames similar to those used in granular bed particulate collectors. Moving beds offer continuous contaminant control and regeneration. Often, moving bed adsorbers and regeneration equipment are integrated components in a process.

**Fluidized beds** contain a fine granular adsorbent, which is continuously mixed with the contaminated gas by suspension in the process gas stream. The bed may be either “fixed” at lower superficial velocities or highly turbulent and conveying (circulating). Illustrations of these types of fluidized beds are shown in Figure 37.

**Solvent Recovery**

The most common use of adsorption in stationary sources is in recovering solvent vapors from manufacturing and cleaning processes. Typical applications include solvent degreasing, rotogravure printing, dry cleaning, and the manufacture of such products as synthetic fibers, adhesive labels, tapes, coated copying paper, rubber goods, and coated fabrics.

Figure 38 illustrates the components of a typical solvent recovery system using two carbon beds. One bed is used as an adsorber while the other is regenerated with low-pressure steam. Desorbed solvent

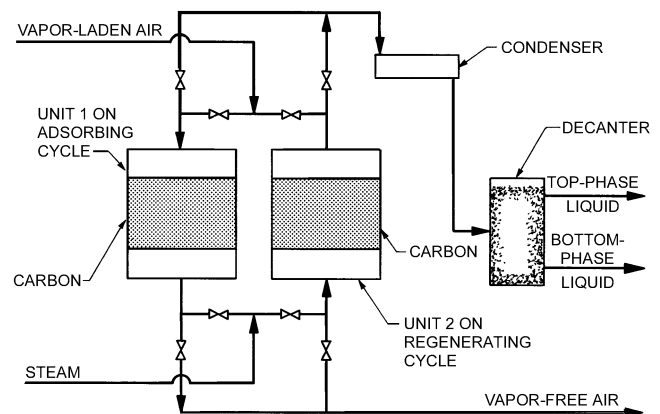


Fig. 38 Schematic of Two-Unit Fixed Bed Adsorber

vapor and steam are recovered in a water-cooled condenser. If the solvent is immiscible with water, an automatic decanter separates the solvent for reuse. A distillation column is used for water-miscible solvents.

Adsorption time per cycle typically runs from 30 min to several hours. The adsorbing carbon bed is switched to regeneration by (1) an automatic timer shortly before the solvent vapor breaks through from the bed or (2) an organic vapor-sensing control device in the exhaust gas stream immediately after the solvent breaks through from the bed.

Low-pressure steam consumption for regeneration is generally about 3.5 lb/h per pound of solvent recovered (Boll 1976), but it can range from 2 to over 5 lb/h per pound of solvent recovered, depending on the specific solvent and its concentration in the exhaust gas stream being stripped. Steam with only a slight superheat is normally used, so that it condenses quickly and gives rapid heat transfer.

After steaming, the hot, moist carbon bed is usually cooled and partially dried before being placed back on stream. Heat for drying is supplied by the cooling of the carbon and adsorber, and sometimes by an external air heater. In most cases, it is desirable to leave some moisture in the bed. When solvent vapors are adsorbed, heat

is generated. For most common solvents, the heat of adsorption is 40 to 60 Btu/lb·mol. When high-concentration vapors are adsorbed in a dry carbon bed, this heat can cause a substantial temperature rise and can even ignite the bed, unless it is controlled. If the bed contains moisture, the water absorbs energy and helps to prevent an undue rise in bed temperature. Certain applications may require heat sensors and automatic sprinklers.

Because the adsorptive capacity of activated carbon depends on temperature, it is important that solvent-laden air going to a recovery unit be as cool as is practicable. The exhaust gases from many solvent-emitting processes (such as drying ovens) are at elevated temperatures. Water- or air-cooled heat exchangers must be installed to reduce the temperature of the gas that enters the adsorber.

Solvent at very low vapor concentrations can be recovered in an activated carbon system. The size and cost of the recovery unit, however, depend on the volume of air to be handled; it is thus advantageous to minimize the volume of an exhaust stream and keep the solvent vapor concentration as high as possible, consistent with safety requirements. Insurance carriers specify that solvent vapor concentrations must not exceed 25% of the lower explosive limit (LEL) when intermittent monitoring is used. With continuous monitoring, concentrations as high as 50% of the LEL are permissible.

Solvent recovery systems, with gas-handling capacities up to about 11,000 cfm, are available as skid-mounted packages. Several of these packaged units can be used for larger gas flows. Custom systems can be built to handle 200,000 cfm or more of gas. Materials of construction may be painted carbon steel, stainless steel, Monel, or even titanium, depending on the nature of the gas mixture. The activated carbon is usually placed in horizontal flat beds or vertical cylindrical beds. The latter design minimizes ground space required for the system. Other alternatives are possible; one manufacturer uses a segmented horizontal rotating cylinder of carbon in which one segment is adsorbing while others are being steamed and cooled.

Commercial-scale solvent recovery systems typically recover over 99% of the solvent contained in a gas stream. The efficiency of the collecting hoods at the source of the solvent emission is usually the determining factor in solvent recovery.

Dust filters are generally placed ahead of carbon beds to prevent blinding of the adsorber by dust. Occasionally, the carbon is removed for screening to eliminate accumulated dust and fine particles of carbon.

If the solvent mixture contains high-boiling-point components, the working capacity of activated carbon can decrease with time. This occurs when high-boiling-point organic compounds are only partially removed by low-pressure steam. In this situation, two alternatives should be considered:

1. Periodic removal of the carbon and return to its manufacturer for high-temperature furnace reactivation to virgin carbon activity.
2. Use of more rigorous solvent desorbing conditions in the solvent recovery system. High-temperature steam, hot inert gas, or a combination of electrical heating and application of a vacuum may be used. The last method is selected, for example, to recover lithography ink solvents with high boiling points. Note that this method may not remove all of the high-boiling-point compounds.

### Odor Control

Incineration and scrubbing are usually the most economical methods of controlling high concentrations of odorous compounds from equipment such as cookers in rendering plants. However, many odors that arise from harmlessly low concentrations of vapors are still offensive. The odor threshold (for 100% response) of acrolein in air, for example, is only 0.21 ppm, whereas that for ethyl mercaptan is 0.001 ppm and that for hydrogen sulfide is 0.0005 ppm (AIHA 1989; MCA 1968). Activated carbon beds effectively

overcome many odor emission problems. Activated carbon is used to control odors from chemical and pharmaceutical manufacturing operations, foundries, sewage treating plants, oil and chemical storage tanks, lacquer drying ovens, food processing plants, and rendering plants. In some of these applications, activated carbon is the sole odor control method; in others, the carbon adsorber is applied to the exhaust from a scrubber.

Odor control systems using activated carbon can be as simple as a steel drum fitted with appropriate gas inlet and outlet ducts, or as complex as a large, vertically moving bed, in which carbon is contained between louvered side panels. A typical moving-bed adsorber is shown in Figure 39. In this arrangement, fresh carbon can be added at the top, and spent or dust-laden carbon is periodically removed from the bottom.

Figure 40 shows a fixed-bed odor adsorber. Adsorbers of this general configuration are available as packaged systems, complete with motor and blower. Air-handling capacities range from 500 to 12,000 cfm.

The life of activated carbon in odor control systems ranges from a few weeks to a year or more, depending on the concentration of the odorous emission.

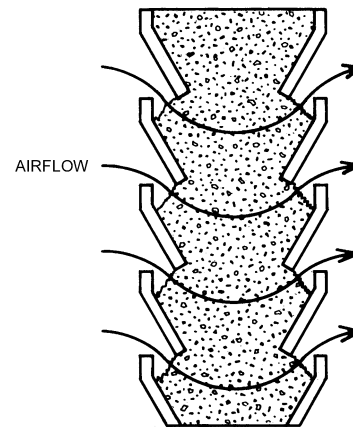


Fig. 39 Moving-Bed Adsorber

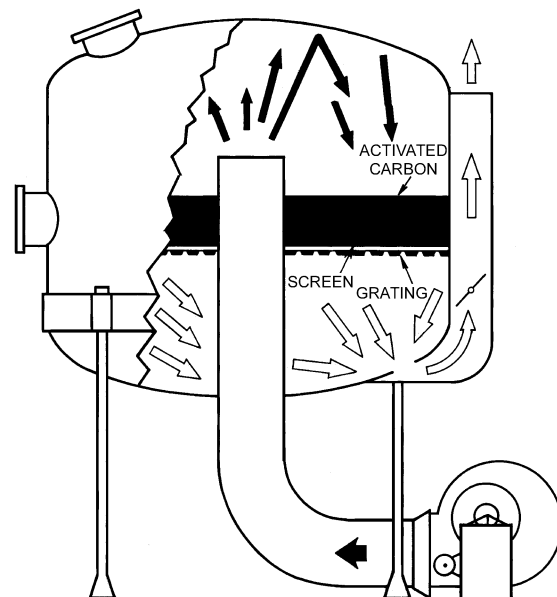


Fig. 40 Typical Odor Adsorber

### Applications of Fluidized Bed Adsorbers

The injection of alkali compounds into fluidized bed combustors for control of sulfur-containing compounds is one example of the use of fluidized bed adsorbers. Another example is the control of HF emissions from Söderberg aluminum reduction processes by a fixed or circulating fluidized bed of alumina.

### INCINERATION OF GASES AND VAPORS

Incineration is the process by which volatile organic compounds (VOCs), organic aerosols, and most odorous materials in a contaminated gas stream are converted to innocuous carbon dioxide and water vapor using heat energy. Incineration is an effective means for totally eliminating VOCs. The types of incineration commonly used for air pollution control are thermal and catalytic, sometimes with recuperative or regenerative heat recovery.

To differentiate such air-cleaning systems from liquid and solid waste incinerators, the preferred term to describe such gas and aerosol phase air pollution control systems is now **oxidizers**.

#### Thermal Oxidizers

Thermal oxidizers, also known as **afterburners** or **direct flame incinerators**, consist of an insulated oxidation chamber in which gas and/or oil burners are typically located. The contaminated gas stream enters the chamber and comes into direct contact with the flame, which provides the heat energy necessary to promote oxidation. Under the proper conditions of time, temperature, and turbulence, the gas stream contaminants are oxidized effectively. The contaminated gas stream enters the combustion chamber near the burner, where turbulence-inducing devices are usually installed. The final contaminant conversion efficiency largely depends on good mixing within the contaminated gas stream and on the temperature of the oxidation chamber.

Supplemental fuel is used for start-up, to raise the temperature of the contaminated gas stream enough to initiate contaminant oxidation. Once oxidation begins, the temperature rises further because of the energy released by combustion of the contaminant. The supplementary fuel feed rate is then modulated to maintain the desired oxidizer operating temperature. Most organic gases oxidize to approximately 90% conversion efficiency if a temperature of at least 1200°F and a residence time of 0.3 to 0.5 s are achieved within the oxidation chamber. However, oxidation temperatures are typically maintained in the range of 1400 to 1500°F with residence times of 0.5 to 1 s to ensure conversion efficiencies of 95% or greater.

Although the efficiency of thermal oxidizers can exceed 95% destruction of the contaminant, the reaction may form undesirable products of combustion. For example, oxidation of chlorinated hydrocarbons causes the formation of hydrogen chloride, which can have an adverse effect on equipment. These new contaminants then require additional controls.

Oxidation systems incorporate primary heat recovery to preheat the incoming contaminated gas stream and, in some cases, provide secondary heat recovery for process or building heating. Primary heat recovery is almost always achieved using air-to-air heat exchangers. Use of a regenerable, ceramic medium for heat recovery has increased due to superior heat recovery efficiency. Secondary heat recovery may incorporate an air-to-air heat exchanger or a waste heat boiler (DOE 1979).

Oxidation systems using conventional air-to-air heat exchangers can achieve up to 80% heat recovery efficiency. Regenerative heat exchanger units have claimed as high as 95% heat recovery efficiency and are routinely operated at 85 to 90%. When operated at these high heat recovery efficiencies and with inlet VOC concentrations of 15 to 25% of the LEL, the oxidation process approaches a self-sustaining condition, requiring very little supplementary fuel.

### Catalytic Oxidizers

Catalytic oxidizers operate under the same principles as thermal oxidizers, except that they use a catalyst to promote oxidation. The catalyst allows oxidation to occur at lower temperatures than in a thermal oxidizer for the same VOC concentration. Therefore, catalytic oxidizers require less supplemental fuel to preheat the contaminated gas stream and have lower overall operating temperatures.

A catalytic oxidizer generally consists of a preheat chamber followed by the catalyst bed. Residence time and turbulence are not as important as with thermal oxidizers, but it is essential that the contaminated gas stream be heated uniformly to the required catalytic reaction temperature. The required temperature varies, depending on the catalyst material and configuration.

The temperature of the contaminated gas stream is raised in the preheat chamber by a conventional burner. Although the contaminated gas stream contacts the burner flame, the heat input is significantly less than that for a thermal oxidizer, and only a small degree of direct contaminant oxidation occurs. Natural gas is preferred to prevent catalyst contamination, which could occur with sulfur-bearing fuel oils. However, No. 2 fuel oil units have been operated successfully. The most effective catalysts contain noble metals such as platinum or palladium.

Catalysis occurs at the molecular level. Therefore, an available, active catalyst surface area is important for maintaining high conversion efficiencies. If particulate materials contact the catalyst as either discrete or partially oxidized aerosols, they can ash on the catalyst surface and blind it. This problem is usually accompanied by a secondary pollution problem: odorous emissions caused by the partially oxidized organic compounds.

The greatest concern to users of catalytic oxidizers is **catalyst poisoning or deactivation**. Poisoning is caused by specific gas stream contaminants that chemically combine or alloy with the active catalyst material. Poisons frequently cited include phosphorus, bismuth, arsenic, antimony, lead, tin, and zinc. The first five materials are considered fast-acting poisons and must be excluded from the contaminated gas stream. Even trace quantities of the fast-acting poisons can cause rapid catalyst deactivation. The last two materials are slow-acting poisons; catalysts are somewhat tolerant of these materials, particularly at temperatures lower than 1000°F. However, even the slow poisons should be excluded from the contaminated gas stream to ensure continuous, reliable performance. Therefore, galvanized steel, another possible source of the slow poisons, should not be used for the duct leading to the oxidizer.

Sulfur and halogens are also regarded as catalyst poisons. In most cases, their chemical interaction with the active catalyst material is reversible. That is, catalyst activity can be restored by operating the catalyst without the halogen or sulfur-bearing compound in the gas stream. The potential problem of greater concern with respect to the halogen-bearing compounds is the formation of hydrogen chloride or hydrogen fluoride gas, or hydrochloric or hydrofluoric acid emissions.

Some organic compounds, such as polyester amides and imides, are also poisonous.

Catalytic oxidizers generally cost less to operate than thermal oxidizers because of their lower fuel consumption. With the exception of regenerative heat recovery techniques, primary and secondary heat recovery can be incorporated into a catalytic oxidation system to further reduce operating costs. Maintenance costs are usually higher for catalytic units, particularly if frequent catalyst cleaning or replacement is necessary. Concern over catalyst life has been the major factor limiting more widespread application of catalytic oxidizers.

#### Applications of Oxidizers

**Odor Control.** All highly odorous pollutant gases are combustible or chemically changed to less odorous pollutants when they are sufficiently heated. Often, the concentration of odorous materials in

the waste gas is extremely low, and the only feasible method of control is oxidation. Odors from rendering plants, mercaptans, and organic sulfides from kraft pulping operations are examples of effluents that can be controlled by incineration. Other forms of oxidation can achieve the same ends (see Chapter 44 of the 2007 *ASHRAE Handbook—HVAC Applications*).

**Reduction in Emissions of Reactive Hydrocarbons.** Some air pollution control agencies regulate the emission of organic gases and vapors because of their involvement in photochemical smog reactions. Flame afterburning is an effective way of destroying these materials.

**Reduction in Explosion Hazard.** Refineries and chemical plants are among the factories that must dispose of highly combustible or otherwise dangerous organic materials. The safest method of disposal is usually by burning in flares or in specially designed furnaces. However, special precautions and equipment design must be used in the handling of potentially explosive mixtures.

### Adsorption and Oxidation

Alternate cycles of adsorption and desorption in an activated carbon bed are used to concentrate solvent or odor vapors before oxidation. This technique greatly reduces the fuel required for burning organic vapor emissions. Fuel savings of 98% compared to direct oxidation are possible. The process is particularly useful in cases where emission levels vary from hour to hour. This technique is common in metal finishing for automotive and office furniture manufacturing.

Contaminated gas is passed through a carbon bed until saturation occurs. The gas stream is then switched to another carbon bed, and the exhausted bed is shut down for desorption. A hot inert gas, usually burner flue gas, is introduced to the adsorber to drive off concentrated organic vapors and to convey them to an oxidizer. The volume of this desorbing gas stream is much smaller than the original contaminated gas volume, so that only a small oxidizer, operating intermittently, is required (Grandjacques 1977).

## AUXILIARY EQUIPMENT

### DUCTS

Basic duct design is covered in Chapter 35 of the 2005 *ASHRAE Handbook—Fundamentals*. This chapter covers only those duct components or problems that warrant special concern when handling gases that contain particulate or gaseous contaminants.

Duct systems should be designed to allow thermal expansion or contraction as gases move from the process, through gas-cleaning equipment, and on to the ambient environment. Appropriately designed duct expansion joints must be located in proper relation to sliding and fixed duct supports. Besides withstanding maximum possible temperature, duct must also withstand maximum positive or negative pressure, a partial load of accumulated dust, and reasonable amounts of corrosion. Duct supports should be designed to accommodate these overload conditions as well. Bottom entries into duct junctions create a low-velocity area that can allow contaminants to settle out, thus creating a potential fire hazard. Bottom duct entries should be avoided.

Where gases might condense and cause corrosion or sticky deposits, duct should be insulated or fabricated from materials that will survive this environment. A psychrometric analysis of the exhaust gases is useful to determine the dew point. Surface temperatures should then be held above the dew-point temperature by preheating on start-up or by insulating. Slag traps with clean-out doors, inspection doors where direction changes, and dead-end full-sized caps are required for systems having heavy particulate loading. Special attention should be given to high-temperature duct, where the duct might corrode if insulated or become encrusted when molten particulate impacts on cool, uninsulated surfaces. Water-cooled

duct or refractory lining is often used where the high operating temperature exceeds the safe limits of low-cost materials.

Gas flow through ducts should be considered as a part of overall system design. Good gas flow distribution is essential for measurements of process conditions and can lead to energy savings and increased system life. The minimum speed of gases in a duct should be sufficiently high to convey the heaviest particulate fraction with a degree of safety.

Slide gates, balance gates, equipment bypass ducts, and clean-out doors should be incorporated in the duct system to allow for maintenance of key gas-cleaning systems. In some cases, emergency bypass circuitry should be included to vent emissions and protect gas-cleaning equipment from process upsets.

### Temperature Controls

Control of gas temperature in a gas-cleaning system is often vital to a system's performance and life. In some cases, gases are cooled to concentrate contaminants, condense gases, and recover energy. In other cases, gas-cleaning equipment, such as fabric filters and scrubbers, can only operate at well-controlled temperatures. Cooling exhaust gases through air-to-air heat transfer has been highly successful in many applications. Controlled evaporative cooling is also used, but it increases the dew point and the danger of acid gas condensation and/or the formation of sticky deposits. However, controlled evaporative cooling to within 50°F of dew point has been used with success. Dilution by the injection of ambient air into the duct is expensive because it increases the volumetric flow of gas and, consequently, the size of collector needed to meet gas-cleaning objectives. Water-cooled duct is often used where the gas temperature exceeds the safe limits of the low-cost materials.

For dilution cooling, louver-type dampers are often used to inject ambient air and provide fine temperature control. Controls can be used to provide full modulation of the damper or to provide open or closed operation. Emergency bypass damper systems and bypass duct/stacks are used where limiting excessive temperature is critical.

### Fans

Because the static pressure across a gas-cleaning device varies depending on conditions, the fan should operate on the steep portion of the fan pressure-volumetric flow curve. This tends to provide less variation in the volumetric flow. An undersized fan has a steeper characteristic than an oversized fan for the same duty; however, it will be noisier.

In the preferred arrangement, the fan is located on the clean gas side of gas-cleaning equipment. Advantages of placing the fan at this point include the following:

- A fan on the clean gas side handles clean gases and minimizes abrasive exposure from the collected product.
- High-efficiency backward-blade and airfoil designs can be selected because accumulation on the fan wheel is not as great a factor.
- Escape of hazardous materials through leaks is minimized.
- The collector can be installed inside the plant, even near the process, because any leakage in the duct or collector will be into the system and will not increase the potential for exposure. However, the fan itself should be mounted outside, so that the positive-pressure duct is outside the work environment.

For economic reasons, a fan may be located on the contaminant-laden side of the gas-cleaning equipment if the contaminants are relatively nonabrasive, and especially if the equipment can be located outdoors. This arrangement should be avoided because of the potential for leakage of concentrated contaminants to the environment. In some instances, however, the collector housing design, duct design, and energy savings of this arrangement reduce costs.

Most scrubbers are operated on the suction side of the fan. This not only eliminates the leakage of contaminants into the work area, but also allows for servicing the unit while it is in operation.

Additionally, such an arrangement minimizes corrosion of the fan. Stacks on the exhaust streams of scrubbers should be arranged to drain condensate rather than allow it to accumulate and reenter the fan.

Fabric filters require special consideration. When new, clean fabric is installed in a collector, the resistance is low, and the fan motor may be overloaded. This overloading may be prevented during start-up by using a temporary throttling damper in the main duct, for example, on the clean side of the filter in a pull-through system. Overloading may also be prevented by using a backward-curved blade (nonoverloading fan) on the clean side of the collector.

### DUST- AND SLURRY-HANDLING EQUIPMENT

Once the particulate matter is collected, new control problems arise from the need to remove, transport, and dispose of the material from the collector. A study of all potential methods for handling the collected material, which might be a hazardous waste, must be an integral part of initial system design.

#### Hoppers

Dust collector hoppers are intended only to channel collected material to the hopper's outlet, where it is continuously discharged. When hoppers are used to store dust, the plates and charging electrodes of electrostatic precipitators can be shorted electrically, resulting in failure of entire electrical sections. Fabric collectors, particularly those that have the gas inlet in the hopper, are usually designed on the assumption that the hopper is not used for storage and that collected waste will be continuously removed. High dust levels in the hoppers of fabric collectors often result in high dust reentrainment. This reentrainment causes increased operating pressure and the potential for fabric damage. The excessive dust levels not only expose the system to potentially corrosive conditions and fire/explosion hazards, but also place increased structural demands on the system.

Aside from misuse of hoppers for storage, common problems with dust-handling equipment include (1) plugging of hoppers, (2) blockage of dust valves with solid objects, and (3) improper or insufficient maintenance.

Hopper auxiliaries to be considered include (1) insulation, (2) dust level indicators, (3) rapper plates, (4) vibrators, (5) heaters, and (6) "poke" holes.

**Hopper Discharge.** Dust is often removed continuously from hoppers by means of rotary valves. Alternative equipment includes the double-flap valve, or vacuum system valves. Wet electrostatic precipitators and scrubbers often use sluice valves and drains to ensure that insoluble particulate remains in suspension during discharge.

#### Dust Conveyors

Larger dust collectors are fitted with one or more conveyors to feed dust to a central discharge location or to return it to a process. Drag, screw, and pneumatic conveyors are commonly used with dust collectors. Sequential start-up of conveyor systems is essential. Motion switches to monitor operation of the conveyor are useful.

#### Dust Disposal

Several methods are available for disposal of collected dust. It can be emptied into dumpsters in its as-collected dry form or be pelletized and hauled to a landfill. It can also be converted to a slurry and pumped to a settling pond or to clarification equipment. The advantages and disadvantages of each method are beyond the scope of this chapter, but they should be evaluated for each application.

#### Slurry Treatment

When slurry from wet collectors cannot be returned directly to the process or tailing pond, liquid clarification and treatment systems can be used for recycling the water to prevent stream pollution.

Stringent stream pollution regulations make even a small discharge of bleed water a problem. Clarification equipment may include settling tanks, sludge-handling facilities, and, possibly, centrifuges or vacuum filters. Provisions must be provided for handling and disposal of dewatered sludge, so that secondary pollution problems do not develop.

## OPERATION AND MAINTENANCE

A planned program for operation and maintenance of equipment is a necessity. Such programs are becoming mandatory because of the need for operators to prove continuous compliance with emission regulations. Good housekeeping and record-keeping will also help prolong the life of the equipment, support a program for positive relations with regulatory and community groups, and aid problem-solving efforts, should nonroutine maintenance or service be necessary.

A typical program includes the following minimum requirements (Stern et al. 1984):

- Central location for filing equipment records, warranties, instruction manuals, etc.
- Lubrication and cleaning schedules
- Planning and scheduling of preventive maintenance (including inspection and major repair)
- Storeroom and inventory system for spare parts and supplies
- Listing of maintenance personnel (including supplier contacts and consultants)
- Costs and budgets for activities associated with operation and maintenance of the equipment
- Storage for special tools and equipment

#### Corrosion

Because high-temperature gas cleaning often involves corrosive materials, chemical attack on system components must be anticipated. This is especially true if the temperature in a gas-cleaning system falls below the moisture or acid dew point. Housing insulation should be such that the internal metal surface temperature is 20 to 30°F greater than the moisture and/or acid dew point at all times. In applications with fabric filters where alkali materials are injected into the gas stream to react with acid gases, care must be taken to protect the clean side of the housing downstream of the fabric from corrosion.

#### Fires and Explosions

Industrial gas-cleaning systems often concentrate combustible materials and expose them to environments that are hostile and difficult to control. These environments also make fires difficult to detect and stop. Industrial gas-cleaning systems are, therefore, potential fire or explosion hazards (Billings and Wilder 1970; EEI 1980; Frank 1981).

Fires and explosions in industrial process exhaust streams are not generally limited to gas-cleaning equipment. Ignition may take place in the process itself, in the duct, or in exhaust system components other than the gas-cleaning equipment. Once uncontrolled combustion begins, it may propagate throughout the system. Workers around pollution control equipment should never open access doors to gas-cleaning equipment when a fire is believed to be in process; the fire could easily transform into an explosion.

The following devices help maintain a safe particulate control system.

**Explosion Doors.** An explosion door or explosion relief valve permits instantaneous pressure relief for equipment when the pressure reaches a predetermined level. Explosion doors are mandatory for certain applications to meet OSHA, insurance, or National Fire Protection Association (NFPA) regulations.

**Detectors.** Temperature-actuated switches or infrared sensors can be used to detect changes in the inlet-to-outlet temperature difference or a localized, elevated temperature that might signal a

fire within the gas-cleaning system or a process upset. These detectors can be used to activate bypass dampers, trigger fire alarm/control systems, and/or shut down fans.

**Fire Control Systems.** Inert gas and water spray systems can be used to control fires in dust collectors. They are of little value in controlling explosions.

## REFERENCES

- AIHA. 1989. *Odor thresholds for chemicals with established occupational health standards*. American Industrial Hygiene Association, Akron, OH.
- Beck, A.J. 1975. Heat treat engineering. *Heat Treating* (January).
- Beltran, M.R. 1972. Smoke abatement for textile finishers. *American Dye-stuff Reporter* (August).
- Beltran, M.R. and H. Surati. 1976. Heat recovery vs. evaporative cooling on organic electrostatic precipitators. *Proceedings of the American Institute of Plant Engineers/Rossmagel & Associates Sixth Annual Industrial Air Pollution Control Seminar* (April 6, 1976), Cherry Hill, NJ.
- Billings, C.E. and J. Wilder. 1970. *Handbook of fabric filter technology*, vol. 1: Fabric filter systems study. NTIS Publication PB 200 648, 2-201. National Technical Information Service, Springfield, VA.
- Boll, C.H. 1976. Recovering solvents by adsorption. *Plant Engineering* (January).
- Chopyk, J. and M.C. Larkin. 1982. Smoke and odor subdued with two-stage precipitator. *Plant Services* (January).
- DOE. 1979. The coating industry: Energy savings with volatile organic compound emission control. Report TID-28706, U.S. Department of Energy, Washington, D.C.
- EEL. 1980. Air preheaters and electrostatic precipitators fire prevention and protection (coal fired boilers). *Report of the Fire Protection Committee 06-80-07* (September). Edison Electric Institute, Washington, D.C.
- EPA. 2004. Air quality criteria for particulate matter. EPA 600/P-99/002aF-bF. U.S. Environmental Protection Agency, Washington, D.C. <http://cfpub2.epa.gov/ncea/cfm/recordisplay.cfm?deid=87903>. (October 2004)
- Frank, T.E. 1981. Fire and explosion control in bag filter dust collection systems. *Proceedings of the Conference on the Hazards of Industrial Explosions from Dusts, New Orleans, LA* (October).
- Grandjacques, B. 1977. Carbon adsorption can provide air pollution control with savings. *Pollution Engineering* (August).
- IGCI. 1964. Determination of particulate collection efficiency of gas scrubbers. *Publication 1*. Industrial Gas Cleaning Institute, Washington, D.C.
- Kane, J.M. and J.L. Alden. 1982. *Design of industrial ventilation systems*. Industrial Press, New York.
- Lapple, C.E. 1951. Processes use many collection types. *Chemical Engineering* (May):145-151.
- Lapple, C.E. and H.J. Kamack. 1955. Performance of wet scrubbers. *Chemical Engineering Progress* (March).
- MCA. 1968. *Odor thresholds for 53 commercial chemicals*. Manufacturing Chemists Association, Washington, D.C. (October).
- Rossmagel, W.B. 1973. Condensing/precipitator systems on organic emissions. *Proceedings of the Third Annual Industrial Air Pollution Control Seminar* (May 8, 1973), Paramus, NJ.
- Rudnick, S.N., J.L.M. Koehler, K.P. Martin, D. Leith, and D.W. Cooper. 1986. Particle collection efficiency in a venturi scrubber: Comparison of experiments with theory. *Environmental Science & Technology* 20(3): 237-242.
- Sauerland, W.A. 1976. Successful application of electrostatic precipitators on asphalt saturator emissions. *Proceedings of the American Institute of Plant Engineers/Rossmagel & Associates Sixth Annual Industrial Air Pollution Control Seminar* (April 6, 1976), Cherry Hill, NJ.
- Semrau, K.T. 1977. Practical process design of particulate scrubbers. *Chemical Engineering* (September):87-91.
- Shabsin, J. 1985. Clean plant air PLUS energy conservation. *Fastener Technology* (April).
- Stern, A.C., R.W. Boubel, D.B. Turner, and D.L. Fox. 1984. *Fundamentals of air pollution control*, 2nd ed. Chapter 25, Control Devices and Systems. Academic Press, San Diego.
- Thiel, G.R. 1977. Advances in electrostatic control techniques for organic emissions. *Proceedings of the Seventh Annual Industrial Air Pollution/Contamination Control Seminar* (March 29, 1977), Paramus, NJ.
- Thiel, G.R. 1983. Cleaning and recycling plant air . . . Improvement of air cleaner performance and recirculation procedures. *Plant Engineering* (January 6).
- Wade, G., J. Wigton, J. Guillory, G. Goldback, and K. Phillips. 1978. Granular bed filter development program. U.S. DOE Report FE-2579-19 (April).
- White, H.J. 1963. *Industrial electrostatic precipitation*. Addison-Wesley, Reading, MA.

## BIBLIOGRAPHY

- ACGIH. 2006. *Industrial ventilation: A manual of recommended practice*, 23rd ed. Committee on Industrial Ventilation, American Conference of Governmental Industrial Hygienists, Cincinnati, OH.
- Bergin, M.H., D.Y.H. Pui, T.H. Kuehn, and W.T. Fay. 1989. Laboratory and field measurements of fractional efficiency of industrial dust collectors. *ASHRAE Transactions* 95(2):102-112.
- Buonicore, A.J. and W.T. Davis, eds. 1992. *Air pollution engineering manual*. Van Nostrand Reinhold, New York.
- Cryneck, R.B. and J.D. Sherow. 1984. Use of a mobile electrostatic precipitator for pilot studies. *Proceedings of the Fifth Symposium on the Transfer and Utilization of Particulate Control Technology* 2:3-1.
- Deutsch, W. 1922. Bewegung und Ladung der Elektrizitätsträger im Zylinderkondensator. *Annalen der Physik* 68:335.
- DuBard, J.L. and R.F. Altman. 1984. Analysis of error in precipitator performance estimates. *Proceedings of the Fifth Symposium on the Transfer and Utilization of Particulate Control Technology* 2:2-1.
- EPA. 1994. Quality assurance handbook for air pollution measurement systems. Report EPA-600R94038A. Environmental Protection Agency, Washington, D.C.
- Faulkner, M.G. and J.L. DuBard. 1984. A mathematical model of electrostatic precipitation, 3rd ed. *Publication EPA-600/7-84-069a*. Environmental Protection Agency, Washington, D.C.
- GPO. Annual. *Code of federal regulations* 40(60). U.S. Government Printing Office, Washington, D.C. Revised annually and published in July.
- Hall, H.J. 1975. Design and application of high voltage power supplies in electrostatic precipitation. *Journal of the Air Pollution Control Association* 25(2).
- HEW. 1967. Air pollution engineering manual. *Publication 999-AP-40*. Department of Health and Human Services (formerly Department of Health, Education, and Welfare), Washington, D.C.
- NIOSH. 1978. A recommended approach to recirculation of exhaust air. *Publication 78-124*. National Institute of Occupational Safety and Health, Washington, D.C.
- Noll, C.G. 1984. Electrostatic precipitation of particulate emissions from the melting of borosilicate and lead glasses. *Glass Technology* (April).
- Noll, C.G. 1984. Demonstration of a two-stage electrostatic precipitator for application to industrial processes. *Proceedings of the Second International Conference on Electrostatic Precipitation*, Kyoto, Japan (November), pp. 428-434.
- Oglesby, S. and G.B. Nichols. 1970. *A manual of electrostatic precipitator technology*. NTIS PB-196-380. National Technical Information Service, Springfield, VA.
- Sink, M.K. 1991. Handbook: Control technologies for hazardous air pollutants. Report EPA/625/6-91/014. Environmental Protection Agency, Washington, D.C.
- SIP. 1991. State implementation plans and guidance available from the Regional Offices of the U.S. EPA and state environmental authorities.
- White, H.J. 1974. Resistivity problems in electrostatic precipitation. *Journal of the Air Pollution Control Association* 24(4).

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